

Multipole Injection Kicker studies and commissioning for a transparent injection in the SOLEIL synchrotron Randy Ollier

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Multipole Injection Kicker studies and commissioning for a transparent injection in the SOLEIL synchrotron

Etudes et mise en service d'un Kicker d'Injection Multipolaire pour une injection transparente au Synchrotron SOLEIL

Thèse de doctorat de l'université Paris-Saclay

École doctorale n°576, Particules Hadrons Énergie et Noyau : Instrumentation, Image, Cosmos et Simulation (PHENIICS) Spécialité de doctorat : Physique des accélérateurs Graduate School : Physique. Référent : Faculté des sciences d'Orsay

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THESE DE DOCTORAT

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ÉCOLE DOCTORALE



Particules, hadrons, énergie et noyau: instrumentation, imagerie, cosmos et simulation (PHENIICS)

Titre : Etudes et mise en service d'un Kicker d'Injection Multipolaire pour une injection transparente au Synchrotron SOLEIL

Mots clés : Sources de lumière synchrotron à anneau de stockage, simulation, injection, Kicker d'Injection Multipolaire, stabilité faisceau, diagnostics à haute performance

Résumé : Les sources de lumière synchrotron à anneau de stockage de troisième génération, à faible émittance de l'ordre de quelques nm rad, furent mises en service à partir des années 90 afin que les physiciens bénéficient de faisceaux de photons hautement brillants. Pour cela, des aimants à plus forte focalisation et des insertions à aimants permanents furent utilisés. En contrepartie, le taux de perte d'électrons stockés augmente. Cela affecte la position des points sources des lignes de lumière, leur optique et les diagnostics de l'anneau, car la baisse d'intensité du courant stocké induit une variation significative de la charge thermique. Les limitations liées aux modes d'opération par décroissance du courant ont conduit à l'avènement du mode top-up. Il s'agit de maintenir l'intensité du courant stocké constante. Ainsi, l'injection de nouveaux électrons est un processus fréquent. Aujourd'hui, la plupart des synchrotrons fonctionnent en mode top-up, mais un inconvénient majeur est mis en évidence par des utilisateurs. Le processus d'injection, malheureusement détecté par certaines lignes de lumière, est devenu gênant par son taux de répétition élevé. En effet, le faisceau d'électrons stocké est systématiquement perturbé par les aimants d'injection impliqués. C'est pourquoi les physiciens et ingénieurs des accélérateurs élaborent des solutions pour préserver la stabilité du faisceau. Opérer un synchrotron en mode top-up tout en garantissant une injection transparente, caractérisée par des perturbations de la position du faisceau stocké inférieures à 10% de sa taille rms, est un véritable défi. Aujourd'hui, cette tolérance est encore plus stricte en raison de l'avènement des synchrotrons de quatrième génération où les seuils de stabilité tombent à 2% ou 3%.

Le schéma d'injection standard de l'anneau de stockage de SOLEIL $(2.75 \,\mathrm{GeV})$ repose sur deux aimants à septum et quatre kickers dipolaires rapides installés dans une section droite de 12 mètres de long. L'injection consiste à déplacer localement

et momentanément le faisceau stocké en utilisant les kickers. Le réglage parfait des kickers, qui permettrait d'atteindre la transparence, est impossible, car il nécessite que les alimentations pulsées, les dépôts de Ti des chambres céramiques et les composants électroniques des aimants soient identiques. Afin d'éviter de déplacer le faisceau stocké, les quatre kickers peuvent être remplacés par un seul aimant pulsé, dont le champ magnétique a une forme octupolaire, fournissant une zone sans champ sur la trajectoire du faisceau stocké et une déviation horizontale au faisceau injecté qui minimise l'amplitude de son oscillation betatron. Ce Kicker d'Injection Multipolaire (MIK), développé dans le cadre d'une collaboration entre SOLEIL et MAX IV, actuellement en opération dans son anneau de stockage (3 GeV), démontre qu'il répond au cahier des charges. Une copie du MIK fut installée dans une section droite courte de l'anneau de SOLEIL en janvier 2021. Des perturbations inférieures à 2% de la taille rms du faisceau stocké furent mesurées en utilisant les diagnostics haute performance récemment mis en service. Dans mon manuscrit, les principales difficultés de conception d'un aimant si innovant sont détaillées (dépôt de Ti, tolérances d'alignement, forme d'impulsion, etc). Les développements apportés à la modélisation et l'optimisation de l'injection MIK, grâce aux codes TRACY-III et Accelerator Toolbox, sont présentés. Les performances de l'injection MIK modélisées sont comparées à celles du modèle d'injection standard, puis corrélées aux résultats expérimentaux. Les diagnostics haute performance, fournissant des mesures tour par tour des pertes électroniques, de la position et de la taille du faisceau, sont essentiels lorsque de tels niveaux de stabilité du faisceau sont atteints. Ils sont aussi présentés en détail. Enfin, les mesures de certaines lignes de lumière caractérisant les performances des deux schémas d'injection sont fournies.

ÉCOLE DOCTORALE



Particules, hadrons, énergie et noyau: instrumentation, imagerie, cosmos et simulation (PHENIICS)

Title : Multipole Injection Kicker studies and commissioning for a transparent injection in the SOLEIL synchrotron

Keywords : Storage ring-based synchrotron light sources, simulation, injection, Multipole Injection Kicker, beam stability, high performance diagnostics

Abstract : Third generation storage ring-based synchrotron light sources, characterized by low emittance on the order of a few nm rad, have been commissioned since the 90s' in response to the need for physicists to benefit from high brilliance photon beams. The requirement was achieved thanks to stronger focusing magnets and permanent magnet-based insertion devices. However, this tipping point has a significant cost. Achieving such emittance levels by means of strong focusing increased the electron loss rate. Hence, the average current intensity in the storage ring decreases more rapidly. This adversely affects the position of the source points, beamline optics and diagnostics due to the large resulting thermal drift of the storage ring. The significant limitations of the so-called decay mode led to the advent of top-up operation. The goal is to keep the average current intensity in the storage ring constant. Thus, injection of new electrons occurs frequently. Nowadays, many light sources are operated worldwide in top-up mode, but a major drawback has been reported by the users. The injection process, which is undesirably detected by the beamlines, has become inconvenient due to its high repetition rate. Indeed, the stored beam is perturbed by the injection magnets involved. Accelerator physicists and engineers are already looking for solutions to overcome this limitation as many projects have been launched. Achieving transparent top-up injection, characterized by stored beam position perturbations lower than 10% the root mean square (rms) of the stored beam size, is very challenging. Today, this tolerance is even more stringent with the advent of fourth generation synchrotrons, thresholds falling to 2% to 3%.

The most common injection scheme for synchrotrons relies on one or several in-air and invacuum septum magnets along with several fast dipole kickers installed preferably in a straight section of the storage ring. In this context, the in-

jection generally consists in providing a local transient bump, using the kickers. The standard injection scheme of the SOLEIL 2.75 GeV storage ring relies on this principle and devices (two septum magnets and four kickers installed in a 12meter-long straight section). Perfect matching of the kickers to meet the perturbation tolerances is impossible since it would require at least identical pulsers, magnets, Ti coated ceramic chambers and electronics. To dispense with the injection bump, the four kickers can be replaced by a single pulsed magnet, benefiting from an octupolar shaped magnetic field providing a field-free region in the stored beam path and a horizontal kick to the injected beam which minimizes its betatron oscillation amplitudes. This Multipole Injection Kicker (MIK), developed in the frame of a collaboration between SOLEIL and MAX IV, and currently installed in the MAX IV 3 GeV storage ring, has proven to meet the transparency specifications. A copy of the MIK has been installed in a short straight section of the SOLEIL storage ring in January 2021. Perturbations of less than 2% the rms size of the stored beam were measured using the newly installed high-performance diagnostics. In my manuscript, the major challenges inherent in designing such an innovative magnet are detailed (Ti coating, conductors' position tolerances, pulse design, etc). The simulation developments as well as the MIK injection optimizations, using TRACY III and Accelerator Toolbox, are reported. The performance of the modeled MIK-based injection is compared to that of the standard injection model. Then, results of the MIK commissioning are presented in depth along with the high-performance diagnostics providing turn-by-turn position, beam size and losses measurements, which are essential when such levels of beam stability are to be achieved. Finally, beamlines measurements characterizing the performance of the bumped-based and MIK injection schemes are provided.

A mes heureux parents et ma tendre compagne. A tous mes proches en somme, ou morts ou bien en vie. A tous mes enseignants, à mes très chers amis. A Laurence pour finir, dont la voix m'accompagne.

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Contents

1	Rés	sumé	7
2	Intro	oduction	21
	2.1	Short history of light sources	22
	2.2	Towards top-up injection	23
	2.3	Technology for transparent injection	25
	2.4	Manuscript outline	26
3	Bas	sics of accelerator physics	29
	3.1	Single particle transverse beam dynamics	30
		3.1.1 Hamiltonian from the Cartesian to the curvilinear coordinate system	30
		3.1.2 Transformed curvilinear Hamiltonian	32
		3.1.3 Linear transverse equations of motion	33
	3.2	Solutions of the linear equations of motion	36
		3.2.1 On-momentum electron	36
		3.2.2 Off-momentum electron	38
	3.3	Some limitations of the beam dynamics	39
		3.3.1 Closed orbit distortions	39
		3.3.2 Energy-dependent tune shift	41
		3.3.3 Non-linear beam dynamics	41
	3.4	Electron beam parameters	42
		3.4.1 Transverse bunch size	42
		3.4.2 Transverse beam emittance	42
		3.4.3 Beam lifetime	44
4	Gen	neral background and diagnostics	45
	4.1		46

4.2	Synch	rotron SC	DLEIL	46
	4.2.1	Overview	Ν	46
	4.2.2	Accelera	ators, transfer lines and synchrotron radiation	48
		4.2.2.1	Linear accelerator, transfer lines and booster ring	48
		4.2.2.2	The storage ring	50
		4.2.2.3	2.84 T permanent magnet-based superbend	53
		4.2.2.4	Synchrotron radiation	55
4.3	Stand	ard injecti	ion into the SOLEIL storage ring	57
	4.3.1	Introduc	tion	57
	4.3.2	Introduc	tion to the current bump-based injection scheme of SOLEIL	59
		4.3.2.1	Overview	59
		4.3.2.2	Principle of the standard injection in the SOLEIL storage ring	60
		4.3.2.3	Limits of the standard injection scheme	65
4.4	MIK in	jection .		67
	4.4.1	Principle	e of the MIK injection scheme	67
	4.4.2	Mechan	ical design of the MIK	70
	4.4.3	Magneti	c field design	73
		4.4.3.1	Ideal simulated field	74
		4.4.3.2	Measured field	78
4.5	Contro	ol comma	nd system and analysis Tools	85
	4.5.1	Control	command system	85
	4.5.2	Analysis tools		
		4.5.2.1	Matlab Middle Layer	87
		4.5.2.2	Accelerator Toolbox	87
		4.5.2.3	TRACY III code	88
		4.5.2.4	General aspects of the AT and TRACY III models	88
		4.5.2.5	The 2.8 T permanent magnet-based superbend	90
4.6	Diagn	ostics and	d measurement methods	92
	4.6.1	Beam po	osition monitors	92
		4.6.1.1	Beam position monitors setup	92
		4.6.1.2	Limitations of the standard beam position monitors	94
		4.6.1.3	Libera Brillance Plus electronics	97
	4.6.2	Beam lo	ss monitors	97
		4.6.2.1	Short description of the beam loss monitors	98

A	Off-	momer	ntum and	longitudinal MIK injection schemes	185
6	Con	clusio	n		177
		5.4.1	Perturba	tions recorded with an infrared beamline	. 172
	5.4	Beam	line meas	urements	. 172
			5.3.2.5	Beam induced heating	. 168
			5.3.2.4	Stored beam-based measurements	. 157
			5.3.2.3	Injected beam-based measurements	. 144
			5.3.2.2	Preliminary experiments	. 139
			5.3.2.1	Overview	. 137
		5.3.2	Commis	sioning of the MIK	. 137
			5.3.1.4	Feasibility study of an active correction	. 134
			5.3.1.3	Optimization of the injection	. 128
			5.3.1.2	Prerequisites	. 123
		-	5.3.1.1	Overview	. 123
		5.3.1	Perform	ance of the modeled MIK injection scheme	. 123
	5.3	MIK in	jection .	· · · · · · · · · · · · · · · · · · ·	. 123
			5.2.2.3	Stored beam stability and temporal variations of the residual injection kick	. 120
			5.2.2.2	Lost electron distribution profile	. 117
		0.2.2	5.2.2.1	First turn orbits	. 116
		5.22	Measure	ements	. 116
			5212	Effect of the superband on the standard injection	
		5.2.1			
	5.2	Perfor	mance of		. 110
	5.1	Introd	uction		. 110
5	Inje	ction ir	nto the S	OLEIL storage ring	109
			1.0.0.2		. 100
			4.6.3.2	Beamline setup and ultra-fast line-camera KALYPSO	. 102
		4.0.0	4631	Extraction system of the diagnostic beamline	102
		463	Diagnos	tics for transverse beam size monitoring	102
			4623	Beam loss monitor setun	101
			4.6.2.2	Beam loss monitor interface and acquisition modes	. 100

Acronyms

ADC Analogical to Digital Converter

AT Accelerator Toolbox
BBA Beam Based Alignement
BLM Beam Loss Monitor
BPM Beam Position Monitor
CEA Commissariat à l'Energie Atomique et aux énergies alternatives
CNRS Centre National de la Recherche Scientifique
COD Closed Orbit Distortion
DLSR Diffraction Limited Storage Ring
DCCT Direct Current Current Transformer
FODO Focusing-Off-Defocusing-Off
FOFB Fast Orbit Feedback
ID Insertion Device
KALYPSO KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy
LS Long Straight section
LURE Laboratoire pour l'Utilisation du Rayonnement Electromagnétique
MIK Multipole Injection Kicker
MML MATLAB Middle Layer
MS Medium Straight section
NLK Non-Linear Kicker
RMS Root Mean Square
RF Radio Frequency
SOLEIL Source Optimisée de Lumière d'Energie Intermédiaire du LURE
SOFB Slow Orbit Feedback
SS Short Straight section

TANGO TAco Next Generation Objects

TL1 First Transfer Line

TL2 Second Transfer Line

TRACY A Tool for Accelerator Design and Analysis

Chapter 1

Résumé

A l'orée de la deuxième moitié du xx^{ème} siècle, la production du rayonnement synchrotron par les accélérateurs de particules éponymes devint un atout pour explorer et comprendre la structure de la matière aux échelles submicrométriques. L'engouement pour ce rayonnement se manifeste par le développement d'accélérateurs de particules dédiés, nommés sources de lumière synchrotron à anneau de stockage. Comme leur nom l'indique, ces grands instruments de pointe, utilisés pour la recherche scientifique et l'industrie, à l'échelle nationale et internationale, reposent sur un accélérateur circulaire constitué d'électroaimants et d'aimants permanents. Les champs magnétiques de ces aimants permettent de guider et focaliser un faisceau d'électrons stocké ultra-relativiste selon une orbite fermée déterminée. Le rayonnement synchrotron intense et extrêmement collimaté, constitué de photons allant de l'infrarouge aux rayons X durs, est produit lors de la déflexion du faisceau stocké par les champs magnétiques des aimants de courbure et des insertions de l'anneau de stockage. La focalisation du faisceau d'électrons permet d'augmenter la brillance du rayonnement synchrotron, c'est-à-dire le nombre de photons par unité de temps, de surface, d'angle solide et de largeur spectrale à 0.1 %. En première approximation, cela équivaut à minimiser l'émittance transverse du faisceau stocké, définie comme le volume de l'espace des phases transverse occupé par la distribution gaussienne des électrons du faisceau, tronquée à un écart-type.

En France, SOLEIL est le centre de recherche national exploitant une source de lumière synchrotron à anneau de stockage de 3^{ème} génération. Cette source est un enchainement ordonné de trois accélérateurs : l'accélérateur linéaire, le booster et l'anneau de stockage. Les électrons sont produits par la source thermoïonique de l'accélérateur linéaire, qui les accélère jusqu'à ce que leur énergie atteigne 110 MeV. A ce stade, les électrons, pré-groupés en paquets, sont extraits du linac et injectés dans le booster, un accélérateur circulaire de 157 m qui accélère le train de paquets jusqu'à l'énergie nominale de 2.75 GeV. Le faisceau, dont l'émittance naturelle vaut 140 nm rad, est alors extrait du booster et injecté dans l'anneau de stockage, dont la circonférence vaut 354 m. A SOLEIL, le courant moyen maximum qui peut être stocké en remplissage uniforme, correspondant à 416 paquets d'électrons dans l'anneau, vaut 500 mA. Lors d'une montée en courant, 2 à 3 mA sont typiquement injectés à une fréquence de 3 Hz.

Hormis une défaillance ou un arrêt prévu de la machine, le faisceau d'électrons circule plusieurs dizaines d'heures dans l'anneau une fois stocké. En opération, le rayonnement synchrotron est acheminé dans les 29 laboratoires implantés tout autour de l'anneau de stockage, appelés lignes de lumières. Afin de compenser l'énergie rayonnée par émission synchrotron, et ainsi maintenir l'énergie du faisceau stocké à sa valeur nominale, quatre cavités radiofréquences supraconductrices sont installées dans l'anneau de stockage. A l'équilibre, l'émittance naturelle du faisceau stocké est de 4 nm rad.

La collimation du rayonnement synchrotron résulte notamment de la forte focalisation du faisceau stocké. En conséquence, la densité électronique par paquet croît, ce qui augmente le nombre d'interactions entre les électrons d'un paquet. L'impulsion des électrons, essentiellement longitudinale, peut ainsi être transférée dans le plan transverse. Ce phénomène, appelé effet Touschek, est un des mécanismes qui contribue à la perte d'électrons. A SOLEIL, en remplissage uniforme à 500 mA, la durée de vie Touschek est aussi importante que la durée de vie dû au vide, c'est-à-dire la durée de vie liée aux interactions entre les électrons et les molécules de gaz résiduelles dans la chambre à vide (la pression nominale à l'intérieur de la chambre à vide dans laquelle circule le faisceau stocké est de l'ordre de 10×10^{-10} mbar). Dans ces conditions, la durée de vie totale du faisceau stocké vaut environ 11 h actuellement. Ainsi, 63 % du faisceau stocké est perdu en 11 h.

Lorsque les premiers faisceaux de SOLEIL furent fournis aux utilisateurs des lignes de lumière en 2008, l'anneau de stockage fonctionnait en mode décroissant. A cette époque, le courant dans l'anneau décroissait d'environ 30% avant d'être rétabli à sa valeur nominale. Les injections étaient alors réalisées toutes les 8 h. De telles fluctuations de l'intensité du courant provoquaient de grandes variations de la température de l'anneau, ce qui avait des conséquences néfastes sur les optiques des lignes de lumière et les diagnostics de l'accélérateur. Finalement, cela impliquait la dégradation des conditions expérimentales, caractérisée par une dérive des points source des lignes de lumière. En mars 2009, SOLEIL mit en service le mode d'injection continue, appelé top-up, afin de restreindre les variations du courant à $\pm 0.2\%$ de la valeur nominale. Ainsi, le courant est perçu comme constant par les lignes de lumière. Afin de respecter ce seuil de stabilité, 2 à 3 mA sont typiquement injectés toutes les 2 à 3 min. Dans ces conditions, le mode top-up requiert de déclencher environ 500 fois par jour les aimants d'injection, qui doivent idéalement préserver le faisceau stocké de toute perturbation. La variation de la position transverse du faisceau stocké ne doit pas excéder 10% de la taille RMS transverse du faisceau. Dans le cas des sources de 4^{eme} génération, caractérisées par des émittances comprises entre quelques dizaines et quelques centaines de pm rad, ce seuil tombe entre 2 et 3%.

Le schéma d'injection standard utilisé pour l'opération de SOLEIL est le plus largement répandu dans le monde pour ce type d'installation. Les électroaimants utilisés lors de l'injection sont des équipements pulsés : quatre kickers dipolaires rapides (K1, K2, K3, K4) et deux aimants à septa, actif et passif, installés dans une section droite longue de 12 m, appelée section d'injection, telle que schématisé par la figure 1.1. A la différence des kickers qui induisent un champ magnétique vertical dans leur chambre à vide, les aimants à septum sont caractérisés par



Figure 1.1: Schéma d'injection standard à quatre kickers. Le faisceau stocké est décalé momentanément et horizontalement (pointillés bleus) de son orbite fermée initiale (droite noire) grâce aux déviations des quatres kickers dipolaires rapides K1,K2,K3 et K4 (rectangles bleus). Simultanément, le faisceau injecté (pointillés rouges) se propage en parallèle du faisceau stocké grâce aux déviations consécutives des septa (rectangles mauves). Une fois que le faisceau injecté se propage dans l'anneau de stockage (ligne rouge pleine), la déviation d'orbite fermée induite par les kickers décroît et le faisceau stocké est replacé sur son orbite initiale en environ trois tours.

une zone sans champ, à travers laquelle se propage le faisceau stocké, et une zone à champ vertical, à travers laquelle se propage le faisceau injecté. Dans le cas de l'aimant à septum passif, la séparation entre ces deux zones est une lame de 3.5 mm d'épaisseur, notée *S*. Les caractéristiques principales des aimants de l'injection standard sont rassemblées dans le tableau 1.1. L'injection standard consiste à translater horizontalement, localement et

Table 1.1: Caractéristic	ues principales	des aimants	pulsés de l'inje	ection à quatr	e kickers de SOLEII
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Paramètre	K1 et K4	K2 et K3	Septum actif	Septum passif
Impulsion	Demi-sinus	Demi-sinus	Demi-sinus	Sinus
Longueur magnétique (m)	0.60	0.60	2×0.50	0.60
Durée d'impulsion (μ s)	7	7	$3.3 imes 10^3$	120
Déviation nominale (mrad)	5.8	-5.8	110	25

transitoirement, le faisceau stocké au moment de chaque injection. L'objectif est de rapprocher le faisceau stocké du faisceau injecté sortant de la ligne de transfert entre le booster et l'anneau de stockage. Ceci permet de maximiser le rendement d'injection et, en théorie, de ne pas affecter la stabilité du faisceau stocké (dans la mesure où aucun aimant non linéaire n'est installé dans la section d'injection). Lors d'une injection, le faisceau stocké est décalé de son orbite fermée initiale grâce aux déviations induites par les kickers, tandis que, simultanément, le faisceau injecté se propage parallèlement au faisceau stocké grâce aux déviations consécutives des septa. Les deux faisceaux sont ainsi positionnés au plus près l'un de l'autre et seulement séparés par la lame de l'aimant à septum passif, comme illustré par la figure 1.2. Lorsque le faisceau injecté se propage dans l'anneau, la déviation d'orbite fermée induite par les quatre kickers décroît et le faisceau stocké est replacé sur son orbite initiale après environ trois tours. Ainsi, le faisceau injecté, qui oscille avec une amplitude horizontale de l'ordre de 10 mm autour de l'orbite fermée, n'est perdu ni sur la lame de l'aimant à septum passif, ni dans le reste de l'anneau. Enfin, le faisceau injecté fusionne avec le faisceau stocké en quelques millisecondes par amortissement radiatif.



Figure 1.2: Positions de la lame du septum passif (grisée), du faisceau injecté et du faisceau stocké à l'injection. Dans un premier temps, le faisceau booster (rouge) et stocké (bleu) sont positionnés aussi près que possible des faces de la lame, par les aimants à septum et les kickers respectivement. Finalement, le faisceau stocké (vert) est replacé sur son orbite fermée initiale, accompagné du faisceau injecté (rose). Les faisceaux injecté et stocké sont représentés par leur enveloppe à 3σ et 7σ respectivement.

Ce schéma d'injection fonctionne sur le principe de la fermeture angulaire horizontale : le faisceau stocké acquiert un angle θ_1 de K1, en entrée de la section d'injection, puis un second angle θ_2 de K2, compensant le premier. L'opération symétrique est réalisée grâce à K3 et K4, fournissant respectivement les angles θ_3 et θ_4 , afin de fermer la déviation d'orbite à la sortie de la section d'injection. Si la fermeture angulaire était parfaite, c'est-à-dire si la somme des angles fournie au faisceau stocké était nulle :

$$\Theta = \theta_1 + \theta_2 + \theta_3 + \theta_4 = 0, \tag{1.1}$$

avec $\theta_{1,4} = -\theta_{2,3}$, l'injection serait transparente pour toutes les lignes de lumière, car le faisceau stocké ne subirait aucune perturbation résiduelle, mise à part l'éventuelle oscillation résiduelle induite par le champ de fuite des septa (à noter que l'amplitude de l'oscillation résiduelle liée à l'allongement transitoire du trajet du faisceau est de l'ordre du micron et n'est par conséquent pas détectée par les lignes de lumière).

En réalité, il est impossible que la fermeture angulaire soit parfaite. Bien que les spécifications des kickers et de leur alimentation soient identiques, il existe des différences entre les équipements issues de la fabrication des éléments, de leur assemblage, de l'alignement des kickers et du réglage des alimentations. Au total, Θ vaut

quelques dizaines de microradians. Par conséquent, le faisceau stocké oscille. Ces oscillations sont mesurées à l'aide des moniteurs de position (BPM) installés le long de l'anneau. Les mesures que j'ai réalisées lors de ma thèse mettent également en évidence une perturbation verticale, qui peut être liée aux erreurs de rotation résiduelles des kickers. En 2017, les perturbations résiduelles horizontales et verticales induites par les kickers et les septa furent minimisées. Cependant, elles restent largement hors tolérances, comme l'indique le tableau 1.2. Ces perturbations

Table 1.2: Perturbations minimales du faisceau stocké par l'injection à quatre kickers de SOLEIL, à 1% de couplage.

Paramètre	Kickers	Septum actif	Septum passif
Amplitude horizontale pic (% of σ_x)	31	6	0
Amplitude verticale pic (% of σ_z)	250	25	0

induisent des fluctuations du rayonnement synchrotron que plusieurs lignes de lumière sont aujourd'hui capables de percevoir lors de leurs expériences. Dans la mesure où SOLEIL II sera beaucoup plus sensible à ces perturbations, comme toutes les machines de 4^{ème} génération, il est indispensable de concevoir un schéma d'injection innovant qui garantisse une injection transparente pour les lignes de lumière.

Dans ce contexte, la stratégie de recherche et développement de SOLEIL s'inscrit dans un effort général, soutenu par l'ensemble des sources de lumière synchrotron à anneau de stockage, pour éviter les perturbations du faisceau stocké induites par l'injection. Différentes solutions sont étudiées selon les besoins de chaque laboratoire. Pour certains, les guatre kickers du schéma d'injection précédemment décrit peuvent être remplacés par un aimant unique dont le champ magnétique est caractérisé par une zone de champ nul le long de la trajectoire du faisceau stocké, afin de ne pas dévier ce dernier, et une zone de champ nominal qui permet de minimiser l'amplitude d'oscillation du faisceau injecté. En 2010, les travaux pionniers de KEK-PF ont démontré de nettes améliorations de la stabilité du faisceau stocké grâce à la mise en service d'un hexapôle pulsé [1]. Plus tard, BESSY conçut un aimant pulsé dont le champ magnétique vertical avait une forme octupolaire [2]. Assimilant les principes de bases de la conception de cet aimant, SOLEIL conçut un kicker d'injection multipolaire (Multipole Injection Kicker, MIK) original, dans le cadre d'une collaboration avec MAX IV, entre 2012 et 2017. Le MIK, adapté aux besoins de MAX IV, fut installé et mis en service pour la première fois sur l'anneau de stockage de MAX IV à la fin de la période de collaboration. Bien que ce MIK fut utilisé pour l'opération de MAX IV et que des niveaux de stabilité jamais mesurés auparavant furent atteints (amplitudes des perturbations de la position du faisceau stocké : $\pm 13 \,\mu m$ en horizontal et ± 8 µm en vertical) [3], des températures élevées invitaient à remplacer l'aimant par un MIK doté d'un dépôt de titane plus épais à l'intérieur de sa chambre à vide, passant de $0.8 \,\mu\text{m}$ à $3.5 \,\mu\text{m}$. En 2019, le second MIK fut installé et mis en service avec succès : les amplitudes des perturbations de la position du faisceau stocké furent réduites à 7 µm RMS en horizontal et 2 µm RMS en vertical. De plus, la température fut nettement diminuée pour un remplissage et une intensité du courant stocké donnés [4]. Le MIK est le premier aimant de ce type à être utilisé quotidiennement pour l'opération d'un anneau de stockage de quatrième génération. Fort de ce succès, SOLEIL construisit une

copie afin de démontrer la faisabilité de ce schéma d'injection innovant pour l'opération de son anneau de stockage actuel. En outre, le projet MIK de SOLEIL permet de mener des études prospectives, présentées ci-dessous, sur lesquelles s'appuiera le futur projet de MIK miniature, destiné à devenir l'élément central du schéma d'injection de SOLEIL II.

Le schéma d'injection de SOLEIL fondé sur le MIK est représenté figure 1.3. Comme pour l'injection à quatre



Figure 1.3: Schéma d'injection MIK. L'orbite fermée du faisceau stocké est stationnaire (ligne noire), tandis que le faisceau booster (ligne pointillée rouge) est approché au plus près du septum passif (trait noir épais de l'aimant à septum passif) grâce aux déviations consécutives des aimants à septa (rectangles violets). Le faisceau injecté (ligne rouge) oscille librement jusqu'à ce que l'amplitude des oscillations soit minimisée par le MIK (rectangle bleu).

kickers, l'injection MIK est une injection hors axe, horizontale et on-momentum (bien que des configurations alternatives fassent l'objet d'études). Cela signifie que les centroïdes des faisceaux injecté et stocké appartiennent au plan médian, soit z = 0 sauf mention du contraire. Outre le fait que le MIK remplace les quatre kickers, cet électroaimant est installé hors de la section d'injection. Il induit un champ magnétique vertical pulsé qui atteint son intensité maximum en un tour $(1.2 \,\mu s)$ et chute également en un tour. A l'injection, le faisceau injecté interagit avec le champ pic lors de son premier passage dans le MIK. A ce moment, la composante verticale du champ magnétique, convertie en champ de déviations horizontales θ_x , présente une forme octupolaire illustrée par les figures 1.4 et 1.5. Ses variations transverses fournissent la zone sans champ, qui permet de ne pas perturber le faisceau stocké, et la zone de champ nominal, à la position cible $x_{cible} = 10.3 \,\text{mm}$, qui permet de dévier le faisceau injecté de $\theta_x = 2.2 \,\text{mrad}$. De cette façon, l'amplitude d'oscillation du faisceau injecté est minimisée par le MIK. Finalement, le faisceau injecté rejoint le faisceau stocké par amortissement radiatif.

Afin d'obtenir le champ illustré par les figures 1.4 et 1.5, les caractéristiques mécaniques du MIK doivent être optimisées. Deux brides sont fixées aux extrémités de la chambre à vide du MIK et le rattachent au reste de l'anneau. La longueur bride à bride vaut 400 mm. L'intérieur de la chambre est recouvert d'un dépôt de titane qui assure la circulation du courant image du faisceau stocké. Le dépôt ne doit être ni trop fin, pour éviter des températures élevées incompatibles avec l'opération, ni trop épais, pour éviter que n'y circulent des courants de Foucault trop intenses, à la montée et à la chute de l'impulsion. Ces courants induisent des champs magnétiques quadripolaires transitoires dans la zone sans champ, qui perturbent la taille horizontale du faisceau stocké. Grâce



Figure 1.4: Variations transverses du champ de déviations horizontales du MIK (équivalent au champ magnétique vertical du MIK), noté θ_x , à $t = 1.2 \,\mu$ s, pour une tension nominale de $10 \,\text{kV}$.



Figure 1.5: Variations transverses du champ de déviations horizontales du MIK (équivalent au champ magnétique vertical du MIK), noté θ_x , à $t = 1.2 \,\mu$ s, pour une tension nominale de $10 \,\mathrm{kV}$. Les enveloppes à 3σ des faisceaux injecté et stocké sont respectivement représentées par des points magentas et noirs. Du fait de la forme octupolaire du champ, $|\theta_x| \leq 0.5 \,\mu$ rad pour $|x| \lesssim 500 \,\mu$ m et $|z| \lesssim 400 \,\mu$ m, et $1.5 \,\mathrm{mrad} \le \theta_x \le 2.5 \,\mathrm{mrad}$ dans la limite de l'enveloppe du faisceau injecté.

au retour d'expérience de MAX IV concernant la gestion de la charge thermique dans le MIK et du battement de la taille du faisceau, l'épaisseur du dépôt fut fixée à $3.5 \,\mu$ m. De plus, la charge thermique est dissipée par un flux d'air autour du MIK induit par un ensemble de turbines. Par ailleurs, huit sillons furent précisément usinés sur les faces supérieure et inférieure de chambre à vide en saphir du MIK, afin qu'ils accueillent chacun un conducteur en cuivre cylindrique de 2 mm de diamètre et de $304 \,\text{mm}$ de long. Les écarts entre les conducteurs sont donnés sur la figure **1.6.** Les tolérances en position et rectitude des conducteurs valent respectivement $10 \,\mu$ m et $10 \,\mu$ rad. Les conducteurs sont collés et recouverts de cales en céramique qui maintiennent leur position durant la polymérisation de la colle dans un four. Une fois la colle durcie, les conducteurs sont immobiles. En effet, des erreurs d'alignement hors tolérances engendreraient des défauts de champs qui dégraderaient la stabilité du faisceau stocké. Par ailleurs, le MIK étant optimisé pour les besoins de MAX IV, il fut nécessaire de concevoir et installer des éléments spécifiques de transition (tapers), en amont et en aval du MIK. Ils permettent d'adapter l'ouverture physique de la chambre à vide standard, $70 \,\text{mm} \times 25 \,\text{mm}$, à celle du MIK, $46.8 \,\text{mm} \times 7.8 \,\text{mm}$, qui est la plus petite de l'anneau de stockage quand les insertions sous vide sont ouvertes. Des absorbeurs protègent le MIK du rayonnement synchrotron et complètent la section illustrée figure **1.7**. Les caractéristiques principales du MIK sont rassemblées dans le tableau **1.3**.

Préalablement à la mise en service du MIK, il fut nécessaire de déterminer son emplacement dans l'anneau de stockage. Ainsi, des études préliminaires furent réalisées à l'aide d'Accelerator Toolbox (AT) [6], avant le début de



Figure 1.6: Vue de face de la section transverse du MIK avec les conducteurs en cuivres numérotés de 1 à 8 (la couleur rouge ou verte donne le sens de circulation du courant). La bride circulaire amont entoure la chambre à vide en saphir (hachures) dont l'ouverture physique vaut 46.8 mm horizontalement et 7.8 mm verticalement.



Figure 1.7: Section MIK. Le MIK est installé dans une section droite courte de l'anneau de stockage délimitée par deux moniteurs de position (BPM). Deux moniteurs de pertes (points rouges) entourent le MIK pour effectuer des mesures de radio protection. L'ultravide est atteint grâce à un triplet de pompes, tandis que les tapers-absorbeurs garantissent l'adaptation de l'ouverture physique.

ma thèse. Il s'agit d'une bibliothèque de fonctions MATLAB utilisée pour la modélisation des accélérateurs et de la dynamique des faisceaux de particules. Quatre critères devaient être vérifiés pour convenir de l'emplacement du MIK : avoir suffisamment d'espace, au plus à quelques dizaines de mètres du point d'injection, pour accueillir l'aimant et ses absorbeurs, la position et l'angle du faisceau injecté au point d'injection, la tension maximum de l'aimant et la minimisation de l'amplitude d'oscillation du faisceau injecté à environ 10 mm. Ces études ont démontré

Ouvertures physiques horizontale/verticale (mm)	46.8 / 7.8
Longueur bride à bride (mm)	400
Longueur magnétique (mm)	304
Durée d'impulsion (μs)	2.4
Positions cibles horizontale/verticale au droit du MIK (mm)	10.3 / 0.0
Champ magnétique à la position cible (mT/kA)	24.85
Déviation nominale $ heta_x$ à la position cible (mrad)	2.2

Table 1.3: Paramètres principaux du MIK installé dans l'anneau de stockage de SOLEIL. Tableau issu de [5].

qu'il était possible d'installer le MIK dans une section droite courte libre, à environ 32 m du point d'injection. Dans cette situation, il suffit que le MIK annule la déviation horizontale du faisceau injecté au droit de l'aimant pour minimiser l'amplitude d'oscillation. De plus, la durée de vie Touschek ne chute seulement que de quelques pour cent, dès lors que les insertions sont en position d'opération. Lorsque ma thèse débuta le 7 octobre 2019, je pus débuter la modélisation et l'optimisation du schéma d'injection MIK, en prenant en main les outils de modélisation AT, pour optimiser le rendement d'injection, et TRACY pour calculer l'ouverture dynamique de l'anneau (zone de l'espace des phases dans laquelle les électrons sont stables) et la durée de vie Touschek du faisceau stocké. Dans un premier temps, j'ai complété le modèle de l'anneau préexistant en incluant la section MIK et ses ouvertures physiques. Le MIK est modélisé comme un aimant infiniment fin, auquel est associé le champ magnétique illustré par les figures 1.4 et 1.5. A l'injection, le MIK est allumé sur les deux premiers tours de sorte que le faisceau injecté interagisse avec le champ nominal et le champ résiduel, lors de la chute de l'impulsion, au deuxième passage dans l'aimant. A chaque passage, le champ magnétique est interpolé à la position des électrons traversant le MIK. J'ai modélisé des faisceaux multi paquets gaussiens, jusqu'à 1×10^4 électrons par paquet, pour mes études paramétriques afin de calculer les rendements d'injection et la distribution des pertes d'électrons le long de l'anneau de stockage. J'ai affiné la modélisation des effets non linéaires en tenant compte de la longueur des aimants hexapolaires et en incluant tous les multipôles des électroaimants. Par ailleurs, j'ai inclus les phénomènes radiatifs en tenant compte de l'émission synchrotron et de l'excitation quantique. En revanche, les cartes de champ magnétique des insertions des lignes de lumières ne sont pas modélisées. Après quelques mois, le modèle fut mis à jour par Pascale Brunelle (groupe Physique des Accélérateurs) qui remplaça l'un des dipôles 1.7 T standard d'une ligne de lumière par un aimant superbend de 2.8 T, en prévision de sa mise en service sept mois après le MIK. L'ouverture dynamique fut alors fortement réduite par la composante sextupolaire du superbend, et le rendement d'injection simulé passa de 99% à environ 90%. A l'issue de quinze mois d'études numériques, complétées par mes mesures du couplage du faisceau injecté à l'extraction du booster et mon analyse des mesures magnétiques du MIK réalisées par Rachid Ben El Fekih (groupe Alimentations et Aimants Pulsés), j'étais en mesure de proposer une configuration optimale pour injecter avec le MIK. Le septum passif doit être positionné à x = -17.5 mm de l'axe longitudinal de l'anneau, c'est-à-dire inséré de 2 mm par rapport à sa position d'opération, et le couplage du faisceau injecté à l'extraction du booster être inférieur ou égal à 20%.

Le MIK fut installé le 21 décembre 2020. En opération, le MIK est éteint. Il resta éteint lors des premiers tests avec faisceau stocké. Ceux-ci visaient à valider la compatibilité du MIK avec l'opération de SOLEIL en termes de température et de radioprotection. Lors de la première montée à 500 mA, l'intensité du courant stocké ne put dépasser 300 mA. En effet, la température maximum du MIK atteignit 130 °C à ce stade. Cela nécessita de désinstaller le capot protecteur autour du MIK et d'améliorer le système de refroidissement. Bien que la gestion de la température soit connue pour être un aspect délicat de ce type d'équipement, cette jouvence rapide permit de contenir les échauffements sous les seuils de tolérance, pour tous les modes de remplissage de l'anneau de stockage [7]. J'ai utilisé les nouveaux moniteurs de pertes de SOLEIL [8] pour confirmer que le MIK accumule les pertes par durée de vie en raison de son ouverture physique étroite et de la dispersion horizontale dans la section droite. Afin de respecter les seuils de radioprotection, les pertes furent relocalisées dans la section d'injection qui bénéficie d'un surblindage. Pour ce faire, le scraper horizontal intérieur fut rapproché du faisceau stocké, passant de x = -28 mm à -20 mm, sans diminuer significativement la durée de vie.

Après ces validations préliminaires, j'ai entamé l'optimisation de l'injection avec le MIK. J'ai réglé la tension du MIK, son délai, et la position et l'angle du faisceau injecté de sorte à injecter, accumuler et stocker les paquets d'électrons avec un rendement maximum de 97 %, avant la mise en service du superbend. J'ai également confirmé la minimisation de l'amplitude d'oscillation du faisceau injecté à 10 mm grâce aux BPM, conformément aux simulations (voir figure 1.8). Ces performances sont aussi bonnes que celles de l'injection à quatre kickers. En revanche,



Figure 1.8: Oscillations horizontales du faisceau injecté lors du premier tour dans l'anneau de stockage, simulées (rouge) et mesurées (bleu). Sur les 32 premiers mètres l'amplitude d'oscillations est trop grande pour être mesurée, passant d'environ 25 mm avant le MIK à 10 mm après le MIK.

le schéma d'injection MIK se démarque de celui à quatre kickers du point de vue de la stabilité du faisceau stocké. Afin de mettre en évidence les différentes performances des kickers et du MIK, j'ai réalisé des mesures comparatives. Puisque les perturbations de la position et taille transverses du faisceau stocké, induites par le MIK, devaient être très faibles en théorie, j'ai utilisé des diagnostics de haute performance, mis en service durant ma thèse. Les mesures furent l'occasion de tester ces équipements, dont SOLEIL envisage l'installation sur l'anneau de stockage de SOLEIL II. Concernant la mesure de position, l'électronique Libera Brilliance Plus [9], mise en service et connectée à un BPM, permet de réaliser des mesures tour par tour, évitant le biais du mixage des tours de l'électronique standard des autres BPM. La résolution spatiale est de l'ordre de 5 µm à 15 mA, soit dix fois plus petite que celle de l'électronique standard. Au moment des mesures, j'ai rempli un quart de l'anneau, correspondant à 104 paquets consécutifs, pour atteindre un courant moyen de 15 mA. Seuls les kickers, ou le MIK, sont déclenchés, sans injecter d'électrons. L'effet des aimants sur les quatre quarts de l'anneau fut mesuré simplement grâce à un scan en délai. Pour commencer, j'ai recherché le centre magnétique du MIK afin d'aligner le faisceau sur cette zone sans champ et ainsi minimiser les perturbations. Le faisceau doit être décalé horizontalement dans le MIK de $\Delta x = -200 \,\mu$ m, à l'aide de correcteurs horizontaux situés en amont et aval de la section droite. Les mesures de la figure 1.9, illustrant l'effet des aimants sur le quart dans lequel on simule une injection, indiquent que l'amplitude de la perturbation horizontale est environ 100 fois plus petite dans le cas du MIK que dans le cas des kickers, et inférieure à 2% de la taille horizontale RMS du faisceau stocké. En revanche, les mesures présentées sur la figure 1.10, indiquent que le MIK perturbe le faisceau verticalement, bien que l'amplitude de la perturbation soit sensiblement plus petite que dans le cas des kickers. Cette perturbation est liée à un défaut dipolaire de la composante horizontale du champ magnétique du MIK, détectée lors des mesures magnétiques précédant l'installation de l'aimant. Ce défaut, spécifique au MIK de SOLEIL, provient probablement d'une accumulation d'erreurs de positionnement des conducteurs. Afin d'annuler la perturbation, j'ai dû optimiser un système de correction actif. Ces résultats furent confirmés grâce aux mesures de la caméra ultra rapide KALYPSO [10], qui permit en outre de quantifier les variations de la taille horizontale RMS du faisceau stocké, qui résultent des champs quadripolaires transitoires induits par les courants de Foucault circulant dans la couche de titane. L'amplitude maximum de ces variations de taille vaut 3.5% de la taille horizontale RMS du faisceau stocké. L'ensemble de ces performances sont parmi les meilleures au monde. Durant ma thèse, j'ai eu l'opportunité de réaliser des mesures avec les lignes de lumière SMIS [11] et AILES [12] (domaine des infrarouges), DEIMOS [13] (domaine des X tendres) et PROXIMA 1 [14] (domaine des X durs), afin d'observer l'amélioration de la transparence de l'injection. En remplissage uniforme de l'anneau de stockage (416 paguets, 500 mA), les interférogrammes acquis avec la ligne AILES sont illustrés figures 1.11 et 1.12. Ils furent acquis sans que la correction verticale ne soit encore déployée. En outre, le faisceau stocké n'était pas encore aligné avec le centre magnétique du MIK. Dans cette configuration, le MIK induit des oscillations horizontales, dont l'amplitude maximale vaut $15 \,\mu m \, (\beta_x = 13.3 \, \text{m})$, et des oscillations verticales, représentées en vert figure 1.10. Ainsi, la configuration MIK n'était pas optimale. Cependant, même dans cette configuration de base, les perturbations du faisceau stocké induites par le MIK restent significativement moins importantes que celles induites par les kickers (voir figures 1.9 et 1.10). Les interférogrammes d'AILES en témoignent. Les pics de l'interférogramme des kickers, en



Figure 1.9: Position horizontale du faisceau stocké en fonction du tour, en un point de l'anneau de stockage ($\beta_x = 13.3 \text{ m}$). La perturbation induite par le MIK seul (verte), et le MIK accompagné d'un correcteur dipolaire vertical est inférieure à 2% de la taille horizontale RMS du faisceau stocké, et environ 100 fois plus petite que celle associée aux kickers (bleue).



Figure 1.10: Position verticale du faisceau stocké en fonction du tour, en un point de l'anneau de stockage ($\beta_z = 8.6 \text{ m}$). La perturbation induite par le MIK seul (verte) est plus petite que celle associée aux kickers (bleue), mais hors tolérance. Un correcteur dipolaire vertical est utilisé pour annuler la perturbation (rouge).

bleu figure 1.11, qui sont des perturbations liées au déclenchement des aimants, sont absents de l'interférogramme lorsque le MIK est déclenché. Changer l'échelle des temps permet de constater que le MIK induit, comme les kickers, des oscillations à 2.1 kHz du signal de l'interférogramme (voir figure 1.12). L'amplitude des oscillations est cependant significativement réduite et le pic caractéristique des kickers absent. Ces résultats suggèrent que si les mesures étaient répétées dans une configuration MIK optimale alors aucune perturbation ne serait détectée.

A l'heure où les sources de lumière synchrotron à anneau de stockage basculent vers la 4^{ème} génération, l'injection est un sujet critique. Il est nécessaire de mettre en oeuvre des schémas d'injection capables d'injecter les électrons plus fréquemment en mode top-up, en raison de la durée de vie raccourcie des faisceaux extrêmement focalisés, et dans des ouvertures dynamiques réduites. A l'heure actuelle, le seul schéma d'injection utilisé pour l'opération d'une machine de 4^{ème} génération (MAX IV) et garantissant la transparence de l'injection est fondé sur un MIK conçu par SOLEIL. Les performances obtenues avec le MIK que j'ai mis en service sur l'anneau de stockage de SOLEIL sont parmi les meilleures au monde. Ces résultats sont très enrichissants pour le développé par SOLEIL. Mon manuscrit présente de façon exhaustive le contexte dans lequel ces travaux s'inscrivent, le schéma d'injection standard à quatre kickers et ses performances, ainsi que les différentes étapes de conception, modélisation et mise en service du MIK. Les résultats que j'ai obtenus à l'aide des nouveaux diagnostics de pointe sont confrontés aux résultats des simulations et aux performances de l'injection à quatre kickers. Ces comparaisons mettent en évidence l'accord entre les résultats des simulations et les résultats expérimentaux, d'une part, et l'amélioration





Figure 1.11: Interférogrammes acquis par la ligne infrarouge AILES, pour un remplissage uniforme de l'anneau de stockage (416 paquets, 500 mA). L'injection est inhibée et seuls les kickers ou le MIK sont déclenchés (interférogrammes bleu et rouge respectivement). Les pics visibles sur le signal bleu sont des perturbations induites par le déclenchement de kickers. La configuration MIK n'est pas optimale (faisceau stocké non aligné avec le centre magnétique et absence de correction verticale).

Figure 1.12: Interférogrammes acquis en mode top-up par la ligne infrarouge AILES (respectivement bleu et rouge dans le cas de l'injection à quatre kickers et MIK), pour un remplissage uniforme de l'anneau de stockage (416 paquets, 500 mA). La configuration MIK n'est pas optimale (faisceau stocké non aligné avec le centre magnétique et absence de correction verticale). La fenêtre d'observation est calée autour d'une perturbation.

significative de la transparence de l'injection d'autre part.

Chapter 2

Introduction

Contents

2.1	Short history of light sources	22
2.2	Towards top-up injection	23
2.3	Technology for transparent injection	25
2.4	Manuscript outline	26

2.1 Short history of light sources

The physicist community has managed to study, understand and benefit from the laws of electrodynamics in very diverse ways. One of these consists in storing a charged particle beam in an electromagnet based circular accelerator, named a storage ring. In the early years of these accelerators, the beams were mainly used for particle collision studies, at a few hundred MeV or a few GeV. After the first circular accelerators, namely the cyclotron [15] (E. Lawrence, 1932) and the betatron [16] (D. Kerst, 1940), both limited in energy and not suitable for accelerating light particles, M. Oliphant proposed the proton synchrotron in 1943 [17]. The energy gain was ensured in a synchronous way by ramping the magnetic field of the magnets and the frequency of the radio frequency (RF) system according to the passage of the beam in acceleration devices, hence the name of synchrotron. A few months later, the phase stability principle was described independently by V. I. Veksler [18] and E. McMillan [19]. Electron or positron beams, as well as proton beams, were used in synchrotrons [17]. Since the 1st generation of synchrotrons, based on phase stability [19, 18] and weak focusing [20, 21] - ensuring respectively longitudinal and transverse stability of a beam circulating in a storage ring -, and the first observation of the synchrotron radiation in 1947 [22], many improvements have been made in order to master this photon emission process. The synchrotron radiation is emitted by accelerated charged particles in deflecting magnetic fields and was considered at first as a parasitic effect which damps the particle beam energy and leads to beam losses. Being lighter than protons, electrons are preferably used to generate synchrotron radiation. Benefiting from the innovative concept of strong focusing, or so-called alternating gradient [23], on which would later rely the 2nd generation of synchrotrons, some accelerator facilities using electrons or positrons were dedicated to the production of synchrotron radiation as X-ray light sources [24]. What characterizes all storage ring-based synchrotron light sources are the very unique properties of the photon beams: pulsed radiation in a wide and tunable range of energies, with high flux and brilliance; the latter is defined as the number of photons emitted per seconds, per unit of surface and per unit of solid angle for a spectral bandwidth of 0.1%. In operation, the synchrotron radiation is collected thanks to various optical setups and propagated towards targets of solid, liquid or gas matter. The interaction between the synchrotron radiation and matter reveals the molecular, atomic and electronic structures as well as various properties of the targets. Although the emittances of the electron beams, characterizing the dimension of the latter in phase space and the brilliance of the photon beams, were on the order of 100 nm rad in the case of the 2nd generation, the ambition was to provide even more reliable and brighter photon beams to the beamlines surrounding the storage ring in order to widen the fields of research. Indeed, various research and development projects are conducted at synchrotron light sources from pharmaceutic chemistry to astrophysics, as well as material engineering and environmental science, to name a few [25].

To meet the accelerator users' need for high brilliance photon beams, accelerator physicists designed 3rd generation storage rings characterized in particular by natural emittance lowered to a few nm rad. This result was deemed achievable thanks to advances in understanding and optimizing the nonlinear dynamics of the beam on one side, and the improvements in accelerator technologies on the other side, resulting especially in much stronger focusing magnets [26]. While this tipping point was a real improvement in the light sources' performance, it had a significant cost. Indeed, achieving such low emittance levels by means of strong focusing leads to the excitation of resonant driving terms, while increasing the intra-beam and Touschek scatterings [27, 28]. All these limiting factors ultimately decrease the electron beam lifetime, the dynamically unstable electrons and scattered off-momentum electrons being lost on the walls of the vacuum chamber. Moreover, the stored electrons undergo various interactions with their environment, such as interactions with the nuclei of residual gas ions and molecules, through elastic and inelastic scattering [29], which also contributes to the decrease in the average current intensity in the storage ring.

There are two synchrotron light sources in France. Each of these accelerators has been designed specifically to meet different requirements, even though they both aim to provide insights of matter. The European Synchrotron Radiation Facility [30] (ESRF) located in Grenoble was the first 3rd generation synchrotron radiation source to be commissioned in 1992. The commissioning of the Storage Ring began in February 1992. Progress was extremely fast and promising since the target intensity of 100 mA in the multi-bunch mode was reached less than four months later. In July 1992, the first undulator was operated without any effect on the beam and the machine diagnostics beamline was run at the full nominal current with a record brilliance in the 10×10^{17} range. After various improvements over the years, X-ray brilliance of 10×10^{21} photons/mm²/mrad²/01% bw is reached in 2011. In 2020, an electron beam has been stored for the first time in the ESRF-EBS storage ring, EBS meaning Extremely Brilliant Source. Indeed, the ESRF has been upgraded after 25 years of operation to become a photon source 100 times brighter than before, namely a 4th generation synchrotron light source, operating a Diffraction Limited Storage Ring (DLSR) [31, 32]. The second synchrotron, called Source Optimisée de Lumière d'Energie Intermédiaire du LURE (SOLEIL), is a 3rd generation light source in Saint-Aubin, commissioned in 2006. The upgrade of SOLEIL, called SOLEIL II, is foreseen in the next coming years, as the Conceptual Design Report of the 4th generation facility has already been published in 2020 [33]. The Technical Design Report phase is currently conducted and planned to finish at the end of 2024.

2.2 Towards top-up injection

Most storage rings are operated with a few hundreds of milliamperes stored beam and beam lifetime on the order of 10 h, which is the duration corresponding to a 63% loss of the stored beam through decay losses. The decrease in the average current intensity results in the loss of thermal equilibrium. Requirement for sub-micrometer electron beam stability, i.e. stability of the beamlines' source points in fine, together with this short lifetime made outdated and detrimental the usual decay mode of injection [34]. Indeed, this leads to time variations of the photon flux, and adversely affects beamline optics and diagnostics stability in the storage ring due to the resulting large thermal drift.

Therefore, the need to maintain constant thermal load in the storage ring has led to the advent of an innovative injection mode, called the top-up mode [35, 36, 37, 38, 39]. Its goal is to keep the average current intensity almost constant. To do so, the injection of new electrons occurs frequently either according to a fixed time (a few minutes) or according to the decrease of the current below a given threshold required (typically a few percents or fractions of a percent). Nowadays, most synchrotron light sources are operated at almost constant current intensity. In this context, it has become mandatory for synchrotron light sources to develop reliable and high-performance injection devices and injection schemes, both in terms of injection efficiency and stored beam stability. The ultimate goal is to make the injection imperceptible by the detectors operated by the beamlines, i.e. implement transparent injections.

The most common injection scheme for 3rd generation storage ring-based synchrotron light sources relies on one or several in-air and in-vacuum pulsed septum magnets located at the end of the transfer line between the injector stage and the storage ring, along with a pulsed septum magnet and several pulsed kicker magnets installed preferably in a straight section of the storage ring, on either side of the injection point, corresponding to the exit of the septum magnet. In this context, the injection generally consists in providing a local transient bump, thanks to the kickers, which aims to shift and bring momentarily the stored beam as close as possible to the inner face of the last septum blade, while in the mean time the injected beam coming from the injector stage is brought parallel to the stored beam, close to the outer face of the blade, thanks to the consecutive kicks of the septum magnets. This is the so-called bump-based injection scheme. In this perspective, the injected and stored beams must be brought closer synchronously, such that the injected bunches are captured in the RF buckets accommodated by the RF system. This requires precision of synchronization on the order of 100 ps for a typical RF frequency of 500 MHz [40]. Eventually, the stored beam is brought back to its original closed orbit when the fast transient bump falls and vanishes. In any case, the injected and the stored beams must initially be separated in phase space regarding Liouville's theorem which states that the particle density in phase space is constant as long as the system undergoes conservative forces. Thus, the injected beam has an initial betatron or synchrotron amplitude in phase space with respect to the stored beam, in order to avoid a stored beam loss at injection. If the incoming beam is injected off-momentum, meaning with an offset in energy compared to the nominal energy of the stored beam, it follows a chromatic orbit according to its energy offset and the dispersion function of the storage ring. It performs synchrotron oscillations, namely oscillations in the longitudinal phase space, until it reaches the stored beam closed orbit by radiation damping to equilibrium nominal energy [41]. Conversely, if the incoming beam is injected on-momentum with a transverse offset, it performs betatron oscillations around the closed orbit of the stored beam, also damped by synchrotron emission. After a few damping times in the storage ring, the injected beam reaches equilibrium and merges with the stored beam, since the photon emission via synchrotron radiation is not a conservative phenomenon.

The principle of a transparent injection relies on the closure of the kicker bump such that the stored beam is brought back to its initial closed orbit after the bump, although synchrotron oscillations characterized by amplitude on the order of a few microns, appear due to path lengthening. Theoretically, the bump closure is met by design of
the kicker magnets and their supply system. Unfortunately, unavoidable discrepancies due to manufacturing precision limits, setup errors and magnet misalignment end up with residual kicks to the stored beam which trigger betatron oscillations and apparent transverse beam size variations. These perturbations are known to be detrimental for some beamlines, which detect photon beam intensity plummeting each time an injection occurs [1]. The development of the top-up mode highlighted this major concern, which occurs frequently since an injection is repeated roughly every few minutes. For synchrotron light sources which managed to install the kickers in a single straight section, the challenge is to set up the kickers such that their kick compensate each other, assuming perfect match of their power supply, cables, triggering, alignment, optics and coated chambers to name a few. Despite many efforts to limit these sources of stored beam perturbations, such as improved kicker pulse matching and jitters or active correction against static errors [42, 43, 44, 45, 46, 47], still persistent defects lead to measurable photon beam fluctuations and potentially lowered injection efficiency [48]. This issue is even more challenging to address as soon as the kicker magnets span over the straight section in the upstream and downstream arcs of the storage ring, due to a lack of available space. Indeed, beta beating due to off-axis trajectories through the non-linear magnets induce additional injection bump leakage [49, 50, 51, 52, 53]. Similarly to the major part of the 3rd generation storage ring-based synchrotron light sources, SOLEIL is equipped with a bump-based injection scheme whose principle, performance and limitations are described in detail in this manuscript.

2.3 Technology for transparent injection

To overcome the limitations inherent to the standard bump-based injection scheme, several synchrotron light sources have explored innovative ways to prevent the stored beam from injection perturbations while operating in top-up mode. One of them consists in implementing a single pulsed magnet whose magnetic field has two essential properties. Basically, the magnetic field of the pulsed magnet must be zero in the stored beam path, defining the magnetic center of the magnet, and non-zero far from its longitudinal axis. The only linear field which meets these specifications is that of a quadrupole magnet. Some studies have been conducted at KEK-PF to determine whether a pulsed quadrupole could be considered as a reliable injection magnet or not [54]. Unfortunately, two limitations are consubstantial to this solution. Firstly, as a focusing magnet it acts on the stored beam size, introducing beam size beating, strongly enough to be inconvenient for the beamlines. Secondly, the quadrupolar field is a linear function of the beam position that gives a non uniform kick to the injected beam. This is a strong limitation especially when the injected beam is large, because it implies injection losses, meaning poor injection efficiency. Following these observations, feasibility studies of Non Linear Kicker (NLK) magnets, designed as the key elements of innovative injection schemes, have been conducted [55]. The first non linear magnet is the sextupole, whose magnetic field is a function of the beam position to the square. The main advantage of the sextupolar field is its enlarged low field region in the vicinity of its magnetic center, compared to the quadrupolar field. During the first successful

commissioning of a pulsed sextupole magnet as the key injection device at KEK-PF in 2010, stored beam stability, in terms of position and size, and injection efficiency have proven to be compatible with operation and beamlines requirements [1]. This aroused a growing interest for NLK [55, 2, 56, 57].

Beamlines exploiting the coherence of the beam or manipulating nano-beams are more sensitive to beam disturbance during injection. This was confirmed by some beamlines of ESRF-EBS which are more sensible to stored beam perturbations since their upgrade. This emphasizes the need for improved injection schemes, which has appeared as a crucial topic for 4th generation synchrotrons since the top-up operation can be significantly affected [58]. In the past oscillations amplitude equal or lower than 10% of the RMS stored beam size was considered as the figure of merit. It is now lowered to 2 to 3% with the advent of 4th generation synchrotrons. Although strategies to meet these tolerances differ from facilities to facilities due to the specific characteristics of the accelerators [59, 60, 61], the NLK solution is promising. The interest for such a technology is real and SOLEIL designed an octupolar field magnet, called MIK for Multipole Injection Kicker, based on the design of a NLK magnet developed by BESSY [2]. The first MIK has been developed and built by SOLEIL in the scope of a collaboration with the 4th generation synchrotron light source, named MAX IV, in Lund, Sweden in 2017. The commissioning of the MIK demonstrated that the position perturbations and the beam size growth were below the stability thresholds, which guarantee the transparency of the injection process for the beamlines. In 2019, a second SOLEIL-built MIK replaced the former, reducing the heat load deposition on the MIK chamber [4]. The second MIK, meeting more stringent mechanical tolerances for its grooves, was also commissioned successfully and is now used in daily operation. As part of the MAXIab-SOLEIL collaboration, SOLEIL has built another copy of the MIK for its own R&D purposes, to deepen its knowledge and know-how, taking benefits from its previous experiences. After suitable adaptations to the SOLEIL environment, taking into account its various filling patterns, the impact on collective effects and injected beam produced by a booster, this MIK magnet has been installed in the first short straight section of the SOLEIL storage ring. during the shutdown of December 2020, and was successfully commissioned in 2021. It is foreseen to be used in daily operation before the ultimate shutdown of SOLEIL. This work has been done to pave the way to the upgrade of SOLEIL as a new miniaturized MIK will indeed be the cornerstone of SOLEIL II's injection to provide users with unmatched stability performance.

2.4 Manuscript outline

I joined the Accelerator physics group of SOLEIL, and the MIK project team led by R. Ben El Fekih, in October 2019 in order to commission and optimize the MIK injection scheme in the framework of my PhD. In the first chapter of my manuscript, I define precisely the key concepts mentioned in this introduction, and present the theoretical framework essential for the understanding of the following chapters. In the second chapter, I present the accelerators of SOLEIL as well as the bump-based injection scheme of the storage ring and the innovative MIK-based

injection scheme. In addition, I describe the high performance diagnostics that I helped put into service and used to characterize the performance of the injection schemes experimentally. In particular, a section is dedicated to the presentation of the numerical tools that I used extensively during my PhD to perform simulation and experimental studies. A third chapter is devoted to the comparison of the injection performance achieved by both schemes. In each case I describe the state of the art of the simulated schemes and the developments I have made to improve the corresponding models. In particular, the optimization of the MIK injection scheme is detailed. In addition, I present the commissioning of the MIK and the experimental studies I conducted, as well as the measurements and their outcomes. Eventually, the conclusion provides an overview of the major achievements and perspectives, which pave the way to SOLEIL II.

Chapter 3

Basics of accelerator physics

Contents

3.1	Sing	le particle transverse beam dynamics	30
	3.1.1	Hamiltonian from the Cartesian to the curvilinear coordinate system	30
	3.1.2	Transformed curvilinear Hamiltonian	32
	3.1.3	Linear transverse equations of motion	33
3.2	Solu	tions of the linear equations of motion	36
	3.2.1	On-momentum electron	36
	3.2.2	Off-momentum electron	38
3.3	Som	e limitations of the beam dynamics	39
	3.3.1	Closed orbit distortions	39
	3.3.2	Energy-dependent tune shift	41
	3.3.3	Non-linear beam dynamics	41
3.4	Elec	tron beam parameters	42
	3.4.1	Transverse bunch size	42
	3.4.2	Transverse beam emittance	42
	3.4.3	Beam lifetime	44

3.1 Single particle transverse beam dynamics

The system studied in accelerator physics is a charged particle beam propagating through electromagnetic fields. In storage ring-based synchrotron light sources, the charged particle is an electron whose dynamics is described using the Hamiltonian formalism in the framework of the classical relativistic electrodynamics theory.

3.1.1 Hamiltonian from the Cartesian to the curvilinear coordinate system

Basically, the Hamiltonian of a dynamical system depends on conjugate variables. In particular, a relativistic electron which interacts with an electromagnetic field is characterized by its position coordinates $\mathbf{r}_c = (x, z, s)_c$, in a Cartesian reference frame, and their canonical conjugate momenta $\mathbf{P}_c = (P_x, P_z, P_s)_c$. The index *c* refers to the Cartesian coordinate system. Given the potential ϕ and the potential vector \mathbf{A}_c , the electromagnetic field is defined by:

$$\boldsymbol{E}_{c} = -\boldsymbol{\nabla}_{c}\phi - \frac{\partial \boldsymbol{A}_{c}}{\partial t},\tag{3.1}$$

$$\boldsymbol{B}_c = \boldsymbol{\nabla}_c \times \boldsymbol{A}_c. \tag{3.2}$$

If the system is supposed to be conservative, the time t can be considered as the independent variable. In this context, the Hamiltonian in the Cartesian coordinate system reads [62]:

$$H_0 = \sqrt{(\mathbf{P}_c - q\mathbf{A}_c)^2 c^2 + m^2 c^4} + q\phi,$$
(3.3)

where *m* is the rest mass of the electron, *q* its charge and *c* the speed of light. The canonical momentum reads $P_c = \gamma m \beta_c c$, where γ is the Lorentz factor and β_c is the reduced velocity.

In accelerator physics, this Hamiltonian is transformed to make various approximations in equation expansions which eventually describe conveniently the dynamics of the system. The system is described relatively to a reference particle which propagates along an ideal reference path defined by the guiding magnets. Even though the system can be described correctly using the Cartesian coordinate system, it is more convenient to study its motion in the curvilinear coordinate system because the ideal trajectory of the reference electron is curved. In the curvilinear framework, an orthogonal basis is defined based on the position vector \mathbf{r}_{0c} of the reference electron in the Cartesian coordinate system [63]:

$$\boldsymbol{u}_s = \frac{d\boldsymbol{r}_{0c}}{ds},\tag{3.4}$$

$$\boldsymbol{u}_{x} = \frac{-1}{\left\|\frac{d^{2}\boldsymbol{r}_{0c}}{ds^{2}}\right\|} \frac{d^{2}\boldsymbol{r}_{0c}}{ds^{2}},$$
(3.5)

$$\boldsymbol{u}_z = \boldsymbol{u}_s \wedge \boldsymbol{u}_x. \tag{3.6}$$



The reference frame and the curvilinear system are illustrated in figure 3.1. The variations of u_x and u_z with s are

Figure 3.1: Trajectory of a particle with respect to the orbit of a reference particle. The dynamics of a particle is described in the frame of the reference particle, considered as the origin of the Frenet-Serret basis (u_s , u_x , u_z) defining curvilinear coordinates. Image from [64] and adapted to match the notations of the manuscript.

related to \boldsymbol{u}_s according to:

$$\frac{d\boldsymbol{u}_x}{ds} = \kappa_{0x} \boldsymbol{u}_s, \tag{3.7}$$

$$\frac{d\boldsymbol{u}_z}{ds} = \kappa_{0z} \boldsymbol{u}_s, \tag{3.8}$$

where κ_{0x} and κ_{0z} are the horizontal and vertical curvatures respectively. The position vector of an electron propagating close to the reference trajectory, at a given position *s* is:

$$\mathbf{r}(s) = \mathbf{r}_{0c}(s) + x(s)\mathbf{u}_{x}(s) + z(s)\mathbf{u}_{z}(s).$$
(3.9)

It follows from the preceding equations that the variation of *r* with respect to s then reads in the curvilinear coordinate system:

$$\frac{d\mathbf{r}}{ds}(s) = [1 + \kappa_{0x}x(s) + \kappa_{0z}z(s)]\mathbf{u}_s(s) + x'(s)\mathbf{u}_x(s) + z'(s)\mathbf{u}_z(s),$$
(3.10)

where ' denotes the derivative with respect to s. The variation along u_s depends on the horizontal and vertical

curvatures, but in the following κ_{0z} is considered to be negligible compared to κ_{0x} , meaning that:

$$h(s) = 1 + \kappa_{0x} x(s) + \kappa_{0z} z(s) \approx 1 + \kappa_{0x} x(s).$$
(3.11)

The canonical change of variables, from the Cartesian to the curvilinear coordinate system is given by the generating function of the third kind [63]:

$$F_3(\mathbf{r}, \mathbf{P}_c) = -c(\mathbf{P}_c - q\mathbf{A}_c).\mathbf{r}.$$
(3.12)

Deriving F_3 with respect to the Cartesian position coordinates leads to unchanged transverse conjugate momenta whereas:

$$c(P_{sc} - qA_{sc})h = c(P_s - qA_s).$$
 (3.13)

Eventually, the Hamiltonian in the Cartesian coordinate system H_0 transforms into the Hamiltonian H_1 in the curvilinear coordinate system:

$$H_1 = \sqrt{(P_x - qA_x)^2 c^2 + (P_z - qA_z)^2 c^2 + \frac{(P_s - qA_s)^2 c^2}{h^2} + m^2 c^4} + q\phi,$$
(3.14)

3.1.2 Transformed curvilinear Hamiltonian

In accelerator physics, the curvilinear Hamiltonian H_1 is transformed in three main steps to simplify the description of the dynamics.

Firstly, considering that in an accelerator the electron passes through electromagnetic fields at fixed location s, it is possible to make a change in the independent variable from time t to position s by means of the principle of least action. The canonical variables become (x, z, -t) and their canonical conjugate momenta (P_x, P_z, E) , where E is the total energy of the system. The Hamiltonian is then defined by:

$$H_2 = -P_s.$$
 (3.15)

Secondly, the system being described with respect to the reference particle, which propagates along the ideal reference path at the nominal momentum P_0 , it is wise to normalize the conjugate momenta (P_x, P_z, E) by P_0 . This transformation enables to deal with small normalized transverse momenta which is useful to make various approximations in equation expansions. The Hamiltonian keeps the same form as long as it is also normalized by P_0 :

$$H_3 = \frac{H_2}{P_0}.$$
 (3.16)

The canonical variables remain (x, z, -t) and their canonical conjugate momenta become $(\frac{P_x}{P_0}, \frac{P_z}{P_0}, \frac{E}{P_0}) = (p_x, pz, \frac{E}{P_0})$. Besides the normalized vector potential is $\mathbf{a} = q \frac{\mathbf{A}}{P_0}$. Thirdly, a generating function of the second kind [62]

$$F_2(x, z, -t, \tilde{p}_x, \tilde{p}_z, \delta, s) = x\tilde{p}_x + z\tilde{p}_z + \left(\frac{s}{\beta_0} - ct\right)\left(\frac{1}{\beta_0} + \delta\right)$$
(3.17)

enables to deal with a small energy deviation δ from the energy of the reference electron rather than the canonical momentum $\frac{E}{p_0}$ which is close to *c*. The Hamiltonian is then given by:

$$H_4 = H_3 + \frac{\partial F_2}{\partial s},\tag{3.18}$$

and the transverse conjugate variables are the same whereas the longitudinal conjugate variables read $(\frac{s}{\beta_0} - ct, \delta)$, with

$$\delta = \frac{E}{P_0 c} - \frac{1}{\beta_0}.\tag{3.19}$$

Eventually, the transformed curvilinear Hamiltonian is:

$$H = \frac{\delta}{\beta_0} - (1 + \kappa_{0x}x)\sqrt{\left(\frac{1}{\beta_0} + \delta - \frac{q\phi}{P_0c}\right)^2 - (p_x - a_x)^2 - (p_z - a_z)^2 - \left(\frac{mc}{P_0}\right)^2} - a_s.$$
 (3.20)

Prior to the derivation of the equation of motion, two approximations might be made in the following sections. Firstly, since the reference electron is relativistic, $\beta_0 \approx 1$ and $(P_0c)^2 = E_0^2 - (mc^2)^2 \approx E_0^2$ which results in

$$\delta = \frac{E - E_0}{E_0} = \frac{P - P_0}{P_0}.$$
(3.21)

In case $\delta = 0$, the system is said to be on-momentum whereas it is said off-momentum otherwise. It is legitimate to consider that $\delta \ll 1$ as a first approximation. Secondly, the paraxial approximation states that $x' = \frac{dx}{ds} \ll 1$ and $z' = \frac{dz}{ds} \ll 1$ which implies, in addition to the first approximation, that

$$p_s^2 = \|\boldsymbol{\rho}\|^2 - p_x^2 - p_z^2 \approx \|\boldsymbol{\rho}\|^2 \approx 1,$$
(3.22)

$$p_x = \|\boldsymbol{\rho}\| \times \|\boldsymbol{u}_x\| \sin\left(\frac{dx}{ds}\right) \approx x', \tag{3.23}$$

$$p_z = \|\boldsymbol{\rho}\| \times \|\boldsymbol{u}_z\| \sin\left(\frac{dz}{ds}\right) \approx z'.$$
 (3.24)

3.1.3 Linear transverse equations of motion

The Equations of motion are derived from Hamilton's equations. In this section, only the horizontal equation of motion is derived but the same procedure should be applied for the other variables. Besides, we only consider

electrons interacting with the fields of the magnets, i.e. there is no potential ϕ anymore.

In accelerator physics, the ideal magnetic fields are defined by a vector potential reduced to its longitudinal component A_s . In this approximation, the fringe fields of the magnets have negligible effects on the beam dynamics (it does not hold for solenoids, insertion devices, etc). Consequently, the magnetic field is a 2-dimensional field reduced to the transverse plane. In this context:

$$-\frac{\partial H}{\partial x} = \frac{dp_x}{ds} = x'' \tag{3.25}$$

$$=\kappa_{0x}\sqrt{\left(1+\delta\right)^2 - p_x^2 - p_z^2} + \frac{\partial a_s}{\partial x}$$
(3.26)

In curvilinear coordinate $\frac{\partial a_s}{\partial x} = \frac{q}{P_0} \frac{\partial A_s}{\partial x} = \frac{q}{P_0} \frac{\partial h A_{sc}}{\partial x} = -\frac{q}{P_0} h B_z$. Substituting $\frac{\partial a_s}{\partial x}$ and performing a Taylor expansion to the first order in δ :

$$x'' = \kappa_{0x}(1 + \delta - \frac{p_x^2 + p_z^2}{2}) - \frac{q}{P_0}hB_z.$$
(3.27)

It is then a matter of expressing the vertical component of the magnetic field to get the equation of motion. A few approximations are commonly claimed: the magnetic field is derived in the vicinity of the center of the magnet, i.e. sufficiently far from the iron yoke where the former does not affect the shape of the field. In addition, the field is derived in the steady state regime (the currents propagating in the coils are constant) while the effect of the space charge distribution of the beam is neglected. It follows that Laplace's equation reduces to:

$$\nabla^2 \phi = 0. \tag{3.28}$$

The solution of this equation is the magnetic field whose multipole expansion reads:

$$\boldsymbol{B}(x,z) = (B_z + iB_x)(x,z) = \sum_{n \ge 0} (B_n + iA_n)(x+iz)^n,$$
(3.29)

where $i \in \mathbb{C}$, $i^2 = -1$, and B_n and A_n are the constant normal and skew multipoles of the field respectively, defined by:

$$B_n = \frac{1}{n!} \left(\frac{\partial^n B_z}{\partial x^n} \right)_{(x=0,z=0)},\tag{3.30}$$

$$A_n = \frac{1}{n!} \left(\frac{\partial^n B_x}{\partial z^n} \right)_{(x=0,z=0)}.$$
(3.31)

(3.32)

The skew multipoles are responsible for the coupling between x and z. The skew multipoles are not taken into account in the following for simplicity. The field expansion is truncated to the first order (n = 1) for linear purposes

and its real part is kept to express B_z . The order n = 0 is associated to the dipolar field for which it is mandatory to take the curvature into account. On the contrary, $h \approx 1$ for the order n = 1 associated to the quadrupolar field. The transverse momenta are neglected in the paraxial approximation and the equation of motion reads:

$$x'' = \kappa_{0x}(1+\delta) - \frac{q}{P_0}hB_0 - \frac{q}{P_0}B_1x.$$
(3.33)

The dipolar field defines the magnetic rigidity

$$\frac{B_0}{\kappa_{0x}} = \frac{P_0}{q} \tag{3.34}$$

which leads to:

$$x'' + (k + \kappa_{0x}^2)x = \kappa_{0x}\delta.$$
(3.35)

The parameter $k = \frac{q}{P_0}B_1$ is the quadrupolar strength, which quantifies the focusing or defocusing effects of the quadrupoles on the beam. The parameters κ_{0x} and k depend on the position s. The homogeneous equation of motion tells that an electron in an accelerator is a system interacting with restoring forces that make it oscillate around the reference orbit. In the case of a circular accelerator, these oscillations define the betatron orbit of the system. The right hand side of the equation is the first order perturbation term in energy and indicates that an off-momentum electron is spatially offset due to its energy deviation δ . In this case it follows a so-called chromatic orbit. If $\delta > 0$, an electron is less deflected by the magnetic field. Conversely, if $\delta < 0$ the electron is more deflected. An electron beam is characterized by a finite distribution of electron energies. Since it is not mono-energetic, the energy offset is defined by the average value $\langle \delta \rangle$ of the distribution, and the energy spread by the standard deviation. The energy spread leads to the dispersion of the electrons by the dipoles which act like spectrometers in the horizontal plane. This effect is neglected in the vertical plane since the dipoles are supposed to be perfectly aligned and induce an ideal vertical field. The linear uncoupled equation of motion in the vertical plane takes the form of the horizontal unperturbed equation of motion:

$$z'' - (k - \kappa_{0z}^2)z = 0.$$
(3.36)

In the next section, some fundamental parameters are defined based on the solutions of the previous equations of motion.

3.2 Solutions of the linear equations of motion

3.2.1 On-momentum electron

The unperturbed equations of motion are analogous to that of an harmonic oscillator:

$$u'' + Ku = 0$$
 (where *u* represents *x* or *z*), (3.37)

except that *K* is a function of the independent variable *s*, and represents the magnet distribution in the lattice. The storage ring-based light sources are designed as periodic lattices of period *L* implying that K(s + L) = K(s) and the uniqueness of the solution to Hill's equation 3.37. For a given position *s* in the accelerator the solution is:

$$u(s) = \sqrt{2J_u \beta_u(s) \cos(\psi_u(s) - \psi_{0u})}.$$
(3.38)

The Twiss parameter β_u is called the beta function and is uniquely defined for a periodic lattice. The phase advance of the system, denoted ψ_u , varies with each pass of the system at s, while J_u and ψ_{0u} are integration constants. Considering the first derivative of u with respect to the independent variable s, it is possible to introduce the second Twiss parameter:

$$\frac{du}{ds} = u' = -\sqrt{\frac{2J_u}{\beta_u}} (\sin(\psi_u - \psi_{0u}) + \alpha_u \cos(\psi_u - \psi_{0u})),$$
(3.39)

with $\alpha_u = -\frac{\beta'_u}{2}$ being the second Twiss parameter. The remaining Twiss parameter $\gamma_u = \frac{1+\alpha_u^2}{\beta_u}$ is obtained naturally after some algebra [63]. The definition of the conjugate variables u and u' equivalently defines the conjugate pair (J_u, ψ_u) , the so-called action-angle variables. The Hamiltonian of the system can be expressed in a very compact form in the action-angle coordinate system [65]:

$$\mathcal{H}(\psi_u, J_u) = \frac{J_u}{\beta_u}.$$
(3.40)

Hamilton's first equation defines the angle ψ_u :

$$\frac{d\psi_u}{ds} = \frac{\partial \mathcal{H}}{\partial J_u} = \frac{1}{\beta_u}$$
(3.41)

leading to:

$$\psi_u(s) = \int_0^s \frac{1}{\beta_u(s')} ds'.$$
(3.42)

On the other hand, by combining equations 3.38 and 3.39 with the Twiss parameters, the action J_u reads:

$$2J_u = \gamma_u u^2 + 2\alpha_u u u' + \beta_u u'^2.$$
(3.43)

According to equation 3.43: in the linear approximation, the uncoupled dynamics of an electron is characterized by an ellipse in the phase space (u,u') whose shape is defined by the Twiss parameters at the given position *s*. This is illustrated in figure 3.2. Even though the shape of the ellipse varies with *s*, its area $A = 2\pi J_u$ is , in this



Figure 3.2: Uncoupled motion of an electron in the horizontal phase space, in the linear approximation. Initially, the electron is at s_0 . After one and two turns in the accelerator it is located at s_1 and s_2 respectively. Image taken from [66].

context, constant. J_u is indeed a constant of motion since ψ_u is a cyclic variable. The action is usually called the Courant-Snyder invariant.

Normalizing u and u', the ellipse is transformed into a circle in the normalized coordinates phase space (U,U'):

$$U = \frac{u}{\sqrt{\beta_u}} = \sqrt{2J_u} \cos\left(\psi_u\right),\tag{3.44}$$

$$U' = \frac{\alpha_u u + \beta_u u'}{\sqrt{\beta_u}} = \sqrt{2J_u} \sin\left(\psi_u\right),\tag{3.45}$$

with ψ_{0u} chosen to be equal to 0. While the electron performs one turn in the storage ring, of circumference C, it

goes around the circle several times, giving the number of betatron oscillations [65]:

$$\nu_u = \frac{1}{2\pi} \int_0^C \frac{1}{\beta_u(s)} ds.$$
 (3.46)

The parameter ν_u is called the transverse betatron tune. It is made of an integer part and a fractional part. The latter implies that after a single turn in the storage ring the electron does not come back to its initial location in phase space.

3.2.2 Off-momentum electron

In case the energy deviation of the electron is different from 0, the solution of the horizontal equation of motion reads:

$$x(s) = \sqrt{2J_x\beta_x}\cos\left(\psi_x\right) + \eta_x\delta,\tag{3.47}$$

where η_x is the dispersion function, depending on *s*. Thus, an electron with an energy deviation $\delta \neq 0$ is offset from the betatron orbit by $\eta_x \delta$ and follows a chromatic orbit. Considering the principal solutions of the homogeneous equation of motion [63]:

$$C_x(s) = \cos\left(\sqrt{Ks}\right)$$

$$S_x(s) = \frac{1}{\sqrt{K}}\sin\left(\sqrt{Ks}\right)$$

$$K > 0 \text{ (focusing)}$$
(3.48)

and

$$C_x(s) = \cosh\left(\sqrt{|K|}s\right)$$

$$S_x(s) = \frac{1}{\sqrt{|K|}} \sinh\left(\sqrt{|K|}s\right)$$

$$K < 0 \text{ (defocusing)}$$
(3.49)

which satisfies the initial conditions:

$$\begin{cases} C_x(0) = 1, \ S_x(0) = 0 \\ C'_x(0) = 0, \ S'_x(0) = 1 \end{cases}$$
(3.50)

the dispersion function at a given location *s* in the storage ring reads:

$$\eta_x(s) = S_x(s) \int_0^s \kappa_{0x}(s') C_x(s') ds' - C_x(s) \int_0^s \kappa_{0x}(s') S_x(s') ds'.$$
(3.51)

As mentioned in the previous section, the energy deviation modifies the deflection of the electron by the magnetic fields. Generally speaking, the overall focusing strength can be expressed to the first order in δ :

$$K_{\delta} = \frac{K}{1+\delta} \approx K(1-\delta).$$
(3.52)

Equation 3.52 means that for an electron too energetic ($\delta > 0$) the focusing strength is decreased whereas it is increased in the opposite case ($\delta < 0$). Consequently, the number of oscillations per turn varies with the energy deviation δ [63]:

$$\Delta\nu_x = -\frac{1}{4\pi}\delta \int_0^C \beta_x(s)K(s)ds \tag{3.53}$$

$$\Delta\nu_z = \frac{1}{4\pi}\delta \int_0^C \beta_z(s)K(s)ds \tag{3.54}$$

The variation of the betatron tunes with respect to the energy deviation is called the chromaticity:

$$\xi_u = \frac{\partial \nu_u}{\partial \delta}.$$
(3.55)

When the focusing is only due to linear magnets, namely the dipoles and quadrupoles, it is called the natural chromaticity. As the natural chromaticity is always negative, it needs to be corrected to avoid detrimental limitations in the operation of the accelerators.

3.3 Some limitations of the beam dynamics

The dynamics of an electron can be affected in various ways. This section provides a non-exhaustive overview of the limitations encountered in accelerator physics.

3.3.1 Closed orbit distortions

Previously there was no mention of error, but a real accelerator exhibits plenty of them, due to magnet misconceptions or misalignments for instance, which can have detrimental consequences, if not managed conveniently. Among these limitations, the first order perturbations are related the dipolar errors. For simplicity, a single permanent dipolar error is considered in the following. Assuming that an on-momentum electron experiences an unexpected horizontal dipolar kick θ at location s_0 , a perturbation term is added to the solution 3.38 of the homogeneous equation of motion 3.35 [63]:

$$\Delta x(s) = \frac{\sqrt{\beta_x(s)\beta_x(s_0)}}{\sin\left(\pi\nu_x\right)} \theta \cos\left(\pi\nu_x + \psi_x(s) - \psi_x(s_0)\right).$$
(3.56)

From equation 3.56, it is clear that the closed orbit distortion induced by the dipolar error is unstable as soon as the horizontal betatron tune ν_x is an integer. This case is illustrated in figure 3.3. This example illustrates the concept of resonance, called integer resonance in this particular case. There exist higher order perturbations which define different resonances. For example, a quadrupolar error leads to a half-integer resonance and a sextuolar error to a third order resonance. Thus, resonances can be driven by individual multipoles, as well as combinations



Figure 3.3: Unstable dynamics of an electron in the horizontal phase space due to coherent dipolar error: the horizontal betatron tune is an integer [67].

of multipoles. More generally, a resonance is defined as linear combination of the betatron tunes, in a periodic lattice [67]:

$$m_x \nu_x + m_z \nu_z = n, \tag{3.57}$$

where $(m_x, m_z, n) \in \mathbb{Z}^3$. The order of a resonance is traditionally defined by $|m_x| + |m_z|$ in accelerator physics. According to equation 3.57, it is possible to plot the tune diagram with the resonances as depicted in figure 3.4. At some point, an electron beam will be close to a resonance or even cross a resonance. In this case, part of the



Horizontal fractional tune

Figure 3.4: Tune diagram with first order (integer), second order (half-integer) and third order resonances plotted in red, blue and green respectively. The beam initial position (orange dot) in the tune diagram defines the working point of the accelerator [68].

beam, or even the entire beam in the most severe case, may be lost. However, it should be noted that the stability

of the beam tends to be less threatened with the increase of the order of a resonance.

3.3.2 Energy-dependent tune shift

The latter section introduced the energy-dependent tune shift and the natural chromaticity, the latter being always negative as previously mentioned (see equations 3.53 and 3.55). The energy deviation compatible with the operation of a circular accelerator is limited. Transversely, an off-momentum electron could get closer to a forbidden resonance due to the tune shift with energy. This is one of the major reasons why the chromaticity needs to be corrected. Additionally, detrimental collective effects arise if the transverse chromaticities are left to their natural value. For instance, the head-tail instability is known to be less dangerous for the stability of the beam dynamics when the chromaticities are zero or slightly positive [69]. In order to correct the chromaticity, the sextupole magnets are used.

3.3.3 Non-linear beam dynamics

The sextupoles are the first non-linear magnets of an accelerator. For an electron with positive energy deviation ($\delta > 0$), they provide additional focusing. Conversely, for an electron with negative energy deviation ($\delta < 0$), they provide additional defocusing. The corrected transverse chromaticities are then defined by [63]:

$$\xi_u = \pm \frac{1}{4\pi} \int_0^C (\beta_u(s)K(s) - m(s)\eta_x(s))ds,$$
(3.58)

where m denotes the sextupolar strength. Theoretically, only two families of sextupoles are required, i.e. one for each transverse chromaticity. However, including sextupoles in the lattice has a cost. Although assuming perfect sextupoles, the latter are responsible for the appearance of two kinds of unwanted perturbations. Indeed, the equations of motion:

$$x'' + Kx = Kx\delta - \frac{1}{2}m(x^2 - y^2)$$
(3.59)

$$y'' - Ky = -Ky\delta + mxy \tag{3.60}$$

have now higher order terms in $(\eta_x \delta)^2$ as soon as we consider $x \longrightarrow x + \eta_x \delta$, known as chromatic perturbation (related to focusing), as well as $(x^2 - y^2)$ and xy terms, known as geometric perturbations (related to transverse coupling) [63]. The non-linearities inherent to the sextupoles lead to unstable regions appearance in the transverse phase space. The region of the transverse phase space enclosed in the last dynamically stable trajectory, defining the dynamic aperture, can be significantly reduced as it is further detailed in the next chapter, or vanish when the tunes are closed to a third order resonance (some examples of non-linear dynamics in horizontal phase space are provided in [67]). In order to partially counterbalance these limitations, other families of sextupoles are conveniently included in the lattice.

3.4 Electron beam parameters

In the previous section, the basic concepts and parameters which characterize the single particle transverse dynamics have been presented. Nonetheless, the number of electrons in a bunch is of the order of 10⁹. A statistical description of the beam combined with the previous parameters is essential and enables to define some of the most fundamental beam parameters. Even though an electron beam can gather multiple electron bunches, these are considered identical. In the following, the definitions describe a single electron bunch but hold for any bunch of the electron beam. In accordance with the above, the beam parameters are presented in the framework of linear dynamics in uncoupled lattices.

3.4.1 Transverse bunch size

Until an electron bunch reaches a given location *s* in the storage ring, it has been deflected by the various electromagnetic fields it interacted with, and consequently it has radiated. The synchrotron radiation process results in the Gaussian distribution of the electrons in the transverse phase spaces. Considering the uncoupled transverse phase spaces (u, u'), *u* denoting *x* or *z*, the electron distribution is either enclosed in the phase space ellipse or partially enclosed if the RMS description of the distribution is preferred. The following deals with the RMS description. A typical horizontal phase space distribution is illustrated in figure 3.5. The projection of the distribution along the phase space directions give the Gaussian distributions of the positions and deviations, centered on the beam centroid (ideally located at u = u' = 0). In this context, the phase space distribution is characterized by a covariance matrix of the form [63]:

$$\Sigma_{u} = \begin{pmatrix} \langle u^{2} \rangle & \langle uu' \rangle \\ \langle uu' \rangle & \langle u'^{2} \rangle \end{pmatrix}.$$
(3.61)

The first coefficient of the so-called beam matrix is related to the RMS transverse size of the bunch (and the beam generally speaking):

$$\sigma_{u} = \sqrt{\langle u^{2} \rangle} = \begin{cases} \sqrt{\beta_{u} \langle J_{u} \rangle} & \text{, if } \eta_{u} \text{ or } \delta = 0\\ \sqrt{\beta_{u} \langle J_{u} \rangle + \eta_{u}^{2} \langle \delta^{2} \rangle} & \text{, otherwise} \end{cases}$$
(3.62)

3.4.2 Transverse beam emittance

The large number of electrons in a bunch implies to approach the concept of invariant differently. Each electron is characterized by its proper action. Statistically, the invariant is called the beam emittance and equals the average



Figure 3.5: Example of a Gaussian electron beam distribution projected in the horizontal phase space (black dots). The emittance is large as the beam extends widely along x, this is typically the kind of beam extracted from the booster ring of SOLEIL in terms of order of magnitude. The envelop at one standard deviation σ is plotted in green, while the Gaussian distributions of the positions and deviations are plotted in red and blue respectively.

action of all the electrons in a bunch [70]:

$$\varepsilon_u = \langle J_u \rangle. \tag{3.63}$$

The emittance can be deduced from equation 3.62 and is equivalently defined by relation [63]:

$$\varepsilon_u = \sqrt{\det(\Sigma_u)}.\tag{3.64}$$

This means that the emittance quantifies the volume occupied by the distribution of the electrons in the phase space. The transverse emittance is an invariant as long as the motion is uncoupled and the energy transfers are neglected. However, the system is not fully uncoupled and conservative experimentally. Consequently, the emittance can fluctuate in real accelerators. However, the operation of an accelerator aims at maintaining the beam in a stable state around an equilibrium value of the emittance. The beam emits synchrotron radiations mostly when it is deflected by the dipoles and the insertion devices. The energy lost turn after turn damps the transverse emittance exponentially while the quantum excitation, resulting from the synchrotron emission, eventually counter balance this effect as the emittance reaches an equilibrium state. The restoration of the energy loss thanks to radio-frequency cavities guarantees the stability of the emittance around this equilibrium state [70].

The transverse emittance is of primary concerns since it is directly related to the brilliance of the synchrotron

light source defined as the emitted number of photons per second, spatial section unit and 0.1% bandwidth range:

$$\mathcal{B} = \frac{d^4 N[\text{photons}]}{dt[\text{s}]d\Omega[\text{mrad}^2]dS[\text{mm}^2](d\lambda/\lambda)[0.1\% \text{ bandwidth}]},$$
(3.65)

where *N* is the photon flux, Ω the solid angle, *S* the cross section, $d\lambda/\lambda$ the wavelength bandwidth. Equation 3.65 implies that to achieve high brilliance, the photon beam must have a large number of photons and a small size. Neglecting diffraction effects, the spatial section unit $d\Omega dS$ is proportional to the product of the transverse emittances $\varepsilon_x \varepsilon_z$ such that the lower the emittances the larger the brilliance.

3.4.3 Beam lifetime

Like the emittance, another crucial parameter is the beam lifetime. Indeed, the average current intensity in a storage ring decreases exponentially with the beam lifetime. The latter, denoted τ , is defined by:

$$\frac{1}{\tau} = \frac{1}{\tau_{gas}} + \frac{1}{\tau_T} + \frac{1}{\tau_q},$$
(3.66)

where τ_q is the part of the beam lifetime related to quantum diffusion, τ_{gas} is the vacuum beam lifetime due to electron losses resulting from elastic and inelastic scattering with the residual gas particles in the vacuum chamber and τ_T is the Touschek lifetime of the beam due to off-momentum electron losses resulting from electron-electron interactions. Qualitatively, the Touschek lifetime increases with the overall size of the bunches and the energy acceptance, whereas it decreases with the current per bunch. The Touschek beam lifetime is a crucial parameter, which will not be theoretically defined in this manuscript (see [27, 28]), but it will be discussed in the following chapters.

Chapter 4

General background and diagnostics

Contents

4.1	Intr	oduction	46
4.2	\mathbf{Syn}	chrotron SOLEIL	46
	4.2.1	Overview	46
	4.2.2	Accelerators, transfer lines and synchrotron radiation	48
4.3	Star	ndard injection into the SOLEIL storage ring	57
	4.3.1	Introduction	57
	4.3.2	Introduction to the current bump-based injection scheme of SOLEIL	59
4.4	MIF	injection	67
	4.4.1	Principle of the MIK injection scheme	67
	4.4.2	Mechanical design of the MIK	70
	4.4.3	Magnetic field design	73
4.5	Con	trol command system and analysis Tools	85
	4.5.1	Control command system	85
	4.5.2	Analysis tools	87
4.6	Diag	gnostics and measurement methods	92
	4.6.1	Beam position monitors	92
	4.6.2	Beam loss monitors	97
	4.6.3	Diagnostics for transverse beam size monitoring	102

4.1 Introduction

In this chapter, a general overview of the SOLEIL complex is provided first. Then, the current injection scheme of SOLEIL is described, as well as its limitations. To overcome these limitations, SOLEIL considers to replace the current scheme by a single magnet-based injection scheme that I introduce here. The innovative MIK magnet, on which the single magnet-based scheme relies, is described precisely, in terms of its mechanical design and assembly, as well as its magnetic characteristics. Then I present the control command system, and the analysis tools that I developed and used to commission the MIK. Eventually, I present the high-performance diagnostics that have been commissioned during my PhD to make the most out of the MIK injection scheme.

4.2 Synchrotron SOLEIL

4.2.1 Overview

Synchrotron SOLEIL is managed as a non-profit civil company and was created on October 16th, 2001, by CEA (Commisariat à l'Energie Atomique et aux Energies Alternatives) and CNRS (Centre National de la Recherche Scientifique), which hold 28% and 72% of the shares repectively. The Île-de-France region and the Departemental Council of Essonne funded 183 M€ of investments and the Centre region is also a partner of Synchrotron SOLEIL (see SOLEIL website [71]). The company is the French national research center operating a storage ring-based synchrotron light source, for national and international scientific community. SOLEIL stands for Source Optimisée de Lumière d'Energie Intermédiaire du LURE (Laboratoire pour l'Utilisation du Rayonnement Electromagnétique) and will refer to the accelerators in the following as a whole light source facility. It was inaugurated on December 18th, 2006, while the first synchrotron radiation for external researchers, called users, was delivered on January 22nd, 2008.

Synchrotron SOLEIL manages an accelerator complex made of three accelerators ordered as follows: a linear accelerator (linac), a booster injector and a storage ring. The linac produces electrons with its electron gun (thermoionic source), and accelerates them up to 110 MeV. The electrons exiting the linac pass through the first Transfer Line (TL1) in order to be injected into the booster ring, which accelerates the electrons to the nominal energy of 2.75 GeV. At this stage, the electrons are extracted from the booster and injected into the storage ring, via the second Transfer Line (TL2). It should be noted that, apart from failure, the electron beam keeps turning for several tens of hours once stored. The storage ring is surrounded by 29 beamlines, which extend tangentially to the storage ring. In order to probe matter at submicrometric scales, the beamline scientists use the synchrotron radiation produced by means of 9 bending electromagnets, called dipoles, and 20 Insertion Devices (IDs) which deflect the ultra-relativistic electron beam. The IDs are divided in two categories: the undulators and the wigglers. A schematic view of the SOLEIL facility is provided in figure 4.1.



Figure 4.1: Schematic view of the SOLEIL facility. The electron path is illustrated in purple. It starts in the 110 MeV linac followed by the booster ring and the 2.75 GeV storage ring. The beamlines with their respective underlined name are colored according to their synchrotron radiation source: blue for bending magnets (dipoles), red for undulators and green for wigglers (see SOLEIL website [72]).

Generally speaking, a beamline is divided in several stages. It has a vacuum chamber, connected to the storage ring, in which the synchrotron radiation, emitted at the source point in the dipoles or IDs, is propagated. The photon beam (high brilliance and highly stable) reaches an optical cabin which filters and focuses it before transferring it to the experimental station as a monochromatic radiation or a pink beam. There, the beam is used to probe a sample of solid, liquid or gas matter enthroned in the experimental setup. The sensors installed in the experimental booth are connected to computers in the workstation, where users can process and analyze the recorded experimental data. Figure 4.2 provides a schematic view of a typical beamline.

Almost 5000 h of beam time was provided in 2021, with an availability of 98.4% (and an overall record of meantime between failure of 109 h).



Figure 4.2: Schematic view of the SOLEIL facility with a typical beamline. The synchrotron radiation from the dipoles or IDs of the storage ring is extracted towards an optical cabin which filters and focuses it before its transfer to the experimental station as a monochromatic radiation. The synchrotron radiation is used to probe a sample of solid, liquid or gas matter enthroned in the experimental setup. The sensors in the experimental booth are connected to the workstation computers where users can process and analyze the recorded experimental data (see [73]).

4.2.2 Accelerators, transfer lines and synchrotron radiation

4.2.2.1 Linear accelerator, transfer lines and booster ring

Linear Accelerator As mentioned previously, it all starts with a linac whose electron gun is based on a thermoionic source coupled with a 90 kV extraction voltage. The 90 keV electrons are focused and cleaned right after the exit of the electron gun by three magnetic focusing lenses and a cleaner, before they pass through the electron prebuncher. This device is supplied with an alternating voltage of ± 10 kV, at 200 W. Thus, the continuous electron beam produced by the electron gun is separated in two electron bunches which are then subdivided in several bunches by the 1 m long buncher, following the fourth magnetic focusing lens. The electron bunches are furthermore accelerated by the buncher to the energy of 15 MeV. The beam is focused once again before it enters the first accelerating section of 4.5 m in order to reach the energy of approximately 70 MeV. The second accelerating section is also preceded by focusing magnets and brings the beam energy to 110 MeV corresponding to the injection energy into the booster ring. The accelerating sections are connected to 3 GHz wave guides. The linac works at a repetition rate of 3 Hz. A schematic view representing the linac is depicted in figure 4.3.

First transfer line The TL1 starts right after the second accelerating section of the linac; it provides diagnostics to characterize the beam, and enables to inject the electron beam into the booster ring. There are two dipoles in the transfer line, each providing a deflection angle of 15° to the beam. The first dipole acts like a spectrometer. The electrons are deflected differently regarding their energy. Tantalum blades, following this dipole, are used to measure



Figure 4.3: Schematic of the linear accelerator of SOLEIL, depicting the girders (green), the electron gun (grey rectangle at the left), the magnetic focusing lenses (red), the pre-buncher and the buncher (blue), the accelerating sections (orange) and some diagnostics (yellow).

the energy spread and the energy deviation of the beam, as well as to select the electrons with the proper energy. The injection efficiency in the booster is maximized to approximately 90% for a beam energy $E = E_0(1 \pm 3 \times 10^{-3})$ (with $E_0 = 110$ MeV), assuming the beam is correctly matched to the transverse acceptance of the booster at its injection point. The horizontal and vertical beam sizes and divergences, as well as the horizontal dispersion and its derivative, are matched using seven quadrupole magnets.

Booster ring The 110 MeV electron beam is injected into the booster. It is a race track accelerator of 157 m with two superperiods between two long straight sections (LSs) for injection and extraction purposes. The booster is based on a 22 cell FODO lattice made of 36 dipoles (with missing dipoles in the LSs), 44 quadrupoles and also 28 sextupoles for chromatic correction at low energy (during a few tens of milliseconds following the injection into the booster). At each turn, the beam is accelerated thanks to a single 5-cell radio frequency (RF) system until it reaches the nominal energy of 2.75 GeV in approximately 300000 turns, equivalent to roughly 156.6 ms. The power supplies of the dipoles, quadrupoles and RF system are ramped up at a frequency of 3 Hz to follow the energy rise of the beam. At 2.75 GeV the beam, the natural emittance of which is on the order of 140 nm rad, is extracted from the booster and propagates in the TL2, before its injection in the storage ring. The main parameters of the booster are given in table **4.1** [74].

Second transfer line The TL2 connects the booster, from which the beam is extracted, to the storage ring, into which the beam is injected. It is a transport line of 40 m providing a total deviation of 45° thanks to four dipoles identical to those in the storage ring ($4 \times 11.25^{\circ}$). It is also equipped with seven quadrupoles, for beam matching purposes, identical to those in the booster. Contrary to TL1, TL2 does not host any energy selecting slit as the energy spread of the beam is damped in the booster to reach 6.6×10^{-4} . The TL2 ends with a thick and a thin septum magnets which cancel the booster beam deviation prior to its injection into the storage ring.

Parameter	Value
Circumference (m)	157
Revolution period (ns)	522
RF frequency (MHz)	352.202
Harmonic number	184
Energy loss per turn (keV)	409
Damping times $ au_x$ / $ au_z$ / $ au_s$ (ms)	6.3 / 5.7 / 2.7
Cycling frequency (Hz)	3
Injection / extraction energy (GeV)	0.1 / 2.75
Energy spread	6.6×10^{-4}
Horizontal emittance (nm rad)	130
Corrected betatron tunes ν_x / ν_z	6.6 / 4.6
Natural chromaticities ξ_x / ξ_z	-1.14 / -1.32
Momentum compaction factor	$3.19 imes 10^{-2}$
Number of dipoles / length (m) / field intensity (min, max) (T)	36 / 2.16 / (0.027, 0.74)
Number of quadrupoles / length (m) / maximum gradient (T/m)	44 / 0.4 / 12
Number of sextupoles / length (m) / maximum strength (T/m^2)	28 / 0.15 / 16

Table 4.1: Main parameters of the booster ring.

4.2.2.2 The storage ring

The 2.75 GeV storage ring is a 354 m long circular accelerator. Its commissioning started in May 2006 [75]. The ultra-relativistic electron beam performs a single revolution in $T_0 = 1.18 \,\mu\text{s}$. The storage ring has four $12 \,\text{m}$ LSs arranged symmetrically (mirror symmetry). Between two LSs, there are four double bend achromat cells separated by three 7 m Medium Straight sections (MSs). Two of these cells are split into two parts, creating two additional $3.6 \,\text{m}$ Short Straight sections (SSs) [76]. All the straight sections equal 45% of the storage ring's length. One of the LSs is dedicated to the standard bump-based injection scheme, and is considered as the first LS and a reference for counting the other straight sections, following the beam direction. In the following I will use the SOLEIL nomenclature to denote the straight sections. It gives the type of the straight section is denoted LS5 because it is located in cell number, from 1 to 16. For example, the second long straight section is denoted LS5 because it is located in cell number 5, following the injection section. According to this rule, the injection section is denoted LS1.

From what precedes, the storage ring lattice consists of 16 cells. A typical cell is depicted in figure 4.4. It has two standard 1.71 T dipoles which bend the beam trajectory in the horizontal plane along a circular path of radius $\rho = \frac{1}{\kappa_{0x}} = 5.36 \text{ m}$ (κ_{0x} being the horizontal curvature of the trajectory, see chapter 3). The deviation angle provided by each of the 32 straight dipoles is equal to 11.25°. In addition, the stored beam needs to be focused in order to provide intense photon beams at the source points. Thus the storage ring is equipped with 163 quadrupoles gathered in twelve families, providing focusing in the horizontal and vertical planes. As mentioned in chapter 3, the quadrupoles exert a restoring force on the stored beam such that it oscillates around an ideal orbit. The transverse betatron tunes of the bare lattice, i.e. when IDs are fully opened, are $\nu_x = 18.156$ and $\nu_z = 10.228$. Since the effect of a magnetic field depends on the energy of the electron which passes through it, off-momentum electrons

experience various focusing strengths proportional to their energy offset, which results in tune shifts with energy (see section 3.3.2). Thus, the natural chromaticities at SOLEIL are $\xi_{nx} = -46$ and $\xi_{nz} = -21$. In order to correct the focusing defects due to energy spread, which would prevent from storing the beam, 122 sextupoles gathered in twelve families are used. The corrected chromaticities at SOLEIL are $\xi_x = 1.2$ and $\xi_z = 2.2$. In addition to their proper coils, the sextupoles also hold those of the correctors. Due to magnet misalignments and magnetic errors, the natural closed orbit reaches approximately 1 mm vertically and 4 mm horizontally. In order to correct the closed orbit, there are 60 horizontal and vertical slow correctors which limit the distortions to 150 µm both vertically and horizontally. Moreover, the stored beam coupling, defined as the ratio of the vertical emittance ε_z to the horizontal emittance of 3.9 nm rad results from the modified Chasman-Green lattice, with



Figure 4.4: Schematic of a typical double bend achromat cell. The cell is composed of two 1.71 T dipoles (red), ten quadrupoles (blue) and seven sextupoles (yellow) sitting on three girders (green).

non-zero horizontal dispersion in the straight sections. Figure 4.5 gives the linear optics of the storage ring. In this configuration, the horizontal betatron function is minimized at the dipole locations to 1 m. Moreover, two canted in-vacuum undulators, for the long beamlines ANATOMIX (Advanced Nanotomography and Imaging with coherent X-rays [77]) and NANOSCOPIUM [78], were accommodated with an additional quadrupole triplet which provides double low vertical beta functions in the LS13 [79]. It should be noted that a moveable absorber is installed for a safe operation with the two cryogenic undulators closed at 5.5 mm of gap [80]. The moveable absorber is inserted horizontally to x = -22 mm in operation. This absorber has not been considered in the simulation studies because all the in-vacuum IDs were always fully opened during the experiments (except during an experiment with PROXIMA-1, but it was not necessary to insert the absorber). Although, the lattice was initially designed to provide a 4 fold symmetry, the optimized optics presented nevertheless reduce it to 1.



Figure 4.5: Twiss functions of the SOLEIL storage ring. Horizontal and vertical betatron functions (β_x , β_z) are plotted in blue and red solid lines respectively while the horizontal dispersion η_x corresponds to the green solid line (partial matching due to the quadrupole triplet of the canted beamlines NANOSCOPIUM and ANATOMIX, around s = 270 m).

This low emittance ring provides high brilliance photon beams by design. The amount of energy lost by the electron beam per turn by synchrotron emission in the dipoles is on the order of 940 keV, while it is of 200 keV in the undulators (other sources of energy loss account for 20 keV). This energy loss is restored thanks to the RF system. It consists of two cryomodules, located in MS2 and MS3, containing two RF cavities each. They are connected to RF amplifiers via RF wave guides. To compensate the energy lost per turn, representing 0.04% of the nominal energy, the power supplied by the solid state amplifiers to a 500 mA stored beam reaches 580 kW. The power is carried by a RF wave reflected in the wave guides. The varying electric field established in the resonant RF cavities oscillates at $f_{RF} = 352.202 \text{ MHz}$, equivalent to a RF period $T_{RF} = 2.84 \text{ ns}$. Regarding the phase advance of the electrons in a bunch with respect to the RF phase, the energy $E = eV \sin(2\pi f_{RF}t)$ provided to each electron of this bunch is slightly different (e is the electric charge of a single electron, V the RF voltage amplitude and t the time at which the electron passes through the accelerating cavity). Thus, each bunch is focused longitudinally around a stable point defined by the synchronous phase $\phi_s = 2\pi f_{RF} t_s = 2.8$ rad. The RMS longitudinal size of the bunch $\sigma_s = 4.6$ mm, equivalent to 15.4 ps, for a total RF voltage of 2.8 MV and an average stored current equal to zero. The bunch length is 189 times less than the delay, equal to T_{RF} , between two consecutive bunches in the uniform filling mode. Knowing the revolution time, the maximum number of bunches stored in the storage ring, in uniform filling mode, is $\frac{T_0}{T_{Rf}} = 416$. In this mode, the maximum value of the average current intensity stored equals 500 mA. This is the primary mode at SOLEIL representing 53.6% of the available beam time in 2021 (the other filling patterns are the hybrid mode (34, 1%), the 1 and 8 bunch mode for high time resolved experiments (5.7% and 3%) respectively) and the low-alpha mode (2.9%); the remaining time being devoted to radiation safety measurements).

In the uniform filling pattern, the beam lifetime lies between 10 and 11 h, mainly due to the electron losses resulting from the Touschek scattering effect and collisions between residual gas particles and the electrons (although the average pressure is as low as 1×10^{-9} mbar in the ultra-high vacuum chamber). Consequently, the storage ring needs to be refilled with electrons regularly. The main parameters of the storage ring are given in table 4.2.

Parameter	Value
Circumference (m)	354
Number of cells	16
Number of superperiods / symmetry	4 / 1
Number $ imes$ length of straight sections (m)	$4\times 12 + 12\times 7 + 8\times 3.6$
Revolution period (µs)	1.18
RF frequency (MHz)	352.202
Harmonic number	416
Number of RF cavities / maximum total RF voltage (MV)	4 / 2.8
Totla energy loss per turn (keV)	1160
Damping times $ au_x$ / $ au_z$ / $ au_s$ (ms)	6.9 / 6.9 / 3.5
Energy spread	1.025×10^{-3}
Horizontal emittance (nm rad)	3.9
Nominal coupling (%)	1
Corrected betatron tunes ν_x / ν_z	18.156 / 10.228
Natural chromaticities ξ_{nx} / ξ_{nz}	-46 / -21
Corrected chromaticities ξ_x / ξ_z	1.2 / 2.2
Momentum compaction factor 1 st / 2 nd orders	4.18×10^{-4} / 4.50×10^{-3}
Beam lifetime (h)	11
Average pressure (mbar)	1×10^{-9}
Number of dipoles / length (m) / field intensity (T)	32 / 1.05 / 1.71
Number of quadrupoles / length (m) / maximum gradient (T/m)	163 / 0.32 or 0.46 / 22
Number of sextupoles / length (m) / maximum strength (T/m^2)	122 / 0.16 / 320

|--|

4.2.2.3 2.84 T permanent magnet-based superbend

In August 2021, the storage ring underwent a major modification, as the standard $1.33 \text{ m} \log 1.71 \text{ T}$ dipole source of the ROCK beamline was replaced with a $1.26 \text{ m} \log 2.84 \text{ T}$ permanent magnet-based (NdFeB) superbend (see figure 4.6). This magnet has been designed and studied by the Magnets/IDs and Accelerator Physics groups of SOLEIL to provide a peak field intensity of 2.84 T, 114 mm after the entrance of the magnet (source point at 1°), while preserving the magnetic field integral equal to 1.831 T m, equivalent to a bending angle of 11.25° . The variations of the vertical magnetic field along the ideal path in the superbend are illustrated in figure 4.7. In order to meet the designed field shape, the vertical gap passed from 37 mm with the previous dipole to 16.1 mm in the high field intensity area and 23 mm elsewhere. Consequently, the vacuum chamber section was modified accordingly, with vertical physical apertures of $\pm 6 \text{ mm}$ and $\pm 6.4 \text{ mm}$ respectively. Moreover, the vertical magnetic field variations imply additional focusing due to the multipolar quadrupole component, the effects of which have been compensated locally by applying linear optics correction based on orbit response measurement (LOCO) [82]. In addition, the



Figure 4.6: The 2.84 T permanent magnet-based superbend installed in the storage ring. In red, the equipment dedicated to extract the dipole if a vacuum chamber bakeout must be performed, the magnetic properties of the permanent magnets being deteriorated for temperatures higher than 120 °C [81]

strong chromatic effects due to the multipolar sextupole component have been corrected globally. Although the linear dynamics is restored, the installation of the superbend drastically reduced the dynamic aperture of the storage ring (see chapter 5). The superbend meets the specifications as the it provides twice and five times more flux than the previous dipole, at 20 keV and 40 keV respectively. This is illustrated in figure 4.8. Moreover, non-linear optimizations have been performed by P. Brunelle using multi-objective genetic algorithms (MOGA), in order to compensate for the dynamic aperture shrinkage. A new set of sextupoles has been used in operation since July 2022 and has proven to work satisfactorily. Experimentally, the injection efficiency has increased by almost 10% after this optimization, returning to the previous performance. It should be noted that I conducted the simulation and experimental studies presented in my manuscript prior to this optimization. Moreover, the thinner vacuum chamber was installed along with the MIK, in January 2021, before the superbend.



Figure 4.7: Variations of the vertical magnetic field of the superbend (red) and standard dipoles (blue) along the stored beam path.

4.2.2.4 Synchrotron radiation

At SOLEIL, the synchrotron radiation is produced in different ways as mentioned above. Considering the deflection of a single ultra-relativistic electron by a dipole, describing a circular path of radius ρ , the spontaneous emission of photons is reduced to an angular aperture equal to $\pm \frac{1}{\gamma}$, where γ denotes the Lorentz factor, because of the relativistic effect of angle contraction. The angle $\frac{2}{\gamma}$ is crossed in $\Delta t = \frac{2\rho}{\gamma c}$, which transforms as $\Delta t_{obs} = (1 - \beta)\Delta t$ for an observer, where β is the reduced velocity. In the ultra-relativistic approximation:

$$\Delta t_{obs} = \frac{2\rho/\gamma c}{\gamma^2 (1+\beta)} = \frac{\rho}{\gamma^3 c}.$$
(4.1)

Knowing that $\rho = 5.36$ m and $\gamma = 5381$ at SOLEIL (E = 2.75 GeV), the photon beams are made of very short pulses of duration $\Delta t_{obs} = 1.18 \times 10^{-19}$ s. Taking into account the billions of electrons in a bunch, the pulse duration is on the order of 1×10^{-12} s. This provides polychromatic photon beams, with large continuous spectrum according to $\Delta \omega \Delta t_{obs} \ge 1$ (1 dimension Fourier transform). This is equivalent to $\hbar \Delta \omega \Delta t_{obs} \ge \hbar$, where \hbar is the reduced Planck's constant. Taking into account a $\frac{3}{2}$ factor in 3 dimensions, the equality case defines the critical energy [83]:

$$\varepsilon_c = \frac{3}{2} \frac{\hbar}{\Delta t_{obs}} = \frac{3\hbar\gamma^3 c}{2\rho},\tag{4.2}$$

Which is the highest energy in a pulse. In operation, the critical energy reached at SOLEIL is on the order of $\varepsilon_c = 8.6$ keV which corresponds to the hard X-ray range.

As 3rd generation light source, SOLEIL is equipped with various IDs in addition to the dipoles. These IDs are divided in three subsets: 21 undulators (2 in-vacuum cryogenic permanent magnet undulators, 6 in-vacuum undu-

lators, 13 Apple-II type undulators), 4 electromagnet-based IDs and 2 wigglers [84]. The design and the properties of the IDs can be found in [85, 86, 87]. Undulator radiation shows a discrete spectrum characterized by a resonant wavelength and its harmonics whereas the wigglers provide continuous spectrum ¹. The overall spectral map of SOLEIL is illustrated in figure 4.8.



Figure 4.8: Variations of the brilliance with respect to the energy range, according to the magnetic elements used at SOLEIL to produce the synchrotron radiation (figure made by O. Marcouillé, Magnetism and IDs group).

Regarding the design of the accelerators, dipoles and IDs of the storage ring, SOLEIL provides a spectrum range which extends over eight orders of magnitude, as illustrated in figure 4.9. Among the other storage ring-based synchrotron light sources, SOLEIL works at an intermediate energy scale. Consequently, although SOLEIL is able to provide synchrotron radiation in the terahertz (1 meV) and hard X-ray (100 keV) ranges, most photon beams lie in the soft X-ray and tender X-ray domains.

Similarly to other ring-based light source facilities, a major upgrade of SOLEIL is foreseen. The design of a new diffraction limited storage ring is underway [33]. The current horizontal emittance of 3.9 nm rad is planned to be divided by a factor 50 in SOLEIL II, reaching a natural emittance of 81 pm rad, as illustrated in figure 4.10. This will increase the brilliance and its coherence by two orders of magnitude enabling new type of sciences: achieving nanoscale resolution on the beamlines, operando studies to address current and future scientific and

¹This behavior results from the fact that wigglers operate at high photon energy with harmonics overlapping each other.



Figure 4.9: Spectrum range provided by SOLEIL. It extends from terahertz (1 meV) to hard X-ray (100 keV), i.e. eight orders of magnitude, although most of the beamlines work in the soft X-ray and tender X-ray domains [72]

societal challenges ahead of us.

4.3 Standard injection into the SOLEIL storage ring

4.3.1 Introduction

SOLEIL is a light source which aims to provide its users with different kinds of filling patterns. In 2021, the most operated filling pattern, achieving 53.6% of the operation time, was the uniform mode, which consists of four quarters full of 104 bunches each, achieving 500 mA maximum. Additionally, 34.1% of the operation time was dedicated to the hybrid filling mode, with only three quarters filled, reaching a current intensity of 445 mA, plus one bunch in the middle of the fourth quarter at 5 mA. It was followed by the single bunch mode, at 16 mA, and the the 8-bunch mode, at 100 mA, representing 5.7% and 3.0% of the operation time respectively, the rest of the time being devoted to radiation safety tests [84]. This is illustrated in figure 4.11.



Figure 4.10: Logarithmic scaled plots of the current and future synchrotron light sources, with their normalized horizontal emittance given as a function of the storage ring circumference. The dark blue points correspond to the current 3rd generation light sources, the red points to the current and future 4th generation light sources based on diffraction limited storage rings (DLSRs) and the clear blue points to the new wave of DLSR. Chart provided by Riccardo Bartolini, PETRA IV.



Figure 4.11: Distribution of beam time (4935 h) for the beamlines and radiation tests of SOLEIL in 2021, according to the filling patterns [84].

As detailed in section 4.2, SOLEIL is a 3rd generation synchrotron light source designed to meet the users' need for high brilliance photon beams produced in the storage ring, characterized in particular by a low natural emittance of 3.9 nm rad. This is achievable thanks to advances in the understanding and optimizing of the nonlinear beam dynamics on one side, and the improvements in accelerator technologies on the other side, resulting especially in much stronger focusing magnets. Although this tipping point is a real improvement, it has a significant cost. Achieving such low emittance levels by means of strong focusing led to the excitation of resonant driving terms, increased the intrabeam interactions, and ultimately decreased the electron beam lifetime. The scattered off-momentum electrons being lost on the vacuum chambers' walls, the average current intensity of the stored beam decreases more rapidly. Requirement for submicrometer stability together with this short lifetime made outdated and detrimental the former decay mode of operation (three injections per day, with beamline front-ends closed and thermalization). Indeed, this adversely affects beamline optics and diagnostics stability due to the resulting large thermal drift. The stored current variations in the decay mode of operation are illustrated in figure 4.12.

Therefore, the need to maintain constant thermal load in the storage ring has led to the advent of an innovative injection mode, called the top-up mode. Its goal is to keep the average current intensity almost constant. At SOLEIL, since the commissioning of the top-up mode in march 2009, an injection occurs as soon as the average current intensity is lower than 99.8% of its nominal value. In this context, new electrons are injected while the stored beam is still circulating in the storage ring. Doing so, the variation of the average current *I* with respect to the nominal average current I_0 reads $|\Delta I/I_0| = |I - I_0|/I_0 \le 0.2\%$. This threshold is typically crossed every two to three minutes, depending on the lifetime variations driven by the IDs configurations. At SOLEIL, the top-up is commonly used for any of the filling patterns shown in figure 4.11.

4.3.2 Introduction to the current bump-based injection scheme of SOLEIL

4.3.2.1 Overview

In top-up mode, the average current intensity is said to be constant because this is how it is perceived by the beamlines. In fact, the average current intensity has a sawtooth profile, as illustrated in figure 4.13, where the tooth height is only 0.2% of the nominal average current. At SOLEIL, the top-up mode relies on a bump-based injection scheme. It imposes strong reliability constraints on the pulsed injection magnets to maintain high injection efficiency in the storage ring. The typical injection efficiency performance of SOLEIL are plotted in figure 4.14. One drawback has been reported by a category of users at SOLEIL: the injection process, which is undesirably detected by the beamlines, has become inconvenient due to the high injection rate (around 480 injections per day in the case of the uniform filling pattern). The perturbations due to the injections can be particularly detrimental for time-resolved experiments, crystallography performed at PROXIMA-1 and 2, and beamlines using nanobeams, coherent beams, like ANATOMIX or NANOSCOPIUM. The infrared beamline AILES is also known to be sensible to the injection



Figure 4.12: Variations of the stored current intensity in the former decay mode of operation at SOLEIL. The stored current intensity used to decrease to 170 mA before going back to the nominal value which was 250 mA at the time.

perturbations (see section 5.4). Gating signals are provided to any beamline if requested. In practice, this is still not very common.

In fact, the stored beam is undoubtedly perturbed by the residual effect of the injection magnets which regularly induce unwanted betatron oscillations (see equation 4.5 and section 5.2.2.3).

4.3.2.2 Principle of the standard injection in the SOLEIL storage ring

In daily operation, the booster beam is injected on-momentum (2.75 GeV) in the storage ring, via the TL2 (see section 4.2.2.1). Ideally, all the injection process is restricted to the horizontal plane. The standard injection scheme used at SOLEIL for top-up operation is made of a thick septum magnet and an in-vacuum thin septum magnet, the blade of which is 3.5 mm thick and fixed at the nominal position x = -19.5 mm [88]. The septum magnets are


Typically 2 mA every 3 mn Current stability below ±0.2 %

Figure 4.13: Machine status of SOLEIL providing the average current intensity in top-up operation, in uniform filling mode. The nominal current intensity is almost stable around 500 mA. The sawtooth profile shows a current stability in the range of $\pm 0.2\%$.

installed together with four identical kicker magnets, called K1, K2, K3 and K4, located in LS1, defining the injection section [89]. The injection section of the storage ring is depicted in figure 4.15. The variations of the optic functions in the injection section and the surrounding arcs are illustrated in figure 4.16. Their value at the kickers locations and injection point, on the storage ring and TL2 sides, are given in table 4.3.

Optic function	@K1 and K4	@K2 and K3	Inj. point
eta_x (m)	14	12	12
eta_z (m)	11	8	8
η_x (cm)	23	23	23

Table 4.3: Optics functions amplitude in the storage ring, at the injection kickers locations and injection point.

The distance between K1 and K2 is equal to that between K3 and K4 and equals 3.002 m, while the distance between K2 and K3 is 4.225 m. The kickers are installed symmetrically with respect to the middle of the injection section, while the injection point, considered as the exit of the thin septum magnet, is located 1.413 m downstream from it. They are powered with a half sine wave of $7 \mu s$ and provide a peak nominal kick of 5.8 mrad, in absolute value. The kickers pulses are designed to fall in approximately 3 turns, preventing the injected beam from being



Figure 4.14: Injection efficiency variations in the booster and the storage ring (before the commissioning of the 2.8 T permanent magnet-based superbend), in the hybrid filling pattern. The Long Pulse Mode (LPM) and Short Pulse Mode (SPM) denotes the type of beam extracted from the booster, corresponding to 104 and 70 continuous bunch beam respectively. The figure also provides the betatron tunes, as well as the average stored current monitored by the DCCT and the beam lifetime. The black arrow gives the starting time of user operation.

scraped by the septum blade on the turns following the injection. The thick septum magnet is powered with a half sine wave, lasting 3.3 ms, and providing a peak nominal kick of 110 mrad. Conversely, the thin septum magnet is powered with a full sine wave of $120 \,\mu\text{s}$, providing a peak nominal kick of $25 \,\text{mrad}$. The main design parameters of the injection pulsed magnets are gathered in table 4.4.

Parameter	K1 and K4	K2 and K3	Thick septum	Thin septum
Wave form	Half sine	Half sine	Half sine	Full sine
Magnetic length (m)	0.60	0.60	2×0.50	0.60
Pulse duration (μ s)	7	7	$3.3 imes 10^3$	120
Nominal kick (mrad)	5.8	-5.8	110	25

Table 4.4: Main design parameters of the standard injection pulsed magnets						
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When injecting, the kickers are triggered to provide a local transient bump which brings the stored beam as close as possible to the inner face of the septum blade. In the mean time the booster beam is brought parallel to the stored beam, close to the outer face of the blade, thanks to the consecutive kicks of the septum magnets. A



Figure 4.15: Synoptic of the injection section. The second transfer line (TL2) connects to storage ring at the thin septum magnet location. The four injection kickers are denoted K1, K2, K3 and K4. The KVCBA is a vertical corrector used to implement an active correction, as detailed in chapter 5. The injection section is surrounded by over shielded walls (red hatching) for radiation safety purposes.

schematic view of the standard bump based injection scheme of SOLEIL is given in figure 4.17.

To inject successfully, the injected beam has to oscillate within the dynamic aperture. The theoretical minimum half horizontal and vertical dynamic apertures required for the injected beam to be captured are defined by relations 4.3 [90]:

$$\begin{cases}
A_x = N_s \sigma_{x,s} + 2N_i \sigma_{x,i} + S \\
A_z = N_i \sigma_{z,i}
\end{cases},$$
(4.3)

where s and i indices denote the stored and injected beams respectively, and S the septum blade thickness. The



Figure 4.16: Variations of the Twiss functions in the 12 m long injection section and in the surrounding arcs. the figure is centered on the middle of the injection section. The horizontal and vertical beta functions are in blue and red respectively, whereas the horizontal dispersion function is plotted in green (the vertical dispersion function is supposed to be zero). The vertical dashed lines in purple locate the four injection kickers and the vertical dashed line in cyan locate the injection point.



Figure 4.17: Standard bump-based injection scheme. The stored beam is bumped (blue dashed line) from the central orbit (black solid line) by the four kickers (in blue), in the injection section. The booster beam (red dashed line) is brought parallel to the stored beam by the septum magnets (in purple). Eventually, the stored beam is brought back to the central orbit with the injected beam (red solid line), as the orbit bump falls in approximately three turns.

beam clearances are N_s and N_i , while $\sigma_{x,z,s}$ and $\sigma_{x,z,i}$ stand for the transverse beam sizes. Regarding equation 4.3, the only parameters that can be tuned to minimize A_x and A_z are the transverse size of the injected beam because S is fixed. This is illustrated by figure 4.18. Some optimizations of the injected beam size, by means of emittance exchange, can be found in [91, 92, 93]. On the one hand, the booster beam exits the thin septum at a horizontal position on the order of -27 mm, with an initial horizontal deviation x' = 0 (according to the characteristics of the injection magnets gathered in table 4.4, and that $N_s = 7$, $N_i = 3$, $\sigma_{x,s} = 320 \,\mu\text{m}$ and $\sigma_{x,i} = 1.2 \,\text{mm}$). On the other



Figure 4.18: Positions of the beams and the thin septum blade (shaded area) during the bump-based injections. Firstly, the booster (red) and stored (blue) beams are positioned as close as possible from the faces of the septum blade, by the septum magnets and the kickers respectively. Eventually, the stored beam (green) is brought back to its original closed orbit together with the injected beam (pink) as the orbit bump falls in approximately three turns. The injected and stored beams are represented by their 3σ and 7σ envelops respectively.

hand, the stored beam is bumped from x = 0, its original closed orbit, to approximately x = -17.4 mm. In this situation, K1 and K2 bring the stored beam centroid about 2 mm away from the inner face of the blade, providing enough clearance to not lose or scrape the beam (see figures 4.17 and 4.18). In this context, A_x and A_z are on the order of 13 mm and 1 mm respectively, at the injection point. Due to the necessary initial horizontal separation between the on-momentum injected and stored beams, the booster beam is injected off-axis. Considering the bump height, the injected beam centroid is located at x = -9.6 mm with x' = 0 ideally, at K4 location. Therefore, the injected beam performs betatron oscillations on the order of 10 mm amplitude and merges with the stored beam when it reaches equilibrium after a few radiation damping times.

4.3.2.3 Limits of the standard injection scheme

The main goal of a synchrotron light source is to provide its users with reliable photon beams which exhibit the required properties to perform their experiments (see chapter 3 and section 4.2.2.4). The stability of the photon beams is closely related to the stability of the stored beam, whether it be from its position and size point of view: the more stable the stored beam, the more reliable the photon beams. As mentioned previously, stored beam perturbations come from various sources with different timescales, involving the pulsed injection magnets. Here,

the main contributor to stored beam perturbations is the residual kick of the kickers, resulting from the unclosed bump. Ideally, the effect of the kickers on the closed orbit would be restricted to the injection section if the kicker pulses were perfectly matched. In this case, the resulting kick of the kickers reads

$$\Theta = \theta_1 + \theta_2 + \theta_3 + \theta_4 = 0, \tag{4.4}$$

where θ_i is the horizontal deviation of the ith kicker, and $\theta_{1,4} = -\theta_{2,3}$.

Although the four kickers are designed to meet the same specifications, internal discrepancies prevent them from being perfectly the same. Their electronics and supplying cables may differ, leading to pulses mismatch, and magnet misalignments also come into play. These are one of the key reasons, to name a few, why they are not identical. Thus, the kicks do not compensate rigorously, leading to a residual kick $\Theta \neq 0$. As a consequence, the stored beam performs betatron oscillations with a maximum amplitude defined in linear approximation by

$$\Delta x(s) = \sqrt{\beta_{x,inj}\beta_x(s)}\Theta,$$
(4.5)

at a given longitudinal position of observation *s* in the ring. The beta functions evaluated at the injection point and the position of observation are denoted $\beta_{x,inj}$ and $\beta_x(s)$ respectively. It is to be noted that this linear model describes what happens for a given turn in the ring, but the residual kick Θ actually depends on time, since the kicker pulse is 7 µs long (see section 5.2.2 and figure 5.16 especially).

In addition, it has been observed that the thick and thin septum magnets also contribute for the position perturbations of the stored beam, even though the amplitude of the perturbations is much lower compared to that induced by the kickers. Indeed, they are not as close as the kickers from the stored beam and their magnetic field decreases with distance. Nonetheless, the effect of the thick septum magnet was known to last up to 20 ms. To address this concern, preliminary studies conducted as of 2007 enabled to simulate and measure the stored beam perturbations due to the septum and kicker magnets, as well as estimate the time variations of the residual kicker kick. This led to various optimization through the 2010s'. The initial half sine wave of the thin septum magnet has been changed into a full sine profile, decreasing the perturbation amplitude. Additionally, shielding of the storage ring inner chamber, including the pumping outlet, with a magnetic alloy screen of 0.5 mm thickness, later prevented the perturbation of the thin septum. In 2009, the perturbation due to the thick septum was reduced by means of μ -metal and grounded upstream Eddy currents. In 2015, a final optimization, by means of grounded downstream Eddy currents, decreased the perturbation amplitude furthermore but did not cancel it totally. According to the experimental studies performed at the ESRF [49], since the perturbation is very reproducible, a feed-forward correction could reduce the perturbation even further, but such a dedicated correction has not been tested at SOLEIL. It is not currently used in operation nor is a dedicated feedback system. Last but not least, the kickers' pulsers were firstly optimized using saturating

self and parallel capacitor. Secondly, two sets of experiment studies, conducted in 2007 and 2009, consisted in kicker pulse matching optimizations through turn-by-turn beam based measurements [94, 95]. Experimentally, only the average residual kick of the pairs (K1, K2) and (K3, K4) can be measured and minimized. It is impossible to estimate the four individual kicks because there is no BPM between the kickers, but only two BPMs at the upstream and downstream ends of the injection section. Moreover, the kickers were realigned, such that their rolling angle was reduced. The lowest contribution of each septum magnet, and the overall lowest kicker contribution to the stored beam perturbations are recalled in table 4.5.

Table 4.5: Optimized stored beam perturbations due to the standard injection magnets of SOLEIL, at 1% stored beam coupling.

Parameter	Kickers	Thick septum	Thin septum
Peak horizontal oscillation amplitude (% of $\sigma_{x,s}$)	31	6	0
Peak Vertical oscillation amplitude (% of $\sigma_{z,s}$)	250	25	0

Despite vigorous efforts to finely tune the injection magnets using state-of-the-art techniques, the figures in table 4.5 demonstrate that the kickers are the major source of stored beam perturbations and that the betatron oscillation amplitudes are way beyond the thresholds that define what can be considered as transparent injection, especially in the vertical plane. Moreover these perturbations increase slowly with time (on yearly scale), and the optimization process must be repeated in order to maintain the performance. I have studied and characterized all these sources of instabilities during my PhD, through simulation and stored beam-based data analysis, in order to have up to date data sets to compare to the MIK performance.

4.4 MIK injection

4.4.1 Principle of the MIK injection scheme

One solution studied at SOLEIL to prevent injection perturbations consists in using a single pulsed MIK, installed downstream the injection section, instead of the injection kickers. The magnetic field of the MIK is designed to only interact with the injected beam. The MIK injection scheme is depicted in figure 4.19. Similarly to the standard injection, this innovative off-axis betatron injection is performed on-momentum, unless explicitly stated otherwise. The main idea is to prevent the stored beam from interacting with any magnetic field during the injection process. In this situation, the closed orbit is kept unperturbed. This means, according to the previous section, that the booster beam is injected roughly 25 mm away from the stored beam, instead of 10 mm in the case of the standard injection scheme (when the bump falls). It follows that if the injected beam is left propagating freely, it will perform betatron oscillations with large amplitudes on the order of 25 mm. In this context, the injected beam would be lost on the walls of the vacuum chamber in less than one turn. Not only the injected beam needs to oscillate within the limits of



Figure 4.19: MIK injection scheme. The orbit of the stored beam is left unperturbed (black solid line), while the booster beam (red dashed line) is brought close to the septum blade thanks to the septum magnets (purple rectangles). It propagates freely (red solid line) until the amplitude of the horizontal oscillations is minimized by the MIK (blue rectangle).

the physical aperture, but it must be captured within the dynamic aperture of the ring as well. Thus, the MIK must minimize the oscillation amplitude of the injected beam, in other words minimize the injection invariant.

According to section 3.1, the linear dynamics of the injected beam centroid can be described by a circular motion in the normalized horizontal phase space, neglecting radiation damping during the first turns. Since the action $J_{x,0}$ is a constant of motion:

$$2J_{x,0} = X_0^2 + {X'_0}^2 = X_{MIK}^2 + {X'_{MIK}}^2,$$
(4.6)

where X_0 and X'_0 are the normalized initial conditions of the injected beam, X_{MIK} and X'_{MIK} its normalized coordinates at the MIK location. This is illustrated in figure 4.20. In order for the injected beam not to be lost on the vacuum chamber, but to be captured within the dynamic aperture, the MIK gives it an additional deviation θ_x . Consequently, another circle is defined in the normalized horizontal phase space:

$$2J_{x,1} = X_1^2 + {X_1'}^2. (4.7)$$

In the thin lens approximation, the coordinates linearly transform like

$$\begin{cases} X_1 = X_{MIK} \\ X'_1 = \frac{\alpha_{x,MIK} x_{MIK} + \beta_{x,MIK} (x'_{MIK} + \theta_x)}{\sqrt{\beta_{x,MIK}}} = X'_{MIK} + \sqrt{\beta_{x,MIK}} \theta_x, \end{cases}$$
(4.8)

where $\alpha_{x,MIK}$ and $\beta_{x,MIK}$ are the horizontal Twiss parameters at the MIK location. Considering its derivative with respect to θ_x and its sign, $J_{x,1}$ is minimized for

$$\theta_x = -x'_{MIK} - \frac{\alpha_{x,MIK}}{\beta_{x,MIK}} x_{MIK}.$$
(4.9)

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Figure 4.20: Trajectory of the injected beam centroid (red line) in the normalized horizontal phase space. The booster beam centroid (red dot) is injected at (X_0, X'_0) , with the initial synchronous phase ϕ_s , and passes through the MIK at (X_{MIK}, X'_{MIK}) , with the phase advance ψ . The MIK kick changes the angle of the injected beam in phase space to (X_1, X'_1) , minimizing the invariant from $J_{x,0}$ to $J_{x,1}$. The green dot represents the unperturbed stored beam at (0, 0).

In addition, according to equations 4.6, 4.7 and 4.8, the change in injection invariant resulting from the MIK deviation is defined by

$$\Delta \varepsilon_x = 2 \times (J_{x,0} - J_{x,1}) \tag{4.10}$$

$$= -2X'_{MIK}\sqrt{\beta_{x,MIK}}\theta_x - \beta_{x,MIK}\theta_x^2.$$
(4.11)

As illustrated in figure 4.19, the MIK is not installed in the injection section. Knowing $J_{x,0}$, the position of the MIK is partly constrained by the $J_{x,1}$ to reach. In terms of phase advance, this reads

$$|X_{MIK}| \le \sqrt{2J_{x,1}} \iff |\cos(\phi_{MIK})| \le \sqrt{\frac{J_{x,1}}{J_{x,0}}},\tag{4.12}$$

with $\phi_{MIK} = \phi_s + \psi$, where ϕ_s is the synchronous phase and ψ is the phase advance with respect to the injection point.

In practice, the stored beam perturbations are drastically reduced using the MIK over the injection kickers. Basically, the magnetic field of the MIK is zero in the stored beam path, defining the magnetic center of the device, and non-zero far from its longitudinal axis. Therefore, the closed orbit is never perturbed while the injected beam is kicked. To make this innovative injection scheme work, the magnet and its pulsed magnetic field must be designed to exacting specifications, and the manufacture of the parts and their assembly must be mastered. To better understand the challenges of its design, the mechanical and magnetic specifications of the MIK are described in the next sections.

4.4.2 Mechanical design of the MIK

Prior to the manufacture of the MIK, feasibility studies proved an injection scheme based on a MIK could be implemented for the SOLEIL storage ring (see figure 4.21 and section 5.3.1.2). Therefore, it has been decided to build a third MIK. Even if SOLEIL has already delivered two MIK devices to MAX IV facility, building such an equipment



Figure 4.21: Main steps of the MIK project prior to the commissioning of the magnet.

remains a technological challenge. Additionally, the MIK has been designed according to the characteristics of MAX IV. Since the geometry and parameters of the SOLEIL storage ring are quite different (cross section of the vacuum chamber, impedance requirement, absorbers, duration of the MIK pulse...) several adaptation and retrodesign were necessary for a safe installation and a transparent operation. The MIK body is made out of a bulk of sapphire, constituting the vacuum chamber. It is 30 mm high, 60 mm thick and 400 mm long. In particular, the MIK has the narrowest physical apertures of the storage ring, when the IDs are opened, equal to 7.8 mm vertically and 46.8 mm horizontally. This chamber, manufactured by Kyocera[™], has four longitudinally machined grooves on its top and bottom faces, which house eight copper conductors, of 8 mm diameter, which form the electro-magnet. The 3D representation of the MIK chamber is presented in figure 4.22, while its transverse cross section is illustrated in figure 4.23. This chamber is identical to that of the MIK installed in the MAX IV storage ring. The inner walls



Figure 4.22: a) Entire vacuum chamber of the MIK, made of sapphire, viewed from above. It is 30 mm high, 60 mm thick and 400 mm long. In the up right corner is the MIK entirely assembled, with its flanges (dark grey) fixed at the entrance and the exit of the chamber. b) Part of the chamber illustrating the four grooves machined symmetrically on the top and bottom faces along the chamber. c) Part of the chamber equipped with the eight conductors (green and red) and their alumina bars on the top. The colors symbolize the direction of current propagation.

of the MIK chamber are coated with a thin layer of sputtered titanium. It should be noted that the quality of the titanium coating has required a very special attention knowing that MAX IV encountered some heating concerns



Figure 4.23: Front view of the MIK cross section with red and green copper rods in the grooves, numbered from 1 to 8. The colors symbolize the direction of current propagation. One circular flange is drawn around the striped vacuum chamber (physical apertures: 46.8 mm (horizontally) x 7.8 mm (vertically)). The injected (blue) and stored (orange) beams are not drawn to scale.

during the commissioning of the MIK prototype installed in 2017 [4, 96]. Although the MIK prototype performed satisfactorily in terms of injection efficiency and residual betatron oscillations, the heating problem due to a $0.8 \,\mu$ m thick titanium layer made it necessary to replace the old MIK with a new one in 2019, exhibiting a $3.5 \,\mu$ m thick coating. This improved MIK is currently being used in daily operation at MAX IV and is reported to have addressed the issue of temperature rise without creating residual out-of-tolerance perturbations [4, 96]. The $3.5 \,\mu$ m thick layer of titanium was coated inside the chamber by the ESRF for the MIK of SOLEIL. Based on the feedbacks from MAX IV, new simulation studies were conducted at SOLEIL by P. Alexandre and R. Ben El Fekih (Power Supply and Pulsed Magnet group), who is the MIK project leader, to determine the convenient thickness of the coating. In fact, the thickness of the coating is chosen to balance the heat load deposited by the stored beam, for one would want a coating as thick as possible, and the magnetic field attenuation resulting from the Eddy currents that circulate in the titanium layer, for one would want a coating as thin as possible. A. Gamelin, from the Accelerator Physics group, also performed detailed impedance simulations and heat load computations. Indeed, even when turned off, the MIK should be impedance-transparent for the operation of SOLEIL, in all the filling patterns. Nevertheless, despite our efforts, unexpected temperature rise was measured during the first stored current ramp. This heating concern has been fully understood and swiftly overcome (see section 5.3.2.5).

The careful assembly of the conductors in their grooves with a radiation resistant epoxy glue has been performed at SOLEIL by a skilled team, that I had the opportunity to assist on this occasion. The positioning of the conductors is very challenging as misalignments may lead to unacceptable field defects. The positioning tolerances equal $\pm 10 \,\mu$ m both horizontally and vertically, while the straightness tolerance equals $\pm 10 \,\mu$ rad. After the gluing, alumina bars were installed on the top of the conductors and the dedicated clamps tightened to maintain the bars and the conductors during the glue curing.

The main engineering part of the assembly consisted in adapting the physical apertures of the standard vacuum chamber of the storage ring, 70 mm horizontally and 25 mm vertically, to those of the MIK chamber. To do so, two pairs of taper-absorber were used upstream and downstream the MIK. Following the electron beam, a main standard taper-absorber reduces the aperture from standard dimensions to ± 23 mm horizontally and ± 5.8 mm vertically. Thus, most of the synchrotron radiation generated by the upstream bending magnet is intercepted. This section also provides pumping capability thanks to its attached ion pump. A second newly designed taper-absorber was also required to adapt the MIK aperture. The horizontal point of this taper is inserted to 20.4 mm in order to fully protect the MIK from synchrotron radiations which could damage the MIK, including cases of electron or photon beam misalignment. This secondary taper-absorber is entirely machined in a bulk of copper chrome zirconium alloy, including the two ConFlat[™] flanges at its ends, and the water circuits for heat transfer. The advantage of this manufacturing method is that neither the welding, nor the brazing, of the vacuum tight parts are required, which is time and cost saving. In addition, it reduces the risk of having rejected parts due to unexpected polluted and leaking weld or brazing. A similar combination of secondary and main taper-absorber is installed at the end of the MIK. So far, the two secondary taper-absorber, as well as the main ones, have performed very satisfactorily and the Engineering and Ultrahigh Vacuum groups of SOLEIL are considering more of these machined-in-one parts for SOLEIL II. The entire SS2 is illustrated in figure 4.24 (the simulated physical apertures of the MIK section are provided in section 5.3.1.2, figure 5.21). During the assembly, and the installation of the MIK in the SS2, careful alignment of the different pieces led to relative misalignment on the order of $100 \,\mu m$.

Prior to the assembly of the taper-absorbers and the MIK, the latter has been powered by R. Ben El Fekih. This crucial phase was planned to conduct a set of magnetic measurements with the aim of ensuring that the magnetic field of the MIK meets the specifications.

4.4.3 Magnetic field design

The MIK is a pulsed electromagnet whose transient field is induced thanks to a capacitive resonant discharge pulser, providing half-sine current pulses up to 3.6 kA, under the maximum allowed voltage of 11 kV. The pulse duration is reduced (in comparison with MAX IV) to 2.4 µs, corresponding to twice the revolution period of the storage ring, in order to avoid strong residual fields which would perturb the injected beam on the turns following the injection. A picture of the MIK pulser is provided in figure 4.25. The design of the pulser is described in more details in [97].



Figure 4.24: MIK section. The MIK is installed in the storage ring, more specifically in the short straight section of cell 2 (SS2). SS2 starts and ends with a beam position monitor (blue rectangles). A couple of taper/absorber chambers, upstream and downstream the MIK, adapt the physical apertures of the standard vacuum chamber and protect the MIK from the synchrotron radiation. Two beam loss monitors (red dots) surround the MIK for radiation safety purposes. The ultra high vacuum is guarantee by a triplet of pumps.

4.4.3.1 Ideal simulated field

In beam dynamics, it is more convenient to consider angles rather than magnetic fields. In the thin lens approximation, the deviation of the MIK can be considered as a single kick, reduced to the transverse plane passing by the middle of the MIK chamber. In this approximation, the Twiss parameters are supposed to be constant functions of *s* along the magnetic length. The deviations corresponding to B_x and B_z are defined by equations 4.13 and 4.14 respectively:

$$\theta_z(x, z, t) = \frac{1}{B\rho} \int_0^{l_m} B_x(x, z, s, t) ds$$
(4.13)

$$\theta_x(x,z,t) = \frac{1}{B\rho} \int_0^{l_m} B_z(x,z,s,t) ds,$$
(4.14)

t being the time variable, $B\rho$ the magnetic rigidity (see equation 3.34) and l_m the magnetic length of the MIK. Spatially, the length of the conductors defines the magnetic length of the MIK, $l_m = 0.304 \text{ m}$. These transient non uniform fields have been simulated with QuickfieldTM Professional [98], as the reference fields to perform tracking studies and measurements characterizations. Spatially, the length of the conductors defines the magnetic length of the MIK $l_m = 0.304 \text{ m}$. It is worth to consider that the magnetic field of the MIK is reduced to the transverse plane. The longitudinal component of the magnetic field, denoted B_s , is induced by the connections between the conductors are perfectly aligned, only the connections at the upstream and downstream end of the MIK are responsible for any perturbations due to B_s . Besides, the connections are designed to limit symmetry breaking at the downstream end

74



Figure 4.25: MIK pulser with its capacitors, high voltage switch and control card, housed in a cubicle of the technical gallery.

of the MIK. In this context, B_s was not taken into account in tracking computations because simulations performed by P. Alexandre proved it would have limited effects on the beams. Firstly, the integrated longitudinal field intensity is small over the conductor length l_m , typically on the order of -6×10^{-4} T m, at pulse plateau ($t = 1.2 \,\mu$ s). Secondly, the momentum vector of the injected beam is almost collinear with **B**_s ($x'_{MIK} = -2.2 \,\text{mrad}$ and z'_{MIK} is supposed to be zero). Therefore, the injected beam, and a fortiori the stored beam, whose deviation is much lower than that of the injected beam at the MIK location, will not experience additional kicks along the MIK due to the deviation induced by B_s . This is why the magnetic field of the MIK is reduced to the transverse components θ_x and θ_z , which only depend on time and on the horizontal and vertical positions of the beams at the MIK location, in the thin lens approximation. Since the injection takes place in the horizontal plane, in first approximation the centroid of the stored and injected beams belong to the horizontal plane z = 0. This means θ_z must be minimized in the stored and injected beams' paths. On the contrary, θ_x is the field of interest. In particular, the topology of θ_x is constrained by two major properties. In order to leave the closed orbit unperturbed, the MIK has a zero field region along the stored beam path at any time, $\theta_x(0, 0, t) = \theta_z(0, 0, t) = 0$. In addition, θ_x minimizes the oscillation amplitude of the injected beam after the MIK, reaching approximately 10 mm. Considering its size, the injected beam must interact with a local field which is as uniform as possible, so as to maximize the injection efficiency. Accordingly, the eight copper conductors have been positioned symmetrically with respect to the horizontal and vertical planes of the MIK, so that θ_x exhibits an octupolar shape, whose peak value is at a target position $x_{target} = \sqrt{\beta_{x,MIK}} X_{MIK} = 10.3$ mm, being the position at which the injected beam passes through the MIK and gets its nominal deviation. The variations of θ_x and θ_z with respect to (x, z), at peak time $t = 1.2 \,\mu$ s, under 10 kV, are presented in figures 4.26 and 4.27, as well as 4.28 and 4.29. In these conditions, the zero field region is characterized by $\theta = \sqrt{\theta_x^2 + \theta_z^2} = 0$ at the magnetic center of



Figure 4.26: Horizontal and vertical variations of the main kick of the MIK θ_x , at $t = 1.2 \,\mu$ s, under $10 \,\text{kV}$.



Figure 4.27: Horizontal and vertical variations of the main kick of the MIK θ_x , at $t = 1.2 \,\mu\text{s}$, under $10 \,\text{kV}$. The 3σ envelop of the stored and injected beams are respectively represented by magenta and black dots. Because of its octupolar shape, $|\theta_x| \leq 0.5 \,\mu\text{rad}$ for $|x| \lesssim 500 \,\mu\text{m}$ and $|z| \lesssim 400 \,\mu\text{m}$, and $1.5 \,\text{mrad} \le \theta_x \le 2.5 \,\text{mrad}$ within the injected beam footprint.

the MIK, and $\theta \le 1 \mu rad$ for $r = \sqrt{x^2 + z^2} \le 500 \,\mu m$, providing few perturbations to the stored beam. Besides, the centroid of the injected beam undergoes a nominal kick $\theta_x = 2.2 \,m rad$, whereas the vertical kick is zero. On the other hand, the variations of θ_x with respect to (x, t), at z = 0, under 10 kV, are presented in figures 4.30 and 4.31. θ_z is not plotted since it is equal to zero, at z = 0, for any (x, t). Restricting to the injected beam path, θ_x provides a convenient uniform kick, in the vicinity of its peak value at $t = 1.2 \,\mu s$. Indeed, the bunch train duration being 295 ns, the centroids of the 104 injected bunches undergo deviations in the range of $2.16 \,m rad \le \theta_x \le 2.21 \,m rad$.



Figure 4.28: Horizontal and vertical variations of the unwanted kick θ_z , at $t=1.2\,\mu$ s, under $10\,\rm kV$.



Figure 4.29: Horizontal and vertical variations of the unwanted kick θ_z , at $t = 1.2 \,\mu$ s, under $10 \,\text{kV}$. The 3σ envelop of the stored and injected beams are respectively represented by magenta and black dots. Because of its octupolar shape, $|\theta_z| \leq 0.5 \,\mu$ rad for $|x| \lesssim 500 \,\mu$ m and $|z| \lesssim 400 \,\mu$ m, and $-0.30 \,\text{mrad} \leq \theta_x \leq 0.45 \,\text{mrad}$ within the injected beam footprint.



Figure 4.31: Horizontal and time variations of the θ_x , at z = 0 mm, under 10 kV. Because of the octupolar shape of the field, the deviation is zero on the stored beam path, at x = 0 mm. The centroids of the 104 injected bunches (black dots) pass through the MIK at $x_{target} = 10.3$ mm and expand over 295 ns. The injected beam is centered on the peak of the pulse at $t = 1.2 \,\mu\text{s}$ (the kicks experienced by the bunches vary between $2.16 \,\text{mrad}$ and $2.21 \,\text{mrad}$). The pulse duration equals $2.4 \,\mu\text{s}$ corresponding to two revolution periods.



Figure 4.30: Horizontal and time variations of θ_x , at z = 0 mm, under 10 kV.

It is to be noticed that θ_x is attenuated in the field free region at the beginning and at the end of the pulse. Indeed, the pulse-induced Eddy currents, propagating in the titanium coating, generate unwanted quadrupolar fields at the magnetic center of the MIK. This is illustrated in figure 4.32. The Eddy currents consequently trigger beam size beating. To decrease the Eddy current intensity, it is possible to lower the titanium coating thickness, at the expense of temperature rise due to heat load deposition along the stored beam path. It is also possible to minimize the variations of the current pulse with respect to time, by increasing its duration, but the injected beam will interact with the MIK field during a few turns, which might decrease the injection efficiency. The time variations of θ_x being



Figure 4.32: Horizontal variations of θ_x , at z = 0, under 10 kV. During the current rise, at $t = 0.2 \,\mu\text{s}$ (blue), and the current fall, at $t = 2.4 \,\mu\text{s}$ (red), the stored beam interacts with opposite quadrupolar fields, for $|x| \leq 500 \,\mu\text{m}$, induced by the Eddy currents propagating in the titanium coating of the vacuum chamber. At peak current, $t = 1.2 \,\mu\text{s}$ (green), the Eddy currents vanish and $\theta_x < 0.5 \,\mu\text{rad}$ for $|x| < 500 \,\mu\text{m}$.

simulated at a 100 ns sampling rate, it has been fitted over time by a polynomial, in the range $|x| \le 5$ mm. The sequenced first and third orders of the polynomials give respectively the variations of the quadrupolar and octupolar components of θ_x , with respect to time. The time variations of these multipoles are illustrated in figure 4.33. The extrema intensities of the quadrupolar field are reached during the current rise, at $t = 0.2 \,\mu$ s, and the current fall, at $t = 2.4 \,\mu$ s. Ideally, they vanish at the peak current intensity, when the octupolar field reaches its nominal value.

The simulated field corresponds to the ideal field to refer to. In November 2020, the magnetic field of the MIK has been measured and compared to the simulated field.

4.4.3.2 Measured field

Prior to the installation of the MIK, it was necessary to measure its magnetic field (see figure 4.21). This step is crucial to acknowledge for proper operation of the magnet and identify any defects that may have detrimental effects



Figure 4.33: Strength variations of the quadrupolar (blue) and octupolar (red) components of θ_x with respect to time, under 10 kV. The extrema of the quadrupolar strength are reached during the current rise, at $t = 0.2 \,\mu$ s, and the current fall, at $t = 2.4 \,\mu$ s, while the field exhibits its nominal octupolar shape at peak current, $t = 1.2 \,\mu$ s.

on the stored beam stability and the injection efficiency.

To do so, the MIK has precisely been aligned on a test bench, and fixed to it. A picture of the test bench is provided in figure 4.34. During the measurements, the MIK was supplied with a half-sine current pulse up to 1 kA, delivered by its capacitive resonant discharge pulser shown in figure 4.25. The corresponding voltage equals 2570 V. Theoretically, the recorded data can be up-scaled linearly to compute the equivalent field intensity at 10 kV, corresponding to the operational voltage. The magnetic field has been measured thanks to two integral magnetic probes made by R. Ben El Fekih, one for each transverse component of the field. The magnetic flux variations are detected across the entire probe area, which is about the length of the MIK, hence the name integral probe. These are fixed to a probe holder as depicted in figure 4.35. Before the measurements, the probes were carefully aligned with respect to the mechanical center of the vacuum chamber. The alignment was performed with a precision of a few tens of micrometers to avoid systematic errors associated to strong local field gradients. This alignment was preserved during the mapping thanks to an automated arm to which the probe holder is fixed. When measuring, the probe is connected to an oscilloscope which estimate the instantaneous voltage defined by the variation of the magnetic flux through the probe area, following the Lenz law. Thus the MIK pulse is measured from start to end. The integrated field of the MIK is then obtained converting this voltage. However only the peak field, reached at $t = 1.2 \,\mu s$, is considered. Indeed, on the one hand, this gives the nominal shape of the field, from which it is possible to reconstruct the rest of the pulse by linear scaling, and on the other hand, the intensity of the quadrupolar fields are too weak to be measurable with this kind of device.

Three sets of measurements were performed using each probe. Firstly, the chamber was probed widely to get



Test bench

Figure 4.34: Test bench on which the MIK is aligned to proceed to magnetic field measurements. The magnetic probe is hold by an automated arm which can move horizontally, vertically and longitudinally. The probe is precisely aligned with respect to the mechanical center of the MIK chamber.

the global shape of the field. It should be noted that the MIK field could not be measured anywhere in the MIK chamber because of the dimensions of the probe holder and the physical apertures of the MIK. This is depicted in figure 4.36. However, the probes could reach the main regions of the field. Firstly, the probe was transposed by steps of 1 mm horizontally and 0.2 mm vertically, in the range $|x| \le 12$ mm and $|z| \le 0.8$ mm. Secondly, the field was measured with greater spatial resolution in the vicinity of $x = -x_{target} = -10.3$ mm. Even though the injected beam path is located on the opposite side of the chamber, the measurements were performed in this region for the sake of comparability with the measurements performed on the MAX IV MIK. In this case, the probe was transposed by steps of 0.1 mm horizontally and 0.2 mm vertically, in the range $-12 \text{ mm} \le x \le -8 \text{ mm}$ and $|z| \le 0.8 \text{ mm}$. Thirdly, the free field region was precisely characterized, with same resolution, in the range $|x| \le 1.5 \text{ mm}$ and $|z| \le 0.8 \text{ mm}$.



Figure 4.35: Schematic of a 450 mm long integral magnetic probe made of a copper coil (green) fixed in the probe holder.



Figure 4.36: Dimensions of the physical apertures of the MIK, probe holder and magnetic probes. The region of the magnetic field which can be measured is shaded in red. Theoretically, the dimensions of the area are $\pm 11 \text{ mm}$ horizontally and $\pm 1.2 \text{ mm}$ vertically. However, the MIK field measurements could have been performed in the $\pm 12 \text{ mm}$ range horizontally. It should be noted that y denotes the vertical direction here.

In the following, the integrated fields have been converted into kick fields, as defined by equations 4.13 and 4.14. Besides, the measurements are linearly up-scaled to match the nominal voltage of 10 kV. To begin with, the global shape of θ_x is in good agreement with the perfect simulated field, as illustrated in figure 4.37. In this figure, θ_x is only plotted for z = 0, as the field vary little in the vertical range specified previously. The field reaches the designed value of 2.2 mrad at $x_{target} = 10.3 \text{ mm}$ (the relative error is lower than 3%). Figure 4.38 provides a closer look at the field free region. According to this figure, the magnetic center of the MIK is located at x = 200 µm (the field is zero). However, the magnetic probe reached is precision limit in the field free region. In fact, the beam based-measurements did not confirm this offset, as it is reported in section 5.3.2.4. On the other hand, θ_z exhibits an



Figure 4.37: Horizontal variations of the measured (red) and the ideal simulated (blue) θ_x , at z = 0 and $t = 1.2 \,\mu$ s, scaled to match the operation at $10 \,\text{kV}$.



Figure 4.38: Horizontal variations of the measured (red) and the ideal simulated (blue) θ_x around the center of the MIK chamber, at z = 0 and $t = 1.2 \,\mu$ s, scaled to match the operation at $10 \,\text{kV}$.

unexpected distorted shape, as illustrated in figure 4.39, with two major defects. Obviously, there is a mismatch on the injected beam path at 10.3 mm, but of primary concern is the offset in the desired field free region. Considering the data associated to the third set of measurements, this defect appears more clearly like a dipolar component, the offset in the field free region reaching approximately $5 \mu rad$ (see figure 4.40).

To fully understand these discrepancies, I launched several simulations. Firstly, the measurement process has been simulated: the ideal MIK field has been interpolated longitudinally, applying various transpositions and rotations to the field, or combination of both, in order to reconstruct the measured data and equivalently estimate the hypothetical misalignment errors of the probe. By doing so, the global shape of the measured field, as well as the offset at $x_{target} = 10.3 \text{ mm}$, have been successfully reconstructed, but two major points were still challenging. The corresponding misalignment errors were completely out of the tolerances managed by the Alignment group of SOLEIL, and they did not lead to any dipolar offset in the field free region. At this time, the dipolar defect has been considered as noise, coming from a lack of resolution, as the probe was thought not to be able to measure such



Figure 4.39: Horizontal and vertical variations of the measured (bold solid lines with blue dots) and the ideal simulated (dashed lines) θ_z , at t = 1.2 µs, scaled to match the operation at 10 kV. The field is mapped vertically with 0.2 mm steps in the range $|z| \le 0.8$ mm (right colorbar). At z = 0, the ideal field is zero for any x. The measured field is unexpectedly attenuated and rotated. In particular, the measurements mismatch the ideal values in the injected beam path and in the field free region.



Figure 4.40: Horizontal and vertical variations of the measured (bold solid lines with blue dots) and the ideal simulated (dashed lines) θ_z in the field free region, at $t = 1.2 \,\mu$ s. The data set is scaled to match the operation at $10 \,\text{kV}$. The field is mapped vertically with $0.2 \,\text{mm}$ steps in the range $|z| \le 0.8 \,\text{mm}$ (right colorbar). At z = 0, the ideal field is zero for any x. The measured field is unexpectedly offset and rotated. In particular, the measurements mismatch the ideal values in the stored beam path. The measured field exhibits a dipolar offset of approximately $5 \,\mu$ rad.

low field intensities. Still the deduced misalignment errors were not understood. At a later stage, design studies made by P. Alexandre provided enlightening results. The effects of titanium coating defects have been simulated first. As a result, it can be stated that the thickness of the left and right side of the coating, whether it be symmetrical or not, has negligible effects on the central region of θ_z compared to an asymmetry between the upper and lower layer. In the later case, the Eddy currents could induce vertical dipolar offsets in the field free region. However, the asymmetry should be very significant, which is not the most probable scenario, as the measured temperature is the same on the upper and lower part of the chamber. Eventually, the explanation can come from the cumulative misalignment errors of the eight conductors, due to the machined tolerances and the thickness of the glue. As mentioned in section 4.4.2, the alignment tolerances of the conductors are very stringent, and a cumulative error of a few microns can lead to field defects whose order of magnitude are very similar to what has been measured. As an example, a cumulative misalignment of 25 µm transposed to the 4th conductor remarkably reproduces the measured dipolar defect in the field free region. One should keep in mind that this cumulative alignment error of 25 µm is thought to be distributed over the eight conductors in fact. In this case, the alignment errors did not compensate each other and resulted in the 5 µrad dipolar offset.



Figure 4.41: Horizontal variations of the measured (bold solid lines with blue dots) and the simulated (dashed lines) θ_z in the field free region, at $t = 1.2 \,\mu$ s. The data set is scaled to match the operation at $10 \,\text{kV}$. The field is mapped vertically with $0.2 \,\text{mm}$ steps in the range $|z| \le 0.8 \,\text{mm}$ (right colorbar). At z = 0, the simulated field reaches approximately $5 \,\mu$ rad for any x. This dipolar offset is simulated by a cumulative misalignment of $25 \,\mu$ m on the 4th conductor.

To end this section, the main parameters of the MIK installed in the SOLEIL storage ring are gathered in table 4.6 [5]. These parameters have been taken into account when I developed the model of the MIK injection scheme with AT. In the next section, I present the analysis/simulating tools that I used to conduct the parametric studies of the MIK injection, prior to the installation of the magnet in the storage ring. Additionally, the control command system is introduced.

Table 4.6: Main design specifications of the MIK installed in the SOLEIL storage ring. Table taken from [5].

Horizontal/vertical physical aperture (mm)	46.8 / 7.8
Total mechanical length (flange-to-flange) (mm)	400
Magnetic length (mm)	304
horizontal/vertical field free region (µm)	800 / 100
Pulse duration (µs)	2.4
Target horizontal/vertical position at MIK (mm)	10.3 / 0.0
Magnetic field at target position (mT/kA)	24.85
Nominal kick θ_x at target position (mrad)	2.2

4.5 Control command system and analysis Tools

During my PhD, I had the opportunity to perform experiments during dedicated machine sessions, in addition to the simulation studies. The experimental work took place in the control room, see figure 4.42, located in the synchrotron building.



Figure 4.42: Picture of the SOLEIL control room.

4.5.1 Control command system

The accelerators are driven from the control room where more than $20\,000$ signals are managed. They are used to monitor and set up all the devices involved in the operation of the accelerators. To do so, the control command

system TANGO [99], for TAco Next Generation Objects, is used. TANGO is an open source device-oriented controls toolkit for controlling any kind of hardware or software. It is operating system independent and supports C++, Java and Python for all the components. It provides a transparent access to all the hardware devices connected to the accelerator network and a suite of services, such as archiving, monotoring and alarm tool, for supervisory control and data acquisition. The hardware structure of SOLEIL is illustrated in figure 4.43. In TANGO, each hardware system is represented by a device, the parameters of which can be modified. In addition, a TANGO software bus enables to use various pieces of software, see figure 4.44. Thus, it is possible to interact with the hardware systems with the softwares, while TANGO works in the background.



Figure 4.43: Hardware structure diagram of SOLEIL.



Figure 4.44: Software structure diagram of SOLEIL.

4.5.2 Analysis tools

4.5.2.1 Matlab Middle Layer

Practically, I mostly used MATLAB to set up the accelerators. The MATLAB Middle Layer (MML) [100] provides a library of accelerator oriented functions, high-level user-friendly applications and graphical interfaces. MML is a software designed to sit between high-level accelerator control applications in Matlab and the low-level accelerator control System. It is a collaborative development started by Jeff Corbett, Andrei Terebilo, and Gregory Portmann at SPEAR3. The roots of the middle layer software start at the ALS where Dave Robin and Gregory Portmann (and later Winfried Decking, Christoph Steier, Tom Scarvie, Laurent Nadolski) wrote many of the basic physics functions. MML is interfaced either to an accelerator simulator, the Accelerator Toolbox (AT) [101], or to the TANGO control system. It provides high-level function packages which avoids to directly deal with the heavy naming system of TANGO. For instance, the function *getx* is a MML function which outputs the horizontal position of the beam at any BPM given in the device list input of the function. To get the horizontal position of the beam at the 2nd BPM of cell 1, it is as simple as executing the function *getx([1 2])* in the command window of MATLAB. The diagram corresponding to this example is depicted in figure 4.45. As shown in figure 4.45, the MML functions are written to



Figure 4.45: MATLAB Middle Layer (MML) diagram.

work with the modeled version of the accelerators, developed with AT. This provides a convenient way to compare the measurements and simulations outputs for experiment data analysis. There are plenty of codes used for accelerator modeling, but I will focus on the two codes I used the most during my PhD.

4.5.2.2 Accelerator Toolbox

AT is another collaborative effort in the light source community to model storage rings and beam transport lines. It is widely used nowadays. The core of AT was developed in the early 2000s' at SLAC by Andrei Terebilo from the SPEAR3 synchrotron light source [6]. It relies on the core tracking routines of the TRACY (A Tool for Accelerator

Design and Analysis) code. It was developed to model an accelerator, support its operation using MATLAB and be linked to MML. It was further extended by the so-called multi-laboratory AT collaboration [101]. AT aims to take advantage of the simple and powerful MATLAB environment. As such, AT is a toolbox of MATLAB, in contrast with standalone accelerator codes like TRACY III. Each element of a lattice has its proper creating function, such that the concatenation of these elements (electromagnets, RF cavities, BPMs, etc) defines accelerator structures that are easily tunable thanks to the lattice tools. AT also provides low-level physics tools to track particles through a sequence of elements or through the whole lattice. The high-level physics tools enable to simulate particle motion taking into account elements' setup and various physical phenomena such as synchrotron emission and quantum diffusion [102]. Moreover, AT can be combined with the other toolboxes of MATLAB, such that it is possible to immediately process, analyze and plot the simulated data using the numerous applications of MATLAB. Each accelerator and transfer line of SOLEIL have been modeled using AT to provide a complete simulator used for commissioning and operation purposes. I further developed the existing model of the storage ring, and developed the MIK injection scheme using AT, as reported below.

4.5.2.3 TRACY III code

TRACY was created at the Advanced Light Source in the 90s' and written in Turbo-Pascal [103]. It is a self-consistent symplectic integrator for charged particle beam dynamics. It shares several similar goals with AT among which providing lattice tools to create lattices and transport lines. It is also possible to perform closed orbit and particle motion simulation, taking into account multipolar fields and alignment errors if needed. Frequency Map Analysis is naturally included in its software library. The code has then been translated in C and C++, in order to be used for the Swiss Light Source, and further developed. In particular, TRACY has been updated to take into account the SOLEIL requirements and became the TRACY III version that I used during my PhD. This is the reference code of the Accelerator Physics group of SOLEIL and was fully benchmarked against the real accelerator. I used these features to compute dynamic apertures and momentum acceptances, as well as tune shifts with energy and amplitude and Touschek beam lifetime. I used the supercomputer operated by the CCRT (Centre de Calcul Recherche et Technologie) to perform massive computations.

4.5.2.4 General aspects of the AT and TRACY III models

In the AT model, I have defined the sextupoles as thick magnets in order to give a better insight of the nonlinear beam dynamics. In this context, I have added the multipoles of all the linear, nonlinear and corrector magnets, up to the 27th order maximum, based on the multipole measurements realized by the Magnetism and Insertion Device group of SOLEIL. In addition, I have included radiation and quantum diffusion effects in order to perform 6D tracking and characterize the variations of the positions and sizes of the beams during transient regimes, induced by radiation

damping. However, the effects of IDs were not simulated in these studies, as well as the residual magnetic field of the septum magnets and the eddy currents of the kickers. The latter being modeled as thin correctors, perfectly aligned. Eventually, I updated the physical apertures of the modeled lattices. The simulated physical apertures of the storage ring are plotted on figure 4.46.



Figure 4.46: Simulated horizontal (blue) and vertical (green) physical apertures of the storage ring. The in-vacuum IDs are red colored. The standard horizontal and vertical apertures are $\pm 35 \text{ mm}$ and $\pm 12.5 \text{ mm}$ respectively. The inner face of the septum blade is positioned at -19.5 mm and the horizontal and vertical scrapers are inserted at their nominal position of -20 mm, 33 mm and $\pm 3 \text{ mm}$ respectively.

The beam First, it should be noted that I only simulated multi particle beams with AT. When I optimized the MIK injection, I created bunch trains similar to the booster beams. Experimentally, the booster beams are made of 104 continuous bunches, in the long pulse mode. However, the number of bunches I simulated was lower in order to save computing time. I could choose ten bunches out of 104 for example. By default, bunch number 53 is centered on the MIK pulse in simulation, meaning that it passes through the MIK at $t = 1.2 \,\mu$ s (when the octupolar component of the MIK field is maximum, see figure 4.33). Experimentally, I acted on the delay of the injection magnets in order to sample their pulse, whether it be the kickers or the MIK. In simulation, it was the bunch number which I changed. As a matter of fact, the time parameter *t*, describing the delay of the pulsed magnets, equivalently represents the temporal structure of the injected beam. Indeed, from the pulsed magnets point of view, bunch number *i* + 1 or *i* - 1 is only a bunch delayed compared to bunch *i*. This made coding easier when I was dealing with multi-bunch beams. A bunch of electron is defined as a 6D Gaussian distribution. The beam is matched to the storage ring optics at the injection point. This was deemed acceptable even though this may not be the optimal beam matching [104, 105]. On another hand, the beta functions of TL2 have never been measured and the beam matching of the real machine has

certainly not been fully optimized. Therefore, the theoretical values of the storage ring optics at the injection point were made as the first choice to match the simulated injected beam. Moreover, in the case of the injection studies I conducted during my PhD, the transverse emittance of the booster beam was adjusted by varying its coupling.

4.5.2.5 The 2.8 T permanent magnet-based superbend

The superbend was included in the TRACY III and AT models prior to its commissioning. The modeled superbend is divided into seven smaller dipoles constituting a seven-in-one element which replaces the second dipole of the 12th arc of the storage ring lattice. The fringe fields of the superbend are taken into account in the multipolar decomposition. The bending angle, as well as the normal multipoles, of each part of the superbend are presented in table 4.7 (the varying focusing and strong sextupolar components are written in red). The input multipoles were measured for a reference radius $R_0 = 20$ mm and are defined as the ratio between the integrated multipolar component strength over the main field strength:

$$B_n^N = \frac{B_n(R_0)}{B_N},$$
 (4.15)

where *N* is the order of the main field (N = 1 for dipoles, N = 2 for quadrupoles, N = 3 for sextupoles, etc) and $1 \le n$ is the order of the multipolar component. The strong quadrupoles significantly changed the focusing while the sextupoles strongly decreased the dynamic aperture. The linear optics was restored thanks to LOCO [82], which adjusted the set point of all the quadrupole magnets in the lattice. On the other hand, the non linear dynamics was restored globally such that the horizontal and vertical chromaticities were fitted to their former value by tuning the 9th and 10th families of sextupoles. A new set of sextupoles has been used in operation and has proven to work satisfactorily, since the injection efficiency increased by almost 10% after the non-linear optimizations made by P. Brunelle using MOGA-Bmad. The physical apertures of the storage ring have been updated as well to take into

Part	Bending angle (mrad)	B_2^1	B_3^1	B_4^1	B_5^1	B_6^1
1	8.5	-0.0302	-0.0768	0.0277	-0.0147	-0.0144
2	8.4	0.0288	-0.3520	0.0201	-0.1321	-0.0337
3	6.2	-0.0173	-0.3473	-0.0230	-0.1439	0.0300
4	7.2	0.0172	-0.0857	-0.0278	-0.0250	0.0149
5	12.0	-0.0188	-0.0070	-0.0008	-0.0010	-0.0002
6	145.2	-0.0045	-0.0038	-0.0003	0.0001	-0.0008
7	8.9	-0.0322	-0.0097	0.0005	-0.0002	0.0003

Table 4.7: Bending angles and normal multipolar field inputs of the superbend.

account the decrease in the vertical aperture, 255 m downstream the injection point. The smallest vertical aperture of $\pm 6 \text{ mm}$ is defined all along the superbend, as it is the most constraining scenario. The horizontal aperture is equal to the standard $\pm 35 \text{ mm}$.

As soon as the models were updated, the TRACY III code was used to characterize the effect of the superbend on the Touschek beam lifetime and dynamic aperture. The estimation of the Touschek beam lifetime relies on the computation of the local momentum acceptance and optical functions at each element of the lattice. The betatron tunes and the chromaticities were initially fitted to $\nu_x = 18.156$, $\nu_z = 10.228$, $\xi_x = 1.2$ and $\xi_z = 2.2$. Besides, the IDs are supposed to be wide opened and the moveable absorber of NANOSCOPIUM fully extracted. Thus, the physical aperture is defined as illustrated in figure 4.46 except that the vertical and horizontal scrapers are also extracted. The beam parameters which were used as inputs to estimate the Touschek beam lifetimes afterwards, using the Piwinski formalism, are presented in table 4.8. The simulations demonstrated that the superbend has poor impact

Table 4.8: Beam parameters for Touschek beam lifetime estimation, using Piwinski formalism [27]

Parameter	Value
ε_x (nm rad)	3.87
RMS bunch length (mm)	6
Bunch current (mA)	1.2
Coupling (%)	1
RF voltage (MV)	2.8
Energy (GeV)	2.739

on the Touschek beam lifetime which passed from 24 h to 23 h. Conversely, the dynamic aperture is strongly reduced, decreasing by a few millimeters as shown in the bottom plot of figures 4.47 and 4.48, respectively illustrating the dynamic aperture in the injection section before and after the integration of the superbend in the lattice. In addition, the top plots depict the betatron tune space shift. At x = 0, the vertical aperture is almost identical in both cases and



Figure 4.47: Frequency map (top) and dynamic aperture (bottom) of the bare lattice computed in the middle of the injection section, with all scrapers and moveable absorber fully extracted, prior to the commissioning of the superbend. The color code refers to the diffusion index of the tune for 1000 turns using frequency map analysis [106]



Figure 4.48: Frequency map (top) and dynamic aperture (bottom) of the bare lattice computed in the middle of the injection section, with all scrapers and moveable absorber fully extracted, including the permanentmagnet based 2.8 T superbend. The color code refers to the diffusion index of the tune for 1000 turns using frequency map analysis [106].

greater than 4 mm. The limitation is due to the MSs whose vertical aperture is $\pm 5 \text{ mm}$. However, the reduction in the

vertical dynamic aperture appears as soon as $x \neq 0$. At z = 0, the horizontal dynamic aperture lost 4 mm on both sides. Eventually the diffusion index increased around x = -10 mm and z = 0, representing the rise of resonances which make it more difficult to inject the booster beam efficiently.

4.6 Diagnostics and measurement methods

The storage ring is equipped with various diagnostics installed all along the accelerator circumference. In operation, they mostly monitor the stored beam properties, such as the beam positions, sizes, lifetime, etc, but also provide major information concerning the injected beam, such as the injection losses for instance. In the framework of the MIK commissioning, as well as for prospecting work about SOLEIL II, new high performance diagnostics, providing fast acquisition rate and low noise level, have been commissioned. In particular, three Beam Position Monitors (BPMs) were connected to the Libera Brilliance Plus electronics in testing phase, the ultra-fast KALYPSO camera was installed in the diagnostics beamline and 80 Beam Loss Monitors (BLMs) are now enable to record decay loss maps in the slow acquisition mode, and turn-by-turn injection loss maps in the fast acquisition mode. In the next sections, the BPMs, BLMs and the KALYPSO camera are successively presented in more detail.

4.6.1 Beam position monitors

The BPMs are standard non-destructive diagnostics used to measure the injected or stored beam position, the beam position being defined as the position of the centroid of a transversely Gaussian beam. An overview of the current BPMs setup installed in the SOLEIL storage ring is provided in the following sections.

4.6.1.1 Beam position monitors setup

The storage ring is equipped with 122 BPMs, divided in three sets: short in the arcs, medium at the entrance and exit of the straight sections, except in the injection section where they are long. All the BPMs are synchronous and can be triggered on the injection event. They are used to perform Beam-Based Alignment (BBA), orbit correction implementing the Slow and Fast Orbit FeedBacks (SOFB and FOFB) and beam characterization (tune, chromaticity, energy, dispersion measurements to name a few). In particular, the BPMs are used to check the stored beam alignment with respect to the IDs [107]. The positions of the BPMs along the storage ring are illustrated in figure 4.49.

A typical BPM block is composed of two mounting flanges, a below, a water cooling circuit and two mechanical references. The maximum physical apertures of a BPM block is $\pm 42 \text{ mm}$ horizontally and $\pm 12.5 \text{ mm}$ vertically. They minimize the impedance by design. Nevertheless, the geometry of the vacuum chamber is partially responsible for the non-linear response of the BPMs at large amplitudes. Here, two pairs of buttons are placed face-to-face,



Figure 4.49: Positions of the BPMs along the storage ring. The dipoles, quadrupoles and sextupoles are respectively denoted D, Q and S. Their numbers describe the family they belong to and their occurrence in the family. For instance, Q4.2 is the second quadrupole of the fourth family.

with 25 mm between the top and bottom pairs, whereas the buttons of one pair are separated by 16 mm center-tocenter. A typical storage ring BPM block is illustrated in figure 4.50. Each 4-button mechanical block is connected to commercial Libera Electron electronics by default (there are additional buttons in double-block BPMs for transverse feedback and tune measurement purposes).

When an electron beam passes through a BPM block, it induces an image current propagating in the opposite direction on the vacuum chamber's walls. The buttons measure this image current by capacitive effect, their potential being proportional to the beam position in the millimeter range. Thanks to their electronics, the BPMs can measure the beam position at various data rates. The sampling frequency equals 10 Hz in order to record the beam orbit with a resolution on the order of 20 nm. In turn-by-turn acquisition mode, the sampling frequency reaches 846.64 kHz with a resolution on the order of 50 µm-RMS, for an average current intensity of 15 mA in the one quarter filling pattern. The BPM digital electronics used at SOLEIL is the first Libera version which was developed within the framework of a collaboration between SOLEIL and Intrumentation Technologies in 2002, introducing a new concept of bar switch.



Figure 4.50: 3D representation of a single BPM block of the storage ring.

It was first tested and validated on the Booster ring in 2005 [107].

During the commissioning of the MIK, the positions of the injected and the stored beam had to be monitored. There were two major challenges: the injected beam must reach a target position in the MIK (this is further detailed in chapter 5) and the stored beam position must be unperturbed when injecting with the MIK.

4.6.1.2 Limitations of the standard beam position monitors

This section deals with the accuracy of the beam position measurement. Three major limitations can bias the measurements depending on the oscillation amplitude, oscillation frequency and charge of the beam. These limitations are the non-linear response of the BPM for large amplitudes, the smearing between turns in turn-by-turn mode and resolution at low current intensity respectively. It should be noted that the measurements on the stored or injected beams are not affected in the same way by these limitations. For example, a measurement on the injected beam is affected by non-linearities, since the amplitude of the oscillation is on the order of 10 mm, but little by the low current intensity (2 mA typically), because the uncertainty due to the latter is negligible compared to the oscillation amplitude. Conversely, since the oscillation amplitude of the stored beam is small, it is encompassed in the linear range of the BPMs, while the lower the current intensity, the larger the uncertainty of the measurement.

On the one hand, the real position of the beam is underestimated at large amplitudes, from 2 mm and beyond, due to the non-linear response of the BPMs (the BPM reading saturates from approximately 8.6 mm) [108, 109]. The read-out position of the beam with respect to its real horizontal position is plotted in figure 4.51. A similar non-linear behavior stands for the vertical position of the beam. Ideally, at the BPM center, the position of the beam is computed according to equation 4.16:

$$u = K_u \times \frac{(\phi_A + \phi_D) - (\phi_B + \phi_C)}{\phi_A + \phi_D + \phi_B + \phi_C},$$
(4.16)

R. Ollier



Figure 4.51: Non-linear response of the BPMs installed in the SOLEIL storage ring with respect to the horizontal position of the stored beam, at z = 0 [108, 109].

with the potentials ϕ_A , ϕ_B , ϕ_C , and ϕ_D of the buttons A, B, C and D, $K_u = 11.4$ mm at SOLEIL, and u = x or z denoting the transverse position of the beam [108, 109]. To avoid measurement errors, it is possible to compute the beam position using polynomials instead of equation 4.16. However, this method is time consuming, which is not convenient for the operation of the storage ring. Consequently, the BPM raw data is linearized offline in order to infer the position of the injected beam. This implies knowing the theoretical response of the BPM, deduced from the estimated potential of its buttons [110, 111, 112, 113]. Further studies, which started at SOLEIL in 2011, led to the development of a reconstruction function developed with MATLAB in 2013 [108, 109]. It is possible to minimize the difference between the theoretical response of a BPM and its output position data thanks to the Newton-Raphson algorithm. The first version of the function was tested successfully, as reported in [108]. A second version of the function was developed in the wake of this success in order to extend the reconstruction process in the vicinity of the buttons. Figures 4.52 illustrates the result of a reconstruction using the ultimate version of this function. As shown in figure 4.52, the algorithm does not converge properly beyond the central region of the vacuum chamber, typically from x = 26 mm at z = 0, due to intrinsic limitations in the Newton-Raphson's method [109]. In this case, the algorithm underestimates the position of the beam, giving the impression that the data is folded. The variations of the error between the real position of the beam and its rebuilt position, in decimal logarithm scale, is provided in figure 4.53. Beyond the central region, blue area in figure 4.53, the reconstruction values are considered not to be numbers.



Figure 4.52: Given positions of the stored beam (blue dots), positions output by the BPM (green dots) and rebuilt positions output by the reconstruction function (red dots) [109].



Figure 4.53: Decimal logarithm of the difference Δu (in mm) between the real beam position and the rebuilt position, inside the physical aperture of a BPM [109].

On the other hand, another systematic error bias the measurements in the turn-by-turn acquisition mode due to data filtering. Indeed, the turn-by-turn position of the beam is computed by the electronics using the ADC recording, sampled at 109 MHz, and convoluted by an observation window. The convolution between the ADC signal and the observation window, which is not ideally rectangular but rather Gaussian, results in a 6-turn overlapping. This implies a smearing of the beam position at a given turn by the positions of the beam at the preceding and following turns. This effect depends on the oscillation frequency of the beam. An option is provided with the reconstruction function in order to correct the overlapping data [108, 109].
Eventually, the resolution of the standard electronics did not meet our need in the case of stored beam basedmeasurements at low current intensity (50 µm-RMS for an average current intensity of 15 mA, in the one quarter filling pattern). Nevertheless, it was interesting to measure the residual perturbations of the MIK on the stored beam in this configuration, such that an improved electronics was tested.

4.6.1.3 Libera Brillance Plus electronics

To overcome the resolution limitation of the standard Libera Electron electronics, the Libera Brillance Plus electronics was used [9]. The stored beam-based experiments I performed during my PhD were perfectly suited for this kind of electronics since the ultimate goal was to measure turn-by-turn beam position variations on the order of a few micrometers. In this context, two Libera Brillance Plus electronics were commissioned in 2021 by the Diagnostics and Synchronization group of SOLEIL. I tested this electronics at various location in the storage ring, in the case of different filling patterns, and gave a feedback through stringent conditions in the context of the MIK commissioning. These feedbacks are valuable as this electronics is considered as a candidate for installation in SOLEIL II. With this electronics, the turn-by-turn position resolution is reduced to $5 \,\mu$ m-RMS, at $15 \,m$ A in the one quarter filling pattern. Besides, the smearing between the turns introduced by the usual signal processing is avoided. The main parameters of the BPMs are provided in table 4.9.

Parameter		Libera electronics
Number of BPMs in the storage ring	122	
Horizontal linear range (mm)	$\begin{array}{c} \pm 2 \\ \pm 2 \end{array}$	Electron Brilliance
Turn-by-turn capability	Yes Yes	Electron Brilliance
Turn-by-turn spatial resolution in uniform filling pattern (500 mA) (µm-RMS)	$< 30 \\ 2$	Electron Brilliance
Turn-by-turn spatial resolution in one quarter filling pattern (15 mA) (µm-RMS)	$50\\5$	Electron Brilliance
Need to linearize data at large amplitude (>2 mm)	Yes Yes	Electron Brilliance
Need to correct overlapping data in turn-by-turn mode	Yes No	Electron Brilliance

Table 4.9: Main parameters of the BPMs installed in the SOLEIL storage ring.

4.6.2 Beam loss monitors

As mentioned in chapter 3, the electron-electron and electron-residual gas particle interactions unavoidably lead to beam losses of different nature, such as regular or irregular losses, fast or slow losses, localized or distributed losses.

The Beam Loss Monitors (BLMs) have proven to be very useful to provide information on beam dynamics and some major accelerator parameters. It is indeed widely used in operation to set up the accelerators and manage the beam losses. For example, it is very advantageous to locate the beam losses with BLMs to prevent damaging certain equipment or intolerably activating their surroundings near an area of preferential loss. Besides, several experiments requiring hours of acquisition, such as the measurement of physical apertures based on beam lifetime variations, can be replaced by faster experiments that provide higher data resolution thanks to the BLMs. These are a few reasons why SOLEIL have used BLMs since its commissioning in 2006. The 36 BLMs that have been used for twelve years were PIN diode loss monitors. However, these diagnostics had two major limitations to measure the beam losses in the SOLEIL storage ring. Firstly, the detection of losses was very sensible to the position of the monitor with respect to the loss source due to a small acceptance solid angle, making data correlation difficult. Consequently, a great number of monitors have to be installed to accurately and precisely map the preferential loss areas, which is not always possible. Secondly, these monitors only detect slow losses, which lets a large number of losses undetected [114]. In order to increase its performance, SOLEIL launched the upgrade of its BLM setup in 2018, based on the fruitful feedback of the ESRF in commissioning an new kind of BLM in 2015.

4.6.2.1 Short description of the beam loss monitors

The principle of the BLMs is based on the detection of electromagnetic showers [115]. High energy electrons (2.75 GeV) may be lost on the physical apertures of the storage ring. Many secondary particles are created during the interaction between these electrons and the various layers of matter they pass through (mainly metallic obstacles). The secondary particles are gamma photons and electron-positron pairs which constitute the electromagnetic shower. This is illustrated in figure 4.54. The shower being globally oriented in the direction of the originally lost



Figure 4.54: Electro-magnetic shower following the loss of an electron. Many secondary particles are created during the interaction between this electron and the various layers of matter it passes through (mainly metallic obstacles). The secondary particles are gamma photons and electron-positron pairs which constitute the electromagnetic shower [115].

electron, the gamma photons can interact with a BLM made of a plastic γ -scintillator, consisting in a 100 mm high rod EJ-200, and a photomultiplier which amplifies the recorded signal [115]. The scintillator is wrapped into a high reflectivity aluminum foil in order to improve the photon flux towards the photomultiplier. The former is embedded with a high voltage source forming the photosensor module of Hamamatsu (series H10721-110). This photosensor is connected to a high power supply and a gain control device to effectively record the electrical signal which is eventually processed by the Libera BLM electronic module. Last but not least, when SOLEIL started its first tests of these new BLMs in 2018, the data analysis revealed that a 3 mm thick cylinder made of lead had to surround the detector in order to provide sufficient shielding against the synchrotron radiation. Due to their cylindrical design the new BLMs are less sensible to their orientation with respect to the source than the former PIN diode monitors. The detector design is depicted in figure 4.55.



Figure 4.55: BLM principle and design. An energetic particle coming from an electro-magnetic shower passes through a scintillator which produces gamma photons, amplified by a photomultiplier tube (PMT) and converted into an electric signal [115].

The relative calibration error of the detectors must be lower than 10% in order to allow the comparison of the recorded data between each detector. During the commissioning of the BLMs, which involved the Diagnostics and Synchronization group as well as L. S. Nadolski and D. Amorim, the detectors were calibrated using a diode in the first place, a cesium source afterwards to have an absolute calibration and finally beam based measurements [114, 8]. Even though these calibration methods gave very similar results, in good agreement with the manufacturer's data, in terms of relative detector sensitivity, a few detectors were far from the 10% calibration error specification. Furthermore, the gain controller of the Libera electronics adds gain control offsets which can reach up to 20% variation applied on the gain value of the photosensor. These limitations are addressed separately by

the Libera electronics and a high level application respectively. Eventually, the errors are compensated to meet the rspecifications, such that it is possible to compare the amplitude of the signal between each detector. In addition, the response of the BLMs to a cesium source is controlled every two years in order to study the obsolescence of the detectors.

4.6.2.2 Beam loss monitor interface and acquisition modes

The electronics used at SOLEIL to control the gain and the attenuation of the BLMs, record and partially process the final signal, is a Libera BLM module [116]. The sampling frequency of the ADC is 125 MHz, providing the smallest temporal resolution of 8 ns. A maximum of four BLMs are interfaced with a single module. Besides, one device is associated to each module in order to manage and process data through the TANGO control system. A schematic of the Libera BLM module is provided in figure 4.56. The BLMs can be operated in two mutually exclusive modes.



Figure 4.56: Front and back panels of a Libera BLM module (grey). Up to four BLMs can be connected to the Libera BLM module. Image from [116].

The fast acquisition mode, called injection mode, enables to measure the variations of losses turn-by-turn during

the injection process, the detector being synchronous with respect to each other and the injection event. The slow acquisition mode, called decay mode, enables to measure the variations of lifetime losses.

4.6.2.3 Beam loss monitor setup

Today, 80 BLMs are installed vertically close to the storage ring and used for daily operation. Their location has been decided in consultation with the Radiation Safety group which uses the BLMs to validate their loss map modeling simulations. The layout of the detectors is depicted in figure 4.57. The BLMs are mostly installed close to the internal



Figure 4.57: BLM layout in the first quarter of the storage ring (red dots). The BLM distribution is similar in the rest of the storage ring. The lattice layout is depicted in the middle of the figure. The dipoles are plotted in yellow, the focusing and defocusing quadrupoles in blue and red respectively. The sextupoles appear as vertical black lines because of the scale. They should not be confused with the first four vertical lines which correspond to the correctors and kickers in the injection section. The cryomodules and the IDs are located in the straight sections.

side of the storage ring because the electrons are most often lost there. Only three BLMs are installed close to the external side of the storage ring : the first one is located at the beginning of the first beamline of SOLEIL, another one is located at the entrance of MS4, and the last one is located in front of the inner horizontal scraper. Basically, there is a BLM at the exit of almost every dipoles, to mainly detect electrons with negative energy deviation, and a BLM at the exit of the straight sections, where the IDs are installed. The remaining BLMs are positioned such that the complete set of BLMs is almost periodically distributed along the storage ring. It should be be noted that two BLMs are installed at the downstream and upstream ends of the MIK respectively, since its physical apertures are the narrowest of the bare lattice.

Besides, the slow acquisition measurements performed during the commissioning demonstrated that the middle of the BLMs must belong to the plane of the synchrotron emission in order to to maximize the recorded signal. In addition, the BLMs are installed as close as possible to the storage ring since the measurements also confirmed that the amplitude of the recorded signal decreases rapidly with the distance from the source. However, the BLMs should not be positioned close to a source of back scattering particles such as a X-ray crotch [115]. The main parameters of the BLMs are provided in table 4.10.

Parameter	Value
Number of BLMs in the storage ring	80
Turn-by-turn capability	Yes
Slow acquisition capability	Yes
Calibration error	< 10%

Table 4.10: Main parameters of the BLMs installed in the SOLEIL storage ring.

4.6.3 Diagnostics for transverse beam size monitoring

There are two types of diagnostics used to measure the transverse beam sizes in the storage ring [117]. In both cases, the stored beam size is inferred from the analysis of the synchrotron radiation emitted by one of the ring dipoles. The synchrotron radiation is imaged at the source point. The first type of diagnostics, pinhole cameras, uses the X-ray part of the synchrotron radiation. They can provide beam size measurements with spatial resolution less than 10 µm-RMS, although their minimum exposure time, in the tens of milliseconds, does not offer turn-by-turn capability. The second type of diagnostics, synchrotron radiation monitors, uses the visible range of the synchrotron radiation. It can be imaged on a high performance camera, as detailed in the following.

4.6.3.1 Extraction system of the diagnostic beamline

The synchrotron radiation is produced by a 1.71 T bending magnet covering a wide range from far infrared to hard X-rays (see section 4.2.2.4). The extraction angle is centered on 0.5° . The radiation is extracted by a slit mirror, which is 130 mm wide and 74.5 mm high, commissioned in January 2022. This enables to perform non-destructive turn-by-turn measurements of the transverse stored beam position and size, using a camera. This copper made mirror is coated with enhanced aluminum to reflect up to the ultraviolet rays and reach reflectivity greater than 90% in the range 425 nm to 535 nm, as it is illustrated in figure 4.58.

A picture of the mirror is given in figure 4.59. The mirror can be inserted in three ways. The slit is 5.6 mm high and machined such that the X-rays can pass through it when the mirror is inserted on the beam axis, preventing from intolerable energy deposition. Additionally, the mirror is equipped with a cooling system. This so-called slit mode, compatible with the uniform filling pattern at 500 mA, mainly provides radiations in the visible range. The slit mode is represented by the top illustration in figure 4.60. The second mode corresponds to full reflection of the synchrotron radiation, the mirror being vertically heightened (see middle illustration in figure 4.60). In this mode the



Figure 4.58: Reflection variations of the newly installed slit mirror of the diagnostic beamline with respect to the photon wavelength λ .



Figure 4.59: Newly installed slit mirror of the diagnostic beamline. The copper mirror coated with enhanced aluminum is grey, the mirror holder has a brassy color.

stored current is 3 mA maximum to prevent the mirror from any damage. This mode has never been set up during my experiments because it was incompatible with the requirements of my measurements. The third mode consists

in increasing further more the vertical position of the mirror, such that its lower edge is fixed to 5 mm above the electron beam. This so-called surf mode enables to only extract the top half of the visible synchrotron radiation. This mode is also compatible with the uniform filling pattern at 500 mA. The surf mode is represented by the bottom illustration in figure 4.60. I needed synchrotron radiations in the visible range to perform the measurements with the



Figure 4.60: Position configurations of the newly commissioned slit mirror of the diagnostic beamline. In slit mode a), the mirror is fully inserted in the storage; the X-rays of the synchrotron radiation pass through the slit (compatible with high current beams). In intermediate mode b), the mirror is heightened to reflect all the synchrotron radiation (maximum stored current equals 3 mA to avoid damages). In surf mode c), lower edge of the mirror is fixed to 5 mm above the electron beam; the visible light of the synchrotron radiation is reflected (compatible with high current beams).

ultra-fast camera KALYPSO. Additionally, I wanted to measure the perturbations induced by the injection magnets with the highest possible temporal resolution. In particular, I expected the residual quadrupolar perturbation of the MIK to be different from quarter to quarter. Therefore, I performed the measurements in the slit mode, rather than in the surf mode, in order to increase the photon flux by a factor 2, for a given average current intensity in the storage ring. It can be seen in figure 4.60 that more photons are collected in the slit mode rather than in the surf mode. The latter would have constrained me to fill more than one quarter of the storage ring with electrons. This is because the minimum charge I would have needed to perform the measurements in surf mode cannot be stored in one quarter, due to beam instabilities.

4.6.3.2 Beamline setup and ultra-fast line-camera KALYPSO

The visible synchrotron radiation, ranging from 400 nm to 800 nm, is transmitted in the beamline cabin through various optics. The entire setup is represented in figure 4.61. The diagnostic beamline ends, in particular, with the



Figure 4.61: Diagnostic beamline setup composed of various optics. The photon beam is plotted in black solid line exiting the dipole. It is eventually transmitted to the KALYPSO camera installed on the optical table (large grey rectangle) thanks to a beam splitter. The photon beam is focused horizontally and vertically with the H and V lenses respectively. It is filtered with band pass filters (BP filter) and polarized with a crossed polarizer.

ultra-fast line-camera called KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy). It has been developed at the Karlsruhe Institute of Technology (KIT) and is currently used in the Karlsruhe Research Accelerator [10, 118]. A KALYPSO has been installed and commissioned at SOLEIL in 2021 by M. Labat (Diagnostics and Synchronization group). The camera is specifically used due to its spatial and time resolution. Even though the electronics enables to reach acquisition rates up to 2.7 MHz, the camera was used in turn-by-turn mode (846 kHz) during the commissioning of the MIK, with exposure time of approximately 295 ns corresponding to the duration of one quarter. The calibration of the camera was done by M. Labat, for the dipole source point: the stored beam was bumped horizontally and vertically at some points in the storage ring. The various offsets were recorded by KA-

LYPSO and two BPMs enclosing the source point. Knowing the optics at the location of the diagnostics, the offsets measured by KALYPSO were correlated to those measured by the BPMs. In particular, M. Labat and I performed measurements during the commissioning of the MIK. I tested various filling patterns (two quarter filling pattern at 200 mA initially, one quarter filling pattern then, at 50 mA and 100 mA) which provided fruitful information concerning the most efficient setup for KALYPSO. These tests revealed that the minimum average current intensity necessary to produce a sufficient photon flux in slit mode equals 100 mA. With such a current intensity, it was necessary to turn on the bunch-by-bunch transverse feedback to avoid beam instabilities. The transverse feedback implements a dipolar correction and therefore does not affect the quadrupolar perturbation of the MIK (see figures 4.32 and 4.33), at first order. Besides, it does not minimize the maximum amplitude of the residual betatron oscillations, but rather decreases the damping time. Thus, I measured the variations of the stored beam position and size precisely (see section 5.3.2.4). A picture of the setup is given in figure 4.62.



Figure 4.62: Picture of the ultra-fast line camera KALYPSO.

The KALYPSO camera used at SOLEIL has a line sensor made of silicon that was chosen to detect synchrotron radiation in the $300\,\mathrm{nm}$ - $1050\,\mathrm{nm}$ range. Cylindrical lenses are used to match the radiation spot to the geometry of the line-sensor. Consequently, the measurements can only be performed in one plane, horizontal or vertical, at a time. The photon beam has been rotated thanks to a crossed polarizer. It should be noted that the lenses had to be set up unexpectedly to maximize the spatial resolution of the measurements: the camera was placed beyond the image plane. This, combined with the slit mode, leads to the detection of two twin signals in the vertical plane (see figure 5.77). In the end, it is not possible to measure the absolute transverse beam size accurately. If the horizontally polarized photon beam is focused in the image plane the twin signals merge into a unique image of the beam with poor spatial resolution. This limitation is not fully understood yet and the Diagnostics and Synchronization group of SOLEIL currently carries out simulation and experimental studies to overcome this limitation. Finally, it was decided to stay in slit mode (see section 4.6.3) and to measure the twin signals, because I was primarily interested in the relative variations of the beam transverse parameters. This configuration indeed does not prevent from performing relative measurements, characterized by resolution on the order of $1 \, \mu m$. Actually, the calibration showed that the equivalent dimension of a pixel at the source point is 5 µm. So it is impossible to measure offsets of a point like beam lower than $5 \,\mu\text{m}$. However, the fact that we work with distributions of points makes it possible to detect variations on the order of 1 µm by fitting the distributions. The main parameters of the KALYPSO camera are provided in table 4.11.

Parameter	
Sensor shape	Line
Number of pixels	1024
Pixel dimensions (µm)	25×25
Relative spatial resolution in the one quarter filling pattern, at 100 mA (µm)	
Turn-by-turn capability	Yes

Table 4.11: Main parameters of the KALYPSO camera installed in the SOLEIL storage ring.

Chapter 5

Injection into the SOLEIL storage ring

Contents

5.1 Introduction
5.2 Performance of the modeled standard injection scheme
5.2.1 Injection simulations
5.2.2 Measurements
5.3 MIK injection
5.3.1 Performance of the modeled MIK injection scheme
5.3.2 Commissioning of the MIK 137
5.4 Beamline measurements
5.4.1 Perturbations recorded with an infrared beamline

5.1 Introduction

This chapter is dedicated to the simulation and experimental studies that I carried out during my PhD, and their results. These two aspects of my work were complementary: the modeled injection schemes were used to conduct preliminary studies, optimize the MIK injection scheme and analyze the experimental data. In both cases of bumpbased and MIK-based schemes, the simulated data were correlated to the measurements based on the injected and stored beams. The chapter is divided into two main parts. The first one concerns the standard injection scheme. The model is described and its injection performance presented in the ideal case, that is ignoring injection jitters in the bare lattice and assuming perfect magnet alignment. However, the multipoles of the magnets have been taken into account in both modeled lattices, one including the superbend and the other not. Moreover, I give a full description of the experimental setup and measurement methods in this section, providing a complete and up-to-date picture of the performance of the standard injection. The second part concerns the MIK injection scheme. As for the standard injection scheme, the simulation work is firstly presented. To begin with, I present the computations and the particular constraints that led to the installation of the MIK in SS2. From then on, I optimized the injection setup, based on injection efficiency and loss maps analysis. I determined a new configuration of the thin septum and the MIK, providing almost 100% injection efficiency in the bare lattice with no superbend, and in the ideal injection case. Eventually, the commissioning of the MIK is fully presented. I commissioned the MIK based on the constant back and forth between simulation and experiment. Additionally, the performance of the MIK injection is compared to that of the standard scheme. As mentioned in section 4.5.2, I developed and used various scripts with MATLAB which allowed me to set up the accelerators and the diagnostics, record and analyze the experimental data. In particular, the storage ring was always checked up at the beginning of any experiment. To compare the data associated to the MIK and bump-based schemes, I always set the storage ring in the same configuration for both injection schemes. Most of the time, IDs were fully opened, except during dedicated experiments with beamlines. The betatron tunes were always corrected to $\nu_x = 18.156$ and $\nu_z = 10.228$, except on purposes (it is specified in the subsequent sections accordingly). The corrected chromaticities $\xi_x = 1.2$ and $\xi_z = 2.2$ are lowered when measuring betatron oscillations, in order to avoid beam decoherence (their value is specified in the subsequent sections accordingly).

5.2 Performance of the modeled standard injection scheme

In the following, the developments that I brought to the models during my PhD, as well as their outcomes, are described. This gives an up-to-date description of the models and simulation results, including the superbend or not. If any result corresponds to achievements reached before the commissioning of the superbend, it will be precised accordingly.

Before moving to the next section, it should be noted that the lattice I used to conduct standard injection simula-

tions took the physical apertures of the MIK section into account. Of course, the MIK was always switched off when the standard injection studies were carried out. Thus, from the point of view of standard injection scheme, the MIK just consisted in a portion of a vacuum chamber of reduced physical aperture.

5.2.1 Injection simulations

5.2.1.1 Injection efficiency of the ideal standard injection scheme

The standard injection scheme was designed before the commissioning of the SOLEIL storage ring, as presented in section 4.3.2.1. The ideal scheme was optimized such that the injection efficiency must reach 100%. I recall that in this ideal case, the residual magnetic field of the septum magnets is not taken into account, nor the Eddy currents of the injection kickers, the latter being modeled as thin correctors perfectly aligned. To verify this, a single centered Gaussian bunch of 10^4 electrons is initially created. The initial coordinates of the injected beam centroid at the injection point are defined by equation 5.1, according to AT (see section 4.5.2.2):

$$\begin{pmatrix} x_{inj} \\ x'_{inj} \\ z_{inj} \\ z'_{inj} \\ \delta \\ l \end{pmatrix} = \begin{pmatrix} x_{blade} - S + \Delta_{blade} - max(X) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ l \end{pmatrix} + \begin{pmatrix} x_{CO} \\ x'_{CO} \\ 0 \\ 0 \\ 0 \\ l_0 \end{pmatrix}$$
(5.1)

with X the Gaussian distribution of the horizontal positions of the injected electrons, $x_{blade} = -19.5$ mm the horizontal position of the inner face of the septum blade (nominal position for SOLEIL operation), S = 3.5 mm the blade thickness, $\Delta_{blade} = 0$ the septum blade shift (the septum blade stays at its nominal position in the case of the standard injection scheme) and max(X) the greatest horizontal position in the X distribution. As soon as the radiation effects are included in the simulations, the second term of the right hand side of equation 5.1 has non-zero coefficients. x_{CO} and x'_{CO} are the horizontal position and deviation of the stored beam on the non-zero closed orbit, at the injection point. x_{CO} and x'_{CO} are small though, on the order of a few tens of micrometers and ten microradians. In this case, $l_0 = c\tau_0 = -45.6$ mm, as τ_0 is related to the synchronous phase $\phi_s = 2\pi \frac{\tau_0}{T_{RF}} = 2.8$ rad. Using equation 5.1, the beam centroid gets closer to the blade as the beam coupling increases, because max(X) decreases. This term allows to always get the injected beam as close as possible to the septum blade outer face.

At the injection point location, the ideal bare lattice of SOLEIL, with all scrapers and moveable absorber fully extracted, has a half acceptance of almost 20 mm horizontally and greater than 2 mm vertically at x = 10 mm (this acceptance computation does not include the superbend). It is limited horizontally by the blade of the thin septum positioned at -19.5 mm. These dimensions being greater than A_x and A_z (see section 4.3.2.2, equations 4.3 and

figure 4.18 especially), the injected beam is captured. Figure 5.1 provides an example to illustrate the latter claim. It shows an uncoupled booster beam capture, the superbend being excluded from the lattice. The acceptance is computed by tracking of a single electron launched off-axis in the bare lattice during 10^3 turns, with $x \neq 0$ initially and all the other initial conditions fixed to 0. The tracking is repeated as long as the electron makes 10^3 turns without being lost, the initial horizontal position being stepped by a few tens of micrometers each new tracking, until the electron is lost. This computation includes the physical apertures of the storage ring with all the scrapers fully extracted. In this example, no electrons are lost during the first six turns in the storage ring. It should be noted



Figure 5.1: Horizontal phase space at the injection point (end of the thin septum), for an uncoupled booster beam (blue dots). The booster beam is injected and tracked over the six first turns in the storage ring (multicolor beam). The injected beam is captured within the horizontal acceptance (black dots surrounding the injected beam).

that the tracking would have provided the same result for any number of turns, as presented in the following. I repeated the 6D tracking for various booster beam coupling values, during more turns. Eleven single bunch beams are generated with a beam coupling varying from 0% to 100% with 10% coupling step, and tracked in parallel thanks to the parallel computing toolbox of MATLAB. For an uncoupled beam of 10^4 electrons, the injected beam clearance $N_i = 3$. It should be noted that if no constraint is added on the injected beam clearance it will increase with the number of electrons in the bunch, shifting x_{inj} away from the blade consequently. This is due to the tails of the Gaussian distribution which get populated when the number of electrons increases. To avoid non sense values, a lower bound of x_{inj} should be defined for bunches of more than 10^4 electrons. Besides, if several distributions are generated for a given number of electrons and beam coupling, x_{inj} varies according to max(X). The variation is on the order of 1 mm, in the case of an uncoupled beam with 10^4 electrons. In the present case of 10^4 electrons, $x_{inj} = -28.5$ mm for the uncoupled beam, which is deemed acceptable. On the other hand, the fully coupled beam exits the thin septum at $x_{inj} = -26$ mm. The eleven single bunch beams are tracked for 500 turns in the storage

ring. The electrons are expected to be lost mostly during the first turns following the injection, therefore 500 turns save time while providing a good indication for the time variations of the injection loss rate. On the one hand, the injected beam is only kicked by K3 and K4, with the nominal kicks presented in table 4.4, as it passes through them for the first time. On the other hand, K1 and K2 are switched off. This means that the booster beam is not bumped in the injection section as soon as it has been injected, i.e. kicked by K3 and K4. This simplification is legitimate because the kicker pulse falls approximately in three turns and it is obvious, regarding figure 5.1, that the injected beam cannot be scraped by the septum blade even if the injection bump is simulated during the first three turns in the storage ring. The loss rate variations with respect to the injected beam coupling are given in figure 5.2. As expected very few electrons are lost during the first 500 turns, regardless of the beam coupling value, and the



Figure 5.2: Variations of the injection loss rate with respect to the booster beam coupling, in the case of the standard injection of single bunch beams of 10^4 electrons in the perfect lattice, excluding the superbend.

maximum loss rate would have been less than 1% even if the beam had completed a few thousand turns. In this context, the modeled standard injection scheme indeed meets the specification (100% injection efficiency), thanks to the large dynamic aperture inside which the injected beam is captured and damped to equilibrium (see figures 5.1 and 4.47).

5.2.1.2 Effect of the superbend on the standard injection

As soon as the superbend is included in the lattice, the injection efficiency drops due to the reduction of the dynamic aperture (see figure 4.48). As an example, the border electrons of the uncoupled booster beam are not injected within the dynamic aperture anymore. This is illustrated in figure 5.3. As a result, these border electrons may be lost after some revolution times. The variations of the number of injection losses with respect to time follows a decreasing



Figure 5.3: Horizontal phase space at the injection point (end of the thin septum), for an uncoupled booster beam (blue dots). The booster beam is injected and tracked over the six first turns in the storage ring (multicolor beam). The injected beam is not fully captured within the horizontal dynamic aperture (black dots surrounding the injected beam).

exponential law, as it is illustrated for instance in the case of a fully coupled booster beam in figure 5.4. The drop



Figure 5.4: Histogram of the number of injection losses with respect to the number of turns, in the case of the injection of a fully coupled single bunch beam of 10^4 electrons, in the perfect bare lattice including the superbend.

in the injection efficiency is depicted in figure 5.5, giving the variations of the injection loss rate with respect to the booster beam coupling. There are injection losses whatever the value of the beam coupling. The minimum injection

loss rate equals 7%, while it reaches 9% at 20% booster beam coupling. A peak is observed at 70% coupling, where the injection loss rate is 19%. Apart from this particular excursion, the injection loss rate is on the order of 10%. Regardless of the beam coupling, the unstable electrons are lost on the vertical physical aperture of the second



Figure 5.5: Variations of the injection loss rate with respect to the booster beam coupling, in the case of the standard injection of single bunch beams of 10^4 electrons, in the perfect bare lattice including the superbend.

half of the storage ring, especially at location where the aperture reduces to $\pm 5 \text{ mm}$, as it is presented in figure 5.6, 5.7 and 5.8 for a 20% beam coupling. It should be noted that no electrons are lost in the MIK chamber despite its narrow physical apertures.



Figure 5.6: Horizontal and longitudinal coordinates of the injection losses (red dots), in the case of a 20% booster beam coupling injected in the bare lattice including the superbend.



Figure 5.7: Vertical and longitudinal coordinates of the injection losses (red dots), in the case of a 20% booster beam coupling injected in the bare lattice including the superbend.



Figure 5.8: Simulated injection loss map associated to the standard injection scheme, in the case of a 20% booster beam coupling injected in the bare lattice including the superbend.

5.2.2 Measurements

Although the stored beam perturbations induced by the standard injection scheme were measured and minimized a few years ago[94, 95], I repeated basic sets of measurements during my fist year of PhD. Indeed, it was necessary to have an up-to-date picture of the performance of the standard injection scheme, knowing that the injection setting degrades slowly over the years. To precisely characterize the performance of the standard injection scheme, it is necessary to monitor transient phenomena. This gave me the opportunity to use the tools developed in the past for turn-by-turn stored beam-based measurements and learn how to operate the storage ring and the injection magnets (using high level applications and also the scripts I developed, which make an extensive use of TANGO). In addition to this necessary and formative work, I investigated furthermore using the newly commissioned high-performance diagnostics presented in chapter 4 and provided unprecedented turn-by-turn measurements of injection loss maps, as well as transverse position and size of the stored beam. These measurements were all the more necessary as they provided a reference database to compare the performance of the MIK.

5.2.2.1 First turn orbits

The betatron oscillations of the injected beam were measured thanks to the 122 BPMs of the storage ring. To do so, the BPMs were configured in turn-by-turn mode and triggered on the injection event. The acquisition started a few microseconds before the injected beam entered in the storage ring to be sure of recording the first turn orbit. K1 and K2 were turned off during the measurements in order to acquire the position of the injected beam during the

first turn only. The septum magnets, K3 and K4 worked under their nominal voltage. In this context, the inner face of the septum blade is positioned at x = -19.5 mm. The horizontal and vertical first turn orbits, in the bare lattice, are plotted in figures 5.9 and 5.10 respectively. Each figure illustrates the first turn orbits of the injected beam, before and after the commissioning of the superbend [84, 119]. In each case the orbit is averaged over three acquisitions.



Figure 5.9: Horizontal betatron oscillations of the injected beam during the first turn in the storage ring. The positions of the injected beam were acquired before (blue curve) and after (red curve) the commissioning of the superbend. Two BPMs were disconnected during the measurements before the superbend was commissioned (two missing blue points around s = 300 m).

The position data were rebuilt and the overlapping corrected in order to estimate the real position of the injected beam, as presented in the diagnostics section 4.6.1.2. The injection is very reproducible and the RMS error made on each position is on the order of $100 \,\mu\text{m}$ and $50 \,\mu\text{m}$ in the horizontal and vertical plane respectively.

It was necessary to optimize the standard injection after the installation of the superbend in order to restore the first turn orbit. It consisted in beam steering using the septum magnets and the last two vertical correctors of TL2. As it can be seen in figures 5.9 and 5.10, the betatron oscillation amplitudes after the installation of the superbend are eventually similar to those measured before. Globally, the horizontal amplitude of the betatron oscillations lies in the $\pm 10 \text{ mm}$ range with a few excursions reaching -15 mm and 20 mm. On the other hand, the orbit ranges in $\pm 0.5 \text{ mm}$, in the vertical plane. Nonetheless, the reduction of the dynamic aperture, due to the strong sextupolar component of superbend, decreased the injection efficiency from 95% to 80%.

5.2.2.2 Lost electron distribution profile

Even though the standard injection is optimized in terms of injected beam oscillations and injection efficiency, still 20% of the injected electrons are lost in the storage ring during the injection process, since the superbend has



Figure 5.10: Vertical betatron oscillations of the injected beam during the first turn in the storage ring. The positions of the injected beam were acquired before (blue curve) and after (red curve) the commissioning of the superbend. Two BPMs were disconnected during the measurements before the superbend was commissioned (two missing blue points around s = 300 m).

been commissioned. The BLMs presented in section 4.6.2 give precious information concerning the preferential loss areas and help to detect any unusual injection and decay losses. If necessary, the BLMs can confirm that the losses are conveniently relocated on the scrapers, when the latter are inserted. Since the MIK is located in a normal shielded area of the storage ring, it is essential to ensure that beam losses are not predominant for radiation safety purposes. In fact, the dispersion function reaches a large value of 23 cm in the MIK section by lattice nature and consequently the MIK accumulates decay losses. In this context, two BLMs were installed in the MIK section and it was decided to relocate the beam losses in the injection section, surrounded by over-shielded walls), using the inner horizontal scraper. A first BLM has been installed near the entrance of the MIK and a second one at the end of the MIK section (see figure 4.24). During my PhD, I measured turn-by-turn loss maps, in particular during radiation safety experiments. Several beam-based measurements were performed in various configurations: during normal operation between two injections, during injections in an empty storage ring, beam loss during a machine lockout, during voluntary beam scraping by operators, etc. In January 2022, dedicated gamma and neutron monitors were added to the personal safety system by the Radiation Safety group.

The MIK was already installed in the storage ring, as well as the vacuum chamber of the superbend, when the first acquisitions were performed. However the dipole has been installed a few months later, modifying significantly the beam dynamics, and consequently the spatial and temporal distribution of the losses. In order to rapidly identify the preferential loss areas, the histograms of losses are presented in first place in figure 5.11. These histograms are deduced from the average value of each BLM over the first 200 turns of the injected beam in the storage ring. The

average values are normalized to the charge lost at injection to avoid any bias related to the charge variation and the losses along the injection chain, from the booster to the end of TL2. The charge lost at injection is estimated using direct current current transformers (DCCTs) providing the charge at the extraction of the booster and at the injection in the storage ring (knowing that very few losses are measured in the TL2). These diagnostics are used to estimate the injection efficiency with a precision on the order of $\pm 1\%$. On the one hand, the injection loss map



Figure 5.11: Injection loss maps of the standard injection scheme. a) Injection loss map before the installation of the superbend (the MIK is installed as well as the vacuum chamber of the superbend). b) Injection loss map after the commissioning of the superbend. Between a) and b) is the drawn lattice. The detected events are represented by green bars with their error bar in red.

measured before the installation of the superbend is plotted in the upper part of figure 5.11. The injection magnets are set up like in daily operation, the septum blade being positioned as far as possible from the longitudinal axis of the storage ring at x = -19.5 mm. Contrary to the operation setup, the scrapers are fully extracted at ± 35 mm horizontally and ± 12.5 mm vertically, in order to let the losses be distributed all along the storage ring. Additionally, the beam is injected in the bare lattice. Thus the maximum injection efficiency is approximately 95%. Parts of the losses are located in the MIK section and in the vicinity of the superbend, while the rest of the losses are distributed at the exit of the injection section and MS2, MS3, MS11 and MS16. On the other hand, the injection loss map measured after the commissioning of the superbend is plotted in the lower part of figure 5.11. The reduction of the dynamic aperture resulted in an increase of the number of injection losses and preferential loss areas, at the exit of LS9. Consequently the maximum injection efficiency dropped by 15%. This means that the injection losses do not vary identically with respect to time (averaging effect). Following the commissioning of the superbend, losses are detected in greater numbers after the turn number 200.

The fast acquisition mode enables to follow the total number of events turn-by-turn. This is illustrated in figure 5.12. Prior to the installation of the superbend, most injection losses occurred during the first 200 turns. The total number of injection losses decreased rapidly until turn 800, at which a steady state was established. Following the commissioning of the superbend, the total number of events reached significant amplitude even after turn 800, as the the loss rate was damped in more than 4000 turns. Besides, the BLMs have detected oscillations of the number of events at the synchrotron frequency. The raw turn-by-turn BLM data acquired before and after the commissioning



Figure 5.12: Log scaled variations of the total number of events detected by the BLMs with respect to the turn number, before the installation of the superbend (blue) and after its commissioning (green). Before the commissioning of the superbend, the buffers of the BLMs were limited to 2000 turns knowing that the injection loss rate was damped in a few hundred turns. After the commissioning of the superbend, the buffers were extended to 8500 turns because the loss rate was damped in more than 4000 turns.

of the superbend are illustrated in figures 5.13 and 5.14 respectively.

5.2.2.3 Stored beam stability and temporal variations of the residual injection kick

The other aspect of injection performance concerns the stored beam stability. As mentioned in section 4.3.2.3, the residual kick of the standard injection scheme, defined by equation 4.4, results from the unavoidable slight discrepancies between the kickers. Firstly, the effect of the kickers on the horizontal position of stored beam was specifically measured turn-by-turn. The kickers were triggered as if an injection occurred while the stored beam was circulating in the bare lattice. The kickers, under nominal voltage of approximately 5.5 kV, were the only injection devices triggered as the septum magnets were turned off. The stored beam consisted in 13 consecutive bunches, for an average current of 15 mA. This beam was chosen to provide uniform kicks over the bunches as well as a convenient spatial resolution of the turn-by-turn stored beam position. The chromaticities were decreased from



Figure 5.13: Turn-by-turn loss maps measured before the commissioning of the superbend in the case of the standard kicker injection (injection efficiency $\approx 95\%$). The major part of the injection losses are detected continuously in the injection section.



Figure 5.14: Turn-by-turn loss maps measured after the commissioning of the superbend in the case of the standard kicker injection (injection efficiency $\approx 80\%$). The major part of the injection losses are detected periodically, at the synchrotron frequency, downstream several medium and long straight sections.

 $(\xi_x, \xi_z) = (1.2, 2.2)$ to (0.6, 0.8) in order to avoid the decoherence of the perturbed beam. During these measurements, all the BPMs were synchronized to the injection like event such that the recording started a few microseconds before the ramp of the kicker pulse. The raw data were acquired during 100 turns. The horizontal betatron oscillations due to the kickers are on the order of hundreds of micrometers and are illustrated in figure 5.15, for a given turn. It



Figure 5.15: Measured horizontal betatron oscillations of the stored beam, along the storage ring, due to the four kickers.

should be noted that there is no BPM installed between the kickers in the injection section. Consequently, each kick cannot be estimated individually. In this context, only the residual kicks $\Theta_{12} = \theta_1 + \theta_2$ and $\Theta_{34} = \theta_3 + \theta_4$, associated to the pairs (K1, K2) and (K3, K4) respectively, can be estimated. Each of them result from voltage, delay and duration discrepancies between the kickers of the corresponding pair. In one acquisition, the residual kick $\Theta = \Theta_{12} + \Theta_{34}$ is sampled at the revolution frequency $f_0 = 846$ kHz for a total of 100 points. I verified that the kicker pulse is very reproducible, and I repeated therefore the acquisition at various injection delays in order to scan the kicker pulse more finely. I fixed the delay step to approximately 74 ns, representing 26 bunches, in order to save time while benefiting from a convenient time resolution. Thus, the sampling frequency reached $\frac{1}{74 \times 10^{-9}} = 13.5$ MHz (16 times greater than the revolution frequency). I stepped the delay of the kickers 16 times, such that the total delay was equal to one revolution period. To summarize, I performed the measurements with an observation window of approximately $120 \,\mu$ s, saying 100 turns, and a time step of $74 \,$ ns. Eventually, I used the AT model to determine the variations of the residual kick Θ are illustrated in figure 5.16, with a display window restricted to $30 \,\mu$ s and centered on the perturbation. The estimated residual kick varies in the $-40 \,\mu$ rad and $35 \,\mu$ rad range during approximately $15 \,\mu$ s, which is roughly twice the theoretical duration of the kicker pulse.



Figure 5.16: Time variations of the estimated residual horizontal kicks of the pair K1/K2 (green dashed curve) and K3/K4 (red dashed curve) as well as the overall residual horizontal kick of the standard injection scheme (blue solid curve).

5.3 MIK injection

5.3.1 Performance of the modeled MIK injection scheme

5.3.1.1 Overview

The optimization of the MIK injection, whether it be from the stored beam stability or the injection efficiency point of view, relied on parametric studies. To conduct these studies, I used the AT and TRACY III tracking codes. In doing so, I improved the pre-existing models of the SOLEIL storage ring, developed with both codes (see chapter 4). In this section, the studies and developments I made with AT and TRACY to model and optimize the MIK injection are presented.

5.3.1.2 Prerequisites

Back in 2019, the preliminary simulation studies consisted in finding a location in the storage ring to install the MIK. The goal was to combine a high injection efficiency and minor reduction of the beam lifetime, compatible with the operation of SOLEIL. The first injection simulations were performed with the AT model. At that time, a single electron was tracked in a perfect lattice, including thin sextupoles but no radiation effects, since we were only interested in the first turns in the storage ring.

Location of the MIK The first requirement was to install the MIK not too far from the injection point. Otherwise, the injected beam would have been lost on the vacuum chamber of the ring because of the large horizontal betatron oscillations. As a second requirement, the injected beam must pass through the MIK at the target position $x_{target} = 10.3 \text{ mm}$. Thus, the problem reduces to finding a free straight section where $J_{x,1}$ is minimum, given x_{target} . From equation 4.12, this condition reads:

$$X_{MIK} = \sqrt{2J_{x,1}} \iff J_{x,1} = \frac{x_{target}^2}{2\beta_x},$$
(5.2)

where β_x is a function of *s*. The variations of $J_{x,1}$, as defined by equation 5.2, are illustrated in figure 5.17. Initially, the first four straight sections depicted in figure 5.17 were considered as candidates to host the MIK, i.e. LS1, MS2, SS2 and MS3. However, the injection section was eliminated because the initial horizontal deviation of the injected beam and the MIK kick would have been beyond specifications: 1 mrad and 2.9 mrad respectively, in absolute value. Similarly, the MIK kick would have exceeded ± 2.9 mrad if it were installed in the two MSs. These sections are also occupied by a cryomodule which would have required a major intervention to install both the MIK and the cryomodule. Eventually, the preliminary studies proved the MIK could be installed in the SS2, 32 m downstream the injection point, because it was a free section where $J_{x,1}$ is minimum around 4 mm mrad, and compatible with the



Figure 5.17: Variations of $J_{x,1}$ with respect to the longitudinal position in the first quarter of storage ring (from the injection point). The lattice is drawn at the bottom of the figure. The only free location to install the MIK is the first short straight section of the storage ring, 32 m downstream the injection point.

MIK strength specification. The optical functions in the SS2, and the surrounding arcs are plotted in figure 5.18. As mentioned in chapter 4, the modified Chasman-Green lattice results in a large dispersion function in the straight sections. In particular, $\eta_x = 23 \text{ cm}$ along the MIK section. The horizontal and vertical betatron functions are also considered constant along the MIK length, $\beta_x = 13.5 \text{ m}$ and $\beta_z = 3.5 \text{ m}$. According to this approximation, $\alpha_{x,MIK}$ is zero in the MIK section and it is worth to note that equation 4.9 reduces to

$$\theta_x = -x'_{MIK}.\tag{5.3}$$

Thus, the MIK must exactly compensate the deviation of the injected beam. When the magnet location was determined, the MIK injection scheme was initially tested performing single particle tracking. In this case, the electron is considered as the beam centroid. This is illustrated in figure 5.19 for instance. The figure depicts the horizontal betatron oscillations of a typical beam centroid injected in the storage ring, during the first turn. If the MIK is switched off, the beam is lost 70 m downstream the injection point due to large oscillation amplitude. If the MIK is switched on, but badly set up - too much strength ($\theta_x = -1.5x'_{MIK}$ in this example) - then the injected beam oscillates with large amplitude, although encompassed in the physical aperture during the first turn. In this case, the beam will be lost during a next turn because it is too close to the vacuum chamber. The beam would have been lost as well if the strength of the MIK had been too weak. Eventually, if the MIK is switched on, and its voltage set up to satisfy equation 5.3, then the booster beam is injected conveniently, exhibiting oscillations whose amplitude is on the order of 10 mm.

124



Figure 5.18: Optical functions of the second cell of the ring. The lattice elements are drawn at the bottom of the figure: dipoles (yellow), focusing quadrupoles (blue) and defocusing quadrupoles (red), sextupoles (pink and green), BPM (black dots). The element free region is the second straight section of the ring, hosting the MIK. The horizontal and vertical beta functions equals 13.5 m and 3.5 m respectively, while the horizontal dispersion function equals 23 cm. There is no vertical dispersion in the perfect lattice. The optical functions are considered constant in the MIK.

The parameters which drive the dynamics of the electron are its coordinates at the injection point and θ_x . As a first approximation, the injection is supposed to be restricted to the horizontal plane, meaning that the only initial injection conditions that matter are the horizontal position x_{inj} and deviation x'_{inj} of the injected electron (z_{inj} = $z'_{inj} = 0$). Given the MIK location and fixing x_{inj} , x'_{inj} can be determined numerically such that the electron can reach x_{target} . As a result, knowing x_{inj} and x'_{inj} gives x'_{MIK} because the slope of the injected beam at the MIK location is determined by the initial injection conditions. Thus, θ_x is determined. This is illustrated in figure 5.20. This figure depicts that the more the injection is off-axis the more the MIK kick increases. Knowing that the maximum MIK voltage is limited to 11 kV practically, corresponding to $\theta_x = 2.4 \text{ mrad}$ at x_{target} , the electron cannot be injected for $x_{inj} \ge -31$ mm. Additionally, if the beam is injected way off-axis, the injection angle needed to reach x_{taraet} is high and greatly amplified by the defocusing quadrupole at s = 5 m, resulting in losses on the vacuum chamber at x = -35 mm. Practically, x_{inj} and x'_{inj} vary in specific ranges defined by operation constraints such as the voltages of the septum magnets, as well as the position of the thin septum blade. In operation, the outer face of this blade is located at x = -23 mm, meaning that $x_{inj} = -27$ mm typically. Based on the above, the computed initial deviation $x'_{inj} = 530 \,\mu$ rad. In this context, the horizontal MIK kick $\theta_x = 2.2 \,\mu$ rad, corresponding to $10 \,\mu$ V. As mentioned previously, the MIK exactly compensates the deviation of the injected beam and consequently equation 4.11 reduces to:

$$\Delta \varepsilon_x = \varepsilon_{x,0} - \varepsilon_{x,1} = \beta_{x,MIK} \theta_x^2. \tag{5.4}$$

R. Ollier



Figure 5.19: Horizontal betatron oscillations of a typical beam centroid injected in the storage ring (first turn). If the MIK is switched off, the beam is lost 70 m downstream the injection point (red dashed curve). If the MIK is switched on, but too strong ($\theta_x = -1.5x'_{MIK}$) then the injected beam oscillates with large amplitude and will be lost during the following turns (green dashed curve). If the MIK is switched on, and its voltage set up to satisfy equation 5.3, then $J_{x,1}$ is minimized by θ_x and the oscillation amplitude of the injected beam passes from roughly 25 mm to 10 mm after the MIK (blue curve). The horizontal scrapers are inserted to their nominal position and the location of the vertical scrapers is represented by the black dotted line.

Typically, $\varepsilon_{x,0} = 73 \text{ mm mrad}$. Besides, for $\theta_x = 2.2 \text{ mrad}$ at x_{target} and $\beta_{x,MIK} = 13.5 \text{ m}$, $\Delta \varepsilon_x = 65 \text{ mm mrad}$. So the injection invariant is minimized to $\varepsilon_{x,1} = 2J_{x,1} = \varepsilon_{x,0} - \Delta \varepsilon_x = 8 \text{ mm mrad}$ (see figure 5.17). In this case, the injection invariant is lowered by a factor of 8, and the amplitude of oscillation is equivalently minimized after the MIK to 10 mm, in order of magnitude.

After the determination of a convenient MIK location providing relevant order of magnitudes, beam lifetime studies were conducted in order to confirm that the installation of such a narrow vacuum chamber, in a section where the horizontal dispersion function reaches 23 cm, was compatible with operation.

Modeled physical apertures of the MIK Prior to Touschek beam lifetime computations, the horizontal and vertical physical apertures of SS2 have been reduced identically in the TRACY III and AT models, according to the mechanical design of the MIK section (see section 4.4.2). The MIK having the smallest physical apertures of the bare lattice, it was expected to accumulate a non-negligible amount of injection and decay losses, that would later define interlock thresholds. Thus, the worst scenario had to be clearly identified for radiation safety purposes. Consequently, for each part of this section, the narrowest dimensions are defined as the physical apertures, to have a pessimistic estimation of the number of electrons lost. The simulated physical apertures of the MIK section are plotted in figure 5.21.



Figure 5.20: Horizontal betatron oscillations of a single injected electron in the case of $(x_{inj} = -22 \text{ mm}, x'_{inj} = 240 \mu \text{rad})$ (blue) and $(x_{inj} = -31 \text{ mm}, x'_{inj} = 602 \mu \text{rad})$ (green). These values are deliberately large to show the impact on the first turn orbit and the MIK kick intensity. Both electrons reach x_{target} at the MIK location, s = 32 m, with two different slopes such that the MIK kick is adjusted accordingly: $\theta_x = 1.6 \text{ mrad}$ (blue) and 2.5 mrad (green). After the MIK the electrons follow the same orbit as the injection invariant is minimized. In this example, the physical aperture has been removed in order not to lose the most eccentric electron after 5 m (green).



Figure 5.21: Horizontal and vertical physical apertures of the MIK section, in the AT and TRACY III models. TAP refers to the standard taper-absorber and ABS to secondary taper-absorber machined in a bulk of copper chrome zirconium alloy.

Touschek beam lifetime studies As soon as the physical apertures of the TRACY III model were updated, the beam lifetime computations began. In this context, the MIK was switched off and only considered as a mechanical

element of the storage ring which decreases the beam lifetime due to its narrower physical apertures. In the case of the bare lattice, with the scrapers and the moveable absorber fully extracted, the drop in the simulated Touschek beam lifetime is estimated to 11 h, passing from 35 h to 24 h. It should be noted that these computations did not include the superbend at the time of the study. Figure 5.22 illustrates the longitudinal momentum acceptance of the storage ring computed with TRACY and used for Touschek lifetime simulations, when the scrapers and the moveable absorber are fully extracted (the computation parameters are given in table 4.8). These studies confirmed that the



Figure 5.22: Simulated longitudinal momentum acceptance of the storage ring. These computations were made using TRACY III in the case of the bare lattice including the MIK, with all the scrapers and the moveable absorber fully extracted. The simulation parameters are: horizontal emittance $\varepsilon_x = 3.87 \text{ nm rad}$, RMS bunch length $\sigma_s = 6 \text{ mm}$, bunch current I = 1.2 mA, beam coupling 1 %, RF voltage $U_{RF} = 2.8 \text{ MV}$, beam energy E = 2.739 GeV.

reduction of the physical apertures in the horizontal and vertical planes is not detrimental to the daily operation. This was confirmed with beam-based experiments, using the scrapers, with a typical IDs configuration: the Touschek beam lifetime is reduced by 20% when the IDs are fully opened and below 3 to 5% when they are inserted. From then on, further developments were included in the AT and TRACY models to give a refined description and a deep understanding of the MIK injection scheme.

5.3.1.3 Optimization of the injection

Prerequisite The optimization of the MIK injection scheme was based on electron bunch tracking. The ideal simulated field described in section 4.4.3.1 was used to perform these tracking computations. It gives the transverse kicks θ_x and θ_z as functions of x, z and t. When a given electron of a bunch is tracked, its transverse positions are in particular determined at the MIK location. Besides, the time t at which the electron passes through the MIK is fixed as an input parameter of the simulation. It can be chosen arbitrarily to study the effect of injection delays on the

beam dynamics. Once the triplet (x, z, t) associated to the electron at the MIK location is known, the MIK fields are interpolated to provide the correct kicks to the electron. Moreover, they are updated turn-by-urn to take the residual transient fields of the MIK into account. After two turns, representing 2.4 µs, the MIK fields are equal to zero and the interpolation stops, whereas the tracking goes on.

Injection efficiency Following the preliminary single particle tracking studies presented in section 5.3.1.2, the optimization of the MIK injection relied on 6*D* tracking of multi-particle Gaussian bunches. It should be noted that the results presented in this "Injection efficiency" paragraph were obtained by simulating single bunch beams interacting with the MIK fields when the MIK pulse is maximum, i.e. perfect match with no delay (the simulation results based on multi-bunch beam tracking, i.e. including delay between bunches, are compared to the measurements in section 5.3.2.3). The necessity of such parametric studies is closely related to the fact that the injected beam oscillates with large horizontal amplitude upstream the MIK and to the transverse properties of the booster beam. Indeed, the booster provides large beams by design. The natural emittance of the booster beam is on the order of 140 nm rad, which is roughly 35 times that of the stored beam. Besides, the booster beam coupling is rather low in operation. In this context, the horizontal envelop of the injected beam is a few millimeters large. Knowing that the outer face of the thin septum blade is positioned at x = -23 mm in operation, the centroid of an uncoupled injected beam can be located as far as x = -28 mm. However, the horizontal physical aperture of the storage ring equals ± 35 mm from the injection point to the MIK, assuming the inner horizontal scraper is fully extracted. Thus, the injected beam grazes the vacuum chamber right after the first defocusing quadrupole, 5 m downstream the injection point, which amplifies the injection angle of the injected beam, as mentioned in section 5.3.1.2 and illustrated in figure 5.20.

On the one hand, dealing with low coupled booster beam, the septum blade can be inserted closer to the longitudinal axis of the storage ring in order to minimize the horizontal oscillation amplitude of the beam between the injection and the MIK. The inner face of the blade can range from the nominal -19.5 mm to the extreme -13.5 mm positions (see chapter 4). However, at a certain point, the more the blade is inserted, the shorter the beam lifetime. The computation of the Touschek beam lifetime with respect to the position of the blade was performed in the case of the bare lattice, including the MIK section, but neither the scrapers nor the moveable absorber of NANOSCOPIUM, using TRACY III. Based on figure 5.23, the septum blade starts to accumulate the losses due to Touschek effect when its inner face is inserted beyond -17.5 mm, the rest being lost on the horizontal physical aperture of the MIK. In addition, figure 5.20 also illustrates that the horizontal oscillation amplitude of the injected beam centroid after the MIK is in the range of 10 mm regardless of the initial injection conditions, meaning that if the blade is inserted too much it can scrap the beam on the turns following the injection efficiency while keeping the beam lifetime compatible with operation.

On the other hand, the coupling of the injected beam has an impact on the injection efficiency as well. Working



Figure 5.23: Simulated Touschek beam lifetime variations with respect to the horizontal position of the septum blade. These computations are made using TRACY III in the case of the bare lattice including the MIK, with all the scrapers and the moveable absorber fully extracted. The parameters for the Touschek beam lifetime computation with TRACY III are: horizontal emittance $\varepsilon_x = 3.87 \text{ nm rad}$, RMS bunch length $\sigma_s = 6 \text{ mm}$, bunch current I = 1.2 mA, beam coupling 1 %, RF voltage $U_{RF} = 2.8 \text{ MV}$, beam energy E = 2.739 GeV.

with the lattice that does not include the superbend, the emittance transfer sounds like an interesting way to increase the injection efficiency because the vertical dynamic aperture is large, even around 10 mm horizontal amplitude, and quite free from resonances (see figure 4.47).

The 6*D* trackings performed with AT were based on these observations. A single Gaussian bunch beam of 5×10^3 electrons was tracked for various positions of the inner face of the blade, ranging from -19.5 mm to -15.5 mm by 1 mm steps, and beam coupling varying from 0% to 100% by 10% steps. The bunch is tracked during the first 10^3 turns because I observed that the major part of the injection losses occurred during this period of time. The injection loss rate variations are illustrated in figure 5.24. For a given position of the blade, the higher the booster beam coupling the greater the injection efficiency. However, the use of emittance exchange would be justified if the blade was inserted between -19.5 mm to -18.5 mm. Since we did not want to lower the beam lifetime more than the MIK already does (see section 5.3.1.2), the optimal position of the blade's inner face is x = -17.5 mm, avoiding the need to modify the booster beam coupling because the injection efficiency is already very close to 100%. In this configuration, the same simulation was performed with twice the number of electrons, tracked over the first 5×10^3 turns corresponding to 85% of the transverse damping times. The greater the coupling, the more electrons are lost over a large number of turns. At full coupling, the histogram of losses with respect to turns is given in figure 5.25. The major part of the injection losses occurred during the first 1000 turns, and the last ones were recorded around turn number 2000. The injection loss rate is low, in agreement with figure 5.24: 2.6% maximum at 0% coupling and



Figure 5.24: Simulated variations of the injection loss rate with respect to the booster beam coupling, in the case of various horizontal positions of the septum blade's inner face. In any case, a single 6D Gaussian bunch beam of 5×10^3 electrons was tracked during 10^3 turns in the bare lattice, excluding the superbend.



Figure 5.25: Histogram of the number of losses with respect to the number of turns, in the case of a fully coupled booster beam. The 6D single Gaussian bunch beam of 10^4 electrons was tracked during 5×10^3 turns in the bare lattice, excluding the superbend. The inner face of the septum blade is inserted to -17.5 mm.

0.3% minimum at 30% coupling, while it is already below 1% at 20% coupling. In this latter case, two third of the injection losses still occur in the horizontal plane, on the septum blade and after the first defocusing quadrupole. The remaining are vertical losses due to ± 5 mm physical aperture (see figures 5.26 and 5.27). This is considered to be the optimal case of MIK injection. The corresponding initial coordinates of the injected beam centroid are given

in table 5.1.



Figure 5.26: Horizontal and longitudinal coordinates of the injection losses (red dots) along the horizontal physical aperture (black solid line) when the septum blade is positioned at x = -17.5 mm, in the case of a 20% 6D Gaussian beam coupling (single bunch). The superbend is not included in the lattice.



Figure 5.27: Vertical and longitudinal coordinates of the injection losses (red dots) along the vertical physical aperture (black solid line) when the septum blade is positioned at x = -17.5 mm, in the case of a 20% 6D Gaussian beam coupling (single bunch). The superbend is not included in the lattice.

Table 5.1: Ideal horizontal injection parameters of the booster beam centroid, in the case of the MIK injection. The septum blade is positioned at x = -17.5 mm.

Transverse plan	Initial position	Initial angle	MIK kick	Beam coupling
Horizontal	$-25.4\mathrm{mm}$	$449\mu rad$	$2.2\mathrm{mrad}$	20%

Effect of the superbend on the MIK injection As depicted in figures 4.47 and 4.48, the dynamic aperture computed with the TRACY III model is reduced by a few millimeters in the horizontal and vertical planes when the superbend is taken into account. Since the AT model also included the superbend, the horizontal dynamic aperture reduction was simulated using AT. The last stable orbit is illustrated in black in figures 5.28 and 5.29, which depict the horizontal phase space along with the 3σ envelope of the booster/injected beam during the six first turns. In these examples, the booster beam coupling is zero. The uncoupled booster beam is well captured in the horizontal acceptance when the superbend is not taken into account (figure 5.28). It can be seen that the MIK leaves its footprint on the injected beam, whose emittance increases slightly. On the contrary, a part of the injected beam propagates outside the horizontal dynamic aperture as soon as the superbend is simulated (figure 5.29), leading to an increase in the loss rate.

New injection simulations were performed in order to determine the effect of the superbend on the injection efficiency and the injection loss maps. I repeated 6D trackings with a single Gaussian bunch beam of 10^4 electrons, performing 5.10^3 turns in the bare lattice. The septum blade was inserted at x = -17.5 mm. Similarly to the previous


Figure 5.28: Horizontal phase space at the injection point (end of the thin septum), for an uncoupled booster beam (blue dots representing the 3σ envelop). The booster beam is injected and tracked over the six first turns in the bare lattice (multicolor 3σ envelops), excluding the superbend. The injected beam is captured within the horizontal acceptance (black dots surrounding the injected beam).



Figure 5.29: Horizontal phase space at the injection point (end of the thin septum), for an uncoupled booster beam (blue dots representing the 3σ envelop). The booster beam is injected and tracked over the six first turns in the bare lattice (multicolor 3σ envelops), including the superbend. The injected beam is not fully captured within the horizontal dynamic aperture (black dots surrounding the injected beam).

case, the higher the beam coupling the more the losses spread out in time. Figure 5.30 gives the histogram of the injection losses with respect to turns at full coupling. The number of losses decreases exponentially such that there are no more losses after 4500 turns. Besides, the variations of the simulated loss rate with respect to the booster



Figure 5.30: Histogram of the number of losses with respect to the number of turns, in the case of a fully coupled booster beam. The 6D single Gaussian bunch beam of 10^4 electrons was tracked during 5×10^3 turns in the bare lattice, including the superbend. The inner face of the septum blade is inserted to x = -17.5 mm.

beam coupling are illustrated in figure 5.31, and compared to the data of figure 5.24, considering the same blade position (inner face at x = -17.5 mm). Including the superbend, the injection loss rate of a uncoupled beam is already twice the maximum of the reference case, reaching approximately 5%. Indeed, an uncoupled booster beam has a part of its border electrons outside of the dynamic aperture in the horizontal plane (see figure 5.29). However, a beam highly coupled also results in the increase of the injection loss rate for similar reasons concerning the vertical plane, because the vertical dynamic aperture is narrower off-axis and crossed with resonances due to the superbend (see figure 4.48). The loss rate is maximum at full coupling, reaching 15%. At 20% coupling, two third of



Figure 5.31: Injection loss rates variations with respect to the 6D single Gaussian bunch beam coupling, when the superbend is included in the bare lattice (green solid line) or not (blue solid line). The inner face of the septum blade is inserted to x = -17.5 mm in both cases.

the injection losses still occur in the horizontal plane, on the septum blade and after the first defocusing quadrupole, and the remaining are vertical losses (see figures 5.32 and 5.33). The loss maps presented in figure 5.34 shows the variation of the injection losses distribution depending on the superbend, in the case of 20 % booster beam coupling and a septum blade inserted at x = -17.5 mm.

5.3.1.4 Feasibility study of an active correction

As mentioned in section 4.4.3.2, a dipolar offset was detected during the measurements of θ_z (see figure 4.40). This magnetic field defect in the field free region of the MIK, assuming it is real and not just a bias related to a misalignment of the magnetic probe, results in residual betatron oscillations in the vertical plane. The defect was estimated around $15 \,\mu\text{Tm/kA}$. Knowing that the MIK was expected to work under $10 \,\text{kV} = I_{peak}/0.302$ and that the magnetic rigidity $B\rho = 9.1384$, the dipolar offset was estimated to be $\Delta \theta_z = \frac{15.10^{-6} \times I_{peak}}{B\rho} = 5 \,\mu\text{rad}.$



Figure 5.32: Horizontal and longitudinal coordinates of the injection losses (red dots) along the horizontal physical aperture (black solid line) when the septum blade is positioned at x = -17.5 mm, in the case of a 20% 6D Gaussian beam coupling (single bunch). The superbend is included in the bare lattice.



Figure 5.33: Vertical and longitudinal coordinates of the injection losses (red dots) along the vertical physical aperture (black solid line) when the septum blade is positioned at x = -17.5 mm, in the case of a 20% 6D Gaussian beam coupling (single bunch). The superbend is included in the bare lattice.



Figure 5.34: Simulated injection loss maps of the bare lattice without the superbend (blue bars) and including the superbend (red bars) when the septum blade is positioned at x = -17.5 mm, in the case of a 20% 6D Gaussian beam coupling (single bunch).

A basic model allowed to estimate the resulting vertical betatron oscillations due to this dipolar offset. The ultimate goal was to demonstrate numerically the feasibility of an active correction based on a vertical corrector installed in the injection section. Three assumptions were made concerning this residual kick: $\Delta \theta_z = 5 \,\mu$ rad is a peak value and it is considered as a rectangular signal lasting only one turn (uniform with respect to the beam

transverse size as well as constant over the MIK pulse). In this context, the stored beam was reduced to a single electron representing its centroid. The electron is tracked over five turns. On the first turn the MIK is turned on and kicks the electron. On the second turn the MIK is turned off and the active correction is whether turned on or off in order to acknowledge for the effect of the corrector kick. This is illustrated in figure 5.35. As expected, the



Figure 5.35: Vertical betatron oscillations induced by the residual kick of the MIK (red dased line) on turn 2 (green curve) and not fully corrected by the corrector (named KVCBA, black dashed line) on turn 3 (red curve) because of the vertical phase advance mismatch ($\nu_z = 0.228$, see figure 5.36).

active correction cannot cancel the perturbation in one turn due to the nominal vertical phase advance between the MIK and the corrector. In order to cancel the perturbation in one turn, the electron must reach $z(s_{corr}) = 0$, where s_{corr} denotes the longitudinal position of the vertical corrector. Additionally, the corrector must cancel the deviation $z'(s_{corr})$ of the electron. However, since the locations of the MIK and the corrector are already fixed, the only parameter left to adjust, to meet $z(s_{corr}) = 0$, is the vertical tune ν_z . As ν_z is increased, $z(s_{corr})$ tends to zero. Thus, the Courant-Snyder invariant decreases as the vertical tune increases, assuming that $z'(s_{corr})$ is canceled at the corrector location. This is illustrated in figure 5.36. For $\nu_z = 0.338$, the stored beam passes through the corrector at $z(s_{corr}) = 0$ after the residual MIK kick. In this situation, the vertical deviation of the electron $z'(s_{corr}) =$ $-3 \mu rad$ and the corrector just needs to provide the opposite kick to cancel the betatron oscillations, as illustrated in figure 5.37. This single electron model gave the order of magnitude of the vertical tune and correcting kick needed to counterbalance the dipolar defect of the MIK, that I had the opportunity to test during the commissioning of the MIK.



Figure 5.36: Variations of the Courant-Snyder invariant with respect to the vertical tune, including the active correction switched on subsequently to the MIK kick, on the next turn.



Figure 5.37: Vertical betatron oscillation induced by the residual kick of the MIK (red dashed line) on turn 2 (green curve) and fully corrected by the corrector (named KVCBA, black dashed line) on turn 3 (red curve) after vertical phase advance optimization ($\nu_z = 0.338$, see figure 5.36).

5.3.2 Commissioning of the MIK

5.3.2.1 Overview

Following the pre-commissioning phase presented in section 4.4.2, including the assembly of the MIK section and the magnetic field measurements, the commissioning phase began. The MIK was originally scheduled for instal-

lation in August 2020, but the COVID-19 pandemic necessitated delaying its installation to the last shutdown of 2020. The timeline of the commissioning is illustrated in figure 5.38. In November 2020, the thin septum magnet



Figure 5.38: Timeline of the MIK commissioning.

was equipped with a motorized translation system, enabling a horizontal translation of the septum blade of 6 mm maximum, ranging from -13.5 mm to -19.5 mm. At the end of December 2020, the former vacuum chamber of the SS2 has been removed after isolating the upstream and downstream arcs with a valve system, preserving the ultralow pressure in the rest of the storage ring. The MIK was eventually installed on December 21st, 2020 (see figure 5.39). During the same period, the new dipole chamber for the superbend was also installed in cell 12 for



vacuum conditioning, anticipating the magnet installation in summer 2021.

Figure 5.39: The MIK section installed in the SS2. The mechanical assembly of the MIK is detailed in section 4.4.2.

5.3.2.2 Preliminary experiments

The month of January was devoted to ensuring that the MIK chamber and its absorbers were fully compatible with the nominal operation of SOLEIL, with the MIK magnet turned off. We mainly focused on the following aspects: vacuum conditioning and level of bremsstrahlung radiation, level of radiation outside the tunnel, radiation safety tests, mandatory according to the French Nuclear Agency (ASN), and monitoring of beam induced heating, in all filling patterns.

Physical Acceptance Measurement The commissioning of the MIK started with preliminary stored beam-based measurements during February and March 2021 (see figure 5.38). In order to estimate the horizontal physical aperture of the MIK and confirm its proper alignment, I firstly measured the stored beam losses at the MIK and

scrapers locations (see chapter 4), using the newly commissioned BLMs (see section 4.6.2). After the IDs were fully opened, and the moveable absorber completely extracted, the storage ring was uniformly filled, reaching an average current intensity of 500 mA. The experiment was conducted at minimum beam coupling ($\ll 1\%$) and started when the storage ring was thermalized and the stored beam polarized [120]. Only one scraper was used at a time, while the others were fully extracted. The chosen scraper was inserted progressively by steps of 500 µm. In this context, the number of losses eventually increases at the scraper location. The scraper was then fully extracted before a complete beam loss and the storage ring refilled to keep high beam current intensity around 500 mA. This measurement has been repeated with the remaining scrapers. The main parameters of the experimental setup are given in table 5.2. The effects of the lower and upper vertical scrapers on the decay losses at the MIK Table 5.2: Main parameters of the experimental setup for the measurements of decay losses at the MIK and scraper locations.

Parameter	Value
Betatron tunes (ν_x / ν_z)	18.171 / 10.217
Corrected chromaticities (ξ_x / ξ_z)	1.4 / 2.1
Filling pattern	Uniform (500 mA)
Beam coupling	Minimum ($\ll 1\%$)

location are illustrated in figure 5.40 and 5.41 respectively. According to these figures, the loss rates measured at the scrapers' location increase identically as the lower and upper blades get closer to the stored beam. This confirms that the limiting vertical aperture is symmetric with respect to the stored beam plane. Besides, this is not the MIK chamber which limits the vertical aperture of the storage ring since the loss rates at the MIK location are constant. Conversely, figures 5.42 and 5.43 show that the MIK chamber has the limiting physical aperture of the storage ring in the horizontal plane as predicted by the simulations. Indeed, the decay losses measured at the MIK location are relocated at the inner and outer horizontal scrapers as soon as they are inserted to -24 mm and 19 mm respectively, equivalent to the physical aperture of the MIK at the scrapers locations (the precision is on the order of the millimeter). Another way to measure the horizontal physical aperture could have been to offset the stored beam in the MIK section, but the corrector strengths were not sufficient. In light of these results, the decision was made to minimize the lifetime losses at the MIK location by inserting furthermore the inner horizontal scraper to x = -21 mm and to add a system dedicated to gamma and neutron radiation monitoring. In this case, the outer horizontal scraper was left to its nominal position of x = 33 mm, as the loss rate at the MIK location was deemed acceptable.

Characterization of the MIK magnetic field After I confirmed that the MIK's horizontal physical aperture and mechanical alignment meet the specifications, I probed its magnetic field with the stored beam in a second step, by means of horizontal static bumps in the MIK section. I used a 15 mA stored beam in the one quarter filling pattern. Thus, the MIK kick is considered uniform on the bunches, avoiding time bias in the kick estimates. I recorded the betatron oscillations induced by the MIK in turn-by-turn mode. At that time, the Libera Brilliance electronics had not



Figure 5.40: Variations of the response of four BLMs with respect to the position of the lower vertical scraper, in uniform filling pattern (500 mA), when all the other scrapers and the moveable absorber are fully extracted, and the IDs opened at full gap. The BLMs surround the vertical scraper and the MIK: upstream and downstream BLMs at scraper location in blue and green respectively, upstream and downstream BLMs at MIK location in red and cyan respectively. The red signal is divided by 4 for convenience.



Figure 5.42: Variations of the response of four BLMs with respect to the position of the inner horizontal scraper, in uniform filling pattern (500 mA), when all the other scrapers and the moveable absorber are fully extracted, and the IDs opened at full gap. The BLMs surround the inner horizontal scraper and the MIK: upstream and downstream BLMs at scraper location in blue and green respectively, upstream and downstream BLMs at MIK location in red and cyan respectively.



Figure 5.41: Variations of the response of four BLMs with respect to the position of the upper vertical scraper, in uniform filling pattern (500 mA), when all the other scrapers and the moveable absorber are fully extracted, and the IDs opened at full gap. The BLMs surround the vertical scraper and the MIK: upstream and downstream BLMs at scraper location in blue and green respectively, upstream and downstream BLMs at MIK location in red and cyan respectively. The red signal is divided by 4 for convenience.



Figure 5.43: Variations of the response of four BLMs with respect to the position of the outer horizontal scraper, in uniform filling pattern (500 mA), when all the other scrapers and the moveable absorber are fully extracted, and the IDs opened at full gap. The BLMs surround the outer horizontal scraper and the MIK: upstream and downstream BLMs at scraper location in blue and green respectively, upstream and downstream BLMs at MIK location in red and cyan respectively.

been commissioned yet, such that I scanned the MIK voltage and probed its magnetic field in ranges compatible with the performance of the Libera Electron electronics, i.e. the MIK voltage varied between 2 kV and 10.4 kV, while the stored beam horizontal position in the MIK section was $1 \text{ mm} \le x \le 2 \text{ mm}$. At the beginning, I set the MIK voltage to 6.2 kV and decreased the corrected chromaticities of the bare lattice to $\xi_x = 0.6$ and $\xi_z = 0.8$ in order to avoid beam decoherence. Table 5.3 provides the main experimental parameters for the measurements of the polarity and MIK field variations. I centered the stored beam on the MIK pulse first. To do so, I bumped the beam by 2 mm in

Table 5.3: Main parameters of the experimental setup for the measurements of the polarity and MIK field variations.

Parameter	Value
Betatron tunes ν_x / ν_z	18.156 / 10.228
Corrected chromaticities ξ_x / ξ_z	0.6 / 0.8
Filling pattern (average beam current mA)	One quarter (15)
Beam coupling	Minimum ($\ll 1\%$)
MIK voltage (kV)	6.2

the MIK section thanks to four horizontal correctors (two upstream the MIK section and the remaining downstream). Then, I scanned the MIK delay by steps of 5.68 ns, corresponding to the delay involving three consecutive bunches, and maximized the resulting perturbation as the MIK was triggered. Then, I verified that the vertical magnetic field of the MIK has the expected polarity, and sampled the region defined by $1 \text{ mm} \le x \le 2 \text{ mm}$ and z = 0 in order to verify its variations. Figure 5.44 provides the estimated horizontal kicks compared to the expected ones, deduced from the ideal simulated field (see figure 4.37). To estimate the MIK kick from the turn-by-turn measurements, in the linear approximation, equation 4.5 was used. Δx was measured at each BPM, and the values of the horizontal beta function at the BPMs and MIK locations were provided by the AT model of a simplified lattice (thin sextupoles, no multipoles). A horizontal bump is simulated to take the beta beating into account. Typically, in the case of a $2 \, \text{mm}$ bump, the beta function in the MIK decreases from 13.5 m to 12.8 m. If the beta beating is not taken into account, it results in an error between 2 and 3% of θ_x at $x = 2 \,\mathrm{mm}$, corresponding to $2 \,\mu$ rad. Figure 5.44 proves that the MIK field has the expected polarity since the estimated kicks are positive, in agreement with the simulated field. According to figure 5.44, the horizontal kicks deduced from the BPM data are greater than expected. In addition, the difference tends to increase the bump amplitude increases. The estimated kicks meet expectations provided that an extra horizontal offset of approximately 450 µm is taken into account. Two sources of static errors are considered to explain this discrepancy. The first error is due to the misalignment of the MIK. In the following, the precise alignment of the beam with the magnetic center of the MIK is detailed: the magnetic center of the MIK is located at $x = -200 \,\mu\text{m}$. Consequently, the stored beam was $200 \,\mu\text{m}$ further away than expected when I performed the static bump. This gives the five green points in figure 5.44. The second error cannot be related to the MIK voltage, as it should be increased by more than 50% in order for the simulated curve to fit the green points. This error is more likely to be related to the bump height. Indeed, it may be underestimated due to the non-linear response of the



Figure 5.44: Variations of the ideal horizontal kick of the MIK (blue solid curve) in the $1 \text{ mm} \le x \le 3 \text{ mm}$ range, at z = 0, under 6.2 kV. The expected MIK kicks are represented by green circles. A one quarter stored beam was used to probe the vertical field of the MIK in the $1 \text{ mm} \le x \le 2 \text{ mm}$ range, by means of static bumps in the MIK section (0.2 mm steps). The five blue points deduced from the measurements are beyond the expected values (the error bars give the enlarged uncertainty for a 95% confidence interval. The estimated kick is averaged over 118 points — number of BPM in the storage ring, excluding four BPMs in the static bump —, leading to a Student coefficient of 1.65). One point is missing at x = 1.6 mm due to wrong data acquisition. The five green points represent the measurements if the MIK has an horizontal offset of $-200 \,\mu\text{m}$. The five red points represent the measurements if, in addition to the MIK offset of $-200 \,\mu\text{m}$, the horizontal bumps had an offset of $250 \,\mu\text{m}$.

BPMs practically, although it is considered linear until x = 2 mm theoretically (see figure 4.51). In summary: the bump height may vary in the $1.25 \text{ mm} \le x \le 2.25 \text{ mm}$ range while the misalignment of the MIK add an extra offset of 200 µm. This is represented by the red points in figure 5.44. It should be noted that the difference between the red points and the expected kick is non-zero and increases for $x \ge 2 \text{ mm}$ because the bump error is not constant a fortiori.

In addition to the previous experiment, I confirmed that θ_x varies linearly with the supplied current. I equivalently increased the MIK voltage, $U_{MIK} = \frac{I_{peak}}{0.302}$, from 2 kV to 10.4 kV by steps of 700 V. The position of the stored beam in the MIK was fixed to x = 2 mm, by means of a horizontal static bump. I took into account the static errors described in the previous paragraph when plotting the calibration curves. They are provided in figure 5.45. The linear regression performed on the estimated kicks provides an increase rate which is equal to 11.5 µrad/kV, while it is of 8.5 µrad/kV for the red curve, corresponding to the expected θ_x taking into account the static errors mentioned in the previous paragraph. At $U_{MIK} = 6.2$ kV, $\theta_{x,estimate} = 55$ µrad and $\theta_{x,expect} = 52$ µrad, in agreement with the corresponding value of θ_x at x = 2.45 mm in figure 5.44. For $U_{MIK} \le 6.2$ kV, the measurements are close to the simulated and corrected curve. These measurements furthermore demonstrated that the MIK pulse is very reproducible. MIK kicks led to oscillation amplitudes ranging from 100 µm to 1.8 mm.



Figure 5.45: Variations of the ideal horizontal kick of the MIK (blue solid curve) with the supplied voltage. A one quarter stored beam was used to probe the vertical field of the MIK, by means of a static bump in the MIK section (x = 2 mm and z = 0). The estimated kicks are plotted as red points (the error bars give the enlarged uncertainty for a 95% confidence interval. The estimated kick is averaged over 118 points — number of BPM in the storage ring, excluding four BPMs in the static bump —, leading to a Student coefficient of 1.65). The estimations are fitted by a linear regression (black solid line). The variations of the kick in the case of a MIK offset of $-200 \,\mu\text{m}$ is plotted in green. Taking an additional offset of $250 \,\mu\text{m}$ in the horizontal bump height leads to the red curve.

Moreover, the MIK pulse has been measured like the kicker pulse (see 5.2.2.3), except the beam of 13 continuous bunches was horizontally bumped by 2 mm in the MIK section in order to get out of the field free region and measure residual betatron oscillations. The kick was expected to last roughly 2.4 µs, as the MIK is supplied with current pulses lasting two revolution periods. This illustrated in figure 5.46. The ideal time variations of θ_x are illustrated in figure 5.47 along with its estimated variations. The peak amplitude of θ_x is in the range of 45 µrad as expected. However, the estimated variations exhibit a residual oscillation at 153 kHz, with a peak amplitude of 7 µrad, whose damping follows that of the BPMs data. Obviously, this is an artifact which cannot be considered as the true values of θ_x because the supplied current of the MIK is zero after two turns (see figure 5.46). Since it cannot be the true variations of θ_x , this is considered as a modulating signal which can be subtracted to the estimated data. Assuming that the additive signal is synchronous with the MIK kick, it is subtracted as of 8 µs. The corrected estimated kick is illustrated in figure 5.48. The kick amplitude is still in good agreement with that of the ideal simulated kick, although the total duration of the measured perturbation corresponds to approximately three turns instead of two.

5.3.2.3 Injected beam-based measurements

Injection optimizations Following the conclusive preliminary characterizations of the MIK, the injection optimizations began. For the first successful injection, the injection efficiency reached 38% without any optimization, the



Figure 5.46: Time variations of the MIK supply current, simulated (blue) and measured (red). The measurement was performed using an oscilloscope. The MIK is supplied with current during roughly $2.4 \,\mu$ s, equivalent to two revolution periods.



Figure 5.47: Time variations of the simulated (blue) and measured (red) horizontal MIK kick, at x = 2 mm in the MIK. The ideal simulated kick lasts $2.4 \,\mu\text{s}$, corresponding to two revolution periods. The estimated kick shows residual oscillations which cannot be true since the MIK is turned off after a few microseconds.

scrapers being fully extracted. The blade of the thin septum magnet was inserted beforehand to -17.5 mm, instead of its nominal value of -19.5 mm. The horizontal and vertical betatron tunes were 18.156 and 10.228 respectively, while the horizontal and vertical chromaticities were lowered to $\xi_x = 0.6$ and $\xi_z = 0.8$. The initial voltage of the MIK was set to 6 kV.



Figure 5.48: Time variations of the simulated (blue) and measured (red) horizontal MIK kick, at x = 2 mm in the MIK. The ideal simulated kick lasts $2.4 \,\mu\text{s}$, corresponding to two revolution periods. The residual oscillations of the estimated kick illustrated in figure 5.47 have been subtracted as of $8 \,\mu\text{s}$.

To go further, I first optimized the delay of the MIK. By roughly adjusting its value, I reached an injection efficiency of 71%. From this point, the delay was scanned more precisely by steps of 50 ns in order to find the optimum. The delay was set to reach a maximum injection efficiency of 75%, as illustrated in figure 5.49.



Figure 5.49: Variations of the injection efficiency with respect to the delay of the MIK. The delay is varied by step of 50 ns from its reference value, which provides 71% injection efficiency. The first set of injections is plotted (dashed blue line), as well as the second set (dashed green line) and the average value (red solid line).

I optimized the voltage of the MIK then. It was scanned by step of 250 V between 8 kV and 10.75 kV, knowing that 11 kV is the maximum voltage allowed experimentally. The nominal voltage was expected to be close to 10 kV. However, the measurements showed that the injection efficiency tended to be maximum beyond 11 kV, as illustrated by figure 5.50. The fact that the injection efficiency was lower than 90% for a supplied voltage of 10.75 kV indicated



Figure 5.50: Variations of the injection efficiency with respect to the voltage of the MIK. The voltage is varied by step of 250 V between 8 kV and 10.75 kV. The first set of injections is plotted (dashed blue line), as well as the second set (dashed green line) and the average value (red solid line). The recorded values at 10.25 kV and 10.5 kV were not updated during the process.

that the injected beam had missed the target position in the MIK, where the nominal magnetic field is induced. Indeed, the simulations predicted that the nominal horizontal kick of 2.2 mrad at $x_{target} = 10.3$ mm, corresponding to a supplied voltage of 10 kV, should provide an injection efficiency as high as 99%. Beam position measurements confirmed that the injected beam had passed through the MIK at a horizontal position which was greater than 10.3 mm, a few millimeters away from this target position, meaning in a region where the octupolar field too weak. Thus, the voltage of the MIK had to be higher than expected in order to compensate the drop of the octupolar field beyond the target position.

Consequently, the next step was to steer the injected beam horizontally and vertically using the thin and thick septum magnets and the last two vertical correctors of TL2 respectively. I performed this optimization in the same configuration as presented previously, except the voltage of the MIK was initially set to 7 kV, providing an injection efficiency around 80%. Firstly, the horizontal position of the injected beam was stepped by 1 mm at the injection point, increasing the injection efficiency to 83%. Then, the horizontal injection angle was scanned by steps of 100 µrad in the range of $\pm 500 \,\mu$ rad. The horizontal injection angle was eventually stepped by 200 µrad to achieve a maximum injection efficiency of 90%, as illustrated in figure 5.51. From this point, the horizontal injection position was scanned

by steps of $100 \,\mu\text{m}$ between $\pm 500 \,\mu\text{m}$. Eventually, the horizontal injection position was steered from the reference by $-500 \,\mu\text{m}$ to achieve a maximum injection efficiency of 91%, as illustrated in figure 5.52. The injected beam was then steered vertically but the initial setting was already optimal.



Figure 5.51: Variations of the injection efficiency with respect to the horizontal angle of the injected beam at the injection point. The angle is varied by steps of $100 \,\mu$ rad from its reference value. The first set of injections is plotted (dashed blue line), as well as the second set (dashed green line) and the average value (red solid line).



Figure 5.52: Variations of the injection efficiency with respect to the horizontal position of the injected beam at the injection point. The position is varied by steps of $100 \,\mu\text{m}$ from its reference value. The first set of injections is plotted (dashed blue line), as well as the second set (dashed green line) and the average value (red solid line).

Finally, the voltage of the MIK was scanned once again to reach a maximum injection efficiency of 97% at 10 kV as expected. In this situation, I had determined a set of nominal setpoints for each magnets involved in the injection process (see table 5.5).

From then on, the first turn orbits of the injected beam were measured. In particular, they were used as input data for the AT model in order to compute the most accurate fit of the first turn orbits. This allowed to estimate the initial injection conditions $(x, x', z, z', \theta_x, \theta_z)$.

First turn orbits of the injected beam As soon as the nominal injection setpoints were determined (see table 5.5), I measured the horizontal and vertical first turn orbits using the standard Libera electronics of the BPMs. I conducted these measurements to verify that the injected beam reached the target position in the MIK and that the amplitude of the horizontal betatron oscillations were minimized as expected (which was already almost certain given the injection efficiency). Eventually, I had to confirm that the initial injection conditions were in the range of the ideal ones (see table 5.1).

The measurements were performed twice, before and after the commissioning of the superbend (in May and September 2021 respectively). In both cases, the booster beam was injected in the bare lattice, with the horizontal and vertical scrapers fully extracted. A sequence of eleven injections was performed such that the current injected beam was killed before any other injection into the storage ring. The BPMs were set in the turn-by-turn mode and triggered on the injection event, such that the recording had to start a few microseconds before the booster beam entered the storage ring. Since the horizontal betatron oscillations were greater than 2 mm, it was necessary to use the rebuilding function to determine the true positions of the injected beam (see section 4.6.1.2). Then, the simulated betatron oscillations were fitted automatically to the measured orbits, in the horizontal and vertical planes, using the AT model and a fitting function I developed. I set bounds for each initial injection condition, and provided these bounds as inputs to my fitting function, to avoid irrelevant solutions. (see table 5.4). The convergence time was on the order of 1 s.

Initial injection condition	Boundary conditions
<i>x</i> (mm)	[-28, -20]
x' (mrad)	[-1, 1]
z (mm)	[-0.5, 0.5]
z' (mrad)	[-0.2, 0.2]
θ_x (mrad)	[1.8, 2.5]
θ_z (mrad)	[-0.5, 0.5]

Table 5.4: Boundary conditions given as inputs of the fitting function.

Concerning the measurements performed in May, the horizontal and vertical first turn orbits, averaged over the eleven acquisitions, are illustrated in figures 5.53 and 5.54 respectively. The corresponding averaged injection efficiency reached 96%. As expected, the rebuilding function had troubles estimating the real amplitude of the





Figure 5.53: Horizontal betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on May 31^{st} , 2021, before the installation of the superbend. The expanded uncertainty at 95%, with Student coefficient equal to 2.201, is represented by red error bars. The MIK is set up in the nominal configuration, with optimal injection parameters.

Figure 5.54: Vertical betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on May 31^{st} , 2021, before the installation of the superbend. The expanded uncertainty at 95%, with Student coefficient equal to 2.201, is represented by red error bars. The MIK is set up in the nominal configuration with optimal injection parameters.

horizontal betatron oscillations before the MIK (in the range of 25 mm). This is why the error bars, determined for a 95% confidence interval with a student coefficient of 2.201, are large in this region of the storage ring. After the MIK, the injected beam oscillates in the $\pm 10 \text{ mm}$ range, where the rebuilding function works well. Moreover, the injected beam also oscillates vertically in the $\pm 0.5 \text{ mm}$ range. I did not manage to further decrease the oscillation amplitude by means of vertical steering of the injection point. The fits corresponding to these measurements are plotted in figures 5.55 and 5.56. The initial injection conditions corresponding to these fits are gathered in table 5.6. These initial conditions are in good agreement with those of the ideal simulated MIK injection. The simulated horizontal orbit in figure 5.55 exhibits peak amplitudes of roughly 25 mm before the MIK, as expected. Besides, this fit confirmed that the injected beam reached the target position in the MIK and that its peak horizontal amplitude was correctly minimized to approximately 10 mm.

Following the commissioning of the superbend, which took place in the summer of 2021. The nominal setpoint values of the magnets involved in the MIK injection remained unchanged, except that of the thin septum (see table 5.5). The delay and the voltage of the MIK were conserved as well. The averaged first turn orbits are illustrated in figure 5.57 and 5.58, for the horizontal and vertical plane respectively. The average injection efficiency dropped by 10% due to the reduction of the dynamic aperture. The horizontal and vertical orbits exhibit the same characteristics than those measured before the commissioning of the superbend, that is a horizontal peak amplitude on the order



Figure 5.55: Measured horizontal betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on May 31^{st} , 2021, before the installation of the superbend. The MIK was set up in the nominal configuration, with optimal injection parameters. The simulated data (red solid line) were fitted to the measurements using the AT model. The horizontal physical aperture is plotted in black solid line. The discrepancies between the measured and simulated data, along the first 25 m of the ring, result from the limitation of the rebuilding function for amplitudes greater than 25 mm (see section 4.6.1.2).



Figure 5.56: Measured vertical betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on May 31st, 2021, before the installation of the superbend. The MIK was set up in the nominal configuration, with optimal injection parameters. The simulated data (red solid line) were fitted to the measurements using the AT model. The vertical physical aperture is plotted in black solid line.

Magnat Tupa	Setpoint		
Magnet Type	Before superbend	After superbend	
Thick septum	90.5 V	90.5 V	
Thin septum	589.2V	593.4V	
4 th vertical corrector (TL2)	1.1 A	1.1 A	
5 th vertical corrector (TL2)	0.1 A	0.1 A	
MIK	$10\mathrm{kV}$	$10\mathrm{kV}$	

Table 5.5: Nominal setpoint values of the magnets involved in the MIK injection.

of 25 mm before the MIK and 10 mm after and vertical oscillations in the ± 0.5 mm range. Again, the simulated orbits, associated to the initial injection conditions in table 5.6, were fitted to the measured data. This is illustrated in figure 5.59 and 5.60. Thus, the linear optics was correctly restored after the commissioning the superbend. However, its strong sextupolar component led to the increase of the injection loss rate and a change in the injection losses distribution.

Loss maps I measured turn-by-turn loss maps in different configurations. In particular, the case of a complete MIK injection failure was studied, numerically and then experimentally, for the sake of radiotion safety studies. In



Figure 5.57: Horizontal betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on September 5th, 2021, after the commissioning of the superbend. The expanded uncertainty at 95%, with Student coefficient equal to 2.201, is represented by red error bars. The MIK is set up in the nominal configuration, with optimal injection parameters. The lack of data, along the first 25 m of the ring, result from the limitation of the rebuilding function for amplitudes greater than 25 mm (see section 4.6.1.2).



Figure 5.58: Vertical betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on September 5th, 2021, after the commissioning of the superbend. The expanded uncertainty at 95%, with Student coefficient equal to 2.201, is represented by red error bars. The MIK is set up in the nominal configuration with optimal injection parameters. The lack of data, along the first 25 m of the ring, result from the limitation of the rebuilding function for amplitudes greater than 25 mm (see section 4.6.1.2).

Table 5.6: Estimated injection parameter
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Date	Transverse plane	Initial position	Initial angle	MIK kick
May 31 st , 2021 (before superbend)	Horizontal Vertical	$\begin{array}{c} -24.0\mathrm{mm} \\ -100\mu\mathrm{m} \end{array}$	$470\mu { m rad}$ $60\mu { m rad}$	$2.0\mathrm{mrad}$ $11\mu\mathrm{rad}$
Sept. 5 th , 2021 (after superbend)	Horizontal Vertical	$-24.1\mathrm{mm}$ $-54\mu\mathrm{m}$	$450\mu\mathrm{rad}$ $-40\mu\mathrm{rad}$	$2.0\mathrm{mrad}$ $3\mathrm{nrad}$

this case, the MIK is not triggered.

Tracking computations were performed with AT. Three electrons were tracked: the injected beam centroid is injected at $x_0 = -24.0 \text{ mm}$, and the two others at $x_0 \pm \frac{3\sigma_x}{2}$. The horizontal first turn orbits are plotted in figure 5.61. Since the injected beam is not kicked by the MIK, it oscillates with large amplitudes and grazes the horizontal physical aperture at several locations. The electron injected at $x_0 - \frac{3\sigma_x}{2}$ is lost around s = 70 m while the centroid is lost around s = 140 m. Eventually, the electron injected at $x_0 + \frac{3\sigma_x}{2}$ is lost around s = 270 m. Theoretically, a few electrons of a Gaussian beam could survive the first turn, although they would be lost on the next turns. Practically, the beam is completely lost in LS9, at s = 170 m, where the simulation predicted the electron injected at $x_0 + \frac{3\sigma_x}{2}$ would graze the vacuum chamber (see figure 5.61). These observations are in good agreement with the measurements.





Figure 5.59: Measured horizontal betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on September 5th, 2021, after the commissioning of the superbend. The MIK was set up in the nominal configuration, with optimal injection parameters. The simulated data (red solid line) were fitted to the measurements using the AT model. The horizontal physical aperture is plotted in black solid line. The lack of measured data, along the first 25 m of the ring, result from the limitation of the rebuilding function for amplitudes greater than 25 mm (see section 4.6.1.2).



Figure 5.60: Measured vertical betatron oscillations of the injected beam (blue solid line), during the first turn in the storage ring, averaged over eleven acquisitions. The data has been recorded on September 5th, 2021, after the commissioning of the superbend. The MIK was set up in the nominal configuration, with optimal injection parameters. The simulated data (red solid line) were fitted to the measurements using the AT model. The vertical physical aperture is plotted in black solid line. The lack of measured data, along the first 25 m of the ring, result from the limitation of the rebuilding function for amplitudes greater than 25 mm (see section 4.6.1.2).

Prior to the installation of the superbend, I injected a beam in the bare lattice while the MIK was off. Even if the measured horizontal first turn orbit cannot be rebuilt correctly at such oscillation amplitudes, the simulation results were confirmed thanks to the sum signal of the BPMs. The sum signal is illustrated in figure 5.62. It is maximum in the first 70 m of the ring where the injected beam propagates freely. Then it decreases rapidly because the injected beam is very far from the BPM buttons, reaching the vacuum chamber walls. It is partly scraped in this region as the sum signal does not reach its former level (divided by 2 around 100 m downstream the injection point). The beam is scraped a second time at s = 140 m as the sum signal is lower than previously, at s = 160 m. Eventually, the beam is completely lost 170 m downstream the injection point, as the sum signal falls to zero. Additionally, I measured the first turn loss map in the mean time, in order to get the full picture of the first turn losses distribution. This is illustrated in figure 5.63. The major part of the beam is lost upstream 100 m and the remaining electrons in the LS9 as predicted by the simulations. It should be noted that the injection losses spread out over several meters. Indeed, when the beam is scraped practically, the energy of some electrons varies. These electrons can travel a few meters, before being lost in the next dipole if their energy deviation is too large. This can explain the difference, on the order of a few meters, between the locations of the losses predicted by AT and the BLM response.

Then, turn-by-turn loss maps were measured in the case of the nominal MIK injection. Following the fine tuning



Figure 5.61: Horizontal first turn orbit of the injected beam in the case of a MIK injection failure (MIK off). The injected beam consists of three particles: the beam centroid (blue) injected at $x_0 = -24.0 \text{ mm}$, and two others at $x_0 \pm \frac{3\sigma_x}{2}$ (green and red respectively). The beam is scraped by the vacuum chamber walls (black) 70 m and 140 m downstream the injection point. The beam is completely lost at s = 270 m.



Figure 5.62: Variations of the sum signal with respect to the BMP location, during the first turn of the injected beam, in the case of a MIK injection failure (MIK off). The three bumps correspond to the part of the storage ring where the injected beam oscillates freely. The first bump is centered around s = 50 m, the second bump is centered around s = 130 m and the third bump is centered on s = 160 m. The second bump is lower than the first one due to the partial loss of the beam in the upstream medium straight section (MS4), at s = 70 m. Similarly, the third bump is lower than the second one because the beam is scraped at s = 140 m. Eventually the beam is completely lost in LS9, at s = 170 m, as the sum signal goes to zero.



Figure 5.63: Location of particle showers induced by injection losses during the first turn of the injected beam, in the case of a MIK injection failure (MIK off). The showers were detected by the BLMs installed along the storage ring. In agreement with the simulations and the BPM measurements, the beam is strongly scraped for the first time 70 m downstream the injection point and completely lost in LS9, which is detected by the following BLMs.

of the MIK, the BLMs detected few losses prior to the installation of the superbend, as the injection efficiency of the optimized MIK injection was close to 100% in the bare lattice. Later on, the turn-by-turn loss maps showed longer injection losses accumulation in additional preferential loss areas, as the injection efficiency dropped by 10%due to the superbend. This is illustrated in figures 5.64 (before the installation of the superbend) and 5.65 (after the commissioning of the superbend). Figure 5.65 shows that the injected beam is scraped at the synchrotron frequency, every 200 turns approximately, suggesting that some electrons are lost due to chromatic coupling, which leads to large vertical oscillations. Indeed, the major part of the injection losses are located where the vertical physical aperture satisfies $|z| \leq 5$ mm, that is in several medium and long straight sections. Additionally, injection losses are detected in the MIK section and in the superbend. The remaining losses occur in the injection section. This was predicted by the simulations performed with the superbend lattice, as illustrated in figure 5.66. A 6D tracking of several Gaussian bunches, of 10⁴ electrons each, injected in the perfect bare lattice gave the simulated loss map presented in this figure (bunches number 1, 26, 53, 78, 94 and 104, of a standard injected beam made of 104 continuous bunches, were tracked, with bunch 53 time-centered on the MIK pulse). The coupling of the injected beam was 10% and the chromaticities were lowered to $(\xi_x, \xi_z) = (0.6, 0.8)$ similarly to their experimental value. The measurements give the averaged number of events detected by the BLMs over the first 200 turns of the injected beam, whereas the simulated data give the total number of electrons lost during the same number of turns. When the MIK injection is optimized, the blade of the thin septum magnet is positioned at x = -17.5 mm, and it was found experimentally that its position could be varied by $\pm 1\,$ mm without affecting the injection efficiency. Beyond that, the



Figure 5.64: Turn-by-turn loss maps measured before the commissioning of the superbend in the case of the nominal MIK injection (injection efficiency $\approx 96\%$). The major part of the injection losses are detected continuously in the injection section.



Figure 5.65: Turn-by-turn loss maps measured after the commissioning of the superbend in the case of the nominal MIK injection (injection efficiency $\approx 86\%$). The major part of the injection losses are detected periodically, at the synchrotron frequency, downstream several medium and long straight sections.



Figure 5.66: Simulated (red) and measured (blue) injection loss maps in the case of the nominal MIK injection, giving respectively the total number of electrons lost during the first 200 turns of the injected beam and the averaged number of events detected by the BLMs over the same number of turns.

blade strongly scraped the injected beam. In order to prevent injection losses on the insertion devices and the MIK, the vertical scrapers are inserted to $z = \pm 3 \text{ mm}$. In this case, the injection losses are relocated in the injection section, surrounded by over-shielding walls.

5.3.2.4 Stored beam-based measurements

Following the optimization of the MIK injection, stored beam-based experiments were conducted in order to measure the effects of the MIK on the stored beam, both from the decay losses distribution and stored beam stability perspectives.

Decay losses The effect of the MIK chamber on the decay losses distribution was measured thanks to the BLMs in the 500 mA uniform filling mode. The decay losses result from elastic, inelastic and Touschek scatterings. They are mainly located in the MIK section where the horizontal dispersion is large, $\eta_x = 23$ cm, and the horizontal physical aperture is minimized due to the upstream secondary taper-absorber of the MIK, ranging from x = -23 mm to 20 mm. The accumulation of decay losses in the MIK section implied to insert the inner horizontal scraper further to relocate partially the decay losses in the injection section, which is surrounded by over-shielding walls. The scraper was inserted to x = -21 mm, instead of -28 mm before the installation of the MIK. Thus, the MIK was satisfactorily protected while providing an injection efficiency still compatible with operation. In operation, following the installation of the MIK, and prior to the commissioning of the superbend, the overall beam lifetime decreased from 12 h to 11 h in the 500 mA uniform filling mode and from 11 h to 10 h in the hybrid filling mode (445 mA in three quarters and 5 mA in one bunch in the remaining quarter). After the commissioning of the superbend, the scrapers which remain inserted to -20 mm. It was not necessary to modify the position of the other scrapers which remain inserted to $z = \pm 3$ mm and x = 33 mm for the vertical and outer horizontal scrapers respectively.

Stored beam alignment The main advantage of the MIK over the kickers is the field free region along the stored beam path, preventing the closed orbit from any perturbation ideally. I presented preliminary experiments which suggested a misalignment of the MIK in section 5.3.2.2 (see figure 5.44). The horizontal offset, on the order of a few hundred micrometers, implies that the store beam is not aligned with the magnetic center of the MIK. Consequently, the stored beam experiences horizontal kicks of a few microradians which lead to residual betatron oscillations. Therefore, the study of the stored beam stability began with the localization of the magnetic center of the MIK.

To do so, the MIK was the only pulsed magnet triggered. Dedicated Libera Brillance Plus electronics have been commissioned and connected to BPMs located at large betatron functions amplitude, because the betatron oscillations were expected to be very small as soon as the stored beam would be aligned with the magnetic center of the MIK. I synchronized the BPMs on the injection like event such that the acquisition started a few microseconds before the MIK kick. Initially, a 15 mA beam was stored in the bare lattice, in the one quarter filling pattern (104 continuous bunches in the second quarter). This filling pattern enables to measure the residual perturbation experienced by each quarter, as further detailed in the following. It should be noted that the MIK is initially triggered as if new electrons were injected in this quarter, i.e. the quarter is centered on the MIK pulse. The corrected chromaticities were lowered to (ξ_x , ξ_z) = (0.6, 0.8) in order to avoid beam decoherence. The betatron tunes were $\nu_x = 18.156$ and

 $\nu_z = 10.228$. The main parameters of the experiment were identical to that set up for the measurements of the polarity and MIK field variations, and are gathered in table 5.7. I bumped the stored beam horizontally and vertically in the MIK section, within a few hundred micrometers range, at the micrometer precision, thanks to local static bumps performed with slow correctors located upstream and downstream the MIK section. I firstly scanned the MIK cham-Table 5.7: Main parameters of the experimental setup for the measurements of the polarity and MIK field variations with respect to the stored beam position in the MIK.

Parameter	Value
Betatron tunes ν_x / ν_z	18.156 / 10.228
Corrected chromaticities ξ_x / ξ_z	0.6 / 0.8
Filling pattern (average beam current mA)	One quarter (15)
Beam coupling	Minimum ($\ll 1\%$)
MIK voltage (kV)	10

ber by performing bump steps of $\pm 150 \,\mu$ m. As expected, according to figure 5.44, a horizontal bump of $-150 \,\mu$ m reduces the residual horizontal kick experienced by the stored beam. Consequently, its oscillation amplitude is almost lowered by a factor of 3 compared to the reference case with no bump. This is illustrated in figure 5.67. I also



Figure 5.67: Turn-by-turn variations of the horizontal position of the stored beam at a location characterized by $\beta_x = 13.3 \text{ m}$. The reference betatron oscillations (blue), averaged over ten acquisitions, were measured when the stored beam was not horizontally bumped in the MIK. As soon as the beam is bumped by $-150 \,\mu\text{m}$, the residual perturbation (green), averaged over ten acquisitions, is decreased.

measured the effect of the MIK on the three remaining quarters. To do so, I changed the MIK delay accordingly by steps of ± 295 ns, corresponding to a quarter length. Since the quarter was centered on the MIK pulse previously, the perturbations presented in figure 5.67 were expected to be maximum. The perturbations associated to each quarter are illustrated in figure 5.68. The residual betatron oscillations associated to the third and fourth quarters

158



Figure 5.68: Turn-by-turn variations of the horizontal position of the stored beam at a location characterized by $\beta_x = 13.3 \text{ m}$. The betatron oscillations, averaged over ten acquisitions, were measured when the stored beam was horizontally bumped in the MIK by $-150 \,\mu\text{m}$. the residual perturbations associated to the first, second, third and fourth quarter are plotted in blue, green, red and cyan respectively.

are as high as those of the second quarter. But most surprisingly, the first quarter is the most perturbed. This means the magnetic center of the MIK exhibits transient dipolar fields.

Following these observations, I found the horizontal positions in the MIK which minimize the perturbation associated to each quarter. I scanned the MIK chamber with smaller bump steps of $\pm 25 \,\mu$ m. In each case, the quarter is centered on the MIK pulse. The optimization began with the second quarter. In order to minimize the amplitude of the betatron oscillations, it was required to locally bump the stored beam horizontally in the MIK by an amount of $\Delta x = -200 \,\mu$ m. The turn-by-turn horizontal position of the stored beam, averaged over five measurements, is plotted in figure 5.69. In this configuration, no perturbation is detected. The bump heights required to minimize the perturbation for each quarter are provided in table 5.8. Table 5.8 shows that the magnetic center of the MIK Table 5.8: Heights of the horizontal bumps required to minimize the MIK perturbation for each quarter of the stored

Stored beam quarter	Bump height (µm)	Residual θ_x (µrad)
First	-300	≤ 1
Second	-200	≤ 0.3
Third	-175	≤ 0.3
Fourth	-200	≤ 0.3

beam. The residual horizontal kick is estimated in each case.

moves according to time, although it is almost fixed for the second, third and fourth quarters to within $\pm 25 \,\mu$ m. The lowest residual perturbation associated to each quarter is plotted in figure 5.70. These last measurements were to be performed to verify the ultimate performance of the MIK, although the gain for the beamlines is imperceptible.



Figure 5.69: Turn-by-turn variations of the horizontal position of the stored beam (second quarter centered on the MIK pulse) at a location characterized by $\beta_x = 13.3 \text{ m}$, in the case of a $-200 \,\mu\text{m}$ horizontal bump in the MIK. The signal, in blue, is averaged over five acquisitions. The error bars, in red, represent the enlarged uncertainty at 95% (Student coefficient equals 2.57).

Consequently, a $-200 \,\mu\text{m}$ bump can be defined in operation.



Figure 5.70: Turn-by-turn variations of the horizontal position of the stored beam at a location characterized by $\beta_x = 13.3 \text{ m}$. The betatron oscillations, averaged over ten acquisitions, were measured when the stored beam was horizontally bumped in the MIK according to table 5.8. In each case, the selected quarter is centered on the MIK pulse. The residual perturbation associated to the first, second, third and fourth quarter are plotted in blue, green, red and cyan respectively.

On the other hand, the turn-by-turn vertical position exhibits strong perturbations reaching almost 40 µm peak.

This is illustrated in figure 5.71. It was not possible to minimize this vertical perturbation by means of vertical or horizontal local bumps, or even combination of both (in the case of bump heights on the order of a few hundred micrometers). This perturbation affects all the quarters equally (it was verified with the BPMs and the KALYPSO camera). As mentioned in section 4.4.3.2, the possibly tiny misalignments of the conductors may result in such a systematic residual dipolar kick. The fitting of the simulated betatron oscillations on these measurements led to an estimated residual kick equal to approximately $5 \mu rad$. An active correction method has been developed and tested to cancel this perturbation as further detailed in the following.



Figure 5.71: Turn-by-turn variations of the vertical position of the stored beam (second quarter centered on the MIK pulse) at a location characterized by $\beta_z = 8.6 \text{ m}$, in the case of a $-200 \,\mu\text{m}$ horizontal bump in the MIK. The signal, in blue, is averaged over five acquisitions. The error bars, in red, represent the enlarged uncertainty at 95% (Student coefficient equals 2.57).

Correction of the vertical distortion A vertical pulsed kicker (KVCBA) was installed in the injection section around the year 2010 (see figure 4.15). Its power supply was removed a few years later because it had never been necessary to use this magnet, neither during the commissioning of SOLEIL nor in operation. However, the corrector remained in the injection section and was requisitioned to demonstrate the feasibility of an active correction of the vertical distortion illustrated in figure 5.71. This corrector has been connected to a specific pulser made in house by the Pulsed Magnet and Power Supply group of SOLEIL. This solution was developed only as a proof of concept in a short period of time, because of schedule constraints. Thus, the pulser delivers a 1 μ s long pulse with a plateau of approximately 300 ns, corresponding to one quarter duration. It can provide a vertical kick in the 2 μ rad to 12 μ rad range, which is needed to correct the vertical distortion. The corrector was commissioned successfully in April 2022, exhibiting a perfectly linear kick variation with respect to the supplied voltage, even at very small amplitude. The

main parameters of the corrector are provided in table 5.9.

Table 5.9: Main parameters of the vertical corrector developed to implement the active correction to use together with the MIK.

Parameter	Value
Beta functions (β_x (m) / β_z (m))	13.4 / 10.1
Phase advance (from injection point) (rad)	0.229 / 0.330
Pulse duration (µs)	1
Pulse plateau (ns)	300
Vertical kick range (µrad)	2 to 12

I characterized the correction in the one quarter filling mode due to the short kick duration. Initially, the experimental configuration was identical to that presented in the previous section (summarized in table 5.7). I detailed the principle of the active correction in section 5.3.1.3, as well as the way to setup the required correction strength and phase advance between the corrector and the MIK to cancel its perturbation. When the MIK kicks the beam vertically the corrector has then to kick it as well during the same turn. Thus, the delay of the corrector was optimized. During the experiment, I additionally increased the vertical tune to the value I found during my simulation studies, which was expected to perfectly cancel the perturbation (see figure 5.36). However, the correction was not perfect although the perturbation was already divided by a factor 6, as illustrated in figure 5.72. Therefore, I scanned the vertical tune to find the perfect match which resulted in a complete correction of the perturbation. In particular, such a correction is possible thanks to the high reproducibility of the MIK and corrector. In the end, the corrector has to provide a 4 µrad vertical kick when $\nu_z = 0.374$ for the perturbation to vanish. The optimization of the correction with respect to the vertical tune is illustrated in fig 5.72.

In the context of schedule constraints, the alignment of the magnet was not verified before the stored beambased measurements. I found that the corrector has a small rolling angle, and kicks the beam horizontally. This horizontal kick cannot be detected regarding the precision of the BPMs at 15 mA. This is illustrated in figure 5.73. Fortunately, the horizontal kick reduces the residual horizontal perturbations measured when there is no static bump to align the stored beam with the magnetic center of the MIK. This was measured using the KALYPSO camera and is presented in the following.

The proposed solution to correct the residual vertical kick of the MIK has proven to be efficient in the one quarter filling pattern as no perturbation can be detected with the Libera Brillance Plus electronics, neither vertically nor horizontally. The improvements on the stored beam stability are presented in figures 5.74 and 5.75, illustrating turn-by-turn measurements recorded thanks to the Libera Brillance Plus electronics. The residual horizontal and vertical betatron oscillations in the case of the MIK used together with the active correction are below the resolution threshold of the BPM (5μ m-RMS, at 15 mA). In the horizontal plane, the oscillation amplitude is almost divided by a factor 100 using the MIK instead of the kickers. On the other hand, the vertical oscillation amplitude is divided by more than a factor 10.



Figure 5.72: Turn-by-turn variations of the vertical position of the stored beam at a location characterized by $\beta_z = 12.1 \text{ m}$. The MIK perturbs the beam which exhibits large betatron oscillations without correction, for $\nu_z = 0.334$ (blue). When the corrector is switched on, the amplitude of the betatron oscillations are divided by a factor 6 (green). The correction is perfect for $\nu_z = 0.374$ (red).



Figure 5.73: Turn-by-turn variations of the horizontal position of the stored beam at a location characterized by $\beta_x = 15.0$ m.

I also confirmed the benefits of such an active correction thanks to the KALYPSO camera (see section 4.6.3.2). New electrons were injected uniformly in the 104 bunches in order to increase the photon flux in its sensor, the extraction mirror of the diagnostic beamline being set in slit mode (see section 4.6.3). The average current intensity was increased to 100 mA. At such a current intensity, it was necessary to turn on the bunch-by-bunch transverse



Figure 5.74: Residual horizontal betatron oscillations due to the four kickers (blue), the MIK (green) and the MIK together with the active vertical correction (red). The BPM is installed where $\beta_x = 13.3$ m.



Figure 5.75: Residual vertical betatron oscillations due to the four kickers (blue), the MIK (green) and the MIK along with the active vertical correction (red). The BPM is installed where $\beta_z = 8.6$ m.

feedback to avoid beam blow up. The transverse feedback implements a dipolar correction. Nevertheless, it does not minimize significantly the maximum amplitude of the perturbation but rather drastically reduces the damping time. In this configuration, it is possible to plot variations of the beam position in the micrometer range, after image processing. The main parameters of the experimental setup to perform measurements using KALYPSO are provided in table 5.10.

Table 5.10: Main parameters of the experimental setup to measure the variations of the transverse beam position and size with the KALYPSO camera.

Parameter	Value
Betatron tunes (ν_x / ν_z)	18.156 / 10.228
Tunes w/ active corr. (ν_x / ν_z)	18.156 / 10.374
Corrected chromaticities (ξ_x / ξ_z)	0.6 / 0.8
Filling pattern (average beam current mA)	One quarter (100)
Beam coupling	Nominal (1%)
MIK voltage (kV)	10
Horizontal bump in the MIK (μ m)	$0\mu{ m m}$
FBT	Switched On

The design of KALYPSO's sensor implies to measure the transverse beam parameter in one plane at a time (see section 4.6.3). The spatial resolution being essential for our studies, it has been decided to measure the twin signals in the vertical plane, as discussed in section 4.6.3. Several raw images are given in figure 5.76 and 5.77. The MIK is synchronized to fake an injection in the second quarter and the storage ring is set at the nominal coupling of 1%. In each figure, the left image is the reference case, the central image corresponds to the working point (ν_x , ν_z) = (0.156, 0.374) without the vertical corrector and the right image corresponds to the same working point including the

vertical corrector. The abscissa axis gives the turn number while the ordinate axis indicates the pixel enlightened. The raw images are color-mapped and become darker with the distance from the centroid of the beam. Thus, each vertical slice contains the information of the beam size and the position of the beam centroid, giving the turn-by-turn variations of these parameters. Considering the reference case, the camera is able to detect very weak residual



Figure 5.76: Raw images of the turn-by-turn stored beam horizontal position and size captured with the KALYPSO camera (the white vertical line helps to distinguish small perturbations due to the triggering of the MIK). The left image is the reference case, the middle and right images correspond respectively to the case where $\nu_z = 0.374$ with and without the active correction.

betatron oscillations in the horizontal plane. They become imperceptible in the two other configurations. This is what is expected since the stored beam is not aligned with the magnetic center of the MIK but the vertical corrector presents an unwanted roll angle, although favorable in our particular case. As mentioned above, two twin signals are



Figure 5.77: Raw images of the turn-by-turn stored beam vertical position and size captured with the KALYPSO camera (the white vertical lines help to distinguish small perturbations due to the triggering of the MIK). The left image is the reference case, the middle and right images correspond respectively to the case where $\nu_z = 0.374$ with and without the active correction.

detected in the vertical plane. Besides, the residual betatron oscillations are easily identified as long as the vertical corrector is turned off (left and central images of figure 5.78). The camera was calibrated such that the stored beam positions and transverse sizes, converted from pixels to micrometers, could be estimated at the source point. Thus, the perfect compensation of the residual vertical perturbation was confirmed, as illustrated in figure 5.78. Moreover,



Figure 5.78: Variations of the vertical position of the stored beam due to a single triggering of the MIK, in the one quarter filling patter (100 mA), when the active correction is off (blue) and on (red). This figure illustrates two processed KALYPSO images. At the source point $\beta_z = 11.4 \text{ m}$ for $\nu_z = 10.228$ (blue) and 10.4 m for $\nu_z = 10.374$ (red).

residual horizontal betatron oscillations with peak amplitude of approximately $5 \,\mu m$ have been observed when the corrector is turned off. Fortunately, we saw that the active correction reduces the residual horizontal perturbations down to approximately $1 \,\mu m$. This is illustrated in figure 5.79. Last but not least, the active correction does not worsen the injection efficiency in the bare lattice which remained unchanged at 85% maximum.

In addition to the stored beam transverse positions, the transverse beam size variations were also measured with the KALYPSO camera.

Beam size variations As mentioned in section 4.4.3.1, a transient quadrupolar field is induced in the field free region of the MIK due to the eddy currents circulating in the titanium coating of the vacuum chamber, when the pulse rises and falls. The quadrupolar field is responsible for horizontal transient beam size variations as further detailed in the following. Since the filled quarter is centered on the MIK pulse when the injection is triggered ($t = 1.2 \,\mu$ s in figure 4.32 and 4.33), the stored beam interacts with the strongest gradient strength when the pulse falls, i.e. when the beam passes through the MIK a second time after the triggering (see figure 4.32 and 4.33). The setup configuration is identical to that presented previously, and summarized in table 5.10, since the transverse



Figure 5.79: Variations of the horizontal position of the stored beam due to a single triggering of the MIK, in the one quarter filling patter (100 mA), when the active correction is off (blue) and on (red). The slow varying modulation corresponds to synchrotron oscillations. This figure illustrates two processed KALYPSO images. At the source point $\beta_x = 1.3$ m for $\nu_z = 10.228$ (blue) and 1.5 m for $\nu_z = 10.374$ (red).

positions and sizes of the beam are recorded simultaneously with the camera. The variations of the RMS horizontal stored beam size reach a maximum of approximately $3 \,\mu m$, meaning 3.5% of the theoretical RMS horizontal stored beam size (the theoretical value provided by the AT model at source point is $\sigma_x = 84 \,\mu\text{m}$). Since the stored beam was positioned at $x = 200 \,\mu m$ from the magnetic center of the MIK (no horizontal bump generated in the MIK section the measurements), it experienced an extra dipolar kick (see figure 4.32). Although the extra dipolar kick is almost uniform over 104 bunches of the beam, it may have add apparent beam size variations. This means that the perturbation measured is an upper bound. Besides, I verified that the active correction has no effect on the guadrupolar perturbation. This is illustrated in figure 5.80. The same measurement was performed using the kickers (see figure 5.81). The kickers are not supposed to trigger beam size variations ideally, although the bunches sample various residual kicks during each injection which results in apparent beam size growth. However, it appears that the perturbation may not be reduced to a simple apparent beam size growth due to horizontal offsets of the bunches, because the transverse feedback would have damped the perturbation as fast as in figure 5.79. Further investigations are in progress, especially spectral analysis since the horizontal beam size perturbation is known to oscillate at $2\nu_x$ (here ν_x denotes the fractional part of the tune), whereas it is ν_x in the case of horizontal position perturbations. The perturbation induced by the kickers is roughly 5 times that induced by the MIK. I repeated theses measurements to characterize the beam size variations induced by the MIK and the kickers in the vertical plane. Considering the MIK case, although it is impossible to estimate the RMS vertical stored beam size accurately due to inherent limitations in the setup (see section 4.6.3.2), it is possible to state that its variations should be little (even



Figure 5.80: Variations of the RMS horizontal stored beam size due to the MIK, in the one quarter filling pattern (100 mA). The peak variation is lower than 3.5% of the RMS horizontal stored beam size. At the source point $\beta_x = 1.3$ m for $\nu_z = 10.228$ (blue) and 1.5 m for $\nu_z = 10.374$ (red).



Figure 5.81: Variations of the RMS horizontal stored beam size due to the kickers, in the one quarter filling pattern (100 mA). The peak variation equals 20% of the RMS horizontal stored beam size. At the source point $\beta_x = 1.3$ m for $\nu_z = 10.228$.

zero ideally). This is expected because the horizontal component of the magnetic field B_x does not exhibit any transient quadrupolar field. Figure 5.82 shows that, without the active correction, the KALYPSO camera measured a beam size perturbation. The perturbation is probably due to the slightly different kicks sampled by each bunch of the beam through the MIK, which results in as many vertical position offsets equivalent to a beam blow up regarding the exposure time of the KALYPSO camera. The difference between the various kick strengths seems to be rather small since the apparent beam size variation is only $5 \,\mu\text{m}$ maximum. The perturbation is most likely damped in 100 turns by the transverse feedback, in agreement with the damping time illustrated in figure 5.78. Besides, it is canceled by the active correction. The same analysis stands for the kicker perturbation which has a similar profile in figure 5.83 (the corrector was unused in the kicker case). I performed the same measurements for each quarter. In the same manner presented for the magnetic center investigations, I delayed the triggering of the MIK in order to measure its effect when the injection like event is synchronized with the third, fourth and first quarters. The horizontal size perturbation is similar for the other quarters because they experience the quadrupolar kicks either on the rise or fall of the MIK pulse.

5.3.2.5 Beam induced heating

Overview After its installation in the storage ring, the MIK exhibited abnormal temperature increases. This section describes the temperature measured, the solution applied to decrease the temperature level to an acceptable value compatible with all the filling patterns. As describe hereafter such heatings were not expected, as the MIK team was aware of this challenge ahead of time and thought that the subject had been well answered with appropriate


Figure 5.82: Variations of the apparent vertical stored beam size due to the MIK (blue). The perturbation is due to the slightly different kicks experienced by each bunch of the beam which results in as many vertical position offsets equivalent to a beam blow up regarding the exposure time of the KALYPSO camera. The perturbation is damped in 100 turns by the transverse feed back. The apparent beam blow up is canceled by the active correction (red). At the source point $\beta_z = 11.4 \text{ m}$ for $\nu_z = 10.228$ (blue) and 10.4 m for $\nu_z = 10.374$ (red).



Figure 5.83: Variations of the apparent vertical stored beam size due to the kickers. The perturbation is due to the slightly different kicks experienced by each bunch of the beam which results in as many vertical position offsets equivalent to a beam blow up regarding the exposure time of the KALYPSO camera. The perturbation is damped in 100 turns by the transverse feed back. At the source point $\beta_z = 11.4$ m for $\nu_z = 10.228$.

cooling system (see section 4.4.2). This experience gave us the opportunity to deepen our knowledge on heating dissipation in the chamber of the MIK and its surroundings.

History Indeed, prior to the installation of the MIK in the storage ring, several impedance calculations were performed, as reported in [7]. At that time, the longitudinal impedance of the MIK had been calculated, neglecting the geometric impedance contribution with respect to the resistive wall contribution because of the uniform shape of the vacuum chamber. It was demonstrated that the titanium coating of $3.5 \,\mu\text{m}$ shields the beam from the sapphire body of the vacuum chamber. The heat load was estimated to be approximately $156 \,\text{W}$, and the maximum power density $3.6 \,\text{Wmm}^{-2}$ in the center of the vacuum chamber, in the 8 bunch filling mode at $110 \,\text{mA}$, for a homogeneous and amorphous modeled titanium coating. These were peak values, all filling modes combined, and since the estimated power density was negligible with respect to that coming from the surrounding synchrotron radiations it was decided not to perform thermal simulations. In addition, the power densities associated to two resonant modes, trapped in the tiny cavity formed by the RF fingers which provide the RF contact in the flanges of the MIK, had been characterized. According to these studies, they were not an issue whether it be from the heat load or coupled bunch instabilities point of view.

During the first ramp to the nominal stored current of 500 mA in January 23rd, 2021, the thermo-couples fixed to the MIK chamber revealed an unexpected temperature rise on the downstream end of the MIK. At 300 mA the

maximum measured temperature was already of 130 °C. The MIK outer frame was removed and two ceramic heat sinks were installed on the vacuum chamber. However, the heat sinks were eventually removed because they were not effective. Hopefully, the heat dissipation has rapidly been improved thanks to three extra heavy duty forced air turbines which increase the air flow around the chamber. A picture of the improved cooling system is provided in figure 5.84. This provides a manageable temperature rise while reaching the nominal current in any



Figure 5.84: Improved cooling system for the MIK. To increase the air flow around the chamber, three extra heavy duty forced air turbines were installed following the unexpected temperature rise during the first ramp to the nominal stored current of 500 mA in January 23rd, 2021.

operational mode. Still, using this setup, a significant temperature imbalance was found between upstream and downstream ends of the MIK. It was detected firstly using a thermal camera (see figures 5.85 and 5.86). Besides, five thermocouples and four additional temperature sensors, installed on the MIK body and its flanges, confirmed the asymmetry between the temperatures of the upstream and downstream part of the vacuum chamber. These sensors are used in daily operation to monitor the temperature in the MIK section, as new interlock thresholds were



Figure 5.85: Picture of the downstream end of the MIK section recorded with a thermal camera (no stored beam). The maximum temperature is measured just before the MIK flange and reaches 58.6 °C (higher than that of the upstream end of the MIK section).



Figure 5.86: Picture of the upstream end of the MIK section recorded with a thermal camera (no stored beam). The maximum temperature is measured just before the MIK flange and reaches 44.1 °C (lower than that of the downstream end of the MIK section).

defined. Later on, dedicated machine studies further concluded the heat load does not vary linearly with respect to the stored current, ruling out synchrotron radiation as a contributor to this unexpected heating. In addition, temperatures were recorded without the fans.

In the mean time, thermal simulations were launched by a subcontractor (Avantis Concept [121]) to give complementary information about the temperature map and the possibly poor electrical contact between the exit of the MIK and CF[™]flange which was thought to be one of the reasons of the temperature rise in the downstream part of the vaccum chamber. The thermomechanical simulations were performed thanks to the Finite Element Analysis approach using ANSYS software. Re-scaled 3D maps of the dissipated power, based on the deposited power estimated relatively to specific beam parameters and the previous impedance computations, were used as inputs to the ANSYS model. The simulations showed that the temperature maps associated to the resistive wall impedance are quite uniform, as the temperature variations along the vacuum chamber are on the order of a few percent. In this context, the temperatures measured for various filling modes, with or without fans, are compared to the corresponding maximum temperature simulated of the MIK body. The results are gathered in table 5.11, taken from [7]. The four and five measured temperatures, recorded at the upstream and downstream part of the vacuum chamber respectively, range between the extrema values given in the fourth and fifth column of table 5.11.

The simulated temperatures are in good agreement with the temperatures measured at the upstream end of the MIK body, all filling modes combined and regardless of the configuration of the fans. The same method was also used to estimate the temperature rise in the flanges. Only two cases could be modeled: with perfect RF contact between the RF fingers or not. In the latter case, the temperature rise would be way too large for it to be realistic. In the other case, the temperature rise would not be an issue as the deposited power is lower than 5 W.

Current	Filling mode	Fans	Simulations	Measurements (upstream)	Measurements (downstream)
$500\mathrm{mA}$	Uniform (416 bunches)	On	61 ° C	52°C to 69°C	86°C to 125°C
$500\mathrm{mA}$	Uniform (416 bunches)	Off	335 °C		
$110\mathrm{mA}$	8 bunches	On	72 ° C	64°C to 74°C	113°C to 164°C
$110\mathrm{mA}$	8 bunches	Off	425 °C		
$100\mathrm{mA}$	1/4 (104 bunches)	Off	72 ° C	69°C to 72°C	85°C to 86°C
$25\mathrm{mA}$	2 bunches	Off	107°C	$103^{\rm o}{\rm C}$ to $112^{\rm o}{\rm C}$	$136^\circ\mathrm{C}$ to $138^\circ\mathrm{C}$

Table 5.11: Comparison between the simulated and	d measured temperatures of the MIK chamber.
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Actually, the temperatures measured on the downstream flange are lower than those measured at the downstream end of the MIK which indicates that the heating source is located on the MIK side rather than in its flange. That is why tiny defects in the titanium coating are thought to be more probably responsible for the temperature rise. Eventually, simulations were performed in the case of a perfect thermal contact between the MIK and its flanges. As expected, a part of the heat, that is assumed to come from the defects of the coating, is transferred to the downstream flange. The simulated temperatures of the flange are in agreement with the measurements but the estimated temperatures of the MIK are lower than the measurements then. This might mean that the resistivity of the coating is underestimated and that the modeling of the thermal contact should be improved. Similar results were found with CST Conjugate Heat Transfer simulations. The MIK is foreseen to be disassembled in the future to have better insight of what caused the anomalous temperature rise.

5.4 Beamline measurements

During my PhD, I had the opportunity to conduct experimental studies in collaboration with several beamlines of SOLEIL. In the following, the experiments and their outcomes are detailed.

5.4.1 Perturbations recorded with an infrared beamline

I conducted dedicated experiments at SOLEIL with the infrared beamlines AILES (Advanced Infrared Beamline Exploited for Spectroscopy) and SMIS (Spectroscopy and Microscopy in Infrared using Synchrotron) [11], on July 12th, 2021, although SMIS faced technical issues that day. AILES is provided with a photon beam produced by a 1.7 T dipole magnet. The standard dipole apertures were enlarged in order to benefit from a photon source with an angular aperture of 80 mrad horizontally and 20 mrad vertically. This makes AILES particularly well suited for the extraction of photon beam from 1 meV (far infrared/THz) to 400 meV (mid-infrared). A detailed description of the beamline is available at [12, 122]. AILES uses a Michelson interferometer to record interferograms which are Fourier transformed in order to get the corresponding spectrograms for users' needs.

Due to fast acquisition measurements, AILES is able to detect the stored beam perturbations induced by the

injection process. A first set of measurements was recorded in uniform filling mode at 500 mA, in the bare lattice ($\nu_x = 0.155$ and $\nu_z = 0.210$ while $\xi_x = 1.25$ and $\xi_z = 2.65$). I tested various configurations in order to characterize the different sources of the stored beam perturbations.

To begin with, figure 5.87 provides two typical interferograms that highlight the performance of the MIK compared to the kickers. The kickers and the MIK were the only injection magnets that I triggered to record a large number of perturbations. It should be noted that the active vertical correction was not commissioned at that time, and the stored beam was not bumped in the MIK section. In this configuration, the MIK perturbations were expected to be maximized. The perturbations induced by the kickers can be easily identified thanks to their specific peak. The



Figure 5.87: Two interferograms recorded with the infrared beamline AILES in the case of the kickers (blue) and MIK (dark red) triggering. The storage ring is operated in uniform filling pattern (500 mA). The triggering of the kickers can be identified by the resulting perturbations which have characteristic peaks contrary to the MIK.

interferogram of figure 5.87 do not show any peak in the case of the MIK. However, the MIK triggering was expected to generate measurable oscillations because the stored beam was kicked horizontally and vertically, as noted. Even in this worst case, the MIK showed promising early results.

I repeated the measurements in the standard top-up mode using the MIK. The processed and averaged perturbations recorded by AILES due to the kicker and MIK injections are compared in figure 5.88. These perturbations are obtained after some data processing. I let the users of AILES set up the beamline conveniently before the experiments, but I processed and analyzed all the recorded interferograms. Each interferogram last around 10 min and consequently contains several signature signals similar to those of figure 5.88. The first step consists in localizing these signature signals in order to extract them from the interferogram. Then, I filtered a slow modulating signal from each raw data. Eventually, I averaged five signature signals in each case to get the damped oscillations plotted in figure 5.88. These perturbations are very reproducible. The first peak of the kicker perturbation is indeed specific



Figure 5.88: Perturbations of the standard top-up injection (blue) and the MIK top-up injection (red) in interferograms recorded with the infrared beamline AILES. Each perturbation is averaged over five acquisitions. The storage ring is operated in uniform filling pattern (500 mA) and the injection set in long pulse mode (booster beam of 104 continuous bunches equivalent to 295 ns. The charge per injection equals 4.5 nC), corresponding to a 2.5 mA step per injection.

to the kicker magnets as it has never been observed in the case of the MIK injections. It is as long as the theoretical duration of the kicker pulse(7 µs). Even if the amplitude of the kicker signal is greater than that of the MIK a few milliseconds after the perturbation rise, it appears that both injection schemes trigger a damped oscillation, lasting roughly 7 ms, whose frequency equals 2.1 kHz. It is twice lower than the synchrotron frequency. Investigations are still underway to determine to which property of the electron beam this oscillation could be linked in terms of frequency and damping time.

I also characterized the effect of the injected beam on the measurements. To do so, the standard injection was triggered in the most common mode of top-up operation at SOLEIL. In this case, the injection was set to the standard long pulse mode, providing booster beams of 104 continuous bunches, corresponding to approximately 4.5 nC (equivalent to a 2.5 mA step per injection). Figure 5.89 provides the perturbation corresponding to this top-up mode along with the perturbations due to the kickers together with the septum magnets (without injecting), and the kickers alone. These perturbations were first processed as mentioned previously. All the perturbations oscillate at 2.1 kHz and are damped in a few milliseconds. According to figure 5.89, the perturbation amplitude is amplified by



Figure 5.89: Perturbations in interferograms recorded with the infrared beamline AILES, in the case of the most common mode of top-up injection at SOLEIL (blue), the kickers together with the septum magnets but without injecting (green) and the kickers alone (red). Five signature signals were processed and averaged to provide these typical perturbations. The storage ring is operated in uniform filling pattern (500 mA) and the injection set in long pulse mode (booster beam of 104 continuous bunches equivalent to 295 ns. The charge per injection equals 4.5 nC), corresponding to a 2.5 mA step per injection.

the injected beam. Conversely, the septum magnets seem to have no significant effect. Further measurements performed in the short pulse (70 bunches injected providing 1 nC) and alpha modes (104 bunches providing 0.6 nC) indicate the perturbation amplitude also decreases with the injected charge.

Eventually, I characterized the perturbation induced by the septum magnets. Their effect was recorded and found to be barely measurable, with the perturbation just exceeding the noise level, as it is depicted in figure 5.90. The septum magnets were the only injection magnets that I triggered in this case. Actually, the perturbations illustrated in figure 5.90 are deemed to be due to the thick septum magnet only, as the thin septum magnet has not disturbed the stored beam for several years (see section 4.3.2.3). The perturbation plotted is the average perturbation over eight acquisitions. It also oscillates at 2.1 kHz and is damped in approximately 10 ms.

These first promising results, which were obtained before the development of the active correction, led us to push the experiments further. We tried to repeat these measurements, during another dedicated experiment session, in the case of the most stable setup achievable using the MIK, including the last improvements in terms of stored beam stability (see figures 5.74, 5.75, 5.78 and 5.79). To do so, only one quarter of the storage ring was fully filled with 104 bunches, such that the average current intensity in the bare was set up to 150 mA. The stored beam was horizontally bumped in the MIK section by $\Delta x = -200 \,\mu\text{m}$ in order to be aligned with the magnetic center of the MIK. The active correction was turned on additionally. The tunes were adjusted accordingly, $\nu_x = 0.156$ and $\nu_z = 0.374$, and the chromaticities initially set to $\xi_x = 0.6$ and $\xi_z = 0.8$. Unlike the former session, two other



Figure 5.90: Perturbations of the septum magnets in an interferogram recorded with the infrared beamline AILES. Eight signature signals were processed and averaged to provide the typical perturbation plotted. The storage ring is operated in uniform filling pattern (500 mA).

beamlines were also acquiring data in addition to AILES. These beamlines were DEIMOS (Dichroism Experimental Installation for Magneto-Optical Spectroscopy), extracting photons produced thanks to an in-air undulator in the 350 eV-2.5 keV range (soft X-rays), and PROXIMA-1, extracting photons produced thanks to an in-vacuum undulator in the 6 keV-15 keV range (hard X-rays). Technical descriptions of the beamlines can be found at [13] and [14] respectively. Unfortunately, the preliminary tests performed with AILES revealed a poor signal over noise ratio. Further investigations confirmed an unexpected white noise affecting the stored beam, despite various attempts to minimize it. The data recorded by AILES were unusable consequently. Besides, the data recorded by DEIMOS did not show any perturbations due to the standard or MIK injection schemes. Eventually, the data recorded by PROXIMA-1 only confirmed that the MIK injection does not perturb the photon beam more than the standard injection, such that the MIK is deemed compatible with operation according to this beamline. Further investigations could be carried in collaboration with the beamline ODE (Optique Dispersive EXAFS for Dispersive Optics EXAFS [123]) which, like AILES, is able to measure fast perturbations on the photon beam.

Chapter 6

Conclusion

My PhD was part of a worldwide effort to achieve transparent injection into storage ring-based synchrotron light sources. Several facilities have considered single magnet-based injection schemes, relying on a fast non-linear kicker, as a way to reach this goal. Many innovative injection magnets have been designed since the first studies pioneered by KEK-PF between 2007 and 2010 (see figure 6.1). In the wake of this global effort over the past



Figure 6.1: Chronology of research and development of single non-linear kicker-based injection schemes for transparent injection into storage ring-based synchrotron light sources.

decade, a MIK was successfully commissioned at SOLEIL in 2021. Several beamline experiments have been conducted during my PhD. Some beamlines have reported that the MIK performance are at least as good as the standard bump-based injection scheme in terms of stored beam perturbations. Better yet, the infrared beamline AILES reported promising improvements. Based on these results, the MIK may be the milestone of an innovative off-axis injection scheme compatible with top-up operation.

To reach such a stage in the MIK project, many developments have been made preceding my PhD. Firstly, the Power Supplies and Pulsed Magnets group of SOLEIL developed the MIK based on the non-linear magnet design proposed by BESSY. Later on, refine design studies were conducted during the collaboration with the 4th generation

synchrotron light source MAX IV, between 2012 and 2017. These studies led to the successful commissioning of the first MIK in the MAX IV storage ring, in 2017. Although the MIK worked satisfactorily in terms of injection efficiency and transparency, a second SOLEIL built MIK has been commissioned successfully in 2019 to prevent temperature rise incompatible with the operation of MAX IV. Impedance simulations have been made to address the titanium coating challenges, responsible for the temperature rise. In the light of this work and the feedback of MAX IV, the thickness of the uniform titanium layer coated inside the MIK chamber has been increased from 0.8 µm to 3.5 µm. It provides an optimal balance between the heat load deposited in the MIK and the intensity of the Eddy current-induced transient quadrupolar fields which perturb the stored beam size. The feedback from MAX IV was used as a springboard to complete the MIK project at SOLEIL. In particular, single particle tracking simulations proved the feasibility of the SOLEIL storage ring, 32 m downstream the injection point. Eventually, it has been verified that the reduction of the beam lifetime due to the narrow physical apertures of the MIK chamber was compatible with daily operation. In this context, the MIK project was validated for SOLEIL and my PhD started from there.

I began by improving the non-linear lattice modeled with AT, replacing the thin sextupoles by thick ones. It was known that the injected beam would perform horizontal betatron oscillations with amplitude on the order of 25 mm, such that I also included the multipolar fields of all the electromagnets modeled in order to take into account a large range of non-linear effects at large amplitude. I also updated the physical apertures of the storage ring especially in the MIK section because it was expected to be a preferential loss area, both from the injection and decay losses point of view. At that time, I had to find the injection setting that would minimize the injection loss rate. To do so, I performed 6D tracking simulations of Gaussian bunch beams in the perfectly aligned bare lattice, using AT. I optimized the coupling and the horizontal position of the injected beam (see figure 6.2). Given the horizontal injection position of the injected beam, the code computes the horizontal injection angle required to reach the target position $x_{target} = 10.3 \text{ mm}$ in the MIK. This target position is different from that of MAX IV which is around -4 mm. Conversely to MAX IV where the injected beam is extracted from a linac providing small natural emittance, the injected beam of SOLEIL is extracted from a booster ring providing natural emittance on the order of 140 nm rad. In this context, it is necessary to reach a target position in the MIK where the field gradient is minimum in order to maximize the injection efficiency. According to the optics functions at the MIK location, the injection invariant is minimized when the horizontal deviation of the injected beam at x_{target} is canceled by the MIK. In this configuration, the horizontal MIK kick was estimated to be 2.2 mrad, corresponding to a nominal supplying voltage of 10 kV. In parallel to these tracking simulations, I made Touschek beam lifetime computations with respect to the position of the thin septum blade using TRACY III. Combining the results from the AT and TRACY simulations, I found that the blade of the thin septum magnet had to be inserted at x = -17.5 mm, knowing that it is fixed to x = -19.5 mm in operation, and that a booster beam coupling of 20% was enough to reach roughly 100% injection efficiency. This configuration provides the highest injection efficiency for a preserved Touschek beam lifetime. Thus, I found a MIK injection set up



Figure 6.2: Simulated variations of the injection loss rate with respect to the booster beam coupling, in the case of various horizontal positions of the septum blade's inner face. In any case, a single 6D Gaussian bunch beam of 5×10^3 electrons was tracked during 10^3 turns in the bare lattice, excluding the superbend.

which has the same performance as the ideal standard injection scheme in terms of injection efficiency. Taking into account the reduction of the dynamic aperture due to the permanent magnet based 2.8 T superbend, the increase in the injection loss rate was found to be similar in the MIK and standard scheme cases, for a given booster beam coupling of 20%, reaching 8 to 9%. However, it revealed the MIK scheme is more sensible to the variations of the booster beam coupling than the standard injection scheme. In the MIK case, the injection loss rate clearly increases with the booster beam coupling, the electrons being mainly lost on the vertical physical apertures of $\pm 5 \text{ mm}$.

In the mean time, the different parts of the MIK were manufactured as well as the upstream and downstream taper-absorbers. The MIK was indeed primarily designed for the MAX IV storage ring, hence the need to adapt its physical aperture to that of the standard vacuum chamber of SOLEIL. The secondary taper-absorber has entirely been machined in a bulk of copper chrome zirconium alloy, including the two ConFlatTMflanges. These taper-absorbers, as well as the main ones, have performed very satisfactorily and the Engineering as well as Ultrahigh Vacuum and Cryogenics group of SOLEIL are considering more of these machined-in-one parts for SOLEIL II. When it comes to assembling the eight copper conductors, this is clearly one of the main challenges in manufacturing a MIK. The stringent alignment tolerances are $\pm 10 \,\mu$ m both horizontally and vertically, while the straightness tolerance equal $\pm 10 \,\mu$ rad. Obviously, meeting these tolerances supposes to machine the grooves of the sapphire chamber very precisely. However, the difficulty also lies in the fact that currently the conductors are glued by hands. In this context, the amount of glue that is deposited in the bottom of the grooves might have detrimental consequences if the thickness of the cured glue is too large. The issue of coating the chamber must not be neglected as well. During the first glue curing of the MIK, the sputtered titanium coating cracked, highlighting the brittleness of the

MIK. The assembly process had to be repeated from scratch with a spare chamber, which has not been damaged. While the commissioning of the MIK was coming, magnetic field measurements were performed. I compared the ideal simulated field with the measurements and found small discrepancies for the vertical component at x_{target} , the relative error being less than 3%. In addition, the vertical component of the field was close to zero in the field free region as expected. Conversely, the horizontal component showed significant discrepancies, preventing the center of the MIK from being truly free of any magnetic field. This has been later confirmed by stored beam based measurements, which revealed a vertical dipolar defect.

The MIK has been installed in the storage ring since December 21st, 2020. After Baking-out and vacuum conditioning of the MIK section, a major concern was encountered during the first ramp to 500 mA in the uniform filling pattern: an unexpected temperature rise was detected in the MIK. The peak temperature of the MIK reached 130 °C at 300 mA, which was not compatible with operation. The initial cooling system has been replaced by three heavy-duty forced air turbines that brought temperatures down to a level compatible with operation. Temperature simulation studies were then conducted and the simulated data was compared to the measurements performed in the case of various filling patterns and fans configurations. Although the simulations and the measurements match at the upstream end of the MIK, which is not the case for the opposite end, it was realized that the cooling system was undersized in any case. This temperature rise is thought to be caused by tiny defects in the titanium coating, because the temperature field exhibits a strong gradient between the upstream and downstream ends of the MIK and because the hottest spot is located inside the MIK chamber. At present, the temperature of the MIK is no longer a concern. Following the improvement of the cooling system, the actual commissioning could begin. Firstly, I measured the physical apertures of the MIK to the millimeter precision thanks to the BLMs and the scrapers and found no significant issues with the alignment of the chamber. Then, I probed the magnetic field of the MIK with the stored beam and foreseen a misalignment of a few hundreds of micrometers, while the relative field variations were in agreement with expectations. In addition, I verified the linearity of the MIK kick with respect to the supplied voltage, although the growth rate is a bit higher than expected: $11.5 \,\mu rad/kV$ instead of $8.5 \,\mu rad/kV$, at roughly $x = 2 \,\text{mm}$. These measurements proved the variations of the MIK kick with respect to time are very reproducible. It has also been verified that the MIK accumulates decay losses as expected. The inner horizontal scraper prevents the MIK from decay losses, and it has been inserted from the former nominal position of -28 mm to -21 mm. Following the commissioning of the the permanent-magnet based 2.8 T superbend the scraper has further been inserted to -20 mm. The resulting decrease in beam lifetime is compatible with operation as it ranges between 10 h and 11 h at 500 mA.

Following the preliminary studies, the first successful injection using the MIK was realized in April 5th 2021, the injection efficiency reaching almost 40%. I could store and accumulate electrons as well. From then on, I optimized the injection efficiency. The careful setup of the MIK injection enabled to reach a peak injection efficiency of 97% in the bare lattice during summer 2021, which is as good as the performance of the standard bump-based scheme.



Figure 6.3: Residual horizontal betatron oscillations due to the four kickers (blue), the MIK (green) and the MIK together with the active vertical correction (red). The BPM is installed where $\beta_x = 13.3$ m.



Figure 6.4: Residual vertical betatron oscillations due to the four kickers (blue), the MIK (green) and the MIK along with the active vertical correction (red). The BPM is installed where $\beta_z = 8.6$ m.

After the installation of the superbend, the injection efficiency reached a maximum of 85% in the MIK case and 80% in the standard case. These results were expected according to the simulation studies, which correctly spotted the preferential loss areas additionally. This was confirmed experimentally thanks to the newly commissioned BLMs which worked satisfactorily in turn-by-turn and decay mode. The MIK was validated after I conducted several set of loss map measurements with J.-B. Pruvost (Radiation Safety group), in various injection configurations.

In terms of stored beam perturbations, the Libera Brilliance Plus electronics was a well suited tool which clearly showed the MIK outperforms the four kickers in the horizontal plane. In this case, the residual perturbation is divided by a factor 100. It is of the order of a few micrometers without additional active correction, below 2% percent of the RMS horizontal size of the stored beam. Moreover, the residual vertical perturbation, specific to the MIK of SOLEIL, has been canceled thanks to a vertical active correction (see figures 6.3 and 6.4). The defect is assumed to be related to conductor misalignment, although it is not really possible to state this with certainty since it is impossible to act directly on the conductors during the experiments now that the MIK is assembled. The active correction is only a demonstrator that had to be implemented quickly to fit scheduling constraints. The active correction suppose a new working point configuration to perfectly compensate the residual MIK kick. Not only this compensation preserved the maximum injection efficiency achievable but it also improved the stored beam stability in the horizontal plane, as confirmed with the measurements performed with the ultra-fast camera KALYPSO (see figures 6.5 and 6.6). A new pulser may be developed in order to provide a larger corrector pulse and consequently extend this correction to the four quarters of the beam in the uniform filling pattern. Additionally, the correction configuration may be improved since I tested it in the case of $\nu_z = 10.374$, saying close to a third order resonance which is not convenient for the operation. In addition, the variations of the RMS horizontal size of the stored beam is held in the 3 μ m range



Figure 6.5: Variations of the horizontal position of the stored beam due to a single triggering of the MIK, in the one quarter filling patter (100 mA), when the active correction is off (blue) and on (red). The slow varying modulation corresponds to synchrotron oscillations. At the source point $\beta_x = 1.3$ m for $\nu_z = 10.228$ (blue) and 1.5 m for $\nu_z = 10.374$ (red).



Figure 6.6: Variations of the vertical position of the stored beam due to a single triggering of the MIK, in the one quarter filling patter (100 mA), when the active correction is off (blue) and on (red). At the source point $\beta_z = 11.4$ m for $\nu_z = 10.228$ (blue) and 10.4 m for $\nu_z = 10.374$ (red).

in the horizontal plane, i.e. roughly 3.5% of the horizontal stored beam size (see figure 6.7). Incidentally, the first



Figure 6.7: Variations of the RMS horizontal stored beam size due to the MIK, in the one quarter filling pattern (100 mA). The peak variation is lower than 3.5% of the RMS horizontal stored beam size. At the source point $\beta_x = 1.3$ m for $\nu_z = 10.228$ (blue) and 1.5 m for $\nu_z = 10.374$ (red).

experimental studies conducted with the infrared beamline AILES revealed first improvements in terms of injection transparency (see figure 6.8). These promising results, obtained while the MIK was not yet optimally adjusted, and

the active correction was not commissioned, led to complementary in-depth studies during summer 2022 that were conducted with other beamlines very sensitive to injection-induced perturbations. However, the data was not very informative this time. This could be related to an unexpectedly high noise level, detected thanks to the BPMs, and that could not be attenuated during the experiment.



Figure 6.8: Perturbations of the standard top-up injection (blue) and the MIK top-up injection (red) in interferograms recorded with the infrared beamline AILES. Each perturbation is averaged over five acquisitions. The storage ring is operated in uniform filling pattern (500 mA) and the injection set in long pulse mode (booster beam of 104 continuous bunches equivalent to 295 ns. The charge per injection equals 4.5 nC), corresponding to a 2.5 mA step per injection.

To conclude, it is the third time that a SOLEIL-built MIK is commissioned successfully. Additionally, it is the first time that such an innovative injection magnet is used, and meets the requirements for daily operation of a 4th generation storage ring-based synchrotron light source (MAX IV). For SOLEIL, all these achievements offer new perspectives. During a dedicated experiment session, the MIK injection has been tested in user configuration, i.e. with the IDs closed to typical gaps of operation. At that time, the storage ring was not optimally configured, as it was a quick test with no direct relation to the originally planned experiment. The injection efficiency was about 60% and there is no doubt that it would have been about the same as the standard injection with some optimization. The open question is related to the use of the MIK as the main injection magnet for daily operation. We list hereafter a list of steps in order to make it real. Firstly, we would like to implement and test an active correction which is adapted to the uniform filling pattern. To do so a new pulser must be designed and built. In addition, some simulation studies must be conducted in order to demonstrate the feasibility of a different kind of kick and cancel: the active correction presented in section 5.3.2.4 has been implemented in the bare lattice for $\nu_z = 10.374$, meaning close to a resonance which is potentially detrimental for operation or even incompatible. Therefore, the principle is to find another working point and to determine the number of turns that would be required to cancel the perturbation

with a sequence of convenient vertical kicks. Besides, the MIK injection must be validated experimentally by all the beamlines and the Radiation Safety group. This process is very long and is not considered as a strong priority at the moment, although it is not impossible that it will happen in the future. Moreover, it is of great interest to test off-momentum and longitudinal MIK injections, that will provide enlightening information for the future injection scheme of SOLEIL II. Marie-Agnès Tordeux has done preliminary simulations, in 2019, to study the performance of both injection schemes. It should be noted that these studies were done for the current lattice, prior to the installation of the superbend [124, 125, 126]. Today, as the technical design studies of SOLEIL II are in progress, lots of simulations are performed in the case of the upgrade lattice [127]. These advances are closely followed by the community of storage ring-based synchrotron light sources, as transparent top-up injection is an aspect that is as delicate as it is crucial for the operation of 4th generation facilities.

Appendix A

Off-momentum and longitudinal MIK injection schemes

Here are a few words about these non-standard MIK injections in the current storage ring. Concerning the offmomentum injection [126], the booster beam is shifted in energy at the booster extraction. It is then injected in the storage ring on the chromatic orbit with zero betatron oscillations. It is known that the non-linear horizontal dispersion at the MIK location varies more significantly for negative energy offset: to reach $x_{target} = 10 \text{ mm}$ the energy offset must be 4.3%, whereas it is only of -3.8% to reach $-x_{target}$. Moreover, such a positive offset leads to a beam loss because the beam path is beyond the 35 mm limit of the physical aperture in the first focusing quadrupole. Assuming an energy offset of -3.5% and letting the septum blade at x = -19.5 mm, the injection efficiency is equal to 89%due to the dynamics of the first 300 turns. If the septum blade is inserted 5 mm further, then the injection efficiency can reach 99%. The MIK kick was estimated to be $\theta_x = 1.6$ mrad. The injection efficiency might not be increased by matching the horizontal betatron function at the injection point, nor by adjusting the beam coupling. Eventually, the TL2 must be tuned to be compatible with the off-momentum booster beam. The longitudinal injection has been studied as well [126], assuming low horizontal dispersion function. In this case the beam is injected off-phase additionally. The energy offset is necessarily positive reaching 3.7%, to avoid injection losses, and the corresponding injection phase equals $-\pi$. In this case the kicker bump ($\Delta x = -18 \text{ mm}$) would be required additionally in order to avoid beam loss in the first focusing guadrupole whatever the position of the septum blade. The RF kick needed to steer the beam in the RF bucket is equivalent to a voltage offset $\Delta V = 2.1 \,\mathrm{MV}$. Knowing that the nominal voltage is already greater than 2 MV this injection scheme seems very challenging because the couplers of the RF cavities may not be well suited. Before they were changed a few years ago, the RF part of this injection scheme was tested successfully though. The simulations including the MIK predicted an injection efficiency of 99% with a MIK kick $\theta_x = 2.1 \text{ mrad.}$ The results are gathered in table A.1. These results are based on the work of Marie-Agnès Tordeux (Accelerator Physics group of SOLEIL).

Table A.1:	Main	simulation	results	of the	off-momentum	and	longitudinal	MIK	injection	schemes,	in the	current
storage ring	g.											

Parameter	Off-momentum	Longitudinal	Septum blade position (mm)
Energy offset (%)	-3.5	3.7	
Phase offset (rad)	0	$-\pi$	
RF voltage offset (MV)	0	2.1	
Kicker bump (mm)	0	-18	
x_{target} (mm)	-10	10	
Initial conditions (mm mrad)	(-27, 0.91)	(-27, 1.18)	-19.5
	(-22, 0.7)	-	-15
MIK kick (mand)	1.6	2.1	-19.5
MIR RICK (mrad)	1.2	-	-15
Injection officiency (07)	89	99	-19.5
injection enciency (%)	99	-	-15

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