




Coexistence of ferroelectricity and magnetism in the multiferroic compound BiFeO_3

-Delphine Lebeugle-

Supervisors : Dorothee Colson and Michel Viret

Strong correlated electrons oxides group, SPEC, CEA Saclay
Nanomagnetism group, SPEC, CEA Saclay

Collaboration with : UMR CNRS/THALES
LLB, CEA Saclay

- 
- I. Introduction to multiferroic materials
 - II. Synthesis and characterisation by X-ray and neutron diffraction
 - III. Ferroelectric properties of BiFeO_3 single crystals
 - IV. Magnetic properties of BiFeO_3
 - V. Magnetoelectric study of BiFeO_3 single crystals

Conclusions et perspectives





I. Introduction to multiferroic materials

II. Synthesis and characterisation by X-ray and neutron diffraction

III. Ferroelectric properties of BiFeO_3 single crystals

IV. Magnetic properties of BiFeO_3

V. Magnetoelectric study of BiFeO_3 single crystals

Conclusions et perspectives



I. Introduction on multiferroic materials

Definition : Materials which present at least 2 of the 4 properties :

Ferroelasticity, ferroelectricity, ferromagnetism, ferrotoroidicity

Coupling between the \neq variables

ex : coupling between ferroelectric and magnetic order parameters $\left\{ \begin{array}{l} \text{H influences } P_S \\ \text{E influences M} \end{array} \right.$

Review : First compounds ~1950

Few multiferroic materials (~60)

Perovskite-type structures **ex : $YMnO_3$, $BiFeO_3$...**

Interest : **Fundamental physics:**

- understanding the origin of the coupling
- studying physics of magnetic oxides + electric fields

Technological applications:

- bifunctional materials : spintronics + ferroelectric technology

☺ **Possibility of switching P_S by H (or M by E)**

I. Introduction on multiferroic materials

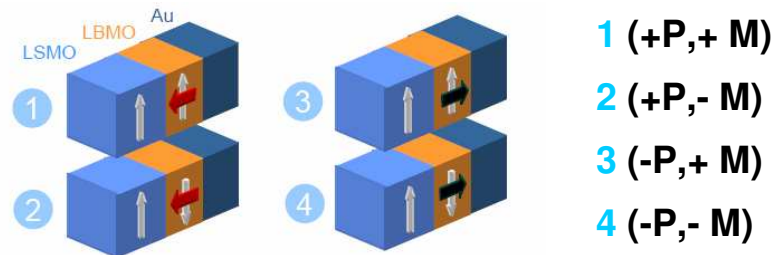
Technological applications

Technological advances : - transducers, sensors

- spintronics (spin-filter, spin-transistor)

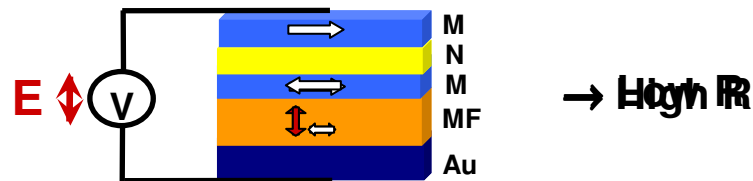
- information storage technology (FeRAM and MRAM)

→ encoding information in a single multiferroic bit : 4 states memory :



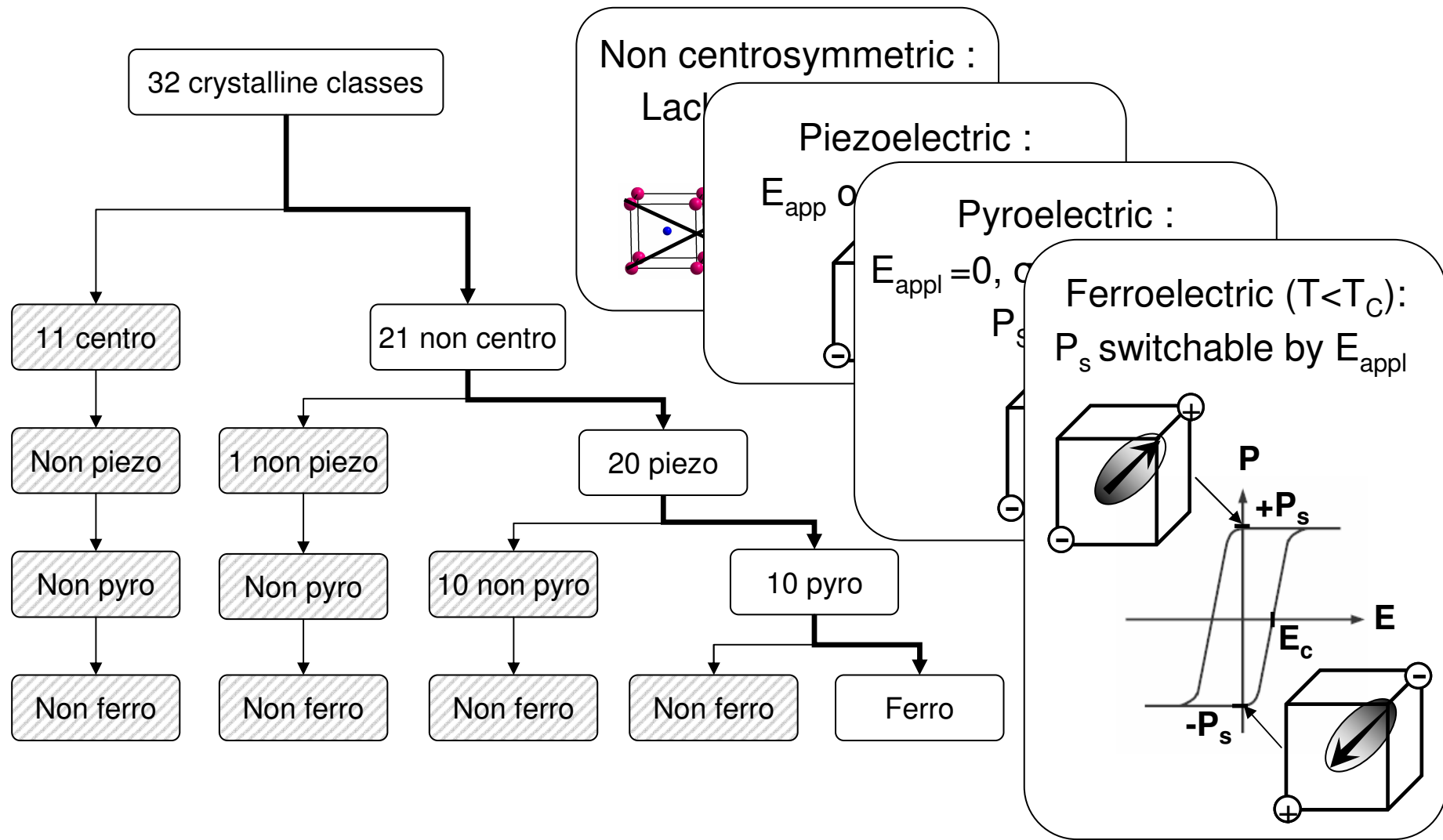
Gajek et al., Nature Materials, 6, 296 (2007)

→ data written electrically (low energy) and read magnetically



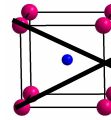
I. Introduction on multiferroic materials

Ferroelectric materials



Non centrosymmetric :

Lack



Piezoelectric :

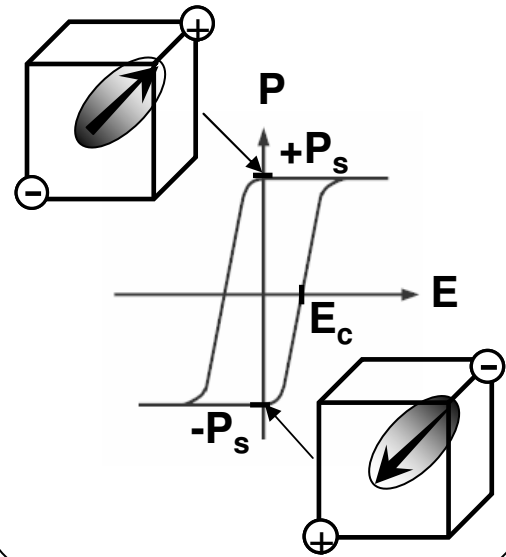
$E_{app} \neq 0$

Pyroelectric :

$E_{appl} = 0, P_s \neq 0$

Ferroelectric ($T < T_C$):

P_s switchable by E_{appl}

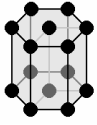






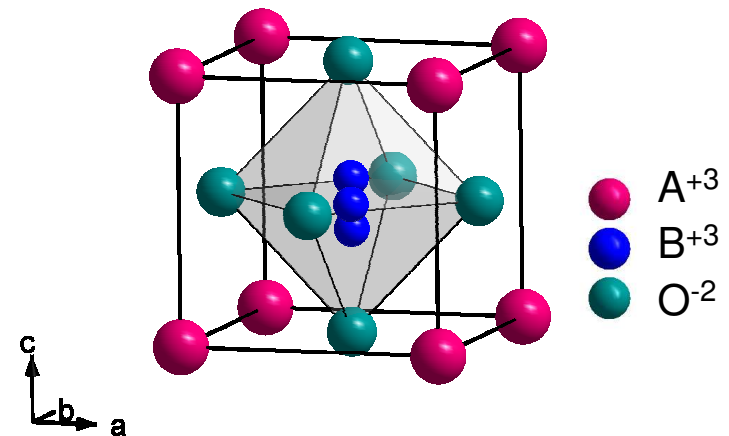
I. Introduction on multiferroic materials

Perovskite-type structure oxides

Ferroelectric + Magnetic properties

Goldschmidt factor : $(r_A+r_O) = t [2^{1/2}(r_B+r_O)]$

$1 < t \leq 1.08$: H		BaTiO ₃ T<200K
$0.95 < t \leq 1$: C		SrTiO ₃
$0,9 < t \leq 0.95$: T		PbTiO ₃
$0,8 < t \leq 0.9$: O		CaTiO ₃ , RMnO ₃ , R = Gd, Tb, Dy
$t \# 0.8$: H		RMnO ₃ , R= Y, Ho, Er, Tm, Yb, Lu, Sc, BiFeO₃

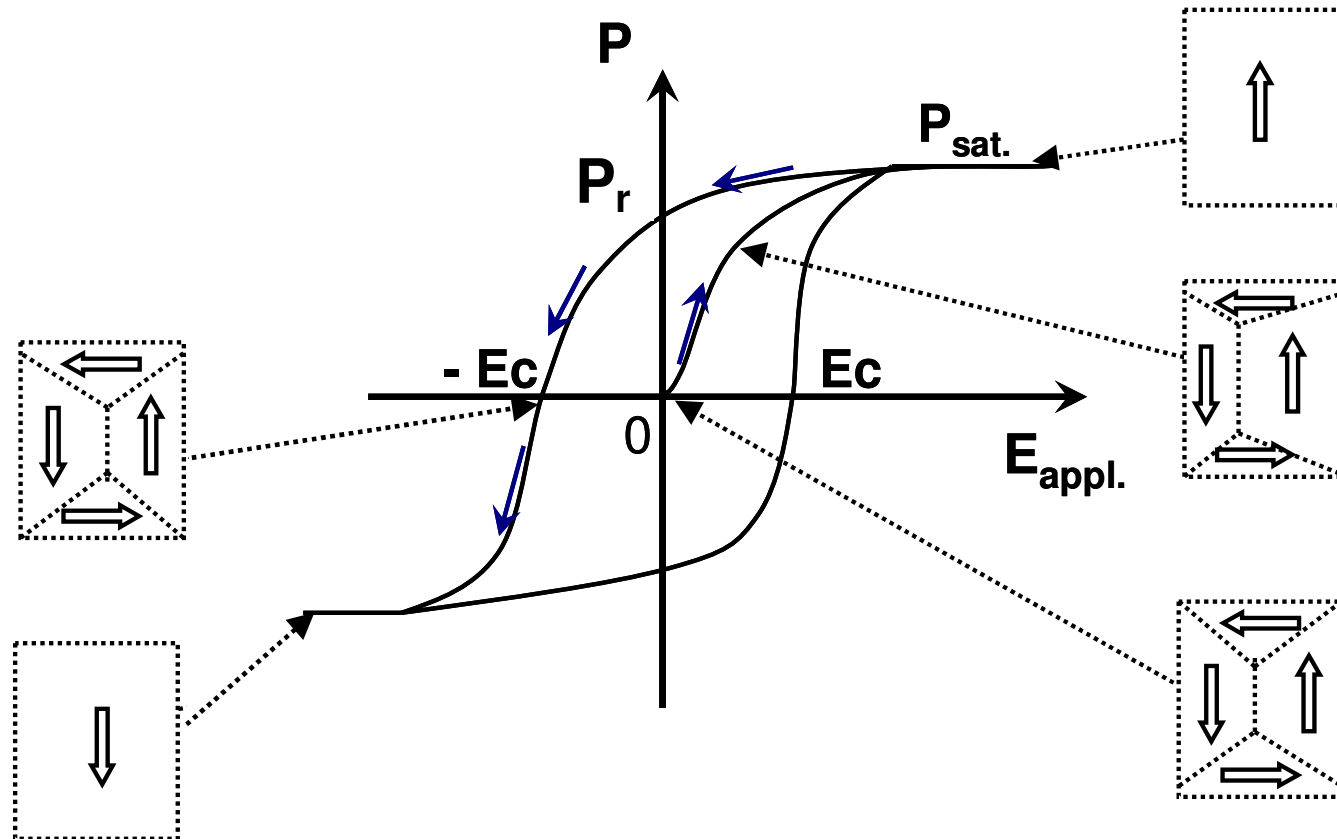


Dipolar moment ($T < T_C$) due to atomic displacements : **displacive-type ferroelectrics**

Several equilibrium states

I. Introduction on multiferroic materials

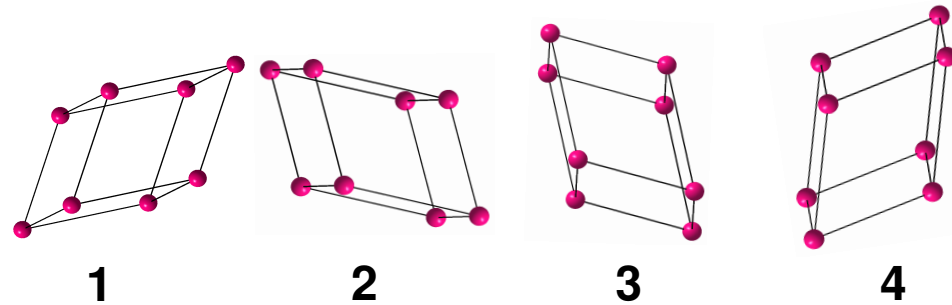
Hysteresis loop and domain structures



I. Introduction on multiferroic materials

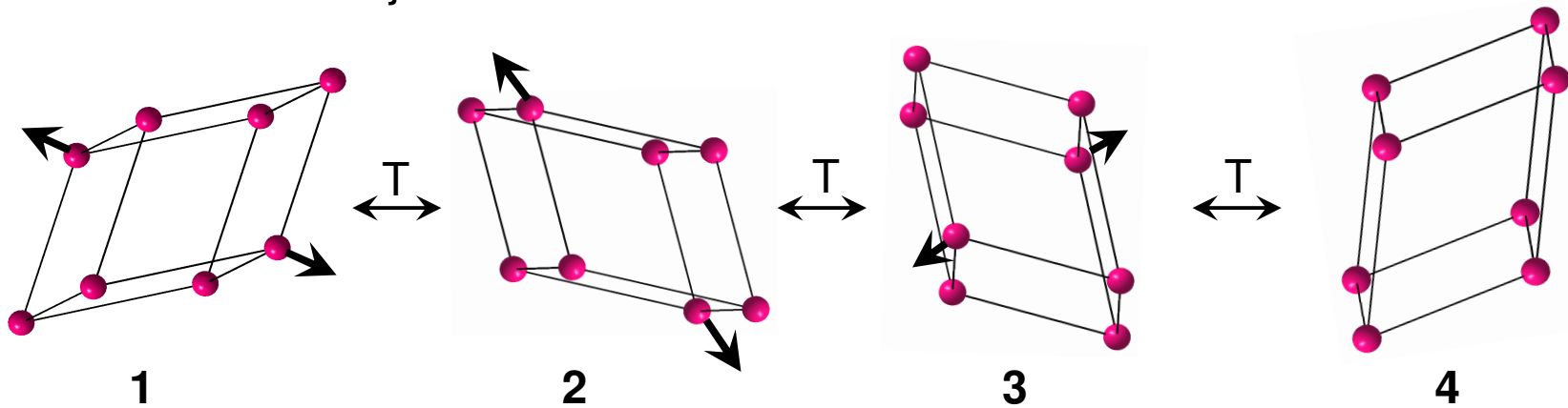
Ferroelastic materials

Several stable strained states without any stress T :



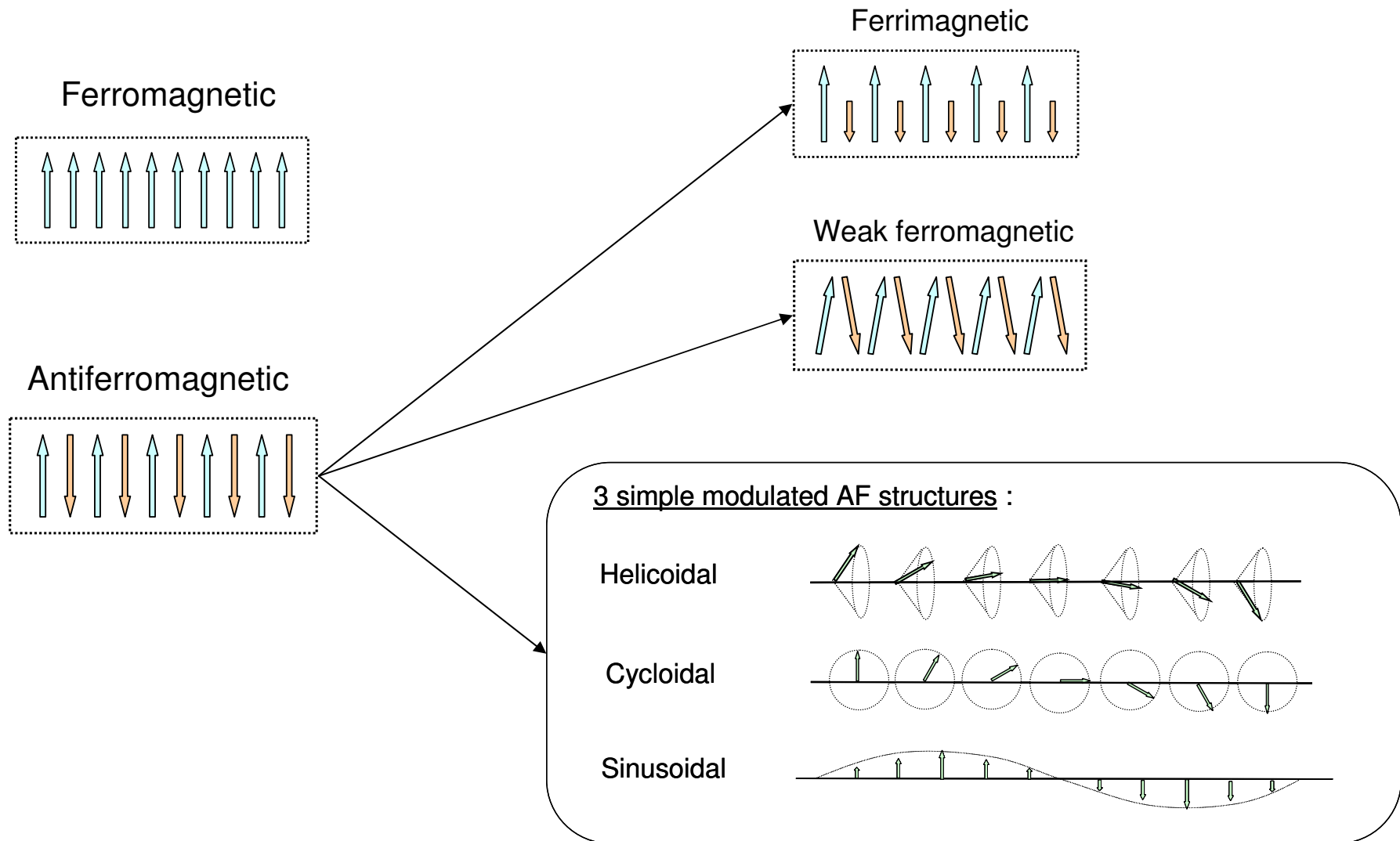
4 states = 4 ferroelastic domains

State $i \xleftrightarrow{T}$ State j



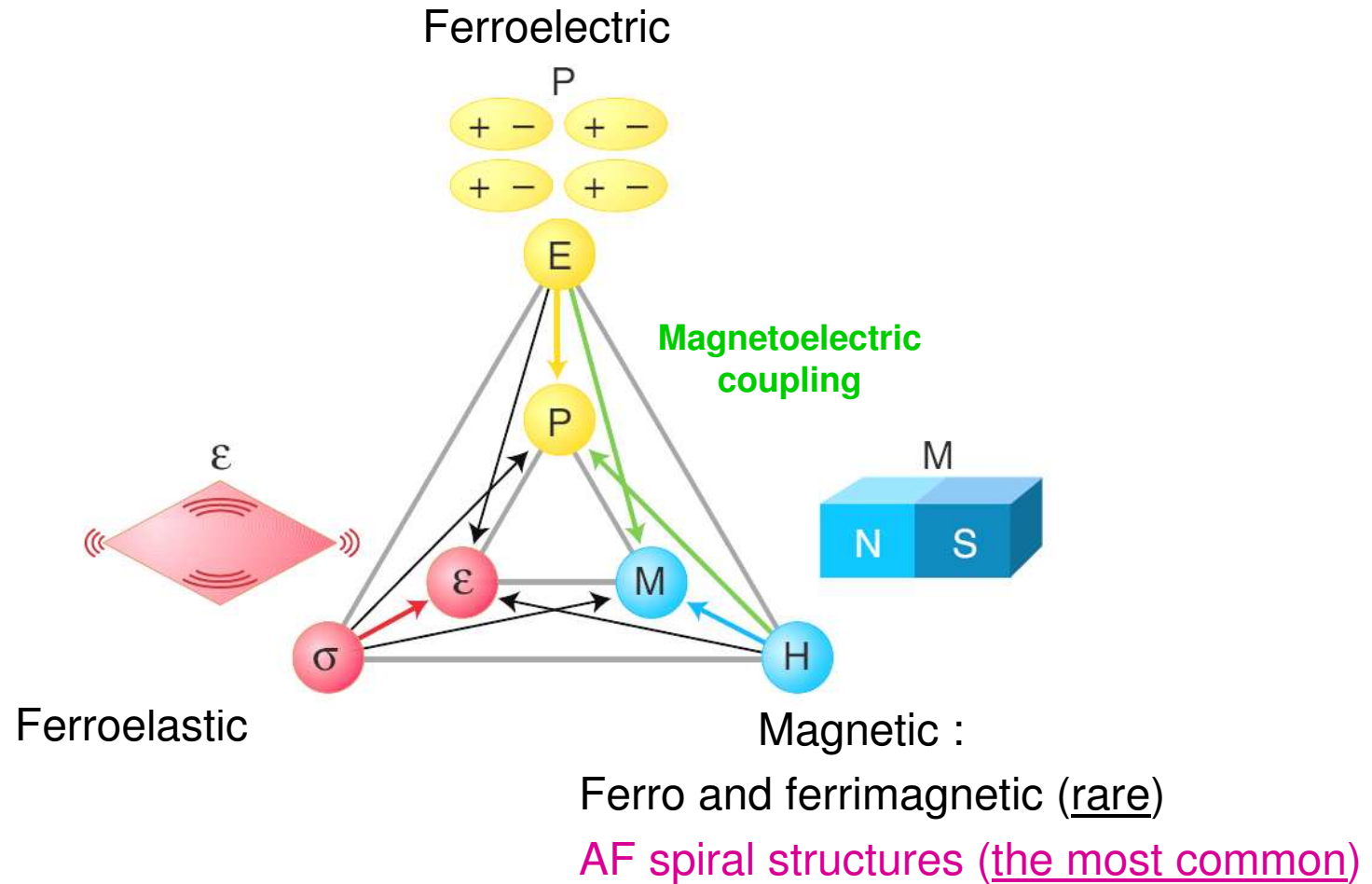
I. Introduction on multiferroic materials

Magnetic materials



I. Introduction on multiferroic materials

Multiferroic materials



Spaldin et al., Science, 309, 391 (2005)

I. Introduction on multiferroic materials

Magnetolectric interaction

→ ME coupling between M and Ps

Thermodynamic theory :

$$P_i = P_i^{(s)} + \chi_{ij}^E E_j + \alpha_{ij} H_j + \chi_{ijk}^E E_j E_k + \alpha_{ijk} H_j E_k + \frac{1}{2} \beta_{ijk} H_j H_k + d_{ijk} T_{jk} \dots$$

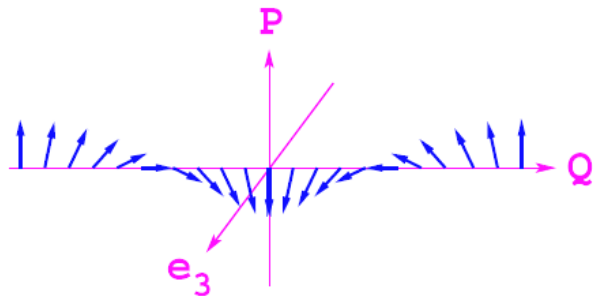
$$M_i = M_i^{(s)} + \chi_{ij}^M H_j + \alpha_{ji} E_j + \chi_{ijk}^M H_j H_k + \beta_{jik} E_j H_k + \frac{1}{2} \alpha_{jik} E_j E_k + g_{ijk} T_{jk} \dots$$

α, β : magnetolectric susceptibility tensor **linear** / **quadratic**

I. Introduction on multiferroic materials

Ferroelectricity in spiral magnets

P_S due to the magnetic structure



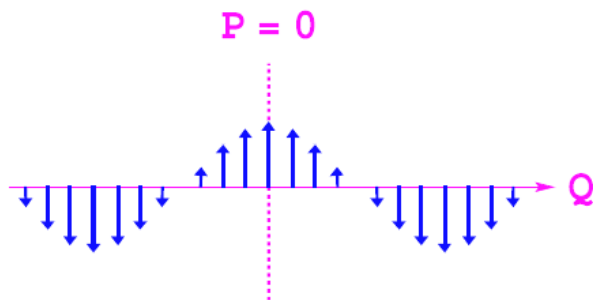
Spiral magnetic structure : (cycloidal or helicoidal)

$P \neq 0 \rightarrow$ Improper ferroelectricity

$$P_S \sim (e \times Q)$$

e : spin rotation axis

Q : propagation vector



Sinusoidal magnetic structure :

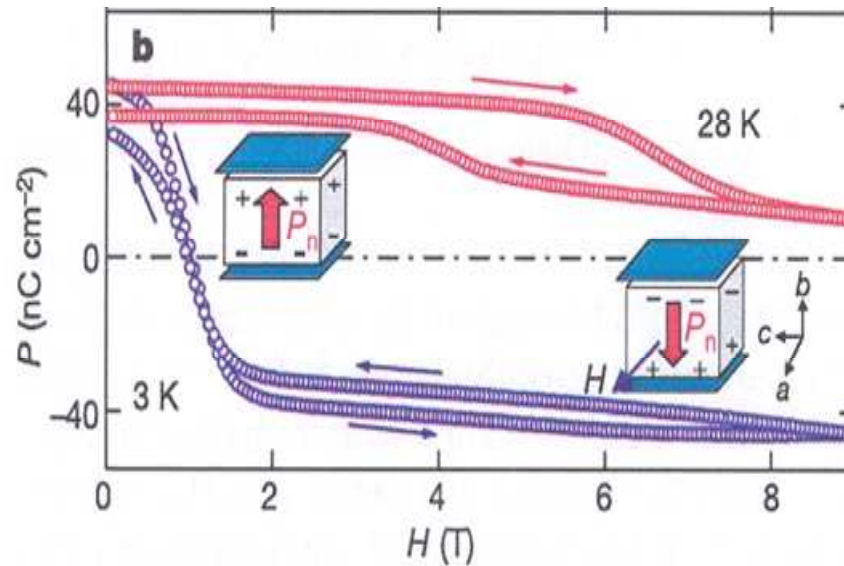
$P = 0 \rightarrow$ No ferroelectricity

Mostovoy, PRL, 96, 067601 (2006)

Sergienko et al., PRB, 73, 094434 (2006)

I. Introduction on multiferroic materials

Magnetoelectric switching in spiral magnets



$P(H)$ in TbMn_2O_5 at 3K and 28K

Low temperature

Weak effect

Hur et al., Nature, 429, 392 (2004)

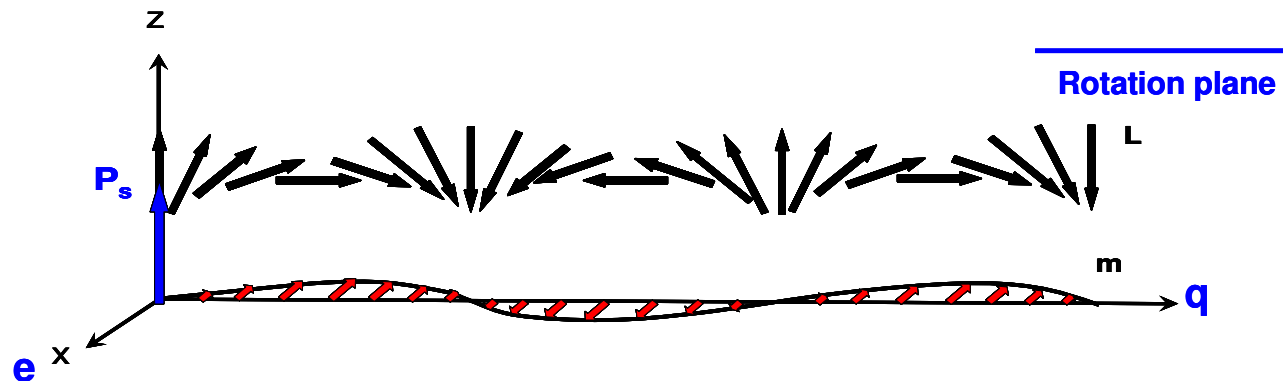
I. Introduction on multiferroic materials

In the case of BiFeO_3

Properties : Ferroelectricity and magnetism allowed by symmetry

P_s due to the Bi^{3+} and Fe^{3+} ions ($T_C \sim 1090 \text{ K}$)

Cycloidal AF structure ($T_N \sim 640 \text{ K}$) with a weak ferromagnetism component



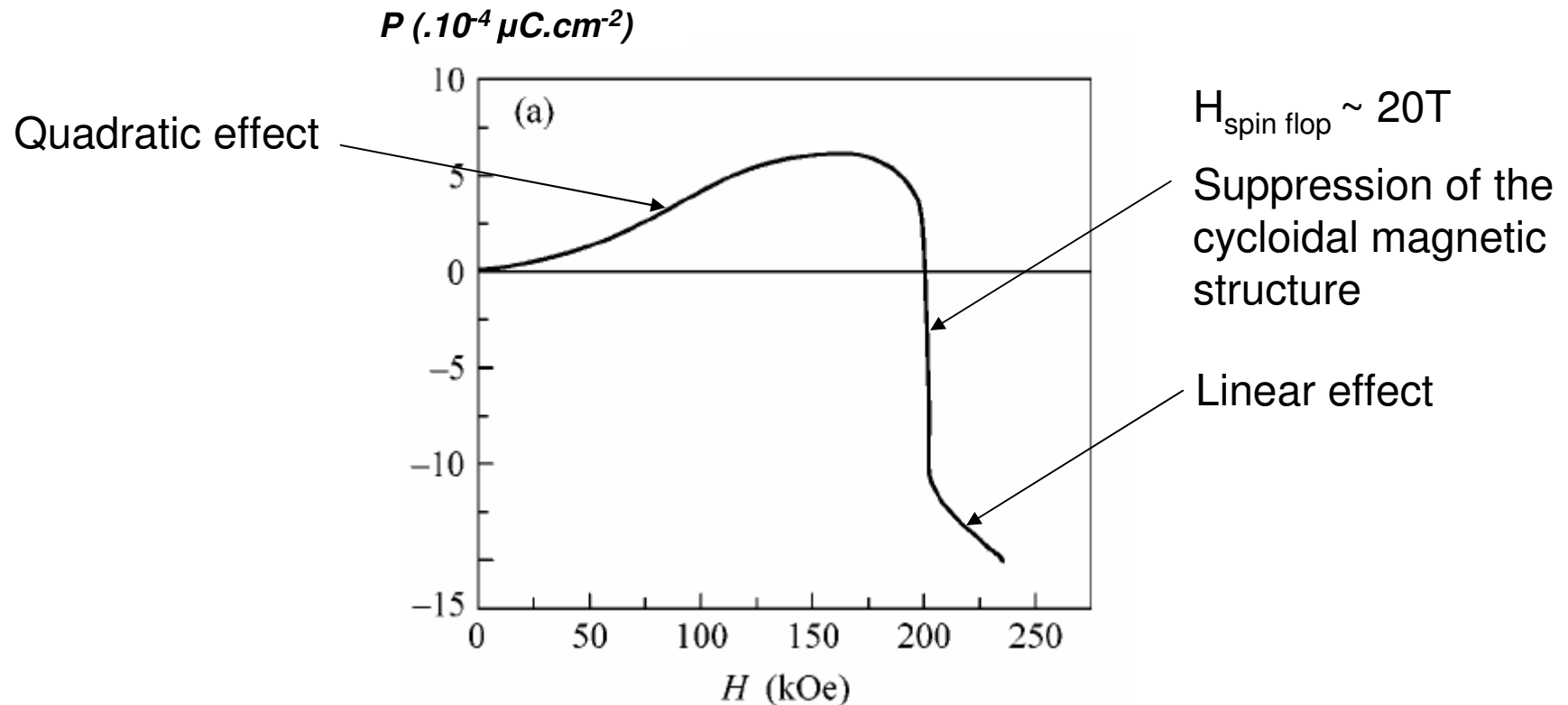
Presence of cycloid in the bulk, in a macroscopic point of view:

$\left\{ \begin{array}{l} m \text{ is averaged } \langle m \rangle = 0 \\ \text{linear ME effect forbidden} \end{array} \right.$

→ For potential applications, the cycloid is a problem

I. Introduction on multiferroic materials

To suppress the cycloid : 1. Application of high H

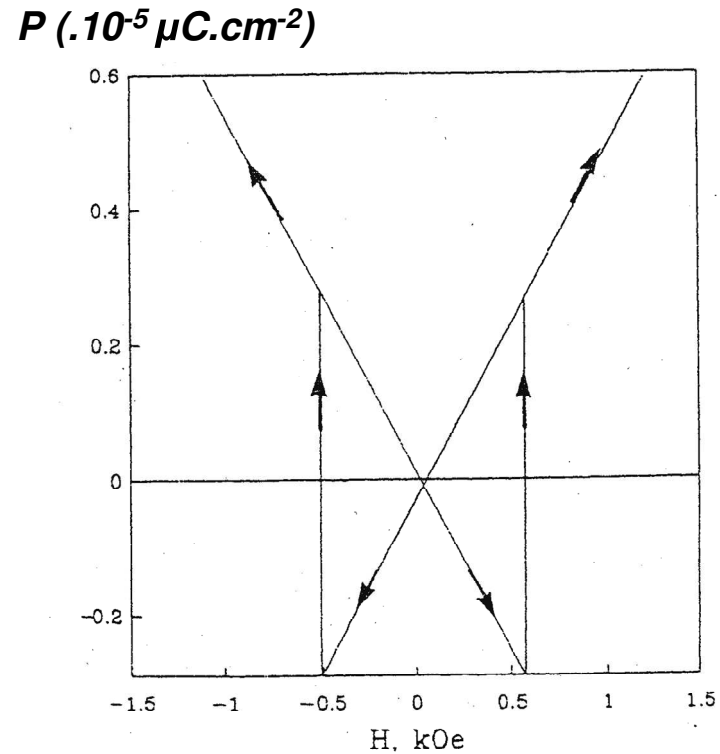


$P(H)$ in a BiFeO_3 single crystal at 18K

Popov et al., JETP Lett., 57, 69 (1993)

I. Introduction on multiferroic materials

To suppress the cycloid : 2. Substitution of Bi by Dy

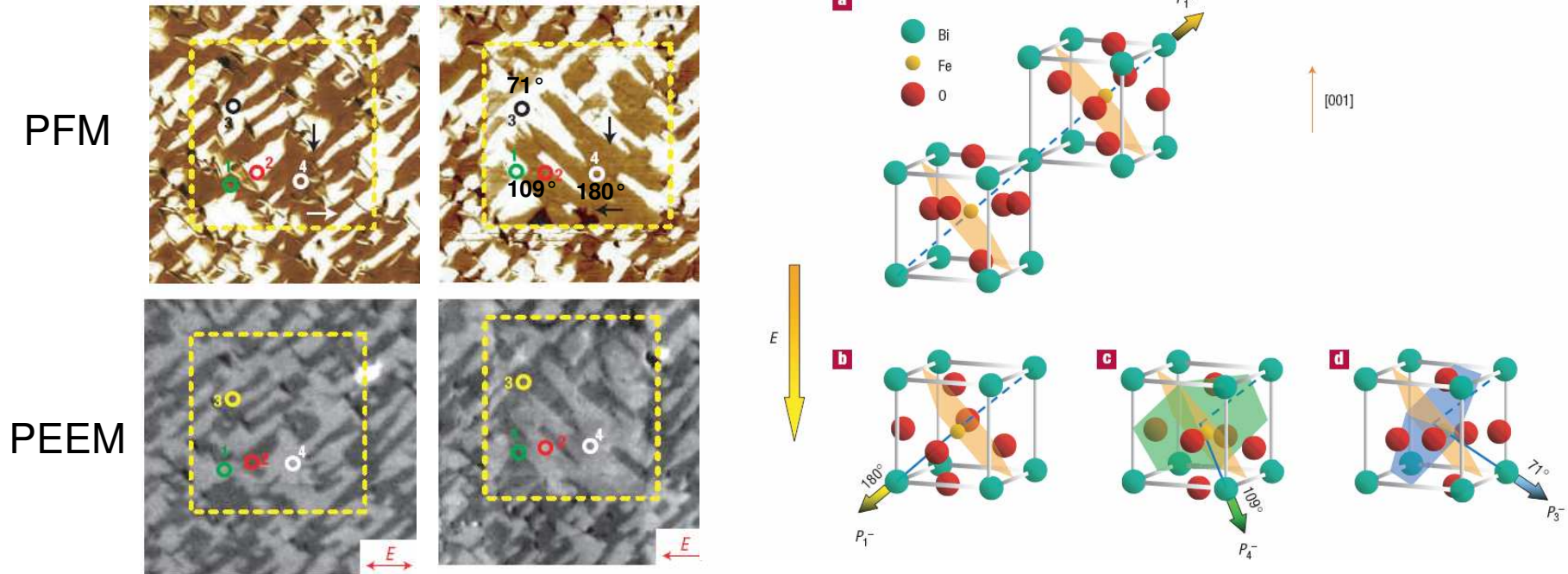


$P(H)$ in a $\text{Bi}_{0.45}\text{Dy}_{0.55}\text{FeO}_3$ single crystal at 77K

Gabbasova et al., Phys. Lett. A, 158, 491 (1991)

I. Introduction on multiferroic materials

To suppress the cycloid : 3. Thin films



In BiFeO₃ (001) films at 300K

Magnetic and ferroelectric contrast by imaging

Correspondance between ferroelectric and magnetic domains.

Zhao et al., Nature materials, 5, 823 (2006)

I. Introduction on multiferroic materials

Goals of this work

Ferroelectricity at 300K ? Large P_S ?


→ requirement of high resistive samples : {

- Densified ceramics
- Single crystals

Studying coupling between M and P on single crystals

Effect of the cycloid ?

Effect of substitution on magnetic and electric properties ($\text{Bi}_{0.45}\text{Dy}_{0.55}\text{FeO}_3$)

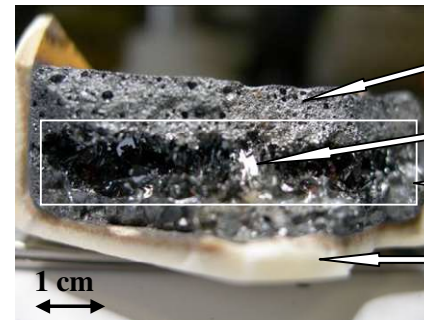
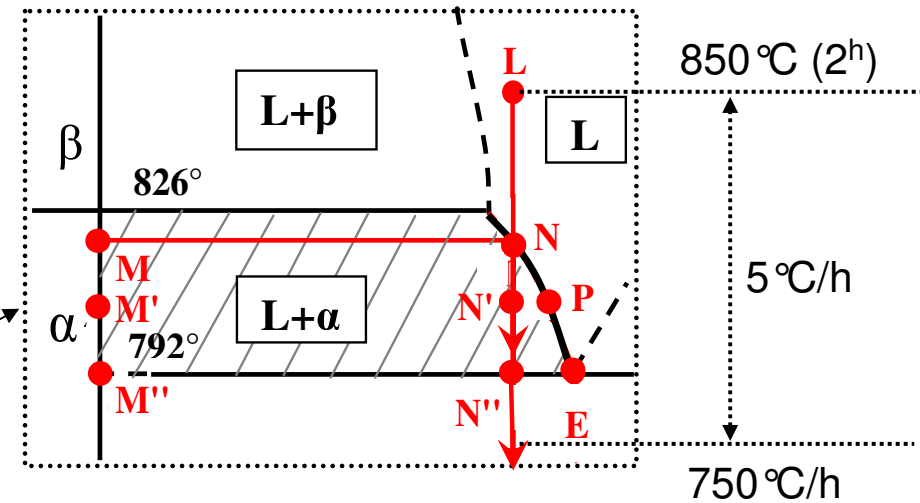
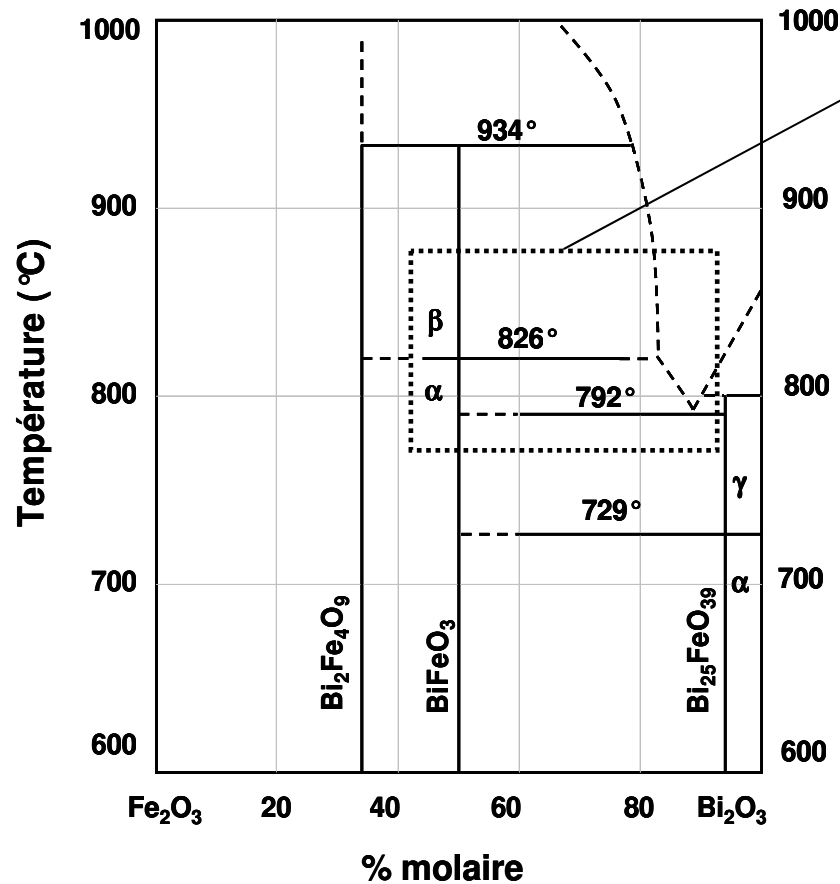
- 
- I. Introduction to multiferroic materials
 - II. Synthesis and characterisation by X-ray and neutron diffraction
 - III. Ferroelectric properties of BiFeO_3 single crystals
 - IV. Magnetic properties of BiFeO_3
 - V. Magnetoelectric study of BiFeO_3 single crystals
- Conclusions et perspectives
- 

II. Synthesis and characterisation by X-ray and neutron diffraction

Peritectic melting point → flux method

Composition : $0.8\text{Bi}_2\text{O}_3/0.2\text{Fe}_2\text{O}_3$

2 impurities : $\text{Bi}_2\text{Fe}_4\text{O}_9$ and $\text{Bi}_{25}\text{FeO}_{39}$



Flux

BiFeO_3 crystal

Crystalline cavity

Aluminate crucible

Importantly : $T_{\text{cryst.}} < T_{\text{Curie}}$

II. Synthesis and characterisation by X-ray and neutron diffraction

X-ray diffraction

BiFeO_3 : Rhomboedric non-centrosymmetric

radiation $K\alpha$ Mo $\lambda=0.71069 \text{ \AA}$

Dim. : $0.3 \times 0.2 \times 0.02 \text{ mm}^3$

$\rho_{\text{calc}} = 8.33 \text{ g/cm}^3$

$\mu = 73.9 \text{ cm}^{-1}$

Groupe d'espace : R3c

Z = 18

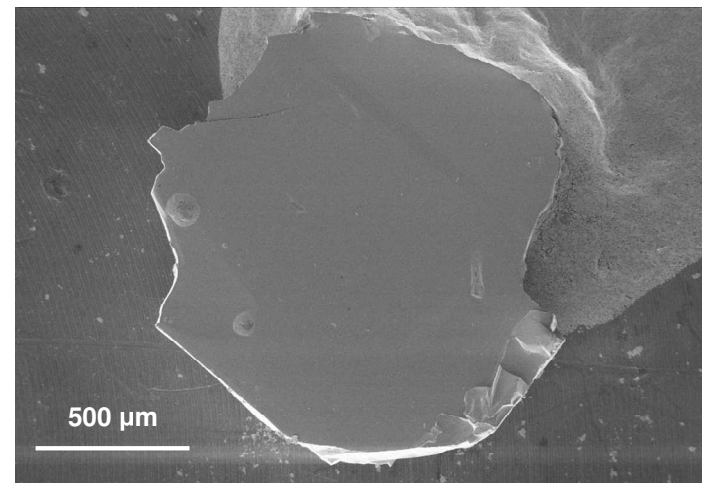
$a_{\text{hex}} = 5.571 (5) \text{ \AA}$

$c_{\text{hex}} = 13.858 (5) \text{ \AA}$

$V_{\text{hex}} = 372.53 (1) \text{ \AA}^3$

Millimetric and highly resistive crystals.

Platelets with a large surface area



*Single crystal of BiFeO_3
 $1.4 \times 1.6 \times 0.04 \text{ mm}^3$ (SEM)*

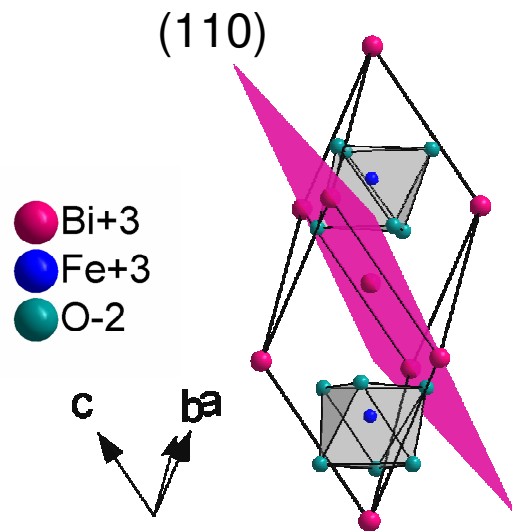
Neutron diffraction

Confirmation of the crystalline structure from 20 reflections

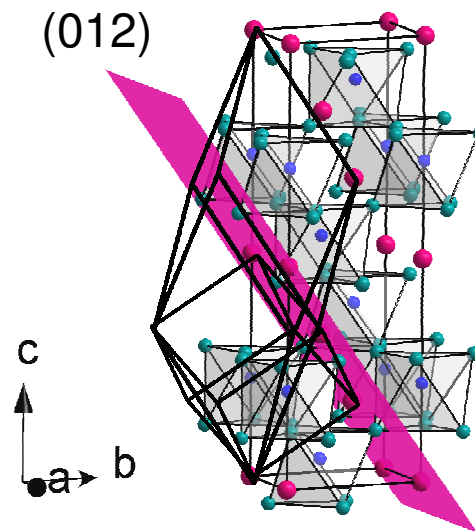
II. Synthesis and characterisation by X-ray and neutron diffraction

Crystalline structure of BiFeO_3

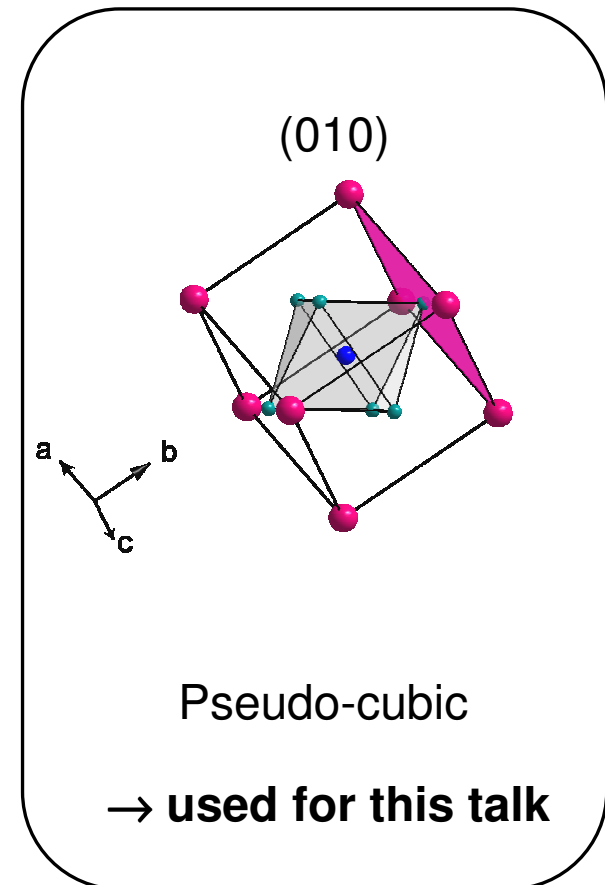
 Platelet plane



Rhombohedral



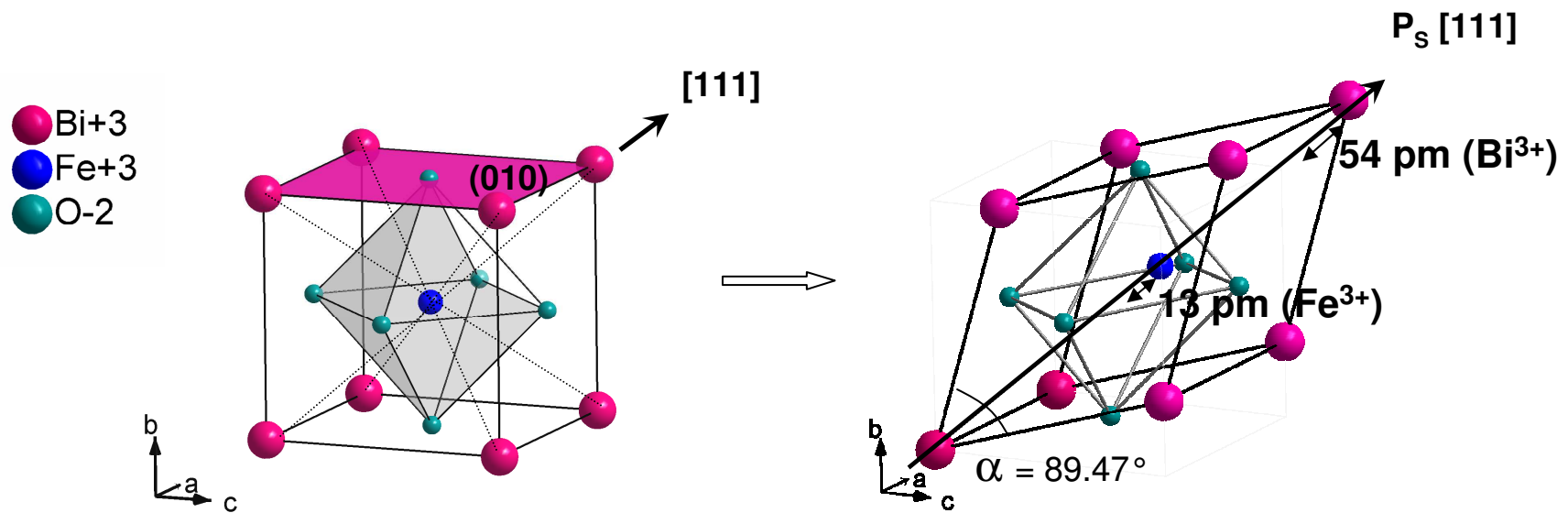
Hexagonal



II. Synthesis and characterisation by X-ray and neutron diffraction

Structural distortions in BiFeO_3

Cubic \rightarrow Pseudo-cubic : distortion along $[111]$

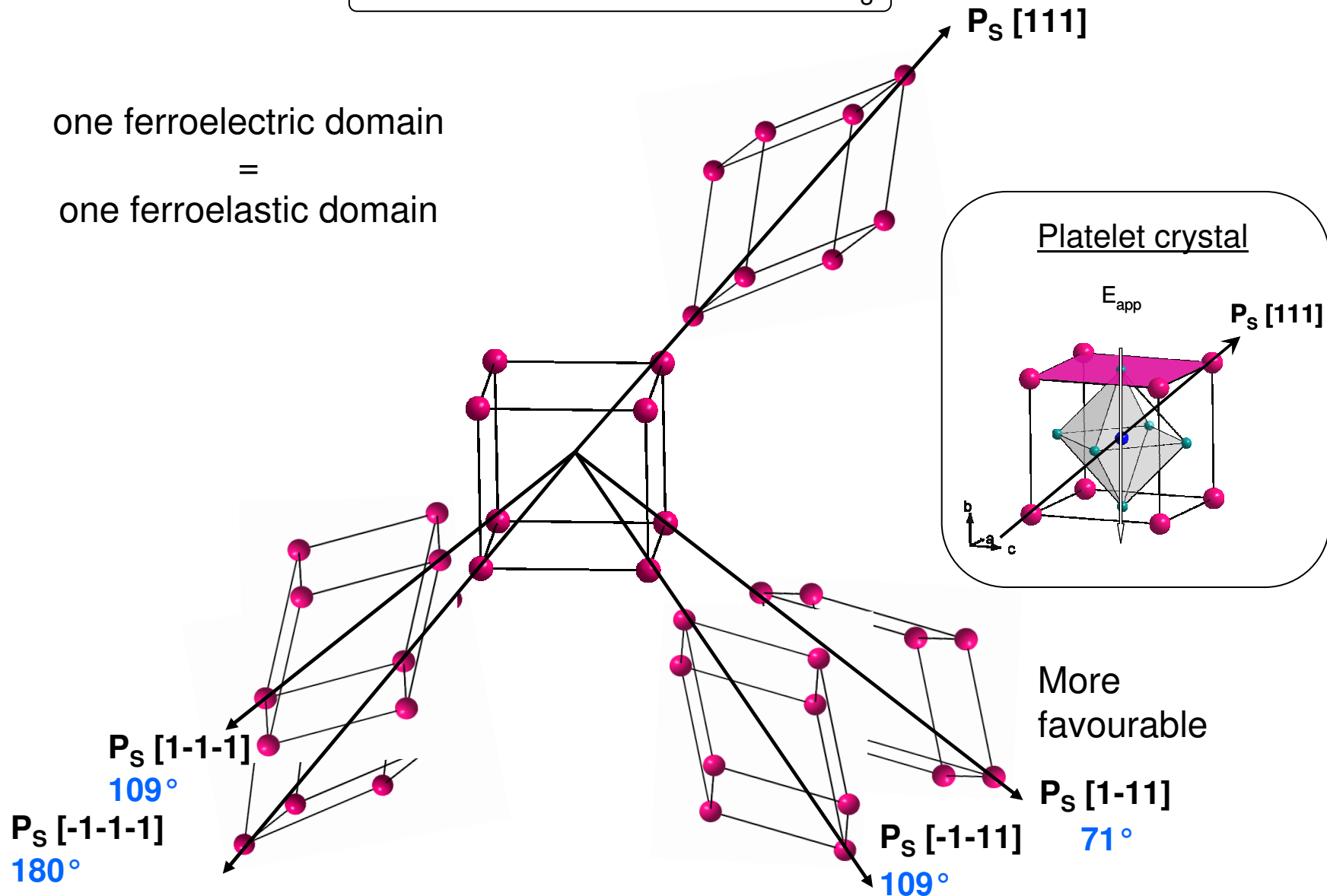


Large atomic displacements \rightarrow large P_s

II. Synthesis and characterisation by X-ray and neutron diffraction

Ferroelastic domains of BiFeO_3

one ferroelectric domain
=
one ferroelastic domain

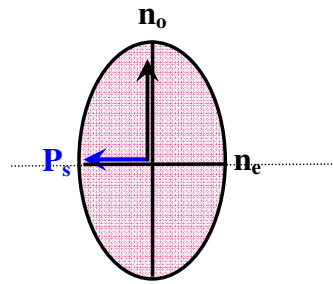


- 
- I. Introduction to multiferroic materials
 - II. Synthesis and characterisation by X-ray and neutron diffraction
 - III. Ferroelectric properties of BiFeO₃**
 - IV. Magnetic properties of BiFeO₃
 - V. Magnetoelectric study of BiFeO₃ single crystals

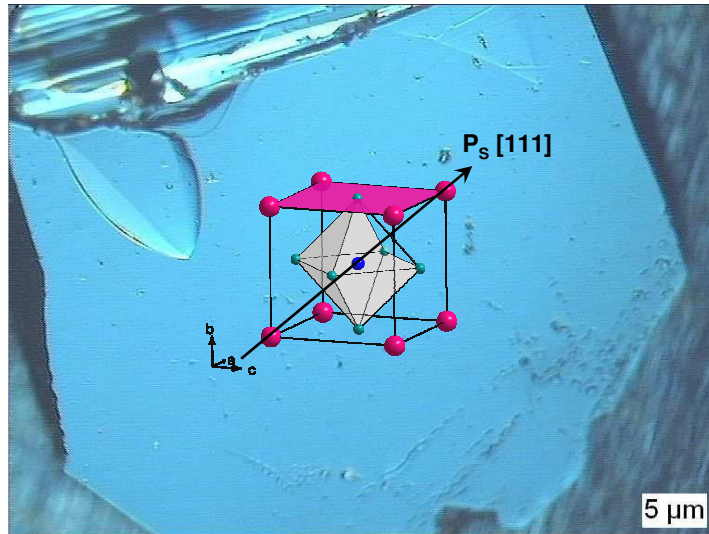
Conclusions et perspectives



III. Ferroelectric properties of BiFeO_3

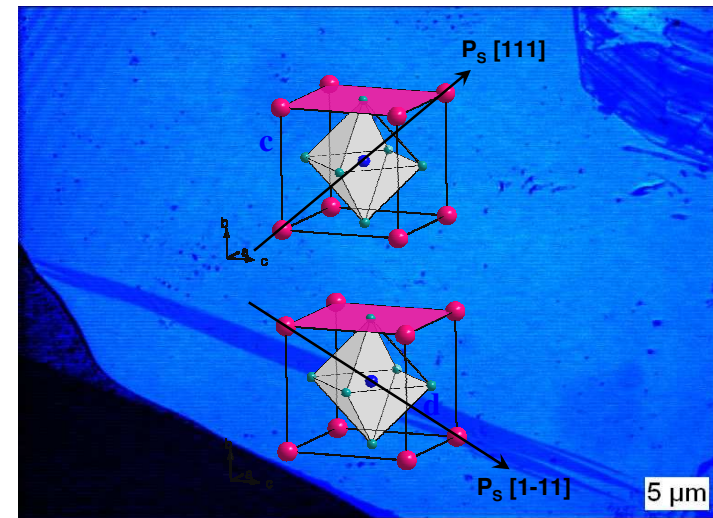


Polarized light optical microscopy



Ferroelastic/ferroelectric single domain crystal

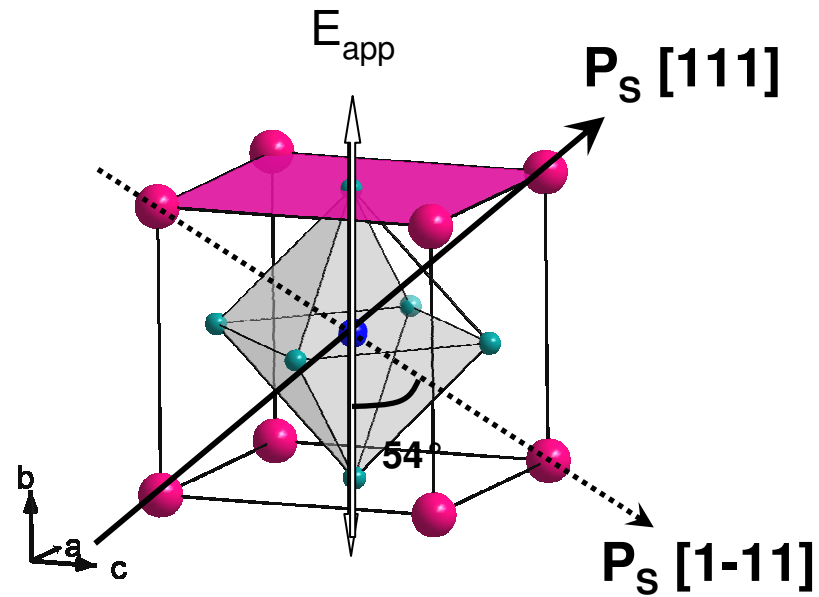
Modification under E



Two ferroelastic/ferroelectric domains (due to mechanical stress during crystal extraction)

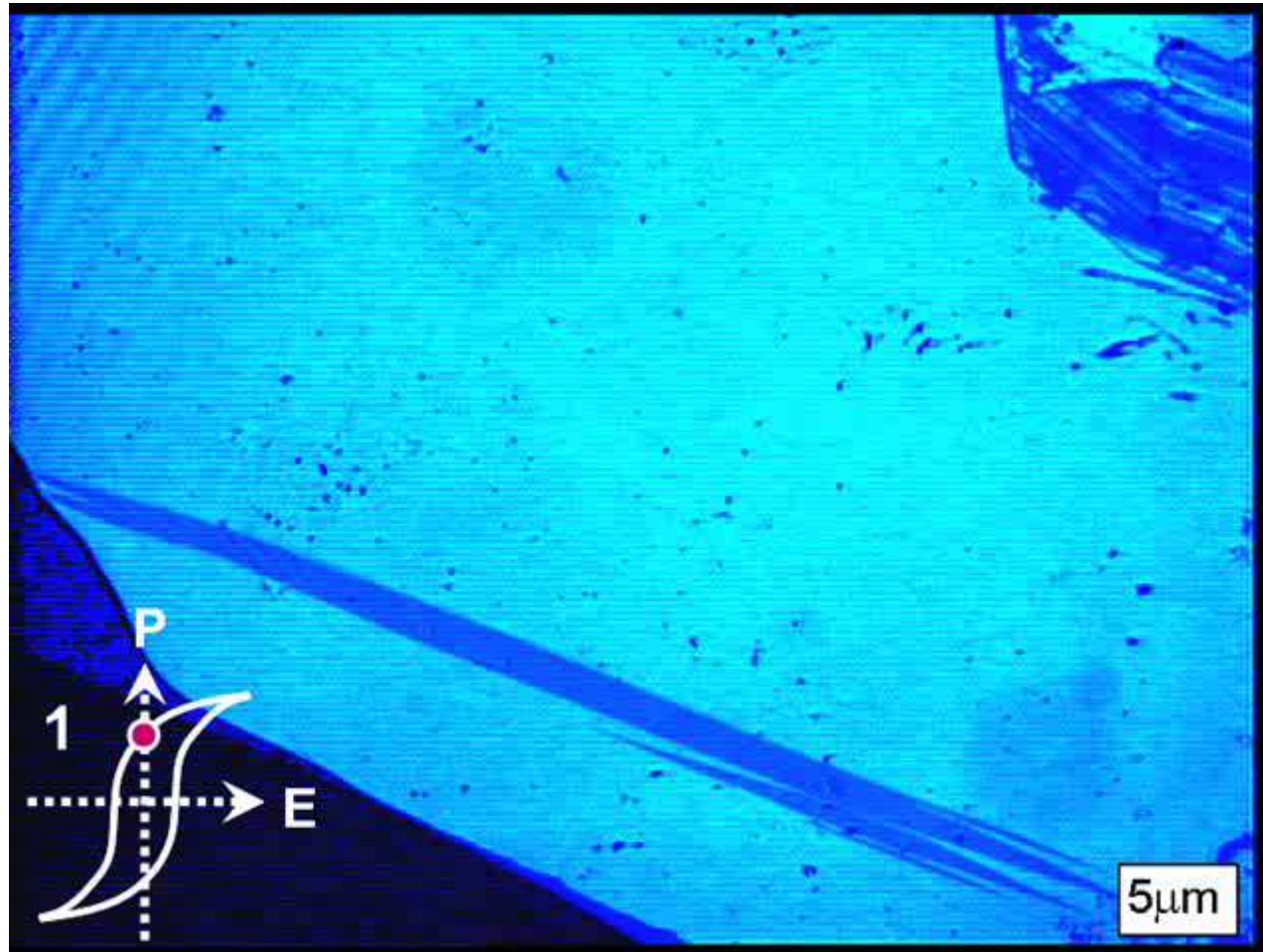
III. Ferroelectric properties of BiFeO_3

Polarized light optical microscopy under electric fields



III. Ferroelectric properties of BiFeO_3

Ferroelastic domain walls motion under electric fields

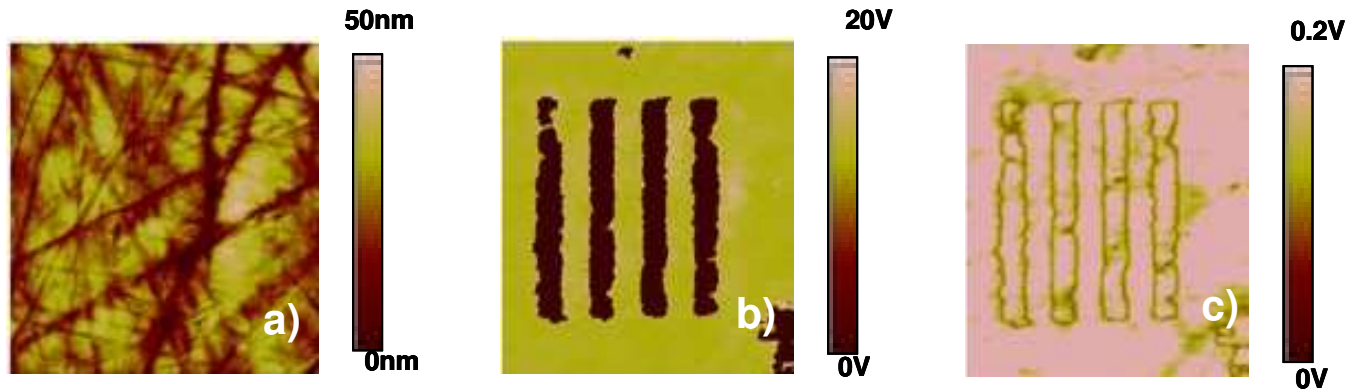
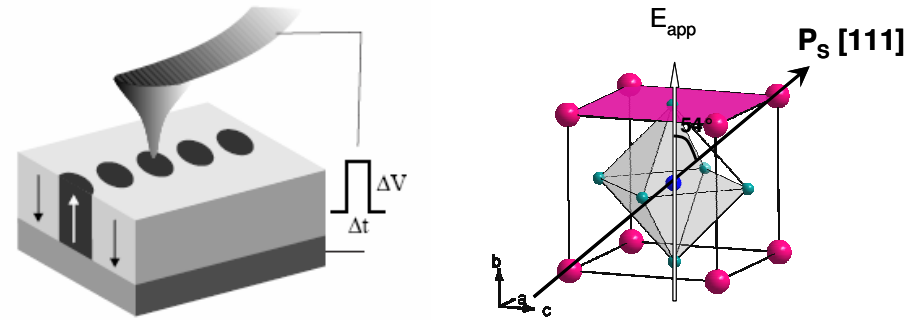


III. Ferroelectric properties of BiFeO₃

Writing and reading ferroelectric domains in a BiFeO₃ single crystal

T = 300K

Out-of-Plane PFM images (6x6 μm² area)
of a BiFeO₃ polished single crystal:



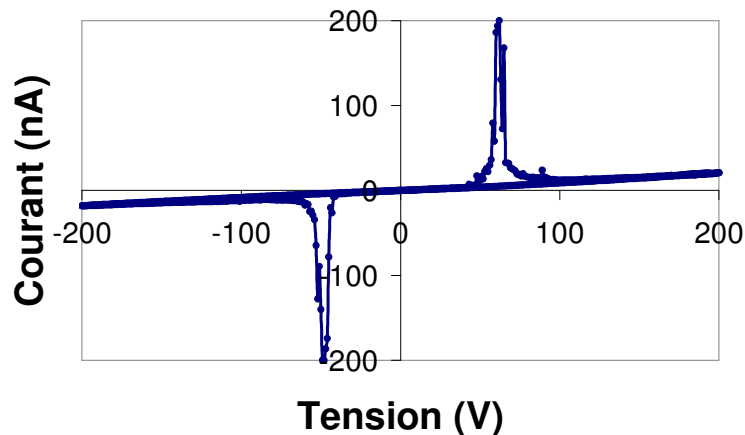
- a) Topography
- b) Phase image after writing « up » and « down » stripes (4 x 0,5 μm)
- c) Amplitude image

Lebeugle et al., PRB, 76, 024116 (2007)

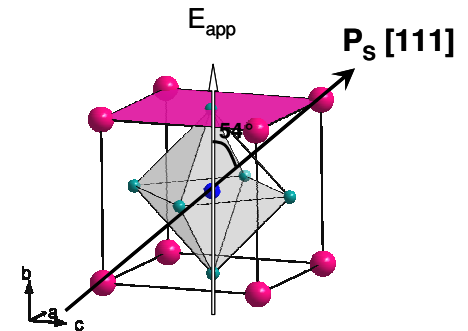
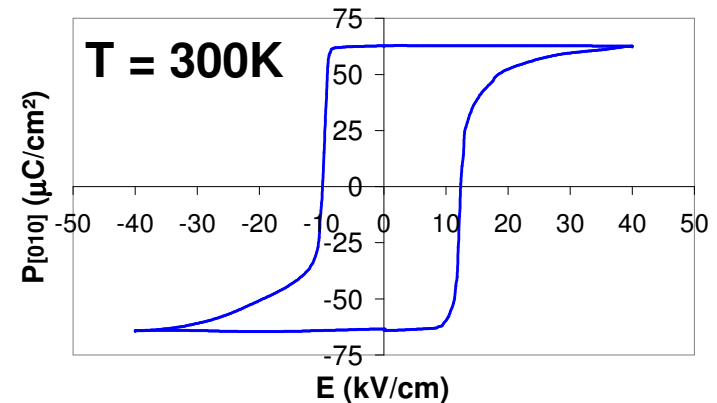
III. Ferroelectric properties of BiFeO₃

Polarization loop on BiFeO₃ single crystals

Charge current versus applied voltage :



$$P \propto \int I \cdot dt$$



High resistivity $\rho(300K, 100V) \sim 6 \cdot 10^{10} \Omega \cdot cm$

Very large $P_s \sim 100 \mu C/cm^2$ (BaTiO₃ $P_s \sim 25 \mu C/cm^2$) as theoretically predicted*

$E_c \sim 12 \text{ kV/cm}$, $E_{max} \sim 40 \text{ kV/cm}$

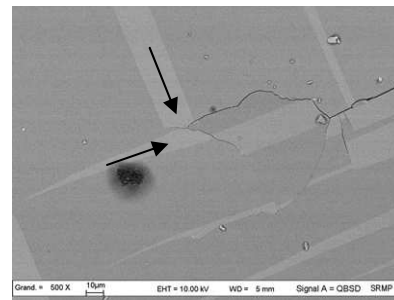
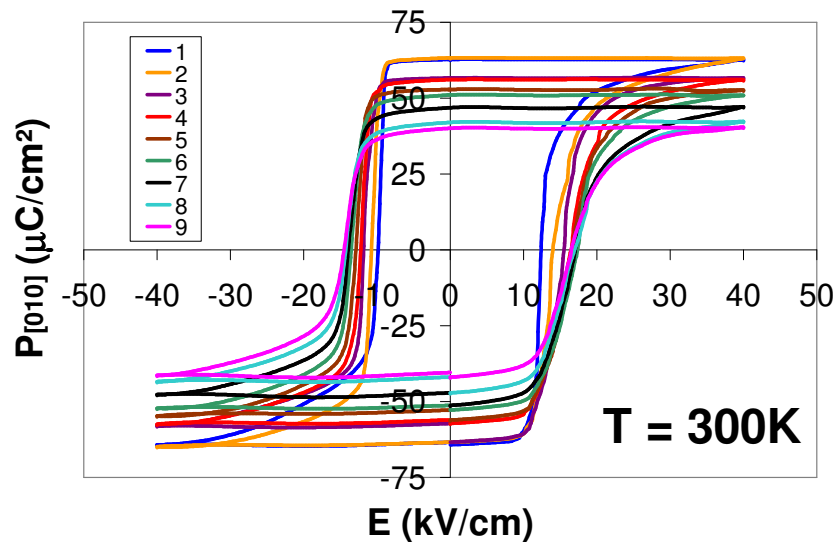
First $P(E)$ at 300K on BiFeO₃ single crystals

Lebeugle et al., PRB, 76, 024116 (2007)

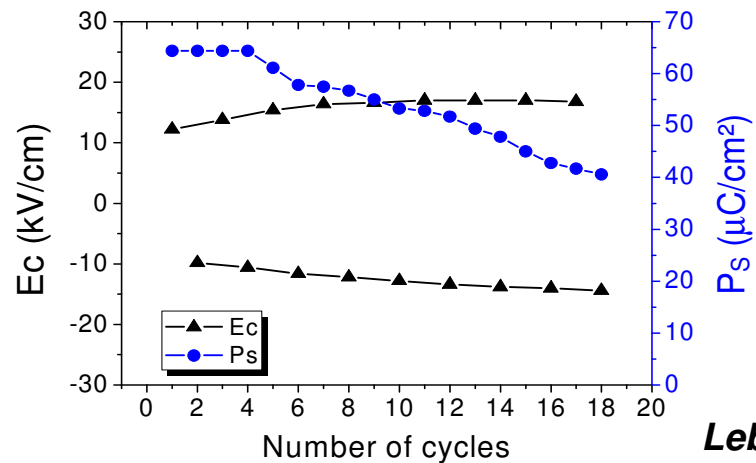
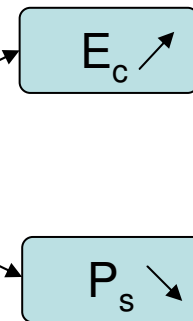
* *Neaton, PRB, 71, 014113 (2005)*

III. Ferroelectric properties of BiFeO₃

Evolution of polarization loops after electric cycling



Multidomain crystal
→ electric fatigue



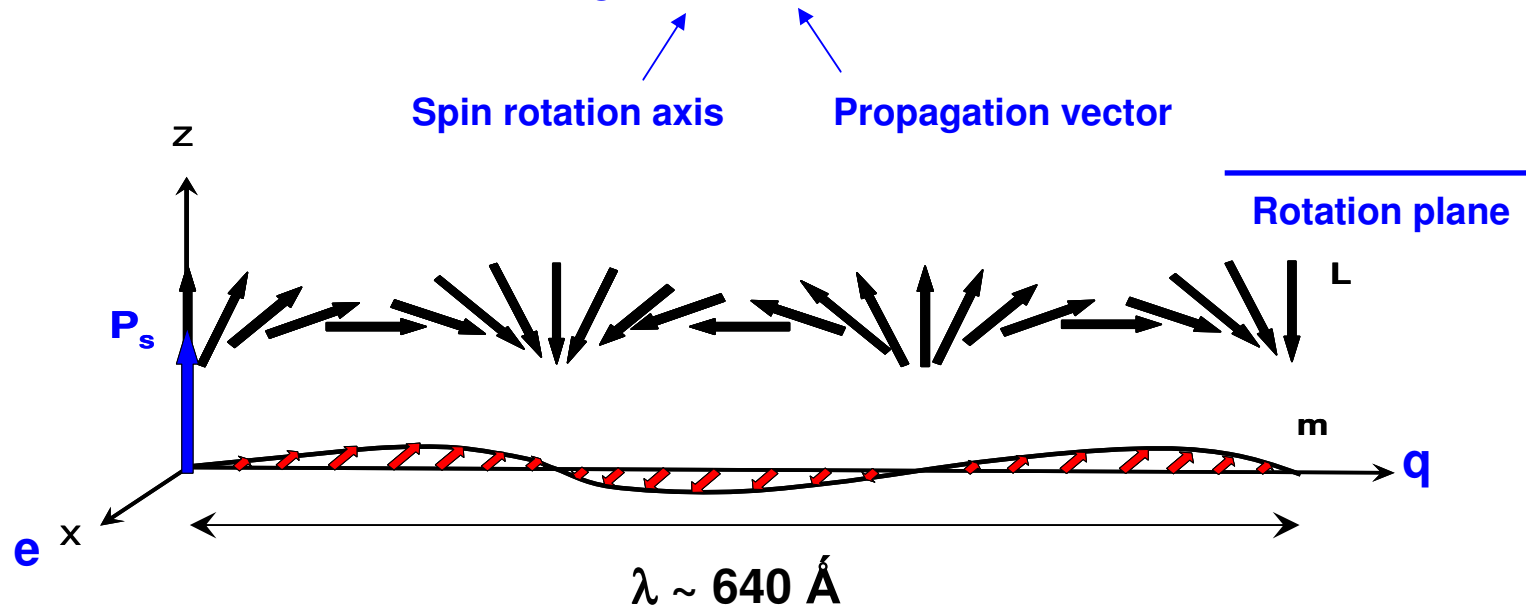
Lebeugle et al., APL, 91, 022907 (2007)

- 
- I. Introduction to multiferroic materials
 - II. Synthesis and characterisation by X-ray and neutron diffraction
 - III. Ferroelectric properties of BiFeO_3 single crystals
 - IV. Magnetic properties of BiFeO_3**
 - V. Magnetoelectric study of BiFeO_3 single crystals
- Conclusions and perspectives
- 

IV. Magnetic properties of BiFeO₃

Magnetic structure of BiFeO₃

Cycloidal magnetic structure : $\mathbf{P}_s \sim (\mathbf{e} \times \mathbf{q})$



Presence of cycloid : $\left\{ \begin{array}{l} m \text{ is averaged } \langle m \rangle = 0 \\ \text{linear ME effect forbidden} \end{array} \right.$

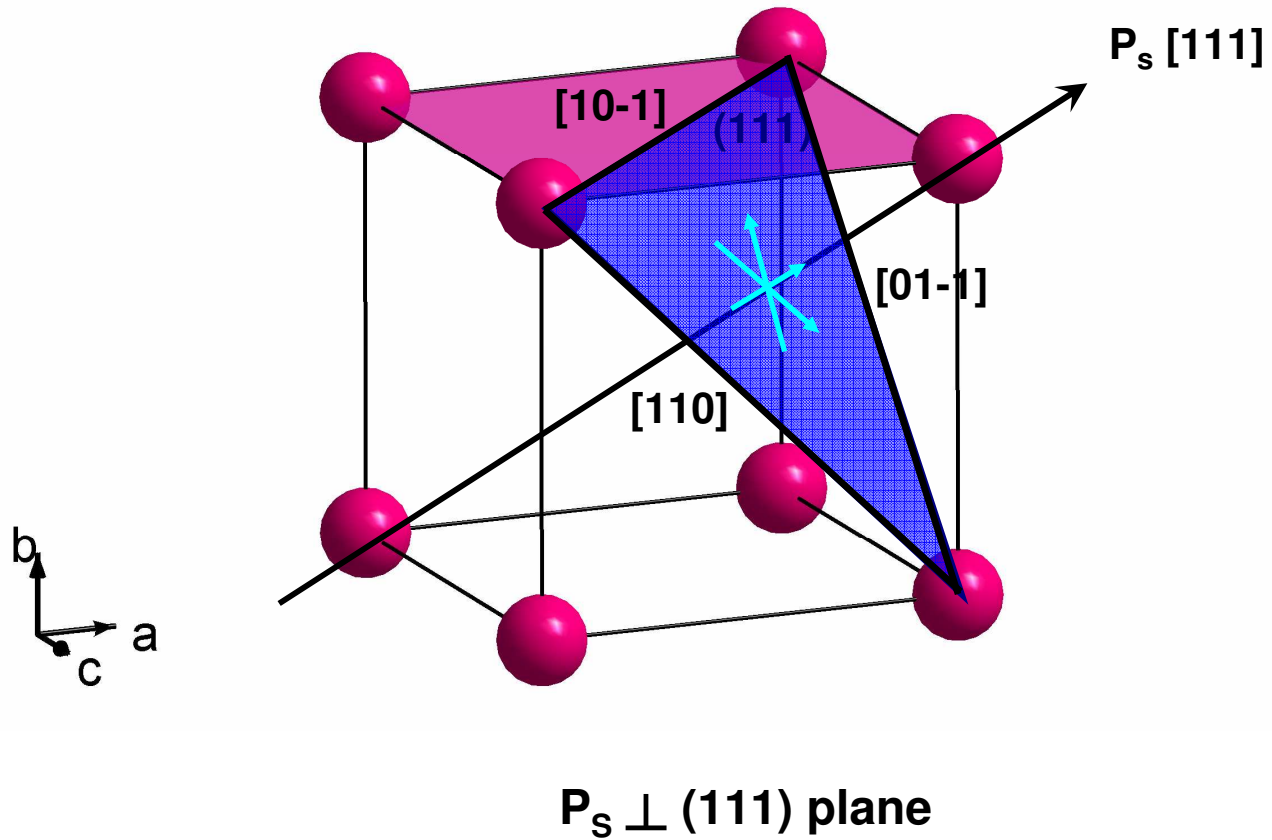
Symmetry : $\left\{ \begin{array}{l} 3 \text{ propagation vectors} \\ 3 \text{ spin rotation planes} \end{array} \right.$

Kadomtseva, JETP Lett, 79, 571 (2004)

Sosnowska et al., J. of Phys. C, 15, 4835 (1982)

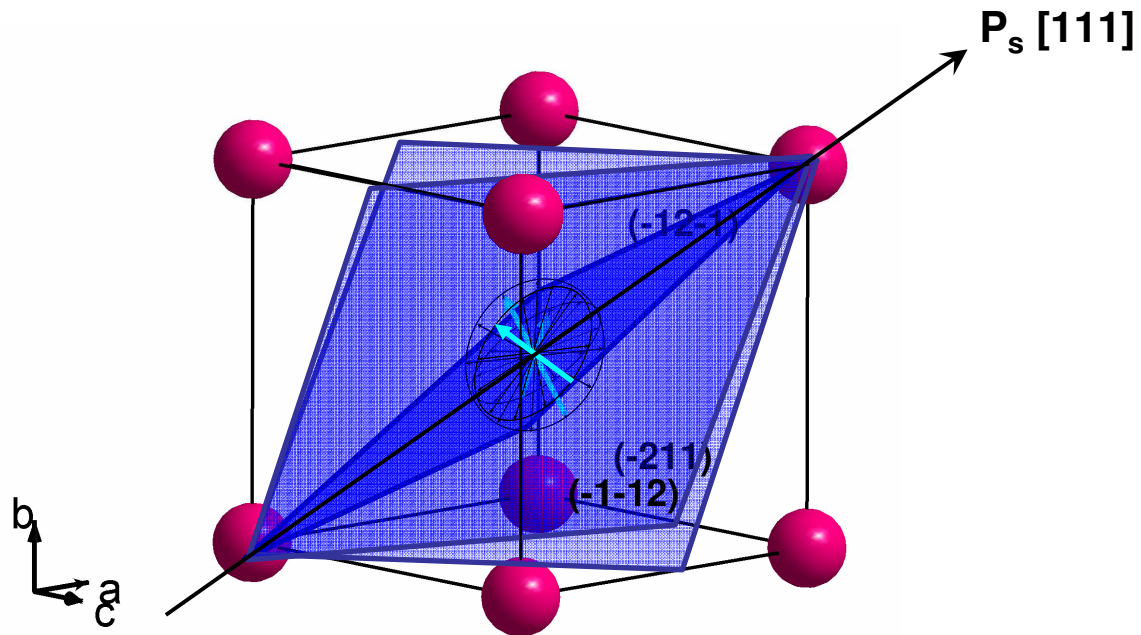
IV. Magnetic properties of BiFeO_3

3 propagation vectors q



IV. Magnetic properties of BiFeO_3

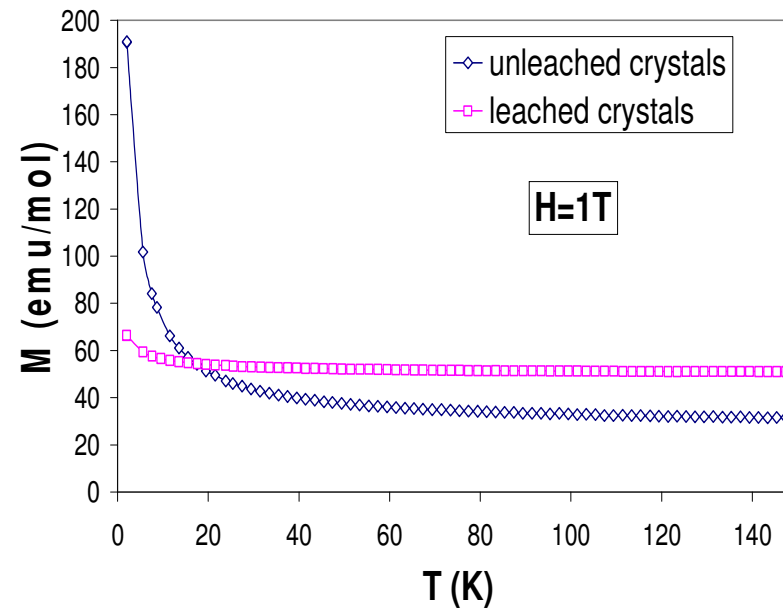
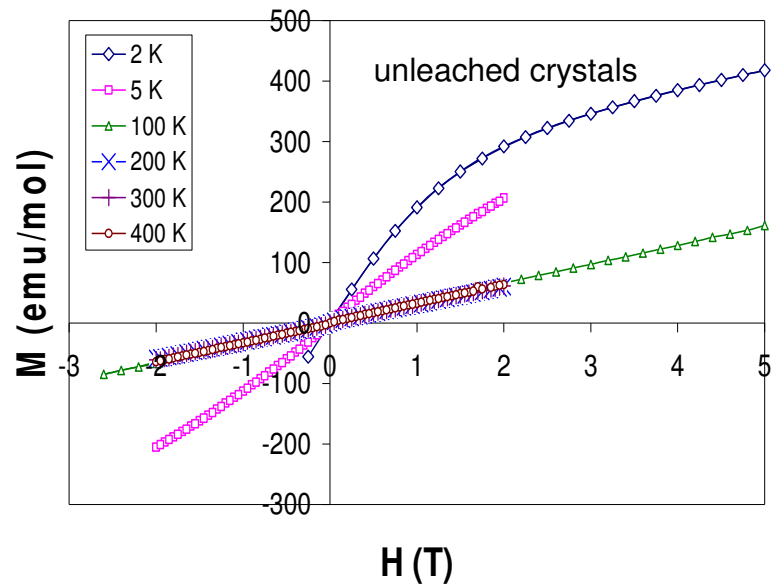
3 spin rotation planes



$$(\text{spin rotation plane}) = (\mathbf{P}_s \times \mathbf{q})$$

IV. Magnetic properties of BiFeO₃

Magnetization curves of BiFeO₃ single crystals



$\mathbf{H}_{\text{app}} // (010)$ plane

100 < T < 400 K : AF order of $m\text{Fe}^{3+}$

2 à 5 K : paramagnetic impurities of Fe^{3+} in $\text{Bi}_{25}\text{FeO}_{39}$ (~16%)

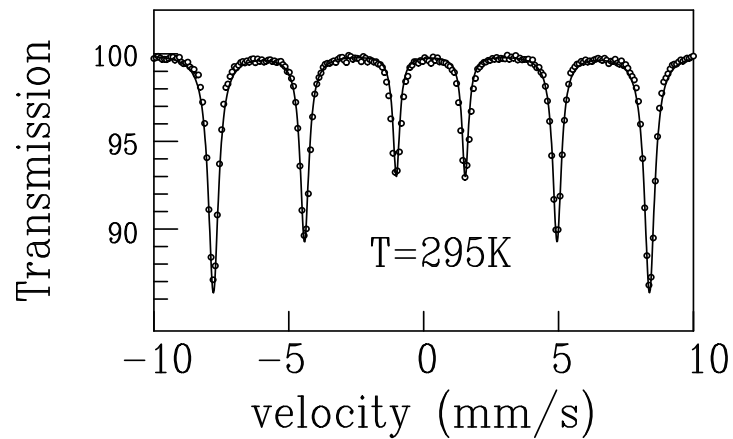
No weak ferromagnetism

Lebeugle et al., PRB, 76, 024116 (2007)

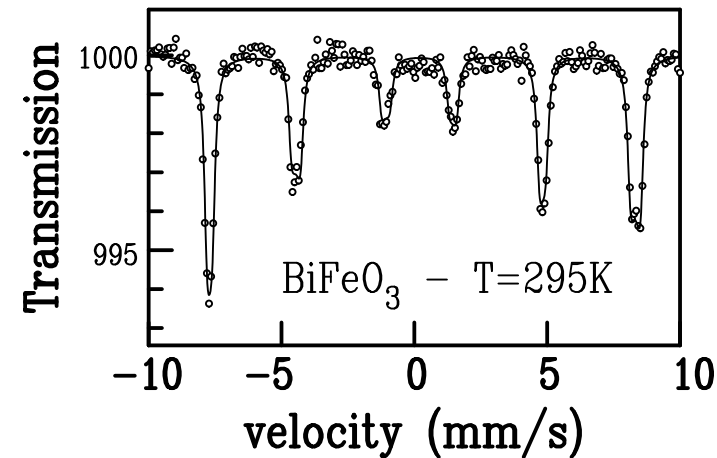
IV. Magnetic properties of BiFeO_3

^{57}Fe Mössbauer spectroscopy

Hyperfine field due to interaction between electronic spins and nuclear levels




Spectrum characteristic of $m\text{Fe}^{3+}$



Spectrum of BiFeO_3 :

- $H_{\text{hf}} = 500 \text{ kG}$
- asymmetry and broadening of the lines : cycloid
- good agreement with ^{57}Fe NMR study

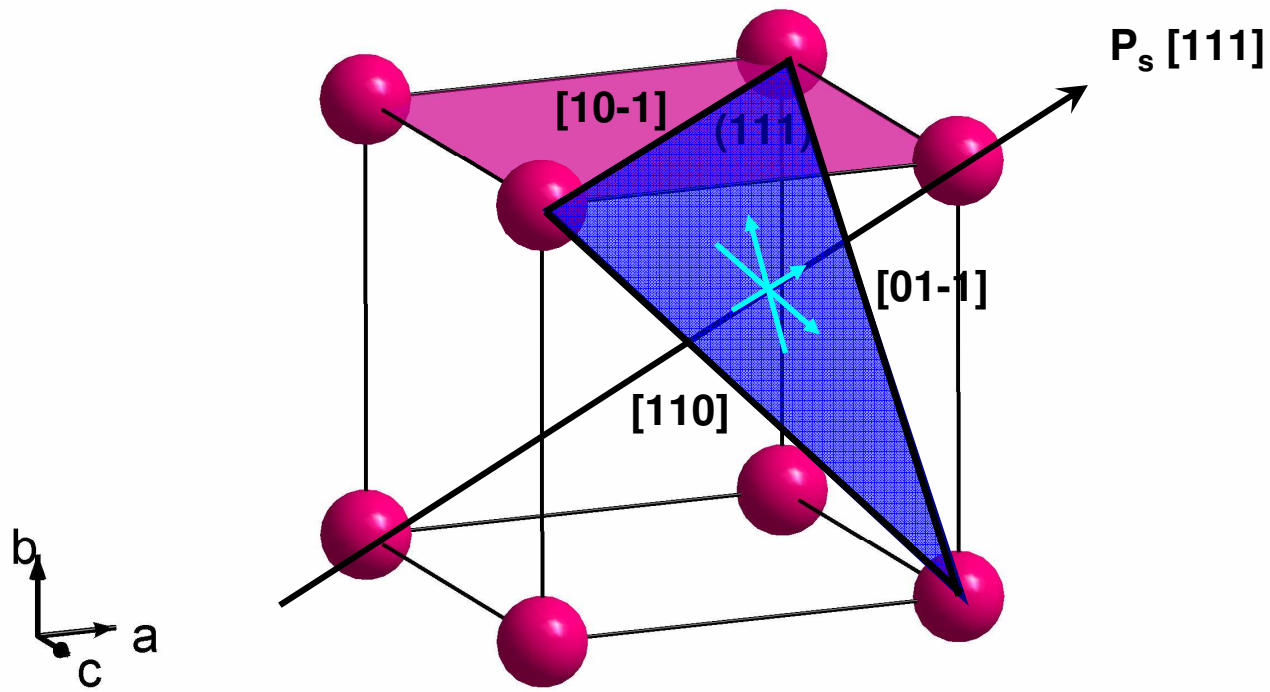
- 
- I. Introduction to multiferroic materials
 - II. Synthesis and characterisation by X-ray and neutron diffraction
 - III. Ferroelectric properties of BiFeO_3 single crystals
 - IV. Magnetic properties of BiFeO_3
 - V. **Magnetoelectric study of BiFeO_3 single crystals**

Conclusions and perspectives



V. Magnetoelectric study on BiFeO₃ single crystals

3 propagation vectors q



$P_s \perp (111)$ plane

Sosnowska et al., J. of Phys. C, 15, 4835 (1982)

V. Magnetoelectric study on BiFeO₃ single crystals

4-circles neutron diffraction

A. Gukasov, Super 6-T2 diffractometer / ORPHEE reactor / LLB, France

Technical specifications :

Neutrons beam $\lambda = 1.4$ and 2.345 \AA

Multidetector PSD and monodetector

Single crystals of BiFeO₃ :

Millimeter sized and highly resistive

Ferroelectric/ferroelastic single domain

→ First measurements by neutron diffraction under electric fields

V. Magnetoelectric study on BiFeO₃ single crystals

6 possible “satellites” around each magnetic peak

1 cycloid \leftrightarrow 2 “satellites” in the reciprocal space

G-Type AF \rightarrow peaks $\{1/2, 1/2, 1/2\}$ purely magnetic

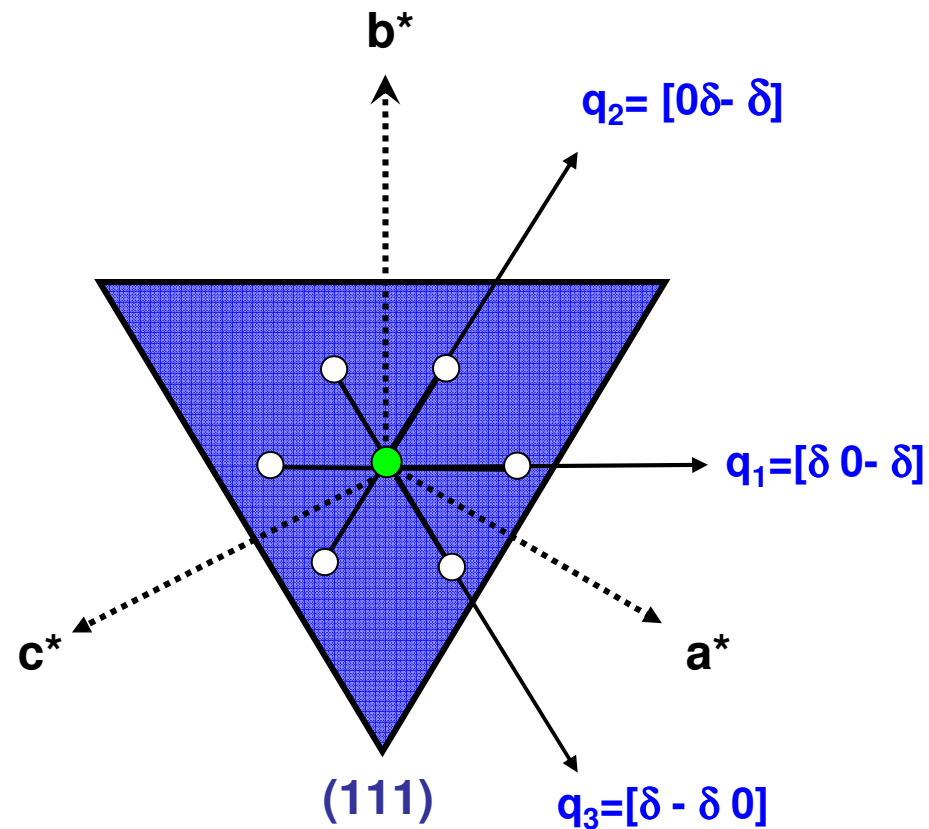
Propagation vector (\AA^{-1}):

$$q = a^* \delta$$

$$\delta = 0.0045$$

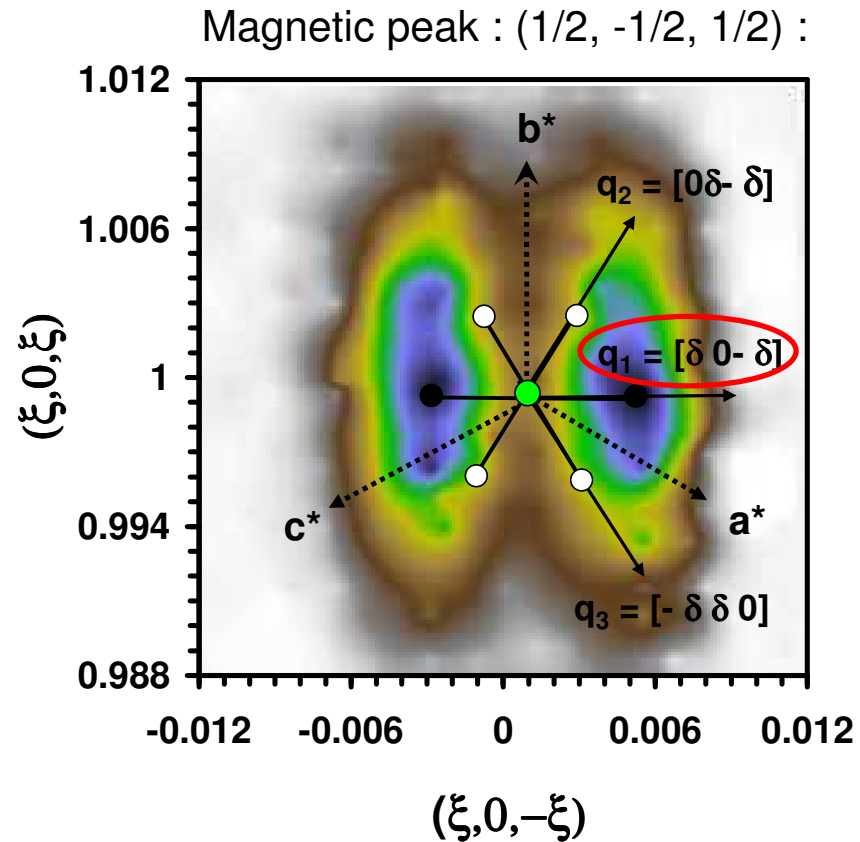
Period (\AA):

$$\lambda_c = 1/q \sim 620 \text{\AA}$$



V. Magnetoelectric study on BiFeO₃ single crystals

Reciprocal lattice scans in the (111) plane



Confirmation of the cycloidal magnetic structure (Sosnowska/powder)

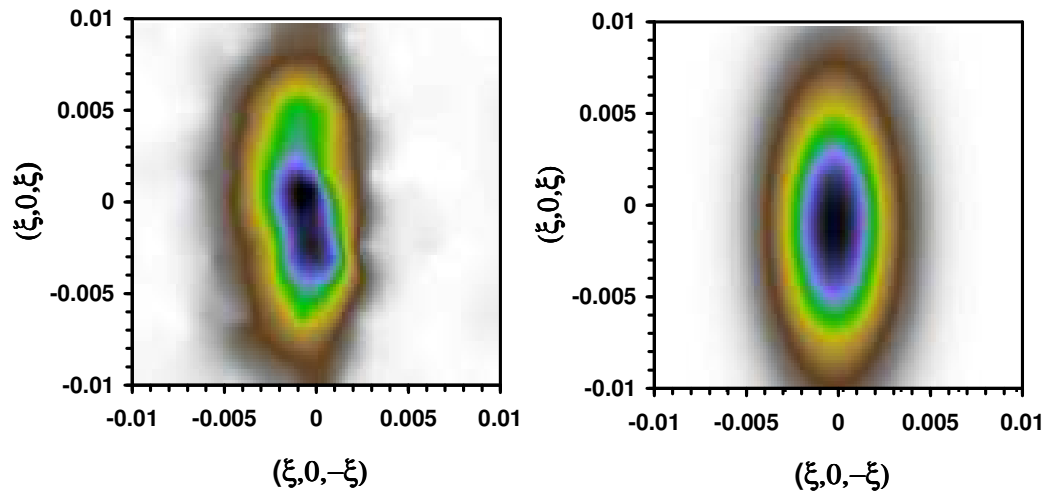
$$|q| = 0.00156(5 \cdot 10^{-5}) \text{ \AA}^{-1} \rightarrow \lambda_c \sim 640 (40) \text{ \AA}$$

One propagation vector $q_1 = [\delta 0 -\delta]$

V. Magnetoelectric study on BiFeO₃ single crystals

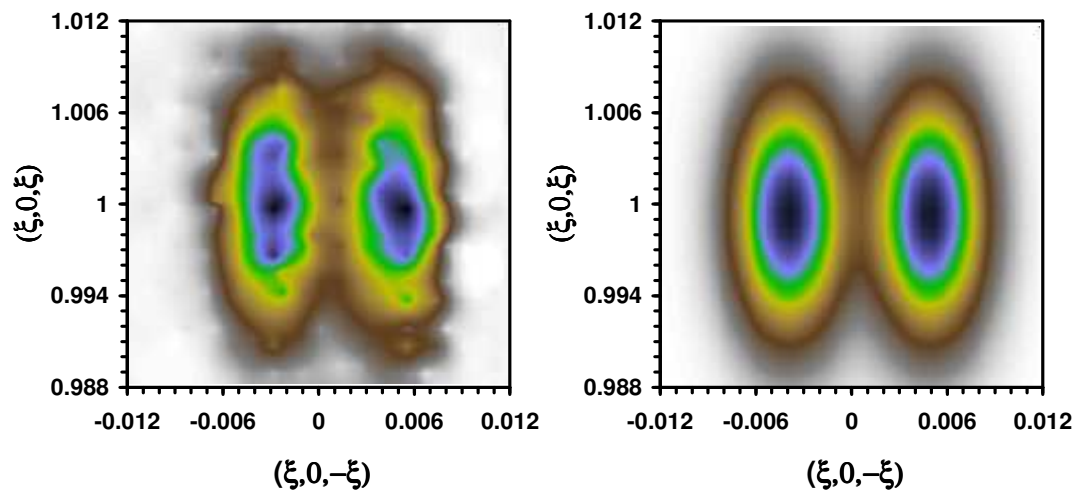
Instrumental resolution

Nuclear peak : (0, 0, 1) :



↕ **Bad resolution**
↔ **Good resolution**

Magnetic peak : (1/2, -1/2, 1/2) :



V. Magnetolectric study on BiFeO₃ single crystals

Fit of the cycloidal structure

Integrated magnetic peaks intensity :

$$I \propto (1 + \cos^2\theta)$$

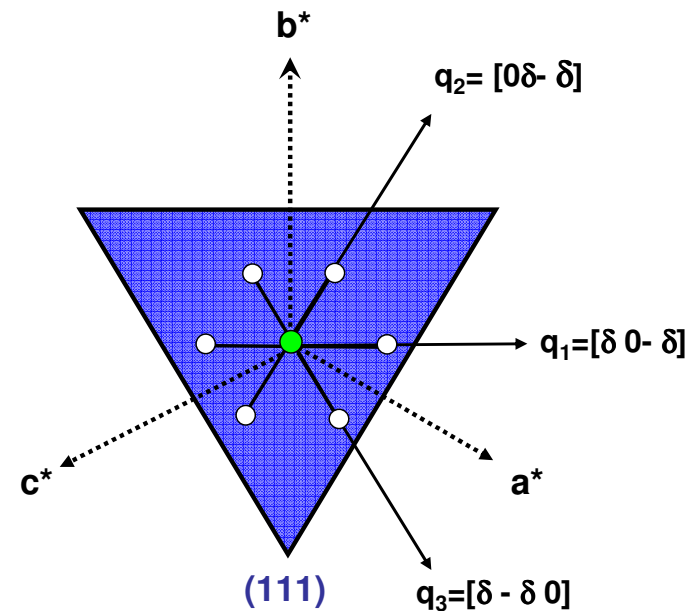
θ = angle between diffraction plane and rotation plane of the moments

Magnetic peaks	$P_s \times q_1$	$P_s \times q_2$	$P_s \times q_3$	I_{obs}
(1/2, -1/2, 1/2)	189	122	122	198(8)
(1/2, 1/2, 1/2)	100	100	100	99(6)
(-1/2, 1/2, 1/2)	122	122	189	116(6)
(1/2, 1/2, -1/2)	122	189	122	114(6)
(1/2, -3/2, 1/2)	113	71	71	111(11)
(3/2, -1/2, -1/2)	71	71	113	83(8)
(-1/2, -1/2, 3/2)	71	113	71	83(8)
(-1/2, -3/2, -1/2)	71	61	61	78(9)
(3/2, 1/2, 1/2)	61	61	71	52(6)
(1/2, 1/2, 3/2)	61	71	61	56(7)

R = 10%

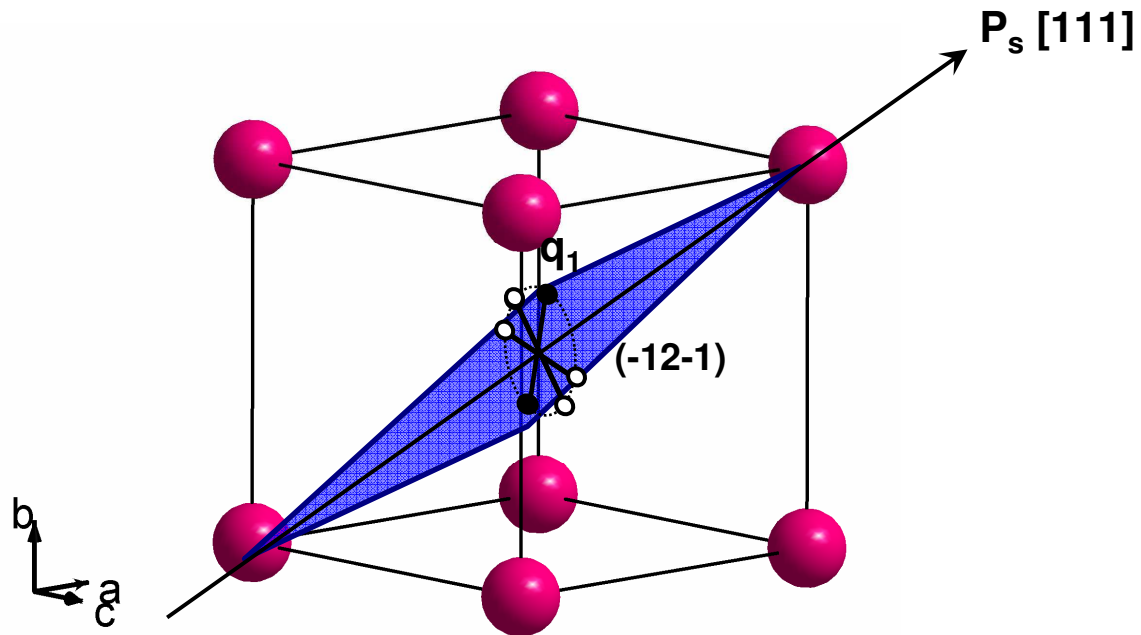
One rotation plane (-12-1) = $P_s \times q_1$

Confirmation of a circular cycloid (ellipticity < 10%)



V. Magnetoelectric study on BiFeO₃ single crystals

Conclusion



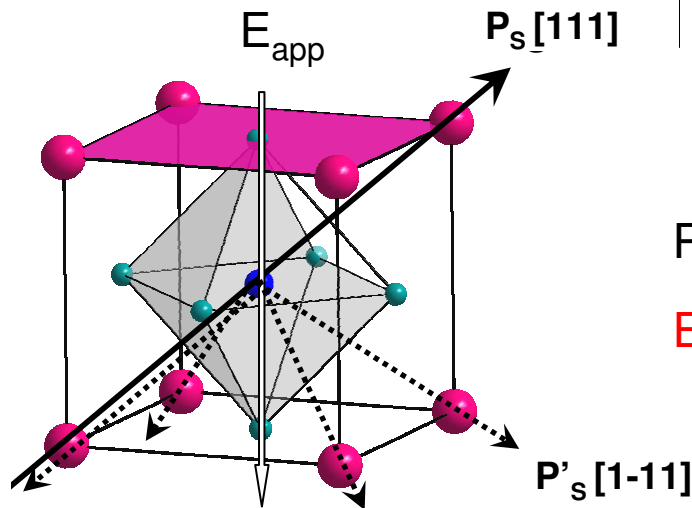
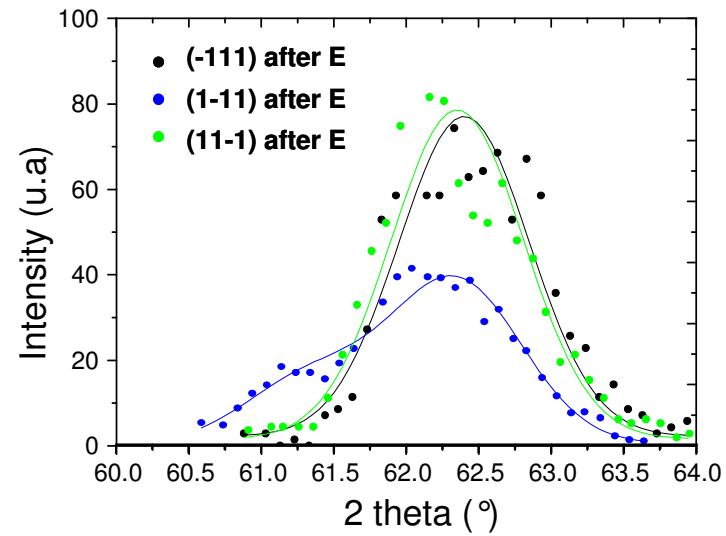
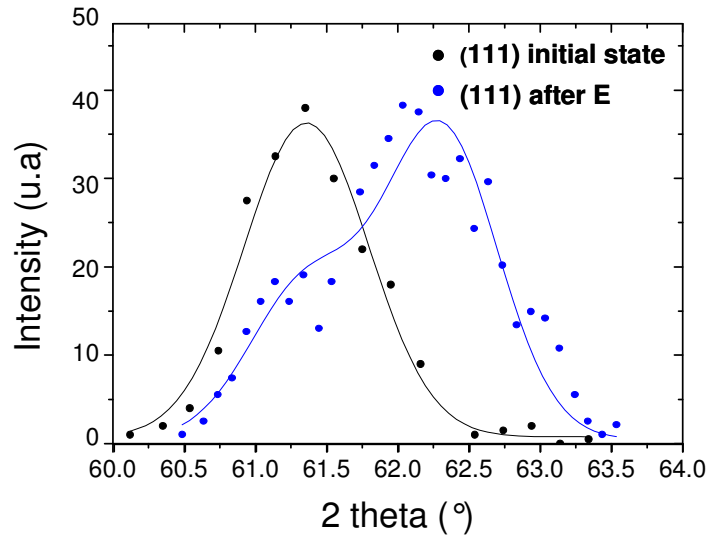
One spin rotation plane (-12-1) containing P_s and q₁ → One cycloid

In the initial state : ferroelectric and magnetic single domain crystal

→ Application of E

V. Magnetoelectric study on BiFeO₃ single crystals

Modification of the ferroelectric domain structure under E



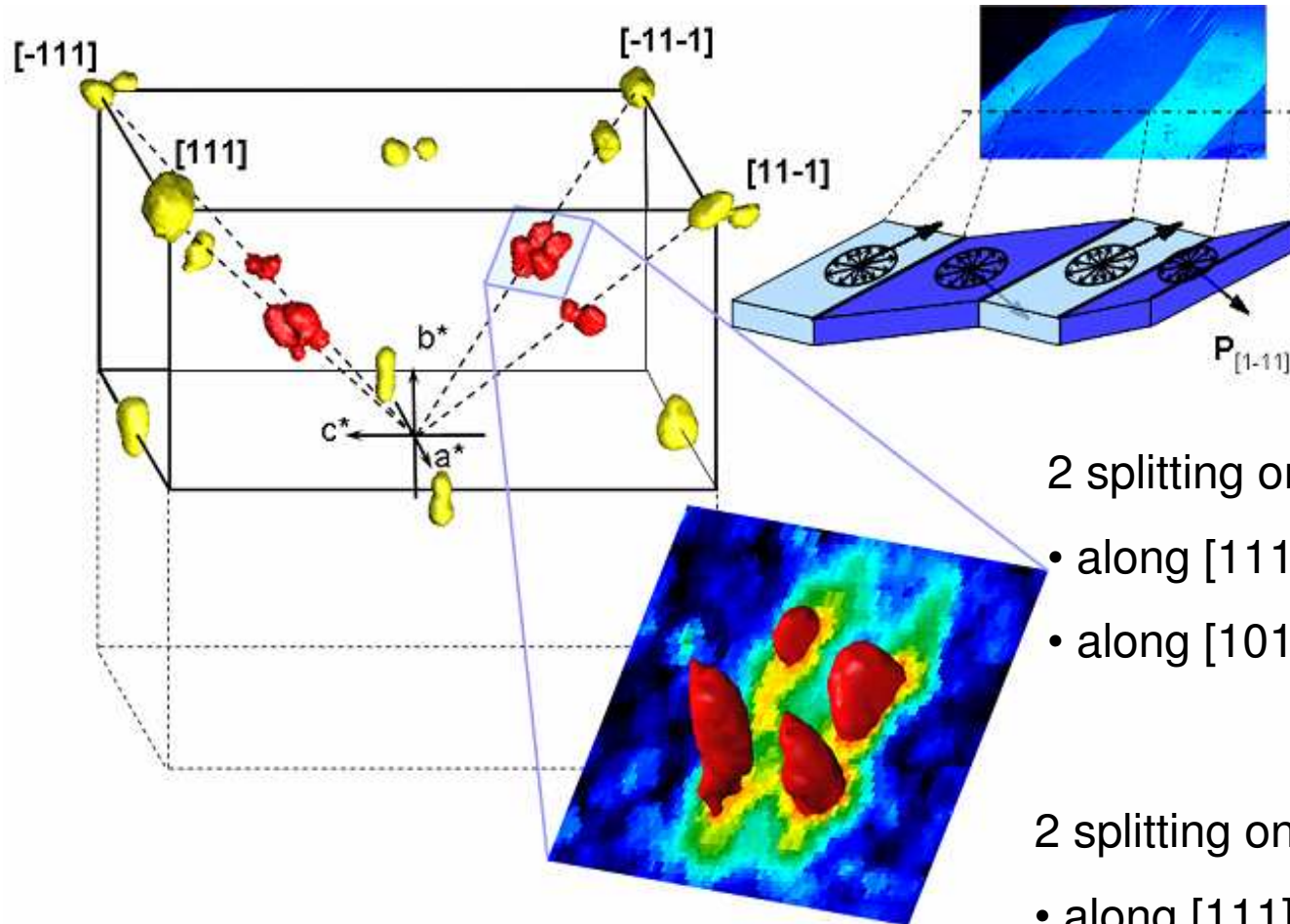
E (~15kV/cm)

Partial switching of P_s by 71°

Evidence for 2 ferroelectric domains (~ 50/50)

V. Magnetoelectric study on BiFeO_3 single crystals

3D reciprocal space mapping using PSD multidetector



2 splitting on **nuclear** peaks :

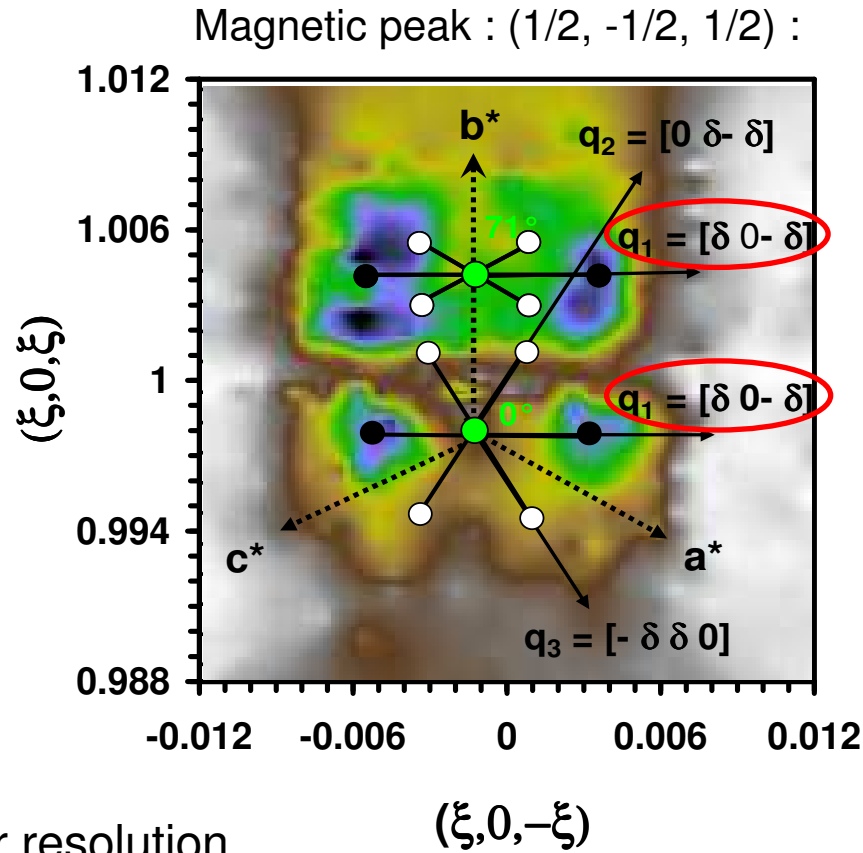
- along $[111]$: rhombohedral distortion
- along $[101]$: crystal buckling

2 splitting on **magnetic** peaks :

- along $[111]$: rhombohedral distortion
- along $[10-1]$: the magnetic cycloid

V. Magnetoelectric study on BiFeO₃ single crystals

Reciprocal lattice scans in (111) plane



Same resolution

Better resolution

One propagation vector for the 2 domains $q_1 = [\delta 0 -\delta]$

Period of the cycloid : unchanged

V. Magnetoelectric study on BiFeO₃ single crystals

Modification of the magnetic domain structure under E

Integrated magnetic peak intensities :

- Strong modification of the intensities
- Sum of 2 (or more) rotation planes

Magnetic peaks	I_{obs} (Initial)	I_{obs} (after E)
(1/2, -1/2, 1/2)	198(8)	158(7)
(1/2, 1/2, 1/2)	99(6)	145(6)
(-1/2, 1/2, 1/2)	116(6)	120(8)
(1/2, 1/2, -1/2)	114(6)	112(10)

V. Magnetoelectric study on BiFeO₃ single crystals

Modification of the magnetic domain structure under E

Integrated magnetic peak intensities :

Magnetic peaks	$P_S \times q_1$	$P'_S \times q_1$	$P'_S \times q'_2$	$P'_S \times q'_3$	I_{obs}	I_{calc}
(1/2, -1/2, 1/2)	189	100	100	100	158(7)	150
(1/2, 1/2, 1/2)	100	189	122	122	145(6)	139
(-1/2, 1/2, 1/2)	122	122	122	189	120(8)	122
(1/2, 1/2, -1/2)	122	122	189	122	112(10)	122

44% 56%

Conclusion from the fit :

44% domain I : Rotation plane : $(-12-1) = P_{[111]} \times q_1$

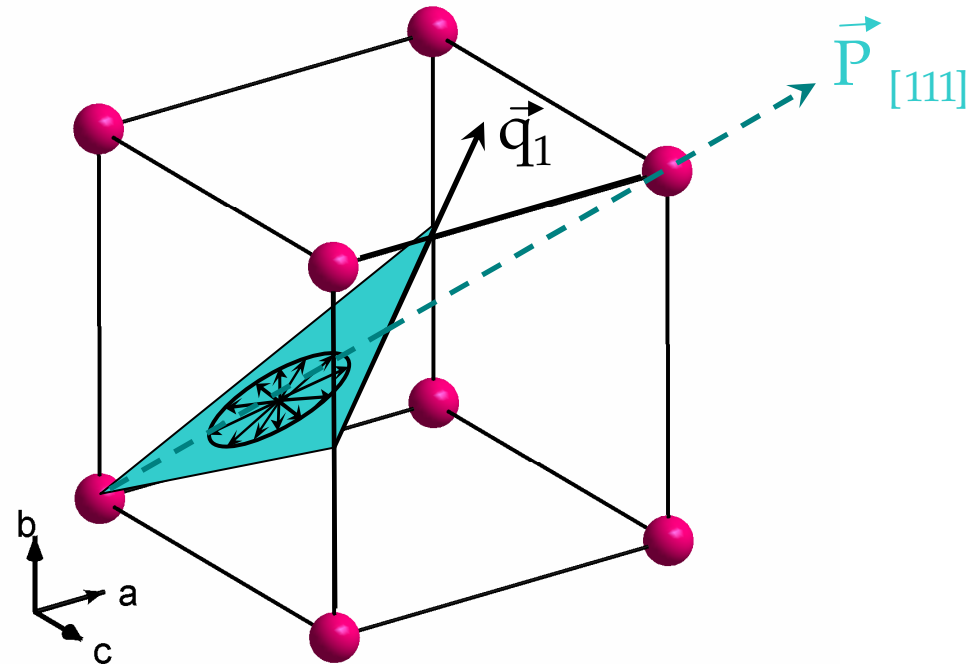
56% domain II : Rotation plane : $(121) = P'_{[1-11]} \times q_1$

Same propagation vector : $q_1 = [-101]$

Evidence for 2 magnetic domains \leftrightarrow 2 ferroelectric domains

V. Magnetoelectric study on BiFeO₃ single crystals

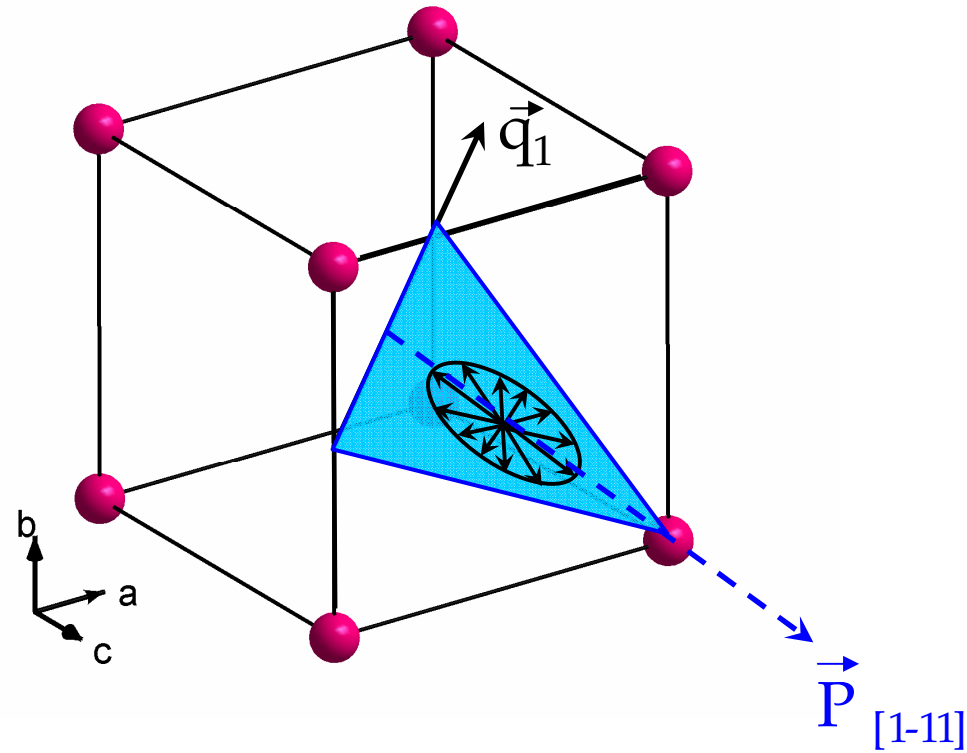
Domain I



$$\text{Rotation plane : } (-12-1) = P_{[111]} \times q_1$$

V. Magnetoelectric study on BiFeO₃ single crystals

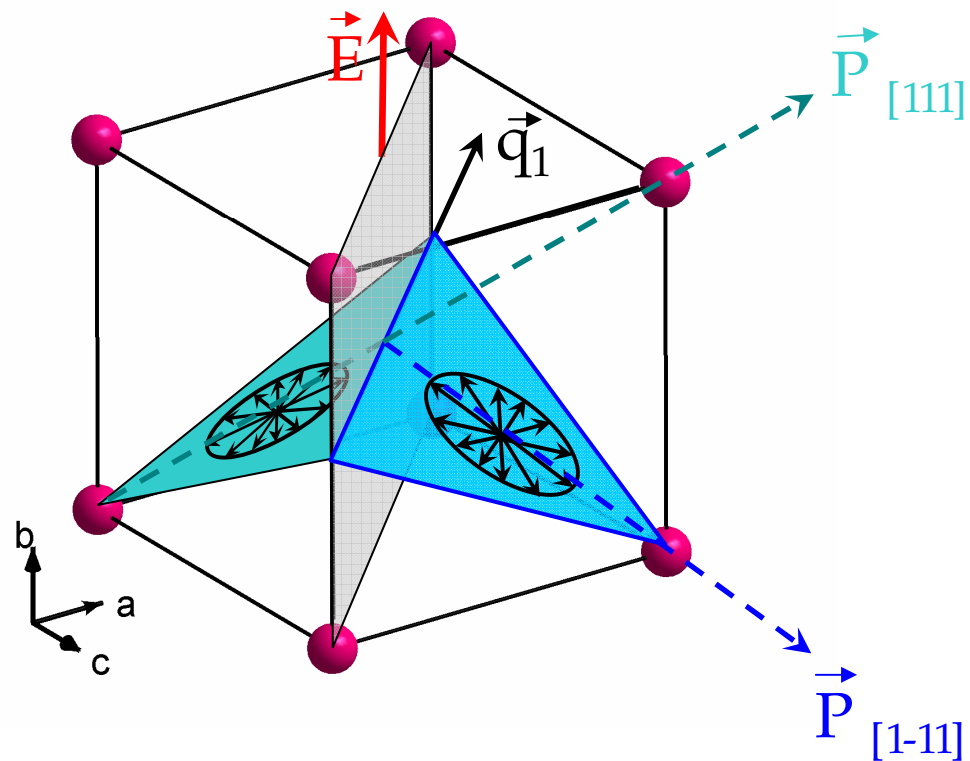
Domain II



$$\text{Rotation plane : } (121) = P'_{[1-11]} \times q_1$$

V. Magnetoelectric study on BiFeO₃ single crystals

Conclusion



Lebeugle et al., submitted to PRL

V. Magnetoelectric study on BiFeO₃ single crystals

Conclusions for neutron measurements

Electric fields on a magnetic and ferroelectric single domain BiFeO₃ crystal :

Twining of the crystal into 2 ferroelectric domains

Switching of P_S by 71°

Switching of the magnetic rotation plane by 71°

The propagation vector remains unchanged

Evidence for the coupling between M and P at 300K by neutron diffraction on BiFeO₃ single crystals.

- 
- I. Introduction to multiferroic materials
 - II. Synthesis and characterisation by X-ray and neutron diffraction
 - III. Ferroelectric properties of BiFeO_3 single crystals
 - IV. Magnetic properties of BiFeO_3
 - V. Magnetoelectric study of BiFeO_3 single crystals

Conclusions and perspectives



Conclusions

Growth by flux method of highly pure BiFeO_3 single crystals : stoichiometric, millimetric, highly resistive and magnetic/ferroelectric single domain

Very large electrical polarization ($\sim 100 \mu\text{C}\cdot\text{cm}^{-2}$) in BiFeO_3 evidenced by P-E loops and in good agreement with theoretical predictions

Evidence for the coupling between antiferromagnetic and ferroelectric domains at 300K by neutron diffraction.

Concerning BiFeO_3 :

M(T) and M(H) measurements under higher E_{app} using SQUID magnetometer

P(E) measurements under higher H_{app}

M measurements under pulsed magnetic fields

Magneto optic measurements

Concerning $\text{Bi}_{0.45}\text{Dy}_{0.55}\text{FeO}_3$:

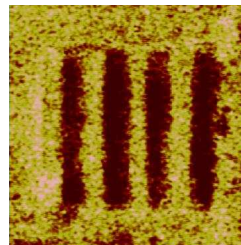
Improving the crystal growth procedure

P(E) on single crystals

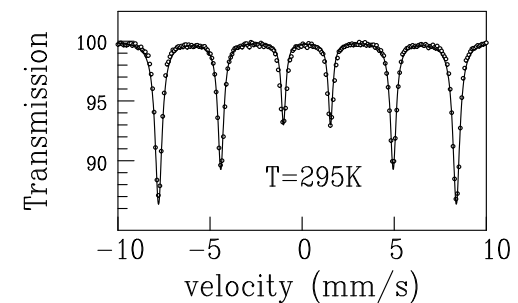
Studying the ME coupling by neutron diffraction



*Single crystal of $\text{Bi}_{0.45}\text{Dy}_{0.55}\text{FeO}_3$
 $0.75 \times 0.15 \times 0.04 \text{ mm}^3$ (optic)*



*First proof of ferroelectricity
at room temperature (PFM)*



No cycloid (Mössbauer spectroscopy)

Thanks to...

SPEC, CEA Saclay : A. Forget, P. Bonville, G. Lebras-Jasmin, F. Albenque

CNRS/THALES : S. Fusil, A. Barthélémy, K. Bouzehouane, H. Béa, M. Bibès, R. Lebourgeois

LLB, CEA Saclay : A. Gukasov, G. André, F. Ott, A. Bataille, J-L. Meuriot, T. Robillard

ICMMO, Orsay : J-F Marucco, G. Dhalenne, R. Guillot, R. Saint-Martin, P. Berthet

MPQ, Paris VII : M. Cazayous, A. Sacuto

ESPCI, Paris : P. Monod, R. Lobo

Ecole Polytechnique, Palaiseau : X. Legoff, L. Ricard

SRMP, CEA Saclay : S. Poissonnet, H. Martin

ANR 2005 « FerroElectroMagnétiques pour l'Electronique de Spin » (FEMMES)