

Characterisation and modelling of the interaction between sub-Kelvin bolometric detectors and cosmic rays

Samantha Lynn Stever

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Characterisation and modelling of the interaction between sub-Kelvin bolometric detectors and cosmic rays

Thèse de doctorat de l'Université Paris-Saclay préparée à l'Université Paris-Sud

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Thèse présentée et soutenue à Orsay, le 8 Janvier 2019, par

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For those of us who were imprinted with fear like a faint line in the center of our foreheads learning to be afraid with our mother's milk for by this weapon this illusion of some safety to be found the heavy-footed hoped to silence us For all of us this instant and this triumph We were never meant to survive.

And when the sun rises we are afraid it might not remain when the sun sets we are afraid it might not rise in the morning when our stomachs are full we are afraid of indigestion when our stomachs are empty we are afraid we may never eat again when we are loved we are afraid love will vanish when we are alone we are afraid love will never return and when we speak we are afraid our words will not be heard nor welcomed but when we are silent we are still afraid

> So it is better to speak remembering we were never meant to survive. - Audre Lorde

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Part I

Introduction
Let woman ask herself, 'Why am I the slave of man? Why is my brain said not to be the equal of his brain? Why is my work not paid equally with his?'

Voltairine de Cleyre, 1890

Chapter

Introduction

The work in this manuscript is predicated upon one question: What effect do cosmic rays have on detectors used in CMB / X-ray space missions, and what is the nature of those effects? Can systematic effects arising from cosmic rays in space missions be predicted or removed?

The answer appears to be obvious in the 'post-Planck' context, which we will introduce in this chapter. The reality, however, is more complex, and we have taken a few avenues here to explore it.

In this chapter, we shall describe the overall context of the 'cosmic ray problem', specifically the Planck experience and the work which was done upon its completion. We will start by (of course) describing cosmic rays and their role in space missions, and the experience of Planck and other missions. We will briefly describe bolometer theory and other relevant physics under the umbrella of the 'cosmic ray problem'.

The following chapters will examine our efforts to understand and model these interactions, using a composite semiconductor bolometer, and later by modelling cosmic ray interactions on the detector wafer level for an X-ray mission under development.



Figure 1.1. A plot of cosmic ray flux vs. particle energy. Yellow: Solar energetic particles; Blue: Galactic cosmic rays of galactic origin; Purple: Galactic cosmic rays of extragalactic origin. Taken from [1] (ⓒ)).

1.1 A brief history of cosmic rays

Cosmic rays (CRs) are high-velocity energetic particles or atomic nuclei travelling through space. Cosmic rays are as varied as they are numerous; primary cosmic rays (i.e. cosmic rays which originate outside of the atmosphere of Earth) are largely composed of nuclei - the majority of which are protons or alpha particles (\approx 99%), and a minority of which are heavy-element nuclei. Cosmic ray flux scales inversely with energy over a vast range of energies, and broadly classified according to the cosmic ray source, as shown in figure 1.1. Cosmic rays are thought to originate from a number of different sources and are divided into types based on their origins. Galactic Cosmic Rays (GCRs) originate from outside the solar system, from within or beyond the local Galaxy. A number of astrophysical processes contribute to the generation of GCRs, particularly in supernovae ejecta which transfer enormous amounts of kinetic and thermal energy into shocked gas and relativistic particles [2]. These findings were confirmed by observations of the *Fermi* instrument in 2013 [3] through direct detection of pion decay signatures. GCRs have a peak energy distribution range of 100 MeV - 1 GeV, although energies up to 3×10^8 TeV have been observed [4].

Cosmic rays were first discovered by Theodor Wulf in 1910, using a 'dual thread electrometer' device of his own design to measure electrical potential difference at the top of the Eiffel tower compared with that observed on the ground [5]. Wulf had previously observed, in multiple locations around Europe, that recorded radiation levels decreased with altitude. However, upon submerging the top of one of his electrometers under a metre of water, Wulf noticed that ionisation loss had slightly decreased; this prompted him to conclude that some amount of radiation must also be coming from the sky. When he measured the radiation levels at the bottom and the top of the Eiffel tower, he noted that the value at the top of the tower (16.2 ions) $\text{cm}^{-2} \text{ s}^{-1}$) was only slightly less than the value at the feet of the tower (17.5 ions $\text{cm}^{-2} \text{ s}^{-1}$) [5]; this effectively excludes the surface of the Earth as the sole source of radiation and pointed toward the idea that such radiation may be coming from elsewhere. In parallel to Wulf's work, Italian physicist Dominico Pacini measured that the gradual rate of ionisation on Earth decreased when the ionisation chamber was moved underwater, implying (like Wulf's work) that the source of radiation had to be coming from a source other than the Earth. However, Wulf's conclusions were not widely accepted until some years later, and Pacini's were largely lost to history [6], as Wulf is most often credited with this discovery.

To follow up on Wulf's discovery, Victor Hess took note of Wulf's letter and concluded that it provided sufficient evidence of radiation being extraterrestrial in nature. He decided to test this himself using an improved electrometer and a radium γ -particle source, over ten high-altitude balloon journeys. Hess found that as the balloon ascended, ionisation indeed decreased in agreement with previous experiments (which were all nominally performed at altitudes of 0 to 500 metres); however, it returned to its ground value at 1500 metres, and continued to rise at a higher rate as a function of altitude. At the peak altitude of 5000 metres, ionisation was $16.1 \text{ cm}^{-2} \text{ s}^{-1}$ above the ground value. Moreover, Hess had tightly controlled systematics throughout this series of experiments: five of his experiments were performed at night (to rule out radiative contribution of the sun); one was performed during a solar eclipse (for the same reason); the remainder of the flights were carried out throughout the day; his electrometer was shielded with zinc and had been thoroughly tested to be able to withstand temperature and pressure fluctuations expected in flights [7][8]. Hess therefore concluded that the only possible source of the majority of the radiation observed was of cosmic (rather than terrestrial) origin. Hess later received the Nobel prize for this work [9]. These results were later confirmed by Werner Kolhorster in additional flights up to 9200 m, where the ionisation level was measured as being 10 times that at sea level [10].

However, this was only the beginning of the story. A paper published by S. E. Forbush in Nature's "Letters to the Editor" in 1937 [11] measured cosmic ray intensity in two locations (Maryland, USA and Huancayo, Peru) in tandem during a magnetic storm. In response, another letter to Nature also in 1937 was published by Victor Hess, where he confirmed that a third measurement had been made on the Halefekar in Austria, which was in excellent agreement with Forbush's results. This showed that cosmic ray ionisation activity was experienced world-wide in April 1937, and that the variations in intensity ($\approx 3\%$) were observed world-wide [12], implying that sudden spikes in cosmic ray / magnetic activity are correlated. This lead to another significant discovery in the history of cosmic rays: the hitherto unknown second type of cosmic ray, which lead to the classification system presently used today.

The second type of cosmic rays are Solar Energetic Particles (SEPs) which are originate in the Sun during solar flares and coronal mass ejections. These types of cosmic rays are variable in flux and can increase or decrease rapidly in short periods of time. Solar-emitted high energy particles were first reported on in 1946 [13].

Today, the study of cosmic ray physics is still a topic of great interest to astronomers and astrophysicists, and detailed treatments of such problems depend heavily on knowledge of their astrophysical origins as well as the particle physics of their generations and interaction with interstellar material, planets, spacecraft, and detectors.

However, within the context of this thesis, CRs are thought of as mostly a nuisance, for reasons which will become clear throughout this manuscript.

1.2 Past and present detector technologies

Detector technology for space-borne astronomy missions has developed in the past few decades, with device sensitivity finally scaling to a point where the cosmic ray effect becomes prohibitive (e.g. Planck). More modern detectors will be even more sensitive to the science signal, and so perhaps more vulnerable. Here we will discuss the technologies of a few previous space missions, as well as their in-flight response to cosmic rays. We will then discuss present technologies and what vulnerability they have to the cosmic ray issue. We will begin with the FIRAS Far Infrared Absolute Spectrophotometer instrument on COBE, then discuss the Wilkinson Microwave Anisotropy Probe (WMAP) and the Infrared Space Observatory (ISO) camera before moving onto Planck and Herschel, and future technologies.

1.2.1 COBE-FIRAS

The Far Infrared Absolute Spectrophotometer (FIRAS) aboard The Cosmic Background Explorer (COBE, in near-Earth orbit), launched in 1989 and developed by NASA, had the overall goal of mapping 'diffuse radiation' from the Universe [14]. FIRAS operated between 30 and 477 GHz, with a goal of measuring differences between the Cosmic Microwave Background (CMB) and a blackbody spectrum[15]. It was developed for launch into space to eliminate systematic effects arising from the atmosphere. It was cooled using liquid helium and contained a Michelson



Figure 1.2. Design of the COBE composite bolometers (GSFC). Image taken from Serlemitsos [16].

interferometer and bolometers, all cooled to 1.5 K. It also contained a reference blackbody source, against which to compare the CMB. The optical design consisted of two input ports, one of which viewed the sky, and the other viewing the internal calibration source (the blackbody). Moving mirrors modulated the path difference of the two signals, creating phase delays, and allowing the instrument to measure CMB deviations from a blackbody <0.0005% of the blackbody peak [15].

FIRAS utilised composite bolometers [16] built from antimony-doped silicon with a 0.14 μ m layer of gold, with a central diamond absorber with a radius of 3.5 mm, suspended from a circular invar frame using kevlar wires. The bolometer is shown in Figure 1.2, taken from the paper describing the detector [16]. The readout consisted of a typical biasing circuit, with the addition of a JFET for noise reduction. The FIRAS bolometers were designed with the purpose of maximising throughput and minimising Noise Equivalent Power (NEP). FIRAS utilised slow ($\tau = 40$ ms) and fast bolometers ($\tau = 6$ ms) where different time constants were desired, which was achieved using different lengths of thermal leads. This difference, of course, affected the NEP of the bolometers - endowing the fast bolometer with an NEP of 1.2×10^{-14} W $\sqrt{\text{Hz}}^{-1}$ at 45 Hz, and the slow bolometer measuring an NEP of 4.5×10^{-15} W $\sqrt{\text{Hz}}^{-1}$ at 4.5 Hz [16]. This NEP, for its time, was remarkably low, and the bolometers exceeded the requirements set out for FIRAS.

COBE-FIRAS and cosmic rays

It was expected that some level of cosmic ray 'glitches' would be encountered in the FIRAS data. Fixsen et al. [17] describes the 'deglitching' process in the data analysis pipeline, which makes use of a modified 'CLEANN' algorithm [18]. Fixsen describes the 'glitches' being the dominant noise component in the FIRAS data, and describes their removal using averaging across many interferograms to develop a template, and using neighbouring pixels to exclude events. The instrumental calibration overview [19] indicates that cosmic ray glitches are the largest source of instrumental noise, but that their effects can be reduced by a factor of 3-4 via post-processing of the data. The csmic ray impact rate on an individual FIRAS bolometer was about 2 events s⁻¹. The unshielded Galactic proton rate is estimated to be 4 events cm⁻¹ s⁻¹, matching the measured impact rate for a detector area of 0.5 cm^2 . At the end of the process (averaging + 'CLEANing'), all events > $3.5 \sigma^*$ are reported to be removed. Cosmic rays were reported to comprise only 2% of the total number of data points in FIRAS, and their removal constitutes a systematic effect of only 30 μ K.

It bears repeating that FIRAS was operated at 1.5 K, and that as the operating temperature decreases, the sensitivity (to photons and to cosmic rays) generally increases. Deglitching was successful in this specific case, but one would be mis-

 $\sigma^* = 1.25 \cdot \text{abs}(\text{Noise}_{\text{resid.}})$

taken to assume that the same result would follow for an experiment with a lower temperature or lower NEP.

1.2.2 COBE DMR and DIRBE

The other two instruments on COBE were the Differential Microwave Radiometer (DMR) and the Diffuse Infrared Background Experiment (DIRBE). Like FIRAS, DIRBE was situated inside the 1.5 K dewar, whilst DMR remained outside [20]. The DMR, measuring at 31.5, 53, and 90 GHz, was an all-sky survey designed to measure temperature anisotropies. The DMR made use of radiometers rather than bolometers, unlike FIRAS and most modern missions. The DMR had two receivers for each frequency band, and measured the antenna temperature difference between the two signals as the satellite rotated, measuring the temperature difference across the sky.

DIRBE, like FIRAS, used bolometers in its two longest wavelength channels (151 and 241 μ m), and the remaining wavelengths (1.2 to 96 μ m) were made up of extrinsic photoconductors, Blocked Impurity Band (BIB) detectors, and photovoltaic detectors [20]. DIRBE's principal objective was to measure 'diffuse infrared' radiation (e.g. dust mapping) between 1 and 300 μ m, using a cryogenically-cooled off-axis Gregorian telescope [21], by measuring the difference between the brightness of the sky and an internal blackbody at such a low temperature that its emmission can be neglected [22].

DMR, DIRBE, and cosmic rays

The DMR detectors showed no sensitivity to charged particles, and it was the only instrument which could take data whilst the instrument was within the view of the Van Allen radiation belt [20]. This was, however, not the case for DIRBE. This was compounded by the various detector types and different behaviour at different parts of the orbit and as a function of wavelength. As we mentioned above, data from the time when COBE was within the Van Allen Belt are rejected due to oversaturation by cosmic particles. During the remainder of the time, the DIRBE team noted four glitches per 1000 data samples for the bolometer and photoconductor detectors, and 8 per 1000 data samples for the larger 60 and 100 μ m Ge:Ga detectors [23].

The DIRBE team developed a two-step deglitching system, consisting of a specially-developed algorithm which applies a series of pass-fail tests, followed by averaging of weekly maps. The end result is removal of 'essentially all remaining glitches' [23] with an error rate < 1/10000 samples⁻¹.

The legacy of COBE

COBE is widely lauded with discovering the temperature fluctuations (anisotropies) in the CMB, which are of the order of 1/100000 [24], for which Smoot and Mather eventually received a Nobel prize for the work.

Meanwhile, the COBE-FIRAS experiment proved (amidst what had been some debate at the time) that the CMB was a perfect fit with a blackbody at 2.73 K [25]. DIRBE also made significant contributions to galaxies, Galactic disc models, and interplanetary dust.

Within the framework of cosmology, COBE was the beginning of a new era in terms of precision measurements which help to understand the origins of the Universe and prove or disprove cosmological expansion. The presence of anisotropies in the CMB implies that regions in these vastly-separated regions of space must have been causally connected at some point, and is strong evidence that the Universe during the Big Bang was a much smaller place than it is now. This has given way to a huge field of study - experimental cosmology - and many new space missions up until now, and into the future.

1.2.3 WMAP

After COBE, it was clear that a pressing science goal in experimental cosmology would be to map the CMB temperature, across the entire sky, precisely and to a high resolution. This was envisaged through the Wilkinson Microwave Anisotropy



Figure 1.3. Lagrange points in the Earth-sun system, taken from [26].

Probe (WMAP), named after David Wilkinson, who spent his career making contributions to cosmology and to the development of WMAP itself. WMAP, unlike COBE, flew in an L2 orbit (the second Earth-Sun Lagrange point, shown along with the other Lagrange points in Figure 1.3) - the same as Planck would later do. It was developed by NASA, was launched in 2001, and measured the sky between 22 and 90 GHz, with 4 channels each at 22 and 30 GHz (synchrotron and free-free emission, respectively), 8 channels at 40 and 60 GHz (dust and CMB anisotropy, respectively), and 16 channels at 90 GHz (contribution from dust). Its reflector used two separate off-axis Gregorian telescopes, facing away from each other. Its focal plane was split between an 'A' side and a 'B' side, and each of those sides was fitted with an orthomode transducer (OMT) which orthogonally polarised each side into two beams, and all were fed through an amplifier chain in which one of the sub-signals of A and B are phase switched. The amplifier chain acted over all sub-channels equally, and the difference between the A and B channels allowed WMAP to measure the signal more precisely than by directly measuring the signal alone. The two A-B were then averaged, which was intended to greatly reduce systematic effects.

Unlike later missions and like COBE-DMR, WMAP used radiometers rather than bolometers. WMAP's radiometers were HEMT-based [27] and many precautions were taken to reduce systematic effects in the detector and the readout systems, the precise details of which will not be explained in this manuscript (which mostly deals with bolometers).

WMAP and cosmic rays

As WMAP used radiometers, similarly to the case in COBE, the detectors appeared to be insensitive to cosmic rays; radiometers detect EM radiation rather than heat, and so are less susceptible and sensitive to the signal arising from CR impacts. If not in the detectors themselves, cosmic particles could/should have impacted the readout electronics (where electron showers could have played a role). As much as this was probably the case, there is no evidence of it in the WMAP literature.

WMAP legacy

WMAP produced many novel discoveries, and advanced experimental cosmology significantly in its time. Its main result was the production of maps of the CMB across the entire sky, showing the temperature variations in much greater detail than had been achieved before. The temperature variations are of the order of 0.00005 K, which is tiny in comparison to the temperature of the CMB 2.725 K.

In addition to producing foreground emission maps in each of its frequency bands, the one year data release measured many parameters based on ACDM (e.g. the age of the Universe, Hubble's constant, Matter and Baryonic content, optical depth to reionisation, and many others [28]. Its three [29], five [30][31][32], seven[33][34][35], and nine [36][37] year releases updated these parameters, with the nine-year data release concluding that the "Cosmic Dark Ages" (era before stars and galaxies began to form) ended about 400 million years after cosmic inflation. It also concluded that the early Universe consisted of 95% dark matter / dark energy, and that the Universe is (almost) flat. WMAP of course eventually led to a greater need to map the anisotropies at an even finer resolution, among numerous other progressive questions which were addressed by later missions, or will be addressed by future ones.

1.2.4 Infrared Space Observatory

The Infrared Space Observatory (ISO) was an ESA mission, developed to measure the sky in the infrared waveband (2.5 to 240 μ m) to probe regions obscured by cosmic dust [38]. ISO was launched in 1995 and operated until April 1998. The ISO cryostat consisted of a dewar large enough to house 2300 litres of liquid He, along with four instruments: the Short and Long-Wave Spectrometers covering 2.4 - 45 μ m and 45 - 196.8 μ m (respectively), both measuring chemical compositions of target objects; the Infrared Camera (ISOCAM), an infrared imager operating between 2.5 and 17 μ m; the photo-polarimeter (ISOPHOT), operating between 2.4 to 240 μ m in order to measure the magnitude of IR emission from various astronomical objects. For brevity, we will talk only about ISOPHOT and ISOCAM.

ISOPHOT was mainly envisaged as a follow-up to IRAS (the first space telescope to survey the entire sky in IR) with many improvements, e.g. wider wavelength range, higher sensitivity, higher spatial resolution, etc [39]. ISOPHOT used low-background bulk photoconductors (Si:Ga, Si:B, Ge:Ga, and stressed Ge:Ga) which had a project goal NEP of 1.5×10^{-17} W $\sqrt{\text{Hz}}^{-1}$, yet the final NEP of all detectors ranged between 2.3×10^{-16} W $\sqrt{\text{Hz}}^{-1}$ (Si:Ga) and 9.3×10^{-18} W $\sqrt{\text{Hz}}^{-1}$ (stressed Ga:Ga). The instrument itself was amusingly described as "compactly filled with precisely aligned moving components such as filter wheels and chopper, a challenge for a space engineer to build and a nightmare to get accepted for flight"[39].

ISOPHOT and radiation

ISOPHOT was less affected by the effects of cosmic rays, and more by the effects of its daily ($\approx 6h$) passage through Earth's radiation belts; it was estimated that ISO's daily journey through the radiation belts of the Earth would impose 3.7 rads

orbit⁻¹ [40]. Separate analyses of radiation effects in photoconductors reveal several forms of vulnerability to radiation: increased noise, long-term responsivity shifts, higher dark current, etc [41]. The ISOPHOT team found the greatest vulnerability in the stressed Ge:Ge detector (which we recall as being the most sensitive), with a shift in responsivity lasting several hours [40].

Radiation damage effects were tested on the Ga:Ga detectors using ¹³⁷Cs (0.51 MeV β -decay) and ⁶⁰Co (0.31 MeV β -decay) sources. They found that a 0.1 rad dose at a V_{bias} of 50 mV increased the dark current by a factor of 17, and that for a V_{bias} of 80 mV, complete saturation was achieved (indicating a dark current increase by a factor of \geq 460). The bias level of the detector affected the 'relaxation rate' after a radiation dose, and it was concluded that the detectors should be biased between 50 - 60 mV, and that infrared annealing must be used to combat the effects of large radiation spikes in orbit [40].

In attempting to simulate long-term radiation damage effects to the detectors, cumulative radiation tests were made, using infrared annealing to curb the effects. The team found the least radiation-induced change to detector responsivity between 50 and 60 mV of V_{bias}. They found that the use of in-flight infrared flashing with an illumination power of 13 mW. They concluded that the Ga:Ga detectors can be calibrated to use a lower bias voltage during the radiation belt passage, allowing them to still be used during that time, with a higher bias voltage used during the remainder of the orbit (allowing for an optimum NEP of 9×10^{-18} W $\sqrt{\text{Hz}}^{-1}$.

ISOCAM

ISOCAM contained two 32×32 pixel Si:Ga detectors, each on an independent channel corresponding to short and long wavelengths. Each channel contained a single aspherised lens, and a beam-folding spherical aluminium mirror which reimaged the focal plane of the telescope on each pixel array. ISOCAM contained internal flat-field calibration source, which had itself been calibrated at IAS by a laboratory blackbody [42].

ISOCAM and radiation

ISO was launched during a solar minimum, when the flux of galactic cosmic rays is the least attenuated (similarly to the case for Planck). Similarly to ISOPHOT, ISOCAM's detectors remained active during ISO's passage through the Earth radiation belts, and the detector remains illuminated throughout. This was believed (and later proven, in flight) to prevent a large increase in the detector responsivity near the end of the radiation belt passage. ISOCAM's data reduction team made use of several deglitching algorithms [43] which were considered effective during its flight; the most effective of which being the ISOCAM Interactive Analysis routine mr1d_deglitch. Remaining detector transients were then removed using a simplified physical model[†] [44].

A comprehensive study of the glitch phenomena in ISOCAM led to the formation of a dedicated working group, and the classification of ISO glitches into families [45]. The working group predicted 0.36 direct impacts s⁻¹ and 0.29 secondary particles or δ -rays s⁻¹ from materials near the detector. In flight, they found an average glitch rate of 1 glitch s⁻¹, with an average of 8 pixels hit per glitch.

ISOCAM avoided integration times > 20 seconds due to the possibility of many glitches present in a single image. They quote that for a 0.28 second image, < 1 glitch is expected in each image, but the co-added images (containing 4) resulted in a sensitivity loss of 1%. The effect of glitches on electrical gain is mentioned, but is not quantified - only indicating that this potential effect would affect the glitch profile with respect to its time-ordered shape [45].

The glitches were classified into 3 families based on their pulse shape. They were called 'common glitches', 'faders' (slow decrease in magnitude), and 'dippers' (fast decrease to a stable value, followed by a long decrease to base magnitude). 'Common glitches' were concluded to be attributable to the linear energy transfer (LET) creating a current in the detectors, composed of electron-hole pairs and

 $^{^{\}dagger}$ An early proof that physical models are important in understanding transient detector behaviour, especially as it relates to cosmic rays in space



Figure 1.4. Left: ISOCAM image examples of glitches during a solar event, at which time the glitch rate increased by a factor of 7-10. Right: Glitches near the beginning of the Van Allen belt, which were believed to be produced by electrons. Both images are taken from Claret et al. ([45]).

thermal relaxation of the detector material post-impact. 'Common glitches' were thought to be from low-energy LETs (minimally-ionising protons or lower-energy cosmic rays), which then become 'faders' for a higher LET (taking longer for the detector to relax to its default state. In this case, 'common glitches' were thought to come from galactic protons and electrons, and 'faders' coming from light galactic ions. The rest, such as heavy particles with very large linear energies, become 'faders'.[‡]

Based on the literature, the pre and post-launch glitch analysis in ISO appears to make use of physical modelling, pre-launch experimental analysis, development of glitch libraries, and a general vast amount of classification and effort. Such efforts should be the gold standard for any space mission with such sensitive detectors, and one might hope that this trend is renewed in the development phases of the next major space mission.

 $^{^{\}ddagger} \mathrm{There}$ are probably some parallels here between ISOCAM and the Planck ordeal.

1.2.5 Herschel Space Observatory

The Herschel space observatory launched in May 2009, using the same rocket as the Planck Space Telescope (as both missiong were developed in tandem). Both were developed by ESA. Herschel observed in the FIR and sub-mm wavebands (55 - 672 μ m), with the goal of studying star and early-Universe galaxy formation, chemical composition of various celestial bodies, and chemistry [46]. The Herschel space observatory contained 3 instruments: the Heterodyne Instrument for the Far Infrared (HIFI); the Photodetecting Array Camera and Spectrometer (PACS); the Spectral and Photometric Imaging Receiver (SPIRE). For brevity and relevance to our study, we will speak only about PACS and SPIRE.

The PACS instrument

PACS itself covered between $\approx 60 - 210 \ \mu\text{m}$, featuring an imaging camera and a spectrometer. Both the imaging photometer and the spectrometer used a common front optics with a grey-body calibration source and chopper [47]. PACS utilised arrays of square bolometers, with sub-arrays forming different colour bands, and kept at an operating temperature of 300 mK by a ³He sorption cooler. The bolometers were developed at CEA Saclay and CEA Grenoble, and used a Si substrate, with thermometers implanted on the Si. Absorption was done by a metallic layer on suspended silicon grids. The grid and the substrate was thermally decoupled via thin Si rods [48]. The PACS bolometers had an NEP of $2 \times 10^{-16} \text{ W} \sqrt{\text{Hz}}^{-1}$ at $160 \ \mu\text{m}$ (with a V_{bias} of 2 V) [49].

The SPIRE instrument

SPIRE was a three-band (250, 350, and 500 μ m) imaging photometer and a Fourier transform spectrometer (FTS) covering 194 - 671 μ m [50]. The detectors were arranged in 5 arrays of single-mode horn-coupled spider-web NTD Ge bolometers (SWBs), developed by NASA (Caltech and JPL) and later used in the BLAST balloon-borne mission [51]. The bolometers were hexagonal in shape, with a $\phi = 725\mu$ m absorber suspended by 5μ m×240 μ m support legs, with NTD thermistors

deposited on the absorber and read out using two leads [52]. The detectors were used at 300 mK and their characterisation found an NEP of 2.4×10^{-17} W $\sqrt{\text{Hz}}^{-1}$ under dark conditions, and 5.8×10^{-17} W $\sqrt{\text{Hz}}^{-1}$ under a typical 2.4 pW optical load[52].

PACS and cosmic rays

The PACS bolometers were studied prior to launch in order to probe long-term (radiation damage) and short term (transient) effects of cosmic ray and radiation interactions. Proton irradiations were performed at TANDEM in Orsay at 20 MeV and a flux of 3 particles s^{-1} pixel⁻¹, and with α particles at 30 MeV with a flux of $0.2 \text{ particles s}^{-1} \text{ pixel}^{-1}$, which found shifts in the detector threshold (thought to relate to the passage of particles through the CMOS readout devices) and the usual glitches from the interaction between the particles and the material of the absorber mesh, with the particle relaxation time and number of effective signals correlating with the responsivity map of the pixels [49]. Further analysis of the PACS bolometers at TANDEM found evidence of both positive (α particles hitting the wall between the pixels, heating the heatsink and affecting ≈ 2 nearby pixels), and negative (direct detector structure hits by both α particles and protons, effect scaling with device sensitivity). This study found that the effects can be easily removed using deglitching algorithms due to the small number of pixels affected, and the lack of gain drift and electrical crosstalk [53]. The PACS arrays were also simulated in GEANT4 in order to probe the level of the effect of galactic-sourced cosmic rays, where it was found that the spacecraft and detector housing was a significant source of secondary particles which impact the detectors (25%) of which affecting neighbouring pixels) [53]. Deglitching algorithms were incorporated into the data analysis pipeline of the instrument.

SPIRE and cosmic rays

Analysis of the SPIRE data [50] revealed glitches which were broadly split into two categories: direct, single sensor hits in which one particle deposits a large amount

of energy in one place, and comorbid smaller glitches which affect many detectors at once (thought to arise from hits on the substrate). The time constant of these glitches was largely dominated by the bolometer's thermal time constant, but were prolonged by the low-pass filtering in the readout circuit. The impact rates were found to be 0.6 events min⁻¹ for the 250 μ m band, 0.7 events min⁻¹ for the 350 μ m band, and 1.5 events min⁻¹ for the 500 μ m band. Glitches were dealt with in postprocessing via flagging and interpolation in the photometer, and did not significantly affect the overall instrument sensitivity [50].

1.2.6 The Planck telescope

The Planck space telescope, launched simultaneously with Herschel in May 2009, sought to measure the CMB anisotropies at a higher sensitivity and greater angular resolution than WMAP. It contained two instruments: The Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI), measuring between 30 to 100 GHz and 100 to 857 GHz (respectively) [54]. Within the context of this manuscript, we will only discuss HFI.

Planck was launched to orbit at L2 along with Herschel, and its High Frequency Instrument (HFI) contained 54 horn-coupled bolometers with an NEP to the order of 10^{-17} W $\sqrt{\text{Hz}}^{-1}$ at 100 mK. For its time, this was the lowest detector temperature achieved in space, and it resulted in the mission's unprecedented sensitivity. The telescope optics had a two-mirror (carbon fibre) off-axis design, with a $\pm 5^{\circ}$ field of view [54].

Planck HFI utilised so-called 'spider-web bolometers' (also used in Herschel-SPIRE) which are shown with dimensions in Figure 1.5. They were fabricated on a 1 μ m thick silicon nitride substrate, with a central NTD Ge sensor (diamond-shape, orange), and 'spider-web' central and external legs (black). The SWBs were fabricated first for BOOMERANG [56] and later used in Planck HFI. They had two overall design goals: to minimise the detector NEP, and minimise the cosmic ray 'cross section'.



Figure 1.5. Design of a Planck HFI Spiderweb bolometer. Blue: Absorber; red Radial legs; Green: Mesh legs; Orange: NTD germanium sensor. Image adapted from Bock et al., [55].

The design and justifications for SWBs has been described in Bock et al. [55], and we will summarise it here only briefly for context.

The spider-web shaped absorber was fabricated from a 1 μ m thick Si₃N₄ membrane and suspended from 16 legs for mechanical support. The legs are shorter and thinner in the central absorber region than they are at the periphery. At the centre of the absorber, an NTD Ge sensor is epoxied to the absorber which acts as the thermistor. The absorber is coated with a metal film for free space impedance matching.

Various tests [57][58] showed at their operating temperature of 100 mK, the HFI detectors achieved a background-limited NEP of 1.5×10^{-17} W $\sqrt{\text{Hz}}^{-1}$ for an amplifier noise maintained below 10 nV $\sqrt{\text{Hz}}^{-1}$. This made the Planck HFI bolometers the most sensitive to be launched into space for their time, but gave them the greatest vulnerability to cosmic rays.[§]

The Planck cosmic ray problem

Prior to the launch of Planck, parasitic signal arising from cosmic rays was not believed to be a major issue. Shortly after the launch, this was quickly noted to be incorrect. In spite of the successful recovery and removal efforts on the part of the Planck consortium, a difficult lesson was learnt; this effect can be severe in highly-sensitive detectors, and must be prepared for. As device sensitivity scales with the demands for scientific sensitivity, this is an issue which must be tackled during the early phases of space mission development. We will outline the Planck experience here.

Planck's time-ordered data, across all bolometers, had an unexpected number of thermal spikes which arose from impacts by cosmic rays, which we can see in Figure 1.6, taken from Catalano et al., 2014 [59]. In this image, we see the signal

 $^{^{\$}}$ A low NEP arises from a high sensitivity, and the sensitivity depends on having a small G and low T. The holes in the absorber of the SWB allow for the reduction of $C_{\rm p}$ and a reduction of the NEP.



Figure 1.6. Raw data from 3 HFI bolometers: *top*: 143 GHz; *middle*: 545 GHz; *bottom* A dark bolometer. Image has been taken from Catalano et al., [59].

of 3 bolometers as a function of time (from t = 0 to t = 200 s). The top two bolometers are observing in 143 and 545 GHz (respectively), whilst the bottom is a 'dark bolometer' which is blanked to the sky. All three bolometers have a significant number of thermal spikes, including the bolometer which is not open to the sky. The 143 GHz bolometer sees these thermal spikes on top of its amplitude shift due to rotation of the spacecraft and its measurement of the Galactic plane and the CMB dipole.

Planck began its operations during the time of a solar minimum [60], during which time (as the case for ISO) the solar magnetic field does not attenuate the incoming cosmic particles from the galaxy as much as usual, and more galactic cosmic rays are observed. In HFI this resulted in a variable thermal load on the 100 mK plate, along with the large (about 1 event s⁻¹) number of cosmic ray thermal fluctuations in the bolometer signal [60]. These glitches were divided into 3 categories, based on flight data and ground-based experiment([61][60]):

1. Short glitches: Quickly-rising (less than the sampling period of 5 ms) highamplitude events which decay quickly. Short glitches looked comparatively similar to the bolometer transfer function [61].



Figure 1.7. Left: Short (blue), slow (red), and long (black) glitch examples. Right Bolometer photograph showing the probable location of hits resulting in short and long events. Images have been taken from Catalano et al., [60] and A. Miniussi Ph.D thesis [62].

- 2. Long glitches: Lower-amplitude events which are more frequent than short glitches, also rising within 5 ms. The short decay constants again resemble the bolometer transfer function, but the long decay is much longer (50 and 500 ms for the polarisation sensitive bolometers (PSBs) and 35, 500, and 2s for SWBs).
- 3. Slow glitches: Much more slowly rising, and slow to decay. Unknown origin.

Typical glitches from each family, along with its potential location on the detector, are shown in Figure 1.7. Ground-based measurements were performed on the HFI bolometers in a cryostat coupled to the beam line at TANDEM, in addition to extra α tests at IAS and Grenoble. These tests concluded that the short rise and short decay of the fast glitches indicated that they occured very near to the sensor, and because of that, the heat was removed quickly. The long glitches were isolated to the absorber in a similar way [61]. These were believed to relate to either ionisation within the Si die, which later thermalises, or to ballistic phonon propagation, which later thermalises. The ballistic hypothesis was supported by breakage of the support legs creating lower amplitude events but not shorter 'long' decay constants, as this reduces the 'cross section' for ballistic phonons. The long time constant is unaffected because the SWB has many thermal outputs.

As far as 'deglitching' is concerned, it was not possible to simply flag and remove all affected data given the high event rate. The sky data was used to produce templates by stacking many of the same types of glitch. Multiple measurements of the same part of the sky were also used to identify the presence of glitches, which could then be removed. Fourier transformation of the data in order to find and remove glitches was not an option due to the variability of the glitch profile. The deglitching algorithm took an estimated sky signal which is subtracted from the time-ordered data, and detects glitches with more than a 3σ variation. Of the selected data, an algorithm detects fast changes (high derivatives) in the signal, indicating a cosmic ray impact. The glitches are then fit to using the same function that was used to analyse them (a variable template), and their signal is removed (with some extra allowance for glitches with tails which might be embedded in the signal). The removed parts of the signal are then reconstructed using unflagged redundant data [63].

Analysis of the noise with and without this processing indicates that there were not significant 'leftovers' in the residuals following this process. Due to the processing, the net data loss on the data is about 10 to 15%. The effect is the worst at high frequencies, where the signal from the galactic plane creates the most difficulty in glitch removal, and results in the least amount of removal [63].

The empirical study and extraction of the (roughly) 2 cosmic ray 'glitches' per second on the bolometers was a matter of great effort for the cosmology community, and was eventually successful owing to a combination of ground-based experimental work and in-situ analysis on Planck bolometer data[59][61]. However, the great deglitching campaign was something of an emergency measure. For future missions (which are even more sensitive), this process has surely proven that it is vital to characterise and understand these effects during the development phase of the space missions.

1.2.7 Cosmic rays in balloon missions

One method of testing prospective space-borne technologies in a space-like environment is to launch telescopes on balloons. This has been employed numerous times in missions like EBEX [64], SPIDER [65], SPIDER-2 [66], ARCHEOPS [67], BLAST [51], and PILOT [68]. Prior to being launched into space, technologies must achieve a high Technology Readiness Level (TRL). As a high-altitude environment is certainly more space-like than ground-based telescopes, a working technology in a high-altitude balloon makes a strong argument for the employment of such technologies in space. Most balloon-borne missions have registered an increased systematic load coming from cosmic rays, and the experimental framework provides an excellent opportunity to evaluate a developing technology such as Transition Edge Sensors (TESs) and Kinetic Inductance Detectors (KIDs) for use in actual space telescopes.

1.3 Cosmic rays in space

One might imagine fairly easily how cosmic rays in space might be considered a nuisance to a space mission which seeks to measure things other than cosmic rays. Even for ground-based experiments (including forays into amateur astrophotography), cosmic ray effects are present in many CCD images. Cosmic rays on Earth are attenuated by the atmosphere, into which they deposit some of their energy; cosmic ray protons typically collide with high-altitude atmospheric particles, giving rise to hadronic showers (from which about 50% of the incident energy goes into the creation of charged pions, which eventually decay to muons.

A typical cosmic ray interaction with a standard ground-based CCD technology is shown in Figure 1.8, with two still images from the Huntsman Telephoto Array[¶]. We see two frames, the second containing 2 events not contained in frame 1. The top figure (red arrow) illustrates a typical cosmic ray candidate (with a long thin

[¶]With special thanks to Anthony Horton of the Australian Astronomical Observatory, both for taking and allowing the author to use this image.



Figure 1.8. Two images taken by the Huntsman Eye telescope of the same area of the sky. There are three features which exist in Frame 2, but do not exist in the same space in the other frames. *Red*: A typical cosmic ray candidate, with a long and thin line as the muon deposits its energy into the CCD. *Green*: Another single-frame event, potentially a cosmic ray, although not displaying the typical shape. *Blue*: Not a cosmic ray, because it is the SpaceX Starman traversing the sky above Australia.

line showing the muon trajectory through the CCD). The second (green arrow) does not have the typical shape, but its presence in only one frame, as well as its comorbidity with the first event, suggest that it may also be a muon event. These types of traces are very common in astrophysics, and are normally combated by the use of redundancy (multiple views of the same part of the sky) in astronomical images. This becomes very important, especially for space missions. Planck was able to cope with its cosmic ray problems only because of redundancy and because of its sky-scanning strategy.

As described by the Particle Data Group [69], muons are produced at about 15 km above sea level, and are the most frequent cosmic particles seen on the ground. The vertical muon flux at sea level is quoted as 70 m⁻² s⁻¹ str⁻¹ for muons > 1 GeV/c, and the classical 'rule of thumb' for muon flux is on a ground-based detector is quoted as 1 muon cm⁻² min⁻¹. Using a typical 'hobby photography' digital SLR camera (a Canon T6i), with a CMOS total detector area of 332.27 mm², this gives an expected muon flux of 3.32 muons per minute (for a detector orientated horizontally). Of course, the camera's detector is orientated at 90° relative to the ground (perpendicular to the lens) so the muon flux in this case is only a fraction of the case of a horizontal detector. However, telescope detectors are pointed to observe the sky, so a significant amount of muon flux is expected in these cases.

In space, there is of course no atmosphere into which the cosmic particles will lose energy, and the expected flux is much larger and more variable.

This thesis will focus on the effects of cosmic rays at the second Earth-Sun Lagrange point, L2, shown compared with the other Lagrangian points.

1.3.1 Particles expected at L2

Cosmic particles at L2 are divided into two primary components - those of galactic origin (the GCRs) and solar protons (sometimes referred to as 'soft protons') [71]. The cosmic ray background at L2 is primarily composed of protons (of the order of 89% during the Planck flight at L2), α particles (of the order of 10% during



Figure 1.9. Blue: Proton activity recorded by SREM measurements aboard Herschel on the 'TC2' channel (protons with E > 39 MeV). Red: The number of sunspots active during that time period, showing an anti-correlation with the proton flux. Image has been taken from Horeau et al., 2011 [70].

Planck), with heavy nuclei and electrons making up the remainder [61] [72]. The solar particle background as well as the particle background varies with solar activity due to the movement of solar magnetic fields, which can attenuate the galactic component. This is illustrated well by the radiation monitors aboard the Hershel space mission [70], showing the anti-correlation between proton counts and sunspot activity in Figure 1.9. We see that as sunspot activity increases, protons with E > 39 MeV have a decrease of activity as the solar magnetic fields attenuate the galactic proton flux.

1.3.2 Energies expected at L2

During solar flares, the sun ejects nuclei at energies between 10 and 100 MeV [61], although the nominal energy for solar particles is much less (\approx keV). Measuring the energy spectra is difficult unless it is done aboard a space mission, and there have only been a handful of such missions at L2 to date. However, the Planck space telescope, the GAIA mission, and the Herschel space telescope were all equipped with ESA's Standard Radiation Event Monitor (SREM), which had been previously used to measure the amount of cosmic ray events in other missions [73]. With



Figure 1.10. Cosmic ray fluxes at L2, as calculated within the context of the IXO mission (now X-IFU aboard the Athena space telescope). Image has been taken from Lotti et al., 2011 [74].

these results, we can estimate the particle flux for prospective future space mission - although this depends, to an extent, on what minimum energy is required to penetrate the spacecraft structure.

Lotti et al. [74] combined the measured particle rates aboard other L2 space missions with Geant4 simulations and found fluxes in general agreement with that which was reported by the Planck mission, and these fluxes are shown in Figure 1.10. The proton contribution continues to dominate over most of the energy range, and peaks at around 1 GeV. The overall particle flux at L2 was measured (by Planck) to be about 5 cm⁻² s⁻¹ [59] (typically 3 orders of magnitude higher than on the ground), with a peak total flux at 300 to 400 MeV.

1.4 Future detector technologies

Since Planck, new technologies have been developed for use in ground and space missions: Transition Edge Sensors (TES) and Kinetic Inductance Detectors (KIDs). We will outline these here, including their potential sensitivity to cosmic rays.



Figure 1.11. R(T) for niobium, showing the superconducting phase transition above 2.2 K.

1.4.1 Transition Edge Sensors (TES)

Transition Edge Sensors are bolometers made from superconducting materials which operate at a temperature range inside their superconducting phase transition. As with composite bolometers, they consist of an absorbing and a sensing element. The superconducting phase transition in many materials is typically a sharp, linear transition (an example is shown in Figure 1.11) which is highly temperature-dependent, which makes these materials able to be used as very precise thermometers with a high sensitivity.

In a normal metal, mobile electrons are free to move about the material lattice, which results in the high conductivity of metals. Under an electric field, electrons are drawn in its direction, but they are scattered by the ions and phonons in the lattice, and this scattering creates heat. As the metal temperature approaches 0, phonons and scattering events decrease, and resistance increases. When a superconductable material reaches a low enough temperature, pairs of electrons form "Cooper" pairs, which are immune to scattering events. This immunity is what gives superconductors an effectively perfect conduction. Any power absorbed by a superconducting thermometer which is within the linear range in its superconducting phase transition will lead to a change of resistance, with the resistance being extremely sensitive to the absorbed power due to the steepness of the superconducting phase transition, which has a much stronger responsivity than the IV curve of a normal semiconductor bolometer. However, this can pose a few problems: the bias voltage must be restricted to a particular regime in order to reduce the contributions from Joule heating, and any large unexpected energy input can knock the thermometer out of its superconducting phase transistion, resulting in its failure to operate as a detector unless and until it returns to an operating point within the transition [75]. These effects can be mitigated with careful engineering and calibration, but TES are more vulnerable to certain other effects (e.g. cosmic rays). Moreover, the readout of TES bolometers is complicated and can add significant weight, required spatial area, or points of failure for a space mission.

TES sensitivity to cosmic rays

TES are not yet space-qualified, and have never before flown on a space mission. They are envisaged for several next-generation missions, including the X-Ray Integral Field Unit (X-IFU) on the Athena mission (see the relevant chapter later in this manuscript) and LiteBIRD [76], although other technologies are also considered. In all cases, the TES will be extremely sensitive to both glitches and fluctuations of the 'effective bath temperature' (the temperature of the substrate they sit upon), which will need to be carefully controlled for during development phases.

TES have flown before on balloon-borne (stratospheric) telescopes, e.g. SPIDER. SPIDER reported one glitch every 3 minutes, and their glitches were removed with minimal effect on the science data. The SPIDER cosmic ray incidence was $10-100 \times$ lower than Planck's [77] in spite of its ≈ 36 km altitude, which could be due to a difference in the energy deposition threshold.



Figure 1.12. Two diagrams showing the concept of multiplexing, with 3 KIDs coupled to one feedline. The result is shown below, with 3 signal dips about the 3 resonant frequencies. (image has been taken from S. Doyle [81])

1.4.2 Kinetic Inductance Detectors

Kinetic Inductance Detectors are superconducting resonators containing an inductor and a capacitor, capacitively or inductively coupled to a coplanar transmission line. They were first developed at NASA JPL , and have since been used in a large number of ground-based experiments, such as NIKA [78], DESHIMA [79], and NIKA2 [80]. KIDs are simple to fabricate in comparison to TES, and many of them can be read out simultaneously using one coaxial cable.

Each KID, containing an inductor and a resonator, resonates at a frequency $\omega_{\rm res} = 1/\sqrt{LC}$. By changing L (the inductance) and C (the capacitance), it is possible to fine-tune the resonant frequency to ensure that each KID has a different one. The signal read out from a coaxial cable with many KIDs coupled to it will have signal 'dips' centred upon each resonant frequency. The principle is shown in Figure 1.12, in which we show 3 detectors coupled to one feedline, and one signal with 3 resonance dips (T1, T2, and T3). When these individual detectors are exposed to radiation, normal electrons in the material are created through the breaking of Cooper pairs by the photon / particle energy, altering the ratio between electrons and Cooper pairs. This process alters the material's kinetic

inductance (the reactive impedence of electrons in the material), causing the shift in the resonant frequency and amplitude. It is in this way that Kinetic Inductance Detectors can be used as sensitive detectors.

KID response to cosmic rays

Recent studies have tested the KID sensitivity to cosmic rays. Catalano et al. [82] tested Lumped Element KIDs (LEKIDs) on a Si substrate, irradiated by an α particle and X-ray source. They used a ²⁴¹Am α particle source, which they atteunate to the equivalent energy of a 200 MeV proton using a 10 μ m copper shield^{**}. Whether or not the remaining particle energy (quoted in the paper as 630 keV) is totally absorbed in the LEKID or in the Si wafer depends on the thickness of the LEKID. The study found that the amplitude of the resulting pulses is mostly constant, and that they affect (at most) a 6×6 detector area in the array. Pulses were also produced using a cadmium X-ray source, where the pulses included two time constants. The fast time constant (10 - 15 μ s) was attributed to the electrons produced by the X-ray energy in the detector relaxing into Cooper pairs, and the slow (80 - 100 μ s) attributed to ballistic phonons [82]. It is believed that ballistic phonons, once thermalised, cannot be sensed by the LEKID if their energy is smaller than the superconducting energy gap.

The same study used a toy proton model to simulate a timeline of glitches, under the assumptions that the LEKID area was twice that of the Planck bolometer, but that the time constants of the glitches are unresolved within the size of the sky sampling rate (producing only one erroneous data point per glitch). They consequently found that the glitch rate was much larger than in Planck HFI, but that the amount of data flagged by the deglitching algorithm was much smaller (1% compared with 12 to 15% on HFI)[82]. Additionally, they found that the collective substrate of the LEKID array (compared with the individual substrates of the Planck HFI bolometer array) resulted in an RMS noise increase of 3%, with non-Gaussian features. Projecting this onto 2.5 years worth of mission sky maps

^{**}A quick simulation in TRIM shows that an α particle at 5.4 MeV has a \approx 92% transmission rate, and a transmitted energy of \approx 500 - 700 keV.

(with a 1 arcminute pixel size), they found that the contribution of glitches is non-Gaussian but insignificant in final maps. These results are encouraging for KID space-qualification, although it will be important to quantify the physical processes in the LEKID detectors in order to completely understand the effect of the superconductivity on the cosmic ray shape and energy propagation.

The same tests with ²⁴¹Am and a 10 μ m copper film were performed on the NIKA detectors, showing again that the pulses have very fast time constants (decaying completely within 5 ms^{††}). A similar study by Monfardini et al. [83] describes the testing of KIDs for the NIKA instrument also irradiated by ²⁴¹Am α particles, where a low coincidence was also noted (no larger than a 2×2 area of detectors). These NIKA detectors were used in the design of the detector array for the prospective CNES balloon-borne mission B-SIDE [83], which would have provided an avenue for the space-qualification of KIDs. The mission was, however, not selected to be carried forward by CNES.

This study was repeated using a NIKA detector covered with a titanium layer, with a critical temperature of 0.45 K and a superconducting energy gap less than that of aluminium, to test whether this prevents secondary phonons from breaking cooper pairs in the LEKID, known as 'phonon trapping', based on the principles of quasiparticle-phonon downconversion [84]. This lowered the coincidences of the cosmic ray hits on multiple pixels from 2.6 cm⁻² to 0.25 cm⁻². The idea of phonon trapping is currently under investigation by other LEKID groups, notably at SRON.

If phonon trapping is indeed an effective means of shielding a LEKID from ballistic phonon interaction, it would make KIDs an optimal choice for space-borne telescopes (especially given that they are far easier to fabricate and multiplex than TESs). However, the usage of a proton beam should be done in (e.g.) beam-line tests, rather than simple attenuation of an α particle, as these particles will behave very differently in a material. Still, knowing that an α will become fully embedded

 $^{^{\}dagger\dagger}We$ compare this with the pulses in a composite bolometer used in this thesis, where the 5.4 MeV energy (unattenuated) decayed only after 20-50 ms, and where the cosmic ray muon energy decayed after about 10 ms.

in a rather thin surface due to its low E_K (and high stopping power), one expects that the α measurements, as compared with protons, will be a 'worst case scenario'. However, one must not neglect the potential effect of frequent (small) impacts on the substrate temperature of the LEKID, which could cause unstable performance in space during times of frequent impact. For some work on this topic, please see Chapter 6.

1.5 Bolometer Introduction and Theory

This manuscript deals largely with the behaviour of a composite bolometer (nonsuperconducting), the same type used in Planck – although we do not specifically use the Planck detectors. A bolometer is defined as a device facilitating the detection of incoming electromagnetic waves via the thermalisation of photon energy, where the impedence of the device changes with temperature, and was first developed by Langely in 1881 [85]. If we imagine a bolometer as a 3-dimensional slab of some material at a temperature T_0 , an incoming photon with energy $E = h\nu$ will deposit its energy into the material as incoming optical power, increasing the temperature of the thermal mass to $T_{\text{material}} = T_0 + T_{\text{final}}$. In practice, bolometers must have a means of transmitting energy to a relaxation temperature, or 'bath temperature'.

The idealised bolometer is shown in Fig. 1.13, with the bolometer material shown in grey and the thermal bath, at T_0 , shown in black. The thermal link between the bolometer and the thermal bath has a thermal conductance G, governing the rate at which thermal energy flows from the bolometer to the bath, and the bolometer itself has a heat capacity C_p . The incoming photon energy translates into an optical incident power, the photon rate P_{photon} , creating a temperature increase

$$\Delta T = \frac{P_{\rm photon}}{G}$$

. The timescale of this process is defined by the intrinsic thermal time constant of the bolometric system, $\tau_{\text{bolo}} = C_p/G$.



Figure 1.13. An idealised bolometer (grey) with thermal link (red) and heatsink (black), with energy deposition by an incoming photon (orange).

To employ this theory in practice, one must utilise electrical readout to measure the resistance of a material acting as a thermometer on the thermal mass. A composite bolometer contains a separate absorber and resistive sensor, whilst monolithic bolometers are those in which the resistive mass and the absorber are the same. To measure the resistance of the thermal mass, the bolometric circuit must be 'biased', where an electrical bias power, P_{Joule} adds additional incoming power to the thermometer. When P_{Joule} is kept constant, the temperature increase becomes $\Delta T = T_0 + \frac{P_{\text{bias}} + P_{\text{photon}}}{G}$. The bolometer can be biased with either a constant voltage (voltage-biasing) or a constant current (current-biasing), in which the resistance is calculated by measuring the current or the voltage (respectively). For all measurements in this thesis, a voltage-biased approach is used.

A bolometer is biased via a load resistor with a resistance R_L which keeps a constant current through the bolometer, provided that $R_L \gg R_{\text{Bolo}}$. A simplified example of a voltage-biasing circuit is shown in Fig.1.14, where the bolometric signal is measured as V_{bolo} .

The temperature of the thermal mass varies both with optical and bias input power. The passage of current in the bolometer produces heat, which is known as Joule heating; the Joule power is described by $P_{\text{Joule}} = I^2 R$. Joule heating



Figure 1.14. A basic electrical bias circuit of a bolometer.

becomes important especially at cryogenic temperatures where the sensitivity is generally the highest. Under a voltage-bias scenario, increased optical input power incident on the thermal mass will decrease the Joule power. This process can result in a feedback loop between the thermal and electrical properties of the bolometer, where the Joule heating results in a temperature change. The R(T) characteristics of a bolometer, alongside the V(I) characteristics, are necessary in understanding the temperature and bias dependence of the device sensitivity.

Electrical characteristics of NTD germanium bolometers

For a bolometer with a doped semiconductor (such as that in the sensor used in this manuscript), the resistance changes as a function of temperature and the bias voltage:

$$R(T) = R_* \exp\left[\left(\frac{T_*}{T}\right)^\beta - \frac{eEL_{\rm hop}}{k_B T}\right]$$
(1.1)

where k_B is the Boltzmann constant, β is a constant, E is the applied electric field $(V_{\text{bias}}/l \text{ where } l \text{ is the thickness of the sensor})$, L_{hop} is the hopping distance (see section 1.5), e is the electron charge, T_* is material-dependent, and R_* is material and device-dependent [86][87]^{‡‡}, and $\beta = 0.5$ in the case of NTD germanium bolome-

^{‡‡} R_* has units of resistance and T_* has units of temperature. R_* depends on the resistivity and dimensions of the sample, and is the resistance of a bolometer at $T \gg T_*$. T_* is the band
ters (the type of detector used throughout this manuscript). The rate at which thermal energy leaves through the bolometer via the thermal link is established by the thermal conductivity, G. In the steady state, the total power in the bolometer is:

$$W = G(T - T_0) = P_{\text{Joule}} + Q \tag{1.2}$$

where P_{Joule} is the bias power and Q is absorbed optical power. When a bolometer is biased, it results in an electric field across the bolometer. The electric field E = V/l, we find:

$$R(V,T) = R(0,T) \exp\left(\frac{-eVL_{\text{hop}}}{k_BTL}\right)$$
(1.3)

We can derive the IV characteristics of any bolometer by varying T and verifying that the output satisfies V = RI.

Transient properties of bolometers

The temperature coefficient of resistance, α , designates the amount by which a change of temperature results in the change of resistance of the bolometer, and acts during temperature changes induced by radiation and by the bias power. It is defined thus:

$$\alpha = \frac{T}{R} \frac{dR}{dT} \tag{1.4}$$

Incoming power, ΔQ , creates a change in the bolometer output voltage ΔV_{Bolo} . The responsivity of the bolometer is defined as the change of the the output quality divided by the change of the input quality, and is found via:

$$\mathcal{R} = \frac{dV}{dP} = \frac{\alpha V_{\text{Bolo}}}{G - \alpha P_{\text{Joule}}} \tag{1.5}$$

where αP_{Joule} is the variation of the Joule power due to the change in bolometer

gap temperature of the material, and dictates the exponential variation in carrier concentration with T.

impedence, and where C/G is the response time τ . The responsivity of the bolometer depends on the conductance G - a high G grants a fast response, where a low G grants a high responsivity. The responsivity also depends on temperature, where the total power W is the sum of the conductive and radiative heat:

$$W = P_{\text{Joule}} + Q = G(T - T_0) + A\sigma_{\text{SB}}(T^4 - T_0^4)$$
(1.6)

where σ_{SB} is the Stefan–Boltzmann constant and A is the area of the bolometer. Taking the derivative of W with respect to T, we find:

$$\frac{dW}{dT} = G + 4A\sigma_{\rm SB}T^3 \tag{1.7}$$

where T_0 and P_{Joule} are assumed to be constants and dW/dT becomes dQ/dT.

$$G_{\rm eff} = G + 4A\sigma_{\rm SB}T^3 \tag{1.8}$$

 G_{eff} is the *effective* thermal conductance, i.e. the total of the conductive and radiative heat flow, and we substitute this into G in Equation 1.9:

$$\mathcal{R} = \frac{\alpha V_{\text{Bolo}}}{G + 4A\sigma_{\text{SB}}T^3 - \alpha P_{\text{Joule}}}$$
(1.9)

In order to maximise \mathcal{R} , we see that α should be high, and that P_{Joule} , G, and T must be low. When $G \ll 4A\sigma_{\text{SB}}T^3$, the responsivity is strongly dependent on temperature, and the need for high responsivities in modern experiments explains the need for very cold detectors.

Variable range hopping

For a bolometer kept in an environment at a constant temperature, increasing V_{bias} will increase the temperature of the bolometer due to Joule heating. The sensitivity of the bolometer can then be derived from the IV relationships, under the assumption that the Joule power and the power dissipated into the detector is equal [88] (and that the electrons and phonons in the sensor always have the same temperature). In the case of NTD Ge sensors, electrons can tunnel to an ionised donor, increasing the current in the sensor without any input power from photons,

and creating a conduction mechanism in the sensor attributed to the current across the sensor rather than the presence of photons [89]. This conduction mechanism is known as variable range hopping, and is dominant in doped semiconductors [86].

Dynamic Conductance

When power is incident on a bolometer, the absorbed power is a function of the thermal energy (heat) Q, the quantum efficiency κ , and the heat capacity C. It is the sum of the bolometer power P_{Joule} and the power of the source. At equilibrium, the power of the source which is measured by the bolometer, P_{Source} , is defined as $P_{\text{equi}} = T \cdot G$. When the bolometer is affected by incident power, that power is described as:

$$P_{\text{Total}} = P_{\text{equi}} + \kappa \cdot P_{\text{Source}} = \Delta T \cdot G + \frac{C \cdot dT}{dt}$$
(1.10)

from which it follows that:

$$T(t) = \frac{P_0}{G} + \frac{\kappa \cdot P_{\text{Source}}}{G} (1 - e^{-t(C/G)})$$
(1.11)

in which $\tau = C / G$ acts as the time constant governing the bolometer's response to the signal. This is the principle by which bolometers operate; the temperature of the bolometer allows you to measure the power. If we remember the definition of Joule heating in the previous section, we also remember that the bias current in the bolometer also causes the bolometer to become warm, meaning that both the bolometer biasing process and the source signal produce power in the bolometer. This electrical power changes with an electrical time constant, τ_{Bias} , which goes as:

$$\tau_{\rm Bias} = \frac{C}{G - \alpha \cdot P_{\rm Bias}} \tag{1.12}$$

This means that the electrical time constant is always smaller than the thermal one, and that the biased bolometer has two time constants. This effect is known as dynamic conductance [90], and will become important in later analyses. The *dynamic* conductance is therefore defined as:

$$G_d = \frac{\alpha R I^2}{T} \frac{Z + R}{Z - R} \tag{1.13}$$

where Z = dV/dI is the complex impedence of the bolometer. The bolometer can have very different behaviour under transient circumstances, including circumstances where it no longer behaves as a first-order device in relation to its thermal properties being uniform across all components and across the absorber [90]. This idea becomes important during this manuscript, where the bolometer is in a very out-of-equilibrium state due to a highly localised high energy deposition.

Electron-phonon decoupling

The phonons and electrons in the sensor will have a phonon temperature T_{phonon} , an electron temperature T_{electron} , and a Joule power. Ideally, the thermometer electronics are well-coupled to the bolometer system such that $T_{\text{phonon}} = T_{\text{electron}}$. However, for low T_{phonon} , electrons and phonons can decouple, which reduces the system's performance. We can model the power flowing to phonons from the electrons using a similar form:

$$P = G_{\text{el-ph}}(T_{\text{electron}}^n - T_{\text{phonon}}^n)$$
(1.14)

where $G_{\text{el-ph}}$ is a constant (over the temperature in question), finite thermal conductance between the electron and phonon components [88]. n is also a constant, with a value of 6 for NTD Ge [91]. Equivalently, the Joule power must also flow from phonons to the thermal bath:

$$P = G_{\text{ph-sink}} (T_{\text{electron}}^m - T_0^m)$$
(1.15)

where G_{electron} and m are again constants. At very low temperatures, and under an applied input power, there are less available states able to be occupied by electrons than by phonons, giving the electrons a higher temperature than the phonons [92].

The electrical field effect

Ideally, the resistance of the thermometer is only a function of the electron temperature. Depending on the bias power level applied to a bolometer, the applied electrical field E can become large enough to create non-Ohmic effects where the resistance of the device diverges in dependence on the temperature [93]; for a small applied bias voltage, the second term in the exponential in Equation 1.3 is unity, and so the resistance scales only with V and T, and if T changes, V also changes with Ohm's law. For a high bias voltage, the thermometer diverges from Ohmic behaviour, and this effect degrades the sensitivity of the thermometer. The characteristic hopping length is not itself dependent on E, but does depend on T_{electron} and takes the form of L_{hop} where $L_{\text{hop}(1\text{K})} = 1 \text{ K} \cdot L_{\text{hop}}$ and therefore $L_{\text{hop}(1\text{K})} \cdot T^{-\beta}$ [91] where we again take $\beta = 0.5$.

1.5.1 Bolometers as a tool in astrophysics

The first bolometer was presented as a tool for 'discriminating the heat in any small portion of the grating spectrum' [94], but it also became an invaluable tool for astrophysics, particularly in the millimetre, sub-millimetre, and far-infrared domains, where they (and their derivatives) are presently the most sensitive detectors available [95]. Their popularity is also due in part to the wide availability of studies of materials' resistivity as a function of temperature [96], allowing for a wide range of application in many materials.

1.5.2 Motivation of irradiation studies

As the scientific requirements increase in the next generation of missions, the 'cosmic ray problem' will only continue to grow as devices become more sensitive and operate at even lower temperatures. Furthermore, the next generation of missions will seek to measure even smaller cosmic signals, and will require a detailed understanding of the subsystem vulnerability to cosmic radiation, as well as the effects this could have on the data itself. Planck's pulse removal work was successful in characterising the physical origin of the cosmic ray pulses in the data. However, future missions must take into account – and attempt to minimise – the potential impact of this important systematic effect, particularly during the early phases of development. Furthermore, comprehensive characterisation of any given bolometer is a requirement for later modelling of that bolometer, especially in the transient regime.

1.6 Description of Bolometer Experiments with 5.4 MeV α Particles

Whilst it must be noted that α particles are not the dominant form of cosmic ray encountered by space missions at L2, preliminary measurements using α particles provides several advantages. Irradiation with α sources is experimentally feasible and can be performed in-situ in any cryogenic test system due to their small size and availability. More importantly, α particles have a higher ionising power and therefore are easily stopped in the first material they encounter (with a skin depth as a function of their energy). This provides a very high, very localised energy deposition into the material of interest, and therefore it can be assumed that all 5.4 MeV is embedded into the absorber structure. This is an important simplification from the standpoint of developing a physical model, which can later be validated using data from other types of particle impacts (e.g. minimally-ionising protons, which completely traverse a material impart only a small amount of its total energy).

1.6.1 'Bolo 184'

These experiments utilised a bolometer (referred to hereafter as 'Bolo 184') which was designed at IAS for the ground-based infrared experiment DIABOLO [97] [98]. Bolo 184 is a composite semiconductor bolometer, containing a disc-shaped diamond absorber with a sputtered back-layer of bismuth, a NTD germanium sensor, and a sapphire slab for mechanical support. The bolometer layers are held together using Devcon epoxy, and the ends of the long, thin germanium and sapphire legs are coupled to the thermal bath using wound copper wire. A diagram of the device

Component	\mathbf{Width}	Thickness	Material
Absorber	$\phi=3.5~\mathrm{mm}$	$40~\mu{\rm m}$	diamond with bismuth coating
Sensor (central)	$800 \ \mu { m m}$	$260~\mu{\rm m}$	NTD germanium
Sensor (legs)	$3.4 \mathrm{mm}$	$150~\mu{\rm m}$	NTD germanium
Mechanical Support	$350~\mu\mathrm{m}$	$68~\mu{\rm m}$	sapphire

Table 1.1 – Dimensions of Bolo 184.

is shown in figure 1.15. A table with the dimensions of the various components of Bolo 184 is given in Table 1.1.

Bolo 184 is held 12.5 mm beneath the α particle source, which is collimated by a 2 mm diaphragm. The detector is orientated at a 45° angle relative to the source, inside an integrating sphere (part of its heritage mounting from the DIABOLO experiment, which coupled light from the feedhorn to the detector). The source, sphere, and detector are enclosed in a block to prevent stray light.

Bolo 184 was chosen as a test subject for several reasons: (1) having been developed at IAS, the mechanical, thermal, and electrical aspects of the bolometer and its components had been thoroughly measured and documented; (2) due to the layout of the bolometer and the heatsink coupling, all energy deposited into the absorber must pass through the sensor before flowing through the sensor legs, sapphire, or test plate. This allows for a greater understanding of energy propagation through the device, which provides advantages in validating modelling of the bolometer.

Electrical characteristics of Bolo 184

As noted in Section 1.5, the electrical characteristics of a bolometer (specifically, the voltage as a function of current, V(I)) are important in deducing the 'working point' (the T, V, and R at which the bolometer is operated) of a bolometric experiment, which affects the sensitivity of the detector. Since Bolo 184's construction at Institut Néel, a wide range of measurements were taken of its V(I) characteristics at several temperatures, which are shown in Figure 1.16. These tests were verified



Figure 1.15. Diagram of the bolometer used in this study, including its enclosure. Left: The bolometer housing (figure adapted from Benoit et al.[97]): (1) conical feedhorn; (2) integrating sphere ($\phi = 4 \text{ mm}$); (3) bolometer (detail at right); (4) optical fibre for control of response stability, disconnected for this experiment; (5) low-pass thermal filter (6) $50\mu\text{m}$ gap in thermal filter; (7) the radioactive ²⁴¹Am source. Below the source is a diaphragm of ϕ = 4 mm, below which a second diaphragm of $\phi = 2 \text{ mm}$ is separated by a distance of 12.5 mm. *Right*: Bolometer details. The diamond absorber (blue) is affixed to a NTD germanium sensor (purple) with thin legs, and affixed to a slab of sapphire (yellow). Each leg of the sapphire and Ge are coupled to the thermal bath with wound copper wire.



Figure 1.16. Original IV measurements of Bolo 184, taken by A. Benoit.

during the experiments performed in this chapter, both in SYMBOL and in the new dilution system at IAS; in the latter experiments, the V(I) characteristics of the bolometer were an important verification step in determining the temperature of the test device.

The attributes will become important in the next few chapters, in which we will outline experimental work done in two cryostats at IAS (SYMBOL, and the new cryogenic test system delivered in April 2018).



Figure 1.17. Three cosmic ray pulses in the Anti-Coincidence detector for Athena X-IFU, with their total double-exponential fit (solid red), fast (dotted), and slow (dashed) components. Image taken from D'Andrea et al. [99].

1.7 Cosmic ray glitch topology

We will describe some previous studies which have measured particle pulses in highly-sensitive detectors, in order to introduce the typical shape of glitches, which we expand upon throughout this manuscript.

It is thought [61] that glitches in these types of detectors contain two components: a fast peak arising from ballistic phonon propagation [100], and a slower component from thermal diffusion. This assumption has been carried forward in various cosmic ray impact studies, including those of Planck-HFI and X-IFU. In a study of the Anti-Coincidence detector for Athena X-IFU, D'Andrea et al. produce pulses in the anti-coincidence detectors using ²⁴¹Am α particles, and fit to them using the sum of two double-exponentials [99]. The ratio of these components in individual glitches is thought to be a function of the amount of energy propagating in each form from an α impact on the detector, and is described with the following shape:

$$f_{\text{glitch}}(t,t>0) = A_1 \times \left(e^{-t/\tau_2} - e^{-t/\tau_1}\right) + A_2 \times \left(e^{-t/\tau_4} - e^{-t/\tau_3}\right)$$
(1.16)

where A_1 and A_2 are the amplitudes of the ballistic and thermal phonon components (respectively), τ_1 is the rise time of the ballistic component, τ_2 is its decay time, τ_3 is the thermal rise time, and τ_4 is the thermal decay time. D'Andrea et al. [99] have set τ_2 and τ_3 to be equivalent in their fits, although this equivalence



Figure 1.18. 466 stacked pulses in ground-based tests on the Planck HFI detectors, in which the two pulse components are fit to using exponential models. Image taken from Catalano et al. [61]

is not universal and may break down in the presence of nonlinearities, e.g. high V_{bias} with a low temperature. We show this typical form in Figure 1.17, in which the total double-exponential sum is shown, along with its split 'fast' and 'slow' components.

The same interpretation was previously used in analysis of cosmic ray pulses in Planck HFI [61], although the nature of the exponential fitting was different. This study did not attempt to fit the rise times of the pulse or the second component, but fitted with a single exponential decay to pulses which had been normalised for amplitude. The 'fast' component was still attributed to ballistic phonons, and the 'slow' component to thermal diffusion.

This thesis is built upon the idea of 'fast' and 'slow' pulse components, but with the hope of expanding its understanding. When a cosmic ray or α particle impacts the bolometer, it loses energy which is distributed into the detector which then thermalises with its surroundings via various thermal pathways. The initial energy 'spike' followed by a slow dispersion is what gives the glitch its characteristic shape. The quickest mechanism of energy deposition is propagation via ballistic phonons which propagate to the sensor and are thermalised within or close to it (athermal diffusion), and this can be seen in the 'fast' part of the glitch. The remaining component of the glitch, which is usually slower and of lower rise / decay times, is the thermal component. When a 5.4 MeV α particle impacts the absorber disc, it loses all its kinetic energy, which is deposited through ionisation concentrated at the end of its trajectory in the absorber, after an average range of 14 μ m (as calculated from the stopping power of α particles in carbon [101]. This energy is converted locally into ballistic phonons [102] which radiate isotropically from the original impact area at high speed (the speed of sound in the media is typically a few km/s) before thermalising on the top or bottom disc surface at distances typically roughly the size of the thickness of the absorber (40 μ m).

The closer (or further) distance of the impact point to the disc center results in a faster (or slower) thermal propagation time to the sensor, where the signal is read (a position effect which has been seen in other experiments [103]). Whilst it is likely true that 'faster' peaks are the result of ballistic phonons which arrive closer to the detector sensor, we assert that the ballistic phonons themselves thermalise at surface boundaries or in the absorber disc, and that all energy passing through the sensor takes the form of thermal phonons. In the case of a particle impact immediately above the sensor, more ballistic phonons thermalise at the Bi/Ge interface, creating a larger initial pulse. As a consequence of this, we believe it is necessary to challenge the assumption within the Planck community that the first exponential comes from 'ballistic energy' and that the second one comes from 'thermal energy'. However, for brevity, we will continue to use the usual 'ballistic' and 'thermal' terminologies to describe the fast and slow components.

Summary of the work

This summary is intended as an overview to the work performed during the time this thesis was undertaken: November 2015 to December 2018. We will outline the work which is presented in this manuscript, and we will also mention the work which was not presented.

'Bolo 184' measurements and modelling

At the beginning of this work, it was originally envisaged that IAS would have access to new detectors from projects under development (e.g. QUBIC, PIXIE – now PRISTINE – Athena X-IFU, and others). Until the arrival of newer technologies, work began using the facilities already available at IAS; two bolometers developed under the purview of N. Coron (Bolo 184 and a massive optical bolometer for measuring rare decays of atoms), and the stationary dilution refrigerator SYMBOL. Bolo 184 was ultimately chosen as a better candidate for experimental and modelling work, due to the relative simplicity of the thermal sinking compared with the optical bolometer (which has many thermalisation paths away from the absorber). The overarching idea of the work is to use Bolo 184 as a generic bolometer to probe the physics of cosmic ray effects.

Mastering autonomous use of SYMBOL was not without difficulty, and required an order of 100 litres of liquid helium. SYMBOL's need for maintenance (to fix a probable leak in the nitrogen trap) posed an issue, specifically with the thermal stability of the final experiment done in this cryostat (shown in Chapter 2, Section 2). Other issues were experienced during this time, including broken buttons on the pumps. Because other detector technologies were not measured at IAS from 2015 to 2018, Bolo 184 was the sole focus of the experimental and modelling work. The full description and results of this work are found in Part 2 of this manuscript, in Chapters 2, 3, 4, and 5.

Athena X-IFU Cosmic Ray Collaboration

The author was approached by members of the international X-IFU consortium in July 2017, and has engaged in modelling work with the cosmic ray working group since that time. During this period, this work was balanced with other projects, and periodic updates have been presented in the Integrated Progress Meetings (cosmic ray splinter group talks) and Consortium meetings (plenary and splinter group talks) by the author. The details of this project, and its most current results, are presented in Chapter 6.

PILOT balloon-borne telescope

The author has participated in the activities of the PILOT balloon-borne telescope, both in the laboratory (since 2016) and during the two-month telescope launch campaign in Alice Springs, Australia in February to April 2017. The contributions of the author were principally on the testing and use of the cryogenic system before, during, and after flight. Cryogenics is not within the context of the work outlined in this thesis, and so it will not be described in this manuscript.

Designs for new cryogenic system (beam line tests)

We will describe the cryogenic system, newly arrived at IAS, which has been commissioned for tests of detectors in the beam line of a particle accelerator (see Section 3.1.1, page 110). Funding for this new system was approved early in the course of this work, and it was originally envisaged to be in front of a beam line for tests during the time when this thesis was still underway. However, delays



Figure 1.19. The author making final preparations on the tarmac for the launch of PILOT (taken by Sébastien Chastanet©).

in funding and construction of the system lead to its delivery only in April 2018. The first preparations for this system, for closed tests on Bolo 184, were a group effort (with special thanks to V. Sauvage). The author has designed windows for the coupling between the beam line and the cryostat, in order to ensure sufficient passage of particle beam energy for detector tests. This work will be described in Chapter 7), in addition to running several experiments in the new system (described in Chapter 3), including the validation study which was presented to CNES in May 2018.

Résumé en français

Ce manuscrit étudie la question de l'effet des rayons cosmiques sur les missions spatiales cosmologiques et rayons X. Après le lancement du télescope spatial Planck en 2009, un taux plus élevé que prévu d'excursions thermiques sur les détecteurs Planck a été observé dès l'arrivée des premières données scientifiques. Un grand effort communautaire a été fait pour éliminer ces effets, ce qui s'est finalement avéré fructueux. Toutefois, l'expérience a servi à rappeler à la communauté l'importance de comprendre les dépôts d'énergie par les rayons cosmiques avant le lancement de la prochaine génération de missions spatiales, et a laissé un écart particulier en ce qui concerne la modélisation de ces effets.

Pour ce faire, nous avons réalisé plusieurs expériences à l'aide d'un bolomètre en germanium NTD à semi-conducteur composite issu de l'expérience au sol DIA-BOLO. A l'aide de ce bolomètre, que nous refroidissons entre 100 et 200 mK sur plusieurs campagnes de mesure, nous produisons des impulsions en utilisant une source de particules alpha. En étudiant ces impulsions, nous cherchons à connaître les propriétés électriques et thermiques de ce détecteur.

Nous trouvons que la forme de l'impulsion est bien décrite par la somme de deux doubles exponentielles, mais que pour que cette fonction résout le temps de montée de l'impulsion, nous devons nous appuyer sur un facteur de non-linéarité quadratique ϵ (pour lequel nous avons été incapables de trouver une base physique). Comme alternative, nous avons développé une nouvelle description de la forme de l'impulsion issue de la physique thermique, en utilisant la convolution entre la fonction de réponse du détecteur et l'évolution temporelle d'une impulsion thermique sur un absorbeur infini. Cette nouvelle fonction débloque la constante de temps de prop-

agation thermique τ_3 , et permet de visualiser le temps de propagation thermique en fonction de la position de l'impact des particules alpha par rapport à l'absorbeur.

Nous avons également produit plusieurs modèles physiques pour Bolo 184, dont un modèle à deux composantes décrivant la fonction de réponse du capteur NTD et des couches de support mécanique en saphir à une impulsion de température delta, convolué avec un modèle de propagation de la chaleur de Monte-Carlo. Ce modèle n'a pas donné les résultats escomptés, ce qui indique un couplage thermique plus fort que prévu entre l'absorbeur et le capteur. D'autres modélisations physiques, investiguant les effets de la rétroaction électrothermique et de la capacité parasite dans le système expérimental, ont reproduit les oscillations observées dans les données dans les mêmes conditions. Un dernier ensemble de modèles, examinant la propagation et la thermalisation des phonons balistiques sur l'absorbeur du bolomètre, a reproduit la distribution des amplitudes observées dans les données (en utilisant à la fois des techniques de tracé de rayons et de trajet libre moyen). Le succès de ce modèle confirme que, dans ce détecteur, les phonons balistiques se reflètent sur les surfaces de l'absorbeur, laissant une fraction de leur énergie à chaque réflexion.

Nous avons également présenté les travaux réalisés dans le cadre de la collaboration Athena X-IFU, pour l'estimation de la vulnérabilité aux rayons cosmiques de la plaquette du détecteur X-IFU. Nous avons simulé la plaquette du détecteur dans COMSOL, en suivant l'évolution d'une simple impulsion de chaleur afin de mesurer l'excursion thermique sur la membrane SiN sur laquelle reposent les détecteurs. Nous produisons des chronologies (timelines) T(t) et comparons leur température efficace avec celle indiquée dans la documentation du budget de la résolution énergétique du X-IFU. Nous constatons que la température efficace est d'environ un ordre de grandeur au-dessus de cette quantité budgétée, mais que les fluctuations de température efficace ne sont pas un marqueur fiable de l'effet de la température sur le détecteur. Nous attendons actuellement que les résultats de notre simulation soient traités au simulateur du détecteur X-IFU pour mesurer l'élargissement d'un rayon X à 7 keV simulé. En regardant les résultats de notre étude sur la propagation des phonons balistiques, nous proposons que l'utilisation d'une simple impulsion de chaleur pour décrire le dépôt d'énergie des rayons cosmiques pourrait être un moyen insuffisant pour simuler ce comportement thermique complexe. D'autres travaux sont prévus pour approfondir ce raisonnement, peut-être en utilisant les techniques de simulation de tracé de rayons utilisées pour le Bolo 184.

Part II

Bolometer Measurements ('Bolo 184')

Bolo 184 Experimental Chronology

Most sensitive bolometric detectors will be able to detect cosmic ray muons arriving at the surface of the earth. How reliably this signal can be measured depends on the sensitivity of the device under test, and whether the noise is low enough to discern useful information from these pulses. A common alternative is to use an internal α particle source. Whilst most cosmic particles at L2 will be protons, a proton source can be logistically and technologically difficult to utilise in many cases. The work described in this chapter began when IAS only had access to a small, non-portable cryostat, and only one radiative source. Whilst α particles behave differently to minimally-ionising protons in target materials, using an α particle source provides the advantage of knowing that all the α energy will be stopped in the target, allowing us to understand the movement of energy in the detector under test. This has been a useful tool for allowing for the characterisation of the bolometer used in this manuscript, and has provided understanding which would not have been achievable by cosmic ray muons alone.

This chapter is intended as a brief chronological history of the experiments on Bolo 184 carried out during this thesis. We have tested our bolometer at a range of temperatures and conditions, mixed between α particle and cosmic ray measurements. The experiments and their goals are outlined and described below, beginning with Table 1.2.

Exp. \mathbf{n}°	Date	Purpose	Temperature	Parameters
1	01/2016	α particles and CRs	100 mK	$V_{\rm bias} = 1 V$
2	06/2016	α particles	$100\text{-}200~\mathrm{mK}$	$V_{\rm bias} = 1.5 V$
3	12/2017	α particles and CRs	100 mK	$V_{\text{bias}}=0.25\text{V}$
4	04/2018	α particles	100 mK	$V_{\text{bias}}=0.25\text{V}$
5	04/2018	α particles and CRs	$127^* \mathrm{mK}$	$V_{\rm bias}=0.4{\rm V}$
6	07/2018	CRs	127^* mK	$V_{\rm bias}=0.4{\rm V}$
7	08/2018	Joule pulsing	$100^{*}-200^{*}mK$	$V_{\text{bias}}=0.2-3.2\text{V}$

Table 1.2 – List of Bolo 184 experiments undertaken in the work. Experiments done in SYMBOL are outlined in red, while experiments done in the BlueFors system are in blue. * indicates experiments where the set T was calculated to be above or below the actual T, which are explained in the paragraph of experiments 4 and 5.

Experiments and their goals

Experiment 1 was carried out in the effort to produce a first dataset of glitches on this detector and another detector (a massive bolometer which was ultimately elected to not be used for this thesis). At 100 mK and with V_{bias} (the total bias voltage across the bolometer and its load resistor) at 1 V, the bolometer is outside the linear regime on the IV curve, resulting in a nonlinear working point. This resulted in pulses with oscillations between the fast and slow components, which we believe to be due to effects arising from electro-thermal coupling of thermal phonons and electrons. Initially, we investigated this effect, before settling on investigating mostly-linear regimes of study.

Ultimately, this experimental set served two purposes: (1) to learn how to use SYMBOL without any assistance; (2) to learn about glitches in this bolometer, and about the bolometer itself. This experiment also involved the introduction of room-temperature gaseous He into the cryostat (an experiment carried out by previous Ph.D. student A. Miniussi, who was present at the time). This created numerous 'mini-pulses' in the data (most likely due to He gas condensing as a superfluid, some of which interacts with the detector), showing that non-particle adulterants in the vacuum can produce glitch-like shapes in the data.



Figure 1.20. An example pulse from experiment 1, with a hint of oscillations at 2.5 ms.

Experiment 2 was taken at two different temperatures: at 200 mK, the working point was very linear in the IV characteristics of this bolometer. At 100 mK, the pulses had oscillations which were most likely due to effects of electrothermal coupling and stray capacitance, making them difficult to analyse. The analysis of the 200 mK pulses is performed in Chapter 2, without the effect of such nonlinearities, was used to form the basis of our understanding of this detector.

Experiment 3 took 100 mK pulses with a much lower V_{bias} , with the aim of decreasing nonlinearities and increasing sensitivity of the detector. Due to some experimental limitations with SYMBOL, this measurement set suffered several systematic effects. Notably, there was significant thermal instability due to a leak in the nitrogen trap of SYMBOL. The lower V_{bias} resulted in a lower signal-to-noise ratio. These measurements were also performed with a new oscilloscope, and were errantly measured with AC coupling. The analysis of these pulses, including the data treatment involved with them, is detailed in the next chapter. This was the final measurement run on SYMBOL (since decommissioned), and will conclude Chapter 2.

Experiments 4 and 5 were done in the new cryogenic measurement system installed at IAS in April 2018. Experiment 5 was a quick validation of the cryo-

genic system, to verify its performance compared with the previous experiments in SYMBOL. It will be presented only briefly, although the limitations of the cryogenic system at the time are described. This new system is not calibrated to the same extent as SYMBOL was, so there is a small difference between the set temperature (100 mK) and the temperature actually achieved. Experiment 6 was at a slightly higher V_{bias} , in search of a higher signal-to-noise ratio. However, a thermal differential was present between the cryogenic cold plate and the detector, where a high thermal load was present. The test plate temperature was set to 100 mK, but IV measurements performed under the same conditions have determined that the test plate was actually at 127 mK. This experiment, the temperature calculations, and the results of the experiment itself will be discussed in detail in Chapter 3.

Experiments 6 and 7 are the final dataset discussed in this manuscript, and were again performed in the new facility at IAS. Experiment 6 was a dataset of cosmic rays at 100 mK (using a higher oscilloscope gain to resolve low-amplitude events and which led to the stronger α particle responses becoming saturated), for the overall purpose of comparing the pulse shapes incident muons with that of α particles. Experiment 7 was an extended campaign in which the bias power of the bolometer was pulsed, in order to probe the fundamental time constants of the bolometer itself. This was performed between 100 and 200 mK, and with bias voltages between 200 mV and 3.2 V (depending on the IV characteristics of the bolometer at the respective temperature). The results of experiment 7 will be discussed hereinafter, in the final sub-chapter of this Bolo 184 section, Chapter 4. These two experiments also had some temperature offsets relative to their calculated values, so the experiments at 100, 150, and 200 mK were calculated to be closer to 108, 137, and 180 mK (respectively). Most women fight wars on two fronts, one for whatever the putative topic is and one simply for the right to speak, to have ideas, to be acknowledged to be in possession of facts and truths, to have value, to be a human being.

- Rebecca Solnit

Chapter

Bolometer Experiments in SYMBOL

This chapter will describe the experiments performed in the characterisation of the behaviour of a cryogenically-cooled composite semiconductor bolometer as influenced by ionising radiation (e.g. α particles or cosmic rays), which were performed in SYMBOL at IAS. More recent measurements in the new cryogenic test system are presented in the next chapter.

The experiments in Chapters 2 and 3 form the basis of our understanding of Bolo 184, which we have used to generate 'typical' α particle pulses from a bolometer, in order to better understand the physical mechanisms taking place during particle interactions.

2.0.1 α Measurements - Methods

Bolo 184 (which has been described in Chapter 1, Section 1.6.1 (page 44) was housed with a radioactive americium-241 α particle source (with a particle energy of 5.48 MeV or 0.8 pJ) in-situ and secured into a copper box to prevent movement of the sources, shown in figure 2.1. The bolometer was held at a 45° angle relative to the α source, and was housed inside an integrating sphere. The source is glued to the end of a 12.5 mm feedhorn, facing the bolometer, with an upper and lower diaphragm diameter of $\phi = 2.5$ mm and $\phi = 2.0$ mm, respectively.



Figure 2.1. Bolometer and source housing in the cryostat cold plate. Bolo 184 is housed with its source in the enclosure shown in blue, while the massive optical bolometer and its source are in the enclosure shown in red. The top connection in the image is a test resistor.

The first series of measurements on this detector were performed in the dilution refrigerator at SYMBOL at IAS.

SYMBOL Dilution Refrigerator

These experiments were performed in a ³He-⁴He inverted dilution refrigerator cryostat SYMBOL, provided to IAS by Air Liquide, with tabletop inverted dilution elements (coined "sionludi") designed by Institut Néel [104]. SYM-BOL consists of six temperature stages (80 K, 20 K, 4 K, 1 K, 300 mK and "test", shown in figure 2.2) in a vacuum chamber, where the test plate can reach temperatures of 15 mK or lower, but can be heated using a resistor heater to keep a



Figure 2.2. Side view of SYMBOL with open, showing six temperature stages.

stable temperature of 15 mK to hundreds of mK. The experiments described in this chapter had temperature variations of about ± 0.1 mK, stabilised by a proportional integral derivative controller (PID).

The outer stages of SYMBOL are cooled via ³He-⁴He injection lines. The ³He-⁴He mixture arrives at the injection site from SYMBOL's mixture injection circuit, shown pictured with the SYMBOL test bench in figure 2.4 along with the cryostat inside its thermal and vacuum shielding cap. A nitrogen-cooled charcoal trap on the injection circuit allows for the cleaning of the mixture prior to injection, and a vacuum pump is used to pump the interior of SYMBOL to a vacuum level of $\approx 5 \times 10^{-5}$ mbar.



Figure 2.3. Engineering designs for SYMBOL. A side view of SYMBOL is shown at the left of the image, with top-down views of each plate shown on the right.



(a) Injection and cleaning circuit



(b) Experimental bench

Figure 2.4. Left: The SYMBOL injection and cleaning circuit, with injection lines shown in the lower left. **Right**: Experimental bench with SYMBOL shown with its shielding cap, with a 100 litre He⁴ dewar for cooling the 4 K stage (left).

SYMBOL's 4 K stage is cooled directly by the introduction of liquified He⁴ via a 100 litre dewar which is lowered into a pit beneath the bench (shown in Figure 2.4(b)). A transfer tube is affixed to the underside of SYMBOL which facilitates the continuous cooling of the 4 K stage, is regulated by an electronically-controlled valve with a flowmeter, and which can cool SYMBOL to 4 K within ≈ 10 hours. SYMBOL uses approximately 30 litres of He⁴ to cool to 4 K and 15 litres per 24 hours of maintenance at 4 K or lower.

The 80 K and 20 K stages contain the He⁴ pumping line and the He³-He⁴ injection line, arranged in an efficient counter-flow arrangement for heat exchange [104]. He³ is extracted from the mixture at the 1 K stage, and the final stage contains the He³-He⁴ mixing chamber where the mixtures separate into two phases.

SYMBOL can cool from 4 K to 100 mK in approximately two hours, and continues using the same amount of He^4 during this time. SYMBOL is capable of producing 4 to 5 days of a stable, low-temperature environment for measurement per 100 litres of helium.

Detector readout

The readout system utilises a typical bolometer biasing circuit with a cold load resistor biased by a voltage source, where the input voltage is modified using a potentiometer. The bias box, connected directly to the cryostat input by a single cable, was made in-house by N. Coron, and can vary the input voltage between \approx 180 mV and 1.3 V (using a potentiometer) and 1.5 and 3.2 V (using switches).

The first experiments performed in SYMBOL used a Yokohama oscilloscope which was limited in its internal hard drive space (it could only record α particles for 8 hours before needing to have the data emptied). All other measurements, including those on the new cryogenic system in the next chapter, were performed using a newer Waverunner oscilloscope without such limitations. In all cases,



Figure 2.5. Diagram of the readout schematics for this experiment. *Red*: Warm electronics - bias box (left), and two warm amplifiers with oscilloscope (right). *Blue*: Bias circuit inside the cryostat, kept at 200 mK. (Figure taken from Stever et al., 2018 [105])

the readout schematics and settings (gain, etc) are unchanged unless specifically mentioned in the text.

2.1 Bolo 184 Measurements at T = 200 mK

For these measurements, the test plate was cooled to 200 mK and its temperature was controlled using a PID. The bolometer was biased by a high impedance (40 M Ω) in series, with a bias voltage of 1.5 V, using the readout schematic shown in Fig. 2.5. At 200 mK, a bias voltage of 1.5 V is within the linear range of the IV curve.

The cryostat did not contain an optical input port in order to minimise other sources of input power. 507 glitches were recorded over 8 hours and 58 minutes (further time being limited by liquid helium) at a sampling rate of 50 kHz, using a warm amplifier gain of 100. Each glitch at 200 mK is verified to be from the impact of an α particle, as the signal from cosmic ray muons and nuclear recoil is beneath the noise at the sensitivity attained at 200 mK. Lower temperature experiments were performed (including those with signal from cosmic ray muons) which will be presented in a later section. The higher temperature and bolometer linearity resulted in a lowered sensitivity, and due to this, the signal from impact with cosmic ray muons is beneath the noise. Therefore, the glitches recorded during



Figure 2.6. A sample of one glitch from the 200 mK data set.

this time were all due to α particle emission interactions.

An example of a typical pulse from this data set is shown in figure 2.6. In the following sections, we will discuss the statistical distribution of the glitches and examine various means of analysis of total energy distribution and thermal/athermal energy dispersion.

2.1.1 Total Energy Distribution

A rough idea of the energy spectra of these interactions can be made by several means. The simplest treatment is by assuming that the total energy corresponds to the maximum signal strength at the peak of the glitch, and so to calculate the distribution of the signal maxima across all samples. A second (and more accurate) method is to calculate the total integral of the signal, with the assumption that the total energy dispersed through the bolometer is present across all parts of the signal. We note that the total pulse integral is generally assumed to be analgous to the energy deposition, which has been shown in the literature [106]. Because the α particle will deposit all of its energy into the upper 14 μ m of the absorber structure (as calculated from the stopping power of α particles in diamond [101]), the pulse



Figure 2.7. Left: Histogram of the distribution of maximum glitch amplitudes. Right: Normalised histogram of energy integrals, corresponding to the 5.4 MeV α line.

energy may travel slower (or quicker) to the sensor due to the position of the impact. Particle hits just above the sensor will create a large, fast energy deposition which decays more quickly. By contrast, particle impacts further from the sensor will have to travel longer across the absorber, and will have shorter amplitudes and longer tails. For this reason, the total integral^{*} is a more accurate indication of the total distributed energy, while the maximum amplitude distribution indicates the positions of the impacts.

A demonstration of this principle can be seen in figure 2.7, where the glitch spectra is much more 'peaked' as visualised by the total integral, on right. The skewed distribution of the maximum amplitudes relates to the striking angle of the α particle.

This basic analysis provides us with an important tool for understanding the movement of energy in the detector, which has been used along with other statistical

^{*}Throughout this manuscript, when we refer to the integral, we are describing the sum of the total signal in a number of time bins, either of the voltage or the temperature, as a function of time, unless we explicitly specify otherwise. In most cases presented, the integral represents the total energy. In cases where it does not, e.g. Chapter 6 on Athena X-IFU, we will specify this.

characteristics in the data set to provide the basis from which the modelling is based.

2.1.2 Exponential Decay Fitting

Each glitch can be fit via the application of a function which describes exponential decay, which is a treatment frequently performed in the literature in Planck bolometers [61][60] as well as other space missions with highly sensitive Transition Edge Sensor (TES) detectors [99]. The treatment herein will be the application of two double-exponential decays convolved with the electronic transfer function, which affects the shape of the signal through the electronics.

We fit to each individual glitch using the typical equation we have already described in Section 1.7 (Equation 1.16) and where the parameters retain their prior meanings.

This equation is further convolved with an simple exponential electronic transfer function $F_{\rm ET}$ to account for the impulse response of the readout to the glitch signal, giving an additional rising time constant θ , which is calculated to be 0.027 ms, and is fixed for all fits. We explicitly convolve one component of Equation 1.16 with $F_{\rm ET}$:

$$\operatorname{out}(t) = \int_{+\infty}^{-\infty} f_{\text{glitch}}(t') \times F_{\text{ET}}(t-t')dt'$$
(2.1)

with:

$$F_{\rm ET}(t) = H(t) \frac{e^{-t/\theta}}{\theta}$$
(2.2)

Developing

$$f_{\text{glitch}}(t) = A_1 \times H(t) \left(e^{-t/\tau_2} - e^{-t/\tau_1} \right)$$
 (2.3)

we find
$$\begin{aligned}
\text{out}(t) &= A_1 \times \int_{-\infty}^{\infty} H(t') H(t-t') e^{-(t-t')/\theta} \left(e^{-t'/\tau_2} - e^{-t'/\tau_1} \right) \frac{dt'}{\theta} \\
&= A_1 \times \int_0^t e^{-t/\theta} e^{t'/\theta} \left(e^{-t'/\tau_2} - e^{-t'/\tau_1} \right) \frac{dt'}{\theta}
\end{aligned} \tag{2.4}$$

which produces:

$$\operatorname{out}(t) = A_1 \times \frac{\tau_2}{\tau_2 - \theta} \left(e^{-t/\tau_2} - e^{-t/\theta} \right) - \frac{\tau_1}{\tau_1 - \theta} \left(e^{-t/\tau_1} - e^{-t/\theta} \right)$$
(2.5)

which keeps a simple exponential form.

The impact of the response function convolution on the goodness of the data fits will be outlined in the forthcoming Section 2.1.5.

2.1.3 Thermal and Athermal Components of Glitches

In the Introduction (Chapter 1, Section 1.7, page 48) we described the fast ('athermal') and slow ('thermal') glitch components. We will use the equations described in that section and in the sections above to fit to the shape of the pulses in this section.

Applying the function we have described to fit the data, we can fit to the total glitch signal as well as to each component separately (e.g. to obtain the 'fast' component, we set A_2 to 0 and vice versa). A more detailed treatment of these fits and their analysis follows, but for demonstration purposes, the glitch shown in image 2.6 is shown again in figure 2.8 showing the full fit, as well as the athermal and thermal components separately. The χ^2 goodness of this fit as well as its residuals are shown in Section 2.1.6.



Figure 2.8. Full fit for a sample 200 mK glitch, in log space. *Blue:* data; *Red:* athermal (ballistic) fit; *Green:* thermal fit; *Black:* total fit.

2.1.4 Analysis

This section details the various treatments given to the glitches of the 200 mK data set, including the fit parameters, the electronic transfer function convolution, χ^2 goodness tests, and the variation of the amplitudes and time constants across the data set.

2.1.5 Impact of the electronic transfer convolution on the goodness of fits

For the fit of these functions to the data, "MPFIT" was used extensively. MPFIT is a nonlinear least-squares fitting algorithm which was originally developed for IDL [107] [108] and based on the MINPACK Levenberg-Marquardt algorithm [109]. The fitting routines were then translated into the Python language, and the version used in this thesis was obtained from the PRESTO toolkit on GitHub [110] which contains a version of MPFIT utilising current Numpy libraries.

Returning again to the sample glitch shown in the previous sections, it is possi-



Figure 2.9. Comparison of the glitch fit with (upper left) and without (upper right) the convolution with the electronic transfer function. Lower left and lower right are the residuals of the above fits, respectively.

ble to illustrate the effectiveness of the electronic transfer function on successfully fitting and modelling the data. By adding the electronic time constant θ to the fit, it was found that a small time constant of 26.97 μ s improved the χ^2 goodness of the fit from $\chi^2 = 2.48$ to $\chi^2 = 1.60$). The improvement in the fits is shown in figure 2.9. The left side of the image shows the fit and the residuals of the fit vs. the data with the electronic time constant added to the fit - the same plots are shown on the right without the fit accounting for the electronics. In addition to the greatly improved χ^2 for the fit accounting for the electronics, the fit is visually improved, which can be seen in the greatly improved point-by-point residuals, improving to error of ± 0.025 V from $\approx \pm 0.04$ V.

Due to the large number of parameters involved in this fit, the fitting algorithm is particularly vulnerable to finding local, nonphysical minima in parameter space. For the remainder of the fits described in this section, θ is fixed at its nominal value of 26.97 μ s, which in every case is negligible compared to the rise-time constant τ_1 , and which provides a fit with the greatest agreement within the constraints required to produce parameters with physical meaning.

2.1.6 The quadratic nonlinearity factor, ϵ

Finally, the introduction of a quadratic nonlinearity term over the entirety of the fit function has been found to increase the χ^2 goodness of the fit by an order of magnitude. The nonlinearity ϵ takes the form:

$$f'_{\text{glitch}} = f_{\text{glitch}} (1 + \epsilon f_{\text{glitch}}) \tag{2.6}$$

From this fit, we find a strong nonlinearity factor ϵ which is correlated with amplitude; ϵ is very large for very small glitches, and small and negative for the largest glitches in the data set, which we show in Fig. 2.10.

Originally, we believed that ϵ arose from the nonlinearities present in the detector during an α particle impact. An incoming α particle creates a large, highly-localised energy deposition where all 5.4 MeV is deposited into the absorber



Figure 2.10. The quadratic nonlinearity factor, ϵ , as a function of the first (ballistic) exponential amplitude A_1 .

structure. This energy can result in dramatic temperature increases in local regions of the absorber. However, the modelling studies described in Chapter 3 failed to yield pulses with the same behaviour as that in Fig 2.10, and a physical basis for this parameter was never found.

The average χ^2 when utilising the electronic band-pass time constant and ϵ in the 200 mK dataset 1.087, and compared with 1.60 without ϵ .

2.1.7 Full dataset fits using conventional analysis

To understand the distribution of energy in the bolometer as a function of the place of impact and means of thermalisation, it is necessary to completely characterise each glitch in terms of the exponential decay constants and amplitudes from the fits in equations ?? and ??. Because Bolo 184 is standing at a 45° angle from the 'path' of the α particle source, and because the position of incoming α particles can vary, they will be striking the bolometer from a range of angles, and will be distributed across the absorber. Combined with the bolometer having multiple thermalisation paths, energy may enter and exit multiple parts of the bolometer, which changes the shape of the glitch. To fully understand and develop a model for the bolometer, it is necessary to understand these changes in shape and how they are affected by the striking angle.



Figure 2.11. Comparison between a glitch resulting from a direct sensor hit, with a large athermal component (left) and an impact further from the sensor, with a large thermal component (right).

For example, an α particle which is directly incident upon the germanium sensor will cause a very large athermal spike with a high initial amplitude, and a smaller thermal tail, due to the α particle distributing most of its energy into the sensor via ballistic phonons, before quickly thermalising. These glitches will have a faster athermal rise time constant τ_1 , and a longer thermal time constant τ_4 . Conversely, an α strike on a region of the wafer which is far away from the sensor will have a smaller proportion of energy carried as ballistic phonons, and it will thermalise in regions outside the sensor; these glitches will have lower amplitudes and longer, higher thermal tails than the first type of glitch. Examples of both extrema from the data set are shown in figure 2.11. The majority of glitches will fall between these two categories, and the goal is to understand the ratio of energies between the thermal and ballistic components of these interactions.

2.1.8 Ratios of thermal and athermal integrals

Each pulse was fit to using the conventional double-exponential equation described previously, and the thermal and ballistic components were split. The total integral of the split components is shown in Figure 2.12. Since this experiment was constrained to only α particles, we expect that the ratio of the so-called athermal



Figure 2.12. The ratio of the split athermal and thermal integrals for the 200 mK data set, using the conventional double exponential analysis.



Figure 2.13. The time constants of each pulse - where red is the athermal rise time, green is the athermal decay time and thermal rise time, and blue is the thermal decay time - as a function of the maximum amplitude of each pulse.

(ballistic) and thermal integrals would exhibit one straight line. We note that the majority of the pulses have large thermal integrals and small ballistic integrals. As the majority of the absorber disc is much larger than the central region above the sensor, the probabilistic distribution of glitches far from the sensor behaves as expected in Figure 2.12.

2.1.9 Distribution of time constants

The time constants of each pulse in the dataset using the conventional doubleexponential have been calculated and are shown in Figure 2.13. We would expect that the rising time constant, τ_1 , has the smallest values due to the fast injection of energy from thermalised ballistic phonons. τ_2 and τ_3 (ballistic decay and thermal rise times) are set to be equivalent in the fit as described previously, and we would expect that these are higher than τ_1 but lower than the thermal decay time τ_4 . The flow of the furthest thermal phonons from the α particle energy is, as expected, the slowest process in the glitch.



Figure 2.14. The same pulse time constants, as a function of the athermal integral of each pulse.

In the case of low A_{max} , where the α particle position of impact is on the periphery of the absorber and most of the glitch energy arises from the thermal component, one expects that the thermal decay time is higher than at higher A_{max} , where a larger proportion of the energy arises from the immediate component from thermalised ballistic phonons.

We can check this conclusion by showing the same time constants, but as a function of the integrals of the athermal component. As we show in Figure 2.14, the glitches with the smallest athermal integrals also have the highest thermal decay time constants, which decrease inversely with the athermal integral (as the α particle arrives closer to the central area with the sensor).

Finally, we check our underlying assumption that the ratio of the component integrals is analysis to the α impact position, by repeating the same treatment as above, but as a function of that ratio, in Figure 2.15. We note that the underlying results are the same, if better constrained. From this, we can conclude that the time constants in this analysis behave in an expected manner, and that the ratio between athermal and thermal integral provides a sensible representation of the



Figure 2.15. The same pulse time constants, as a function of the ratio of the athermal and thermal integrals.

position of the α particle's impact on the absorber disc.

2.1.10 Pulse amplitudes

If we believe that the ratio of the thermal and ballistic integrals is a suitable description of the α impact position, and we believe that the total integral (the sum of the two components) is a constant, we can assert that the maximum pulse amplitude, A_{max} , depends also on that position. To keep the total integral constant, if the time constants depend on the α position, the amplitude must increase or decrease to compensate.

We test this in Figure 2.16. We find that for pulses with much larger thermal components (far-away positions), the amplitude is low. As the distance to the sensor decreases (the athermal component becomes larger), the amplitude increases, but at a slower rate (the relationship, as we expect, is not linear). The majority of pulses fall on the former end of the spectrum due to the large size of the absorber relative to that of the sensor. This viewpoint is coherent with what we outlined in Section 2.1.1 - the total integral is the best description of the energy deposited in the detector



Figure 2.16. The maximum pulse amplitude as a function of the ratio of the ballistic and thermal integrals.

from an α particle [106], whilst the amplitude is a more specific case which depends on the geometrical configuration of the absorber and the deposition of energy into it.

To analyse the exponential amplitudes with respect to each other, we take the maxima of the functions and plot them, as we show in Figure 2.17. We find a linear relationship between the two amplitudes, with most pulses having a small ballistic amplitude A_1 and a large thermal amplitude A_2 due to the geometrical reasons outlined above.

2.1.11 Interpretation of and Conclusions from 200 mK measurements

The 200 mK measurements of α particles on Bolo 184 represent a 'best case' scenario in many ways - thermal stability in SYMBOL was very high, and the bolometer was sensitive enough to have a high signal-to-noise ratio, but low enough to be insensitive to cosmic rays or other sources of pulses. This has resulted in a dataset which was easy to work with and analyse, providing us with the understanding necessary to do more detailed work on this bolometer. The main conclusions which



Figure 2.17. Thermal amplitude as a function of athermal amplitude.

we draw from this data are:

- The total pulse integral is the best representation of the total energy in the pulse.
- The maximum amplitude alone depends on the position of the α impact.
- The total integral can be split into a hermal (ballistic) and thermal components.
- The ratio of the athermal and thermal integrals is analogous to the position of the α impact on the absorber, and is the dominant factor in the pulse shape.
- The time constants and individual amplitudes scale to compensate for a constant total integral and the ratios of the separated component integrals.
- For every pulse, there is always a ballistic and thermal component.

From these phenomena in the data, we assert that when the α particle in this experiment impacts the absorber disc, it deposits all 5.4 MeV of its energy into the uppermost 14 μ m of the absorber. This energy is converted locally into ballistic

phonons, which radiate isotropically from the line-of-sight of the initial impact site. Each phonon first propagates at a few km s⁻¹ in the disc, and thermalises either at the bismuth interface, or on the disc border. This process is instantaneous compared to the thermal time constants of the internal parts and connections of the bolometer, and once thermalised, the phonons give an initial temperature profile in the disc. We believe that all energy takes the form of thermal phonons before it passes through the sensor, and that the fast 'ballistic' peak are simply phonons which have thermalised geometrically close to the sensor. The amount of energy in the fast or slow (athermal or thermal) pulse components depends on the location and orientation of this thermal profile, which is itself dependent on where the α particle impacts the disc. The characteristic double-exponential shape of the pulses arises from the response function of the bolometer. Therefore, we believe that the 'fast' and 'slow' components are not from 'ballistic' and 'thermal' energy, but rather from thermal phonons which can travel quickly or slowly depending on the profile of the thermalised ballistic phonons.

This understanding forms the basis by which we perform the modelling in the next chapter, and will be referenced heavily in the other analyses for α particle and cosmic ray measurements made with a 100 mK detector temperature. However, in spite of this analysis being coherent with our physical understanding of α pulses in this detector, the dependence on ϵ is still an open question. In the next section, we will explore an alternative pulse shape description which eliminates the need for this non-physical parameter, and is based on the physical phenomenon of heat propagation.

2.2 Bolo 184 α Measurements at 100 mK

In this section, we describe the same experiment, but performed at 100 mK. We will also describe the same analysis as previously, which will be compared with a new pulse shape description based on known aspects of thermal physics. This description is the same as that which was published by the author during the making of this thesis [111].

2.2.1 Changes from experiment at 200 mK

Besides T_0 being lowered to 100 mK, V_{bias} was also lowered to 250 mV in an attempt to reach a linear working point for the bolometer at this lower temperature. A total of 620 α particle events were recorded, although it is important to note that at 100 mK and $V_{\text{bias}} = 0.25$ V, the detector is sensitive enough to also record cosmic ray events. To account for this, the oscilloscope trigger voltage was set to be just below the typical α particle amplitude. Remaining cosmic rays in this data set can be removed manually based on interpretation of the pulse attributes.

Data Preprocessing

In order to finely resolve the important physical characteristics of the glitches, a sampling rate of 1 sample every 4 μ s was used in experimental data acquisition. Due to the lowered bias voltage (which was below the peak of the sensitivity curve at 100 mK) and high sampling rate, the pulses had significant noise, with an average noise RMS (quadrature sum) of 0.067 mK. In an effort to reduce noise and computational time, the pulses were processed before fitting with uneven downsampling. The regions of the glitch with the most information (e.g. the initial athermal rise and decay points) had higher sampling than regions with less information (e.g. initial rise and decay times had 1:1 sampling whilst thermal decay areas had 1:20 or 1:50 sampling). For calculating the noise levels on the pulses, we take the RMS value of the first 2500 (of 25002) points – buffered data regions before the pulse trigger – which is divided by the square root of the sampling factor to produce a flat error with respect to the sampling.

The pulses were taken on an AC-coupled oscilloscope, which changes the pulse shape (specifically, it adds a non-physical negative component to the signal). This introduces a significant systematic effect into the data - however, since this data is from the final measurement run on this test system, it must be reversed via preprocessing rather than by re-measuring. To remove this effect, we use an algorithm which integrates the signal to reconstruct an equivalent DC-coupled input – this has the drawback of introducing a small artificial slope, which we account for in



Figure 2.18. Left: A square wave fed directly into a DC-coupled oscilloscope. Right: The same wave, with AC coupling.

the next section. We will demonstrate the 'AC-reversal process' here.

As a proof-of-concept, we will measure a square wave directly from a pulse generator to the oscilloscope, both in AC-coupled and 1 M Ω DC-coupled mode. We see in Figure 2.18 (left and right) the AC and DC-coupled (respectively) versions of the same square wave. Clearly, the AC-coupled signal exhibits many attributes which do not resemble reality.

To address this, we designate the unmanipulated square input to be $V_{\rm in}$ and the AC-coupled output $V_{\rm out}$, corresponding to the typical high-pass filter circuit shown in Figure 2.20. In this case, the oscilloscope behaves as a high-pass filter with a time constant $\tau = R \cdot C$ (the resistance and capacitance of the input, respectively). Neglecting the current that flows into the oscilloscope, all the current (I = dQ/dt) in this circuit goes from $V_{\rm in}$ to $V_{\rm out}$. We have:

$$Q = C(V_{\rm in} - V_{\rm out})$$
 and $V_{\rm out} = R \frac{dQ}{dt}$ (2.7)

Given V_{in} as a function of time, V_{out} is the solution of the following equation:

$$\frac{dV_{\text{out}}}{dt} + \frac{V_{\text{out}}}{R \cdot C} = \frac{dV_{\text{in}}}{dt}$$
(2.8)

To recover $V_{in}(t)$ from the measured $V_{out}(t)$, one can simply reverse and inte-



Figure 2.19. The directly DC-coupled square wave (blue) compared with the output of the recovery algorithm (red).



Figure 2.20. A typical high-pass filter circuit.

grate (2.8), which gives, up to an non-physical constant c:

$$V_{\rm in}(t) = V_{\rm out}(t) + \int_{t_{\rm arb}}^{t} V_{\rm out} \frac{dt'}{\tau} + c$$
(2.9)

Computing the integral at every time step, we regenerate a $V'_{in}(t)$ signal which is unbiased if we know the proper value of τ . If δt is the oscilloscope step size, we have:

$$V_{\rm in}'(t_i) = V_{\rm out}(t_i) + \sum_{j=0}^{i-1} (V_{\rm out}(t_j) - O) \frac{\delta t}{\tau} + (V_{\rm out}(t_i) - O) \frac{\delta t}{2\tau}$$
(2.10)

For pulses, the offset O is set at the mean value of V_{out} before the pulse. In the square pulse case, used to measure τ , O has to be the mean value of V_{out} over a pulse cycle. τ and O are then adjusted by hand to recover the square shape. We find $\tau = 23.52 \pm 0.01$ ms.

We show the results of the square wave filtering ('undoing' the AC coupling) in Figure 2.19, in which we recover the shape of the pulse.

We applied the same algorithm to compensate for a much lower high pass filter present in the amplification chain (with a cut-off frequency of 0.1 Hz, which has a negligible effect compared to the first loop).

The final algorithm then converts the pulses (in volts) to units of resistance, and then into temperature based on the R(T) characteristics of the detector (which are based on measurements). The final output of the preprocessing is T(t) curves in mK with uneven temporal sampling. These are the curves used in the remainder of this analysis. A sample pulse demonstrating each stage of the pulse processing is shown in Fig 2.21.

Whilst working with 'regenerated' pulses is not ideal due to the systematic effects introduced by the integration of the AC-coupled signal, it should be noted that this data set was the final one taken in SYMBOL, after which the system



Figure 2.21. One sample pulse, showing the data processing stages. Black: Untreated AC-coupled pulse signal, in V; Red: Recovered pulse signal, in mK; Green: Unevenly sampled (packed) pulse, in mK. (Taken from Stever et al., 2018 [111])

was decommissioned. The new system offered greater stability and reliability for these measurements, but was not available immediately. Hence, a compromise was made and this data was chosen as the proof-of-concept for the new fitting algorithm.

2.2.2 Amplitude and Energy Spectra

For all data, the maximum amplitude spectrum of the dataset was compared with the energy spectrum (represented as the total integral of each pulse [106]) and the results are shown in in Figure 2.22. We note that in this particular case, the 'integral' is the sum of the fitted template after the preprocessing and fitting stages, but that the shape is unchanged from the pre-processed, summed data. As in the 100 mK case, we show that the pulse amplitudes have a wide distribution with a skew toward low amplitudes.

Both of the above analyses are common to both data treatment algorithms used in the analysis of these 100 mK pulses - these results are obtained directly from preprocessed data, irrespective of later analytical techniques (and so are not based on fitted pulse templates).



Figure 2.22. Left: Spectra of maximum amplitude for each pulse in the data set. Right: Energy integrals as a percentage of the average value, normalised by the 0.8 pJ 241 Am α emission line. (Taken from Stever et al., 2018 [111])



Figure 2.23. Left: One sample pulse (black) using the typical double-exponential fit (blue) and the same for $\epsilon = 0$ (green). Right: The difference between the two left fits (with free ϵ and $\epsilon = 0$.)(Taken from Stever et al., 2018 [111])

2.2.3 Limitations of standard numerical analysis

We repeat the same fitting procedure as outlined in Section 2.2.3. We find the same fits with the same phenomena, including the same dependency on the nonlinearity factor ϵ . The chi-squared goodness of the fits were again improved (particularly over the smallest pulses) by applying ϵ , which was well-correlated with amplitude; ϵ is very large (as high as 20%) for low amplitude pulses, and small and negative for high amplitude pulses. We show the significant effect of ϵ on our sample fit in Fig 2.23 (right), where we have the difference between the best fit with ϵ and the best fit where $\epsilon = 0$.



Figure 2.24. The quadratic nonlinearity factor ϵ (%) as a function of the ballistic amplitude A_1 for 100 mK α particle pulses. (Taken from Stever et al., 2018 [111])

We show ϵ as a function of amplitude in Fig. 2.24. We also note that this sample fit is one with a positive ϵ , but with a value of 4.65% - the smallest fits can reach a much higher ϵ , where there effects are even more pronounced.

For the sake of comparison, we show the time constants and the ratios of the ballistic and thermal integrals for this dataset using this classical mathematical model in Fig. 2.25. We note that the behaviour is as one would expect; the smallest pulses have the largest rise times (τ_1). Comparing with the time constants shown for the 200 mK pulses, there appears to be a discontinuity (a non-straight distribution) between pulses with $A_{\text{max}} < 1.6$ mK and pulses with $A_{\text{max}} > 1.6$ mK. The source of this discontinuity has not been ascertained, and is not associated with fitting errors or χ^2 uncertainties.

The ballistic and thermal integrals have a strongly linear relationship (seen in Figure 2.26), with the majority of the pulses being dominated by the thermal component due to the position effects mentioned previously. This is in agreement



Figure 2.25. Plots of the four time constants found by the double-exponential fit as a function of the maximum pulse amplitude A_{max} : τ_1 (red) : Ballistic component rise time; τ_2 (black) : Ballistic component decay constant, which is equal to the thermal rise time; τ_4 (green): Thermal component decay time. (Taken from Stever et al., 2018 [111])



Figure 2.26. Separated component integrals (ballistic vs. thermal) as a function of each other. (Taken from Stever et al., 2018 [111])

with what was already shown in the 200 mK measurements, but with slightly different scales due to a different bolometer working point.

The typical mathematical fitting method applied to pulse analysis in the literature provides a good fit to most pulses, as we can see in the residuals, as is also the case for the 200 mK pulses. The addition of ϵ improves the χ^2 goodness of the fit, particularly for the smallest pulses, where ϵ aids in resolving the rise time of the pulse - this portion of the pulse is the most important for understanding the effect of ballistic phonons. The average χ^2 per degree of freedom over the dataset without ϵ is 1.052, and with ϵ is 1.022 - an effect which dominates in the small-pulse regime, as we have shown in Fig. 2.24. The improvement in the χ^2 of the fit dominates in the rise time of the pulses. However, ϵ does not appear to arise from any identified physical phenomena, which is necessary to quantify in order to truly understand the pulse shape.

2.2.4 New analytical fitting algorithm

With the thermal physics involved in this experiment in mind, we have built a new analytical model for the pulse shape. This new model has been developed to reproduce the real pulse shapes without the nonlinearity coefficient ϵ , for which a physical basis was not found. Using this function, we seek to quantify heat propagation in the absorber disc with a new parameter extracted from the fit, for each pulse. We plan to use the same fitting model on simulated pulses to improve our understanding of this bolometer. This section presents the basic ingredients of this fitting function.

We surmise that the thermalisation of ballistic phonons is very rapid compared to all other time constants in the bolometer; an absorber of diameter $\phi = 3$ mm divided by a 3 km s⁻¹ speed of sound yields a thermalisation time of 1 μ s. This first process gives a starting lateral heat profile on the disc which depends on the α impact point. For impacts near the central region of the absorber disc, the shape of the profile is invariant; however, this is not the case for α particles falling near the absorber disc border. In any case, it presents as a peaked core centred on the α impact point with a geometrical $1/x^2$ tail, where x is the radial distance from the impact point.

With this in mind, we propose an alternative to the standard double-exponential form of glitch analysis. For brevity, we will continue to use the usual 'ballistic' and 'thermal' terminologies to describe pulse components, amplitudes, and attributes; however, in the case of this detector, we assume that all athermal phonons relax to thermal phonons before they reach the sensor. The following process consists of heat diffusing on the absorber disc before moving through the sensor towards the heatsink.

We expect a potentially large heat propagation time in the thin diamond absorber (particularly for far-away pulses) due to Casimir predictions for thermal conduction in thin layers [112], in the 0.1 ms range. These characteristic times are higher than the thermal coupling time constant from the central part of the absorber to the sensor. We simplify the absorber thermal coupling to the nonabsorber layers by considering heat diffusion in the absorber and heat flow to the sensor as two independent processes. From this, we get a pulse shape $T_{\text{sensor}}(t)$ based on the combination of both processes. In the ongoing modelling of this detector, we use a combination of two methods: (1) a Monte-Carlo particle propagation model for isotropically radiating ballistic phonons, which thermalise and then diffuse as thermal phonons, and (2) a thermal block model for the impulse response function of the sensor and sapphire layers. Using the same reasoning for the pulse fitting, we can also use two components: (1) f_{therm} , the temperature at the centre of an isolated absorber, and (2) f_{response} , the bolometer response function.

 f_{response} corresponds to the particular case when f_{therm} is a temperature Heaviside step function $f_{\text{therm}} = \Delta T H(t)$ above the sensor. Using the identity:

$$f_{\text{response}}(t) \equiv \int_{-\infty}^{t} \delta_{\text{Dirac}}(\tau) \times f_{\text{response}}(t-\tau) d\tau$$
$$= \delta_{\text{Dirac}} \otimes f_{\text{response}} = \frac{1}{\Delta T} \frac{d(\Delta T H(t))}{dt} \otimes f_{\text{response}}$$
(2.11)

we get the relationship between the two components and the pulse shape:

$$\frac{T_{\text{sensor}}(t)}{\Delta T} = f_{\text{response}}(t) = \frac{1}{\Delta T} \frac{df_{\text{therm}}}{dt} \otimes f_{\text{response}}$$
(2.12)

Which we keep in order to build a model function for the general case where the temperature of the central part of an isolated absorber increases slowly:

$$T_{\text{sensor}}(t) = \frac{df_{\text{therm}}}{dt} \otimes f_{\text{response}} = \int_{-\infty}^{t} \frac{df_{\text{therm}}(\tau)}{dt} \cdot f_{\text{response}}(t-\tau)d\tau \qquad (2.13)$$

To be able to quickly compute this function, we make further approximations in the evolution of the temperature profile. In the temperature domain used, the diamond heat capacity and thermal conductance are both dominated by their T^3 dependence, so they cancel out in the heat propagation differential equation. Therefore, temperature evolves like in the constant C and G case.

If we approximate the initial heat profile with a 2-dimensional Gaussian, we can rely on the properties of standard heat propagation. Letting $\Delta T(\rho, t)$ be the differential temperature profile centred on the α impact position, we have:

$$\Delta T(\rho, t) = \frac{A}{t + t_{\rm dep}} \exp\left(\frac{-a\rho^2}{(t + t_{\rm dep})}\right)$$
(2.14)

where the lateral size increases with the square root of time, and t_{dep} represents spread of the initial heat profile. $a\rho^2$ has the dimension of time, and we denote it τ_3 . It is expected to depend on the distance ρ between the α impact and the absorber disc centre, increasing like ρ^2 in this simplified picture.

This approximation is suited for an infinite plate. A simple way to take the small disc dimension into account is to keep only the exponential dependence, so ΔT reaches a nonzero asymptotic value after a long period of time, as expected for an isolated absorber. Finally, on top of the sensor, we have:

$$f_{\text{therm}} = H(t) A_{\text{therm}} e^{-\tau_3/(t+t_{\text{dep}})}$$
, with $H(t) = 0$ for $t < 0$ and $H(t) = 1$ for $t \ge 0$
(2.15)

For f_{response} , we take a standard 2-component exponential response function which was produced by the thermal block model of the bolometer (and is discussed in Chapter 5). The complete function contains 11 parameters, outlined in Table 2.1.

These parameters[†] represent the initial thermal profile of amplitude A_{therm} with a width proportional to t_{dep} , spreading over the disc with a characteristic time constant τ_3 , and a standard two-component exponential response function (where the amplitudes and the time constants have their usual meanings).

[†]NB: It should be noted that the denotion of A_1 for the fast ('ballistic') amplitude and A_2 for the slow ('thermal') amplitude are reversed for the new fitting algorithm.

Parameter	Description	Constraints
$ au_1$	rise time (response function)	fixed, 0.079 ms
$ au_2$	Thermal pulse decay time (resp. fn.)	$2 < \tau_2 < 75 \text{ ms}$
$ au_3$	Thermal energy propagation time	$0 < \tau_3 < 5 \text{ ms}$
$ au_4$	Athermal pulse decay time (resp. fn.)	$0.05 < \tau_4$
$t_{\rm dep}$	Initial thermal profile spread	fixed, 0.507 ms
$A_{\rm therm}$	Amplitude of thermal profile	fixed, 1 mK
A_1	Amplitude of thermal pulse	$A_{max}/20 < A_1 < A_{max} \cdot 2 \text{ mK}$
A_2	Amplitude of ballistic pulse	$A_{max}/5 < A_1 < A_{max} \cdot 4 \text{ mK}$
offset	Oscilloscope / data offset	0 < offset < 1 mK
slope	Artificial slope induced by filtering	-1 <slope $<-1 mK ms$
$t_{trigger}$	Pulse trigger time (time offset)	$-1 < t_{trigger} < 0 ms$

Table 2.1 – Table of new function parameters and their descriptions, along with the parameter constraints for this 100 mK experiment.

To decrease computation time, we can set τ_1 to an average calculated value of 0.08 ms in order to be short enough to compensate for the fastest high-amplitude pulses, allowing τ_3 to compensate for lower rise times. We also set A_{therm} to 1 to normalise the amplitude of the thermal profile in the convolution. Using this technique, we can compare the output of this function with fits from the typical numerical method [99] we have already shown in Sec. 2.2.3, e.g. by splitting the total pulse into separate 'ballistic' and 'thermal' components, comparing the relationship of their integrals as an approximation for initial α impact position, etc.

2.2.5 Output and analysis of fits from new algorithm

In this section, we show the output of fits with the new pulse shape, comparing this with the results of the commonly-used methods (shown in Sec. 2.1.4).

Goodness of fits

Employing the new pulse shape described in Sec 2.2.4, we are able to fit to the total pulse, as well as the 'fast' and 'slow' components, as we have done previously. We find an average χ^2 per degree of freedom of 1.13. We note that the error in this fitting appears to be dominated by measurement noise sources, particularly a



Figure 2.27. Left: A sample pulse (data in black), total pulse fit (blue), ballistic pulse fitting (red) and thermal pulse fitting (green). Right: The evenly-sampled residuals of the total fit of the same unpacked pulse, with the plotted residuals sampled every 100µs. (Taken from Stever et al., 2018 [111])

high amount of digitisation noise in the pulses (of the order of 0.1 V), which has been attributed to the oscilloscope and readout chain. In analysing the residuals of the fitted pulses, we find that the residuals are evenly distributed about 0 mK, and we are therefore primarily limited by noise rather than parametric uncertainty. Comparing with the fits of the typical mathematical model outlined in Sec. 2.1.4, we note that the average χ^2 appears to be roughly equivalent to that of the typical fitting method (with an average χ^2 per degree of freedom of 1.012). In some cases, the artificial slope induced by the filtering technique is prominent for both fitting methods, but has been accounted for in both fitting processes, and does not appear in the residuals. These features are demonstrated in Figure 2.27.

Statistical data features

In further processing the pulses as shown in Fig. 2.27, we can compare the fit amplitudes as well as the time constants of each pulse (with the exception of the response function rise time, τ_1 , which is fixed). Finally, we can also compare the integral of the measured pulses with those of the split fast and slow components of the response functions, to understand the distribution of energy in each pulse, following the comparative treatment using the typical fitting method in Sec 2.2.3.

In Figure 2.28, we show the relationships between the maximum amplitude



Figure 2.28. Plots of the four time constants as a function of the maximum pulse amplitude A_{max} : τ_2 (green) : Slow response function time constant; τ_3 (blue): Thermal profile time constant; τ_4 (black): Fast response function decay time. (Taken from Stever et al., 2018 [111])

of each pulse and the time constants produced by the fitting. The shortest time constant, τ_1 , is fixed to 0.079 ms to account for the fastest (highest-amplitude) pulses. Pulses which rise slower than this are compensated for in the convolution with the thermal profile. The thermal propagation time constant, τ_3 , appears to be strongly correlated with the thermal response function decay constant τ_4 - they rise and decay inversely with one another, indicating regions in parameter space where the effects of thermal propagation become more or less prolific than the response function decay effects. We note that the maximum amplitudes are affected by digitisation noise coming from the oscilloscope and the low V_{bias} of the experiment.

We also see in Figure 2.29 the relationships between the two fit amplitudes A_1 (the slow component arising from propagation of thermal energy across the absorber) and A_2 (the fast component arising from thermalised athermal phonons). For the most part, the relationship between these two amplitudes appears to be linear, showing the expected sharing of energy between the two components; however, that relationship appears to break down at high A_1 , which are the impacts most likely to be on the periphery of the absorber. In these pulses, A_2 tends toward 0



Figure 2.29. Response function amplitudes A_2 (ballistic) and A_1 (thermal) as a function of each other. (Taken from Stever et al., 2018 [111])

more quickly than expected. We note that the fit amplitudes are not directly linked to the maximum pulse amplitude A_{max} - it also depends on τ_3 , and divergences may be an effect of the convolution.

Fig. 2.30 demonstrates the relationship between the thermal and ballistic integrals. We find a correlation which is mostly linear, with exception for the highly-thermal pulses which we have mentioned previously. This relationship is very similar to that which we find using the classical mathematical method outlined in Section 2.2.3 – the linearity of these two components serves as a validation measure for the new fits, demonstrating that the overall distribution of component ratios is much the same, owing largely to position effects, with only a small divergence for the furthest α impacts.

Figure 2.31 shows the relationship between the thermal (green) and athermal (red) components of the fit amplitudes with the thermal and athermal integrals (respectively), showing a relationship which is mostly linear, but is affected by the same divergences at high A_1 and low A_2 .



Figure 2.30. The relationship between athermal (ballistic) and thermal integrals with the new fitting methods. (Taken from Stever et al., 2018 [111])



Figure 2.31. Response function amplitudes as a function of their respective (thermal or ballistic) integrals. (Taken from Stever et al., 2018 [111])



Figure 2.32. Linearly-scaled τ_3 as a function of the maximum amplitude. (Taken from Stever et al., 2018 [111])

Finally, we show the relationship between the maximum pulse amplitude and τ_3 , in linear scale for clarity, in Figure 2.32. We expect a potentially large propagation time in the thin diamond absorber (particularly for far-away pulses) due to Casimir predictions for thermal conduction in thin layers [112]. We find that this relationship is mostly linear until low A_{max} , where the dispersion increases inversely with amplitude.

Discussion

Using the new fitting method as a means of testing the current physical understanding of energy propagation in this bolometer, we find some validation of our physical interpretation. In particular, we find that the convolution of a thermal input with the bolometer response function appears to be a valid way to describe α particle pulses in this detector. Pulses arising from alternative particle energy deposition (e.g. minimally-ionising protons) is planned in order to validate these theories, and will be the subject of future study.

The results of the model appear to be equivalent to the previous fitting methods in terms of agreement with the data, but represent an improvement due to the lack of necessity for the nonlinearity factor ϵ , which has not been physically quantified. The new fitting method appears to produce similar overall behaviour to that of the sum of two double exponentials, but is based on the principles of thermal physics, rather than on a mathematical expression alone. The ratio of the total energies in the fast and slow pulse components remains similarly position-dependent, lending credibility to the idea that the pulse shape is mostly a result of the position of the α particle's impact on the absorber, which creates differences in the way energy propagates before being measured as a signal in the sensor.

When the α particle impacts the absorber, the distance between the impact position and the sensor is the main driver behind how much of its energy is distributed into the fast and slow pulse components. In the numerous cases where the α impact is closer to the absorber border than to the sensor, many ballistic phonons will likely thermalise at the border of the sensor, and the thermal phonons which would normally have a Gaussian distribution in the absorber will be 'stacked' at the border. Those thermal phonons will eventually travel to the sensor, but less quickly than the energy distributed closer to the sensor. When a large amount of energy is initially stored at the border, that energy can appear as a second 'wave' which arrives at the sensor some time after the initial energy spike in the 'fast' component. We see this effect in τ_3 and τ_4 - their behaviours are complementary at very low and very high initial amplitudes. The effect of the thermal propagation time τ_3 is particularly prevalent when compensating for pulses with a very small ballistic component, where a large amount of energy is temporarily stored at the periphery of the absorber. However, τ_3 also displays a significant improvement on the high (nearby to sensor) pulses; a nonzero τ_3 allows for better resolution of the initial pulse rise and decay times, compared with a zeroed τ_3 , which is mathematically analogous to the classical exponential model used previously.

The fitting algorithm is also computationally intensive, and requires highlysampled data to be resampled to save computational time. Even using the data preprocessing steps outlined in the previous section, analysing a data set of 620 pulses requires computational time of about 6 days on a typical desktop computer with 16 GB of memory. The new algorithm does not show an increase in the χ^2 goodness, but is roughly equivalent, and with a greater physical significance. I never am really satisfied that I understand anything; because, understand it well as I may, my comprehension can only be an infinitesimal fraction of all I want to understand.

Ada Lovelace

Chapter

Bolometer Experiments in new cryogenic system

This chapter will outline the experiments and results obtained in the new cryogenic system at IAS, as well as the details of that system and the motivations for using it.

3.1 Bolo 184 α measurements at 100 mK

As the new cryogenic system offers greater thermal stability and a longer experimental time which is not limited by liquid helium, we have used Bolo 184 to validate the electrical and thermal configurations of the system. Whilst the system was configured to maintain the cold plate temperature at 100 mK, we find from the IV characteristics that the experiment was actually closer to 127 mK (the next chapter in this section will detail the IV measurements). The measurements outlined in this section are based on a total of 4450 total pulses at 127 mK.

3.1.1 Description of new system at IAS

The final measurements shown in this thesis were performed in the new facility at IAS, which was delivered in late April 2018. The system, the Detector irRAdiation Cryogenic faciLity for Astrophysics (DRACuLA), has been funded by CNES and the region of Ile-de-France via the proposal DIM-ACAV+. It has been designated as a common-user test facility to test the interation between particles and space mission detectors and focal plane components. The system has been described more comprehensively by Janssen et al [113], but a brief overview will also be described here.

The system is a dilution refrigerator provided by BlueFors, with a Cryomech PT415RM pulse tube. The available workspace of the cold plate is $\phi = 290$ mm, with an available height of 300 mm. The pulse tube is a source of vibration-induced thermal noise, which is addressed by the suspension of the cryostat on bellows. The entire system is then suspended and mechanically supported by a large frame with deployable wheels for transport to experimental test sites. The cryostat, bellows, and various mechanical and cryogenic minutæ of the main system are shown in Figure 3.1.

Perhaps more importantly, the cryostat contains four ports from the exterior of the vacuum cans to the test plate, which are presently blanked, but into which windows can be inserted. These ports have been envisaged to contain windows for the coupling of a particle accelerator (e.g. ALTO's TANDEM in Orsay) to the device under test. This is to allow for the testing of components and detectors under a wider range of particle energies than internal sources can provide. The windows are orientated at 0° , 45° , 90° , and 180° to the device under test, which is shown in Figure 3.2.

The DN50 ports are situated at various angles to allow for the measurement of the effect of varying angles of impact of particles, as we have shown this to be an interesting effect in this thesis. The cryogenic system can reach a base temperature of 6 mK within 24-27 hours depending on the mass load (0 to 7 kg of internal mass


Figure 3.1. An image of the cryogenic test system, showing the frame, cryostat, window ports (orange), and bellows, with various measurements shown (yellow). [113]



Figure 3.2. Image from the design of the BlueFors cryostat, showing the test plate and 3 of the ports. The red port shows the path of incoming energy through one of the ports. (Image produced by M. Bouzit)

have been tested). The system has been measured to have a cooling power of 650 μ W at 100 mK, 170 μ W at 50 mK, and 23 μ W at 20 mK, with a standard RMS temperature fluctuation at 100 mK of 76 μ K [113] (which can be improved with optimisation).

The system overall benefits from increased cooling power relative to SYMBOL, a lack of dependence on liquid helium, and reliability. Out-of-the-box tests were performed using α particles and Bolo 184 operating at 100 mK, which had several limitations in relation to noise and other parasitic sources. These initial tests are described below.

In preparation for these experiments, the box holding Bolo 184 and the load resistor were moved from SYMBOL into the new system, and wired by V. Sauvage at IAS, with input from N. Coron and R. Janssen, in April 2018.



Figure 3.3. Amplitude spectra of the first cryostat commissioning run. Amplitudes determined to be from α particles are shown in red, with chiller pulses in green, and baseline fluctuations or potential cosmic rays in blue.

3.1.2 Removal of erroneous signal sources

When the chiller of the new system activates (which is at a random interval decided by the system), there is a large electrical pulse which saturates the amplifiers but registers as a triggered pulse and is recorded by the oscilloscope. This electrical impulse is followed by a baseline voltage fluctuation for several seconds, which can be recorded as a triggered pulse, or which induces an artificial slope in the signal. This is due to a grounding leak in the cryostat, which makes it sensitive to electrical interference. Following the liberal usage of aluminium foil, shorting caps for the unused input ports on the cryostat, orientation of the amplifiers to minimise electrical field effects, and running all amplifiers on portable batteries instead of mains electricity, the effect of the chiller pulses and 50 Hz signal is greatly reduced; however at low temperatures and/or high sensitivities, this signal is still present and will require further work to eliminate entirely.

The pre-optimisation limitations of the initial test of α particle pulses in Bolo 184 are shown here. Pulses were recorded over the course of one day, with a low



Figure 3.4. Left: Sample saturated pulse from the activation of the cryogenic chiller. Right: Several sample pulses from the blue segment in Fig. 3.3 - the lowamplitude events. The blue event is most likely a cosmic ray.

enough oscilloscope trigger voltage to also capture pulses from cosmic ray muons. We show the amplitude spectra of all recorded pulses, split into categories based on analysis, in Figure 3.3.

We note that the green segment in Figure 3.3 are at a signal amplitude of 1.5 volts - these are the pulses from the operation of the chiller, which create massive fluctuations that saturate the amplifiers. An example of one such pulse is shown in Figure 3.4 (left).

In addition to the saturation in the chiller pulses, we also find that the pulse has a significant negative component. Whilst these pulses are certainly disruptive, the use of an appropriate gain level can assure that they saturate and are easy to remove from the data. However, the baseline fluctuations which come after the signal from the chiller is removed, and the signal takes time to return to baseline, are mixed in with other low-amplitude events such as cosmic rays (see Figure 3.4, right). This proves to be more problematic if left un-addressed.

We note in Figure 3.5 an example of the relationship between the low-amplitude events and the high-amplitude (chiller) events. Most of the low-amplitude events (<0.2 V) are preceded by a high-amplitude, saturated chiller pulse. Figure 3.5 shows this in order of time. It is also worth noting that using the integrals to remove



Figure 3.5. An example of 100 recorded pulses and their amplitudes (black points) with blue dashed lines linking between them. Amplitude cutoffs for chiller pulses (at 1 V) and post-chiller baseline fluctuations (0.2 V) are shown in red.

the fluctuations of the baseline is an untenable solution, because the cosmic rays they are mixed with do not have discrete energies; therefore, a solution to remove some or most of the electrical parasite produced by the chiller is necessary. Also of note is the fact that the α pulses themselves have been shown to be vulnerable to the ground leak in this system, showing a significant 50Hz component. This is shown in Figure 3.6.

The 50 Hz sinusoid in Figure 3.6 is quite concerning for a number of reasons. These are the largest-amplitude events of interest, so any systematic issues should be the least-prevalent with α pulses, which are much larger than cosmic rays. A 50 Hz component is more noticeable in the tail of the pulse, but is also hidden in the initial rise and decay times. If our interest was only in the amplitude distributions in the study, this may be acceptable. However, since we are attempting to probe sensitive and fast geometries of the pulses as we have done above (e.g. the initial rises and decays), a systematic bias of the shape is undesirable. Thankfully, some careful experimental measures can eliminate all of the 50 Hz noise, and most of the interference from the chiller pulses:



Figure 3.6. A typical alpha particle pulse in the commissioning run, showing a significant 50 Hz component.

- Use of as few mains-powered electronics as possible using battery-charged amplifiers and bias circuits
- Crocodile clips between inputs and outputs of cables or devices connected to the signal line
- Shorting covers on the unused input ports of the cryostat
- Aluminium foil covering every surface of every cable on the input and the output of the system
- Orientation of the pre-amplifier on a foam board, at a location and angle to minimise the effets of local magnetic fields

By employing these tactics at every run, we can take data with an acceptable noise level and where chiller pulses are minimised (but not totally eliminated). Future work of the group necessitates a further study into the grounding leak of the new system for new experiments.



Figure 3.7. Left: Unscreened amplitude distributions in new data set. Right: Unscreened integral spectra.

3.1.3 α particle study using new system

Increasing V_{bias} to 400 mV in an attempt to gain a better signal-to-noise ratio, using this system and all other parameters (gain and electronic readout) the same as just described, we describe one final α particle measurement. The goal is to reproduce what was achieved in SYMBOL, and also to exploit the increased stability of the system to re-check the physics we believe to have seen (the effect of heat propagation) in a more stable and DC-coupled system.

Systematic effect reductions and screening

The total experimental time was 40 hours and 43 minutes, during which time 2612 total pulses were recorded. We have used the tactics above to reduce electrical interference, and have eliminated the 50 Hz component. We have reduced (but not eliminated) the contribution of the chiller, although we note only the low-amplitude baseline shifts, and no longer have the large saturated pulses from the chiller.

The unscreened amplitude and integral distributions are shown in Fig 3.7. We find the usual distributions, including the low-amplitude events (either cosmic rays or chiller pulses). To screen for α particles, we run a simple loop which keeps pulses if they fall between $2 < \int \text{Signal} > 3.2$ V ms. We are left with 2219 probable α



Figure 3.8. Black: τ_4 ; Green: τ_2 ; Blue: τ_3 – as a function of the maximum amplitude of each pulse.

particle pulses, or $\approx 0.9 \alpha$ pulses per minute.

Distribution of time constants

We run the usual recovery algorithm on the signal (excluding the DC-coupling loop because the system was already DC-coupled), producing unevenly-sampled T(t)curves across the screened pulses. We run these pulses through the new fitting algorithm, finding a distribution of time constants as shown in Figure 3.8, in which the time constants are comparatively well-constrained compared with the last case (recovered AC-coupled pulses from SYMBOL). There are some outliers from the usual relationships, specifically between $A_{\text{max}} = 0.4$ to 0.6 mK.

Energy distributions

We decouple the 'thermal' and 'ballistic' components in the usual way (including the removal of the slope and offset to the fit, because these are due to the baseline signal fluctuations from the chiller). The time constants are shown in Figure 3.9, finding a very surprising result; there appear to be two 'branches', and the integrals



Figure 3.9. Split thermal integral as a function of the ballistic integral.

do not follow the usual distribution (a straight 5.4 MeV line).

We look at the amplitudes to see how those behave, and we find again that what is usually a straight line is instead a curved one with two branches. To investigate this effect, we split the pulses into 'branch 1' and 'branch 2' and look at where these branches manifest in the remainder of the data.

To probe the differences between the two branches, we choose a specific thermal integral (in this case 1.3 mK ms). We would expect that for the case of both thermal integrals being equal, the athermal integral would compensate equally in both cases to sum up to 5.4 MeV. We find in Figure 3.11, with pulses from branch 1 and branch 2, that this is not the case. The branch 1 pulse is a low-amplitude and still very thermal pulse. The branch 2 case has a large athermal component, which is the expected behaviour. In spite of having equal thermal integrals, the two branches exhibit very different behaviour in terms of their shape.



Figure 3.10. Split thermal amplitude as a function of the ballistic amplitude.



Figure 3.11. Example pulses (with fits) from branch 1 and branch 2, where the thermal integral = 1.3 mK ms.



Figure 3.12. Red: τ_4 ; Green: τ_3 ; Blue: τ_2 – as a function of the total integral of each fit (slope and offset excluded)

Branching effects in the time constants

To further visualise the branching effects, and to convince ourselves that this effect is not related to the slope of the pulses or the fits, we plot the time constants against the total integral in Figure 3.12. Whilst the total integral is (mostly) constant, there is still clearly a trend between branch 1 and branch 2, where branch 2 affects mostly the higher end of the integral spectra. The anomalous part of this behaviour appears to lie in the low-amplitude area (pulses which have a large contribution from the thermal propagation time, rather than fast 'ballistic' energy).

Looking at linearly-scaled time constants, broken up by branch, and as a function of amplitude, we find more clear trends (Figure 3.13). The most interesting parts of this behaviour are the time constants relating to the rise of the pulse, τ_2 and τ_3 , which are shown in the figure. The two branches appear to separate at the



Figure 3.13. τ_2 and τ_3 as a function of the maximum amplitude, split into branches.

apex of τ_2 (left), and a similar behaviour happens at τ_3 (right). We expect that the propagation time τ_3 increases for pulses which are smaller in maximum amplitude, because these (border) cases will have energy which must travel a longer distance across the absorber. This is what happens in Figure 3.13, but with a noticeable divergence just after an inflection point in the overall trend; it seems that at these specific amplitudes, τ_3 suddenly wants to increase to a very high number (but settles at 0.3 ms, a limit of the constraints of the fit).

We will also examine these effects further by running the typical exponential fit on these pulses, to rule out a systematic bias produced by the new fitting algorithm.

Classical exponential fit on new system α particles

We check these pulses using the typical exponential fit we outlined in Section 2.1.2 (page 74), which allows us to rule out the possibility that the branching effects we see in this data are produced solely by the new fitting algorithm.

We begin by examining the time constants of the old fit in Figure 3.14. We find that all pulses were well-fitted (as with the new fitting algorithm) producing an average χ^2 per degree of freedom of 0.205. The magnitudes of τ_4 and τ_2 are mostly the same as the previous case, but with a much wider spread in the rise time τ_1 . In the new fitting algorithm, the initial rise time τ_1 is set as a constant



Figure 3.14. Time constants of the old fit, as a function of the maximum amplitude. Blue: τ_1 (rise time), Black: τ_2 (initial decay time), Green: τ_4 Thermal decay time.



Figure 3.15. The thermal integral as a function of the ballistic integral, for the typical exponential fit applied to this data. The data is split between branch 1 (red) and branch 2 (blue).

and is 'absorbed' by the thermal propagation time τ_3 whilst taking into account the propagation of heat across the absorber disc. The treatment of the initial rise is, in the old case, slightly more limited, which explains the wider spread. At the lowest maximum amplitudes (the pulses with the largest thermal components), the rise time slows and the initial decay time quickens, to the point where they are almost equal.

Interestingly, the thermal decay constant τ_4 is much slower than was found using the new fitting algorithm (Figure 3.8, page 118), but with almost the same shape. If the time constants do not obey the usual properties (like we see in the decreasing τ_4 and τ_2 at very low amplitudes, it implies that the integral is not always conserved (which is what we see in the 'branching' effects above).

To verify this, we must examine the relationships between the decoupled ballistic and thermal integrals. For brevity and clarity, we will do this by plotting them with different colours for branches 1 and 2. We will continue to use the same branch distributions as we have done in the previous sections (branches which we designated from the results in Section 3.1.3), and we show the results in Figure 3.15. We find that the integral is again not a single continuous 5.4 MeV line, and instead contains some 'bunching' in the centre, which appears to be the intersection between two separately-gradiented lines. Recall that, in the previous chapter (Figure 2.11, page 80), we had obtained some very typical fitting from the 200 mK data in which the majority of pulses had highly-thermal integrals (which was explained due to the large geometric size of the disc as compared with that of the sensor). In contrast with that case, the integrals in this fit appear to be distributed homogeneously, with the highest concentration of pulses being in the location where the two branches meet. It is this same location which is a point of inflection for the time constants. It is possible that we are simply resolving features which only exist at a higher sensitivity (which we have here at 100 mK and with a $V_{\rm bias}$ of 400 mV). This is supported by the fact that branch 2 looks quite similar to the integrals in the 200 mK case, and we only see unexpected behaviour in branch 1.

This is further explored by splitting the ballistic and thermal amplitudes (the maxima of the thermal and ballistic fits), shown in Figure 3.16. Here we find even more strange behaviour at low thermal amplitudes, where the effects of thermal propagation would dominate.

Looking at the time constants on a linear plot and splitting them into branches, we find the same sort of relationships for τ_1 in this fit as we had for τ_3 in the new fit, with no significant inflection between the two branches. τ_2 also does not indicate any significant inflection, and is well-constrained. τ_4 also lacks significant inflection between the branch boundaries, and experiences a significant jump in magnitude for $A_{\text{max}} = 0.4$ mK.

We can recall that the accuracy of the old fitting algorithm depends on the use of a quadratic nonlinearity factor, ϵ (see 2.1.6, page 78) to reduce χ^2 , which is usually a large positive number (of the order of 10-20% of pulse height) for the lowest-amplitude pulses, and small and negative for the others. We examine



Figure 3.16. The split thermal and ballistic amplitudes of the classical exponential fit of this data, split into branch 1 (blue) and branch 2 (red).



Figure 3.17. Linear plots of τ_1 (left), τ_2 (middle), and τ_4 (right), split into branch 1 (blue) and branch 2 (red).



Figure 3.18. The quadratic nonlinearity factor ϵ as a function of the maximum pulse amplitude.

the properties of ϵ in this particular dataset in Figure 3.18. Bizarrely, all values for ϵ are now negative, and ϵ has the same oscillations as the time constants do. One might surmise that the oscillation in the time constants and in ϵ relate to electro-thermal coupling effects, which can be seen in the signal of the bolometer in other experiments.

χ^2 goodness of the fits

The mean χ^2 per degree of freedom for the classical exponential fit on these pulses is 0.715, compared with the new fitting algorithm which had a mean χ^2 of 0.768. We show that both fits equivalently describe the pulse shapes, but that the classical exponential fit depends on a non-physical parameter and is more difficult to interpret for the new behaviour uncovered in this highly sensitive data set.

Discussion

It does appear that this specific experiment has uncovered some kind of effect which has not been seen in the previous experiments. Since the 'branching' effect appears at low amplitudes and low integrals, it is possible that the increased thermal stability of the new system is responsible. Potential explanations include:

- 1. The first branch (the slightly-lower integrals and slightly-lower amplitudes, with a smaller ballistic contribution) are simply chiller pulses which have been attenuated to such a state that they have become mixed with the α particles and we have been incredibly (un)lucky that the pulse attributes more-or-less match what we see in the α s.
- 2. Since the branching effects actually include a branch which appears to begin in the middle of the amplitude / integral distributions, rather than outside of them, we can surmise that it may be an effect of the absorber border from α pulses that impact somewhere between the sensor and the border - i.e. the ballistic energy thermalises partially close to the sensor and partially at the absorber edge, and then creates a thermal energy component 'wavefront' travelling to the sensor more slowly than usual, thus falling out of the usual time and integral distributions we had expected.

Possibility (1) would be extraordinarily unlucky in the sense that the detector system is still sensitive to the chiller pulses, but only *exactly* as sensitive as it is to α particles. We also later find (and outline in the next section) why we believe the chiller pulses may be intertwined with the low-amplitude cosmic ray muons in that case. Furthermore, if possibility (1) is to be believed, it implies that the electrical impulse created by the chillers produces pulses which still have a significant contribution from (a) ballistic phonons and (b) thermal propagation. If the chiller pulses are indeed convolved in the integral spectrum with the α particles, one would expect them to have only one exponential component due to the lack of need for all energy to be stored in the absorber before passing to the sensor. In fact, the electrical impulse would most likely come to the bolometer via the heatsink connection, implying that the ballistic contribution should be much larger than the thermal one. This is not the case in the data shown above, so we surmise



Figure 3.19. Diagram of the absorber, sensor, and α particle 'heat' just after ballistic phonon thermalisation (left) and as that thermalised energy propagates as thermal phonons (right). The thermalised ballistic phonon profile is large and falls close to the sensor, but also stores some of its energy at the border (due to a mid-way impact point). As the thermalised phonons from the border begin to propagate away from the border, they behave as secondary wavefronts.

that this effect is not due to the chiller.

Possibility (2) is best described with a diagram (Figure 3.19). Here we have an α particle impacting somewhere on the mid-point of the absorber between the sensor and the disc border. Because ballistic phonons propagate very quickly (at the speed of sound of the material), the thermal profile can reach very close to the sensor, but also store a significant amount of energy at the disc border (where it is effectively 'stacked up'). In the right side of Figure 3.19, the thermalised ballistic phonons begin to propagate as thermal phonons. The ones closest to the sensor have reached it fairly quickly, which would manifest as a low-amplitude pulse. However the energy coming from the border would begin to propagate across



Figure 3.20. The total integral of each pulse, as a function of the sum of the split thermal and ballistic integrals. *Left*: The new fit with thermal propagation effects. *Right*: The typical double-exponential fit.

the absorber as a secondary wavefront, which would not nicely match up with the thermal profile which began closer to the absorber. These reflective effects would create a pulse which does not obey the usual laws, if true. This would also result in the huge increase we see in the propagation time τ_3 , and may even explain why the conventional methods of fitting shown in Section 2.2.3 had some low-amplitude divergences and uncertainties, and may have even been hinted toward using the new function in that experiment, but was obfuscated by the uncoupling filter and large amount of 50 Hz and thermal noise in that experiment.

Finally, the Bi layer on the bottom (sensor-side) of the absorber dominates the absorber C_p (see the next chapter) and so we expect the ballistic phonons to be immediately attracted there - but we don't know very much about its thickness. We know that it was evaporated on the diamond, but depending on attributes of its surface tension, it could be thicker on the periphery of the absorber than in the centre. In this case, it would support the hypothesis that more heat is 'trapped' near the border in the case of mid-way α impacts.

Furthermore, these events are described very differently by the typical exponential fit vs. the new fit which takes into account the thermal propagation. The new fit produces much 'cleaner' relationships in the amplitude and integrals, which are far more difficult to interpret using the typical double-exponential technique. The strange behaviour of the nonlinearity factor ϵ further confuses things. If not for a more physically-descriptive fitting method, these pulses would be very difficult to interpret. This is further demonstrated in Figure 3.20 - one would expect that the sum of the thermal and ballistic integrals would follow a linear relationship with the total integral of the pulse. We see that for the physically-motivated fitting method (left), this is mostly true. By contrast, the typical double-exponential fit seems to have some pulses which do not obey this rule for smaller total integral values. This suggests that to adequately describe all the processes happening in these pulses, a physically-motivated pulse description is more valid.

We surmise that the branching effects and the behaviour we see in these pulses, but did not see before, might be due to the greater sensitivity resulting from the application of the new test system, and that we are seeing a 'border' effect which has not been observed before, and supports our view of the physics occurring in the absorber under various conditions. It also further illustrates the need to account for thermal propagation time in certain circumstances (such as the way Bolo 184 operates under α particles). However, this definition is subjective and can only be 'proven' with modelling.

3.2 Bolo 184 cosmic ray measurements at 100 mK

Using the new cryogenic system, a measurement dedicated to cosmic rays was conducted at 100 mK. Due to the aforementioned temperature difference in the new system, the temperature was most likely to be around 108 mK. The bias voltage was 400 mV in order to keep the detector on a linear part of the IV curve. Pulses were recorded for about 24 hours, during which time a total of 1642 total pulses were recorded. However, the chiller pulses and the baseline signal fluctuations are still present, so the total number of α pulses + the total number of cosmic ray pulses is less than this total.



Figure 3.21. Left: The amplitude spectra of the measurement, with the low-amplitude data set in blue and the high-amplitude data set in green. Right: The same for the energy (integral) spectra.

In order to exclude α pulses, the oscilloscope was set up to record from two input sources simultaneously, both connected from the output of the second amplifier and split using a coaxial splicer. The closest input to the second amplifier was the input line into higher-gain settings on the oscilloscope (for cosmic rays), in order to minimise the effect of delay from the signal cables (although this effect is most likely negligible).

In Figure 3.21 (left) we show the distribution of the amplitudes for the dataset in the low-amplitude (blue) and high-amplitude (green) regions. We note that the maximum amplitudes of the blue part of the spectra are saturated by design; this data set is only to exclude α particles from the low-amplitude events, so we expect the α s and the chiller pulses to be saturated. The lower-amplitude dataset (blue) was taken at a higher oscilloscope gain (with a greater precision). This image shows the spectra with the α particles and high-amplitude chiller pulses not yet excluded. Knowing the general distribution of α particles peaks at 5.4 MeV, we find that the low-amplitude events peak at about 150 keV.

This distribution shows a much smaller number of cosmic rays than α particles,

but low-amplitude pulses from the chiller are still convolved with this component and need to be removed. In order to do this, we must assess how many cosmic rays we expect to see.

3.2.1 Expected muon flux in the detector

The detector is orientated at a 45° angle relative to the α source, which is itself orientated at a 90° angle relative to the fixture of the cold plate. The flux of muons arriving at the surface of the detector will change depending on its angle; fewer muons will reach the detector at its current 45° angle than if it were at 90° normal to the surface.

According to the Review of Particle Physics [114], the average vertical intensity of cosmic ray muons > 1 GeV / c at sea level is $I \approx 70 \text{ m}^{-2} \text{ s}^{-1} \text{ str}^{-1}$ or roughly 1 muon per square centimetre per minute on a surface-level detector [115]. Bolo 184's orientation relative to the sky is 45°, attenuating the flux by a factor of $\cos(\theta)$. This gives us a flux of 117.9 muons $\text{m}^{-2} \text{ s}^{-1}$ or an expected 97.6 muons per day, calculated using only the largest surface (the diamond absorber).

In isolating the cosmic rays, we keep only pulses which have integrals > 0 and < 1 V ms in Figure 3.21. Of those, we run a loop over the leftover pulses to isolate those for which the argument of the pulse minimum is within 100 arguments of the maximum (to eliminate chiller pulses with a negative component before the main pulse). A final loop removes pulses for which the maximum of the pulse is not present at the expected place (removing double, triple, and quadruple pulses). We are left with 171 pulses over 24 hours, which is much larger than the expected \approx 98 pulses one would expect over this time period. If we take the peak of the α particle distribution to be 5.4 MeV, we find that the loweramplitude events peak at 200 keV, whereas we would expect the actual majority to be at 50 keV for minimally-ionising protons in the 40 μ m diamond absorber [101].

In practice, resolving 50 keV events is difficult even in the best of circumstances



Figure 3.22. Examples of 3 low-amplitude, post-cleaning pulses in the dataset which fall within the parameters classifying them as cosmic ray candidates, but which are unlikely to be cosmic rays.

(low systematics, high sensitivity). Given that these measurements were one of the first in the new cryogenic system, which has unresolved electrical coupling to ground and a large amount of thermal leakage from other temperature stages, it is not unsurprising that we are limited in what we can achieve. Finding cosmic rays is certainly possible, but will take some work to reduce these effects.

3.2.2 Unexplained pulses in the data

We find a few examples of recorded data which escape the 'cleaning' routine, and are held within the general population of 'low-amplitude' cosmic ray candidates described above.

We show three examples of these in Figure 3.22. The left example has a higher amplitude, but contains two pulses. These could either be muon energy deposition (but are unable to be treated by our fitting algorithm due to the overlap of the second rise time with the first decay time), or they could relate to recoil nuclei, or they could result from the chiller switching on. The central pulse is very small and very noisy, and is most likely an electrical impulse from the chiller. The right pulse has a slightly larger signal to noise ratio, but with a significant negative component following the positive one. These cosmic rays were recorded in AC-coupled mode to

attempt to account for baseline signal fluctuations induced by the chiller, but they were recovered to an equivalent DC signal using the process outlined in Section 2.2.1 (page 88); we therefore expect that the pulses should not have significant negative components. Their presence indicates other factors, and we can use this to exclude cosmic ray candidates. ²⁴¹Am also emits a 50 keV γ ray upon decay, precisely in the energy range where we expect to see cosmic rays.

It is worth noting that Bolo 184 was not explicitly designed to see cosmic rays, and resolving them is difficult even under the best conditions. This would most likely not be a problem if we had access to more sensitive detector technologies.

3.2.3 Cosmic ray candidates

We show four examples of events which might be cosmic rays, recoil nuclei, or pulses resulting from impurities in the vacuum. We will not fit to these pulses, as there is not a lot of information which can be gleaned from them, however we do notice that only some of them show the characteristic shape we have seen throughout this manuscript; some of them appear to have only a single exponential decay, which might be consistent with an energy injection directly into the sensor.

3.2.4 Discussion

We have performed an experiment specifically designed to measure cosmic ray muons. We have filtered the events to account for α particles and electrical interference coming from the cryogenic system, leaving us with 171 pulses over 24 hours. This is roughly twice the expected cosmic ray flux. Due to the high systematics in this cryostat when dealing with low-amplitude pulses, especially a strong electrical pickup coming from the chiller system, the lowest-amplitude 'cosmic ray' events are convolved with the electrical pickup coming from the cryostat chiller. We cannot confirm whether these pulses are from cosmic ray muons, or are recoil nuclei. The electrical susceptibilities of the system must be treated before attempting to measure



Figure 3.23. Examples of four low-amplitude events from the dataset of potential cosmic rays.

cosmic ray muons, as the measurements are very sensitive and prone to interference.

Unknown in Paris, I was lost in the great city, but the feeling of living there alone, taking care of myself without any aid, did not at all depress me. If sometimes I felt lonesome, my usual state of mind was one of calm and great moral satisfaction.

- Marie Skłodowska Curie

Chapter

Thermal Transient Analysis of Bolo 184

In this chapter, we study the transient properties of Bolo 184. In particular, we use a simple technique for pulsing the bias voltage of the bolometer to investigate momentary variations in its behaviour and measure the time constants of the detector and thermal chain, at a range of temperatures and bias voltages. We will also compare its sensitivity across these temperatures and ranges of bias power.

4.1 Description of experiment

Using the Bluefors cryogenic system delivered to IAS, the detector block containing Bolo 184 and its bias circuit was cooled to 100 mK, in a cryogenic system with a measured RMS thermal fluctuation of 76 μ K during 24 hours [113] on the mixing chamber thermometer. Due to the system requiring some optimisation at the time of the experiment, there was an uncertainty between the temperature of the cold plate and the temperature of the detector. Whilst the system was set up for experiments at 100, 150, and 200 mK, we must analyse the IV curves of these experiments to estimate the temperature of the device based on simulations.

4.1.1 Temperature estimation from the IV curves

A significant set of IV measurements was inherited from A. Benoit or from earlier measurement campaigns on SYMBOL. These were used to validate the setup of the BlueFors cryostat, in which Bolo 184 was the comparison by which we validate the system. The principle verification motivating this step is the temperature of the cold plate, especially following a significant thermal load noted during the first run in this cryostat. The electrical characteristics of the bolometer, for the most part, should be largely the same, with the exception of extra capacitance of the (longer) signal and bias cables. Therefore, we have taken IV measurements at each temperature stage during the experiment, with the main purpose of verifying the actual detector temperature during the experiment.

We find that the 100, 150, and 200 mK IV curves clearly do not correspond with the same curves in SYMBOL. The first run using this system, which had been set to 100 mK initially, was set up with large holes still present between the cold plate and another cryogenic stage. That was responsible for significant optical input power, and thermal leakage raised the detector temperature to an estimated 127 mK. This error was fixed before the runs outlined in this chapter, however some thermal uncertainty is still present. We conclude, based on the IV curves, that the 100, 150, and 200 mK measurements in this chapter more closely correspond with 108, 138, and 180 mK (respectively). However, the differences between these IV curves are still enough to be relevant for this experiment.

4.1.2 Transient study (Joule pulsing)

Reading out the signal of the bolometer requires a constant input (bias) voltage. By pulsing this bias power, we bring the bolometer out of equilibrium and we can observe its transient (temporary) properties via a process known as Joule pulsing. Bolo 184 has been biased on one signal line, and read out using a separate line which feeds into the amplifier circuit. Powering the biasing system is done by way of a 'bias box' - batteries and a potentiometer which provide a constant voltage / current. In this experiment, we have modified the bias box with additional electronics on the



Figure 4.1. IV curves of Bolo 184 from SYMBOL or A. Benoit (stars), from the initial commissioning (the experiment preceding the one in this chapter - dots), and from each stage in this experiment (hexagons). The measured data are the symbols and the fits from the IV simulation are shown as lines. The three traces labelled '(BF)' are those used in this experiment.



Figure 4.2. The modified biasing circuit and readout system for the Joule Pulsing experiment (from bias up to the first amplifier). *Red:* Warm components. *Blue:* Cold components, inside the cryostat.

input and output signal lines to generate a fast additional voltage increase coming from the bias box, and small additional resistors and capacitors in the input box to override the stray capacitance effects and view the transient behaviour of the bolometer under a small step in its working point, giving us a greater understanding of its transient behaviours (and perhaps those of the entire thermal chain). This creates an extra ΔI (always pA level) which charges a capacitor and pulses the bolometer.

We show the modified readout schematic in Figure 4.2. The capacitance between the cables is an effective capacitance in the form of:

$$C_{\text{Stray}} = C_{\text{Cables}} + \frac{C_G}{2} \tag{4.1}$$

where C_{Cables} is the capacitance of the cable (either the input or the output cable) and C_{G} is the cable capacitance to ground (respectively). The cabling in the new cryostat is Habia 102 μ m diameter constantan, which has a capacitance to ground of 68 pF m⁻¹ and a wire/wire capacitance of 39 pF m⁻¹. Calculating the stray capacitance of the input and the output, we find an effective stray capacitance on



Figure 4.3. Triangle wave fed to the bias box from the pulse generator.

the output of 368 pF, and an effective stray capacitance on the input of 147 pF. This diagram is missing the second amplifier, which can be seen in the original readout scheme in Figure 2.5 (page 71). Between the battery and the bolometer, we have added a small potentiometer in series with a value of 13.35 k Ω (chosen specifically to attenuate the current into the stray capacitance, to attenuate the longer time constant it creates, in order to avoid obscuring the delay constant(s) of the bolometer with an artificially large rise time). There is an extra input coming from the pulse generator, in the form of a triangle wave between -5 and 5 V, with a frequency of 7.21 Hz, which is shown in Figure 4.3.

For a triangle wave with a total amplitude of 10 V, with a frequency of 7.21 Hz, we have 1.39 V s⁻¹. The 10 V triangle wave is connected to a 4 pA capacitor $(C_{\text{PulseInput}})$. If I = CdV/dt, 4×10^{-12} F $\times 1.39$ V s⁻¹ makes a current of ≈ 5.5 pA. This current is shared between the circuit branch containing the load resistor, bolometer, and input cable capacitance, and the branch containing the 13.35 k Ω resistor (R_{poten}) . The low resistance of R_{poten} allows us to lower the effect of the stray input capacitance on the rise time of the pulse, and allows us to image



Figure 4.4. Mean Joule-pulsed signals at 108 mK, for V_{bias} between 200 and 1000 mV.

its thermal properties without this interference. The choice of the triangle wave (as opposed to a square wave) allows us to measure the long thermal tails of the thermal chain, rather than simply re-simulating the effect of a fast pulse with a square wave, which would be more similar to what we measure with α particles.

Joule pulsing at 108 mK

We performed the Joule pulsing experiment at 108 mK, for V_{bias} between 200 mV and 1 V. We used the phase-matched trigger output of the signal generator to trigger the oscilloscope, capturing the pulses in the same region at every sweep. The experiment was run for 10 minutes at each bias voltage, and we take the mean pulse from these (about 3100 pulses per bias voltage).

We show the preliminary results of the average of all of the full pulses in Figure 4.4. In the figure, at ≈ 69 ms, we inject a fast pulse into the Joule power with a positive voltage, creating a negative slope. At ≈ 139 ms, the pulse reverses sign. We find that for a V_{bias} below 500 mV, the pulses have a large negative slope



Figure 4.5. Mean Joule-pulsed signals at 108 mK, for V_{bias} between 200 and 1000 mV, zoomed in to view the initial rise times. At ≈ 69.5 ms, the triangle wave inflects, creating a new pulse. Colour scale refers to V_{bias} , indicated by the legend at the left.

which decreases as V_{bias} increases. At about 475 mV, the profile flattens. Above this, up to the maximum V_{bias} of 1 V, the slope is positive.

If we adjust these pulses so their baseline voltage before the voltage adjustment is (mostly) the same, and we zoom into the beginning of the pulse (Figure 4.5, we find that the rising time constant is equivalent in most cases (with exception for the smallest V_{bias} . This rise time is the convolution of many issues, e.g. the stray capacitances in the system, the load resistance, bolometer resistance, and filter resistance, etc. The fact that this rise time remains the same suggests that the addition of an extra resistor attenuates this effect, allowing us to view the remaining time constants in the experiment uninhibited by an artificially large rise time. This was achieved by the use of a small extra resistor set to 13.35 k Ω we showed in the previous section, which reverses the effect of the cable capacitance. The measured rise time of the bolometer is an amalgamation of many rise times, e.g. $C_{\text{stray}} \cdot R_{\text{Poten}}$ (which would be $\approx 5 \ \mu \text{s}$), the thermal rise time of the bolometer,



Figure 4.6. Mean Joule-pulsed signals at 137.8 mK, for V_{bias} between 200 and 1821 mV.

and the interplay between the components in the circuit - however, we see an actual rise time which is closer to 200 μ s due to the combination of all of these. We see that the first decay time varies with V_{bias} , which is the same behaviour seen in α particle pulses.

We can also see the extra small decay constant before the signal normalises to a zero or near-zero slope starting from $V_{\text{bias}} = 600 \text{ mV}$, which corresponds to the 'double peak' behaviour we will show in the α particle analysis in the next section.

Joule pulsing at 137.8 mK

We show the same experiment, repeated at 137.8 mK over a larger range of V_{bias} , in Figure 4.6. We find the same initial rise time constant as in the 100 mK case, with extra time constants arising for bias voltages between 800 to 1821 mV.

The 137 mK traces have far less oscillations than the 108 mK pulses do, which we expect as the temperature increases.


Figure 4.7. Mean Joule-pulsed signals at 137.8 mK, for V_{bias} between 200 and 1000 mV, zoomed in to view the initial rise times.

Joule pulsing at 180 mK

Finally, we repeat the procedure again at 180 mK, for V_{bias} between 400 and 3200 mV. This higher range was chosen based on the IV curves and the probability that the sensitivity is maximised at a much higher V_{bias} due to the higher temperature.

We show the results of this in Figure 4.8. We find that the central slope of the signal is always negative, even up to 3.2 V, suggesting that the region of highest sensitivity is higher than $V_{\text{bias}} = 3.2$ V, where the slope would level off.

Zooming into the initial rise in Figure 4.9, we find that the initial rise times do appear to vary slightly, increasing inversely with V_{bias} . The lowest V_{bias} , 401 mV, has only a single exponential rise time.



Figure 4.8. Mean Joule-pulsed signals at 180 mK, for $V_{\rm bias}$ between 400 and 3200 mV.



Figure 4.9. Mean Joule-pulsed signals at 180 mK, for $V_{\rm bias}$ between 400 and 3200 mV, zoomed in to view the initial rise times.

Discussion

We have shown that, by rapidly varying the Joule power in the bolometer, we can measure its transient properties. We find initial rise times which are consistent with the transfer function of the bolometer, unbiased by other sources (e.g. stray capacitance), but with a slow decay / slope (second-scale) on each trace which varies with V_{bias} , but for reasons currently unknown. High V_{bias} appears to produce oscillations at lower temperatures, which could be due to electro-thermal coupling or nonlinear effects (and which would agree to what we have shown for α particle pulses). The short decay constant of each pulse increases inversely with V_{bias} , which is the same behaviour as with α particles (see Section 4.1.3), indicating that this is bolometer-level thermal behaviour under all conditions, rather than relating to ballistic phonon thermalisation, etc.

Initially, it had been hoped that by injecting a fast power pulse directly into the sensor, we would be able to view pulse shapes which are similar to the α particle pulses, but whose time constants relate only to those of the bolometer. However, when we inject power into the sensor in this way, we also rapidly change the working point of the bolometer, which creates complex effects. It may be the case that we are indeed pulsing the full thermal chain, and that some of the effects seen in the measurements relate to thermal chain reactions to the Joule pulsing. We have observed the rise time of the thermal chain, and potentially its first decay time (which varies with V_{bias} , but observing it in detail is difficult due to the precision required in the measurements and the complexity of the thermal system.

There appears to be a long time constant in all the pulses which varies with V_{bias} , and is the shortest for the the smallest V_{bias} (where the current is highest) in many of the data sets. In the most extreme cases, this long time constant obfuscates the rest of the pulse features. The origin of this long time constant is unknown, and is not reproduced by modelling. We show our attempt at modelling this experiment in Section 5.8, page 209.

It is possible that this long time constant could be due to the low-pass thermal

filter present in the Bolo 184 block (Figure 1.15, page 46). Originally, the author had assumed that this thermal low-pass filter was disconnected - however, a private communication with N. Coron revealed that it had not. If the thermal filter is still active, it would have a time constant of a few seconds, which is roughly what we have measured in the long time constant of the Joule pulses. There is also the further possibility of an extra time constant arising from the silver-epoxied gold wires on the edges of the bolometer, which bring heat to from the device to the thermal bath - these would likely have a time constant closer to 30 ms^{*}. Altogether, it is difficult to comprehensively understand every aspect of these traces without also directly measuring the shape of the pulse arriving at the bolometer from the modified electrical circuit. These possibilities must be explored further before any conclusions can be drawn, but whatever the source for the long time constant, we have proven Joule pulsing to be a powerful tool for measuring the impulse response not only of the bolometer, but of the whole thermal chain.

4.1.3 Alpha particle shapes as a function of V_{bias} and T

The shape of the α particle pulse will be a function of the sensitivity of the bolometer, which is itself a function of the working point. If the bolometer is biased at a linear point in its IV curve, the behaviour should be more-or-less predictable. If we depart significantly from this point of linearity, we will still see a signal, but this signal may be affected by other factors (such as electro-thermal feedback with a high bias power, or electrical field effects leading to a divergence from usual R(T)behaviour).

To demonstrate this principle in Bolo 184, we will take α particle pulses at three temperatures and over the entire range of the IV curve. We will compare the total energy (total integral) of the average alpha particle at each of these temperature / bias combinations, and compare that with what we see on the IV curve and on the results of the Joule pulsing.

^{*}Analysis based on a private communication with N. Coron.



Figure 4.10. Mean alpha particle pulses at 108 mK as a function of changing bias voltage.

At each temperature, we sweep over the active bias range of the bolometer. Due to the equipment used, bias voltages are only selectable up to 1.842 V and 3.2 V. However, the maximum sensitivity is generally attained by this point anyway (with exception for the 180 mK case).

Pulse shapes and time constants - 108 mK

At 108 mK, the magenta curve in Figure 4.1, the linear regime is limited as the point of inflection is present as early as $\approx 250 \text{ mV}$ ($\approx 30 \text{ nA}$). We expect the highest sensitivity to radiation or alpha particles to be in this region. By varying the bias voltage from 200 to 1000 mV and taking the average of many alpha particle pulses, we can assess this sensitivity and the effect of varying V_{bias} on the time constants. One can expect that as the bias power is increased, the bolometer becomes hotter, and the components of the pulse become faster.

We find in Figure 4.10 that the lowest V_{bias} values, 200 and 300 mV (black and

dark pink, respectively), have the slowest rise and decay times, and the lowest peaks. 350 mV (red) experiences a huge jump in pulse height. The pulse heights and integrals then (generally) decrease, although we see a general increase in the speed of the rise and decay time constants. As we venture into higher V_{bias} (800 and 1000 mV), we can see that the athermal and thermal components appear to 'decouple', which is believed to be an effect of strong electro-thermal feedback at this high bias power (which we have already shown in Part 2). The evolution of the pulses with varying V_{bias} is mostly coherent with our present understanding of the detector as far as the sensitivity (total integral) and time constants are concerned, though some variations are seen in this figure (which could be due to the low statistics). We note that the averaged pulses may be vulnerable to some non-alpha influence; although we have removed the large, saturated pulses produced by the cryogenic chiller, baseline fluctuations may affect some of the pulses, as may cosmic rays which have α -like attributes.

Pulse shapes and time constants - 137.8 mK

Repeating the same treatment as above but for pulses at 137.8 mK, we record several α pulses at 200, 400, 600, 800, 1000, 1500, 1821 mV. Based on the IV characteristics in the teal curve in Figure 4.1, we expect that the maximum sensitivity of this data set will be higher only at a higher operating point voltage.

In Figure 4.11, we find similar behaviour. The pulses at the lowest V_{bias} begin slow and low, with longer thermal time constants. We then see a large jump in the pulse height at 600 mV, with a decrease at 800 and 1000 mV. At 1500 and 1821 mV, the pulses again become very 'peaked' and fast, with the second component becoming separated at 1821 mV, in the nonlinear regime.

From this plot, it seems clear that the highest sensitivity at 137.8 mK is achieved at 600 mV.



Figure 4.11. Mean alpha particle pulses at 137.8 mK as a function of changing bias voltage.



Figure 4.12. Mean alpha particle pulses at 180.0 mK as a function of changing bias voltage.

Pulse shapes and time constants - 180.0 mK

At 180.0 mK, we expect that the linear regime will be reached at a much higher point than in the previous measurements, as we do not fully hit the point of inflection even at 3.2V on the IV curve. We therefore expect that the sensitivity will increase up to 3200 mV, which is the highest V_{bias} we can apply using our equipment.

In Figure 4.12, the picture is much clearer than in the previous two cases. We can clearly see the pulses increasing in height as V_{bias} increases. We also see that the time constants decrease inversely, which is most notable at 3200 mV, where the first and second components - while not decoupled - become very strong relative to each other. We will calculate the integrals of each of the average α pulses, which will show us the energy (analogous to sensitivity) in the next section.



Figure 4.13. The total integral of each average α particle, at each temperature and bias.

Pulse integrals as a function of V_{bias}

With each alpha particle at each V_{bias} and temperature, we calculate the integral of the average α particles and plot it against the bias voltage. As we are using a 5.4 MeV α particle source, the total energy distributed in the detector will remain constant. The point at which the integral is the highest will therefore demonstrate the bias voltage at which the device is the most sensitive. It will also demonstrate overall trends in that sensitivity.

In general, we find the highest integrals exist in the 108 mK data set. The general trend appears to be that the total pulse integral decreases inversely with V_{bias} - as the sensitivity of the bolometer decreases. The maximum sensitivity of the bolometer is generally expected to be at a slightly lower V_{bias} than the maximum value in the IV curve, which implies that this bolometer is the most sensitive at 108 mK in the region of 200 mV bias voltage. However, the bias input is more unstable in this low regime using the bias box applied in this experiment. Using a more stable low-voltage source may solve this problem, although acceptable SNRs are still obtained at 400 mV.



Figure 4.14. The IV curves (with fits) for the new 100 mK (blue), 150 mK (green), and 200 mK (red) measurements.

Pulse energy as an analogue for device sensitivity

We can confirm the above using the total α integral to describe the sensitivity of Bolo 184. If we remind ourselves of the IV measurements taken during the experiment, we can use those IV curves to calculate the sensitivity of the detector, and compare the sensitivity curves to what we have shown above. We show these specific IV curves in further detail in Figure 4.14.

By taking the values of the IV model fit to this data, and increasing Q by a small value, we subtract the elevated curve from the original fit to find the responsivity (dV/dQ). We then plot scaled (to the highest responsivity value at 108 mK) values of the pulse integrals as a function of V_{bias} , and find that the shape of the curves are coherent with that of the responsivity, as we see in Figure 4.15.

We note a small discontinuity in the 100 mK case in Figure 4.15, which could



Figure 4.15. The responsivity of the bolometer at each temperature (solid lines) and the normalised integrals (which are in units of V ms).

be attributable to a small drift in the IV measurements due to the added small resistors in the modified bias circuit. However, we note that the slope of the curve is mostly unaffected by this, and that the values of the integrals are generally in good agreement of the qualitative shape of the responsivity curves.

Small deviations in the total integral, especially for the 150 and 200 mK measurements, are expected to be due to the low number of α particles used at each V_{bias} , due to experimental time constraints.

If we calculate the V_{bias} which results in the maximum responsivity at each of these temperatures, we find that the 100 mK curve has a maximum sensitivity at a V_{bias} of 0.121 V (below our measurement range), that the 150 mK curve has a maximum responsivity at a V_{bias} of 0.371 V, and that the 200 mK responsivity is maximised at 1.19 V. This is in qualitative agreement with what we see in the integrals.

Finally, we can use these properties to calculate the detector responsitivity \mathcal{R} (V/W):

$$\mathcal{R} = \frac{Z - R}{2IR} \tag{4.2}$$

where Z = dV/dR. To use the measured integral, we calculate the deposited energy $\Delta E_a = 5.48$ MeV = 8.8×10^{-13} J, and find $E_{\text{base}} = \int \text{pulse} / G_{\text{exp}}$ (the total experimental gain, which is 200 in our case). \mathcal{R} is then found by:

$$\mathcal{R} = \frac{E_{\text{base}}}{\Delta E_a} \tag{4.3}$$

The result is not different to that which is already shown, but we shall include it for completeness. Taking our calculated responsivity arrays and using them to normalise the dV/dQ curves at each temperature, we find the same relationships, which we show in Figure 4.16.

Therefore, we have shown that we can use the α particle shape to measure the responsivity of the detector at multiple bias voltages even in the absence of



Figure 4.16. Calculated Bolo 184 responsivities at each temperature, compared with normalised dV/dQ from the IV curve.

photon sources[†], and the results are in agreement with the shapes predicted by the IV curves of the bolometer (with exception to some early roll-off at high V_{bias} . This kind of characterisation using α particles to replace photon sources should be generally applicable to any detector that has pulse integrals which stay constant under a single-energy pulse source (and may not be applicable to detector technologies with more complicated thermal pathways). Depending on the experimental apparatus available in a particular cryostat, this method of measuring the detector responsivity might be a quicker or easier method than the usual treatment using photons.

4.2 Alpha particle impact rates at varying V_{bias}

We can use the impact rate of the measured α particles to examine how many alphas are measured, and whether this changes as a function of V_{bias} or temperature. We expect it to change due to the sensitivity of the detector.

 $^{^{\}dagger} \mathrm{The}$ idea is credited to N. Coron.



Figure 4.17. The α particle impact rate as a function of V_{bias} at 108 mK.

At 108 mK, we measured α particles at every V_{bias} for approximately 20 minutes at each bias voltage. Non- α pulses (chiller pickup) were removed manually and the trigger voltage was high enough to exclude cosmic rays or recoil nuclei.

We show the calculated rates in Figure 4.17. In spite of the large error, we see that as V_{bias} increases, the overall rate tends to decrease. This is coherent with the responsivity we have shown above, and shows us that the measured α particle impact rate is most likely associated with the sensitivity of the device at a given V_{bias} and T.

At 137.8 mK, we only recorded α particles for a few minutes (between 3 and 7 minutes) due to time constraints on the experiment. We therefore expect a slightly larger amount of variation in the reported α particle impact rates.

Much like the 108 mK case, we see a slight trend in Figure 4.18 where the measured impact rate decreases with V_{bias} . Interestingly, the largest α particle measured in this data set was the 600 mV averaged α particle, indicating that the sensitivity is the highest in this region. This is not supported by the comparisons with the α particle impact rate. This could be due to the relatively low amount of



Figure 4.18. The α particle impact rate as a function of V_{bias} at 137.8 mK.

statistics for the α particles and the rates at each temperature, compared with the 108 mK case. However, the overall trend does appear to be in general agreement with the calculated responsivities above.

Finally, the process is repeated once more at 180 mK. These α particles were measured at each V_{bias} for slightly longer; between 7 to 14 minutes.

We see in Figure 4.19 that the distribution is much more flat. We see in the section above (Figure 4.16) that the sensitivity and responsivity at 180 mK is much more flat than it is at 108 or 137 mK; this behaviour is roughly equivalent to what we see in the distribution of the count rates (but any slope is likely lost in the statistical error).

4.3 Conclusions

We have performed measurements on Bolo 184 in the new cryogenic system at IAS, with the intention of measuring the effect of varying V_{bias} on the sensitivity and the transient properties of the bolometer. We have measured α particles at



Figure 4.19. The α particle impact rate as a function of V_{bias} at 180 mK.

a large range of V_{bias} at 108, 137, and 180 mK, and have observed the changes to α particle shape, integral, and amplitudes. We have compared the α particle integrals with the calculated device sensitivity arising from fits to the IV curves measured during the experiment, and we have used the integrals to calculate the responsivity of the bolometer as a function of V_{bias} at each temperature. We find responsivity curves which are in agreement with the calculated sensitivity of the device, and we compare this with the α particle impact rate as a function of V_{bias} at each temperature. The overall trends are aligned with the expectations arising from the device sensitivity, with some divergences which are likely due to a lack of statistics for some of the data sets. We note that using α particle sources to measure responsivity in this fashion could potentially be a useful monitoring mechanism for future space missions; an α particle source with a low emission rate would introduce an insignificant amount of noise to the science signal, but allow ground teams to continuously monitor detector response on-sky.

We have also modified the biasing circuit to pulse the readout power on the detector, in order to probe the transient behaviour of the bolometer. In spite of initially hoping to find a 'glitch-like' shape, the result was a more unique shape of the bolometer adjusting for the sudden spike in the input power and the effects this has on the bolometer's working point. This allowed us to view the impulse response of the bolometer system, with a decay which appears to relate to the sensitivity. We have utilised an extra resistance in the bias circuit which is intended to minimise the rise time, so that a slower rise time (which would be due to the stray capacitance in the bias circuit) would not obfuscate the other time constants involved in the pulses. A first decay constant is present in some of the pulses, although further analysis is a complex issue which would require deeper work to analyse.

In order to comprehensively understand these behaviours, detailed modelling is necessary.

Part III

Bolo 184 Pulse Modelling

Bolo 184 Modelling Introduction

This chapter is an introduction to the Bolo 184 modelling introduced in the effort of reproducing α particle and cosmic ray pulses. The details of the final modelling will be described in the next chapter, but the earlier efforts (and their limitations) will be described chronologically here.

Early Bolo 184 Modelling Approaches

Based on the first Bolo 184 data, in which the fast and slow pulse components appeared to be decoupled (see the introductory section for Part 2), it was initially believed that this effect was due to electro-thermal feedback. A simple simulation was produced for R(t) of a bolometer pulse with a constant current and simple thermal coupling. This did not produce an oscillation as seen in the data, leaving the possibility of significant parasitic capacitance on the signal line inside the cryostat to be a contributor; essentially, that the fast energy deposition into the bolometer charged the cryogenic cabling, leaching signal from the actual pulse.

A simulation with a high stray capacitance in the bolometer circuit did show oscillations, but with a different shape to that in the data. Direct measurement of the measurement lines in SYMBOL showed that the capacitance of the cables was low ($\approx 0.48 \text{ nF}$) which may not lead to as significant of an effect as anticipated; these measurements were later repeated for the new cryogenic system, with much longer cables, and a resulting higher cable capacitance. However, the effect of the stray capacitance was temporarily set aside from the modelling point of view.

The first semi-successful iteration of the full physical model is a two-component model with separated components for the sensor and the absorber. The absorber is simulated using two Monte-Carlo codes; a first one for ballistic phonons which radiate isotropically from a specified α particle impact point, which thermalise in one time step at a distance corresponding to the ballistic phonon mean free path. Phonons which encounter the disc border are trapped there. The next phase of the absorber model considers the ending points of every phonon as starting points for 'thermalised' ballistic phonons, which diffuse as thermal phonons. These thermal phonons propagate around the disc, and we read the 'temperature' (N_{phonons}) above the sensor at every time step. This model assumes that the disc component is completely decoupled from the rest of the bolometer, which is a simplification.

The second component of the model is a standard thermal block model, in which we split the NTD germanium and sapphire layers into 7 segments, each coupled to the bath at the ends of the legs. Using measured or estimated values for the heat capacity and thermal conductivity of the components, we allow a δ temperature pulse to propagate from the top block, which is the glue between the absorber and the NTD sensor. This gives us the bolometer's impulse response function. The T(t) from the disc model is convolved with the T(t) from the sensor block model to produce T(t) pulses which account for the α particle impact location and its effect on the pulse shape.

The next model discussed is a variation of the single-block oscillation model, with an additional stage included in the study. This two-stage model allows us to investigate electro-thermal coupling and stray capacitance in the system, accounting for behaviour in a second temperature stage of the bolometer (the sapphire). The second stage has a simple linear thermal coupling to the heatsink, whilst the bolometer has a T^4 dependence.

We then revisit the absorber and the behaviour of ballistic phonons using two approaches: we generate evenly-distributed α particles across a disc the size of Bolo 184's absorber. For each α particle, we propagate a large number of ballistic phonons isotropically from the α impact point. One of the models assigns each phonon a thermalisation length based on a mean free path law, and the other model uses a simple geometrical law. The mean free path model assumes that ballistic phonons deposit all of their energy at the end of their path, and the geometrical law assumes that ballistic phonons deposit a fraction of their energy at every impact in the absorber. Both models assume that the phonons reflect off the disc border and are only stopped once they reach the bismuth layer. We then count the number of phonons which arrive in the centre of the disc, which is thermally coupled to the sensor, allowing us to generate a simulated distribution of 'ballistic' amplitudes.

Finally, we alter the two-stage model to account for the circuit we have used in the Joule pulsing experiment described in the previous chapter. We remove the ΔT pulse input and instead we pulse the Joule power of the bolometer through a capacitor.

These models will be described in detail in the next chapter.

Whatever women do they must do twice as well as men to be thought half as good. Luckily, this is not difficult.

- Charlotte Whitton

Chapter 5

Bolo 184 Modelling

In this chapter, we will describe the modelling efforts in reproducing α particle and cosmic ray pulses in Bolo 184. We will begin by describing the heritage modelling which was produced by Noel Coron (IAS), which was useful in producing the rest of the work outlined in this chapter. We will then describe our contributions: the IV simulation used in this thesis, the first two-component model (with some of its results and its limitations), a two-block model for simulating electro-thermal effects in the bolometer system, various modelling approaches to account for ballistic phonon thermalisation in the absorber, and reproduction of the Joule pulsing experiment. All codes are currently running in python 2.7.

In many cases, the exact values of specific parameters are unknown. In the case where we know the value of a parameter (such as one which can be measured, calculated, or has been inherited from other work), we use that parameter. The remainder of the modelling is focused on probing the physical effects by tweaking the unknown parameters in various models in order to produce the most data-like results.

5.1 Heritage modelling: Work of N. Coron

Upon beginning this project, we were lucky to obtain a vast amount of documentation and contributions from N. Coron (IAS) on some preliminary modelling for Bolo 184. This work was comprehensive in examining the IV characteristics of the bolometer, as well as the heat capacity (C_p) and thermal conductivity (G)properties.

We should note that for work at cryogenic temperatures (especially sub-K), material parameters are not documented in the literature to the same extent as they are in other measurement regimes; this makes cryogenic work, in general, an experimental science. This means we rely heavily on the previous work and documentation, such as that provided by N. Coron through many years of laboratory experience. That work will be described here. In the work, Coron provides the relevant dimensions of Bolo 184's components (the diamond disc, bismuth coating, the NTD sensor, sapphire mechanical support, the epoxy between the absorber and sensor, and the epoxy between the sensor and the sapphire). He uses a combination of geometrical and parametrical calculations to derive the individual and total C_p and G of Bolo 184.

5.1.1 Heat capacity (C_p)

Coron calculates the total volume of each component and adapts its C_p (J cm⁻²K⁻¹) into a temperature-dependent C_p for each individual component, giving coefficients which scale with temperature. These coefficients are used in our later modelling work, so we will describe them now.

Diamond disc

The diamond disc has a diameter of $\phi = 3.5$ mm and a thickness of $t = 40 \ \mu$ m, giving it a volume of 3.8×10^{-4} cm⁻³. Diamond has a C_p of $5.2 \times 10^{-8} \cdot T^3$ J cm⁻³K⁻¹. Multiplying by the volume, we find a C_p of $1.976 \times 10^{-11} \cdot T^3$ J K⁻¹.

Bismuth coating

The bismuth coating has been evaporated on the diamond absorber, and its exact thickness is not known. Coron has estimated the Bi coating to be approximately 0.4 μ m thick. In this case, its volume is 3.8×10^{-6} cm³. Coron quotes the C_p of bismuth to be $5.2 \times 10^{-5} \cdot T^3 + 2.0 \times 10^{-7}$ T J cm⁻³K⁻¹, giving our disc of bismuth a C_p of $1.9 \times 10^{-10} \cdot T^3 + 2.7 \times 10^{-12} \cdot T$ J K⁻¹.

NTD sensor

The sensor has a slightly more complicated geometry, containing a central rectangle (affixed by epoxy) and two long, tapering legs on either side. The central part has a volume of 800 μ m × 260 μ m × 260 μ m = 5.4 × 10⁻⁵ cm³. The two legs, about $\frac{1}{3}$ the thickness of the central part, are ≈150 μ m long, giving them a volume of 3.75×10^{-5} cm³. The total volume comes to ≈9.2 × 10⁻⁵ cm³. Coron quotes NTD doped germanium having a C_p of ≈5 × 10⁻⁷ · T J cm⁻³ K, giving a component C_p of 4.6 × 10⁻¹¹ · T J K⁻¹.

We note that for the modelling outlined in the upcoming sections, we treat the C_p of the central sensor and the C_p of the arm separately, but using these same methods.

Sapphire mechanical support

The sapphire support has a thickness of 68 μ m, a width of 350 μ m, and a length of 5 mm, giving a total volume (with a $\frac{1}{3}$ multiplier) of 3.97 $\times 10^{-5}$ cm³. The sapphire C_p is quoted as $3.4 \times 10^{-7} \cdot T^3$ J cm⁻³ K⁻¹, which gives a component C_p of $1.4 \times 10^{-11} \cdot T^3$ J K⁻¹.



Figure 5.1. $C_p(T)$ for Bolo 184's constituent components, as derived by N. Coron.

Inter-layer epoxy

Coron initially calculated the epoxy layer based on the known C_p of Stycast 1266 (with a quoted C_p of $3 \times 10^{-5} \cdot T^3 + 2 \times 10^{-6} \cdot T$ J cm⁻³ K⁻¹. We were later informed, via private communication, that the epoxy used in the detector was most likely Devcon epoxy, and that the exact C_p is unknown (but could vary up to a factor of 10). Two surfaces are epoxied in Bolo 184, with areas of 800 × 260 μ m and thicknesses of 100 μ m, giving 2.08×10^{-5} cm³ total volume per epoxy layer. This gives each epoxy layer a C_p of $6.3 \times 10^{-10} \cdot T^3 + 4.2 \times 10^{-11} \cdot T$ J K⁻¹ for the case of Stycast, but with a large uncertainty in the case of the Devcon epoxy. This will become important in the next sections.

C_p discussion

We show a rough distribution of the C_p as a function of T from Coron's model in Figure 5.1. This gives us our first hint as to how important the C_p of the glue actually is in the thermal properties of this bolometer, where the glue and the



Figure 5.2. R_{Bolo} (T) provided by N. Coron (blue stars) and fit to the bolometer resistance equation (red line).

sensor dominate. Given the uncertainties in the actual C_p of the Devcon epoxy, this may well turn out to be a very significant component in the thermal modelling. If we consider only the absorber, knowing that it is only attached to the sensor via the glue, we see that the absorber is strongly dominated by the C_p of the bismuth. This is an important factor which has been taken into account in the modelling below.

5.1.2 R(T)

Resistance of the bolometer as a function of temperature $(R_{\text{Bolo}}(T))$ curves have been provided by Coron and used during later modelling, which we show in Figure 5.2 (blue stars). We have fit to this using the standard bolometric resistance equation:

$$R_{\text{Bolo}}(T) = R_* \cdot \exp^{\sqrt{\frac{T_g}{T}}}$$
(5.1)

where T_g and R_* are material parameters of the sensor. We find that $T_g = 24.84$ K and $R_* = 11.39 \Omega$. These values are used later in the modelling of Bolo

184.

5.1.3 Thermal conductance (G)

Coron calculated the G of the total bolometer from the IV characteristics provided by A. Benoit during the development of the detector, and from the R(T) of the detector (which is shown above). He has provided curves for the total bolometer as well as several components:

- 1. Total G(T) from experimental IV curves
- 2. 2 arms of the sensor, using G(T) of pure germanium with Casimir's law
- 3. Sapphire mechanical support, from Casimir's law (unpolished case)
- 4. Sapphire mechanical support, from Casimir's law (polished, as in the bolometer)
- 5. Epoxy between the sensor and the absorber (most likely value)
- 6. Epoxy between the sensor and the absorber (minimum value)
- 7. Diamond wafer, estimated between perimeter and centre.

The calculations are shown in Figure 5.3. We see that the slope is essentially identical in each case, and that the largest magnitude effect comes from the glue between the absorber and the sensor (which we have also seen in the component C_p s). We see a significant difference between the polished and unpolished cases for sapphire, although our sapphire layer is polished and thus has a larger thermal contribution.

Coron's data was the basis from which the modelling was begun, in addition to the many datasets which were outlined in the previous chapter. We will now describe the modelling, using what we know about Bolo 184 as a starting point.



Figure 5.3. G(T) of bolometer and constituent components, as estimated by N. Coron.

5.2 Current-voltage (IV) simulation of Bolo 184

As was described in the previous chapter, the current and voltage characteristics as a function of temperature are a vital characteristic of bolometer function - the working point of a bolometer defines its sensitivity to input power, as well as its nonlinearities. To find an optimum working point for Bolo 184, we made many series of measurements at various temperatures. To validate those measurements (especially in the commissioning of the new cryogenic system), we fit to them using a IV(T) simulation based on the work of Piat et al [87].

5.2.1 Simulation description

The simulation code calculates (for a given current) the thermal conductance as a function of temperature. In the last chapter, we established that:

$$W = G(T - T_0) = P + Q \tag{5.2}$$

where G is the thermal conductance, P is the bias power, Q is the input power (from the environment), and W is the total power of the bolometer. The simulation calculates:

$$\sum_{T_0}^T \left[G(T)dT \right] = RI^2 + Q \tag{5.3}$$

as a function of T. Again, the resistance of the semiconductor varies with E (the applied electric field) and with T, in the following way:

$$R(T,E) = R_* \cdot \exp\left[\left(\frac{T_g}{T}^\beta\right) - \frac{eEL_{\text{hop}}}{k_BT}\right]$$
(5.4)

where $\beta = 0.5$ for NTD germanium and $L_{\text{hop}} = L_{\text{hop}}^1 / \sqrt{T}$. Hence, we get the self-consistent equation for the potential $V = L \cdot E$, L being the length of resistance R:

$$V(R,T) = I \cdot R \exp\left(\frac{eVL_{hop}^1}{Lk_BT\sqrt{T}}\right)$$
(5.5)

and we find the solution using iteration.

The simulation produces IV curves for a given temperature, and includes the electric field effect. Its free parameters are T_0 , optical input power Q, the hopping coefficient L_{hop} , and the thermal conductance g_0 .

5.2.2 Demonstration of IV simulation

Taking the 100 mK data as an example, we demonstrate the effect of the free parameters of the IV simulation by varying them and comparing the results. The 100 mK line of best fit has the following free parameters:

• $T_0 = 100 \text{ mK}$

• $L_{\rm hop}$ (variable range hopping factor) = 1.466 × 10⁻⁸ m



Figure 5.4. IV curves of the baseline 100 mK data fit (red), a variation where $L_{\text{hop}} = 0$ (orange), where g_0 has been divided by 5 (green), where Q has been multiplied by 5000 (blue), and where T_0 is raised to 125 mK (purple). All unmentioned values are at the nominal value for the red fit.

- g_0 (thermal conductance between bolometer and T_0) = 4076 pW K⁻¹
- Q (input power) = 3.0×10^{-5} nW

We demonstrate this in Figure 5.4. The red curve uses the nominal values for the 100 mK data which have been shown previously in this text. We show that the variable range-hopping factor L_{hop} has little effect in the linear IV regime, but a larger one at the inflection point between linear and nonlinear behaviour. When we divide g_0 by 5 in the green curve, we see a lessening of the part of the IV curve and a larger incursion into levelled-off working points as the thermal output to the bath becomes weaker. Increasing the incoming power on the detector by 5, we see an overall downward shift in the voltage of the curve, similarly to the case where an increase of the temperature also results in a downward shift and a longer linear regime (into higher currents), although the effect is more complex (see the actual IV data in the previous section).

5.3 Signal oscillation study

To investigate the effect of stray capacitance, dynamic inductance, and electrothermal coupling, and determine whether it is responsible for the 'decoupling' of the pulse components as described in Part 1 (Introduction), we have developed a simple model for the evolution of a pulse across a bolometer. At t = 0, a perturbation in temperature is translated into a perturbation (pulse) of resistance on the bolometer. We use this pulse to investigate the effect of dynamic conductance, which we described in Chapter 1. We measure V_{Bolo} , assuming it to be constant during each time step. V_{Bolo} is defined as:

$$V_{\text{Bolo}} = V_{\text{Bias}} \cdot R_{\text{Bolo}}(R_{\text{Bolo}} + R_{\text{Bias}}) = Q_s / C_{\text{stray}}$$
(5.6)

where C_{stray} is the stray capacitance and Q_s is the charge. We know that:

$$I_{\text{Bias}} = I_{\text{Bolo}} = \frac{dQ_s}{dt} = \frac{V_{\text{Bias}} - V_{\text{Bolo}}}{R_{\text{Load}}}$$
(5.7)

It then follows that:

$$\frac{V_{\text{Bias}}}{R_{\text{Load}}} - V_{\text{Bolo}} \left[\frac{1}{R_{\text{Load}}} + \frac{1}{R_{\text{Bolo}}} \right] = C_{\text{stray}} \cdot \frac{dV_{\text{Bolo}}}{dt}$$
(5.8)

 V_{Bolo} as a function of time is determined by:

$$\frac{dV_{\text{Bolo}}}{dt} + \frac{V_{\text{Bolo}}}{\tau} = \frac{V_{\text{Bias}}}{\tau'} \tag{5.9}$$

where $\tau = R_{\text{Load}} \cdot R_{\text{Bolo}} / (R_{\text{Bolo}} + R_{\text{Load}}) \cdot C_{\text{stray}}$ and $\tau' = R_{\text{Load}} \cdot C_{\text{stray}}$. Solving Equation 5.10, we take the integral:

$$V_{\rm Bolo} = \int_{t_0}^t \frac{V_{\rm Bias}}{\tau'} - \frac{V_{\rm Bolo}}{\tau} dt$$
(5.10)

which is solvable via:



Figure 5.5. Example results of the oscillation modelling. Keeping all parameters constant except C_{stray} , we show the effect of varying C_{stray} and the oscillations produced by the pulse as it increases.

$$V_{\text{Bolo}}(t) = \sum_{t_i=0}^{t_i=t} \left[\frac{V_{\text{Bias}}}{\tau'} - \frac{V_{\text{Bolo}}(t_i)}{\tau}\right] \Delta t$$
(5.11)

over small time steps Δt . The model takes T_0 , C_{stray} , δT , C_{B0} , and g_0 and calculates the steady state (working point) for the Bolometer, finding the equilibrium point. From there, a ΔT is inserted and translated into a resulting ΔR . Under the assumption that V_{Bolo} is constant during the time step, a loop updates each variable at every time step. τ is calculated at every step with $\tau = R_{\text{Load}} \cdot R_{\text{Bolo}}$ / $(R_{\text{Load}} + R_{\text{Bolo}}) \cdot C_{\text{stray}}$, used to calculate V_{Bolo} using equation 5.10, T_{Bolo} , and R_{Bolo} as a function of time.

5.3.1 Results

We show some sample results in Figure 5.5, where C_{stray} is varied over a few orders of magnitude. We find that as C_{stray} decreases, oscillations and negative components begin to appear in the pulses. Although some of the pulse attributes

are present (specifically the variation in rise and decay times), the model does not produce the characteristic 'response function' we usually see for Bolo 184 (due to the lack of a second 'slow' component), which is the sum of two double exponentials. This is most likely because it contains only one temperature stage, suggesting that the second one (e.g. sapphire layer), which is also coupled to T_0 is necessary for reproducing the characteristic shape.

5.4 Two-component model for Bolo 184

One major limitation of the model described above is that it does not take into account the important role of ballistic phonons, nor the actual energy deposition into the detector. The mechanisms by which an α particle deposits energy into the detector are very different to the mechanisms affecting cosmic ray muons or photons, for example, but the above model used a simple ΔT to describe the energy deposition. Whilst it is a useful tool for examining electro-thermal coupling and dynamic conductance, it is limited in describing the physics of particle energy deposition. We have developed a two-component model for analysing this further, in an effort to reproduce the data features described in the previous chapter. This is done by decoupling the absorber and the sensor layers of the detector; it was initially believed that the variation of the rise time was due to ballistic phonon thermalisation in the absorber disc, whereas the lower layers of the bolometer (the NTD sensor and sapphire mechanical support) are responsible for the bolometer response function.

5.4.1 Description of full model

The two-component has been developed and will be explained here. The first component describes the absorber disc, which has the following properties:

1. The α particle energy is converted locally into ballistic phonons, which are simulated by a Monte Carlo code as a large number of particles.
- 2. Each phonon first propagates at a few km s⁻¹ in the disc, and thermalises either at the bismuth interface with an exponential probability relating to its mean free path, or on the disc border. This process is instantaneous compared to the thermal time constants of the internal parts and connections of the bolometer, and gives an initial temperature profile in the disc.
- 3. The particles (now as heat particles, representing thermal phonons) are propagated over time by a diffusion code.

The output of the disc model is T(t) over the disc centre, the region just above the sensor, demonstrating a dependence on the α particle impact position. This simple 2-dimensional model, as a first trial, is justified by the ratio of length against thickness for the carbon-cismuth structure; in this regime, the absorber is dominated by surface effects [112].

The second component of the model is a standard thermal block function, similar to modelling which has been done for other detectors [116], of the sensor and sapphire, built from the measured or estimated physical parameters of each component in the device. This module gives the transfer function of the bolometer itself, or the pulse response from disc to sensor, thermal link, and cryostat, to explain multiple time constants of the pulses.

Both component outputs are convolved, which allows for the adjustment of model parameters to reproduce data features.

The disc component

The disc model contains two functions: the first for ballistic phonon propagation and thermalisation in a single time-step, and the second for thermal diffusion (with starting locations of each heat particle taken from the output of the ballistic phonon function). The ballistic phonon thermalisation function loops over a large number of particles, N (acting as heat quanta) where $N \approx 100000$. As an input, it takes a starting point (analogous to the α impact point) in x and y between 0 and



Figure 5.6. Output of step 1 of the disc component, showing ballistic phonon thermalisation locations with initial particle impacts at 0%, 50%, and 100% of the total x-axis. The disc border is filled in gray (with particles as semi-transparent red dots) and the thermometer region is filled in white.

1. The disc area is a circle centred around 0,0 with a radius of 1 with arbitrary units.

In the main loop, the position of the first particle in x and y is simply the input impact point. After that, each particle starts from that initial position and draws a random ϕ (displacement angle) and displacement using random numbers. The displacement is taken as a constant λ multiplied by the log of a random number between 0 and 1 to create a probability distribution which decreases as distance from the impact centre increases. In this disc model, we assume that λ is small compared with the disc radius (with $\lambda = 20\% r_{\text{disc}}$).

The loop calculates whether the total displacement of each particle falls outside the border of the disc edge, and places the particle location at the border if it does. Otherwise, the particle lands where it does in x and y as calculated by ϕ and d. Examples of typical results of this loop are shown in Figure 5.6, with α inputs at (0,0) (left), (0.5,0) (middle), and (1,0) (right).

We see in Figure 5.6 that for an α impact point in the centre, most of the particles remain in the centre due to the logarithmic effect on the random displacement. As we begin to increase the distance of the impact point away from the central thermometer, more particles thermalise at the disc border. When the impact point



Figure 5.7. Left: Output of the thermal diffusion function at $t = t_{\text{max}}$ (heat quanta in blue) Right: T(t) curves for particles starting at percentage distances from 0,0 in x.

is at the periphery of the disc, most of the particles begin their lives as thermal phonons on the disc border.

The ballistic phonon function produces x and y coordinates for N particles. The thermal diffusion function takes these coordinates as input, and loops over all particles during each time step. The displacement of the particles is calculated in the same way as the ballistic phonon code, with the exception that instead of being 'caught' at the border, particles are reflected from it and will continue to diffuse in the next time step. The thermometer is taken to be a smaller circle in the centre of the disc, equal to 15% of the total disc radius, calculated based on the ratios between the size of the absorber of Bolo 184 and the size of its NTD Ge thermometer (although the real thermometer is a rectangle rather than a circle).

If the heat particle falls within the thermometer at a given timestep, the temperature (which is written as a function of time, but is added to during each nested particle trajectory) increases. The output of the function are again x and ycoordinates, but also the temperature as a function of time (approximated as the number of particles which pass over the thermometer). We see an example of a typical output in Figure 5.7 (left) - the heat quanta are homogeneously distributed



Figure 5.8. Diagram of the thermal block model. 2 glue layers (grey), 7 NTD Ge sensor legs (purple), 7 sapphire slab legs (blue). A dT is injected into the glue above the sensor (where heat would travel from the absorber). Each arrow is a heat link based on known parameters, scaling with T of the components around it.

after a time t_{max} , regardless of where the particle began. Figure 5.7 (right) shows an example of T(t) (represented here as $N_{\text{particles}}$ at each time step) for several starting points as a percentage of distance from point 0,0 (just above the thermometer). We see that as the distance from 0,0 increases, the rise time is slower, and when the distance is close (or at) 0,0, the temperature shows a fast initial rise time.

Because the thermal function begins after the thermalisation of the ballistic phonons, t = 0 starts with a significant temperature in most impact locations - due to this, the rise-time is not resolved (and all temperature curves begin at T = 0). However, the results of the model are valid insofar as all starting impact points eventually relax to the same temperature (due to homogeneous distribution of the particles after a long enough t), and the model is enough to produce a variation in rise time. The use of the derivative of $N_{\text{particles}}$ should be enough to produce an effective flux which more closely represents the actual temperature in the disc as a function of time.

Thermal block model

The second part of the two-component model is a standard thermal block model, based on the construction of the 'bottom' of Bolo 184 (NTD Ge sensor, sapphire slab, and two glue layers). The germanium and the sapphire have been split into 7 uniform leg segments, the outermost of which is coupled to T_0 . A basic diagram of the model is shown in Figure 5.8.

In this model, each block has a temperature-dependent C_p which is based on known parameters (see Section 5.1) and takes the form $C_p = \text{Coeff}_1 \cdot T$ or $C_p = \text{Coeff}_1 \cdot T + \text{Coeff}_3 \cdot T^3$, depending whether or not the material in question has a T or T^3 -scaling heat capacity. The thermal conductance between each block, G, is based again on known or estimated coefficients (known parameters coming from N. Coron's work), scaling with T^3 relationships and taking the form:

$$G_{i} = G_{\text{coeff}} \cdot \left(\frac{T_{i} + T_{(i+1)}}{2}\right)^{3}$$
(5.12)

where *i* is the block in question and i + 1 is its nearest neighbour in the chain. Before looping over time, the temperature of all components is set to T_0 . The code loops over a large number of time steps and calculates each leg's $C_p(T)$ and each link's G(T). The δT of each block is solved for taking into account the *G* of its links, its C_p , and the temperature of its nearest neighbour(s). For blocks with only one *G* and only one neighbour (the top glue layer, for example):

$$dT_i = \frac{G_{(i \leftrightarrow i+1)} \cdot (T_{(i+1)} - T_i)}{C_i}$$
(5.13)

for blocks with multiple neighbours:

$$dT_{i} = \frac{G_{(i\leftrightarrow i+1)} \cdot (T_{(i+1)} - T_{i})}{C_{i}} - \frac{G_{(i\leftrightarrow i-1)} \cdot (T_{i} - T_{(i-1)})}{C_{i} \cdot dx}$$
(5.14)

where dx is the total proportion of the slice in question (so 1/7). For the NTD sensor, we take into account the heating arising from the Joule power, as well as its 3 neighbours:



Figure 5.9. Results of the thermal block model, showing T(t) for the sensor and the 7 sensor legs. Cosmic ray dT is injected at ≈ 0.13 s.

$$dT_{\text{sens}} = G_{(\text{sens}\leftrightarrow\text{leg1})} \cdot (T_{\text{leg1}} - T_{\text{sens}}) - G_{(\text{glue}\leftrightarrow\text{sens})} \cdot (T_{\text{sens}} - T_{\text{glue-up}}) -G_{(\text{sapp0}\leftrightarrow\text{sens})} \cdot (T_{\text{sens}} - T_{\text{glue-down}}) + R_{\text{Bolo}} \cdot I^2 / C_{\text{sens}}$$
(5.15)

the block temperature is then found by multiplying each dT by the step size dt at each time step. After a large number of time steps, the Joule power eventually normalises to its nominal value, after which we inject a dT directly into the upper glue layer, in one time step only. This dT represents the cosmic ray, and the form of the pulse in the sensor is our bolometer's response function.



Figure 5.10. Sensor temperature after the dT pulse.

To produce an example, we will begin with the starting parameters where $T_0 = 100 \text{ mK}$, $V_{\text{bias}} = 400 \text{ mV}$, and $R_{\text{Load}} = 40 \text{ M}\Omega$ (matching our final Bolo 184 measurements). We show the results over all time steps in Figure 5.9 for the sensor (T_{sens}) and the 7 sensor legs. We can see that the Joule power brings the legs from T_0 to a steady temperature which stabilises at about 0.02 s. The thermal impulse is injected at about 0.13 s.

We find a two-component exponential decay with an instantaneous rise time and a very fast 'first' component, and a long 'second' component. This two-component finding is consistent with what we see in the data pulses, although it must be noted that this specific result is our 'response function' rather than what we expect from pulses themselves; we surmise that the pulse rise time and the variation of the rise time and amplitudes is, again, an effect of the particle position. In the case of this response function, we have only an instantaneous dT, so we expect that this output is the bolometer's response function (response to a delta pulse) only.

We note that in order to produce the characteristic 'fast' and 'slow' peaks, we must assume a rather large C_p for the glue layers; without this, we find only a simple single-exponential decay. The exact C_p and thickness of the epoxy between the absorber and the sensor is not known as precisely as the rest of the thermal parameters for the model, but we have seen (from Coron's work in Figure 5.1) that the C_p of the glue is the dominant one, especially in temperatures above 100 mK. The glue turns out to be one of the larger factors in producing the characteristic pulse shape seen across this work.

5.4.2 The convolution

It was initially believed that the convolution of the two components above could reproduce pulses which had the attributes of the data pulses, i.e.:

- Rise time which varies with particle position
- Relationships between a thermal and thermal amplitudes as seen in the data
- 'Sharing' of the two-component integrals depending upon the particle position

The block model provides the transfer function of the system to a fast dT of the temperature of the disc. The disc model provides the T(t) of a disc, disconnected from the remainder of the bolometer. This T(t) is effectively the integral of the heat propagating toward the centre of the disc:

$$T(t) = \int_{-\infty}^{t} \frac{dT}{dt}(t')dt'$$
(5.16)

and the convolution of both outputs should give us the temperature of the sensor:

$$T_{\rm sens}(t) = \int_{-\infty}^{\infty} \frac{dT}{dt}(t')dt' \cdot f_{\rm transfer}(t-t')dt'$$
(5.17)

where f_{transfer} is the response function, i.e. the output of the thermal block model.

Results

Results of the convolution of the disc model results shown in Figure 5.7 and the block model results shown in Figure 5.10 are shown in Figure 5.11 (left). We see that the pulses maintain many of the features of both the impulse response



Figure 5.11. Left: The convolved output at various impact distances; Right: The convolved output at various distances, zoomed into the rise time.

function, but are attenuated by the thermal profile of the disc model. However, we do not find the changing rise times we had hoped to produce with this convolution, which is more clear in Figure 5.11 (right). The variation in distance from the disc model mainly appears to impact the amplitude of the convolved pulse, as well as the decay of the pulse (creating an increase in signal after the initial decay for far-away pulses, and a negative component in the initial decay in the closest pulse). Because the convolution relies on the assumption of zero thermal coupling between the disc and sensor, the slow increase in signal will always be present for far-away impacts.

This effect becomes even more pronounced when we fit to the pulse using the typical double-exponential function from the first sections of Chapter 2. The fit is not in good agreement with the expected shape, due to the extra positive (far-away hits) or negative (close hit) component which is present in the convolution, which can be seen in the residuals in Figure 5.12. The convolution method assumes that the components are disconnected (zero coupling) and that we can treat their thermal effects separately; this is likely to be an oversimplification, and may contribute to the results we see^{*}. In reality, the heat in the disc is likely to be strongly coupled to the sensor, in a much larger area than the geometrical area of the sensor. For

^{*}We see in Section 5.6 that the coupling might indeed be larger than initially expected.



Figure 5.12. Residuals of the simulated pulse fits.

this reason, treating the two models separately does not produce the correct results.

Whilst this is a disappointing result, it serves the purpose of demonstrating that something is missing in the 'big picture' of the movement of energy in this bolometer. A functional model which fully describes these pulses will need to take thermal propagation into account, whilst making use of the correct things coming from this model (e.g. the response function).

5.5 Signal oscillation study: revisited

A two-level bolometer simulation should allow us to examine the effects of electrothermal coupling and stray capacitance in this detector system. In this updated model, the sensor block is directly attached to the heatsink through a thermal conductance, and there is an intermediate stage which is also linked to the sensor and the intermediate stage (analogous to the sapphire layer). We find the starting bolometer working point from the T_0 , V_{Bolo} , V_{Bias} , and R_{Load} . We find the equilibrium point where $P_{\text{Joule}} = P_{\text{Conduction}}$, which is described as:

$$P_{\text{Conduction}} = g_{(\text{Bolo}\leftrightarrow\text{bath})} \cdot (T_{\text{Bolo}}^4 - T_0^4) + g_{(\text{int}\leftrightarrow\text{Bolo})} \cdot (T_{\text{Bolo}} - T_{\text{int}})$$
(5.18)

where $g_{\text{int}\leftrightarrow\text{Bolo}}$ is the thermal link between the intermediate stage and the bolometer, and $g_{(\text{Bolo}\leftrightarrow\text{bath})}$ is the thermal link between the bolometer and the thermal bath. The T⁴ dependence of $g_{(\text{Bolo}\leftrightarrow\text{bath})}$ comes from a G with a T³ conductance integrated along the link. For a starting zeroed thermal power between the intermediate stage and the bolometer (P_{int}) :

$$P_{\text{int}} = (g_{(\text{int}\leftrightarrow\text{Bolo})} \cdot (T_{\text{Bolo}} - T_{\text{int}}) - g_{(\text{int}\leftrightarrow\text{bath})} \cdot (T_{\text{int}} - T_0) = 0$$
(5.19)

The temperature of the intermediate stage is then found by:

$$T_{\rm int} = \frac{g_{\rm (int\leftrightarrow Bolo)} \cdot T_{\rm Bolo} + G_{\rm (int\leftrightarrow bath)} \cdot T_0}{g_{\rm (int\leftrightarrow Bolo)} + G_{\rm int\leftrightarrow bath}}$$
(5.20)

giving a Joule power of:

$$P_{\text{Joule}} = g_{(\text{Bolo}\leftrightarrow\text{bath})} \cdot (T_{\text{Bolo}}^4 - T_0^4) + \frac{g_{(\text{int}\leftrightarrow\text{Bolo})} \cdot g_{(\text{int}\leftrightarrow\text{bath})}}{g_{(\text{int}\leftrightarrow\text{Bolo})} + g_{(\text{int}\leftrightarrow\text{bath})}} \cdot (T_{\text{Bolo}} - T_0) \quad (5.21)$$

An initial loop over temperature calculates T_{Bolo} , R_{Bolo} , V_{Bolo} , and I_{Bolo} as a function of T. The Joule power on the bolometer is found from $P = V_{Bolo}^2 / R_{Bolo}$. The temperature of the intermediate stage is calculated from equation 5.20, and the total thermal link g from:

$$g = g_{00} \cdot (T_{\text{Bolo}}^4 - T_0^4) + g_{(\text{int}\leftrightarrow\text{Bolo})} \cdot (T_{\text{Bolo}} - T_{\text{int}})$$
(5.22)

where g_{00} is the coefficient of thermal conductance between the bolometer and T_0 . The loop continues until the total conduction is greater than the Joule power, stopping at the working point of the bolometer. At the working point, a ΔT is

injected into T_{Bolo} and the new R_{Bolo} is calculated. The system contains the same filters as exist in the amplifier readout chain of the experiment, with a R_{filter} of 20 M Ω , giving a time constant $\tau_{\text{filter}} = R_{\text{filter}} \cdot C_{\text{stray}}$ where C_{stray} is the stray capacitance on the output. The typical signal rise time is $\tau' = R_{\text{Load}} \cdot C_{\text{stray}}$.

Looping over time, we take an additional time constant which accounts for all the resistances in the system:

$$\tau = \left(\frac{1}{R_{\text{Load}}} + \frac{1}{R_{\text{Bolo}}} + \frac{1}{R_{\text{filter}}}\right)^{-1} \cdot C_{\text{stray}}$$
(5.23)

and the various time constants attenuate the signal via the following mechanism:

$$V_{\text{Bolo}}(t_i) - V_{\text{Bolo}}(t_{(i-1)}) = V_{\text{Bolo}}(t_{(i-1)}) + \left(\frac{V_{\text{Load}}}{\tau'} + \frac{V_{\text{Bolo-WP}}}{\tau_{\text{filter}}} - \frac{V_{\text{Bolo}}(t_{(i-1)})}{\tau}\right) dt$$
(5.24)

where $V_{\text{Bolo-WP}}$ is the bolometer voltage at the working point which is stored in memory before the ΔT injection. These and all other parameters are updated at each (small) dt. The signal is produced by subtracting V_{Bolo} from $V_{\text{Bolo-WP}}$. The final output of the code is to produce a signal V(t), which should allow us to reproduce the electro-thermal effects seen in the early double-peaked pulses, and how this behaviour changes at different temperatures.

5.5.1 Results and comparison with data

We will compare the results of this simulation with a short dataset of pulses taken at 100 mK. V_{bias} was 1 V for this experiment, so the pulses had the 'double-peaked' behaviour we saw in the first experiments. We surmise that this relates to the effect of stray capacitance and electro-thermal coupling. If this is true, we should be able to reproduce the same behaviour in this two-level simulation.

We look first at the pulse with the highest amplitude (the case which is the



Figure 5.13. Simulated pulse from the two-level thermal bolometer simulation (blue), with equal amplitude to the maximum amplitude pulse of a 100 mK 1 V $V_{\rm bias}$ dataset (red).

most similar to a direct ΔT in the sensor), which would indicate that the 'thermal' component is small. Since this simulation does not contain any thermal input from anything other than a sudden ΔT spike (and is missing input from an absorber), the pulse with the highest amplitude is most likely to be a very similar case to what we simulate.

We show a comparison between the measured and simulated pulses in Figure 5.13. We find that the simulation quantitatively reproduces the shape of the largest-amplitude pulse, for $V_{\text{bias}} = 1 \text{ V}$, $R_{\text{Load}} = 40 \text{ M}\Omega$, $\Delta T = 0.014 \text{ K}$, $g_{00} = 320 \text{ pW K}^{-1}$, $C_{\text{stray}} = 0.15 \text{ nF}$, $g_{(\text{int}\leftrightarrow\text{Bolo})} = 9.5 \text{ pW K}^{-1}$, and $g_{(\text{int}\leftrightarrow\text{bath})} = 0.2 \text{ pW K}^{-1}$.

We would expect that for smaller pulses, the absence of position dependency and the usual complexity of the bolometer would make it more difficult to reproduce the pulse shape using this simulation. To verify this, we choose a mid-amplitude pulse of 2 V, and check whether the simulation can reproduce its attributes. We expect the thermal propagation effects to be more significant in this pulse, and the simulation may have difficulty in reproducing the features of this (especially in what is normally thought of as the 'thermal' part of the pulse).



Figure 5.14. Simulated pulse from the two-level thermal bolometer simulation (blue), with equal amplitude to a 2 V pulse of a 100 mK 1V V_{bias} dataset (red).

We show that this pulse, shown in Figure 5.14 (left), does not have the negative dip we have seen in the 3V pulse in Figure 5.13. The simulated pulse (right) appears to reproduce its overall shape, with a slightly slower return to its second amplitude. In the real pulse, the signal oscillates after the fast thermal energy input into the sensor, but the oscillation relaxes during the time where the remaining thermal energy in the absorber arrives at the sensor, giving it a larger second 'thermal' component. In the simulation, the second component is simply left-over heat in the sensor (as there is no absorber coupled to the sensor in this case).

Due to the complexity of balancing many free parameters, a χ^2 minimisation routine was used to fit to these pulses. The pulse could not immediately be fit to using the parameters we have found above which produce the 3V case. In order to resolve the 2V pulse, some non-physical parameter values have emerged, e.g. R_{Load} increasing to 56.8 M Ω (which is not compatible with reality) which was locked to its actual value of 40 M Ω for the largest pulse fitting. This supports the idea that this simulation is best suited to pulses which have a minimal thermal propagation component.



Figure 5.15. Simulated pulse from the two-level thermal bolometer simulation (right), with equal amplitude to a 1.5 V pulse of a 100 mK 1V V_{bias} dataset (left).

We verify this once more using a pulse with with a lower amplitude of 1.5 V.

As we expect, the simulation is less able to reproduce the behaviour of a loweramplitude pulse, where position effects likely come into play (see Figure 5.15). The shape is still qualitatively similar, but the simulation is unable to render the precise depth of the first 'dip' between the two peaks. In this case, the χ^2 minimisation again resorted to less physical parameter values, e.g. increasing R_{Load} to 65.89 M Ω . As the fitting algorithm needs to resort to nonphysical parameters to reproduce smaller-amplitude pulses (which did not need to be increased to fit to the largest-amplitude pulse), this indicates that the thermal propagation effects are still significant under this regime, and this simplified simulation is unable to account for them.

However, we have shown that the double-peaked behaviour in the high V_{bias} 100 mK data set is most likely to be due to oscillations produced by the combination of electro-thermal coupling and stray capacitance on the bolometer electronics.

5.5.2 Discussion

The two-block model is much simpler than the two-component model, and produces output which is far more similar to the pulses seen in the data. It has the drawback of not having any input from the disc, and so it is incapable of producing some vital pulse attributes, e.g. the rise time varying as a function of the α particle impact distance, or the energy-sharing between 'ballistic' and 'thermal' components. It does have a more accurate and complicated representation of the mechanisms of electro-thermal coupling, and we surprisingly find that this effect alone can account for many attributes of the once 'mysterious' double-peaked 100 mK data. This allows us to reasonably conclude that the component decoupling seen at high V_{bias} is a nonphysical systematic effect resulting from the high bias current and the interplay between electro-thermal coupling and the stray capacitance of the readout circuit.

5.6 Reflective absorber model

In our earlier work described here, we have always assumed that ballistic phonons thermalise at the disc borders or in the nearest Bi interface they encounter in the absorber, and that their thermalisation distance is described by an exponential probability relating to their mean free path. We will now examine whether a reflective phonon schema, also relating to a mean free path, can reproduce the defining characteristics of these pulses. The main characteristics we will look at are the energy-sharing between the fast and slow pulse components. In particular, we will return to one result of the 200 mK measurements described in Section 2.1.8 (page 80), where we show the results of the fast vs. slow split integrals for the pulses.

We show the results here again in Figure 5.16. As a reminder, the 200 mK case was the simplest possible to interpret, as there were no extra branches. We see only linear energy-sharing between the 'ballistic' and 'thermal' components, distributed in the 5.4 MeV line.



Figure 5.16. The ratio of the split athermal and thermal integrals for the 200 mK data set, using the conventional double exponential analysis.

5.6.1 Description of the model

The model is a Monte-Carlo style model in which a large number of α particles (evenly distributed across the disc) propagate as a larger amount of ballistic phonons. We take a disc of equal size to the diamond/bismuth absorber ($r_{\text{disc}} = 1.75 \text{ mm}$). For each α particle, we generate a random ρ with a linear probability to define a random position between the centre of the disc and its perimeter. We define a ϕ with a flat probability between 0 and 2π , and we determine the α particle starting location using that ρ and ϕ .

A Monte-Carlo code loops over all ballistic phonons belonging to that α particle (10000 phonons per α). For each phonon, we choose a random θ_{phonon} and ρ_{phonon} , where ρ_{phonon} is a function of the mean free path λ in the form:

$$\rho_{\rm phonon} = -\lambda \cdot \sin(\theta_{\rm phonon}) \cdot \log(\text{random}) \tag{5.25}$$

where λ , in contrast to the first disc model described in Section 5.4.1, is now assumed to be much larger than the disc size ($\approx 3 \times r_{\text{disc}}$). Each phonon also draws a random ϕ_{phonon} between 0 and 2π as for the α particle. The phonon position is iterated upon by adding the phonon $\rho_{\text{phonon}} \cdot \cos(\phi_{\text{phonon}})$. The simulation takes a sensor radius r_{sens} - the actual sensor is 800 μ m \times 260 μ m in size, so we would assume the size of the disc in good thermal contact with the sensor to be roughly this size (or larger, depending on the strength of the thermal coupling). r_{sens} is taken as a free parameter in order to probe the simulation results, and the result most similar to the data is found for an r_{sens} of 600 μ m. If the phonon's new distance is less than r_{sens}^2 , the phonon counts toward the count of the total number of phonons arriving in the area with good thermal contact with the sensor, i.e. having a strong 'ballistic' pulse.

If the phonon falls outside r_{disc} , it reflects off the border. We find the square of its movement distance, $d^2 = r_{\text{disc}}^2 - \rho^2$, and translate the coordinates of its movement using $b' = x \cdot \cos(\phi) + y \cdot \sin(\phi)$. We find the new distance travelled by the phonon, $s = -b' + \sqrt{b'^2 + d^2}$. If it is less than ρ_{phonon} , we calculate the x and y locations where the phonon intersects with the border:

$$x_{\text{border}} = x_{\alpha} + s \cdot \cos(\phi_{\text{phonon}}) y_{\text{border}} = y_{\alpha} + s \cdot \sin(\phi_{\text{phonon}}) \tag{5.26}$$

We define the ϕ_{border} of the newly-reflected phonon by taking the arctangent of the x and y border interaction locations, and invert the angle using $\phi_{\text{reflect}} = 2 \cdot \phi_{\text{border}} - \phi_{\text{phonon}} + \pi$. We subtract s from ρ_{phonon} and use it to find the translated phonon location:

$$x_{\text{trans}} = x_{\text{border}} + \rho_{\text{phonon}} - s \cdot \cos(\phi_{\text{reflect}})$$
(5.27)

$$y_{\text{trans}} = y_{\text{border}} + \rho_{\text{phonon}} - s \cdot \sin(\phi_{\text{reflect}})$$
 (5.28)

The new distance is calculated in the usual way using $d = \sqrt{x_{\text{trans}}^2 + y_{\text{trans}}^2}$. We check again whether $d^2 < r_{\text{sens}}$, and add it to the total number of ballistic phonons caught in the central radius if it is. If not, the process is repeated if the new distance of the phonon falls outside the edges of the absorber again. The phonon continues to reflect off the borders in this way until it is either caught within r_{disc} or it thermalises in an area which is $> r_{\text{disc}}$ but $< r_{\text{absorber}}$.

5.6.2 Results

This model allows us to count the number of ballistic phonons arriving in the central sensor area, giving us a simulated distribution which should be similar to the fast 'ballistic' amplitude, A_1 . It also allows us to image the thermalisation patterns of ballistic phonons, so we can image the final places in which a ballistic phonon rests and deposits all of its energy. We will show both of these results here.



Figure 5.17. Left: Histogram of the 'fast' amplitude from the 200 mK data set, compared with Right: the simulated ballistic amplitude distribution from the reflective absorber model.

Simulated ballistic phonon amplitude

We compare the number of ballistic phonons thermalised in the central sensor area, analgous to a the fast 'ballistic' amplitude in the pulses, to the distribution of the first amplitude in the 200 mK data, shown in Figure 5.17. We note that the numerical results (which represent the ratio of the number of phonons in the central sensor vs. the total number of phonons) are normalised in the simulation, but that the *shape* of the distribution (which is what we are trying to reproduce) qualitatively reproduces that of the first amplitude, with no peak at zero and with a small buildup of events at high 'amplitudes' coming from far-away ballistic phonon reflection on the borders.

Simulated ballistic/thermal ratio

Finally, we compare the ratio of the simulated 'ballistic' and 'thermal' integrals produced by the simulation (see Figure 5.18) with that in the 200 mK data set shown above. We note, again, that the numerical values are normalised, but the distribution is identical to the data in terms of the proportion between captured



Figure 5.18. Simulated ballistic vs. thermal integrals in the reflective absorber model.

and non-captured ballistic phonons.

Phonon thermalisation patterns

We have shown some thermalisation patterns already, under the assumption that the phonons thermalise at the disc border (see Figure 5.6, page 184). The behaviour is quite different now that the phonons reflect off the border.

We see the difference in Figure 5.19, where there are clear areas where the phonons deposit their energy the most often, which change based on where the α particle began in the disc. These images are not overwhelmingly useful unto themselves, but they do show that ballistic phonons, under these kinds of assumptions, tend to have 'ray-like' qualities. There are some similarities between this behaviour and that of ray-tracing results.



Figure 5.19. Four random ballistic phonon thermalisation patterns for $N_{\text{phonon}} = 10000$, for one α particle. Blue dots are the places in the disc where the ballistic phonon has deposited its energy.

5.6.3 Discussion

This model appears to reproduce the proportions of captured ballistic phonons in an area in direct thermal contact with the sensor, representing the distribution of pulse heights in the data as a function of particle position. We find the best results with a r_{sens} of 600 μ m, which is coherent with the known sensor size of 800 \times 260 μ m.

This simulation is predicated upon the idea that ballistic phonons reflect off the walls of the absorber disc, rather than thermalising in them. The reflective properties are the only way to resolve an amplitude distribution which does not peak at 0 and which does not have a large peak which decreases very quickly.

We will now compare the 'reflective mean free path' line of reasoning with another possibility for the way ballistic phonons behave in this absorber, which is a geometrical approximation.

5.7 Geometrical ballistic phonon model

The main open question is whether ballistic phonon thermalisation depends on a distance relating to the mean free path λ , or whether the distance is a simple geometrical law, i.e. the proportion of ballistic phonons falling on the central sensor region depends only on whether it has a geometrical line-of-sight to the central region after reflecting on the disc borders (analogous to ray tracing in optics). We test this by producing a model similar to the last one, but where the ρ has been replaced with a $\theta = r_{\text{disc}} \cdot \sqrt{\text{random}}$ and an azimuth between 0 and 2π instead of an exponential distance with a dependence on a mean free path. Similarly to the last case, the x and y locations of each phonon are continuously updated, with an additional component in z, and when their $d = \sqrt{x^2 + y^2}$ is $> r_{\text{disc}}$, they are reflected back into the disc. At each reflection on the border or the bottom of the disc (but not the top of the diamond, which is polished and assumed to be 'mirror-like'), the phonon is assumed to lose a proportion of energy into the disc. Each phonon continues to propagate until it loses all of its energy, or until it makes 1000 reflections. The code then keeps track of the total amount of energy deposited inside the central radius relative to outside of it.

There are a few options for how much energy a phonon loses into the disc with each impact: the energy loss per reflection, ϵ , can be a flat amount $E_{dep} = \epsilon$; an energy deposition which is maximum when parallel to the Bi layer (bottom of the disc) where $E_{dep} = \epsilon \cdot (1 + \cos^2(\theta)) / 2$; energy deposition which favours perpendicularity with the Bi layer $E_{dep} = \epsilon \cdot (\cos^2(\theta))$. The mechanisms of phonon energy loss into the diamond crystal may be anisotropic due to crystal lattice structure, the exact mechanics of which are not presently available; to this end, we will attempt several possibilities, and we will examine each of these, denoting them 'flat', 'absorption', and 'perpendicularity' (respectively).

5.7.1 Results

We will compare the results of this model in the same fashion as the results of the reflective absorber model, because the models are similar and they produce the same sets of results.

Simulated ballistic phonon amplitude

Comparing the simulated amplitudes with those from the data, as we have done previously, we find in Figure 5.20 that the shape of the distribution is again similar for a r_{sens} of 600 μ m. The numerical value (non-normalised in this case) represents the ratio of energy distributed inside vs. outside r_{sens} . The absorptive and perpendicular distributions appear to be very similar, and produce output which more closely resembles the actual amplitude distribution of the data; the flat energy deposition is slightly too peaked.

The relationship between the 'ballistic' and 'thermal' energies deposited in the sensor area is identical to the case of the reflective absorber model, so we will not discuss it here. As a result, the numerical value of the simulated amplitudes has



Figure 5.20. Simulated ballistic phonon amplitudes from the geometrical approximation using $r_{\text{sens}} = 600 \ \mu\text{m}$ with *Left/blue*: absorption law E_{dep} ; *Centre/green*: E_{dep} with perpendicularity law; *Right/pink*: flat E_{dep} .

not been normalised and may be different to the result shown from the reflective absorber model.

Phonon thermalisation patterns

The phonon thermalisation patterns for this model are very different to the last case, with some of the phonon paths containing many reflections (Figure 5.21). When $E_{dep} = \epsilon \cdot (\cos^2(\theta)) / 2$, we see far fewer reflections, and many more instances of energy deposition along a single line. The $E_{dep} = \epsilon \cdot (1 + \cos^2(\theta)) / 2$ traces have similar. There is not a huge amount of information available in the phonon traces, but they are nonetheless interesting.

5.7.2 Discussion

We have compared the results of a mean free path law (reflective absorber model) with a geometrical law for ballistic phonon propagation. Both results reproduce the distribution of the fast 'ballistic' amplitude seen in the data. The reflective absorber model produces a simple exponential decay which then rises again to a second peak at high simulated amplitudes. The three geometrical laws also produce similar results, with the energy schemas preferring shallow angles relative to the bismuth, or



Figure 5.21. Three random ballistic phonon thermalisation patterns for $N_{\rm phonon} = 1$, for one α particle. Dots are locations of phonons which have deposited some of their energy, lines are their paths as they reflect, and red stars are the α particle impact position. *Top/blue*: $E_{\rm dep} = \epsilon \cdot (1 + \cos^2(\theta)) / 2$; *Centre/green*: $E_{\rm dep} = \epsilon \cdot (\cos^2(\theta))$; *Bottom/pink*: flat $E_{\rm dep}$.



Figure 5.22. The circuit diagram simulated in the Joule pulsing model.

the scheme preferring angles parallel to the bismuth, producing the most data-like results compared with an energy deposition which is not angle-dependent.

Both of these models only work when one accounts for phonon reflection on disc boundaries. Our previous two-component model, which had assumed that phonons thermalise at the border of the disc, did not account for this. From this, we can infer that the previous model of assuming that ballistic phonons thermalise in the border might be incorrect.

5.8 Joule pulsing model

In Chapter 4, we modified the Bolo 184 experiment to pulse the Joule power of the bolometer to reveal its transient properties. We had some unexpected results (particularly the long time constant present in the low V_{bias} pulses), which require further investigation. To this end, we have modified the two-block bolometer model discussed above to account for a ΔI through a capacitor, the same as we have done in the experiment. This section discusses that modelling and its results.

5.8.1 Description of model

This model is a modification of the two-block bolometer model from Section 5.5. The equivalent circuit is shown in Figure 5.22. We solve for the working point of the bolometer given the starting parameters in the usual way. Once the simulated device is in a steady state, we inject a small current ΔI through $C_{\text{PulseInput}}$ by ramping V_{Pulse} with a constant slope.

$$\Delta I = C_{\text{PulseInput}} \cdot \left(\frac{dV_{\text{Pulse}}}{dt} - \frac{dV'_{\text{Bias}}}{dt}\right)$$
(5.29)

This extra current is shared between the battery side through the small added resistance (13.35 k Ω), and the bolometer load chain with the cable capacitance C_{input} . So the sum of the currents I_{Load} (the current in the load resistor), I_{Battery} (the current across R_{Poten}), I_{Stray} (the current across the stray input capacitance C_{Cinput}), and ΔI is null:

$$0 = I_{\text{Load}} + I_{\text{Battery}} + I_{\text{Stray}} + \Delta I \tag{5.30}$$

 $V'_{\rm Bias}$ computed on the three branches gives:

$$V'_{\text{Bias}} = R_{\text{Load}} \cdot I_{\text{Load}} + V_{\text{Bolo}} = V_{\text{Bias}} + R_{\text{Poten}} \cdot I_{\text{Battery}} = \int \frac{I_{\text{Stray}}}{C_{\text{input}}} dt \qquad (5.31)$$

Hence:

$$I_{\text{Load}} = \frac{V'_{\text{Load}} - V_{\text{Bolo}}}{R_{\text{Load}}}$$
(5.32)

$$I_{\text{Battery}} = \frac{V'_{\text{Load}} - V_{\text{Load}}}{R_{\text{Poten}}}$$
(5.33)

$$I_{\text{Stray}} = C_{\text{input}} \cdot \frac{dV'_{\text{Load}}}{dt}$$
(5.34)

On the bolometer side, there are two branches. The variations of the capacitance C_{output} loading gives:

$$\frac{dV_{\rm Bolo}}{dt} = \frac{I_{\rm Load} - I_{\rm Bolo}}{C_{\rm output}}$$
(5.35)

which gives the self-consistent equation for V_{Bolo} :

$$V_{\rm Bolo} = \int \frac{R_{\rm Bolo} \cdot I_{\rm Load} - V_{\rm Bolo}}{R_{\rm Bolo} \cdot C_{\rm output}} dt$$
(5.36)

removing I_{Load} through Equation 5.32 gives

$$V_{\rm Bolo} = \int \frac{V_{\rm Load}'}{R_{\rm Load} \cdot C_{\rm output}} - \frac{V_{\rm Bolo}(R_{\rm Bolo} + R_{\rm Load})}{R_{\rm Bolo} \cdot R_{\rm Load} \cdot C_{\rm output}} dt$$
(5.37)

The sum condition (5.30) on currents reads:

$$\frac{V_{\text{Load}}' - V_{\text{Bolo}}}{R_{\text{Load}}} + \frac{V_{\text{Load}}' - V_{\text{Load}}}{R_{\text{Poten}}} + C_{\text{input}} \cdot \frac{dV_{\text{Load}}'}{dT} - C_{\text{PulseInput}} \cdot \left(\frac{dV_{\text{Poten}}}{dt} - \frac{dV_{\text{Load}}}{dt}\right) = 0$$

$$= 0$$
(5.38)

which gives a first order differential equation for V_{Load} coupled to V_{Bolo} , put into the self-consistent integral form:

$$V_{\text{Load}}' = \int \frac{V_{\text{Load}}}{R_{\text{Poten}} \cdot (C_{\text{input}} + C_{\text{PulseInput}})} + \frac{C_{\text{PulseInput}}}{C_{\text{input}} + C_{\text{PulseInput}}} \cdot \frac{dV_{\text{Pulse}}}{dt} - \frac{V_{\text{Load}}' \cdot (R_{\text{Poten}} + R_{\text{Load}})}{(C_{\text{input}} + C_{\text{PulseInput}}) \cdot R_{\text{Poten}} \cdot R_{\text{Load}}} + \frac{V_{\text{Bolo}}}{R_{\text{Load}} \cdot (C_{\text{input}} + C_{\text{PulseInput}})} dt$$
(5.39)

From the equilibrium starting point, we simulate an injected current ΔI by a constant value of dV_{Pulse}/dt (different from 0). We then get, from the differential version of Equation 5.37 and Equation 5.8.1, the variation of V'_{Load} and V_{Bolo} for each time step.

After this, at each time step, the Joule power $(V_{\text{Bolo}}^2 / R_{\text{Bolo}})$ is calculated, as is thermal conductance in the usual way:

$$g(T, t_i) = g_{\text{(Bolo\leftrightarrow bath)}} \cdot (T_{\text{Bolo}}^4(t_{i-1}) - T_0^4) + g_{\text{(Bolo\leftrightarrow int)}} \cdot T_{\text{Bolo}}^3(t_{i-1}) \cdot (T_{\text{Bolo}}(t_{i-1}) - T_{\text{int}}(t_{i-1}))$$
(5.40)

The heat capacity of the bolometer and the intermediate level are found via:

$$C_{\text{Bolo}} = C_{\text{Coeff-Bol}} \cdot T_{\text{Bolo}}(t_{i-1}) \tag{5.41}$$

and

$$C_{\text{int}} = C_{\text{Coeff-int}} \cdot T_{\text{int}}(t_{i-1}) \tag{5.42}$$

(respectively). $C_{\text{Coeff-int}}$ is the heat capacity coefficient of the intermediate level, and $C_{\text{Coeff-Bol}}$ is the heat capacity coefficient of the bolometer, and both are set as constant. We then find the flux through the intermediate level:

$$dT_{\rm int}(T, t_i) = g_{\rm (bolo\leftrightarrow int)} \cdot T^3_{\rm Bolo}(t_{i-1}) \cdot [T_{\rm Bolo}(t_{i-1}) - T_{\rm int}(t_{i-1})] -g_{\rm (int\leftrightarrow bath)} \cdot T^3_0 \cdot (T_{\rm int}(t_{i-1}) - T_0)$$
(5.43)

and we update the bolometer temperature via:

$$T_{\text{Bolo}}(t_i) = T_{\text{Bolo}}(t_{(i-1)}) + \frac{(P_{\text{Joule}}(t_i) - g)}{C_{\text{Bolo}}(t_i)} \cdot \Delta t$$
(5.44)

where g is the thermal conductance and is defined as:

$$g = g_{00} \cdot (T_{\text{Bolo}}(t_{i-1})^4 - T_0^4) + g_{\text{Coeff(bolo\leftrightarrow int)}} \cdot T_{\text{Bolo}}(t_{i-1})^3 (T_{\text{Bolo}}(t_{i-1}) - T_{\text{int}}(t_{i-1}))$$
(5.45)

where g_{00} and $g_{\text{Coeff(bolo\leftrightarrow int)}}$ are the thermal conductance coefficients between the sensor and the bath, and between the sensor and the intermediate stage (respectively).

The temperature of the intermediate stage is found via:

$$T_{\text{int}}(t_i) = T_{\text{int}}(t_{i-1}) + g_{\text{Bi}} \cdot T_{\text{Bolo}}(t_{i-1})^3 (T_{\text{Bolo}}(t_{i-1}) - T_{\text{int}}(t_{i-1}))$$
$$-g_{\text{Coeff}(\text{int}\leftrightarrow\text{bath})} \cdot T_0^3 \cdot \frac{(T_{\text{int}} - T_0)}{C_{\text{int}}} \cdot \Delta t$$
(5.46)

where $g_{\text{Coeff(int}\leftrightarrow\text{bath})}$ is the coefficient of thermal conductance for the link between T_0 and the intermediate stage. We then recalculate the bolometer R(T) in the usual way. This code loops over time, saving the signal as:

$$S_{\text{Bolo}} = -(V_{\text{Bolo}} - V_{\text{Load}}) \cdot G_{\text{exp}}$$
(5.47)

where G_{exp} is the experimental gain (200) and S_{Bolo} is multiplied by 1000 to get an output in mV.

We note that this method of solving for two coupled first-order differential equations has a solution consisting of a second-order differential equation. To solve via integration, iterating over a small Δt , depends on very small time steps ($\approx 10^{-7}$ s) to limit divergences. Furthermore, certain parameter windows can produce oscillating solutions which can amplify with time. Solving for the unknown parameters in the simulation is therefore a matter of trial and error.

5.8.2 Results

Setting the parameters of the simulation to be equal to that in the simulated circuit in Figure 5.22, we have a few parameters with unknown values, specifically dV_{Pulse}/dt (mostly affecting the amplitude), $C_{\text{Coeff-Bol}}$ (heat capacity coefficient of the bolometer), $C_{\text{Coeff-int}}$ (heat capacity coefficient of the intermediate stage), $g_{\text{Coeff(bolo\leftrightarrow int)}}$ (thermal conductance coefficient between the bolometer and the intermediate stage), and $g_{\text{Coeff(int\leftrightarrow bath)}}$ (thermal conductance coefficient between the between the intermediate temperature stage and the bath). The rest of the parameters are known either from the circuit construction or from the IV fits (e.g. $g_{\text{Coeff(bolo\leftrightarrow bath)}}$).

For each temperature and V_{bias} measured in the previous chapter, we produce pulses using its parameters (changing relevant simulation values for each).

108 mK pulses

At 108 mK, we pass $T_0 = 0.108$ K, $g_{\text{Coeff(bolo\leftrightarrow bath)}} = 2431$ pW K⁻¹, and V_{bias} for each experiment performed.

The results, which we compare with those of the experiment (Figure 4.5, page 145) are shown in Figure 5.23. We see that the pulse height increases inversely with V_{bias} , which is the same as the data. The highest V_{bias} traces have oscillations in both the model and in the data, although the oscillations in the model are stronger



Figure 5.23. Signal trace results of the 108 mK Joule pulsing simulation.

than we see in the data. The rise time is equal throughout across every V_{bias} , and the decay time decreases as V_{bias} increases, as we also see in the data. However, the rise times of the simulated pulses are slower than in the data. Finally, the most obvious difference between the simulated pulses and the data pulses is the absence of the long time constant, which is seen only in the data.

The model appears to produce many of the data features, but its productions of them are not exact. The absence of the long time constant indicates that something exists in the experiment's thermal chain which is not accounted for in the model.

137 mK pulses

At 137 mK, we pass $T_0 = 0.137$ K, $g_{\text{Coeff(bolo \leftrightarrow bath)}} = 4503$ pW K⁻¹, and V_{bias} for each experiment performed.

The results, which we compare with those of the experiment (Figure 4.7, page 147) are shown in Figure 5.24. The oscillations are smaller this time, most likely



Figure 5.24. Signal trace results of the 137 mK Joule pulsing simulation.

because this effect is dampened at higher temperatures (which is compatible with what we've seen in the Bolo 184 data). The rise times, again, are slightly longer than what is shown in the data, as are the decay times. The change in amplitude with V_{bias} are compatible between data and simulation. The lowest V_{bias} , 200 mV, again seems to be obscured by the slow rise time in both simulation and data.

180 mK pulses

At 180 mK, we pass $T_0 = 0.180$ K, $g_{\text{Coeff(bolo\leftrightarrow bath)}} = 7351$ pW K⁻¹, and V_{bias} for each experiment performed.

The results, which we compare with those of the experiment (Figure 4.9, page 148) are shown in Figure 5.25. The results at this temperature have no oscillations, like the data. The rise time is much faster than at the other two temperatures, and approaches the rise time of the data pulses. The decay time, however, is still slower. The two lowest bias voltages, 401 and 601 mV, simply increase to a base value, with no decay seen after the rise time. In the data at this temperature, the



Figure 5.25. Signal trace results of the 180 mK Joule pulsing simulation.

lowest V_{bias} has a much slower rise time than the other traces, however this effect is not seen in the modelling, nor (again) is the long time constant.

5.9 Discussion

We have modelled Bolo 184 in several different ways, to investigate the thermal and electrical properties of the system. Originally, we had intended to reproduce pulses in this bolometer through modelling. However, this device - as simple as it is compared with other bolometers - has a complex interplay of thermal, electrical, and material physics which need to be taken into account to fully reproduce realistic pulses. The thermal block model (Section 5.4.1) fully reproduces the pulse shape - the sum of two double exponentials - which is most likely to be the 'impulse response' of the bolometer. What is uncertain is how to treat the absorber to reproduce position-dependent effects, which we have modelled several different ways.

Of these various methods, we have discovered that the only way to reproduce

the distribution of the fast amplitude seen in the data is by allowing ballistic phonons to reflect at the border, rather than assuming that they thermalise there. Using the reflective absorber model, which assumes a mean free path, we find that using a mean free path which is larger than the radius of the disc, and allowing the phonons to reflect off the disc border, produces a very similar shape to that which we see in the data. Another model, which assumes that the phonon thermalisation lengths follow a geometrical law, reaches a very similar conclusion using three energy deposition mechanisms. All rely upon ballistic phonon border reflections, from which we infer that the ballistic phonons in the data truly do reflect in this way. This also explains the effects we see in the data (where even highly-ballistic pulses have a thermal component, and vice-versa, and also the branching effects in Chapter 3).

The Joule pulsing experiment is the experiment with the largest number of unknown factors. Since we do not know precisely how the data should look, and which experimental factors may interfere with the results, reproducing it with modelling is only a very preliminary part of the work required to understand the results. We have been able to reproduce most of the behaviour, including the general shape of Joule pulses as we change V_{bias} and temperature. We have not reproduced the long time constant seen across the experimental data, suggesting that there might be something in the thermal chain which is poorly-understood. Answering these questions is a topic of further study.
Part IV

Thermal Simulations for X-IFU

Let us choose for ourselves our path in life, and let us try to strew that path with flowers.

Emilie Du Châtelet, mathematician, physicist and author

Athena Simulations - An Introduction

This chapter will outline the work undertaken by the author for the X-IFU collaboration on the Athena instrument. This work began in November 2017, after the author was approached by interested parties at the Space Research Organisation of the Netherlands (SRON). The thermal simulations described in the next chapter are a product of a collaboration between NASA Goddard Space Flight Center (GSFC) and Institut d'Astrophysique Spatiale (IAS), where the author worked in parallel with A. Minuissi (GSFC). This work has been done in the wider context of the Athena X-IFU background working group led by CNES.

The simulation was developed from prior work done by M. Bruijn at SRON. The final product was developed using the repurposed COMSOL simulation and Python adaptation by the author, and integration using GEANT4 results produced by S. Lotti at the National Institute of Astrophysics in Rome (INAF), which was a joint effort between the author and A. Rousaffi (IAS).

Simulation background

The 'cosmic ray problem' affecting space missions has been described in previous chapters. All types of missions carrying high-sensitivity arrays of detectors are potentially affected by this effect; this includes the upcoming X-ray Integral Field Unit (X-IFU) mission aboard the Athena space telescope, which is currently being developed between CNES and NASA. Athena is an ESA mission in Phase A study in the Cosmic Vision 2015 - 2025 programme, and X-IFU is one of the instruments on Athena, and is currently led by CNES. Based on a thermal fluctuation report

performed by SRON for the SAFARI instrument, the Athena working group produced a report which predicted the susceptibility of the X-IFU detector wafer by extrapolating the SAFARI results with Athena-like parameters [117].

The primary question of this work is to ascertain to what extent the X-IFU detector wafer is sensitive to thermal fluctuations arising from impacts with cosmic rays, at which timescale, and what effect this has on the energy resolution of the instrument. If a problem is found, the simulations will be used to refine instrumental parameters in order to keep the overall instrument susceptibility to cosmic rays within the energy resolution requirements.

Results of preliminary study at SRON

The primary cosmic proton impact rate on X-IFU at L2, including the production of secondary particles, is estimated to be ≈ 6.3 protons s⁻¹ cm⁻² [118] [117] for protons with energy > 39 MeV, and with an average deposited energy of 552 keV into 350 μ m of Si. These values will be updated with new results from the working group in the next chapter.

The preliminary study at SRON [117] reviewed similar analysis done for the SA-FARI instrument (based on Finite Element Analysis (FEM) COMSOL simulations), extrapolated for the requirements and parameters of X-IFU. In brief, the report concluded that the thermal noise expected on the X-IFU wafer is estimated to be 2.5 (for low frequency) to 18 (for high frequency) times in excess of the nominal budgeted amount for the instrument. Whilst these conclusions are alarming, the report concludes with the necessity for detailed modelling to address the open questions, as well as experiments to verify the results of the modelling. The detailed modelling (and its results) is what will be discussed in this chapter. Ensure that women are recognised and honoured as women. Those of us who have been early in a field have often had to behave like 'we-males'... More bluntly, we've had to play the male game, because we are such a minority.

Jocelyn Bell Burnell

Chapter **C**

Athena X-IFU Thermal Simulations

This chapter will describe the thermal simulations performed to analyse the effect of cosmic rays in the Athena X-IFU detector wafer, using Finite Element Analysis (FEA) in COMSOL Multiphysics. This simulation has been adapted for Athena X-IFU from the original simulations produced by SRON for SPICA-SAFARI.

6.1 Simulation structure

The simulation uses COMSOL Multiphysics' Heat Transfer in Solids module. It is a two-dimensional model with a projected z-axis. It contains 4 layers, each dedicated to a different material layer in the mechanical structure of the wafer.

6.1.1 Athena X-IFU detector wafer

The X-Ray Integral Field Unit (X-IFU) instrument aboard the Advanced Telescope for High-ENergy Astrophysics (Athena) space telescope is being developed by an international collaboration between several ESA member states (principally France, the Netherlands, and Italy), as well as by groups in the United States (specifically NASA Goddard) and Japan [119]. The development of X-IFU is done in the effort to address the 'Hot and Energetic Universe' instrument development call by ESA [120]. X-IFU aims to provide mapping of the 'hot and energetic universe' from



TES + Absorber on a SiN membrane

Figure 6.1. Top: Image of the central pixel structure, taken from the side, showing the TES atop the SiN membrane, with the Si muntin below. Bottom: Image depicting the angular deposition of the Cu for thermal sinking. (Image taken from poster presented by M. L. Ridder (SRON) at Low Temperature Detectors 2017)

48.4 PHz (200 eV) to 2.90 EHz (12 keV) i.e. upper-ultraviolet to lower-energy hard X-rays. X-IFU is an imaging spectrometer and seeks to map cosmic gas and plasmas in the environment around black holes, from which X-rays escape and provide a useful tool for understanding the dynamics and compositions of these regions [119].

These applications will require a large number of highly-sensitive detectors with well-constrained systematic effects. X-IFU will employ an array of 3840 Transition-Edge Sensors (TES) [119] in a 50 mK environment. TES are incredibly sensitive to thermal fluctuations, as they operate within the superconducting phase transition of their construction material. As is the case in composite bolometers (such as the one analysed in the previous chapters in this thesis), the sensitivity to science signal equates to a sensitivity to systematic effects such as cosmic rays.

X-IFU's TES detectors will be suspended on the thermal bath by a 1 μ m



Figure 6.2. DRIE etching mask of the X-IFU detector wafer, showing the overall structure of the wafer and the central muntins (the pixel region shown in red). (DRIE mask provided by M. Bruijn of SRON)

layer of Silicon Nitride (Si₃N₄). Beneath this, a 350 μ m silicon layer supports the bolometers, with the central pixel region incorporating a muntin structure produced by Deep Reactive Ion Etching (DRIE), and the outer wafer having a solid mass of 350 μ m Si. The outer and inner wafers holding the detectors are both hexagon-shaped. Sinking to the thermal bath is done by a $\approx 3 \mu$ m layer of gold, which is deposited on the bottom of the outer wafer and on the sides of the Si muntins. The structure of the central wafer region, with detectors, is shown in Figure 6.1 (top), with details of the Au heatsinking (bottom).

Figure 6.2 shows the overall shape of the wafer from the top down, courtesy of a DRIE etching mask employed by SRON. The etching is mostly present on the central hexagon, where the detectors are situated. The detectors are developed by NASA Goddard Space Flight Center (GSFC) [121] using technology developed for X-ray observatories with similar requirements [122].

Maintaining an energy resolution of 2.5 eV (with a goal of 1.5 eV) is paramount to the success of the project, but frequent impacts with cosmic rays can create thermal fluctuations on the wafer, which are seen by the detector as an increased bath temperature. These thermal fluctuations can decrease the energy resolution of the instrument, and so it is vital to address the issue using experiments and



Figure 6.3. Block diagram of the COMSOL simulation.

simulation to assure that the energy resolution requirements are met.

6.1.2 COMSOL model

The COMSOL model of the X-IFU wafer is a 2D model with 4 layers and projected z-thicknesses. Each layer contains separate 'solid' components for the wafer and the muntin. The coefficients for C_p and κ are the same between the 'wafer' and 'muntin' regions for a given material, but the parameter values are attenuated by the decreased area of the muntins (for Si) and the asymmetric deposition (for Au). A block model of the simulation design is shown in Figure 6.3, in which the thicknesses of the blocks are not to scale.

The deposited gold is separated into layers in the simulation, separated for the contributions for electrons and that of phonons. The temperature of the Au phonon layer is that of the phonon temperature, i.e. of the phonons / crystal. The temperature of the Au electrons is then the temperature of the charge carriers.



Figure 6.4. Top-down view of the COMSOL model (membrane approximation).

Heat flows from the gold phonon layer to the gold electron layer, and Q_{EPC} is the power transferred between the two layers from electron-phonon coupling. Due to Au being a metal, the phonon contribution to the heat capacity is expected to be small, but should not be neglected altogether.

The passage of heat from different material layers is due to interfacial thermal resistance and is Kapitza-like, with coefficients determined either from direct measurements at SRON/GSFC, or values from the literature. Similarly, each Q in the diagram is a transfer of power from a different physical process; Q_{Kap} is from Kapitza coupling between two layers (e.g. Si₃N₄ to Si), and Q_{wirebond} is power transfer from the heatsink to the thermal back, Q_{Joule} is the Joule power acting on the Si₃N₄ layer from the detector readout, and Q_{Pulse} is the power injection representing a cosmic ray.

However, the actual wafer is more complicated than in this case, which shows the 'membrane approximation' used throughout this chapter. A more accurate geometry for this array exists as a model, but is not used for the reasons which will



Figure 6.5. The central pixel region of the full pixel model (left) and in further detail (right).

be outlined in the next section. An image of the 'full pixel' geometry is shown in Figure 6.5, and contains the details of the Si muntins which are beneath the Si_3N_4 membrane.

The membrane approximation

Although we have shown that the X-IFU wafer contains 'muntins' which are etched, and upon which a Si_3N_4 membrane holds the detectors, the full rendering of the muntins is computationally intensive due to the complexity of the geometry. However, we can account for this in the definition of various parameters (such as the relevant areas of the undersides of the wafer, as well as their effect on the thermal conductivity). The calculations in this section are used throughout the remainder of this chapter, and have been provided by M. Bruijn of SRON in group correspondence [123].

In this approximation, we replace the muntin structure of the simulation with a flat membrane as shown in Figure 6.4. In considering the replacement of thermally-relevant simulation parameters, we first treat the Si beams and metal which has been deposited onto them. This is illustrated in Figure 6.6 (left), where two beams of the muntins are viewed in detail in the y-axis. The evaporation of the metal is perpendicular to the beams in x and then perpendicular to the beams in y, with an evaporated thickness of d_evap . The metal (shown in the diagram as copper, but



Figure 6.6. Left: Two pixel beams and their geometrical parameters (Si in grey and Cu in gold). Right: Top-down view of 9 etched-out regions between the Si beams. The green hatching shows the area of one 'unit cell'. Images were provided by M. Bruijn [123].

has been since changed to gold) is deposited at an angle of 28° relative to y = 0. The thickness of the deposited gold on the bottom of the beam is dCu_chip (or dAu_chip for the gold-backed wafer) and the thickness on the sides is dCu_beam (dAu_beam). These thicknesses are defined by:

$$dCu_chip = 2 \cdot d_evap \cdot \cos(\theta) \tag{6.1}$$

where $\theta = \tan^{-1}(\texttt{hole/hCu})$. The thickness of the Cu on the sides of the beams, dCu_beam, is simply d_evap $\cdot \sin(\theta)$. To account for this in the thickness, to compensate in the electron-phonon coupling, thermal conductivity, and heat capacity, we define an effective thickness of the copper on the sides of the beam which transfers the thickness of the metal evaporated on the beams to the bottom of them:

$$dCu_eff = \frac{dCu_chip + 2 \cdot dCu_beam \cdot hCu \cdot hole}{bSi(hole + pitch)}$$
(6.2)

where **bSi** is the width of the Si beams. The Kapitza-like coupling will need to be handled by an effective area rather than an effective thickness. This has been

done by splitting the Si muntins into 'cells' where A_cell = bSi*(hole+pitch), and the area of the metal coating where A_coated = A_cell + 2*hCu*hole. The ratio of the metal-coated area with the area of each 'cell' is the effective Kapitza surface:

$$ACu_eff = \frac{(A_cell + 2 \cdot hole \cdot hCu)}{A_cell}$$
(6.3)

In this way we can simulate using the simplified geometry of the 'membrane model', whilst accounting for the thermally-important air-gaps which are present in the muntins in reality.

Limitations of the membrane approximation and context

The membrane approximation serves the purpose of simulating the propagation of a heat pulse from the outer wafer region as the heat moves to the heatsink and to the pixels themselves (inside the muntin structure). However, its use is not appropriate for heat pulses originating inside the muntin structure itself - for this, it is necessary to use the full-pixel model to fully simulate the movement of heat around each specific detector through the Si muntins. This chapter will focus on the specific contributions of the author; the full-pixel model (by contrast) was simulated by A. Minuissi (GSFC) and one can find those results elsewhere - and so the question of cosmic ray impacts in this specific region are not addressed here. We shall focus instead on wafer impacts.

Furthermore, due to time constraints, we shall focus on the specific case of the wafer shown above (the 4-inch hexagonal wafer with Si_3N_4 membrane, Si muntin, and Au backing, with a central heatsinking ring) rather than several proposed alternatives. Alternatives, including a 6 inch wafer, more complicated heatsinking structures, or palladium backing, are currently under investigation by the working group. These alternatives are outside of the context of this chapter due to time constraints.

We shall therefore focus on this specific geometry, the behaviour of thermal

pulses with respect to distance and energy, and a first attempt at a simulated timeline. We will also show one recent alteration to the heatsink ring location, showing its results. Alternative iterations of this are subject to future work, either by the author or by other persons in the Working Group. The case of direct pixel impacts is partially addressed by the use of X-IFU's anti-coincidence detector ('Anti-Co') and partially addressed by the relative prevalence of impact probabilities on the detector vs. wafer regions (see a later section), but it will be important to not neglect these effects entirely in further study.

Thermal propagation between each layer

As we have shown in the diagram in Figure 6.3, the heat propagation (denoted as 2 'heat sources' – chip and muntin) between each layer is as follows:

- 1. $Si_3N_4 \leftrightarrow Si$: 'Kapitza-like' (T^4), attenuated in the muntin region by the effective area of the Si muntins, ASi_eff.
- 2. Si \leftrightarrow Au phonons: 'Kapitza-like' (T^4), attenuated in the muntin region by the effective area of the Au coating, AAu_eff.
- 3. Au phonons \leftrightarrow Au electrons: Electron-phonon coupling (T^5) , attenuated in the muntin region by the effective thickness of the Au coating, dAu_eff.
- 4. Au electrons \leftrightarrow thermal bath: Measured G heat transfer, where $Q = N_bonds * G_{1bond} / A_heatsink \cdot T^1$ temperature difference.

The heatsink area is artificially large in the geometrical sense, but we account for this manually. In the Si, Si_3N_4 , and Au phonon layers, the heatsinking region is uniformly integrated into the 'chip' region, and its total size is equivalent to that which is present in the CAD drawings. In the Au electron layer, the geometrical 'wirebond' region has the same thermal conductivity and heat capacity calculations as the rest of the chip (the wirebonds are Au wirebonds), but are attenuated by a wirebonding fill-factor ff_wb and the wirebond diameter wb_diameter. The filling factor ff_wb = (N_bonds*wb_diameter)/heatsink_perim assumes that (i) the wirebonds are stacked next to each other around the perimeter and (ii) that the G across these wirebonds is constant over their length (i.e. that the G does not have a gradient along its length). These are both, of course, approximations. The true orientation of the wirebonds is hitherto unknown; they may be placed side-to-side as we have calculated here, or they may be laid flat in certain places, or they may be in other configurations (lines or rings rather than a single hexagon). They will most likely be moved to a further distance away from the muntins (to avoid overlap with the Anti-Co). Concerning the assumed lack of a G gradient, it is very possible that there will be one. However, G_wb was measured directly at GSFC as reported by K. Kilbourne [121], and so we believe this to be the best possible approximation we have for the foreseeable future.

It should be noted that this modelling has been iterative, and what is presented here is only the latest layout and results. The original SAFARI model had only a mandated T_0 at the outer edges of the wafer for thermal regulation. The following iteration used Kapitza-like coupling to the thermal bath, but with a Kapitza constant which is not known for this specific experiment. Therefore our current application of specific wirebonds with measured parameters, where the only thermal exit from the model is via a G which is experimentally verified (and was quoted in a publication by GSFC [124]), is a much more realistic view than what was used previously - in spite of these assumptions and limitations.

Thermal properties of each layer

In each layer, the simulation is split between the 'wafer' and the 'muntin' components, which are each declared as solids with specific properties. These specific properties are thermal conductivity, k, and heat capacity C.

Many of the k values used in the current iteration of the simulation are heritage values from the work of M. Bruijn for SAFARI, but are generally applicable. In general, k follows the form from general thermal transport theory:

$$\mathbf{k} = \frac{1}{3}\nu\lambda C_{\nu} \tag{6.4}$$

where ν is the mean speed of sound in the material, λ is the phonon mean free path, and C_{ν} is the lattice specific heat. The lattice specific heat scales as T^3 in the case of Si (where the mean-free paths are heritage values from the SAFARI work). For Si₃N₄, it scales with T^2 in a similar way, and scales with T^3 for Au phonons. The Au electron layer has a simple T-scaling relationship which utilises the Weidemann-Franz law and the Lorenz number for gold:

$$\mathbf{k}_{Au} = N_{Lor} \cdot T \cdot \sigma_{Au} \cdot \mathbf{dAu}_{chip} \tag{6.5}$$

where we can replace dAu_chip with dAu_eff in the muntins.

For the heat capacity, all parameters have been taken from Ashcroft and Mermin [125], except for the phonon contribution to the heat capacity coefficient cV_p_Au which is a reasonably-estimated dummy value. Sensitivity-testing of this value over a wide range has shown that it does not have a significant effect on either the baseline bias temperature or the height of pulses within the regime of interest, most likely because the contribution from phonons in Au (a metal) is negligible compared to that of the electrons.

In the case of both Au layers, the C_p is multiplied by dAu_chip on the wafer and dAu_eff on the muntins. In the heatsink region in the Au electron layer, the C_p and the k is multiplied by the filling factor of the wirebond (ff_wb).

Some parameters are still uncertain (especially the mean free paths in Si, which were heritage values left over from the SAFARI work). The k of Au electrons is highly dependent on the Residual Resistance Ratio (RRR) of the gold coating. The RRR of a material is the ratio of its resistivity at room temperature compared with its resistivity at 0 K (where 0 K is approximated). RRR can vary drastically depending on the method of deposition, as the RRR is dependent on surface impurities (a disordered surface usually grants a low RRR). In the literature, spin-coated and annealed Au coatings have reached RRRs as low as 1.6 [126], where other publications have shown that RRR can reach much higher values (up to 1000) depending on the deposition methodologies and thickness, which affect the elastic scattering in the films [127][128]. This question alone is a study unto itself. To get a good agreement with the actual wafer (once it is built), the RRR of the gold coating will need to be specifically measured and applied into this model for the work to be carried forward. For the entirety of this chapter, RRR_Au is set to 6 based on a Kilbourne et al. publication using the same design specifications of X-IFU [124], which is the best estimate we can get in the absence of a constructed wafer and measurements on it. This same publication is where a number of parameters have come from, including the measured G of the wirebonds and the electron-phonon coupling factor of the gold.

Thermal energy input

The first thermal energy input into the model is that of the pixel self-heating in the muntin area, due to the readout electronics of the detectors. This region hosts 3840 TESs, each releasing 2.5 pW of power. We apply $Q = 3840 \cdot 2.5$ pW of input power across this region uniformly, which results in a thermal gradient across the central Si₃N₄ membrane.

We show the result of the steady state solution in Figure 6.7. The periphery of the wafer is held at a uniform temperature, whilst the central (muntin) structure is at a much higher temperature due to the pixel power heating applied by the detectors. There is a 'bump' on either side of the muntins, due to the application of the heatsink in that area, and also due to uneven meshing (using a CAD drawing as a surface map of the simulation, which has small defects). Using a heatsink just outside the pixels produces an almost-flat temperature gradient across the majority of the wafer. A slight discontinuity is noted at the steady state solution of the simulation at positive x, which is likely due to uneven meshing.

In the model, thermal energy from the cosmic ray is simulated as a heat pulse into the Si portion of the wafer using a specific geometry (a 0.1 mm square) which



Figure 6.7. The temperature of the wafer with y = 0 mm and across the full range in x in the steady state (without a cosmic ray).



Figure 6.8. The input pulse used to inject the 'cosmic ray' energy.



Figure 6.9. Sample output of a 'cosmic ray' thermal input, full wafer scale (left) and zoomed in (right).

is otherwise identical to the surrounding wafer (in terms of thermal conductivity, heat capacity, and other thermal inputs / material parameters). Because COM-SOL experiences difficulty with a delta pulse of any kind, the thermal input is approximated as a very fast heat pulse, in the form of:

$$f_{\text{pulse}} = \frac{\exp(\frac{-t}{t_f}) - \exp(\frac{-t}{t_r})}{t_f - t_r}$$
(6.6)

where $t_f = 1 \times 10^{-7}$ s and $t_r = 5 \times 10^{-9}$ s. Its y-axis magnitude is arbitrary and it is multiplied by the cosmic ray energy, hit_J, in eV. This energy input is heritage from the SAFARI model produced at SRON; we have investigated alternative methods, such as using a uniform domain heat source into which we specify a starting x and y position along with a designated input shape - this was ultimately abandoned as it would not provide a significant benefit unless we were to desire to change that impact point during the simulation itself (i.e. to have a moving cosmic ray source). We do not, and it would not save computational time due to the lack of necessity for remeshing. We have decided to keep the pulse input as it is, as it has shown to be reliable for our use.

It must be noted that the average cosmic ray will be a minimally-ionising particle (MIP) which will deposit only some of its energy into the wafer structure, and will traverse through each layer on its linear trajectory. However, the Si layer is the thickest (with $dSi = 350 \ \mu m$ in the present model) compared with the 0.5

 μ m Si₃N₄ or the 4.2 μ m Au in the wafer. Insertion of the thermal energy into the Si layer of the wafer is therefore the most reliable approximation we can use, as it will be the part of the wafer receiving most of the MIP energy. However, this also assumes that every CR will traverse at 0° from the normal of the wafer, which will not be the case in space. The final version of this model will be used in production of look-up tables (LUTs) for the end-to-end simulator (e2e) of X-IFU, into which it is possible to account for impact angles by (e.g.) deriving the specific amount of energy placed into each layer with respect to the particle angle and superposing the resulting pulses from the input tables. However due to time constraints on the part of the author, only the preliminary work in this effort is presented here.

Some sample output of a thermal pulse in the model is shown in Figure 6.9. Here we have used a particularly large energy input to clearly demonstrate the propagation of heat from the impact point across the wafer. Figure 6.9 (left) shows the impact relative to the entire wafer, and Figure 6.9 (right) is zoomed in to the impact point and the nearby interface for the heatsinking. We can see variable 'thermal wavefronts' due to the propagation across the various interfaces.

It should also be noted that the solver uses two steps:

- 1. The steady-state solution, where the cosmic ray input is excluded, but the pixel power input is not;
- 2. The time-dependent solution which begins from step 1, into which the cosmic ray thermal input as a function of time is measured.

Meshing

Finite-element analysis relies upon the fracturing of a simulation into smaller pieces, otherwise known as the concept of meshing. Equations are solved for the individual 'pixels' (meshes) of the geometry, and heat moves through the geometry by propagating through the mesh. A very fine mesh will provide a well-resolved thermal profile (but will take longer to run), and a courser mesh will have a more 'spotty' one (but a faster computation time). The solution of meshing is a



Figure 6.10. Left: The full wafer, with meshing. Right: Zoomed-in view of the meshing on the heatsink, muntin, and on the cosmic ray impact point.

compromise between the two. Areas which must be more finely meshed are those around complicated geometries, like the regions surrounding the heatsinking ring, the cosmic ray input region, or other boundaries. We show the meshing used in this analysis in Figure 6.10.

6.2 Linearity tests

The COMSOL modelling is a useful tool for understanding the wafer and its vulnerability to thermal excursions coming from cosmic rays. However, to produce a timeline of potential cosmic ray events using the cosmic ray spectra we expect to see, we would need to run the COMSOL model using many inputs for CR energy and CR impact distance. This is computationally and temporally prohibitive; the computer used to run these simulations has 128 GB, and a simulation of a temperature excursion from one cosmic ray of given energy and input location takes about 20 minutes with fine meshing.

If the behaviour of the pulses with respect to impact location and input energy is predictable enough, we can exploit these properties using separate programming languages (in this case Python) to produce T(t) curves at any location or energy we wish, which will save time and increase overall simplicity. Moreover, verifying the linearity of the model (or a lack thereof) allows us to explore whether the model behaves in ways which we expect.

The principal questions we must ask are:

- How do the pulses (especially their integrals) change as we increase or decrease the input energy?
- How do the pulses change as we increase the distance of the impact point across the wafer from the point at which we measure the temperature?
- Can we reasonably superimpose pulses over each other and remain consistent with the model? e.g. Is the combination of Pulse 1 (at energy E_1 and location x_1 and y_1) and Pulse 2 (at energy E_2 and location x_2 and y_2) = Pulse1 + Pulse2?

The simplest case would be that the integral scales predictably in terms of energy and distance, but there are workarounds if they do not. It is, however, critical that Pulse $1 + Pulse 2 = \sum Pulse 1 + Pulse 2 - at least if we wish to produce this analysis outside of COMSOL[*].$

6.2.1 Superposition tests

Our overall goal of producing a library of pulses which can be added together in Python to produce a sample thermal timeline for multiple CR hits is predicated on the need for the pulse waveforms to be simply added. We will simulate two pulses in COMSOL and add them, and then make one simulation with both of these pulses to verify this. The two pulses take the following form:

- 1. x = -10 mm, y = 20 mm, E = 700 keV, d = 22.3 mm
- 2. x = -12 mm, y = 33 mm, E = 2300 keV, d = 35.11 mm

^{*}Producing T(t) curves in COMSOL for one set of starting parameters takes approximately 20 minutes on a desktop PC with 160 GB of RAM. Producing 86 seconds of data from 11 billion sets of starting parameters would take 460 years in COMSOL. It is therefore vital that we realise this using an external production method, such as Python.



Figure 6.11. Left: Pulses 1, 2, and (simulated) 1+2 as a function of time. Right: Pulse 1+2, simulated and superposed.

parameter name	value
d_Au	3.5e-6 m
N_bonds	100
$hit_J (sweep)$	$500~{\rm keV}$ - $50~{\rm MeV}$
Px	0 mm
Ру	10 mm

Table 6.1 – Parameters for the variable energy simulation.

where $d = \sqrt{x^2 + y^2}$ and is the distance of the particle impact from the centre of the wafer, which is the measuring point (0,0).

We show the results of the test in Figure 6.11. In the left figure, we show pulses 1 and 2 simulated separately, and the two pulses simulated together (red line). In the right figure, we show the superposition of pulses 1 and 2 (black) compared with the original simulated version of Pulse 1+2. We note small differences between the two pulses, which are due to the interpolation function run on the simulated pulses in order to reproduce them. The interpolation has the advantage of 'smoothing' the pulse over regions where it would normally have jagged edges due to sampling or where the temperature reaches the limits of the solver tolerance. These effects compound slightly in the superposition, but are still within acceptable limits.



Figure 6.12. T(t) curves at a constant position (0,10) for energies between 500 keV and 50 MeV.

6.2.2 Pulses with constant distance and variable energy

We will use a generic set of parameters to show the pulses as we sweep over the input energy (hit_J), with constant parameters otherwise (shown in Table 6.1). We shall sweep between 100 keV and 50 MeV - a much larger energy range than we shall see in reality - to verify that our energy relationships are linear with respect to the range we might reasonably hope. The temperature is read at the location of pixel 0,0.

Given that the energy input is the only thing changing in these scenarios, we expect that the integral would scale linearly with respect to energy. That is what we find in Fig 6.12, although it is not obvious from the image. What we do find is that the time at which the pulse begins and ends does not change (much), and that the main indicator of the energy change is the size of the pulse. To inspect this more closely, we must look at the total integral, which we expect to change linearly for a constant distance.



Figure 6.13. Left: Total pulse integrals as a function of injected thermal energy (blue stars), along with a linear line of best fit (green line). Right: Pulse amplitudes as a function of injected thermal energy (red stars), and a linear line of best fit (blue line).

We find in Figure 6.13 (left) that the integrals scale 'mostly' linearly with input energy (as expected in a constant-distance case), but we add a small E^2 component to increase the accuracy of the calculated slope. For a fit with the form $y = mx^2 + nx + c$, we find $m = -8.88 \times 10^{-16}$ mK s keV⁻², $n = 1.78 \times 10^{-8}$ mK s keV⁻¹, and $c = -8.62 \times 10^{-8}$ mK. We find that the amplitudes (Figure 6.13 (right)) scale as $m = -6.10 \times 10^{-11}$ mK s keV⁻², $n = 1.05 \times 10^{-5}$ mK s keV⁻¹, and c =0.00317 mK. We do not use these scaling relationships later in this chapter because we find the linear fit to be inaccurate when scaling to low energies, but we have verified the linearity of the energy-amplitude relationship is working as expected.

6.2.3 Pulses with constant energy and variable distance

To test the effect of distance on the pulses, we sweep over distance in y (keeping the energy injection at a constant x), using a higher energy (5000 keV) to produce large pulses to resolve the properties easily. We sweep over distances between 9.75 and 40 mm, covering the entirety of the outer wafer.

The distance relationships are not as simple as the energy relationships, for several reasons:

- The heatsink is situated between the pixels (muntin) and the wafer, meaning that some of the heat will be evacuated through the heatsink, which may complexify the distance relationships. Older iterations of the model, with the heatsink at the edge of the wafer, had integrals which scaled with an inverse square relationship. The current layout of the heatsink complicates this scenario.
- The C_p and k of the model are temperature-dependent and can scale between T to T^3 , and the model has four layers, throughout which the heat can propagate; the translation of energy into the integral is not as simple as it was in the case of Bolo 184, where all the energy was stored in the absorber and had to pass through the sensor. Our sensor is only one of several places where the heat can go, and it is not necessary for it to pass the pixels before passing the heatsink especially since the heatsink is physically situated between the heat pulse and the pixel muntin. This complicates the movement of the heat, especially in relation to distance.

The above properties make the integral an unreliable measure of total energy in the scenario of scaling distance.

We shall sweep between a CR impact distance of 9.75 mm and 40 mm, taking T(t) at point 0,0, for hit_J of 50,000 keV, 5000 keV, and 500 keV. These highest energies are far outside the usual range we would expect from cosmic rays, but serve the purpose of verifying energy linearity and scaling ratios whilst allowing us to test the properties of distance of impact. They are also 'worst-cases' in relation to smaller energies, which would result in smaller temperature changes and more constant values for thermal conductivity and heat capacity.

50 MeV sweep

We show the results of 50 MeV heat pulses injected between d = 9.75 and 40.0 mm distance from 0,0, in which we read T(t) at 0,0. We note that this is a huge energy input, and so we expect huge thermal fluctuations as a result. In Figure 6.14,



Figure 6.14. T(t) curves for 50 MeV thermal input, at distances varying between 9.75 and 40 mm distance from 0,0.

we show the T(t) curves for all distances. We can see that as d increases, the initial amplitude decreases, but the pulses get much longer (note the log scale in Figure 6.14.

We find that the amplitudes as a function of the distance show a 'semiexponential' relationship, with a discontinuity due to the location of the heatsinking ring. With the overall goal of producing T(t) pulses from these, we find it will be most helpful to scale the pulses at mid-distances by using definite amplitude values rather than approximated ones (e.g. x^{-2} or exponential relationships). We show the amplitude-distance relationships in Figure 6.15 (red stars) along with the continuous interpolated relationship (red line).

As expected, the relationship between the total integral and the distance of the pulse (Figure 6.16) is complicated. Starting with close impacts, the pulse integral is very large, and decreases with distance to about d = 17 mm, just outside of the heatsinking ring. After this point, the integrals increase again up to a maximum of ≈ 0.0012 mK s, where they begin to decrease again due to increasing distance.



Figure 6.15. Maximum pulse amplitudes as a function of the impact distance (red stars), with a continuous interpolation (solid red line).



Figure 6.16. Total pulse integrals as a function of impact distance (50 MeV thermal input).

Before the heatsinking ring was applied to the central wafer (when the heatsinking was at the edge of the wafer, in a previous iteration), the integral decreased with a more predictable $1/x^2$ relationship. We surmise that although the central heatsinking ring is a more realistic scenario for how the heatsinking will work in this device, having the only thermal exit from the wafer coming from between the pixels and the wafer complexifies the way energy moves from layer to layer. It is worth remembering that we are reading T(t) on the Si₃N₄ layer, while the thermal input from the cosmic ray is injected into the Si layer below, and the sinking to the thermal bath is in the bottom-most layer (Au electrons). For this reason, one might expect that the integral might not be the best representative of the total energy.

We have noted in the previous chapters that the total integral of the pulse is usually considered to be the best representation of the 'total energy' in the pulse, which is supported by the literature [106]. However, we challenge that this paradigm is not valid in all cases, such as this simulation. In Torres et al. [106], the absorber is directly below the ²⁴¹Am source, and there are few alternative thermal pathways between the absorber and the sensor. This is the opposite to the case of this wafer, where the 'absorber' is the same surface as where we read T(t), the heat can spread laterally (across the wafer), or down into the Au (electron or phonon) layers, and some heat will be lost in the heatsinking ring (which is between the pulse and the 'thermometer'. Since there are so many thermal pathways, we do not expect for the pulse integral to be a reliable form of energy measurement in this case, as the pulse energy is not conserved like it is in Bolo 184.

We will re-run the above tests at 5 MeV and at 500 keV. We assume that the behaviour will be the same. Then we will outline how to produce a python model to exploit the linearities which exist, in order to produce a simulated cosmic ray timeline.



Figure 6.17. T(t) curves for 5 MeV thermal input, at distances varying between 9.75 and 40 mm distance from 0,0.

5 MeV sweep

Repeating the above procedures, we sweep over distance for a 5 MeV thermal energy injection. The first thing we see in Figure 6.17 is that the maximum amplitude of the pulses is much smaller, peaking at 0.087 mK for the furthest away pulse. The rest of the behaviour of these pulses is the same, i.e. the far-away pulses are initially larger, but are over much more quickly than the closest pulses, which scale more slowly in amplitude but quickly become very long.

Comparing the amplitudes (left) and integrals (right) again in Figure 6.18, the relationships are largely the same, with amplitudes scaling nicely as distance⁻². We will continue to use a continuous interpolation to find the intermediary amplitudes as we have done in the 50 MeV case. The integral relationships vary slightly - rather than levelling off as they do for far-away pulses in the 50 MeV case, there is a secondary decrease in integral with distance. However, we stress again that we will not actually use the integral in this specific case, and instead have chosen to rely more on amplitude.



Figure 6.18. Left: Amplitudes as a function of the impact distance. Right: Total pulse integrals as a function of impact distance (5 MeV thermal energy input).

500 keV case

Repeating the treatment one final time, we find that the pulses are largely the same at 500 keV, only divided by 10 (as we see in Figure 6.19. Although most cosmic rays impacting the wafer will be between 150 - 200 keV, we find that producing a reliable scaling relationship begins to degrade below 500 keV because the pulses become too small to produce reliable results (the amplitude of the pulses rapidly approaches the tolerance of the software).

We show in Figure 6.20 that the amplitudes and integrals are largely the same, only downscaled in the 500 keV case. From this, we assert that the integrals are unreliable, but that the amplitudes appear to be consistent as the energy changes. In the overall effort of producing reliable pulses for a given energy and distance, we will exploit the amplitude relationships, which will be described in the next section.

6.3 Production of pulses

The (re)production of pulses will utilise the amplitude relationships with respect to distance, as well as the integral relationships when scaling up (or down) in energy. For the moment, we will only consider reading the temperature at pixel 0,0. The steps are:

1. Choose a 'base pulse' based on the energy required, from the library of pulses (as a function of distance) shown above. Find the closest energy involved in



Figure 6.19. T(t) curves for 500 keV thermal input, at distances varying between 9.75 and 40 mm distance from 0,0.



Figure 6.20. *Left*: Amplitudes as a function of the impact distance. *Right*: Total pulse integrals as a function of impact distance (500 keV energy input).

the pulse (e.g. if we need a pulse at 900 keV, we start from the pulse set at 500 keV).

- Find a 'base pulse' closest in distance from the pulse library chosen above (e.g. if we require a pulse at d = 25.5 mm, we use the 25 mm pulse as the basis).
- 3. Use the continuity of the amplitude-energy-distance scaling relationships to match the pulse height with what is needed (from nearest neighbour only, to minimise the error in time shifting).

By taking into account only the temperature at 0,0, we can simplify the effects of wafer hits by only considering the relative distance to 0,0. Expanding this to deal with pixels other than 0,0 would not be terribly difficult, but it would require re-simulating and re-fitting everything we have just done above. It will not be included here due to time constraints.

6.3.1 Energy scaling

We have shown above that we have sample pulse sets at 500 keV, 5 MeV, and 50 MeV. The mean energy deposition in the wafer is only 0.575 keV, so the majority of pulses will be 'scaled down' versions of the 500 keV pulse. Whilst it may seem more logical to simply simulate a 0.5 keV case, we note that below 150 - 200 keV, the amplitude change in the simulated temperature approaches the tolerance limit set by COMSOL, and we run into issues such as amplitude offsets due to a combination of the solver tolerance and the meshing. We will get a much more accurate pulse (albeit small ones) by scaling down a larger event.

For the energy scaling, we will choose the energy which is closest to the energy deposited in the GEANT4 simulations, to avoid accuracy errors. The pulse shape as a function of energy should be the same, but it is still safest to use the nearestneighbour from the pulse library.



Figure 6.21. 0 to 50000 pulse amplitudes and distances (solid lines), with their interpolations (black dashed lines).

For a given pulse from the pulse library (those shown above), we normalise and rescale in terms of energy, first by using a min-max normalisation:

$$y' = \frac{y - \min(y)}{\max(y) - \min(y)}$$
(6.7)

where y is the pulse we are rescaling (the desired energy's 'nearest neighbour'). We then scale this pulse using:

$$y_{\text{Escaled}} = y' \cdot A_{\text{interp}}(d, E)$$
 (6.8)

where A_{interp} is the scalar result of an interpolation of the amplitudes over all distances and over all energies from the data (which we show in Figure 6.21). The regions between these lines (the distances between the measured distances from the data) is also achieved using interpolation, using the relationships we defined in the previous sections. We define another scaling, in the form of:

$$A_{\text{dist}} = \frac{A_{\text{interp-dist}}(d_{\text{new}}, d_{\text{scale}})}{\max(y_{\text{Escaled}})}$$
(6.9)



Figure 6.22. 500 keV pulses (solid lines), their 5000 keV downscaled counterparts (black dashes), and 'half-distance' distance scaled pulses (red dashes).

where d_{new} is the distance to which we are scaling a pulse whose nearest distanceneighbour is at distance d_{scale} in the pulse library. This gives us the differential amplitude between the energy-scaled y_{Escaled} and the projected amplitude of the pulse which is dx mm away from its nearest neighbour. We multiply this by y_{Escaled} when we need distances which lie between those existing in the pulse library.

We show some results in Figure 6.22, where we show the 500 keV pulses from the pulse library, the downscaled $5000 \rightarrow 500$ keV pulses, and the half-distance scaled versions of these. We note some small irregularities with the half-distance scaling at the smallest distances, however these have been taken with a greater regularity in the pulse library (as they dominate due to the wafer geometry). For a first-order test, and due to time constraints, these results will be used in the generation of simulated timelines.

6.4 Simulated timelines

GEANT4 data was provided by S. Lotti of the Institute for Space Astrophysics and Planetology (IAPS) at the National Institute of Astrophysics, to produce simulated timelines of thermal excursions on the X-IFU wafer based on the COMSOL simulations and projected energy depositions from cosmic particles on the X-IFU wafer in space. The simulations are based on the cryostat and focal plane array GEANT4 (version 10.2) mass models [129]. The simulation contains 113×10^5 total events, uses the Space Physics List developed by the ESA AREMBAS[†] (ATHENA Radiation Environment Models and X-ray Background Effects Simulators). The integrated intensity of 10 MeV to 100 GeV particles 0.407 particles cm⁻² str⁻¹ s⁻¹. In this section we will outline the process of using this GEANT4 to produce a simulated timeline of the wafer temperature at 0,0 as a function of time.

Due to time constraints, we will only use particles which impact the wafer region in Si, which is the dominant effect due to the size of the Si relative to the gold or Si_3N_4 . A complete simulation would need to take these other layers into account, but the effects would most likely be second-order due to their much smaller thicknesses.

6.4.1 Preliminary analysis of GEANT4 results

We have two sets of GEANT4 data: The 'sample' data and the 'full' simulation. The sample data and the full simulation are the same, but the sample data comprises about 7 seconds of information, whilst the full data is 83s. The full GEANT4 data contains 11909590 energy depositions (secondary events) over the course of 83 seconds, with 15155 total primary events. The sample data contains 1337 primary events and 1045116 secondary events. The data is split into 'event numbers', which usually produce many secondary particles depositing energy in x and y locations close to each other, separated by a few ns. The data averages approximately 183 primary events per second. The mean deposited energy from the secondary energy

[†]http://space-env.esa.int/index.php/news-reader/items/AREMBES.html
depositions is approximately 0.576 keV, with a minimum of 6.4×10^{-160} keV (clearly below our interest) and a maximum of 1.71 MeV. The average energy of the particles *after* traversing the spacecraft and *before* depositing energy into the Si wafer is 1658.88 MeV (with a minimum of 0.23 keV and a maximum of 84313.3 MeV). The mean dt (temporal difference between the primary event and the energy deposition of the secondary event) is 4.5 ns but has a large spread (between 2.72 and 575.5 ns). The mean particle impact distance from the centre of the wafer (where T(t) is simulated) is 27.95 mm.

6.4.2 Timeline generation

We use the relationships described in the first part of this chapter to scale pulses in terms of energy and distance. We start by looping over each parent event, choosing a δt using the exponential distribution of time between two events (derived from Poisson statistics) [130][‡] in the form of:

$$\delta t = \frac{1}{\text{rate}} \log(1 - \text{random}) \tag{6.10}$$

where random is a random number between 0 and 1 drawn from a uniform distribution. Within the primary event, an array of all secondaries is created with their x and y locations, energies, and energy deposition times relative to the primary event. During a specific primary event, we then loop over all secondaries within that primary event (which can be between 150 and 45000 energy depositions). For each secondary event, we choose a simulated event from the nearest energy (which is the 5000 keV pulse library in most cases), and we find the distance in that pulse library which is closest to the distance of the energy deposition. Once a pulse is chosen from the library, it is normalised and scaled using the relationships shown above. The secondary event's x and y data are then appended to a larger timeline array for the event, profile_x and profile_y.

Once the loop has run through all secondary events in a particular primary event, the appended arrays are sorted in order of ascending x. They are then

[‡]The author wishes to thank P. Peille for providing this source.



Figure 6.23. T(t) data for the wafer described in this chapter at (0,0), using particle impacts from GEANT4 results.

linearly interpolated for a sampling rate of $6.4 \times 10^{-6} \text{ s}^{-1}$, which is the sampling speed of the readout. The interpolated single-event timeline is then saved to a text file, and the profiles are deleted to free up memory.

Memory management

11909590 individual energy depositions translated into pulses is computationally difficult to achieve. The resulting data is approximately 55 GB, where every primary event has its own file. This was necessary to avoid memory errors in Python. The separated text files for each primary event are concatenated and then sorted according to their order in x, producing the larger timelines.



Figure 6.24. T(t) data for the wafer described in this chapter at (0,0), using particle impacts from GEANT4 results, using the full 83s data.

6.4.3 7 second timeline

We show the results of the 7 second timeline in Figure 6.23, where we find a RMS temperature of 1.24×10^{-4} mK. The budgeted $\Delta T_{\rm RMS}$ for X-IFU is 1.8×10^{-4} mK for f > 3 Hz and 4.2×10^{-4} mK for f < 3 Hz [117], so this value is near the budget, bearing in mind that it is likely to be an underestimate due to reasons we will outline at the end of this chapter.

6.4.4 83 second timeline

We show the results of this simulation in Figure 6.24, where we have calculated the entire 86 seconds. The data has been sampled for a sampling rate of 6.4×10^{-6} s, which is the sampling rate of the detector readout. The RMS temperature excursion over the full 86 second data set is 1.27×10^{-4} mK, which is slightly higher than that of the sample data set, but is explainable by large T excursions

happening later in the data.

By splitting the full timeline into 10 slices, we can see the behaviour in better detail in Figure 6.25. We have calculated the $\Delta T_{\rm RMS}$ of each slice in Table 6.2, where we see differences between the various slices depending on the impacts happening during the given Δt .

slice	$\Delta T_{\mathbf{RMS}}$ (mK)
1	1.36×10^{-4}
2	1.19×10^{-4}
3	1.20×10^{-4}
4	1.24×10^{-4}
5	1.31×10^{-4}
6	1.12×10^{-4}
7	1.49×10^{-4}
8	1.19×10^{-4}

Table 6.2 – RMS temperatures in the timeline slices.

6.5 Wirebond location modification

Repeating the process above, we change the location of the wirebonds in the COMSOL simulation to reflect something more similar to the current design specifications. The location of the wirebonds for the wafer described above, just outside of the pixel array, is within the area of the Anti-Coincidence detector (CryoAC). The CryoAC is designed to detect cosmic ray impacts inside and immediately outside the wafer area, to reject certain periods of time as 'pixel dead time' due to cosmic ray impact detection. The region of the CryoAC is slightly larger than the pixel array itself, and the wirebonds need to be outside of this space. We have therefore modified the model to move the wire bonding ring slightly further away from the pixels.

No other parameters of the simulation have been changed. We expect that the



Figure 6.25. T(t) data for the wafer described in this chapter at (0,0), using particle impacts from GEANT4 results, using the full 83 second data, split into 10 increments.



Figure 6.26. CAD drawing of the modified wafer design, with a relocated heatsink.



Figure 6.27. The steady-state temperature across the wafer, with the new heatsink location modifications.

pulses will, in general, be larger - especially for distances between the heatsink and the pixel area. Having the heatsink directly next to the pixels will artificially shrink them, and we expect that moving the heatsink further away from the pixels, even if we change nothing else in the simulation, will result in pulses which are larger - especially for the cosmic rays which arrive closer to the heatsink.

We expect that the steady-state solution for the temperature across the wafer is affected by the alternative location for the heatsink, due to the readout power of the pixels having to travel a longer distance before reaching the further-away wirebonds. We show the results of this in Figure 6.27, where the slope to the minimum ambient wafer temperature is exaggerated due to the further location of the heatsink. We have eliminated some of the issues with meshing by re-drawing the hexagons on this altered version of the wafer design, which should provide more stable results.

For brevity, we will not show the full results of the modification on the pulses, but we will give a general description here. For example, the profiles of the pulses as a function of distance are slightly different, as we will demonstrate in the 500 keV case in Figure 6.28. We see that the closest pulses are about 3 times larger in maximum amplitude than their unmodified counterparts (Figure 6.19, page 250), so our assumption that the closeness of the heatsink would unnaturally lower the temperature excursions seems to be correct. Conversely, the pulses with the highest



Figure 6.28. T(t) curves for 500 keV thermal input, at distances varying between 9.75 and 40 mm distance from 0,0, with the modified heatsinking ring.

d are 0.5 to 0.3 times smaller, as they encounter the heatsink much sooner than they did in the unmodified case.

We expect that the relationships between distance and amplitude will be more complicated under this new regime. Since the scaling functions we have defined in this chapter rely upon interpolation rather than polynomial fitting, the scaling functions should work reliably even though the A(d) behaves differently. They are shown here for the 500 keV simulated pulses in Figure 6.29, which we compare with the unmodified heatsink in Figure 6.20 (page 250). We see that the overall A(d) behaves less exponentially than before, and that the amplitude decreases less quickly with d until the pulses are past the heatsinking ring, where the usual 'exponential-like' behaviour resumes. There is a discontinuity around the region of the heatsinking ring, which is expected behaviour since some heat will go more quickly to the thermal bath, which disrupts the 'exponential-like' behaviour we saw before. This behaviour is not unexpected for a heatsinking ring which is neither



Figure 6.29. Top: Pulse amplitude as a function of d for 500 keV simulated pulses (red stars) and the interpolation used for scaling between distances (red lines.) *Bottom*: Amplitudes of the heatsink modification model (blue) in comparison with the unmodified model (green).



Figure 6.30. T(t) data for the wafer with the modified heatsink at (0,0), using particle impacts from GEANT4 7 second sample results.

directly outside the pixels, nor on the edges of the wafer.

6.5.1 Simulated timelines

We show the results from the simulated timelines, both from the 7 second 'sample' timeline and the 83 second 'full' timeline.

7 second timeline

We show the results of the 7 second timeline for the modified heatsinking ring model in Figure 6.30. For this sample data, we find $\Delta T_{\rm RMS}$ of 3.91 × 10⁻⁴ mK, more than 3 times the $\Delta T_{\rm RMS}$ of the sample timeline for the unmodified wafer model. This corresponds roughly with the increase in pulse size seen for the low dpulses, and an increased $\Delta T_{\rm RMS}$ is not a surprising result. However, this pushes



Figure 6.31. T(t) data for the wafer with the modified heatsink at (0,0), using particle impacts from GEANT4 full 83s results.

 $\Delta T_{\rm RMS}$ of the sample timeline of the modified wafer model to be higher than the budgeted $\Delta T_{\rm RMS}$ of 0.18 μ K.

83 second timeline

For the full 83 second timeline of the modified heatsink model, shown in Figure 6.31, we find $\Delta T_{\rm RMS}$ of 3.28×10^{-4} mK, which is compatible with the 7 second timeline for the same simulation taken above. $\Delta T_{\rm RMS}$ is about three times the $\Delta T_{\rm RMS}$ of the full unmodified simulation. $\Delta T_{\rm RMS}$ increases between the sample and the full simulation by roughly the same amount, which is coherent in both cases.

We show a comparison of the two cases in Figure 6.32. There is a slight difference in the length of time between the unmodified and modified results, which is most likely to be due to the randomised arrival time we have denoted in Equation 6.10. However, the count rate is constant throughout the calculations, and we believe that the final $\Delta T_{\rm RMS}$ would be unchanged if the simulation results had provided



Figure 6.32. T(t) data for the wafer with the modified heatsink at (0,0), using particle impacts from GEANT4 full 83s results. *Red*: The full unmodified simulation. *Blue*: The full simulation of the modified heatsink model.

us with the exact arrival times coming from the GEANT4 simulation. This is the same reason why the specific event pulses do not match up in the comparison; if the exact arrival times had been added to the GEANT4 data, it would be possible to do a direct side-by-side comparison.

slice	$\Delta T_{\mathbf{RMS}}$ (mK)
1	4.23×10^{-4}
2	3.52×10^{-4}
3	3.26×10^{-4}
4	3.56×10^{-4}
5	2.84×10^{-4}
6	2.71×10^{-4}
7	3.72×10^{-4}
8	1.87×10^{-4}

Table 6.3 - RMS temperatures in the modified timeline slices.

We show 10 slices of the full results in Figure 6.33, in which we can see the events in greater detail. We note the very frequent but very small pulses, of the order of 0.1 μ K, the most likely to pose a problem for the energy resolution of the instrument. There is a variation in $\Delta T_{\rm RMS}$ across the 8 slices, which we show in Table 6.3. The variation is larger than the unmodified case, but does roughly correspond to this model's increased 'sensitivity' in $\Delta T_{\rm RMS}$ to the energy deposition.

6.6 Discussion

We have adapted the SAFARI wafer model in COMSOL for the detector wafer of the X-IFU space mission. We have tested the behaviour of the model under a number of circumstances, including verifying the linearity of the model in relation to superposition. The model is made with the idea that the resulting pulses on the wafer from energy depositions via cosmic rays can be scaled in terms of distance and energy, from a pulse library at a number of distances and energies coming



Figure 6.33. T(t) data for the wafer with the modified heatsink at 0,0, using particle impacts from GEANT4 full 83s results, sliced for further detail.

directly from the COMSOL output. We have adapted this model to accurately scale the pulses in Python.

The X-IFU cosmic ray working group has produced energy deposition data on the wafer using GEANT4, which calculates the frequency, level, dt, and location of energy depositions in the wafer due to cosmic particles interacting with the telescope at L2. The data contains primary events, which are composed of a large number of secondary energy depositions in specific x and y locations. Particle impacts occurring at angles relative to the normal of the wafer are handled by a large number of secondary events at varying dt and location.

6.6.1 Secondary event generation vs. primary event spectra

The code loops over each secondary event in each primary event, generating a pulse during a specific period of time which is appended to the timeline array. The output of every 'primary array timeline' (itself made from thousands or tens of thousands of smaller pulses from secondary energy depositions) is saved at the end of each primary event. The files are later appended to the timeline array and sorted in the order of their x, creating a coherent timeline of all events and sub-events occurring during the simulation timeline.

In the GEANT4 data, there is also a data file containing 'analysed' counts on each constituent material. In these files, the secondary energies for each primary particle are added up and assumed to impact the wafer simultaneously, and in the same x and y location. The COMSOL modelling and timeline production described here has been performed twice - once by the author, and again - separately but in parallel - by A. Miniussi (GSFC) and P. Peille (CNES)[§]. They have produced that separate COMSOL model to produce wafer temperature timelines, which have been put through XIFUsim (the end-to-end simulator for X-IFU) to estimate the effect on the energy resolution of the instrument. Their timelines have been

[§]The parallel COMSOL study has been done by A. Miniussi and S. Beaumont (GSFC) and timelines from that COMSOL model have been produced by A. Miniussi and P. Peille.



Figure 6.34. *Red*: The full unmodified simulation. *Blue*: The full simulation of the modified heatsink model, zoomed in between 10 and 11 seconds.

produced using the 'analysed' GEANT4 data, which assumes that the secondary energy depositions from each primary energy deposition are added together. Their timelines find a random E_{dep} from the primary event list, and assign it a random x and y location. This is likely to be the source of the difference between the timelines contained in the Phase A cosmic ray report, and those produced by the author.

This tactic is much more computationally agreeable and generates timelines far more quickly than looping over individual secondary events. However, it should be noted that each secondary energy deposition comes with its own location, dt, and individual energy; particles with a shallow striking angle are addressed as multiple (smaller) energy depositions at various distances along the Si wafer. The dt of a secondary deposition from its primary particle can be between 2 and 575.5 ns. Given that the main concern of the cosmic ray issue on X-IFU relates to thermal excursions on the wafer (i.e. an increase in the 'effective bath temperature' seen by the detectors), the effect of distance or time-delayed secondary particles in specific locations is vital to understanding how frequent, small energy depositions affect the energy resolution of the instrument. We illustrate this principle in Figure 6.34, in which we show the modified and unmodified timelines only between 10 < t < 11seconds. We note some of the wider pulses, especially at t = 10.8 seconds; these pulses are the superpositions of primary events which contain many secondary events. It is the small but frequent, spaced-out secondary energy depositions which create the most insidious noise source in these timelines. Furthermore, drawing a random particle distance rather than choosing one from the primary event list results in distances with a uniform distribution rather than the specific output of the GEANT4 data, which might be different due to interactions with telescope components outside the wafer. 'Glitches' in space instruments are likely due, at least in part, to a dense set of MIPs generated by hadronic interactions of protons with the spacecraft, and so a single-particle approximation is likely to be inappropriate. In total, the treatment described in this chapter is more faithful to the GEANT4 data and presents the least risk of biasing the output.

Cosmic rays impacting the wafer will be arriving at a range of angles, and not simply normal to the wafer. If the 'full' GEANT4 data is accounting for this by providing a string of secondary particles in moving x and y locations, depositing a fraction of the energy at a particular δt , it effectively recreates particles striking at shallow incident angles (even if our comsol simulation is in 2D). Adding all secondaries into one large primary impact would be 'flattening' the distribution of energy from what should be a range of distances due to the shallow angle, and instead putting all of that energy into one place, and at one time - this treatment could be far less accurate, as it only accounts for the energy and not for the location or time variations across the particle path.

If we were to simply add these primary events up, these peaks would likely appear to be much sharper. It may be the case that by adding the secondary pulses into a single primary pulse overestimates the pulse amplitudes whilst also underestimating the spread of those pulses. We may, therefore, be remiss in concluding that the secondary energy depositions are not a problem.

We will therefore repeat, for the same COMSOL simulation, the timeline reproductions using the reduced GEANT4 data, and compare the results.

Reduced GEANT4 data timeline comparison

We have produced 83 second timelines from the reduced GEANT4 data using two methods:

- 1. The same procedure used by GSFC/CNES, with random energies from the reduced GEANT4 data, and random distance (from a uniform distribution) across the wafer.
- 2. Going through each primary particle in order, using the (averaged from the secondary particle list) distances provided for each particle.

Method **2** is more directly comparable with the timelines produced by going through the full GEANT4 data, as this is done in chronological order.



Figure 6.35. *Blue*: Timeline from the full GEANT4 data set. *Green*: Timeline from the reduced GEANT4 data, using method 2.



Figure 6.36. *Left:* Energy deposition locations on the wafer (shown in red). *Right:* Distribution of deposition location distances.

We show the results of Method **2** in Figure 6.35. Because the secondary energy depositions have been added together[¶], in one time and place, in the reduced GEANT4 data, the energy depositions into the Si wafer are much larger, producing a large variation in the wafer temperature. The new results produce a $\Delta T_{\rm RMS}$ of 1.64×10^{-3} mK, which is almost an order of magnitude higher than the results from the non-reduced simulation. It is also an order of magnitude higher than the stated $\Delta T_{\rm RMS}$ budget of 0.18 - 0.42 μ K.

Some quick checks to verify that the reduced GEANT4 data is doing what it is supposed to do include (a.) verifying that the distances where particles impact the wafer are distributed in a realistic and reasonable way in Method 1, and (b.)verifying that the summed secondary energy depositions are equal to the primary energy deposition for the same particle ID. By summing over all secondary events from the 'full' simulation, we have verified that they are equal to 'Edep' from the reduced GEANT4 data. We then show the distribution of the distances in Figure 6.36, in which the locations of the particle impacts on the wafer are shown

[¶]We have independently verified that the sum of secondary energy depositions for a given primary particle is equal to the deposited energy presented in the reduced GEANT4 data.

in the left figure, and the distribution of $d = \sqrt{x^2 + y^2}$, where x and y are the absolutes of the impact points, is shown on the right. We find that the distribution of energy depositions follows the expected behaviour, covering the wafer evenly, with the peak at ≈ 42 mm coming from wafer edges and the roll-off coming from the shape of the wafer. Therefore, we have proven that the energies and the distances are the same; the difference must be from the small differences in distance and time coming from the full simulation.

The cosmic ray working group have taken the simulations from the reduced GEANT4 results calculated at GSFC/CNES (using Method 2) and put them into the X-IFU detector simulator, checking how the energy resolution of a 7 keV X-ray is affected by the fluctuations on the detector wafer. Their report [131] does not state the $\Delta T_{\rm RMS}$ calculated from the thermal timelines used in the simulation. The report concludes that the spectral line broadening of the simulated 7 keV X-ray is below the energy resolution budget of 0.2 eV (the exact broadening figure is not given). They have then concluded that cosmic ray thermal fluctuation effect is within the budget and does not pose an immediate problem.

Statistical comparisons

Using $\Delta T_{\rm RMS}$ as a metric is unreliable when it is biased by large pulses (as produced by the reduced GEANT4 timelines). As the $\Delta T_{\rm RMS}$ of the timelines used in the recent cosmic ray report is not available, we cannot directly compare the results shown in this section with those in the report. We can calculate the Full Width Half Maximum (FWHM) of the sensitivity in a similar way that the X-IFU simulator would, by calculating the difference between the 88th and 12th percentiles of the (sorted) temperature data, in the same way the figure has been calculated in the report [131]. This is clearly less accurate than by simulating the timelines in X-IFUsim, but it should produce values within the correct order of magnitude.

For the timeline produced by the reduced GEANT4 data, the difference between the 88^{th} and 12^{th} percentiles is calculated to be 0.040 μ K, corresponding to a 0.006

eV broadening. For the timeline produced by the full GEANT4 data, the difference between the 88th and 12th percentiles is calculated to be 0.038 μ K, corresponding to a 0.0057 eV broadening. For a Gaussian distribution, the difference would be 2.35 σ . σ is 17.0 μ K for the reduced timelines, and 16.2 μ K for the full timelines; clearly, neither of these distributions is particularly Gaussian. Both produce distributions of energy percentiles (simulated broadening) which are nearly two orders of magnitude less than the budgeted value of 0.2 eV. We have seen, therefore, that $\Delta T_{\rm RMS}$ is not a reliable metric in this case, and that passing these timelines through X-IFUsim is necessary.

From all of this, we raise the following points:

- Using the same COMSOL output, we produce thermal timelines which differ by an order of magnitude between the 'full' and reduced GEANT4 results.
- We cannot directly ascertain the effect on the energy resolution without putting the results into the X-IFU simulator to calculate the broadening of a 7 keV spectral line. We can only compare the budgeted $\Delta T_{\rm RMS}$ between the two sets of results with the stated budget from the original report [117], and calculate the statistical differences between the full and reduced simulation outputs.
- The results of the 'full' simulation produce a $\Delta T_{\rm RMS}$ which is roughly equal to the stated $\Delta T_{\rm RMS}$ budget value. The results of the simulation from the reduced GEANT4 data are one order of magnitude above the $\Delta T_{\rm RMS}$ budget value. However, $\Delta T_{\rm RMS}$, as a metric is biased. We can only draw conclusions by simulating the interaction between these thermal profiles and the detector response to a 7 keV X-ray.
- If we assume a linear relationship between the thermal distribution and energy in eV, based on the FWHM of the temperature distributions, we find a nearly-equal result for the energy broadening in eV for both simulations, which is an order of magnitude below the budgeted amount.



Figure 6.37. *Green*: Timelines from the reduced simulation. *Blue:* Results from the full simulation. Both are zoomed into the first 2 seconds.

slice	$\Delta T_{\mathbf{RMS}}$ (mK)	Difference (μK)	Difference (eV)
1	1.79×10^{-3}	0.053	0.0079
2	1.31×10^{-3}	0.045	0.0068
3	1.97×10^{-3}	0.038	0.0057
4	2.36×10^{-3}	0.045	0.0067
5	1.82×10^{-3}	0.053	0.0080

Table 6.4 – RMS temperatures, T_{diff} , and E_{diff} of five temperature profiles using the reduced GEANT4 data and Method 2 of timeline production.

Based on this, we conclude that the findings (which are already likely to be underestimates, due to reasons we will explain in the next sections) should be followed up with further analysis before concluding a lack of a problem. If the $\Delta T_{\rm RMS}$ budget value in the original report was an underestimate, and the much larger thermal excursions still do not affect the energy resolution, we must still verify whether the reduced GEANT4 data provides an adequate scheme for estimating the thermal excursions, or whether the estimates are too inaccurate to produce meaningful results. We believe that the results produced are markedly different under the reduced scheme, and that the larger pulses result in an underestimation of low-level thermal fluctuations, as we see in the zoomed-in comparison in Figure 6.37. We see in the blue traces that there are many superpositions of pulses at low temperatures, and that there are more of these for the full simulation than for the reduced one. The estimated pixel dead times in the IPRR report come from the large pulses rather than from the smaller thermal excursions, and we believe this to be a major difference. As the full simulation is the most faithful reproduction of the data coming from GEANT4, we may be within the realm of safety where it concerns cosmic ray thermal fluctuations. However, there are a great many unknowns, and these open questions should be flagged for further study.

Finally, we will check our results against method 1, which is the timeline production method used by GSFC/CNES to produce the timelines used in the IPRR cosmic ray report. Because the energies (randomly chosen from the list) and distances (randomly chosen from a uniform distribution) change in every simulation, this method produces a large variation in results.



Figure 6.38. Five random timelines produced using the reduced GEANT4 results and Method 1 of timeline production.

We see five random timelines produced using Method 1 in Figure 6.38, and their parameters in Table 6.4. We see a considerable variation in results due to the randomised distances, even if the energy input comes from the GEANT4 results. Simulation 4 has the highest $\Delta T_{\rm RMS}$, demonstrating just how much this metric is biased by a large pulse; the same pulse does not have significant broadening of its FWHM. It should be noted that there is greater variability between this one simulation run 5 times than there was between the full and reduced GEANT4 simulations. If Method 2 has been used to predict the spectral line broadening, care must be taken to ensure that this specific timeline is not under or over-estimating the results (although an over-estimate is safer than an under-estimate). In any case, it is probably safer to use Method 1 to produce the timelines.

In summary, further review (and results from X-IFUsim) are required because:

- the primary conclusions of the study in this manuscript (of the full, nonreduced simulation) are in the same order of magnitude of the $\Delta T_{\rm RMS}$ budget (meeting and exceeding it in some cases);
- the 'predicted' spectral broadening is (in both cases) an order of magnitude below the budget level (but is probably not valid due to the non-Gaussianity of the data);
- the apparent discrepancy between these treatments;
- these are likely to be underestimates (see below);

the author wishes to reiterate these many uncertainties as something which needs to be flagged for further review.

6.6.2 Residual Resistance Ratio

The assumptions, parameters, and variables used in the COMSOL simulation are a combination of heritage values from SAFARI, measured parameters from



Figure 6.39. Left: Modified timeline pulses for a 1000 keV pulse at d = 11 mm, with varying RRR. Right: The steady state temperature of the wafer as a function of the RRR.

SRON or GSFC, and literature values (particularly Swartz and Pohl [132]). Some parameters, such as the RRR of the gold, need to be measured once the wafer has been manufactured. The RRR in particular is a very sensitive parameter in terms of the output produced, and important parameters such as this (along with N_{bonds} , which is part of the design specifications) must be clearly defined in order to get trustworthy results. We demonstrate this in Figure 6.39, where we have simulated a 1000 keV pulse at d = 11 mm from the central pixel, whilst varying the RRR between 3 and 15. We see that as RRR increases, the amplitude also increases, but pulses at the same distance become shorter. This implies that, from a background standpoint, we should balance the RRR to avoid having too much of any one effect; too high of an RRR (e.g. 100 or 1000) and the pulse amplitudes could become enormous unless they eventually level off due to another effect. Too low of an RRR and the pulses are short, but last much longer. In terms of the particle background, it is probably better to have pulses with shorter decaying time constants, but not at the expense of high pulse amplitudes.

The RRR also decreases inversely with the steady state temperature of the wafer

area at 0,0. The steady state (bias) temperature comes into play when considering the thermal stability on the array-scale; a larger thermal gradient across all of the detectors could contribute to an energy resolution gradient. Based on these findings, we believe that a slightly higher RRR would be favourable - this avoids a larger thermal gradient and long time constants from pulses, but at the expense of CR pulse heights. This is a parameter which will become very important to define, as it represents a potential scaling factor in pulse amplitude and relaxation time. The RRR depends on the deposition methods used and varies per-application, as it changes based on surface impurities. It represents one of the uncertainties in these results, demonstrating that experimental deduction is necessary, and perhaps even tests with various deposition methods in order to fine-tune the RRR to decrease the array systematics mentioned here.

6.6.3 Other sources of uncertainty

The timelines we have presented here deal only with hits on the Si wafer of the instrument, and not on the pixel area (where the detectors are) or the other materials in the wafer (Au and Si_3N_4). The Au and Si_3N_4 layers are comparatively smaller in thickness, and any particle traversing the wafer will deposit the vast majority of its energy into the Si. Due to the relative size of the outer pixel vs. wafer area, most of the cosmic ray impacts will be in the outer wafer. Inner hits should be flagged by the CryoAC. Effects on the pixels which are not flagged by the CryoAC may be present if the effect of secondary energy depositions is a small but constant baseline temperature shift on the wafer. Furthermore, the muntin structure must be simulated in detail - energy deposited into the Si muntins could be stored there for a long time, creating a large and lengthy temperature change which takes a longer period of time to dissipate to the thermal bath.

Furthermore, these timelines are only simulating the wafer temperature at the central pixel. Thermal excursions will be much higher for detectors at the outer pixels, especially for hits occurring between the heatsinking ring and the Si muntins. The central pixel is, in a way, a 'best case scenario'. It will be equally necessary to

redo these simulations to account for pixels near the edge of the muntin structure, for which nearby cosmic rays will have a larger effect. In theory, we could have an RMS temperature gradient (and thus an energy resolution gradient) over the full pixel structure, which would be a significant systematic effect that would need to be dealt with at the instrument level, probably in the calibration stage.

The simulation assumes that all particles deposit their energy in the same way into the wafer. The energy depositions are a simple heat pulse, as we described above. However, as we have seen in this manuscript, the mechanisms by which a particle deposits energy into a material can vary drastically depending on the type of particle, and it is not sufficient to treat all particles as the same kind of heat pulse. According to the 'analyzed' GEANT4 data, the average energy of a cosmic ray which has penetrated the spacecraft and arrives at the wafer is 1658.8 MeV. This is usually in the form of primary, secondary, or inelastic protons, although other particles are also present. This is the energy of an arriving particle which has had enough energy to penetrate the spacecraft, and has had its incoming energy attenuated by this process. If we look at the stopping power plot for Si (Figure 6.40), we see that 1658.8 MeV (the red line) is near the low point of the dE/dx for this material, granting a stopping power of 1.696 MeV cm² g⁻¹. Multiplying by the density of silicon ($\rho = 2.33$ g cm⁻³), we have a stopping power of 3.95 MeV cm⁻¹. Our wafer is 350 μ m thick, meaning that this average proton will deposit 118.5 keV in the wafer.

An impacting particle will excite the crystal structure, putting all 118.5 keV of its energy into isotropically-radiating ballistic phonons. These ballistic phonons will reflect off crystal borders over potentially a very large area (depending on their mean free path) until they encounter the Au metallisation layer. Even if 99% of this energy is immediately caught in the metallisation layer, ≈ 1.18 keV of the proton's remaining energy will be thermalising somewhere in the wafer. With 183 impacts per second over the wafer, we can imagine that this could pose a problem for a 0.2 eV energy resolution budget. Ballistic phonons have not been taken into account in this simplified COMSOL model, which deals only with a heat pulse; errant ballistic phonons which have escaped the metallisation layer could be a source of more thermal noise. It is possible to probe these effects further using



Figure 6.40. Stopping power for protons in Si, as calculated by PSTAR [101], showing the electronic, nuclear, and total stopping power. The average deposited energy in the Si wafer, according to the GEANT4 results, is 452.17 keV (red line). Data taken from PSTAR [101].

COMSOL; COMSOL is not directly able to simulate ballistic phonon effects, but approximations can be made using ray-tracing techniques using the Optics module (see the 'Geometric Absorber Model' in Chapter 5 for the general idea).

As each type of particle has different mechanisms of energy deposition, the results presented here should be taken as a 'rough' calculation. In particular, the effect of ballistic phonons must be investigated. Finally, and most importantly, there have been no experiments to determine the magnitude of thermal effects via protons or α particles in this wafer. Whilst α particles are not likely to be present (they would be stopped by the outer parts of the spacecraft), a study using α particles or protons (using a cryostat like the one described in Chapter 7) is necessary. There are currently no clear plans at the project level to test this in either a full wafer or a representative one during these stages of instrument development. This means that whatever we believe to have found in these simulations remains wholly unsubstantiated by an experiment. Modelling without evidence cannot be taken as definitive (especially with so many unknowns), and that this step is crucial toward verifying whether or not cosmic rays will truly affect the instrument, and to which level. Because the work presented here contains results which are likely an underestimate, and are already very close to the maximum $\Delta T_{\rm RMS}$ allowed by the instrument systematics budget, and conclusive effects on the energy resolution are not possible without XIFUsim, follow-up by all actors and using concrete experimental results is necessary before concluding that cosmic ray thermal fluctuations should not be addressed.

6.6.4 Potential mitigation techniques

The effect of thermal fluctuations coming from cosmic rays can be mitigated using design alterations. For example, we have assumed 100 wirebonds are present in the heatsinking of this wafer. If we were to increase the number of wirebonds, the strength of the thermal heatsinking would increase substantially - we are, of course, limited by size. We have also shown that changing the location of the wirebonds alters the thermal behaviour, and this could perhaps be exploited by

keeping multiple wire bonding rings in various locations, to better attenuate the high d cosmic rays which create excursions with long tails.

$\mathbf{Part}~\mathbf{V}$

Window designs for portable cryogenic system

Everything was so new - the whole idea of going into space was new and daring. There were no textbooks, so we had to write them.

Katherine Johnson, NASA mathematician

Chapter 7

Beam Line Tests - Window Designs

This chapter will briefly describe the efforts towards the design of windows for the new BlueFors cryogenic system at IAS. The basic principles of the new system have already been described in Section 3.1.1. We intend to use a particle accelerator to irradiate prototype detectors, arrays, and focal planes over a large range of space-like energies.

In this chapter, we focus on the interface and particle beam coupling with the cooled device under test located inside this cryogenic system, passing through the windows of each shield located on the various temperature stages necessary to go from 300 K to 100 mK. It is hoped that in the next few months, the windows will be prepared and the system will be ready for first tests in front of the beam line at TANDEM in Orsay.

7.1 Window requirements

We wish to couple the detectors to a beam line, but we also need to maintain the cryogenic vacuum, as well as the temperature stages. This requires us to reach a trade-off for the window design which is thick enough to achieve both, but thin enough so that the particle beam is not severely attenuated. There is also a another trade-off between optical and infrared rejection (to avoid excess background power) vs. beam energy loss. The experiment requires irradiation incident upon the bolometer at some known energy > 5 MeV (as lower energies can be obtained using simpler internal sources). In order to comprehensively characterise the bolometer, it is necessary to maintain as much of the incoming beam energy as possible, whilst attenuating the flux to such an extent that we see only one particle impact during each 'relaxation' phase of the detector (e.g. approx. 1 particle per 300 ms for Bolo 184). The maximum proton energy available at TANDEM is 25 MeV, so we will use 25 MeV for a 'best case' and 5 MeV for a 'worst case' scenario. We also require that impacts with the window components do not cause a particle spread greater than the geometric size of the detector (and ideally, it would be far more controllable than this). However, as we decrease the incoming beam energy, we can expect a wider spread of particles.

7.2 Underlying physics

This section makes use of the principles of stopping power and ionisation, which we will briefly describe here.

7.2.1 Energy loss of particles in matter

Stopping power is the main principle we are interested in when determining how much of a material we can provide in our windows whilst minimising the energy loss and ion range of a charged particle. It is defined as the energy loss for a particular thickness of material (or simply S = -dE/dx). As a charged particle passes through a material, it ionises and loses energy as it interacts with the atoms of the substrate. For a thick enough material, a charged particle of a particular energy may lose all its energy via ionisation. The thickness at which the particle loses all its energy is that particle's range in that particular material.

Particles with a positive or negative charge (the case for α particles and protons, both of interest to our work - we will neglect electrons for the moment, as their effects will be quantum in nature) will interact with substrate material electrons,
causing a loss of kinetic energy. Thus, the stopping power range depends on the mass and charge of the particle as much as it does on the target material. The energy loss per unit distance increases as the particle loses more energy, leading to an eventual peak (known as the Bragg peak, on the Bragg curve [133]). The density of the impacted material affects how much particle energy will be lost inside of it, and we can divide the stopping power by the target density to obtain the 'mass stopping power', defined as:

$$\frac{S}{\rho} = -\frac{dE}{\rho dx} \tag{7.1}$$

An accurate description was developed by Bethe [134] which takes into account relativistic and quantum mechanical effects:

$$\frac{dE}{\rho dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \beta^{-2} \left[\frac{1}{2} \log \left(\frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$
(7.2)

where N_A is Avogadro's number, r_e is the classical electron radius, m_e is the electron mass, z is the charge number of the incident particle (for protons it is 1, for α particles it is 2), Z is the atomic number of the target, A is the target's atomic mass, $\beta\gamma$ is p/Mc (where p is momentum), I is the mean excitation energy in eV, $\delta(\beta\gamma)$ is the density effect correction to ionisation energy loss, and W_{max} is the maximum energy transfer from a single collision:

$$W_{\rm max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/m)^2}$$
(7.3)

or for 'low energies', $W_{\text{max}} = 2m_e c^2 \beta^2 \gamma^2$. These equations have been taken from "Passage of particles through matter" (the unabridged version of the Particle Data Group (PDG) booklet [135]).

There are several types of collisions which result in an energy loss in a particle passing into a target:

1. Electronic stopping power: The incident particle passes near to a target

atom, resulting in an inelastic (loss of energy) collision with an electron orbiting a target atom. This can excite or eject local electrons. The incident particle, if it is a proton or an α particle, will not lose a significant amount of energy in this collision, nor will its trajectory be altered very much, due to its momentum which is much larger than that of an electron. Slowing by electronic stopping power is mostly a macroscopic result of a very large number of such collisions.

- 2. Nuclear stopping power: The incident particle passes near to a target atom and collides elastically with it, having its trajectory altered by the repulsive potential energy of the target nucleus. For the purposes of this chapter, we can neglect nuclear losses which only have a significant contribution at a few keV and give a sub-µm track length in Si.
- 3. **Radiative stopping power (Bremsstrahhlung)**: The incident particle impacts with a target atom and interacts inelastically with the atom, creating secondary particles (incident proton with altered energy + recoil nucleus) and photons.

When the ion first passes into a material, the stopping power is dominated by the electronic stopping domain as the ion still has the majority of its initial momentum. As it begins to lose more of its energy, its momentum will decrease, and it will be more vulnerable to nuclear collisions (which will increase the straggle of the ion). Eventually, this develops into cascades of collisions. At this point, the ion is usually stopped unless it has traversed the full thickness of the target material. A diagram of this process is shown in Figure 7.1.

Of particular interest to the case of window development for this experiment is the notion of multiple (Coulomb) scattering, where the particle is deflected many times by the nuclei of the medium it is impacting, changing its trajectory each time by a small angle. This is particularly problematic when the target material consists of many layers (which is our case, having multiple windows). We would like to know (almost) exactly where we are irradiating the detector, which becomes difficult when our particle beam will traverse many thick layers of material which



Figure 7.1. Contributions of stopping power domains in the slowing of an incident particle as it is absorbed by a target material. Taken from [136] (ⓒ())

will scatter the incoming particle in a 'random' way. The distribution of scattered angles is approximately Gaussian [135] with RMS:

$$\theta_0 = \frac{\Delta pms}{\beta p} z \sqrt{\frac{x}{X_0}} [1 + 0.038 \cdot \ln(\frac{x}{X_0})] \tag{7.4}$$

where $\Delta pms = 13.6 \text{ MeV} / \text{c}$ and where x/X_0 is the thickness of the medium in radiation lengths:

$$X_0 = \frac{4\alpha r_e^2 N_A}{Z(Z+1) \cdot \ln(287/\sqrt{Z})}$$
(7.5)

where α is the fine structure constant. We see that the angular distribution of the incoming ion is inversely proportional to its momentum (and therefore its energy) and velocity, so we expect less straggle for a higher-energy beam [137]. The first term in equation 7.4 is the strongest in terms of the angular distribution, as the radiation-thickness of the medium is square rooted. Part of the problem of using a beam line for these types of measurements is that they will not have relativistic velocities / high momenta, and the $\sqrt{x/X_0}$ term therefore becomes



Figure 7.2. dE/dx for muons in copper, showing the various regimes of stopping power energy loss as a function of the incoming particle energy. Image taken from [137].

significant; we have to keep the windows as thin as possible. For this reason, we simulate the lowest energy we might get from our experiment, which is the 'worst case' scenario in terms of energy loss and scattering radius.

We show a visual representation of the stopping power and its various regimes in Figure 7.2, for muons in copper. At the lowest energies, dE/dx is dominated by nuclear losses. The stopping power decreases rapidly between 1 to ≈ 150 MeV/c, where it reaches its lowest point - the regime of minimum ionisation. dE/dx climbs again up to ≈ 9 GeV/c, where radiative effects reach 1%. As energy increases further, radiative losses become the dominant effect.

7.3 Computer simulations of ion collisions

The simulations we describe in this chapter operate on the principle of the Binary Collision Approximation (BCA). In our specific case, we will Monte-Carlo BCA, in which we will simulate a large number of incoming particles in order to obtain a distribution of probable ion scattering and energy losses in a host material. For these simulations, we have used Stopping and Range of Ions in Matter (SRIM), a software package by James Ziegler [138]. SRIM assumes that each target layer is amorphous and injects N particles of a particular energy, and a set angle, into the material, and chooses random locations and parameters of collidable target atoms based on the atomic composition of the target material. It illustrates the incoming ion trajectories and provides the energy loss from the ion into the material. For the purposes of testing window designs, it is an ideal candidate.

7.4 Candidate materials for the windows

The outer window separates the inside of the cryostat (which is under vacuum) from the atmospheric pressure outside the experiment. It is also the window presenting the most risk in terms of external radiation leakage (optical and thermal). For these reasons, it must be the thickest window. Previous experiments have tested bolometers in TANDEM - post-Planck, the HFI core team tested HFI bolometers in a cryostat on the beam line at TANDEM. However, those tests involved a much smaller cryostat (holding only a small number of detectors), which allowed for enough flexibility to utilise a split-vacuum configuration directly from the output of the beam line itself. A split-vacuum configuration may be possible in our case, but until this is confirmed, we have based our window design on the assumption that it will not couple with the beam line vacuum.

We have chosen to test windows made from Mylar, polypropylene, and Kapton. For the outer window, we will test 100 μ m of Mylar with a 1 μ m layer of aluminium on the outside. We will apply a coating to shield for radiation later, but for the moment we will measure only the transmission in 100 μ m of each material.

Atom	Stoich. (at·mol $^{-1}$)	Disp. E	Lattice bind. E	Surface bind. E
Н	8	10 eV	3 eV	2 eV
С	10	28 eV	$3 \mathrm{eV}$	7.41 eV
Ο	4	28 eV	3 eV	2.0 eV

Table 7.1 – Atomic parameters for Mylar window simulation in SRIM.

7.4.1 100 μ m of Mylar

This section will outline the tests on transmission in 100 μm of Mylar, using 5 MeV incident protons.

We simulated^{*} 20000 H ions (protons) at 5 MeV (worst-case). We take the composition of Mylar to be $H_8C_{10}O_4$ with parameters (stoichiometry, displacement energy, lattice binding energy, and surface binding energy) shown in Table 7.1. Parameters were largely taken from TRIM 2008 material libraries [139].

5 MeV protons in Mylar

We find a mean collision location of 54.6 μ m in x, 0.034 μ m in y, and 0.009 μ m in z. We find that out of 20000 ions, 19997 are transmitted (for a total transmission of 99.98%). Each ion produces an average of 3.7 vacancies.

We show visual results of the simulation in Figure 7.3, a heat map of the longitudinal collisions in the Mylar. We see that up to 10 μ m, most collisions are electronic, e.g. they do not affect the trajectory of the particles. After this point, the collisions appear to be the product of Coulomb interactions, where the effects of multiple scattering become more apparent. These angular deflections do not result in a significant straggle ($<\pm 2000 \ \mu$ m). Thus, we conclude that Mylar is a suitable candidate for our uses, even in the 'worst case' scenario of 5 MeV of input

 $^{^*}$ Using TRIM-2008 [139] inside the pysrim wrapper [140] using pysrim's extensive analytical tools.



Figure 7.3. Heat map of collisions of a 5 MeV proton plotted as a function of x and y location in 100 μ m thick Mylar, using log-scaled colour mapping. The units of one pixel are 2 μ m².

energy.

We can see the radial distribution of the collisions in Figure 7.4, in which we can see more detail about ions which have lost most of their energy and are subject to frequent electronic collisions which move their trajectory. The majority of the collisions are still in the central part of the material (0,0) and we see very few collisions outside of $\pm 1.2 \ \mu$ m, which indicates that the ions keep the majority of their energy.

Zooming into the central 2000×2000 nm and setting the bin size to be very small in Figure 7.5, we can see even more details about some of the electronic collisions and we see that the majority of the collisions are still remaining in the centre. As a result of all of this, we are confident that 100 μ m of Mylar is an appropriate thickness and material combination for the outer window, provided it can hold the vacuum of the cryostat.

7.4.2 100 μ m of Kapton Polyimide Film

We repeat the above simulation using 100 μ m of Kapton with 5 MeV protons. We take the Kapton composition to be H_{2.63}C_{69.1}N_{7.3}O_{29.2} with the parameters listed in Table 7.2 and a density of 1.42 g/cm⁻³.



Figure 7.4. Radial heat map of collisions of a 5 MeV proton plotted as a function of x and y location in 100 μ m thick Mylar, using log-scaled colour mapping. The units of one pixel are $4 \times 10^{-4} \mu m^2$.



Figure 7.5. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in 100 μ m thick Mylar, using log-scaled colour mapping. The units of one pixel are $4 \times 10^{-6} \mu m^2$.

Atom	Stoichiometry (atm.·mol. $^{-1}$)	Disp. E	Lattice bind. E	Surface bind. E
Η	25.641	10 eV	3 eV	7.41 eV
С	56.41	28 eV	3 eV	7.41 eV
Ν	5.128	28 eV	3 eV	2 eV
0	12.82	28 eV	3 eV	2 eV

Table 7.2 – Atomic parameters for Kapton window simulation in SRIM.



Figure 7.6. Heat map of collisions of a 5 MeV proton plotted as a function of x and y location in 100 μ m thick kapton, using log-scaled colour mapping. The units of one pixel are 2 μ m².

5 MeV protons in Kapton

We find a mean collision location at $x = 54.67 \ \mu$ m, which is considerably closer to the interface than the Mylar case. The mean collision in y and z are 0.01138 μ m and -0.00348 μ m (respectively). This means that the x, y, and z average collision locations are smaller than those in Mylar (in the case of y and z, smaller by an order of magnitude). We find that all 20000 ions are transmitted (transmission is 100%) and we produce an average of 3.6 vacancies per ion. The vast majority of the energy which is lost (99.96%) is again lost to ionisation, as in the Mylar case.

We show again collision heat plots, using pixel sizes which are identical to the ones in the previous section for Mylar. We see that the longitudinal collision locations (Figure 7.6) look almost the same, as we expect due to the average xlocation of the collisions being very close to the Mylar case.

The radial collisions are shown in Figure 7.7, with the same pixel size as the Mylar plots. We can see that the spread appears to be slightly smaller than in the Mylar case, which is supported by the greater transmission and lower average x and y collision locations.



Figure 7.7. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in 100 μ m thick Kapton, using log-scaled colour mapping. The units of one pixel are $4 \times 10^{-4} \mu m^2$.



Figure 7.8. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in 100 μ m thick Kapton, using log-scaled colour mapping, zoomed into the central 2000 nm. The units of one pixel are $4 \times 10^{-6} \mu m^2$.

If we zoom again into the central $4 \ \mu m^2$ region and decrease the pixel size to $4 \ \times \ 10^{-6} \ \mu m^2$ in Figure 7.5, we can more clearly resolve some of the behaviour of the collisions in the very centre of the target. We find that the 'collision cloud' is considerably smaller than in the Mylar case, which again supported by the increased transmission and the smaller x and y collision location averages. From this, we believe that Kapton is better for transmission and conserving the beam energy.

Atom	Stoichiometry (atms.·mol. $^{-1}$)	Disp. E	Lattice E	Surface bind. E
Н	6	10 eV	3 eV	2 eV
C	3	28 eV	3 eV	7.41 eV

Table 7.3 – Atomic parameters for polypropylene window simulation in SRIM.



Figure 7.9. Heat map of collisions of a 5 MeV proton plotted as a function of x and y location in 100 μ m thick polypropylene, using log-scaled colour mapping. The units of one pixel are 2 μ m².

7.4.3 100 μ m of Polypropylene

We repeat the experiment one final time using 100 μ m of polypropylene, chosen for its lower density (0.9 g/cm⁻³) and simpler composition with lighter atoms (H₆C₃). The parameters put into the simulation are shown in Table 7.3.

5 MeV protons in polypropylene

We find again a transmission of all 20000 ions, with an average collision location of $x = 53.35 \ \mu\text{m}$, $y = -0.0032 \ \mu\text{m}$, and $z = 0.0016 \ \mu\text{m}$. This is more-or-less the same as the Kapton case. We again have 3.6 vacancies per ion, and the energy which is lost goes 99.95% into ionisation and 0.01% into producing recoils.

We show again collision heat plots, using pixel sizes which are identical to the ones in the previous section for Mylar. The longitudinal collision locations (Figure 7.9) are very similar to the Kapton case, as we expect.

The radial collisions are shown in Figure 7.10, and the pixel side is again unchanged. The radial distribution of collision locations is almost indistinguishable from the Kapton case.



Figure 7.10. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in 100 μ m thick polypropylene, using log-scaled colour mapping. The units of one pixel are $4 \times 10^{-4} \mu m^2$.

If we zoom again into the central 4 μ m² region and decrease the pixel size to 4 \times 10⁻⁶ μ m², we see in Figure 7.11 that the radial behaviour with a smaller pixel size is again indistinguishable from the Kapton case.

Based on these simulations, we find that Kapton and polypropylene provide minimal energy loss in the target, and have 100% transmission. We have decided to move forward with window investigation using polypropylene, although the usage of either polypropylene or Kapton should be equivalent. Even using Mylar would not introduce a significant loss.



Figure 7.11. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in 100 μ m thick polypropylene, using log-scaled colour mapping. The units of one pixel are 4 $\times 10^{-6} \mu$ m².

Layer n^o	Material	Thickness (μ m)	Density (g/cm^3)	Composition
1	Al	1	2.702	Al
2	polypropylene	100	1.42	H_6C_3
3	air	22×10^3	1.19×10^{-13}	$O_{23}N_{75.5}Ar_{1.3}$
4	Al	1	2.702	Al
5	polypropylene	4	1.42	H_6C_3
6	air	9000	1.19×10^{-13}	$O_{23}N_{75.5}Ar_{1.3}$
7	Al	1	2.702	Al
8	polypropylene	4	1.42	H_6C_3
9	air	150×10^{3}	1.19×10^{-13}	$O_{23}N_{75.5}Ar_{1.3}$

Table 7.4 – Full multi-window simulation setup.

7.5 Simulations of full window setup

The first window must be the thickest, and we will simulate it using 100 μ m of polypropylene. In order to shield against thermal and optical radiation, we will coat the outside of the windows with 1 μ m of aluminium (chosen over copper due to the smaller Z, recalling that $\frac{dE}{dx}$ - equation 7.2 – increases proportionally to Z). The layout of each window is shown in Table 7.4. This gives us three windows, with residual atmosphere gaps[†] between them which are the equivalent size of the areas between the windows in the cryostat.

However, we quickly found that SRIM is prone to 'underflow errors' for unexpectedly low densities ('vacuum' is not an option when setting the material parameters for a gas). Setting the air density to $< 1 \times 10^{-4}$ g/cm² (to simulate air at lower pressure) causes the air density to default to 0 g/cm³, and interestingly this causes no collisions to be registered past the first air gap. We do expect some collisions to occur in these air gaps (because the vacuum is imperfect and a few O₂ and N₂, and Ar molecules will exist in the space), but the effect will probably be negligible. So for the simulations performed in this section, we have removed the air gaps, and will stack only layers 1, 2, 4, 5, 7, and 8.

[†]An air density of 1.19×10^{-13} corresponds to air at 1×10^{-7} mbar - this is higher than the vacuum we achieve in the cryostat.



Figure 7.12. Heat map of collisions of a 5 MeV proton plotted as a function of x and y location in the full window setup (minus the vacuum gaps), using log-scaled colour mapping. The units of one pixel are 2 μ m².

5 MeV protons in the full window setup

We find a transmission of 19996 / 20000 ions (99.98%) for the full window setup with zero air gaps. We show the full heat map of xy collisions in Figure 7.12 (and with greater resolution in Figure 7.13). Up to 104 μ m is the first window (Al + polypropylene), and the more 'interesting' collisional attributes occur in the thinner windows following. The 5 MeV beam maintains 76% of its original energy. Since 5 MeV is a 'worst case' scenario and our experiment will be at higher energies, we expect a less significant attenuation at the energies of interest (10 - 25 MeV).

In spite of the extra layers (including the thin layer of Al), the radial spread (Figure 7.14) is not much different to the 100 μ m case. There are many events which have experienced collisions outside of the main 'column' of central collisions, but these are 1-2 collisions at the most. Zooming into the inner 2000 nm of the radial spread, we can see particle trails from nuclear collisions (Figure 7.15. Even zoomed into the centre and with a much smaller bin size, the majority of the collision sites with more than 10 collisions along the entire window system are constrained very close to the centre, indicating that the beam energy is mostly conserved.

The average collision location in x is at 59.39 μ m. In y and z, the average collision location is 0.0079 μ m and 0.024 μ m (respectively). The radial spread is



Figure 7.13. Heat map of collisions of a 5 MeV proton plotted as a function of x and y location in the full window setup (minus the vacuum gaps), using log-scaled colour mapping, zoomed into the final 3 thin windows. The units of one pixel are 0.02 μ m².



Figure 7.14. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in the full window setup, using log-scaled colour mapping. The units of one pixel are $4 \times 10^{-4} \ \mu m^2$.



Figure 7.15. Radial heat map of collisions of a 5 MeV proton plotted as a function of y and z location in the full window setup, using log-scaled colour mapping and zoomed into the inner 2000 nm. The units of one pixel are $4 \times 10^{-6} \mu m^2$.

slightly larger than the case of 100 μ m polyethylene alone, but not significantly so. The extra layers do not appear to make a huge difference in the beam behaviour.

7.6 Conclusions

We have simulated a window system for the cryogenic test system at IAS, in order to verify conservation of the beam size and energy for our experiment. We have tested 100 μ m thickness Mylar, Kapton and polyethylene as materials for the thickest window, finding that all 3 materials are suitable and do not significantly attenuate a 5 MeV proton. Kapton and polyethylene both exhibit 100% transmission of all 20000 ions in our Monte Carlo test. We then simulated a 4 window setup using our 100 μ m of polyethylene, coated with 1 μ m of aluminium. The remaining windows are 4 μ m polyethylene with a 1 μ m Al coating to minimise stray thermal and optical radiation.

We find that the transmission of the entire setup is almost 100% for 5 MeV protons, and that the average spread of the ions (as measured by the details of their collisions from SRIM) is negligible compared with the size of the proton beam at TANDEM (which is of the order of 150 mm², several orders of magnitude higher). In addition to the windows, we will need a thick metal diaphragm on the outside of the cryostat (and perhaps outside each window on the other stages) to attenuate the beam; the beam has a variable current, but the rate is presently unknown. In order to carry out our measurements, we will need to have no more than one particle per the time period it takes for thermal energy from impacts to relax. The development of the diaphragms remains to be done and will be the topic of future work, such that the interfaces are completely ready by mid-2019.

Part VI

Conclusions

Water does not resist. Water flows. When you plunge your hand into it, all you feel is a caress. Water is not a solid wall, it will not stop you. But water always goes where it wants to go, and nothing in the end can stand against it. Water is patient. Dripping water wears away a stone. Remember that, my child. Remember you are half water. If you can't go through an obstacle, go around it. Water does.

- Margaret Atwood

Chapter

Conclusions

8.1 Review

We have investigated the effect of cosmic rays in CMB and X-ray space missions in a number of different ways; first by measuring and modelling the effect of charged particles on highly-sensitive, low-temperature detectors, then by simulating the thermal fluctuations from cosmic ray arrivals on the detector of the X-IFU instrument for ATHENA, and then by reporting on contributions to the design of a cryogenic test system for measuring high-energy protons impacting on detectors via coupling to the beam line of a particle accelerator. In this section, we will discuss the conclusions of these studies.

8.1.1 The Bolo 184 study

Reproducing pulses in a detector is difficult. In some ways, Bolo 184 is a simple case; there is no thermal coupling of the absorber to anything other than the sensor, so in the case of a monoenergetic particle source, the total energy deposited in the absorber is always the same (for a given α particle). Bolo 184's purpose was to act as a generic detector and source of pulses, which we can use to understand the complex physical mechanisms behind 'glitch physics'; to be generic, it is advantageous that the bolometer's thermal processes are simple. However, the

pulses measured in Bolo 184 have nonstandard and varied statistical effects; the pulses change shape with particle impact position, the shape is affected by various nonlinearities depending on the working point, the pulse amplitude is determined by position which determines the speed of thermal phonons arriving to the sensor, and we can neglect neither the effect of ballistic phonons, nor the effect of thermal propagation. A balance of many types of physics comes into play when modelling the bolometer behaviour - solid state physics, various aspects of thermal physics, and, of course, bolometer physics. Many lines of thinking were followed throughout the course of this manuscript. Some of them were successful, and others were not.

This leads us to what we now believe to know about this bolometer. We have found that the standard assumptions about glitch topology, i.e. the belief that cosmic ray glitches are composed of 'ballistic energy' and 'thermal energy' is most likely incorrect. The classical pulse fitting techniques, the sum of two double-exponentials, are a good approximation of the shape of the glitch. However, they are heavily dependent upon a nonphysical parameter, reaching about 20% of the pulse height for the smallest pulses and reaching a small negative number for the largest ones, in order to fine-tune the χ^2 . We have concluded that the maximum amplitude of the pulse does not relate to its energy, but to its position. We have found that, because of this, normalising the amplitude of all pulses throws away valuable information. It is, indeed, possible to measure the rise time of a glitch, and it is necessary for finely resolving its characteristics.

In Section 2.2.4, we introduced a new function for resolving the shape of these pulses, which is based on thermal physics. A time constant describing the propagation of heat from the absorber to the sensor, τ_3 , has been shown to play a significant role for the smallest-amplitude (most distant from the sensor) pulses. All of this leads us to conclude that heat propagation is an important aspect of the glitch shape in this detector, but also that the once-believed 'ballistic' and 'thermal' components of the pulse are neither 100% ballistic, nor 100% thermal.

We first examined the behaviour of ballistic phonons through a Monte-Carlo model, assuming that ballistic phonons have a thermalisation length related to their mean free path (assumed to be smaller than the disc radius), that the thermalisation time is nearly instantaneous, and that phonons impacting the disc border will thermalise there due to Casimir effects for surface irregularities in thin films. This model was intuitive because it explained many of the statistical data attributes; far away α impacts had a slower rise time, and closer α impacts had a faster one. Intuitively, it seemed we could simply convolve the $\frac{dT}{dx}$ of the model output with the bolometer's response function, obtained through a different model. The results did not reproduce the expected data features, hinting that modelling this bolometer was more complicated than expected. From this, it was decided to simplify the modelling in order to probe the more basic behaviour of the system.

The decoupling of the 'fast' and 'slow' pulse components from measuring the bolometer at a low temperature (100 mK) with a high V_{bias} were always attributed to general nonlinearities in the data. These pulses were dismissed as 'unideal' since some of them expressed a temperature dipping below the steady state temperature of the device, which was believed to be a nonphysical effect. A closer look at this behaviour via modelling has allowed us to examine the effects of electro-thermal feedback and stray capacitance in this device, allowing us to reproduce the behaviour of the pulses using a very simple two-block model. The reproducibility of the data pulses using this simple model allows us to visualise and explain this particular nonlinearity.

We saw in the final set of α particle data (Section 3.1, page 109) that some behaviour occurred which did not match the previous conclusions - the fast and slow pulse components were not distributed in a straight line, but rather as a curved one with branches (in both integral and in amplitude). This behaviour was resolvable only with the new fitting algorithm, taking into account heat propagation in the disc, and through employing the new cryogenic system with very high thermal stability. This result was surprising, but we may have seen hints of it sooner than initially believed; the final 100 mK data in SYMBOL (Section 2.2.5, page 100) also had some anomalies for pulses with a high ballistic and low thermal component - the same region where the branching occurs in the latest data. One potential explanation for the branching effects in this data would be reflections on the border, either from thermal energy or from ballistic phonons which reflect off the disc border and thermalise at a mid-point. It became clear at this point that heat propagation effects play a significant role, and that reflections need to be considered.

Returning again to the absorber, two models were tested to see whether ballistic phonon thermalisation is governed by a geometrical law (similar to ray-tracing) or whether it is dependent on a mean free path law. Both studies produced similar results. The geometrical model assumes that the phonon deposits part of its energy at every reflection, whereas the mean free path model assumes that all the energy is deposited at the final resting point. Both models produce results which are similar to what is seen in the 200 mK data, both in terms of 'energy-sharing' between the particles deposited inside and outside the region of the central sensor, and in terms of reproducing a distribution similar to the first fit amplitude A_1 . These results both depend on the assumption that ballistic phonons reflect at the disc border, lending credence to the earlier idea that this behaviour plays a part in the pulse attributes we see in the final 100 mK data set. Both models produce results which are similar to in shape to the fast amplitude distribution. The reflective absorber model requires an effective central radius of 600 μ m, indicating that the part of the absorber disc with a strong thermal coupling to the sensor is much larger than the geometrical size of the sensor. The geometrical model also produces quantitatively similar results, for a slightly smaller radius. If phonons thermalise following a mean free path law, the mean free path must be larger than the disc radius. If they follow a geometrical law, the behaviour depends only on the size of the strongly-coupled central region of the disc. In both cases, we must allow ballistic phonons to reflect on the disc border. From this, we conclude that ballistic phonons do indeed reflect on the disc border rather than thermalising there (which might have been the case depending on the surface conditions of the disc edge). This lends credence to our earlier interpretation of the branching effects in the most recent Bolo 184 data.

Finally, a nonstandard experiment was performed where we pulse the bias power of the bolometer in order to visualise its transient properties. This does not relate directly to the cosmic ray issue, but helps us to understand how the bolometer and thermal chain behaves. Quickly pulsing the bias power of the bolometer results in a change in the working point of the bolometer, and the pulse shape as the signal relaxes is difficult to interpret physically. We find that the rising time constant throughout the experiment is constant over all temperatures and bias voltages, meaning that the rise time we see is one which relates to the bolometer and its convolution with the various capacitances in the system. These pulses have a long decaying slope which varies with V_{bias} , and some of the pulses at specific V_{bias} have second time constants which likely have meaning, but are difficult to interpret physically. This long time constant may relate to the rapid change in the working point of the bolometer, but this is speculative at this time. We have followed this experiment with modelling, which produces some data features, but not all of them; lower V_{bias} produces larger shifts in the data, obfuscating the initial rise and decay times, and the effect changes with increasing V_{bias} as expected. The overall pulse shape is the same, but with a longer rise time, and missing the long decay time constant seen in the data. It does produce the generic response function which we have seen throughout the work, and we see how this varies with temperature and bias power.

We have also used averaged α particle pulses over a range of bias voltages (thus a range of places on the IV curve at a particular temperature) to measure detector responsivity, which are mostly coherent with the responsivity curves predicted by the IV characteristics. This treatment is advantageous in the case where responsivity calculations using photons are not directly available given the configuration of a cryostat. This treatment could also be potentially useful in an active space mission e.g. by employing an α particle source with a low emission rate to calibrate and check detector responsivities during flight (at the drawback of adding a small but well-characterised noise source).

We have not fully reproduced every single aspect of the data we measured using this bolometer. We have increased our understanding of its behaviour under α particle radiation, and this understanding should the way towards predicting pulse behaviour in this detector. This knowledge could be applied to other detectors, as long as we account for thermal pathways and other types of physics (e.g. superconductivity in the case of superconducting detectors).

8.1.2 The Athena X-IFU wafer study

This study was not a 'detector study' inasmuch as the detectors are not actually taken into account. The context of the work product requested of the author was instead to simulate the detector wafer, estimating the thermal excursions resulting from impacts with cosmic rays. In many ways, this study was an inversion of the Bolo 184 study; no detectors, no ballistic phonons (not possible to directly simulate in COMSOL), no experiment (not even to verify the simulation results), and mainly focused on macroscopic properties derived from finite-element analysis. We have produced a COMSOL model for the X-IFU detector wafer based on the engineering information we have been given about the device, and using a simple heat pulse of a specific energy to simulate an impact from a cosmic ray. The final simulation accounts for all the layers and connections in the wafer, except for the detectors.

The instrument itself has many strong constraints in its systematics budget, particularly with respect to the energy resolution. The size of the wafer results in frequent impacts from cosmic rays, with an estimated impact rate during operation at L2 of 183 pulses / s. The cold plate is at 50 mK, and with superconducting detectors, problems from cosmic rays are highly likely. The instrument itself has a budget of 0.2 eV effects on energy resolution, above which the systematic effects degrade the energy resolution to unacceptable levels. The maximum budgeted $\Delta T_{\rm RMS}$ is 0.18 $\mu {\rm K}$ (f > 3 Hz) and 0.42 $\mu {\rm K}$ (f < 3 Hz). The result we obtain, that the most realistic model produces an RMS temperature of $\approx 0.33 \ \mu\text{K}$, is not a particularly surprising one. 0.32 - 0.39 μK RMS denotes these results as an area of further concern which could affect the energy resolution of the instrument to unacceptable levels. Moreover, the simulation has not been verified by any experimental study; the parameters used have been found using best practices, but some of them might be uncertain (with the RRR of the Au layer being particularly sensitive and showing implications for $\Delta T_{\rm RMS}$, which require further study). The study does not account for the effect of ballistic phonons, which we have previously concluded (in the Bolo 184 study) impart 100% of their energy into the crystal

structure, and reflect off crystal borders until they thermalise in the metallisation layer. Even if 99% of the ballistic phonon energy is immediately caught in the Au layer, the average incoming proton (1659 MeV), which will deposit 188.5 keV in the wafer (assuming a normal incidence, and larger otherwise), will leave a remaining 1.18 keV of thermalised ballistic phonon energy in the wafer. As we have seen in the study of Bolo 184, we never catch all of the ballistic phonons immediately in the metal layer, and can probably expect a much larger percentage of ballistic phonon thermalisation in the wafer. It may be the case that under a more realistic energy deposition scenario, the particle energy would present as a thermal profile of thermalised ballistic phonons rather than in the small area used in the COMSOL study. This could result in longer but lower-amplitude thermal excursions, and perhaps reduce the RMS temperature seen by the pixel. This is an effect which will need to be probed using experiments, or by supplemental studies in COMSOL.

The study in this manuscript made use of the second, larger set of GEANT4 data provided by INAF; this 'raw' simulation gave every secondary energy deposition. This data accounts for particles at a shallow striking angle by creating many smaller secondary energy depositions at varying x, y, and dt. A smaller and more manageable dataset, called the 'analysed' dataset, adds the secondary energies into one primary pulse at an average location and time. This 'reduced data' effectively flattens the primary event; the total energy is taken into account, but the particle is assumed to deposit all of that energy into one place and at the same time. The working group has presented results which state that their simulated timelines, which make use of the reduced data, produce a degradation of the energy resolution that is within the budget of concern. The results we present here imply that this assumption does not accurately account for the deposition of energy into the wafer, and that secondary particles must be taken into account.

We have proven the difference between the full and the reduced data sets by producing new timelines using both, using random and specific distances coming from the reduced data set. We find that $\Delta T_{\rm RMS}$ of timelines produced using the reduced data is larger by an order of magnitude, which is also an order of magnitude greater than the budgeted $\Delta T_{\rm RMS}$. However, calculating the FWHM of the sorted temperature profiles in both cases, and converting that FWHM to eV, allows us to simulate the degradation of the energy resolution budget. We find that the main difference between the two is in the 12^{th} percentile value (consistent with greater low-level thermal fluctuations in the full data), but that the overall energy difference in both cases is ≈ 0.006 eV; nearly 2 orders of magnitude below the upper limit dictated by the energy resolution budget. We conclude that $\Delta T_{\rm RMS}$ is not a reliable metric for determining the magnitude of the fluctuations on the wafer temperature, but that the predicted energy FWHM is not either, as this is determined by the heat capacity (and because the noise arising from thermal fluctuations is non-Gaussian; the only way to conclude whether or not the energy resolution is affected is by putting the results into X-IFUsim and checking how the thermal fluctuations interact with the detector. Furthermore, the dT of the wafer for pixels at the edge of the array should be much higher (due to being closer to the particle impacts). Finally, the results here are already likely to be an underestimate, for the reasons we discussed in Chapter 6.

This study should be flagged for further review, and the effect on the energy resolution of the system should be put into the XIFUsim pipeline to verify the effect of this on the energy resolution - for both the 'full' and 'reduced' data. The parallel COMSOL model produced at GSFC should also be part of a parameter study between the two parallel models, to check the results against each other. The effects of different particle effects (e.g. α particles vs. protons) must also be accounted for. The author will also be repeating the timeline production process using the superposition assumption, to verify whether or not it is a valid assumption for the production of T(t) timelines.

8.1.3 Cryogenic system window study

It is unfortunate that the cryogenic system could not be completed in time for the windows to be fully implemented before the end of this work. It has been very useful to use such a reliable internal source of 5.4 MeV α particles throughout this work - the reliability of the energy distribution of ²⁴¹Am has allowed us to

completely characterise this detector. However, to fully understand how a detector will behave under space-like conditions, we have to measure the most space-like particles; protons, at a wide range of energies. Once the windows for this system have been constructed, it will be possible to measure the behaviour of a full detector array or even focal plane elements under a significant range of space-like conditions. This could be further supplemented with (e.g.) electron sources such as 207 Bi, which has been used in the past to provide conversion electrons of 482 and 976 keV (a few e⁺ / min) using a source internal to the cryostat [141].

8.2 Final thoughts

The Planck data removal was largely successful, but many aspects of those pulses are still not understood. Some of the pulses, for example, appeared to have no 'ballistic' (fast) component at all^{*}. Discussions with various actors in Planck and in Athena have posed the idea that it might be best to find ways of cancelling out the ballistic phonon propagation in detectors or detector arrays. Stopping ballistic phonons from propagating is certainly useful in the case of large arrays where many detectors can be affected by a single impact. However, the energy imparted by impacts, as we discussed either, is never 100% ballistic, and the ballistic phonons radiate isotropically, so eliminating them completely before they thermalise and create a thermal signature with a much longer time constant is nontrivial. There is always some thermal component to a cosmic ray glitch, and by removing the fast part of the signal, we are left only with a baseline temperature variation which could add a non-Gaussian noise source to the data. By leaving the fast component intact, we at least have a better chance of fitting to and removing the entire pulse. This is highly detector and array dependent; an independent decision needs to be made for each technology. The takeaway message is, then: ballistic phonon and heat propagation are both important mechanisms, and you cannot have one without having the other. Both must be understood in these systems in order to minimise the glitch effect in modern space instruments.

^{*}There is no citation for this claim, as it is based on a conversation during a meeting with G. Patencheon at APC.

We only would have learnt about the pulses in Bolo 184 by using experiments. We have formed our complete understanding about the physics happening in this detector based on the statistical distribution of the analyses found in the data. We' already know from Planck that we cannot forget about systematic effects, and that as the scientific requirements of various missions increase, so does the technology vulnerability to the systematic effects. We have studied the cosmic ray problem in Athena X-IFU, but we would be remiss in concluding that a problem, or a lack thereof, exists based on simulations alone. There are far too many unknown variables in the complex schema of glitch physics in multi-layer, multi-physics systems such as Bolo 184 or X-IFU. We must substantiate our findings with experimental science, because that is the only way we will capture the complex physical mechanisms and their interaction with each other.

In terms of carrying this work forward into the future, e.g. for a potential postdoc, there are a few streams:

- 1. Addressing the ground leak on the new cryogenic system, in order to remeasure the branching effects on α particle pulses at 100 mK. There appears to be interesting physics to understand here, and verifying that the effects appear again under stable conditions are a first step. Some work on the systematics of that system, e.g. electrical leakage leading to the false pulses from the chiller, could allow for us to finally resolve a reliable cosmic ray signature in addition to probing the potential reflective effects from the α pulses.
- 2. Adding the windows we described in Chapter 7, and doing first tests of Bolo 184 in front of a particle accelerator, would give us a reliable source of protons at various energies. This would allow us to compare the pulse shape from α particles with that of protons, which will be very useful in understanding the thermal physics, the role of ballistic phonons vs. heat propagation in these conditions, and the way that pulse behaviour scales with energy. Ability to scale with energy would also give us more tools to produce a reliable pulse

'library', which is a technique that could be moved to other detectors.

- 3. A deeper study on X-IFU, to compare timeline simulations with and without secondary energy depositions, is vital in the more immediate sense. Following this, a study on the RRR would be useful in probing its potential effects on the RMS temperature. Various other mitigating effects could be tested, including variations on the heatsink and various aspects of wafer design. These changes could be integrated into the design specifications during the beginning of development phase B. Of course, the results of the study presented here (and any subsequent studies) should be investigated using an experiment on a representative wafer. A cryostat designed for testing such a wafer, and large enough to accommodate its readout electronics, exists at IAS and would be simple to coordinate for these purposes.
- 4. A ballistic phonon study or experiment on X-IFU would allay some suspicions about their effects in this specific wafer.
- 5. Disconnection of the thermal low-pass filter on the Bolo 184 block and a repeat of the Joule pulsing study, to test whether this is the source of the long time constant.

Cosmic ray effects in highly-sensitive detectors probably cannot be eliminated completely. However, they can be understood and managed through careful balancing of the relevant thermal and nuclear physics. This relies on experimental work, which can be used to form the basis of understanding for every detector. We have used Bolo 184 as a generic bolometer to show this principle. Careful examination of the bolometer, the physics of energy deposition, and its effects on the thermal chain should be carried out early in the development of any sensitive space-bound mission, rather than aiming for full 'removal' (which is impossible and can introduce further systematics).
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Titre : Caractérisation et modélisation de l'interaction entre les détecteurs bolométriques sub-Kelvin et les rayons cosmiques

Mots clés : astrophysique, instrumentation, cosmologie, interactions des particules, bolométres, submm, rayon X

Résumé : Nous avons étudié l'effet des rayons cosmiques dans les détecteurs en utilisant un bolomètre de germanium composite NTD à basse température, et une source de particules alpha comme source générique d'impulsions. Nous avons caractérisé ce bolomètre en constatant que la forme de son impulsion était due à la combinaison de sa réponse impulsionnelle (la somme de deux exponentielles doubles), et des effets liés à la position découlant de la thermalisation des phonons balistiques en phonons thermiques dans son absorbeur. Nous avons établi un schéma décrivant la forme de l'impulsion dans ce bolomètre en comparant une impulsion mathématique générique à une seconde description basée sur la physique thermique. Nous constatons que la thermalisation des phonons balistiques, suivie de la diffusion thermique, jouent un rôle important

dans la forme de l'impulsion, en parallèle avec le couplage électrothermique et les effets électriques dépendant de la température. Nous avons modélisé les impulsions en observant que leur comportement peut être reproduit en tenant compte de la réflexion de phonons balistiques sur le bord de l'absorbeur, avec un couplage thermique fort au capteur central du bolomètre. Compte tenu de ces résultats, nous étudions également les effets des rayons cosmiques sur l'instrument Athena X-Ray Integral Field Unit (X-IFU), en produisant des timelines simulées et en testant la hausse de la valeur moyenne de la température (RMS) sur la plaquette du détecteur. Nous montrons que le flux thermique attendu des rayons cosmiques est au même ordre de grandeur que le maximum autorisé $\Delta T_{\rm RMS}$ ce qui constitue une menace sur le budget de la résolution énergétique de l'instrument.

Title : Characterisation and modelling of the interaction between sub-Kelvin bolometric detectors and cosmic rays

Keywords : astrophysics, instrumentation, cosmology, particle interactions, bolometers, sub-mm, x-ray

Abstract : We have studied the effect of cosmic rays in detectors using a composite NTD germanium bolometer at low temperatures and an alpha particle source as a generic source of pulses. We have characterised this bolometer, finding that its pulse shape is due to a combination of its impulse response function (the sum of two double exponentials), and position-dependent effects arising from thermalisation of ballistic phonons into thermal phonons in its absorber. We have derived a scheme for describing the pulse shape in this bolometer, comparing a generic mathematical pulse shape with a second description based on thermal physics. We find that ballistic phonon thermalisation, followed by thermal diffusion, play a significant role in the pulse shape, along with electro-thermal coupling and temperature-dependent electrical effects. We have modelled the pulses, finding that their behaviour can be reproduced accounting for ballistic phonon reflection off the absorber border, with a strong thermal coupling to the bolometer's central sensor. With these findings, we also investigate the effects of cosmic rays on the Athena X-Ray Integral Field Unit (X-IFU), producing simulated timelines and testing the average RMS temperature increase on the detector wafer, showing that the expected cosmic ray thermal flux is within the same order of magnitude as the maximum allowed $\Delta T_{\rm RMS}$, posing a threat to the instrument's energy resolution budget.