Condensed Matter and Materials Physics Group

Magnetism for Energy Efficient Devices

S. A. Cavill, University of York

Ferromagnets and Ferroelectrics

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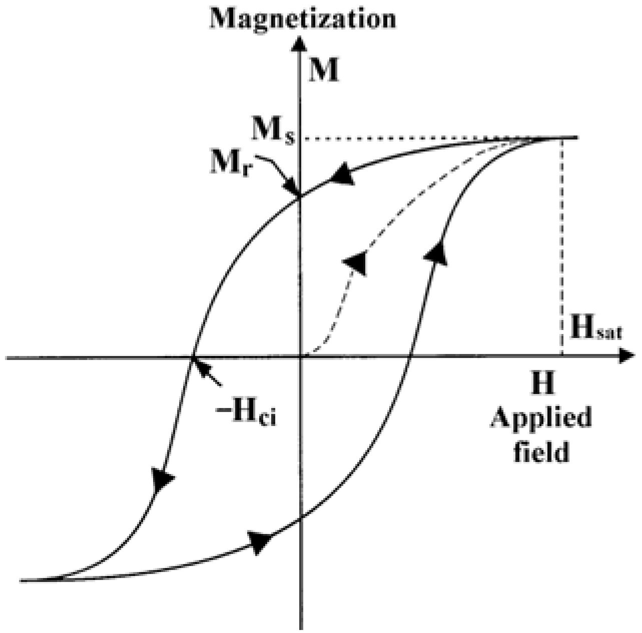

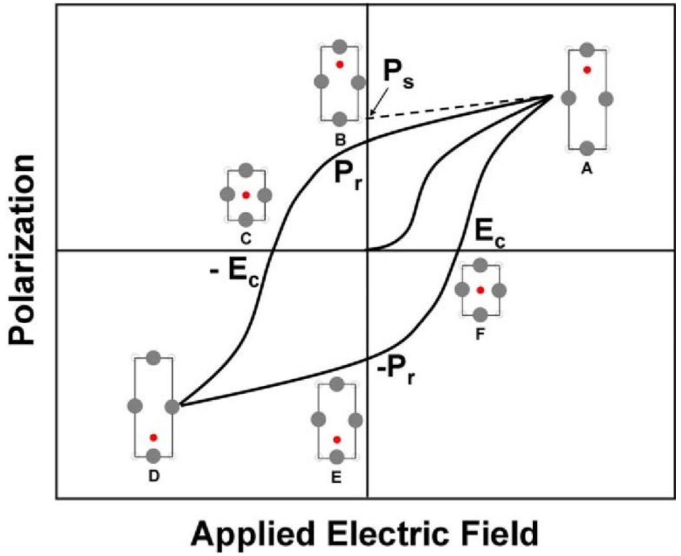

Ferromagnet : any material that exhibits spontaneous magnetization (a net magnetic moment in the absence of an external magnetic field) that can be reversed by the application of an external magnetic field.

Ferroelectricity : is a property of certain materials which possess a spontaneous electric polarization that can be reversed by the application of an external electric field. Ferroelectrics – also piezo and pyroelectrics.

Deformation with applied field

Hybrid Magnetoelectrics

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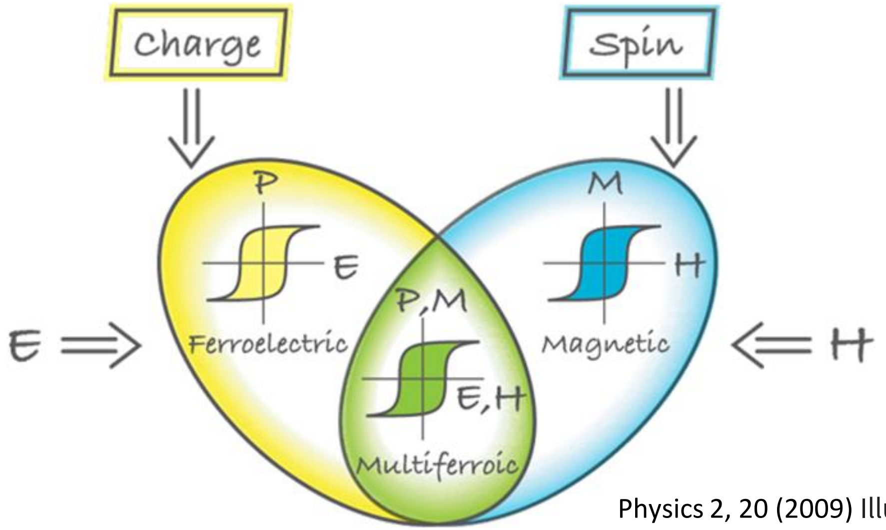
Multiferroics combine the properties of ferroelectrics and ferromagnets.

If we manage to create multiferroics that are simultaneously ferromagnetic and ferroelectric (and coupled) then there is a magnetic response to an electric field, or, vice versa.

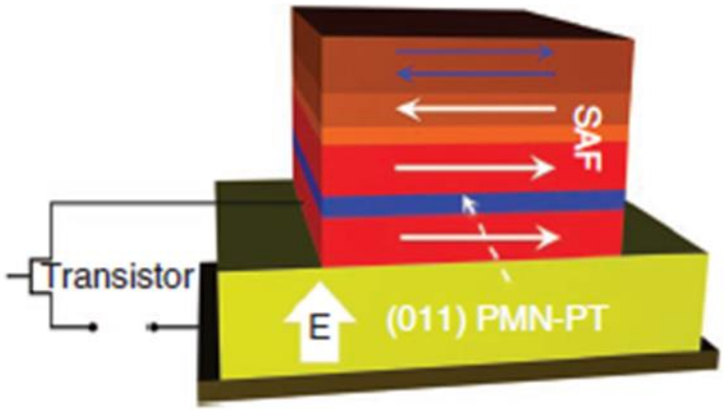
Ideal material for spintronic applications

No current flow = low power consumption.

Intrinsic or multilayer composites?



Physics 2, 20 (2009) Illustration: **Alan Stonebraker**



Nat Commun **2**, 553 (2011)

Single Phase Magnetoelectrics

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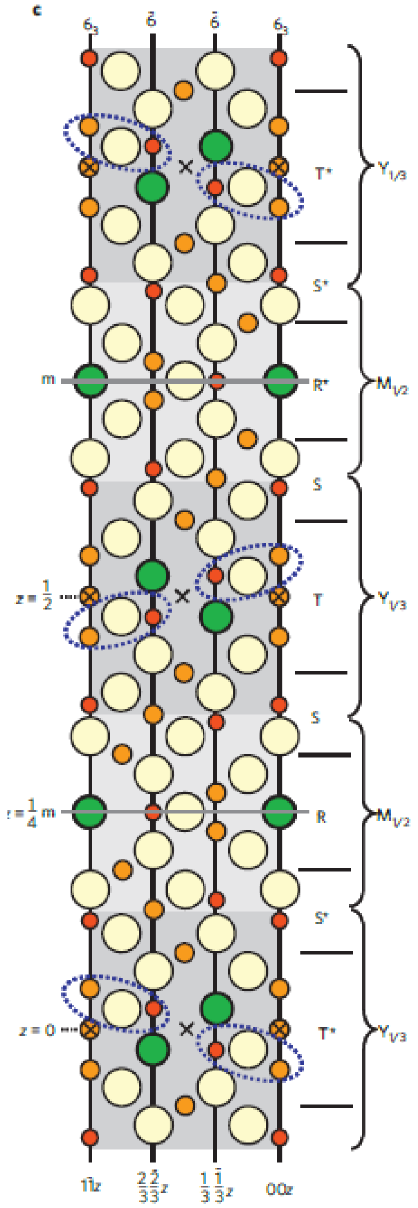
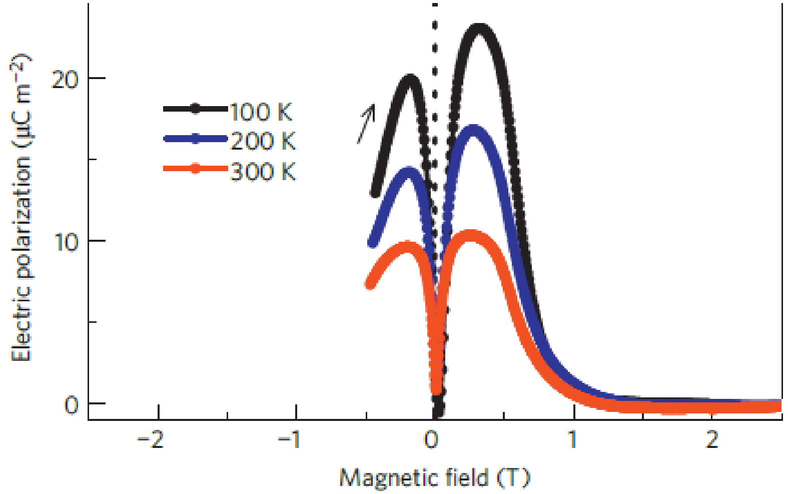
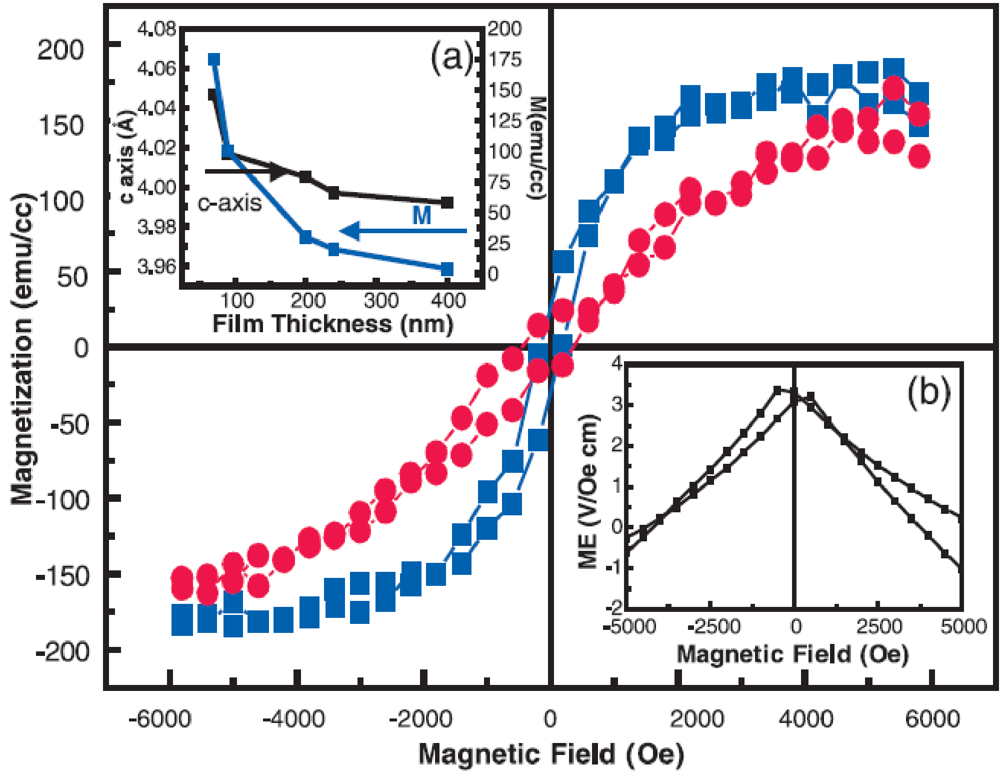


Z-type hexaferrite $Sr_3Co_2Fe_{24}O_{41}$



Nat. Mat. 9, 797 (2010)

Thin film $BiFeO_3$



Science **299**, 1719–1722 (2003)

Magnetostriction

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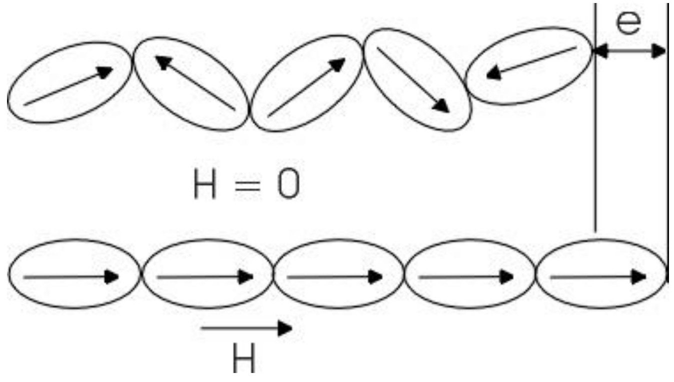
Magnetostriction is the change of a material's physical dimensions in response to changes in its magnetization. The inverse magnetostrictive effect characterizes the change of domain magnetization when a stress is applied to a material.

Remember: The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical stress and the electrical state

$$\lambda = \Delta l/l = s$$



$$\Delta l = sl \approx Ed_{ij}l$$

Can we make use of materials with these properties?

Magnetostriction

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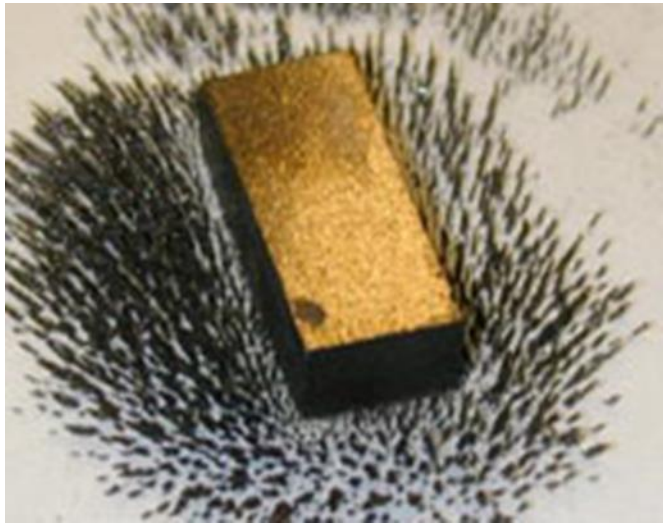
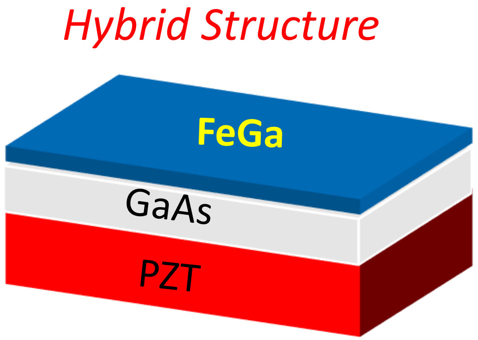




Fe has a relatively low magnetostriction λ=20ppm

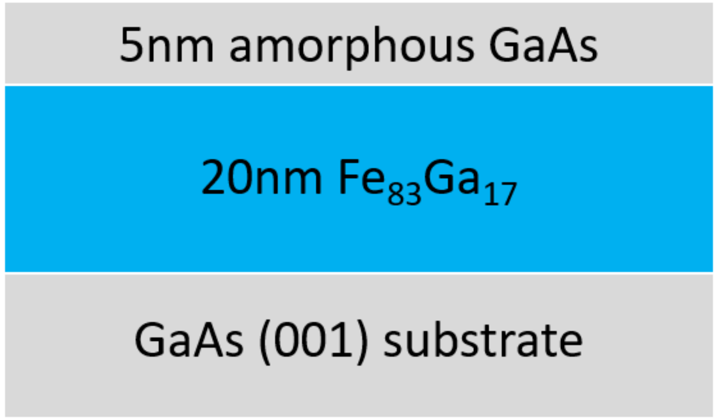
FeGa alloys formed by quench cooling the melt are known to have λ=400ppm for Ga concentrations 17% – 28%

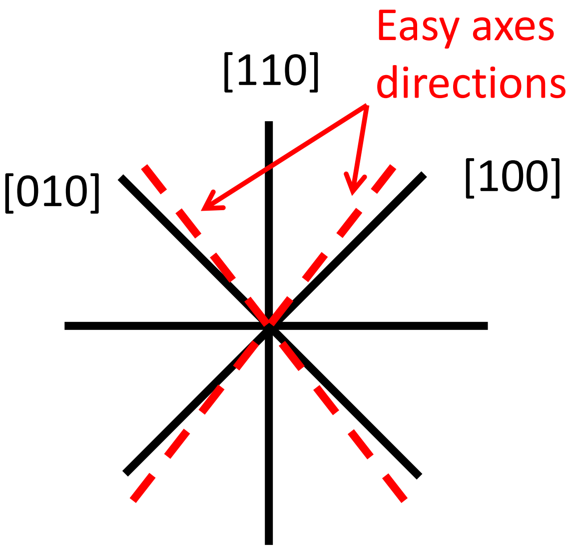
Epitaxial thin films grown on GaAs have $\lambda \sim$ bulk samples

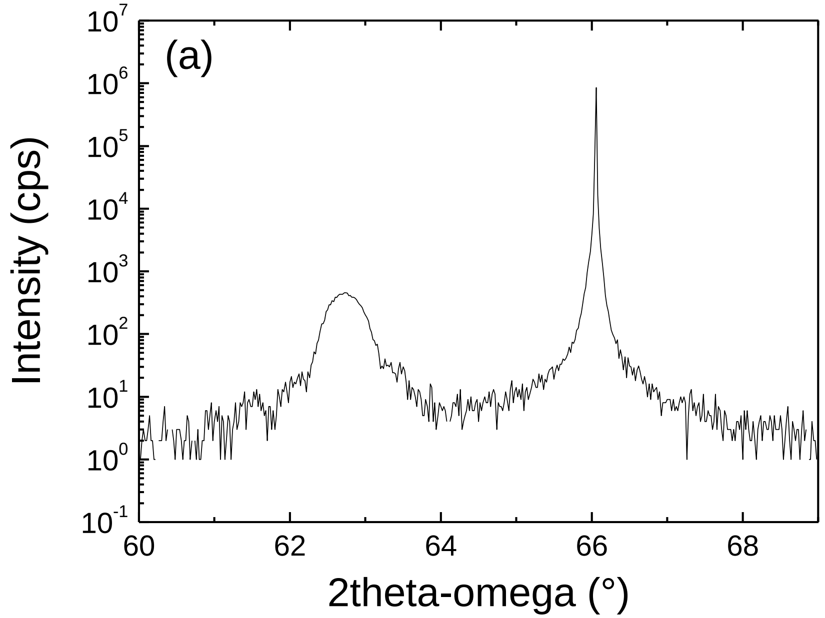
Create a hybrid magnetoelectric by forming a laminate structure with PZT (or FE)

Non-volatile voltage control

MBE growth at 0°C







Non-volatile voltage control

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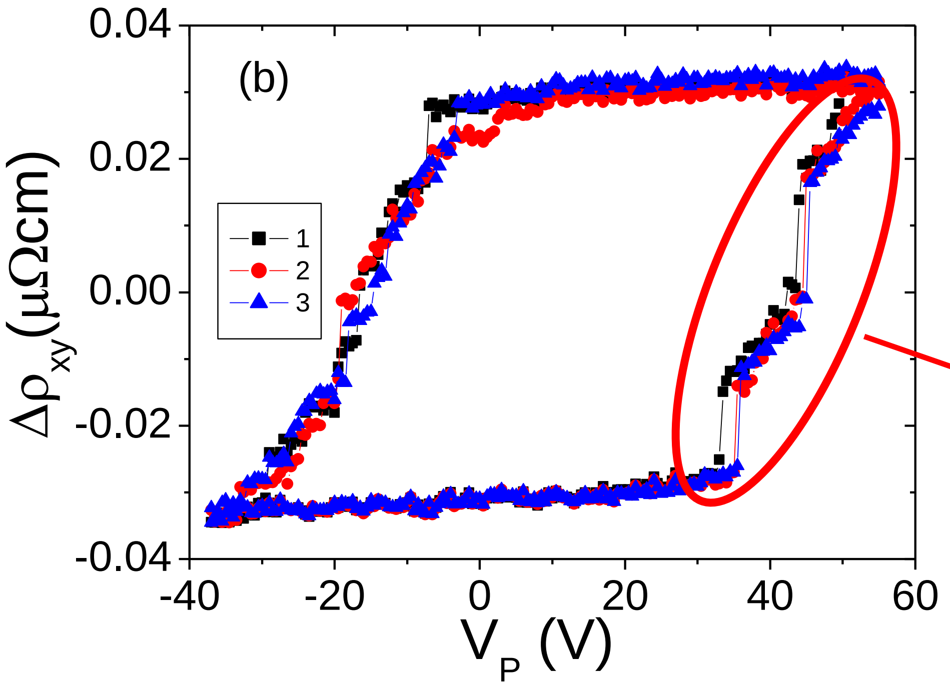
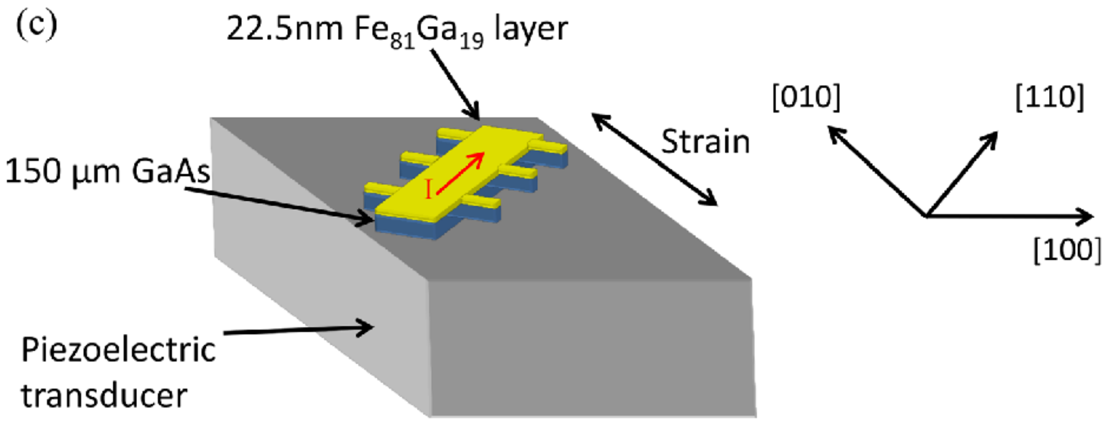
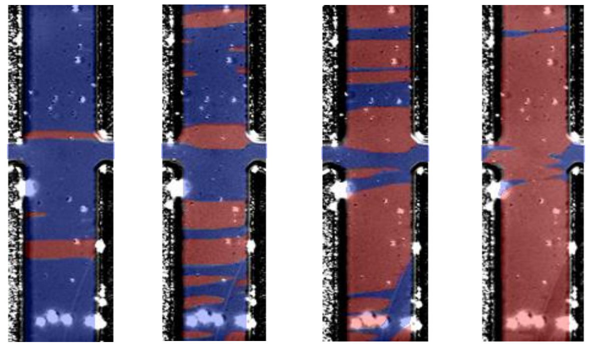
$$\rho_{xx} = \rho_{av} + \Delta\rho\cos 2\phi$$

$$\rho_{xy} = \Delta\rho\sin 2\phi$$







Applied Physics Letters **101**, 072402 (2012)

Biaxial EA – “Voltage” allows us to switch between one of the two

Ferromagnetic resonance

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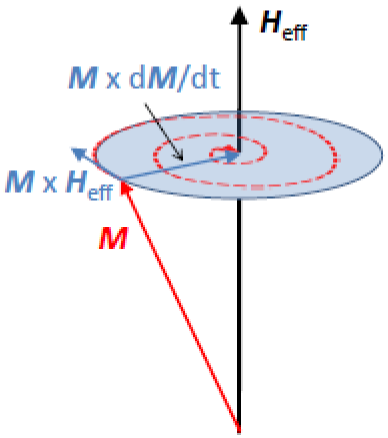
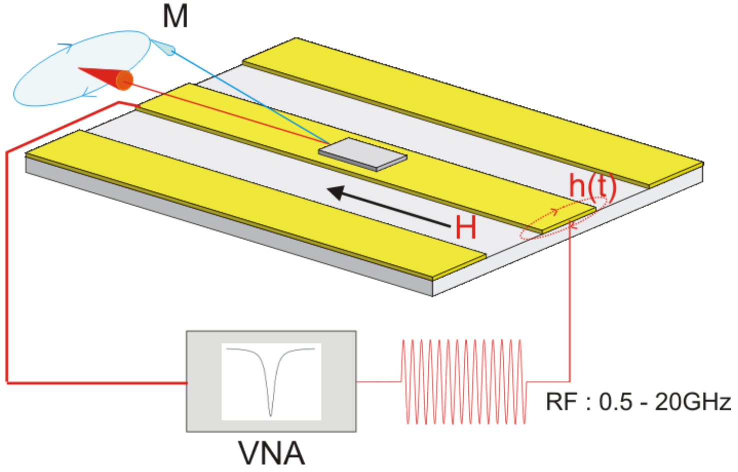
FMR is a method to measure magnetic properties by detecting the precessional motion of the magnetization in a ferromagnetic sample



Zeeman splitting in FM materials leads to Zeeman frequencies that are typically in the microwave region : $\gamma = 17.6\,\mathrm{MHzOe}^{-1}$

$$\omega_o = \gamma H_{res}$$



Therefore the absorption of a magnetic field of frequency ω_o can be pictured as the excitation of a precession mode of the magnetisation `gyroscope'.

Ferromagnetic resonance

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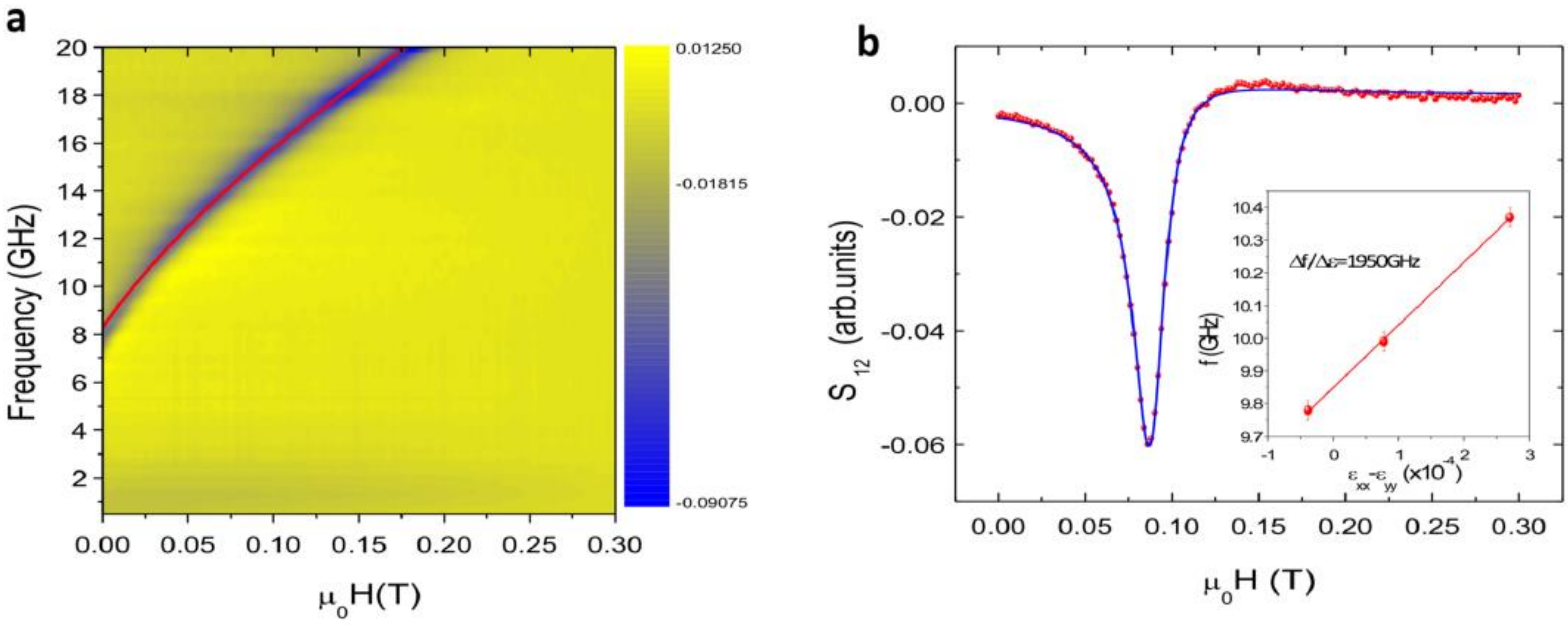
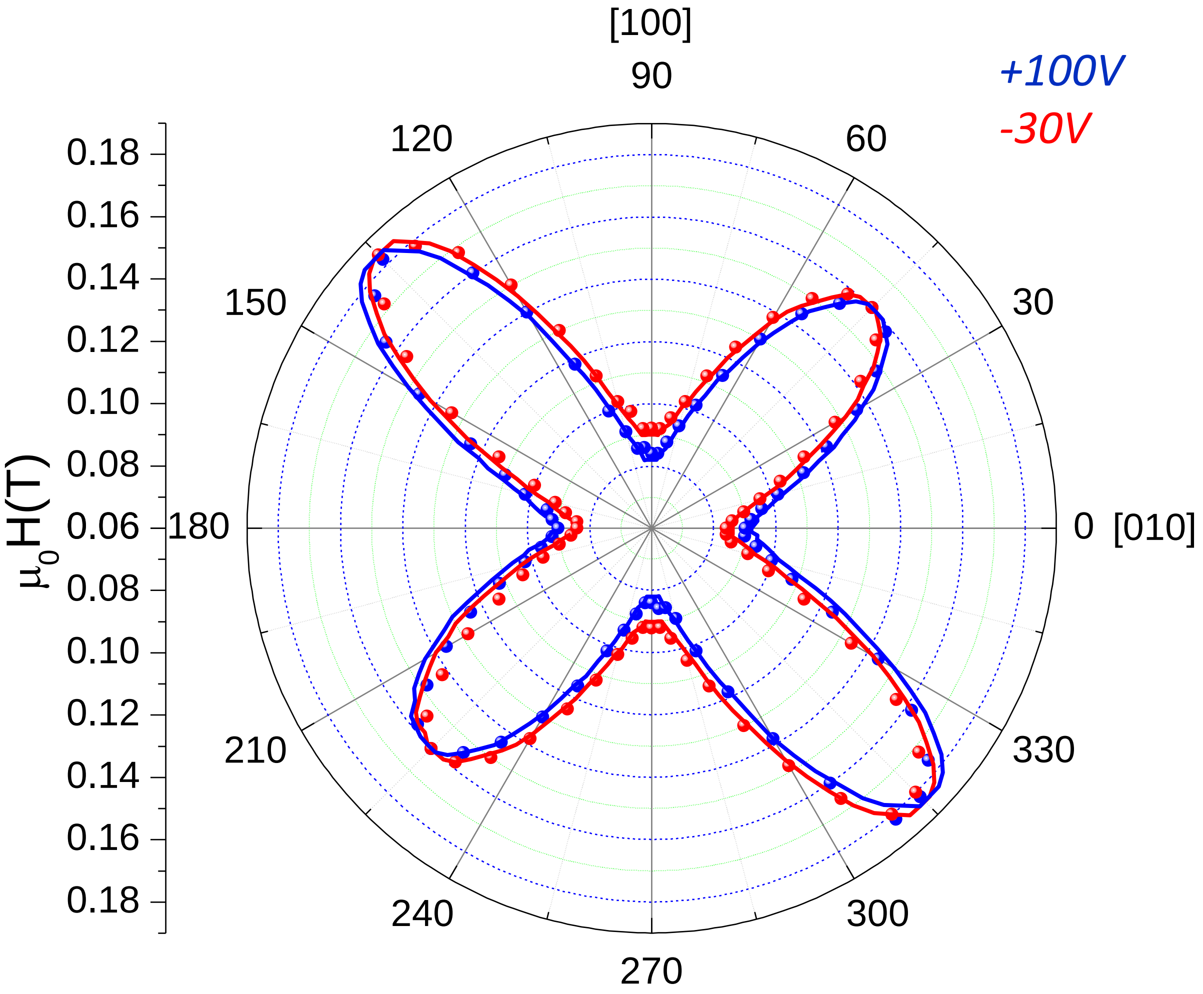
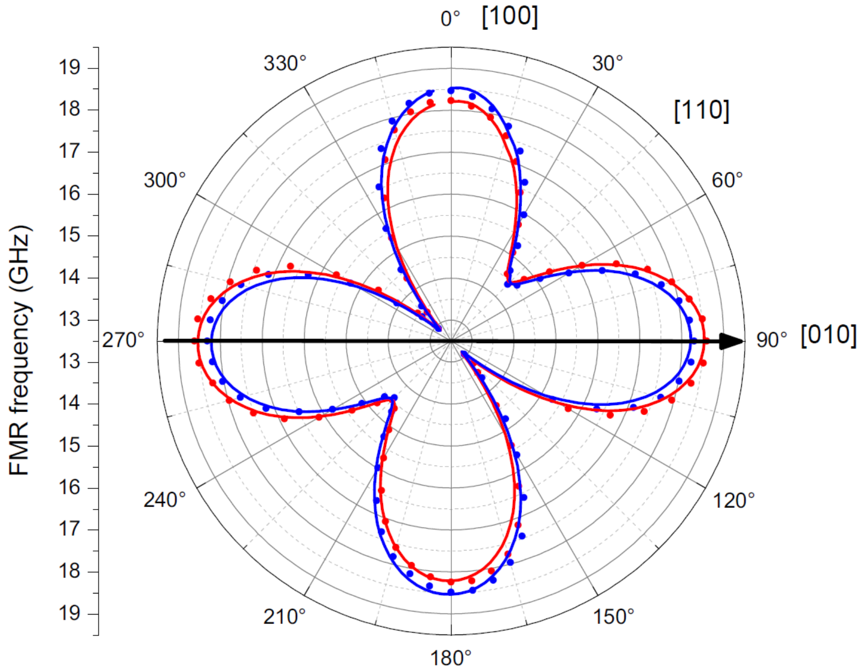


Sci. Reports 3:2220 (2013)

Ferromagnetic resonance

Anisotropy - ϕ dependence





$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{\sin^2\vartheta}\left(f_{\vartheta\vartheta} f_{\phi\phi} - f_{\vartheta\phi}^2\right),$$

Sci. Reports 3:2220 (2013), *Sci. Reports* **9**, 3156 (2019)

Electrical control of reversal processes

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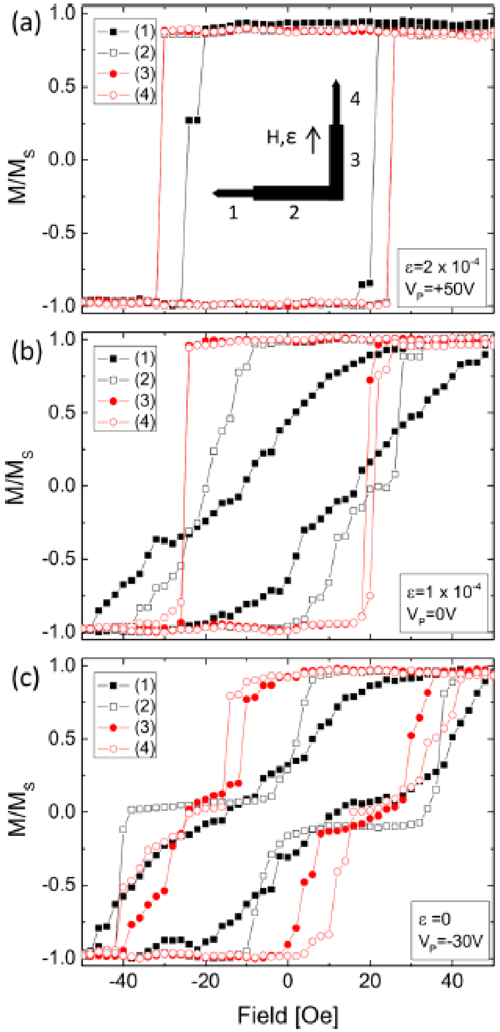

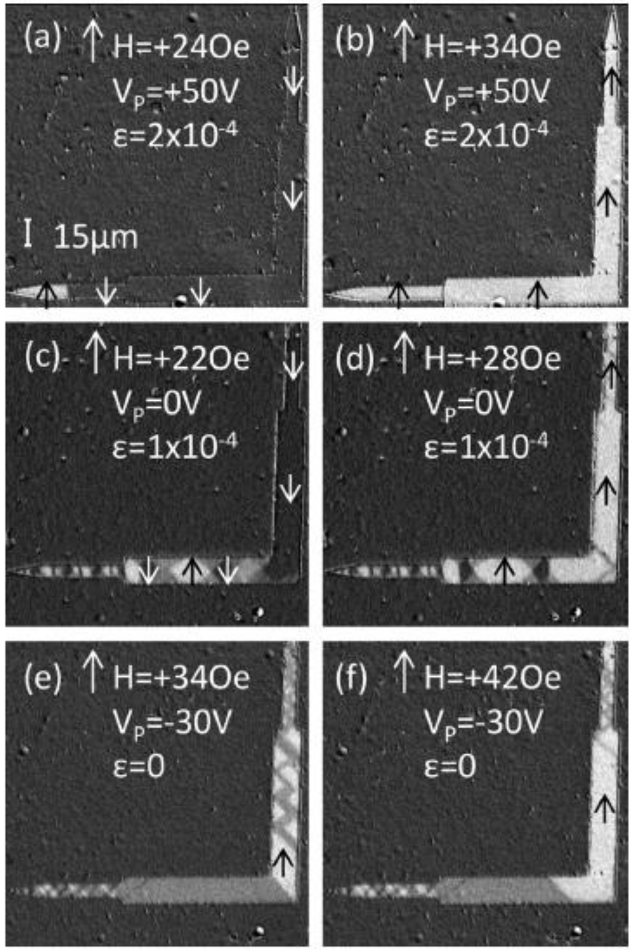

Appl. Phys. Lett. 102, 032405 (2013)

Magnetic Nanostructures

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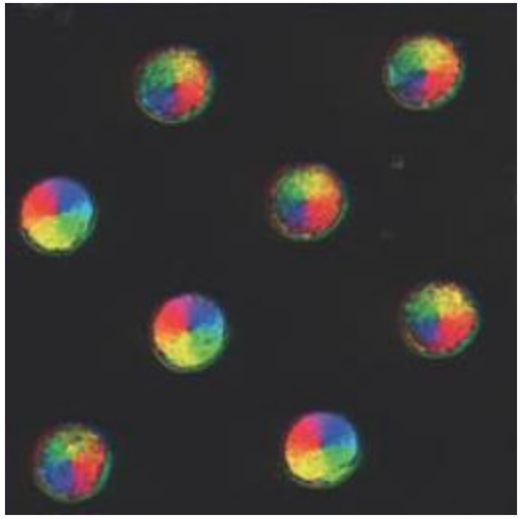

What happens when we reduce the size?

XMCD - PEEM

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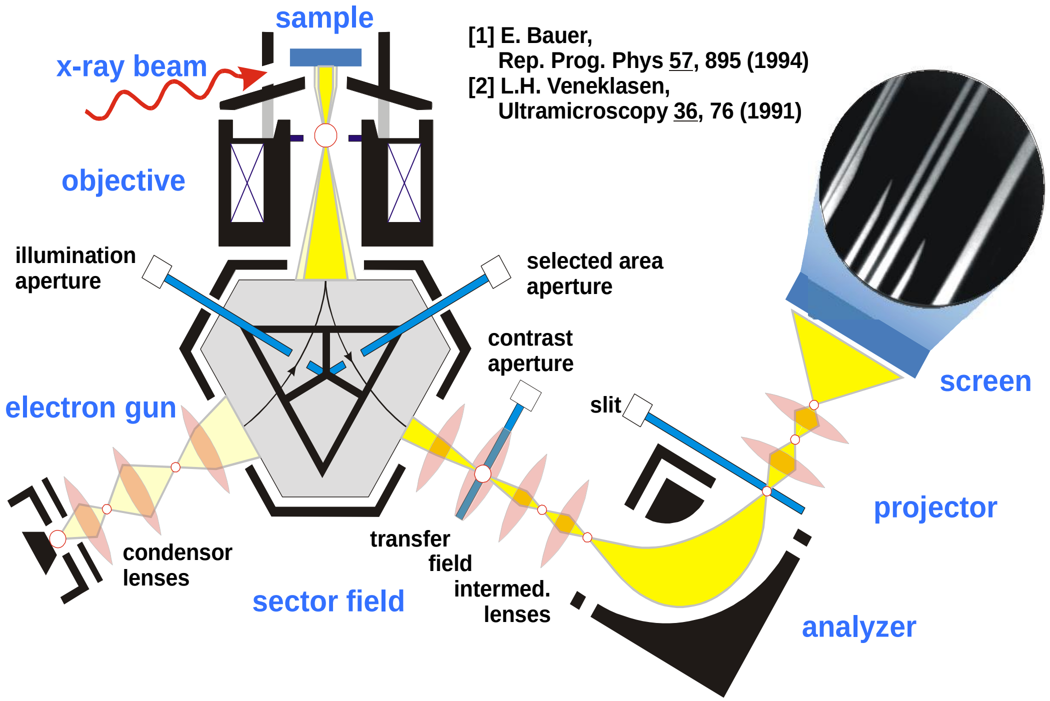
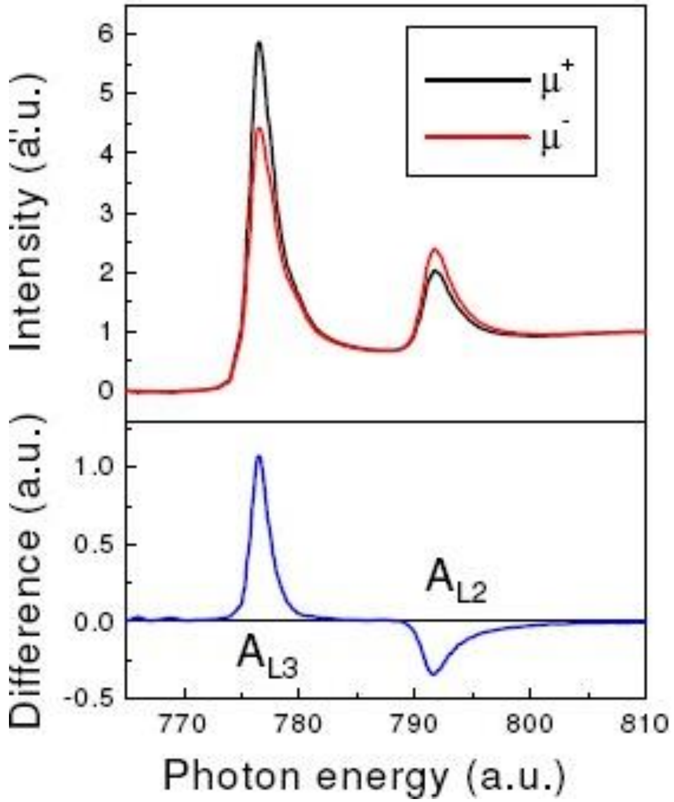


[1] E. Bauer, Rep. Prog. Phys 57, 895 (1994)
[2] L.H. Veneklasen, Ultramicroscopy 36, 76 (1991)



- Spin dependent probe of Fermi level occupation. Element specific measurement
- Potential for resolving spin and orbital moments with the XMCD sum rules.
- Measures projection of M onto photon propagation vector

XMCD - PEEM

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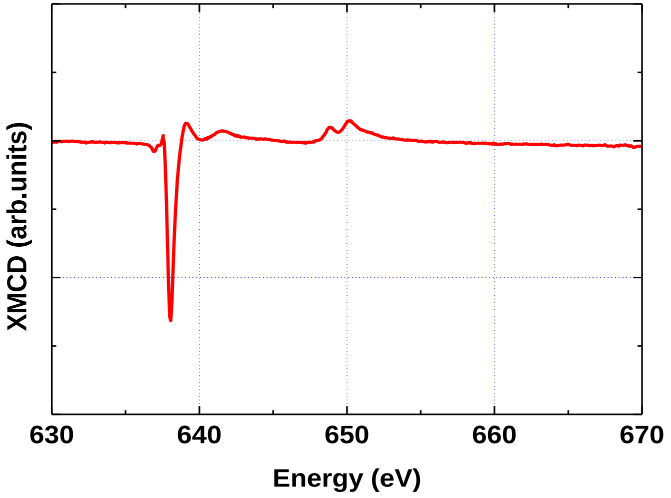
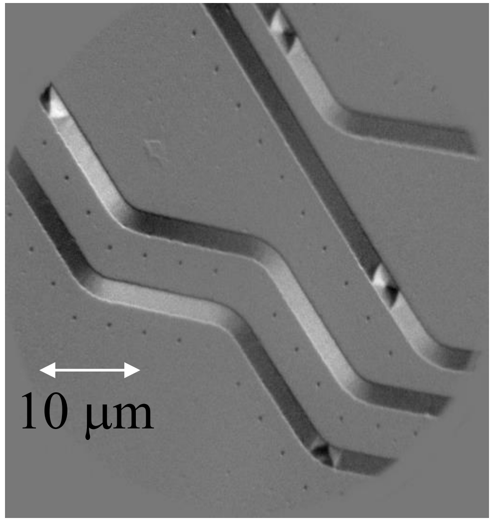
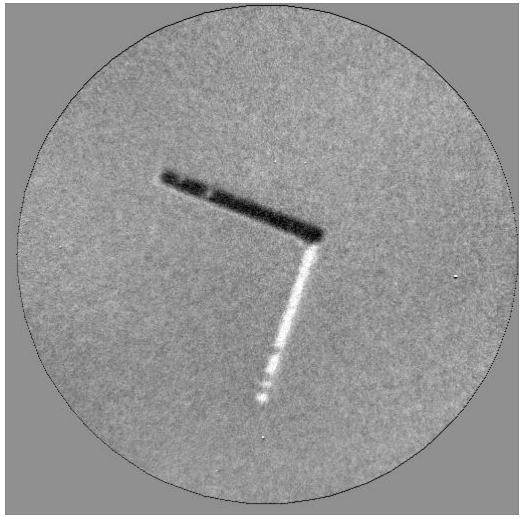
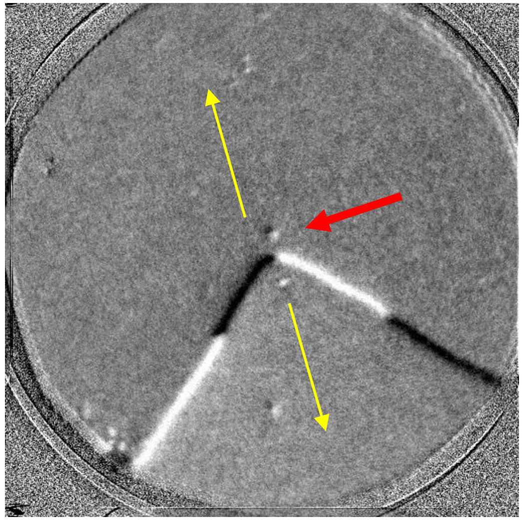


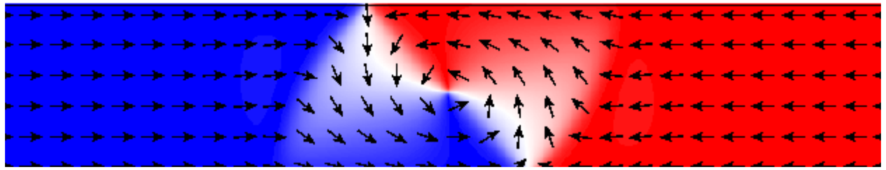
$$I(x,y) = \left[{I_{\sigma+}^{L3}}\big/{I_{\sigma+}^{PE}} - {I_{\sigma-}^{L3}}\big/{I_{\sigma-}^{PE}} \right]_{x,y}$$







Vortex domain walls



A vortex domain wall is a spin texture

The structure is determined by competing energy terms:

- Exchange energy
- Shape anisotropy
- Magnetocrystalline anisotropy
- Inverse magnetostriction

Vortex domain walls

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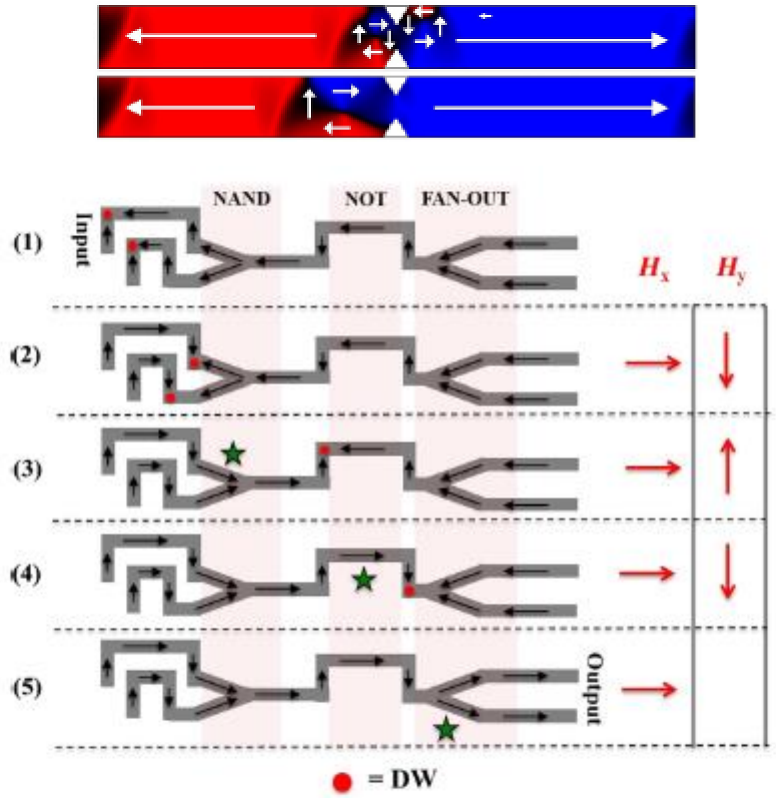

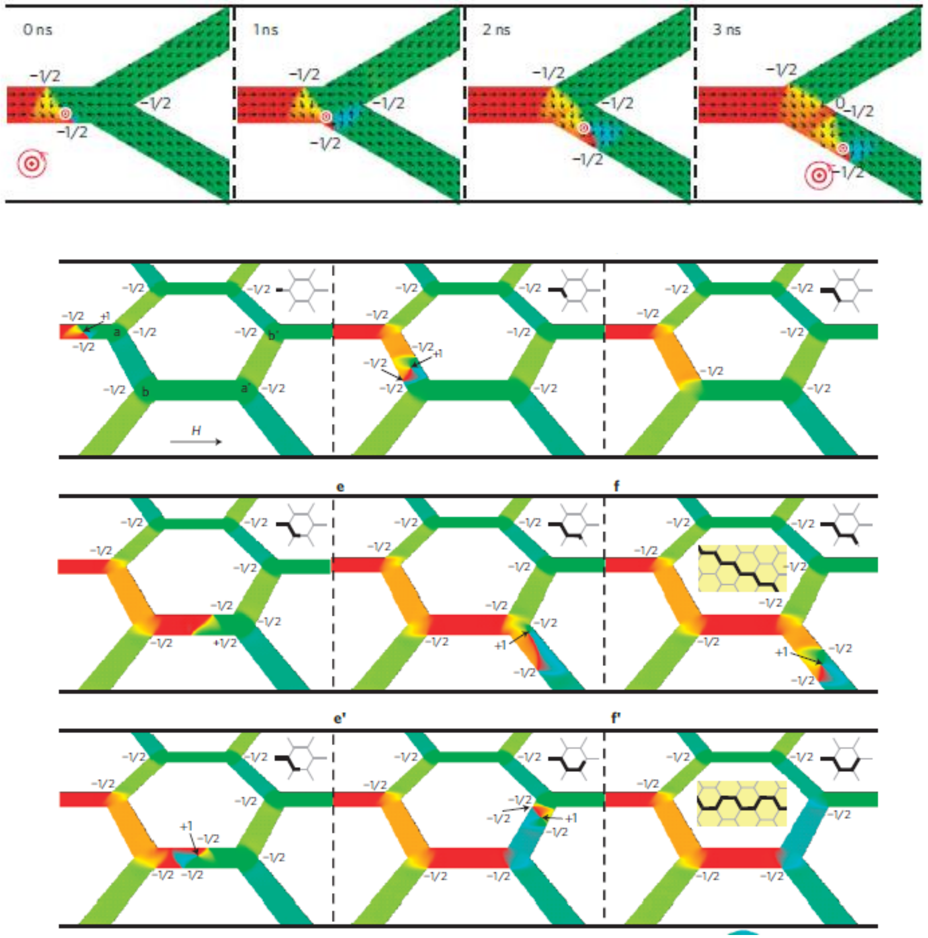

Omari *et al.*, Phys. Rev. Appl. 2, 044001 (2014)

Pushp *et al.*, Nature Physics 9, 505 (2013)

Vortex domain walls

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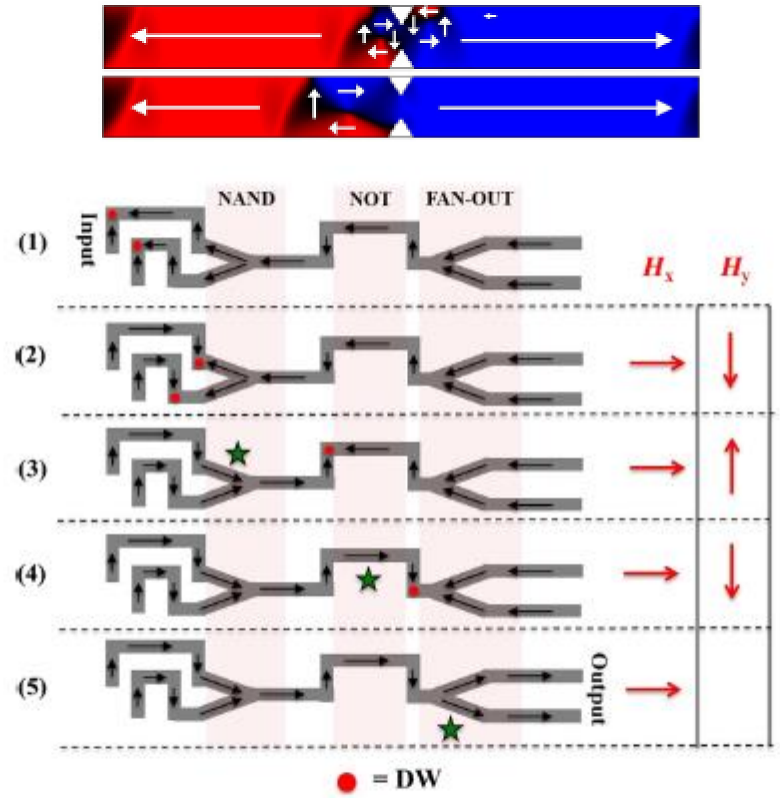
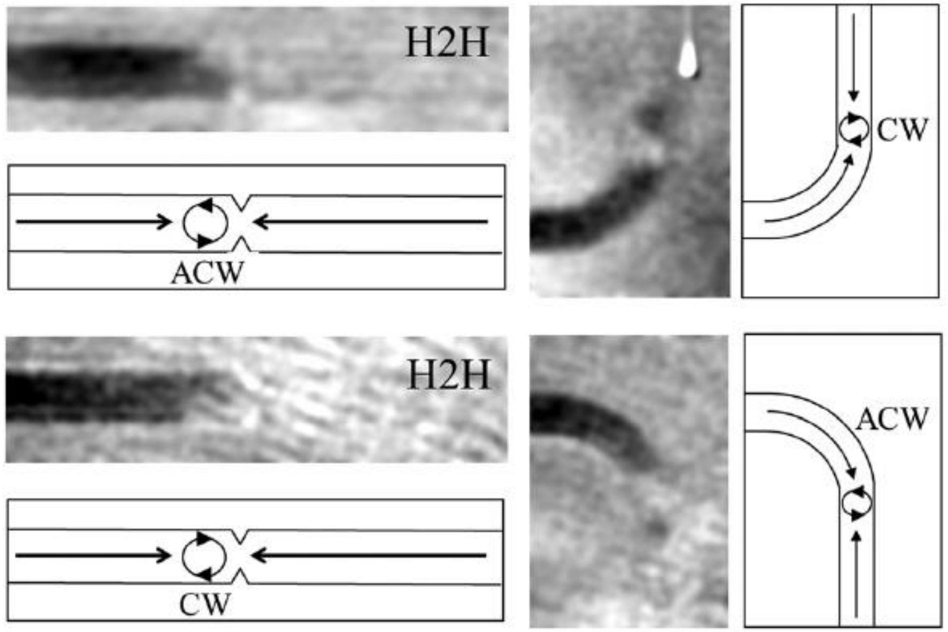


Omari *et al.*, Phys. Rev. Appl. 2, 044001 (2014)

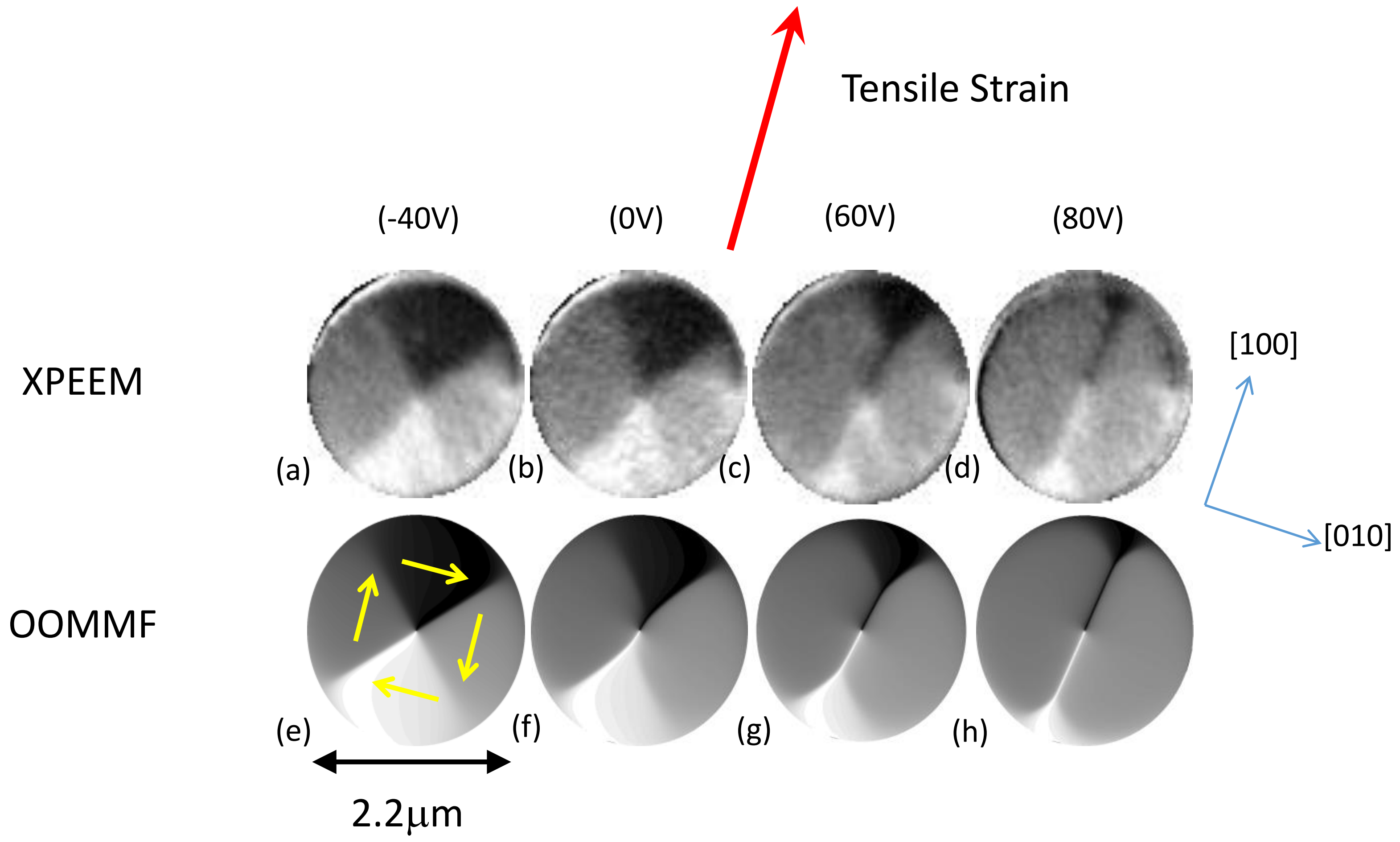


Omari *et al.*, Appl. Phys. Lett. 107, 222403 (2015)

XMCD - PEEM

Voltage induced strain modification of flux closure domains

Condensed Matter and Materials Physics Group



Applied Physics Letters **105**, 062405 (2014)

XMCD - PEEM

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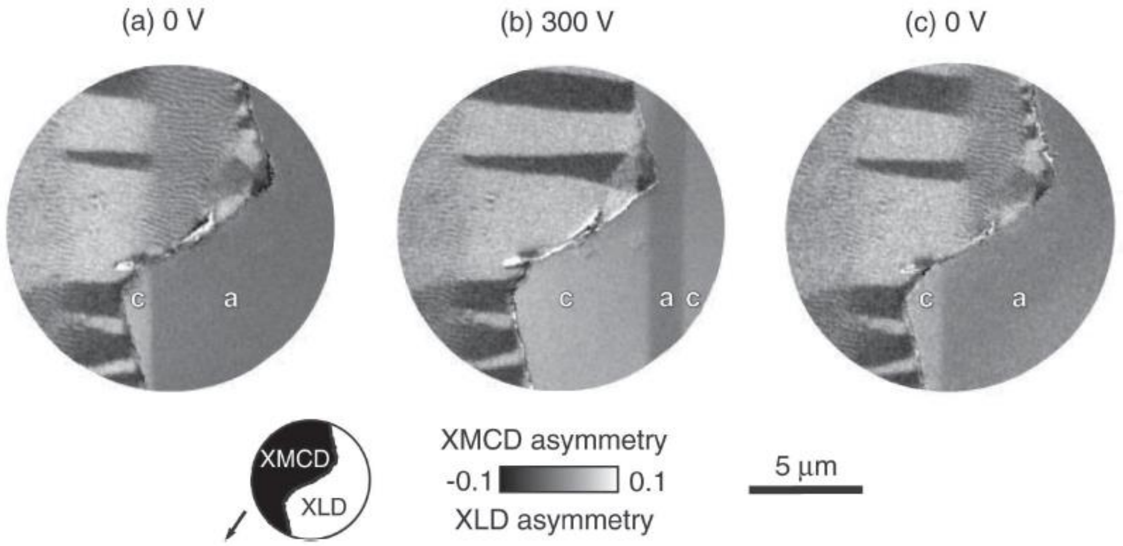
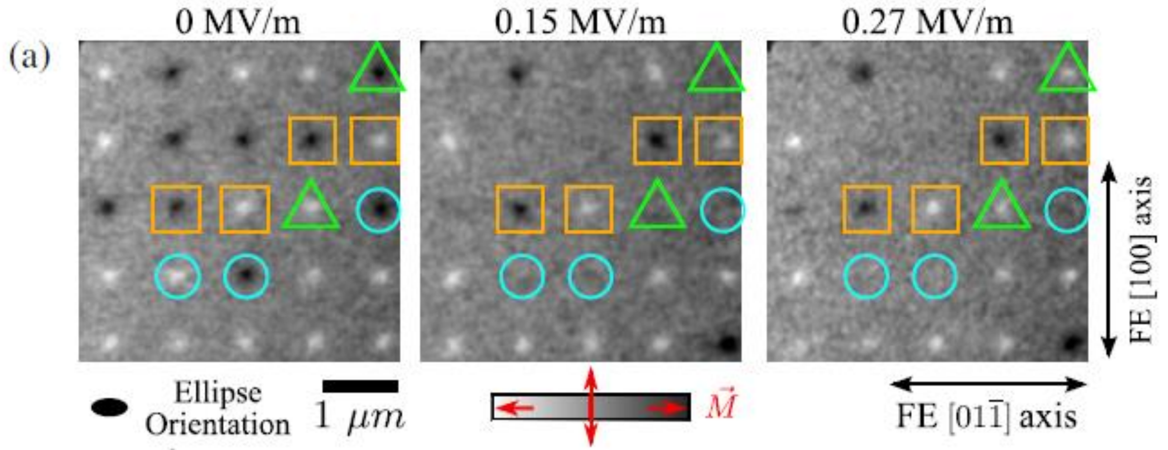
Ni on BTO



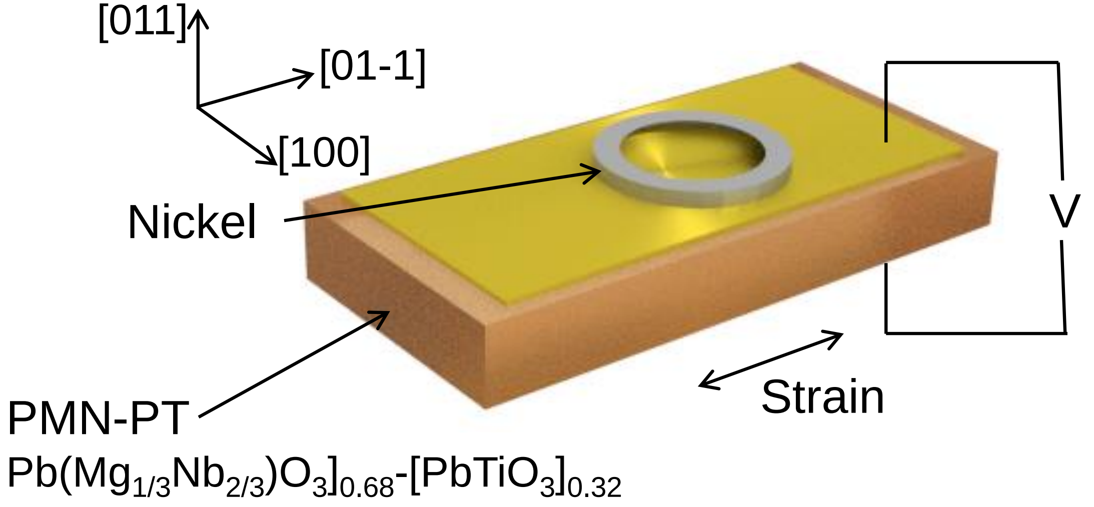
Ni on PMN-PT



M. Ghidini *et al*. Adv. Mater. 27, 1460 2015

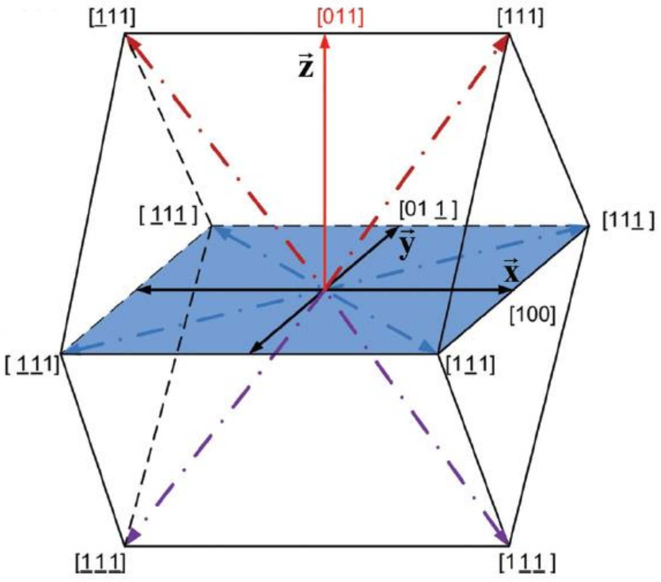
M. Buzzi *et al*. PRL 111, 027204 (2013)

Device

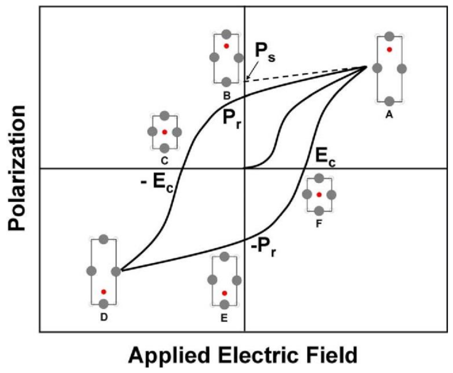


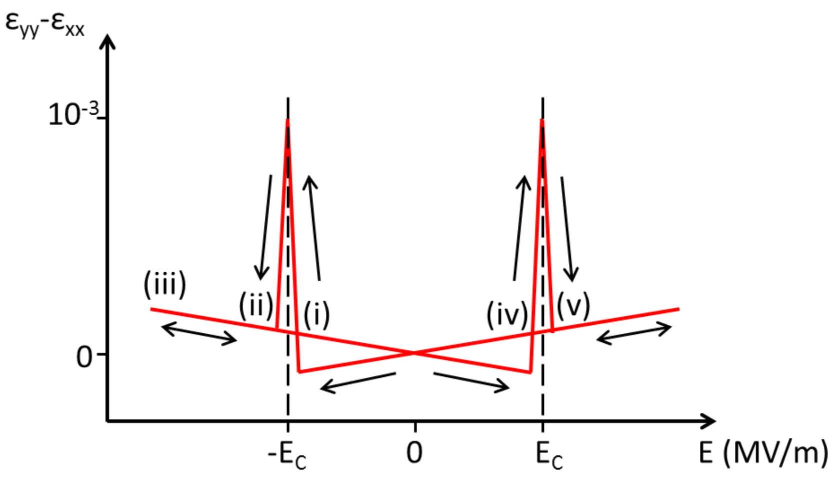
$$\varepsilon_{xx} - \varepsilon_{yy} \approx 10^{-3}$$

$$E_{ME} \approx 10kJm^{-3}$$



Wu *et al*., J. Appl. Phys. 109, 124101 (2011)





XMCD - PEEM

Voltage induced switching of vortex chirality

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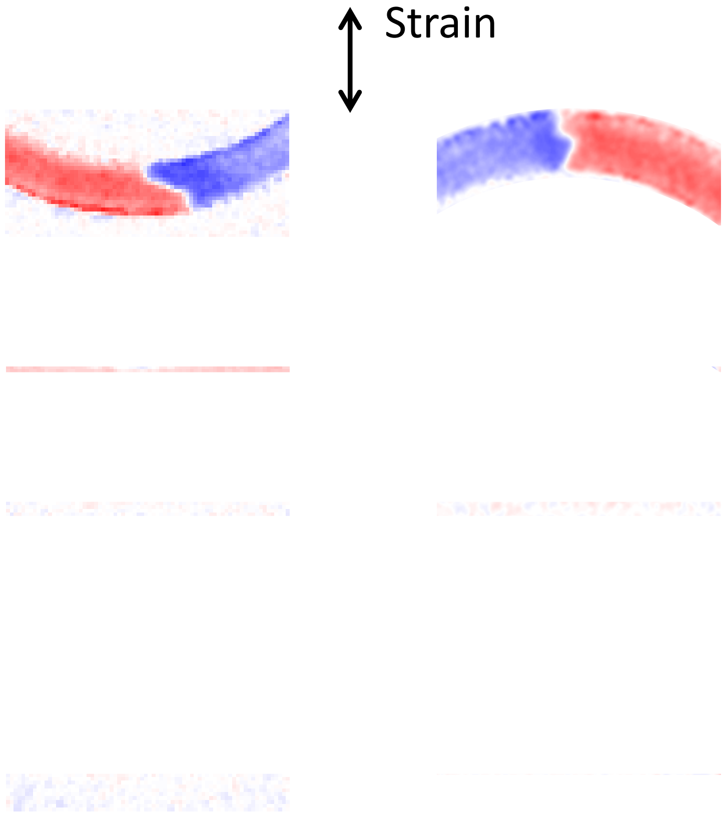
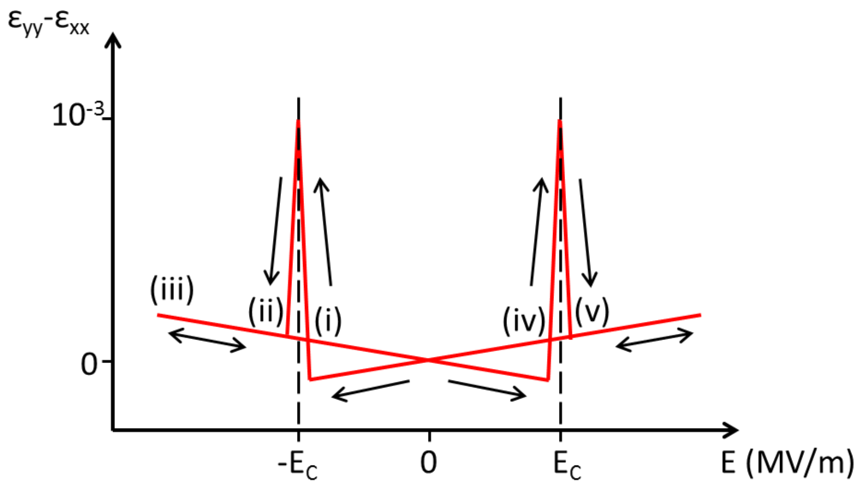
Diameter = 7.7μm
Width = 1 μm
Thickness = 20nm



Electric field (MV/m)

-0.17 (i)



X-ray magnetic circular dichroism – photoelectron emission microscopy (XMCD-PEEM)

Sci Rep **7**, 7613 (2017)

Micromagnetics

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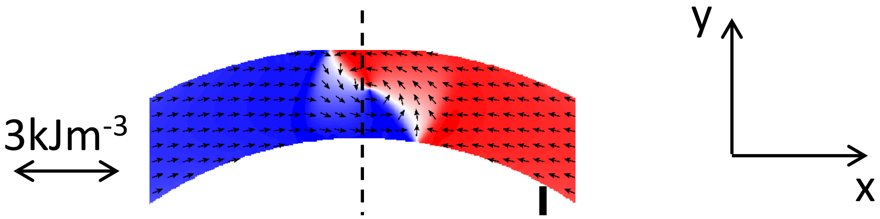
Object Oriented Micro-magnetic Framework (OOMMF)



$$M_S = 490kAm^{-1}$$
$$\alpha = 0.02$$

Sci Rep **7**, 7613 (2017)

Micromagnetics

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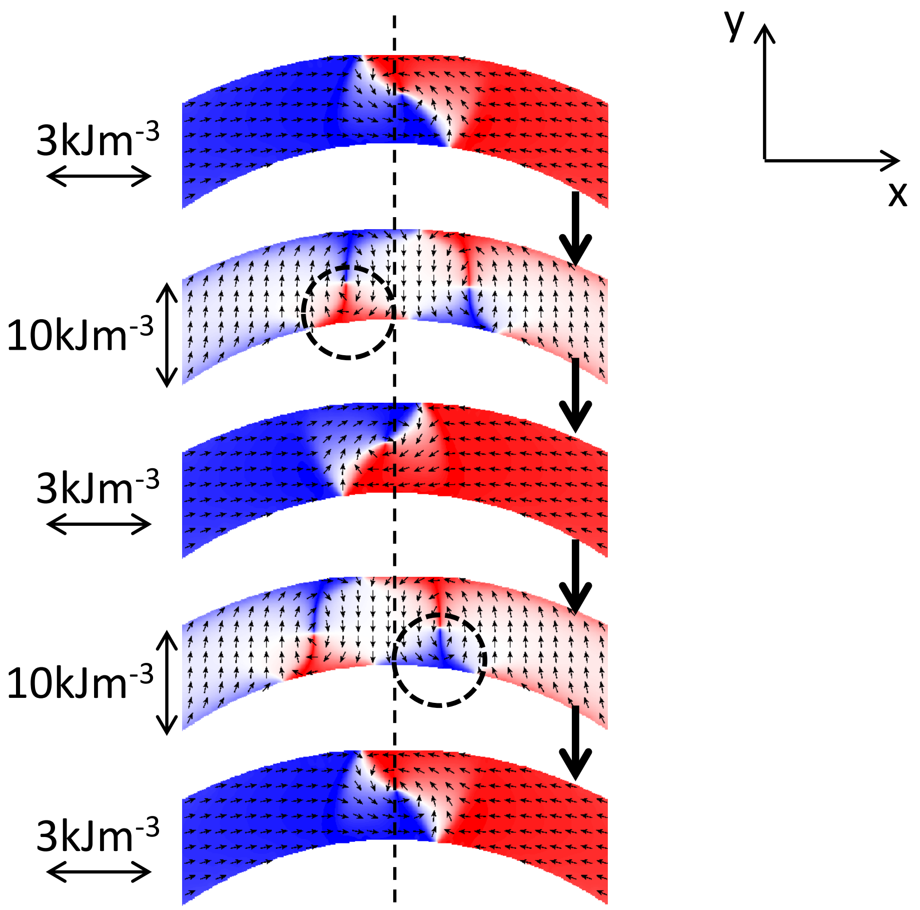
Object Oriented Micro-magnetic Framework (OOMMF)



Sci Rep **7**, 7613 (2017)

Micromagnetics

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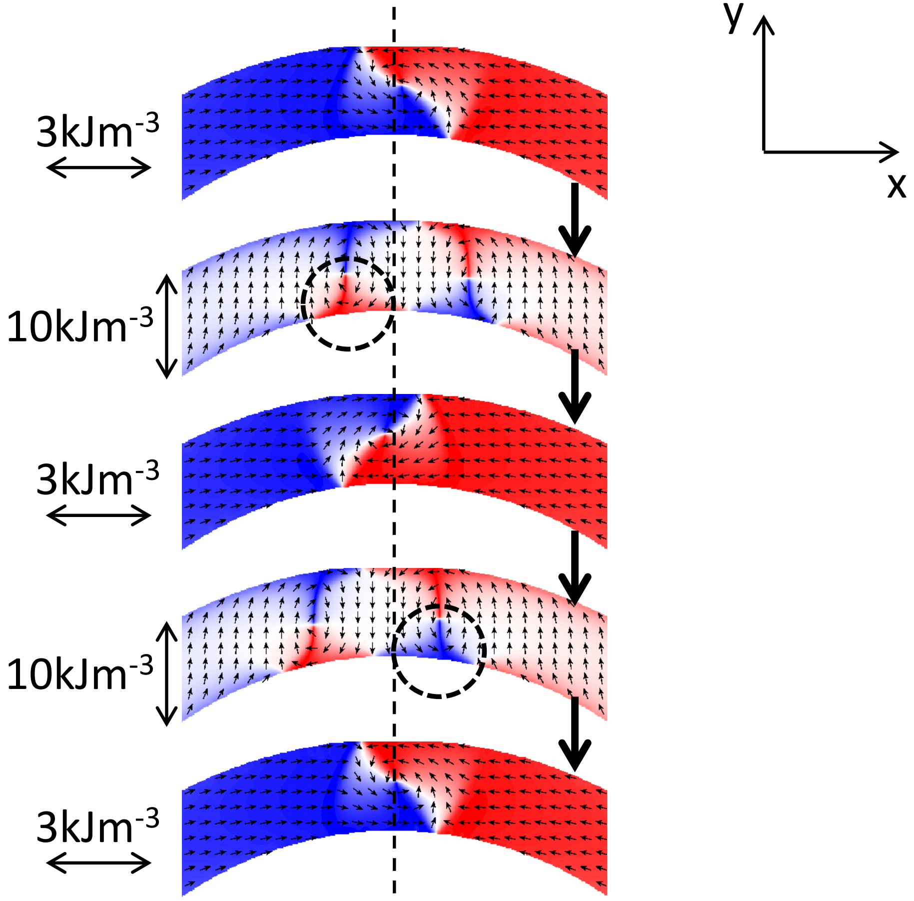
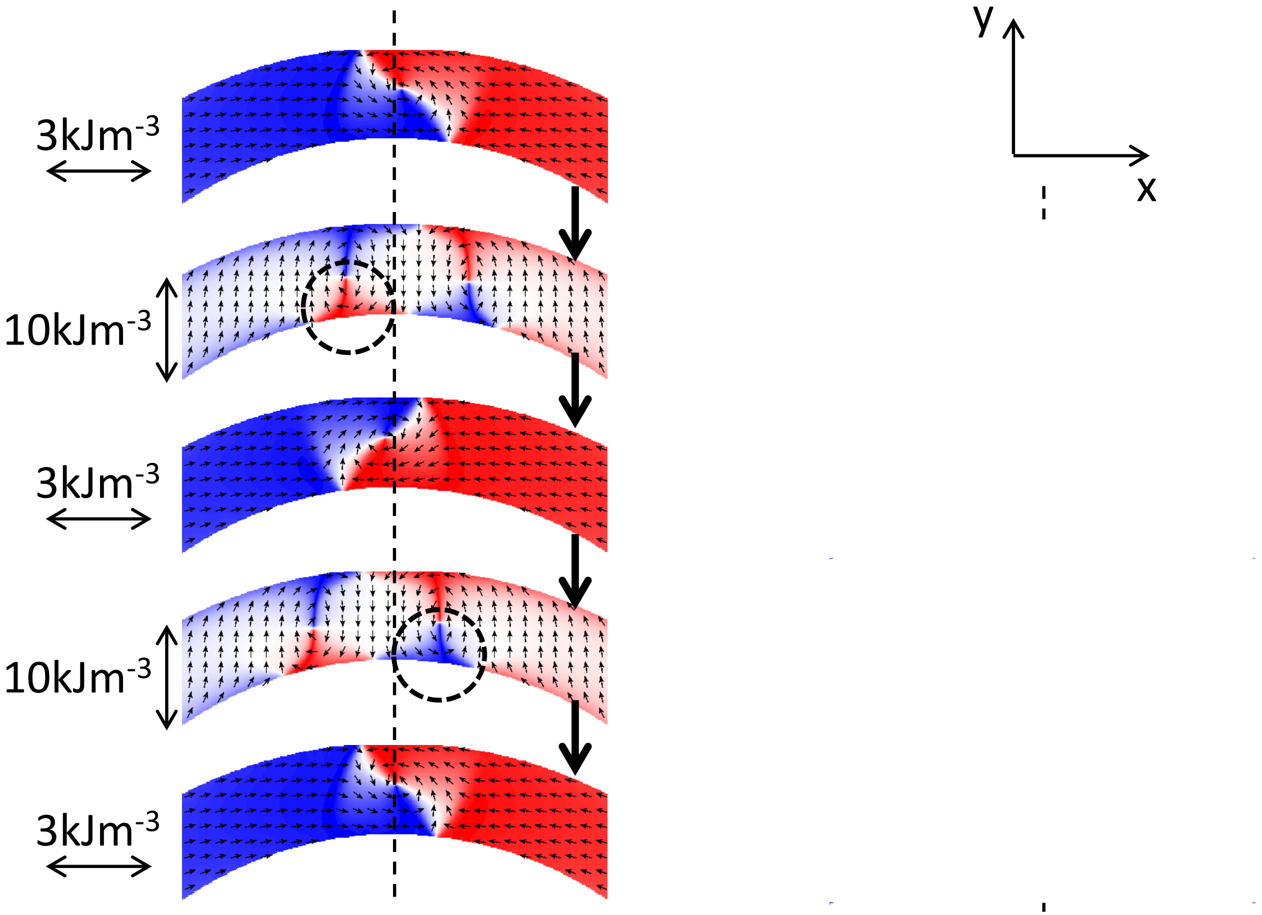


Sci Rep **7**, 7613 (2017)

Micromagnetics

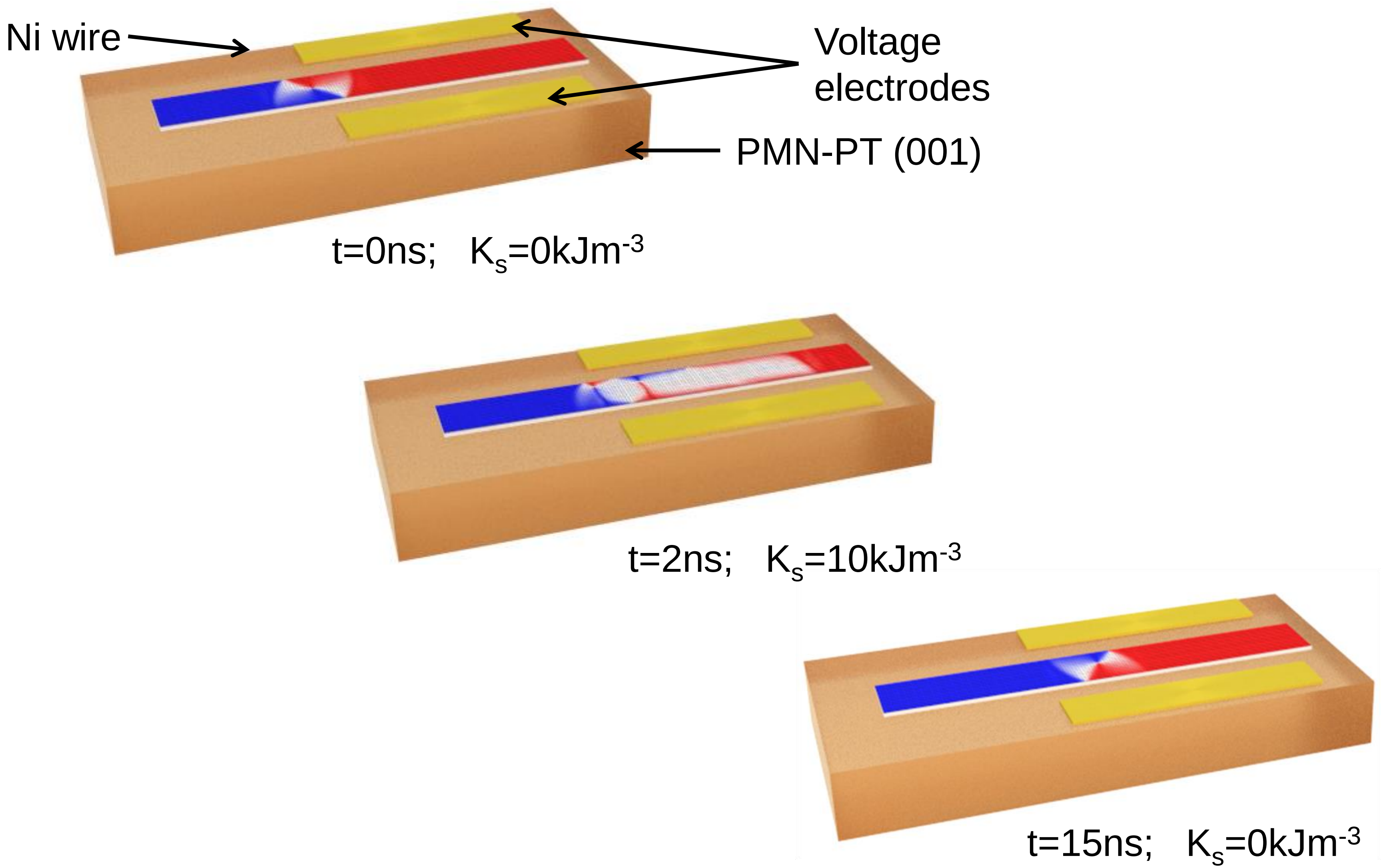
University of York
Condensed Matter and Materials Physics Group

Object Oriented Micro-magnetic Framework (OOMMF)



Sci Rep **7**, 7613 (2017)

Control of chirality in race track



Sci Rep **7**, 7613 (2017

Memory Device

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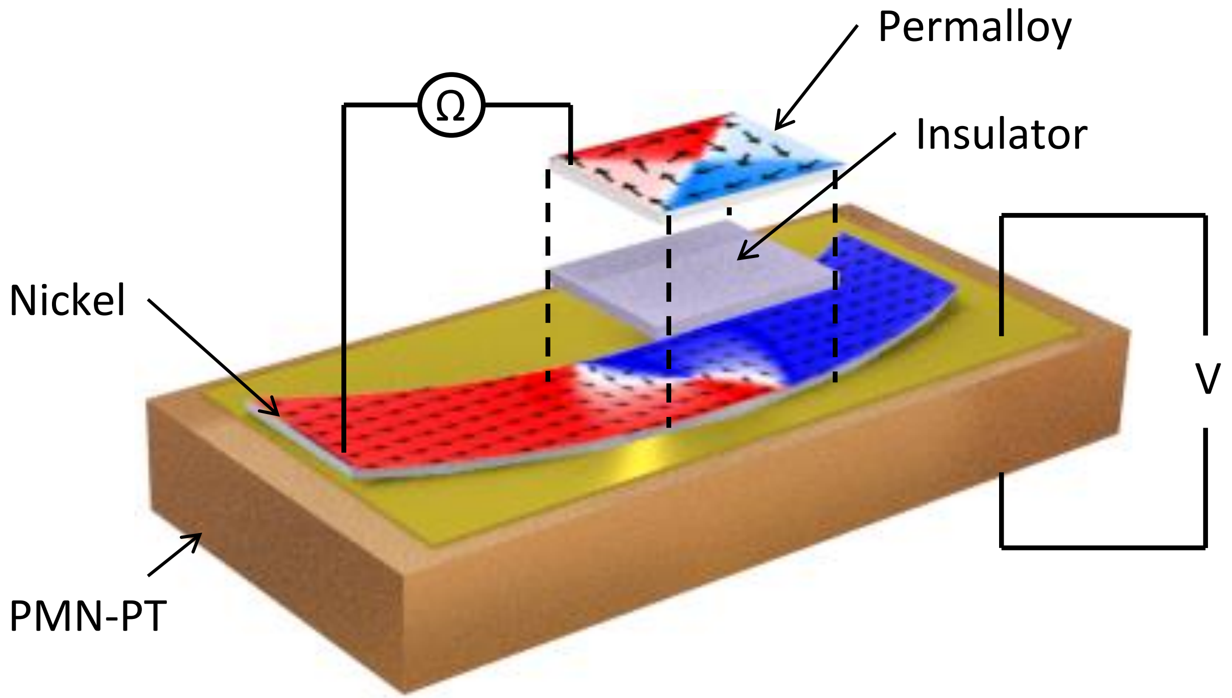

Bottom chirality = Top chirality ⟶ Low resistance

Bottom chirality ≠ Top chirality ⟶ High resistance

Dynamics

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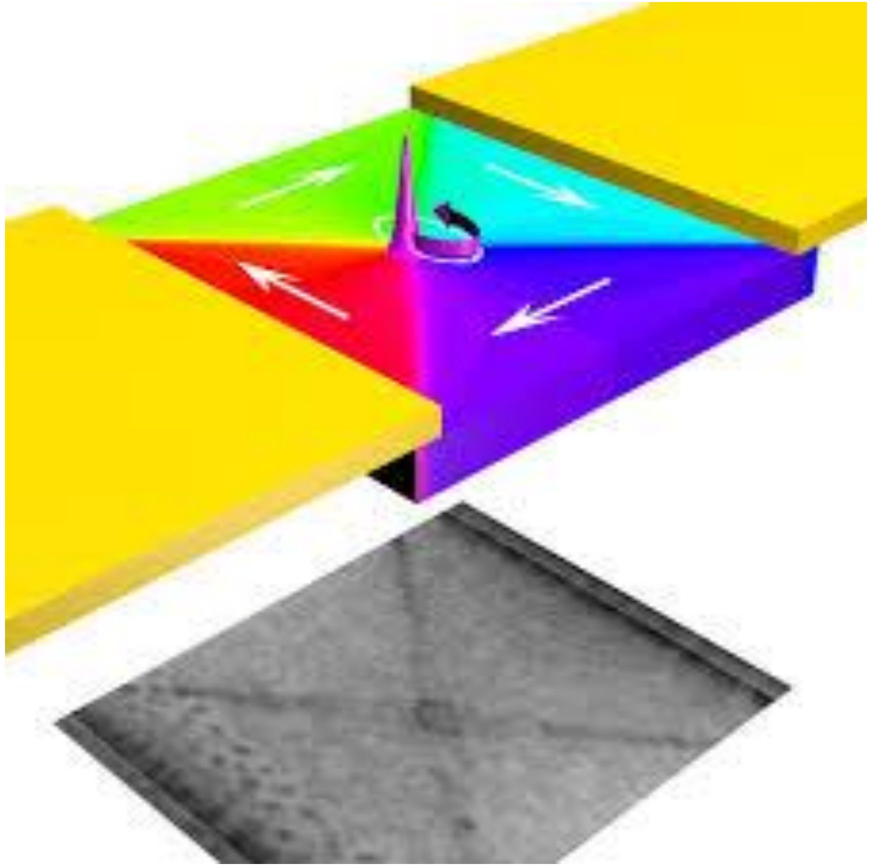

Image courtesy of DOE/Brookhaven National Laboratory

Micromagnetic Parameters

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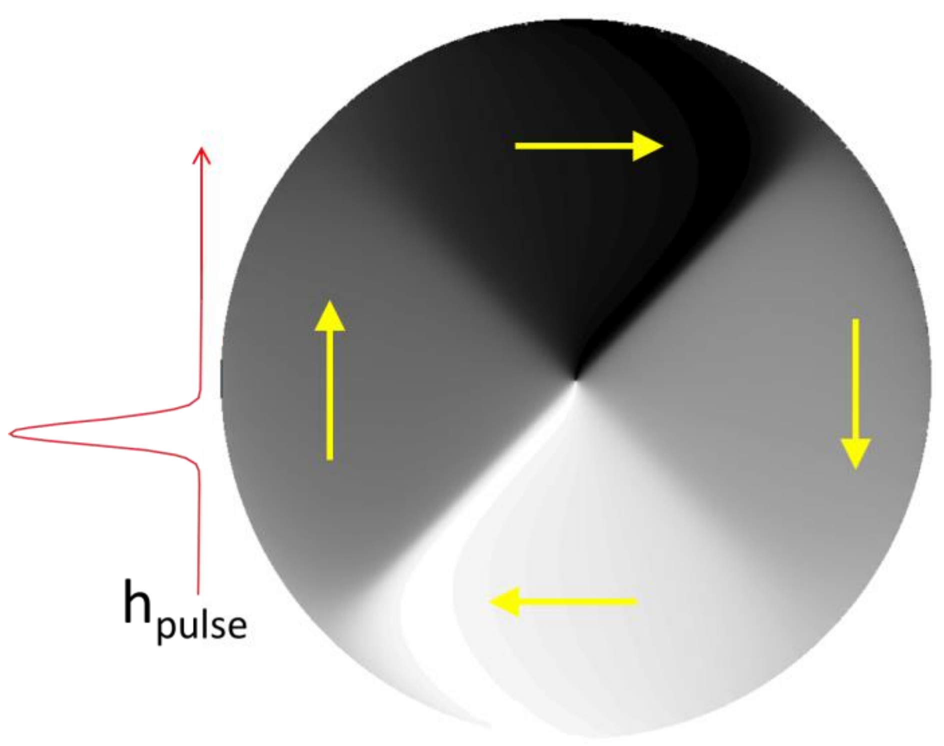
FeGa disc

10 nm thick
2.2 μm diameter

K_c = 18 kJm^{-3} [100],[010]
K_u = 12 kJm^{-3} [110]
K_s = 0 – 10 kJm^{-3} [010]
h_{pulse} = 70 ps, 80 Oe along [010]

OOMMF



Magnetization Dynamics

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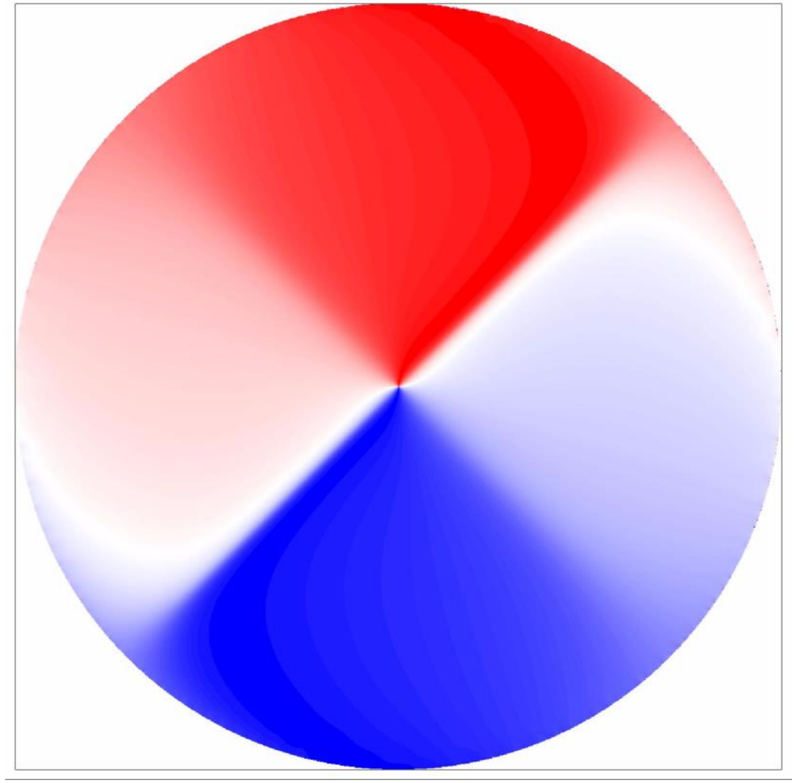
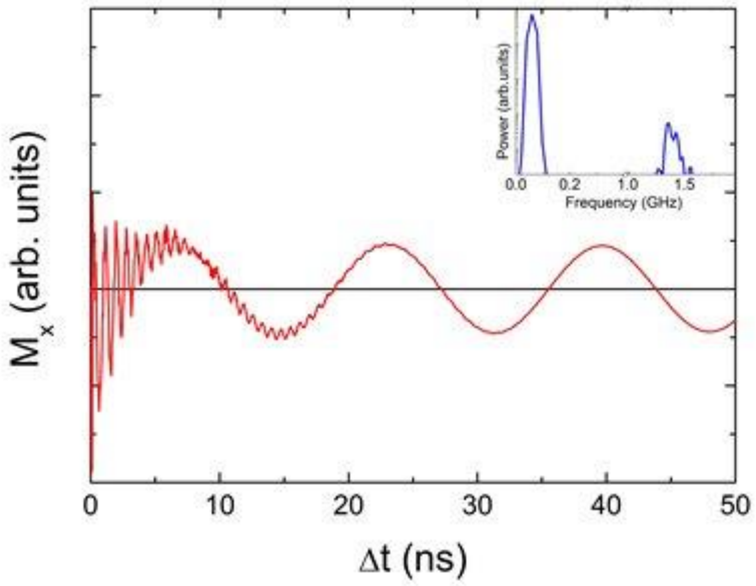
K_s = 0 kJm^{-3}





f_1= 1.38 GHz – spin wave modes
f_2 = 60 MHz – vortex gyrotropic mode

Magnetization Dynamics

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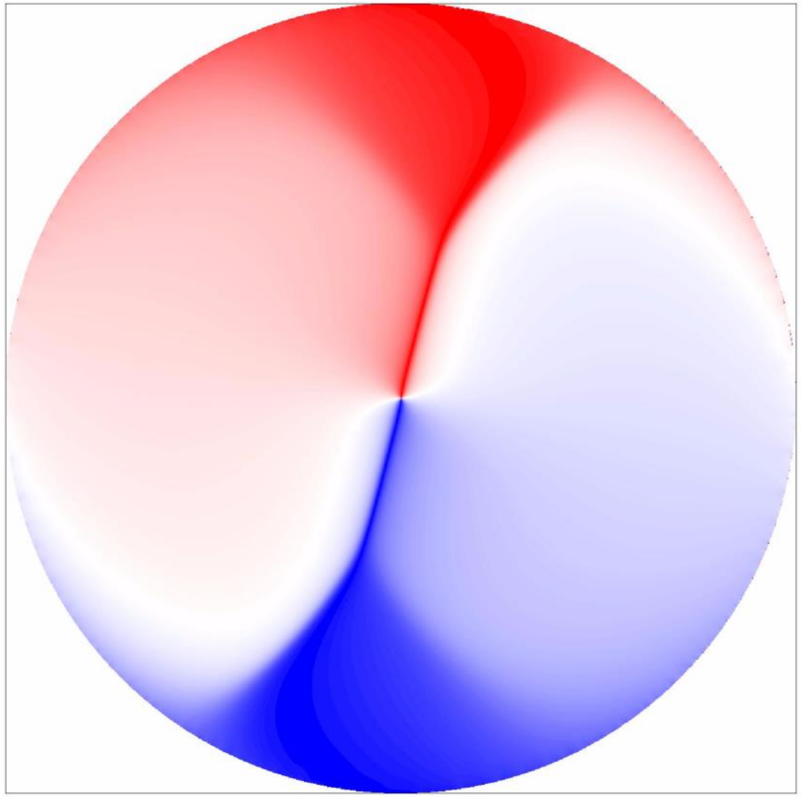
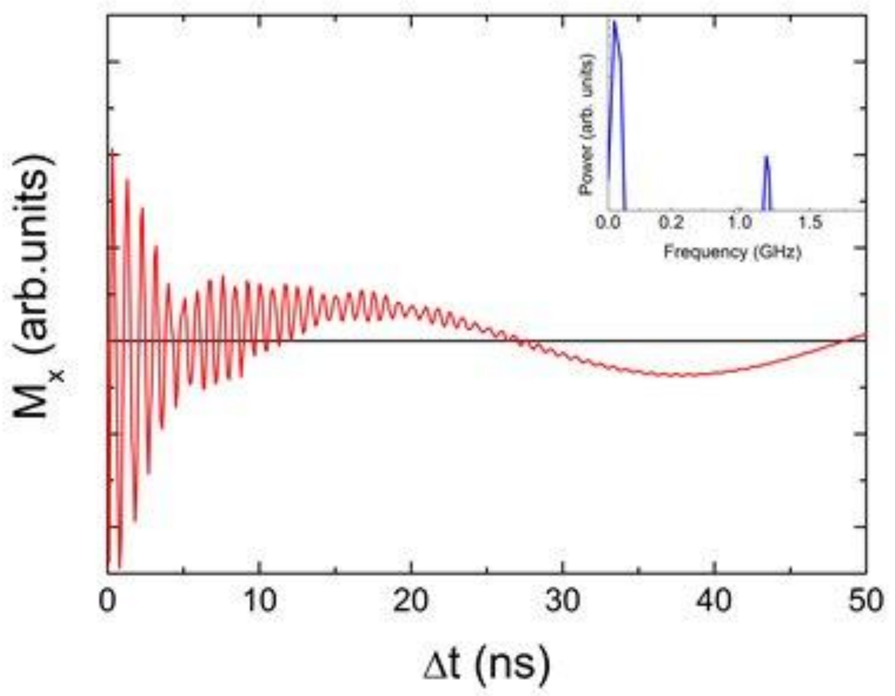
K_s = 10 kJm^{-3}





f_1= 1.2GHz – spin wave mode(s)

f_2 = 25 MHz – vortex gyrotropic mode

Modification of vortex core orbit

University of York
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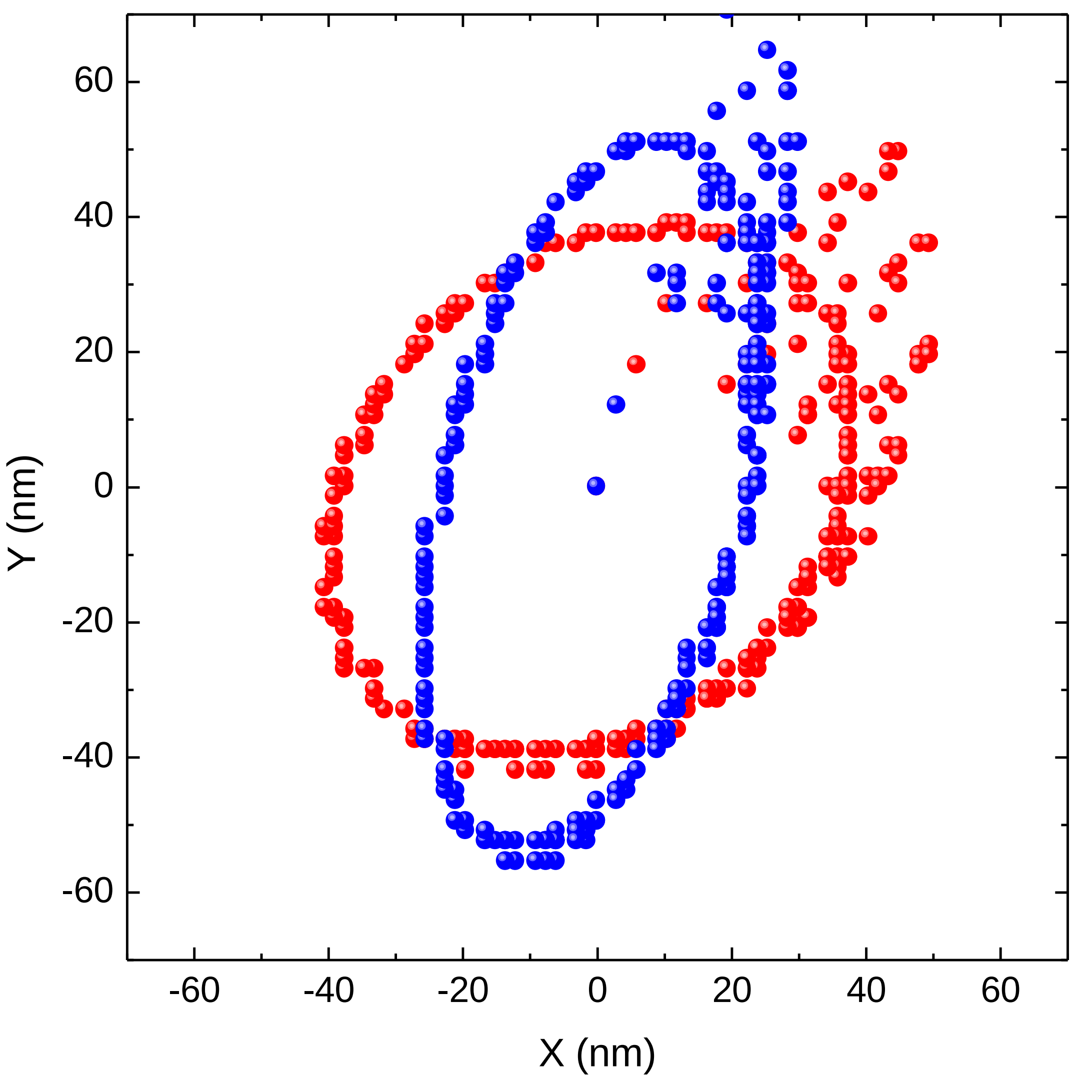
K_s = 10 kJm^{-3} – blue
K_s = 0 kJm^{-3} – red



Strain Induced Magnetization Dynamics

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Landau – Liftshitz – Bloch (LLB)

$$\dot{\boldsymbol{m}}_i = -\gamma \boldsymbol{m}_i \times \boldsymbol{H}_i^{eff} + \frac{\gamma \alpha_\parallel}{m^2}\left(\boldsymbol{m} \cdot \boldsymbol{H}_i^{eff}\right)\boldsymbol{m} - \frac{\gamma \alpha_\perp}{m^2}\boldsymbol{m}_i \times \boldsymbol{m}_i \times \boldsymbol{H}_i^{eff}$$

$$H^{eff} = -M_S \boldsymbol{B} \cdot \boldsymbol{m} - K^u_{1,(110)}(\boldsymbol{M} \cdot \hat{\boldsymbol{n}}_1)^2 - K^u_{1,ep}(\boldsymbol{M} \cdot \hat{\boldsymbol{n}}_2)^2 + K_1^c\left(M_x^2 M_y^2 + M_y^2 M_z^2 + M_z^2 M_x^2\right)^2 - {}^3/_2\, \lambda \varepsilon(y) Y (\boldsymbol{M} \cdot \hat{\boldsymbol{n}}_s)^2 + \frac{M_S}{8\tilde{\chi}_\parallel m_e^2}(m^2 - m_e^2)^2$$

Allows us to produce time varying effective fields – either from the Zeeman term, Strain term or both

Strain Induced Magnetization Dynamics

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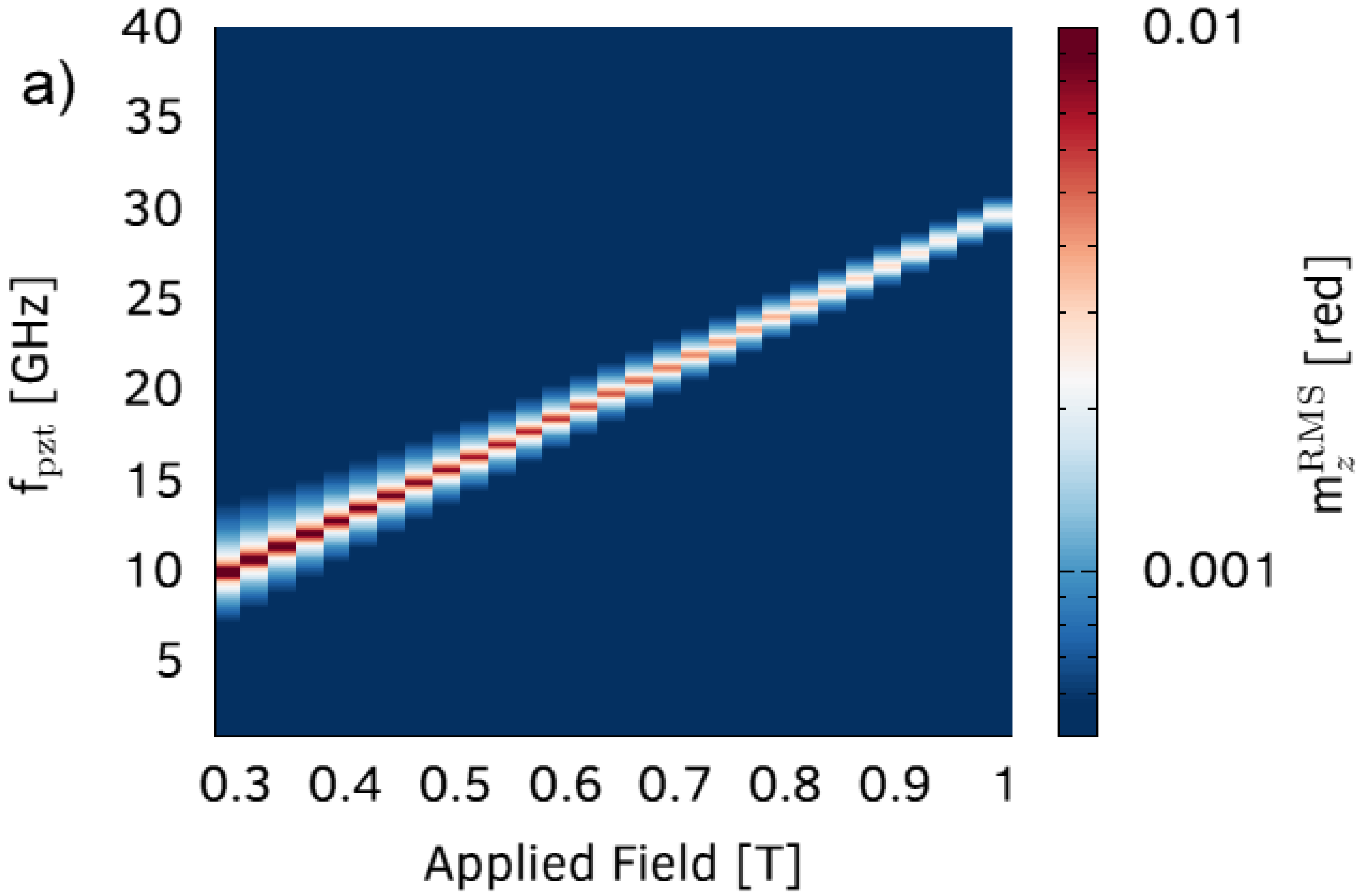
Strain [010], H [100]



Strain Induced Magnetization Dynamics

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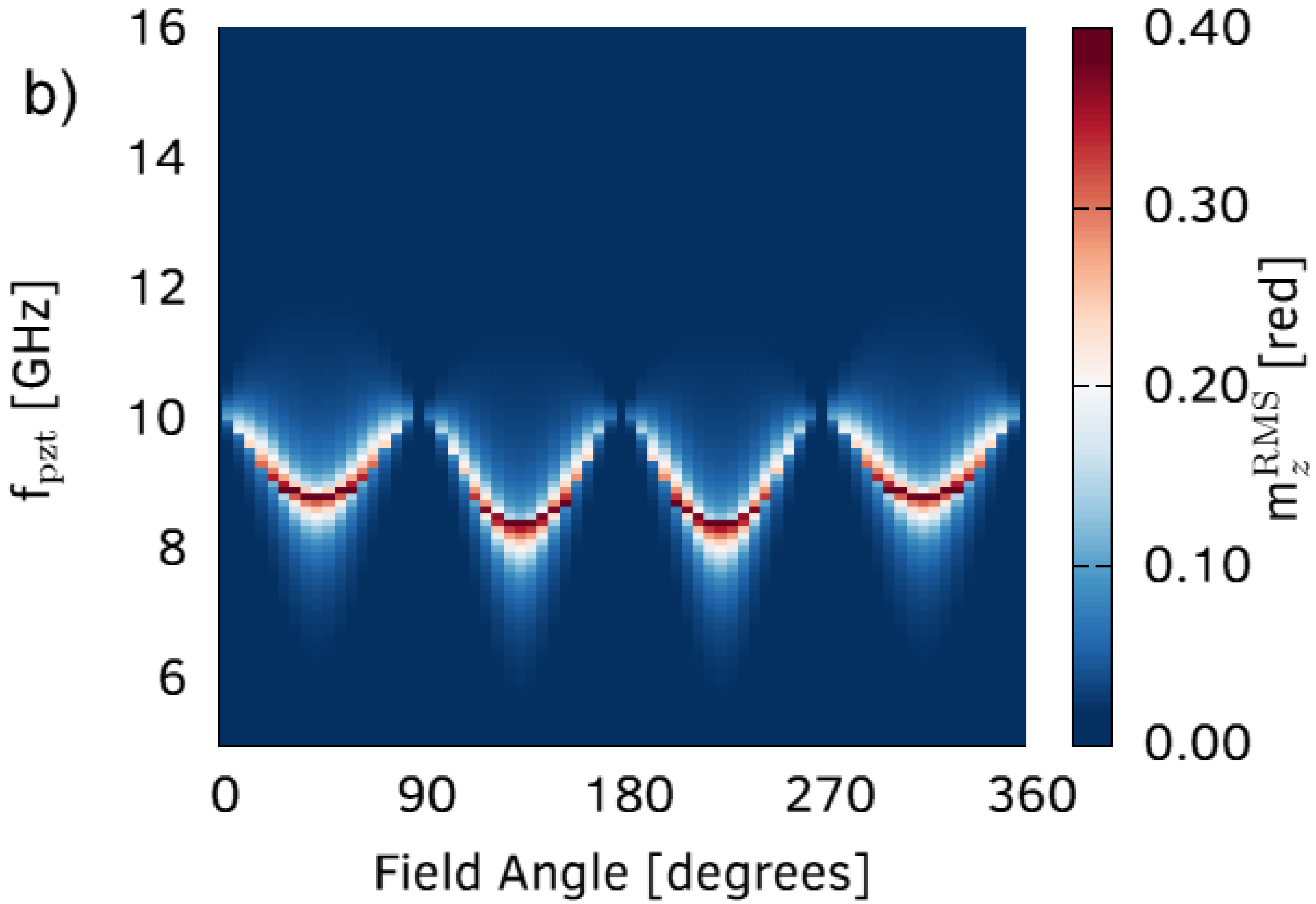
Strain along [010], Field angle relative to [100]   B = 0.3T



Largest amplitude when ϕ along a hard axis

Vortex Core Dynamics

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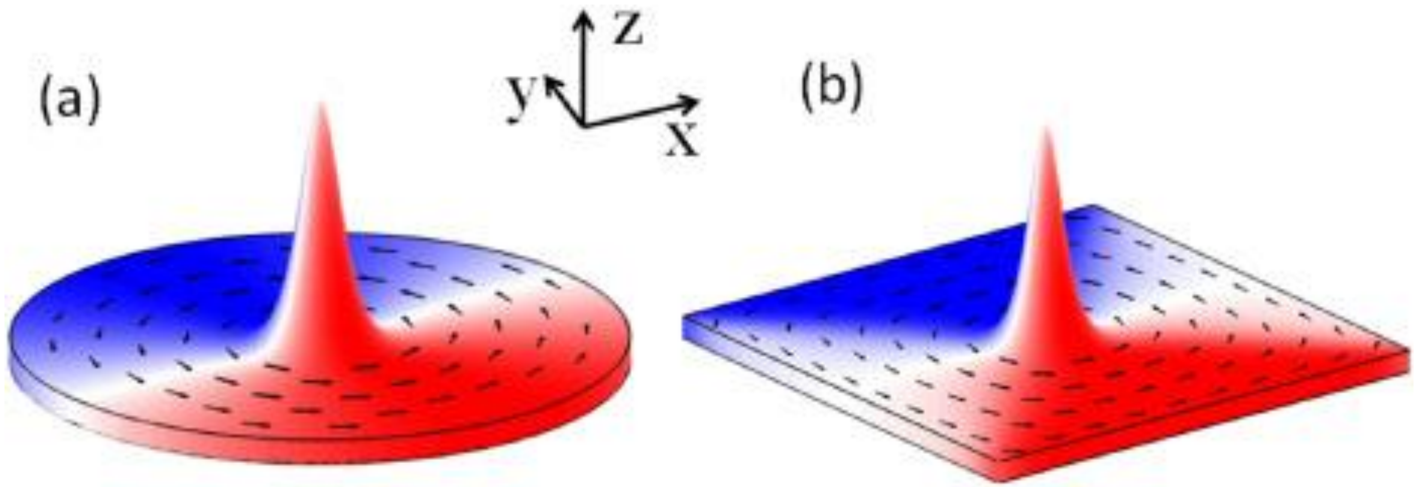
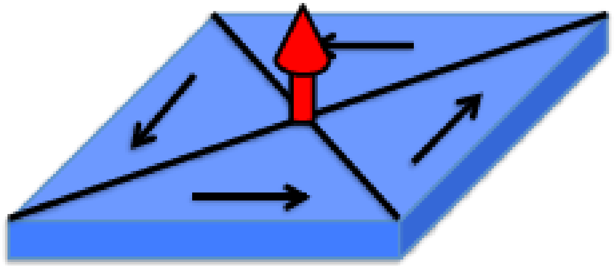
Can we apply the same methodology to confined geometries - Landau flux closure state?

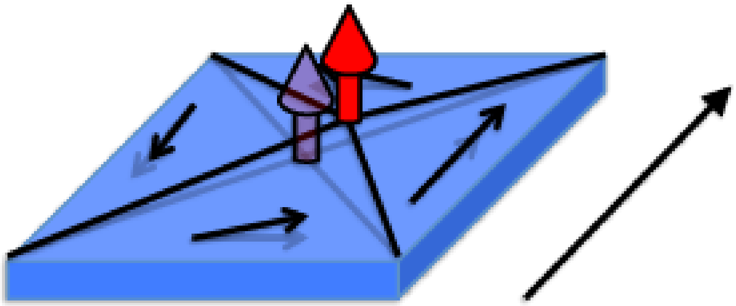


Vortex Core Dynamics

H – field is unidirectional, so



Ground State



core displacement is possible…..

Vortex Core Dynamics

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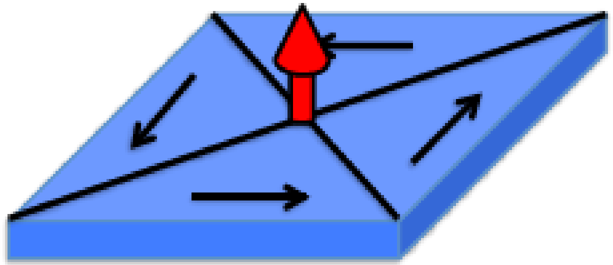
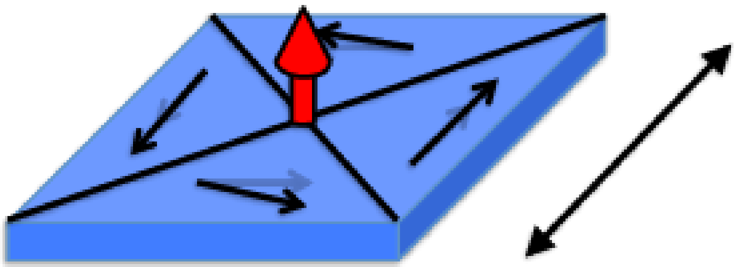
ε – field is uniaxial, so



Ground State



Applied Strain

core displacement is not possible.....

Vortex Core Dynamics

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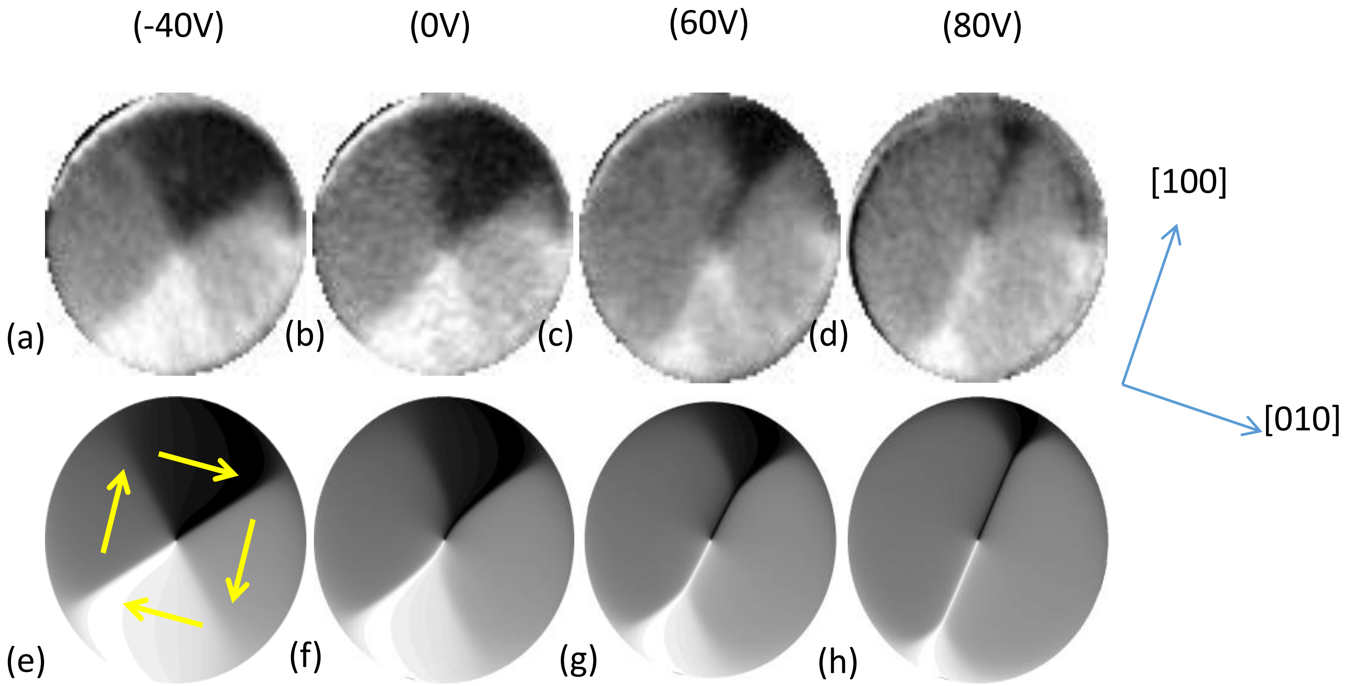

Strain Induced Vortex Core Dynamics

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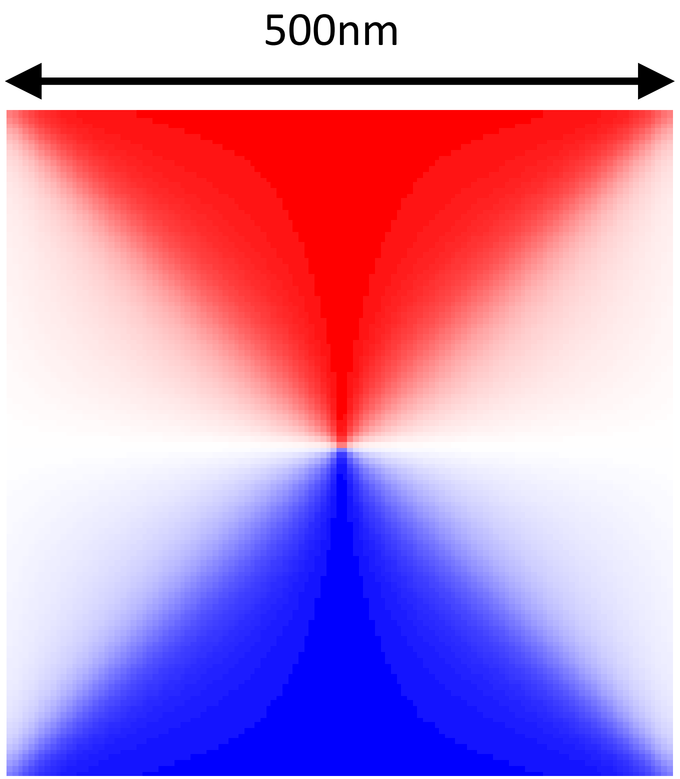
Solution



Introduce a time varying strain gradient:
Measure position of the vortex core as a function of time.

Strain Induced Vortex Core Displacement

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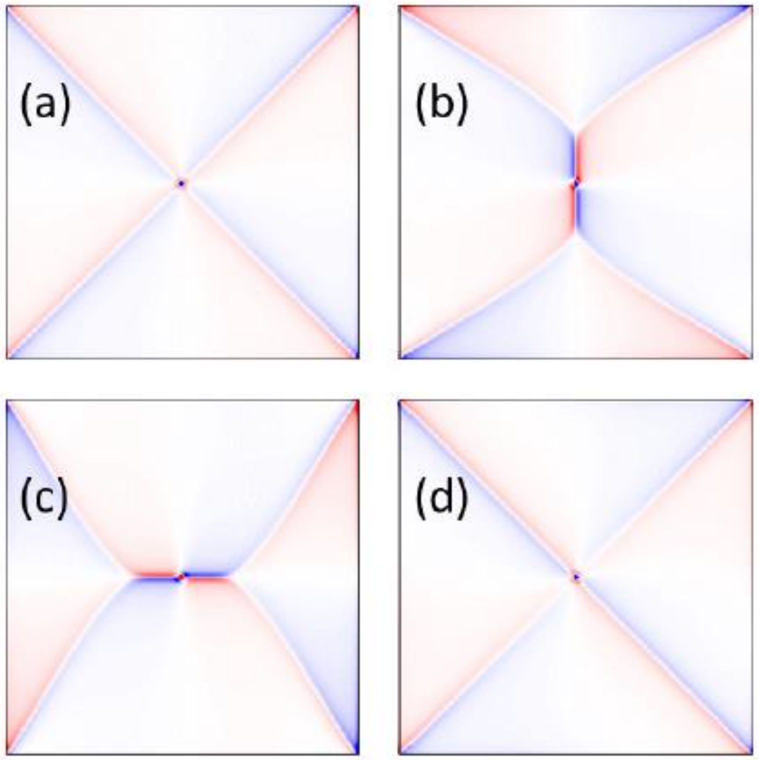

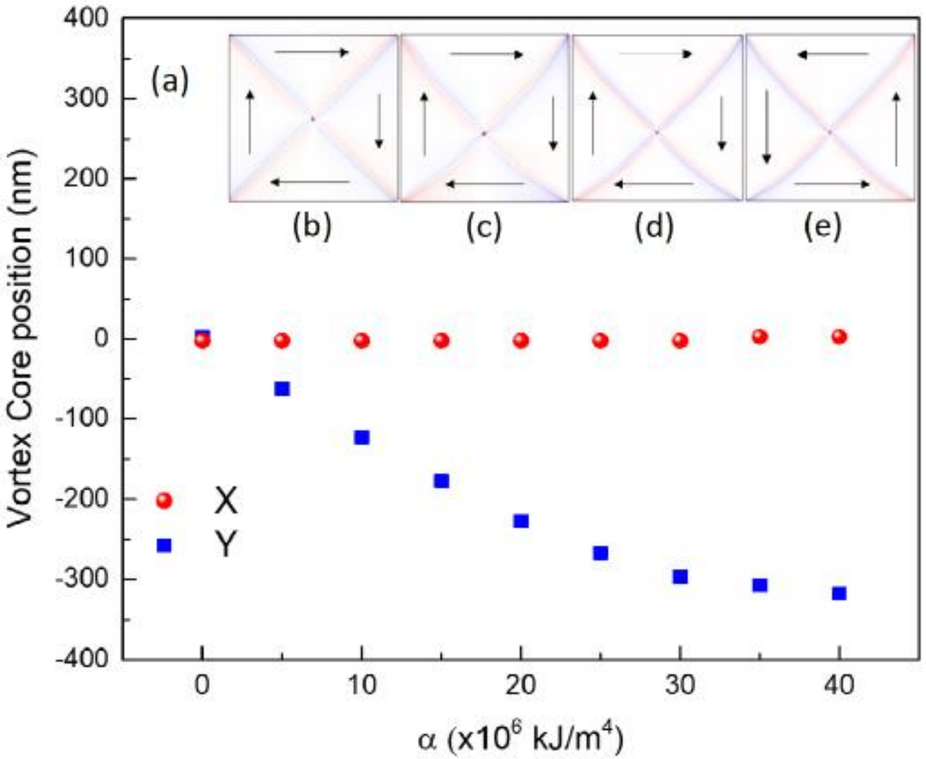

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Strain Induced Vortex Core Displacement

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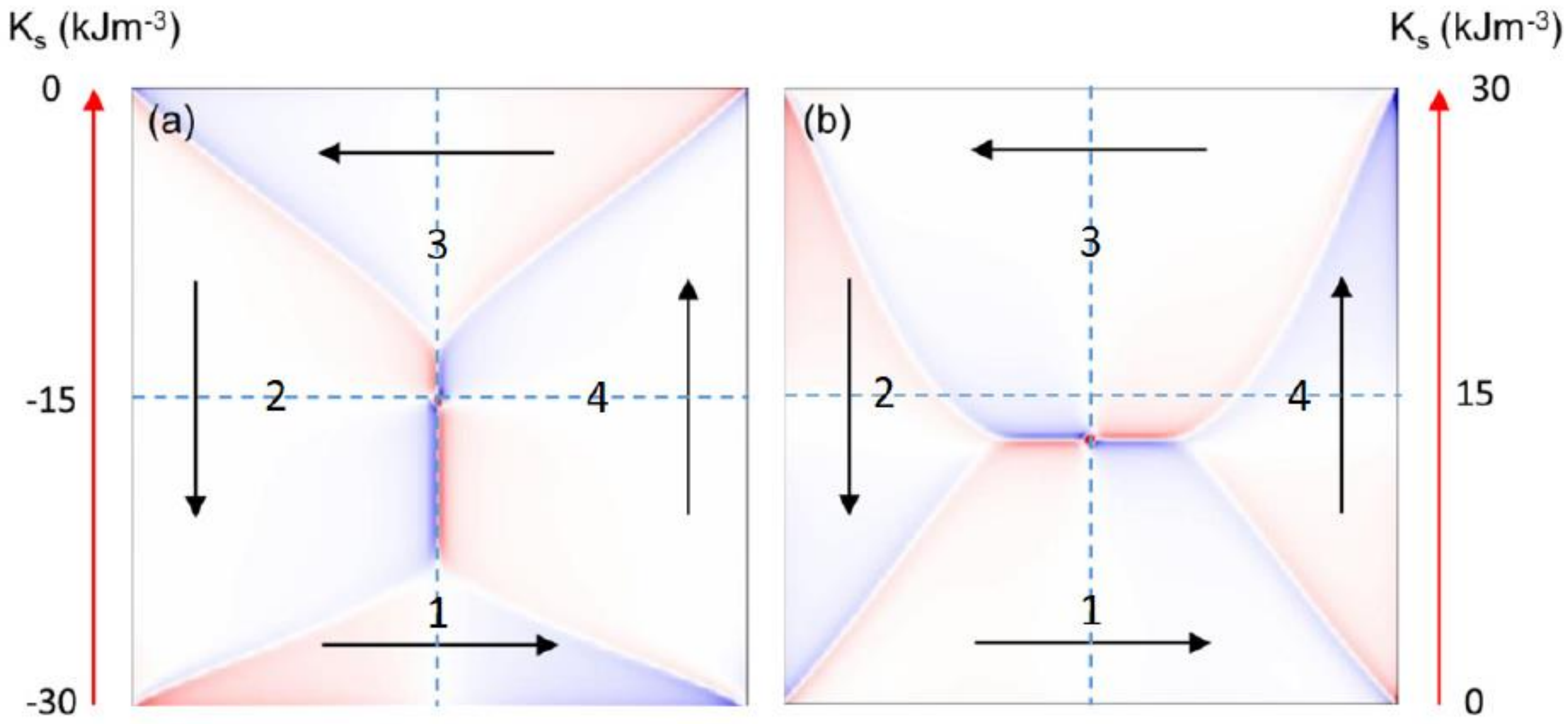

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Strain Induced Vortex Core Dynamics

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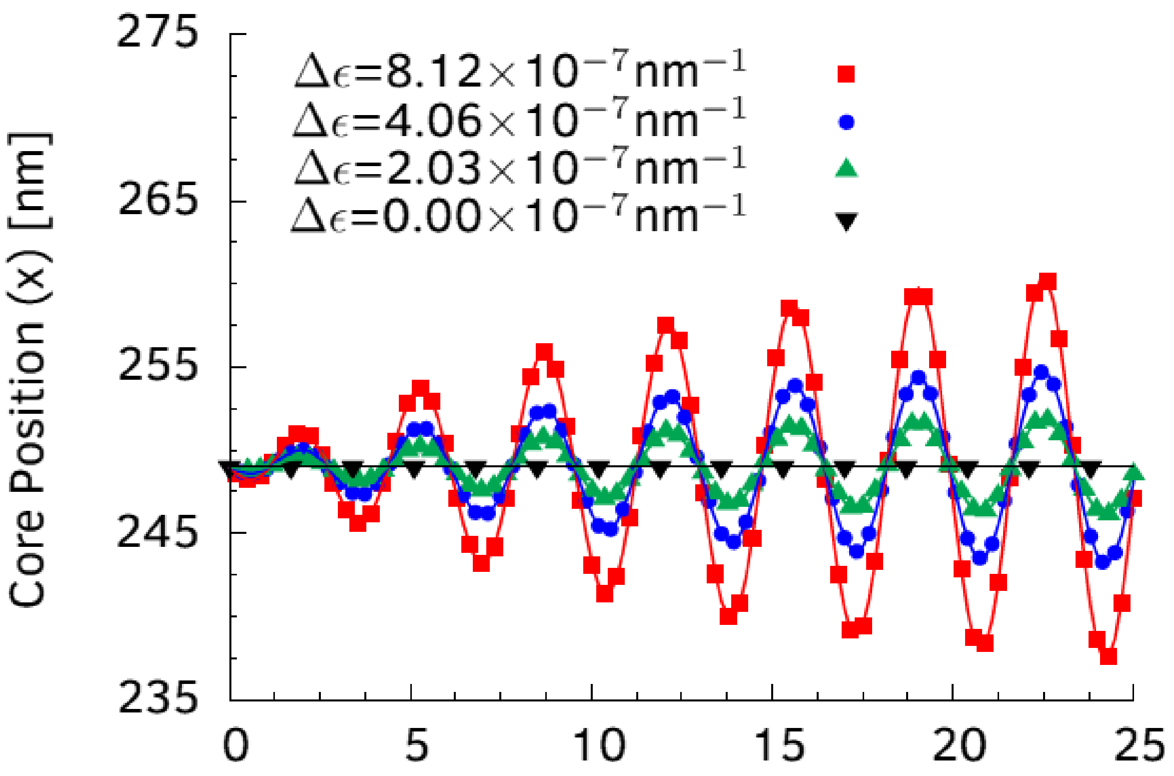

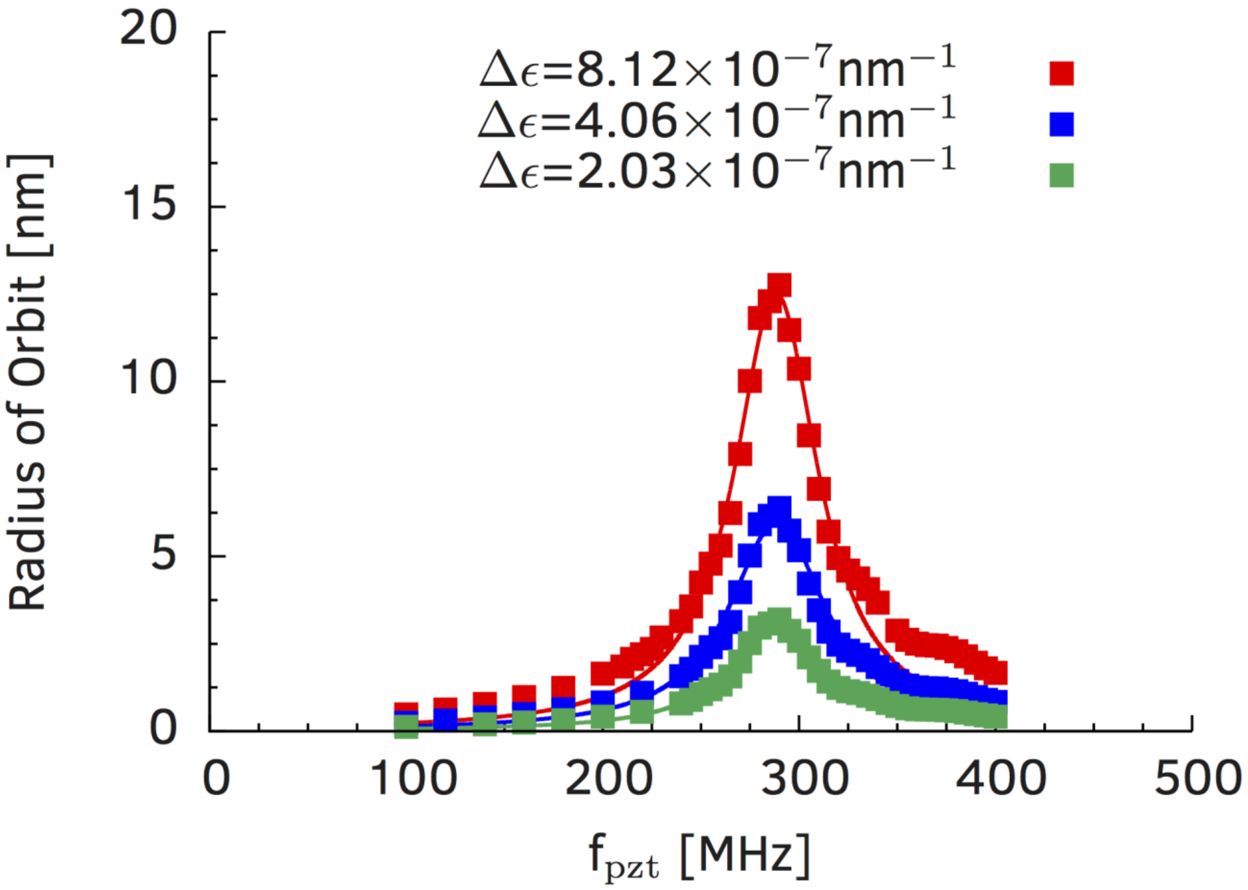

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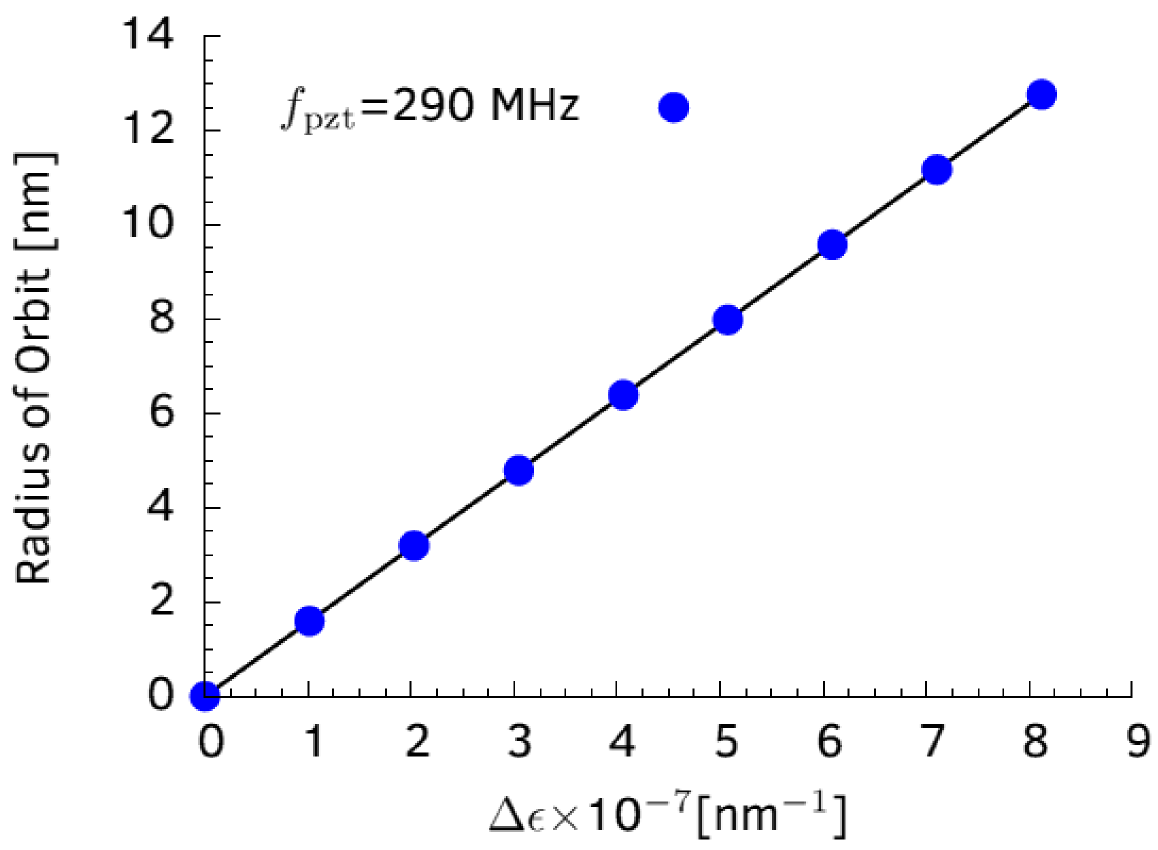
Radius of vortex core orbit proportional to the strain gradient



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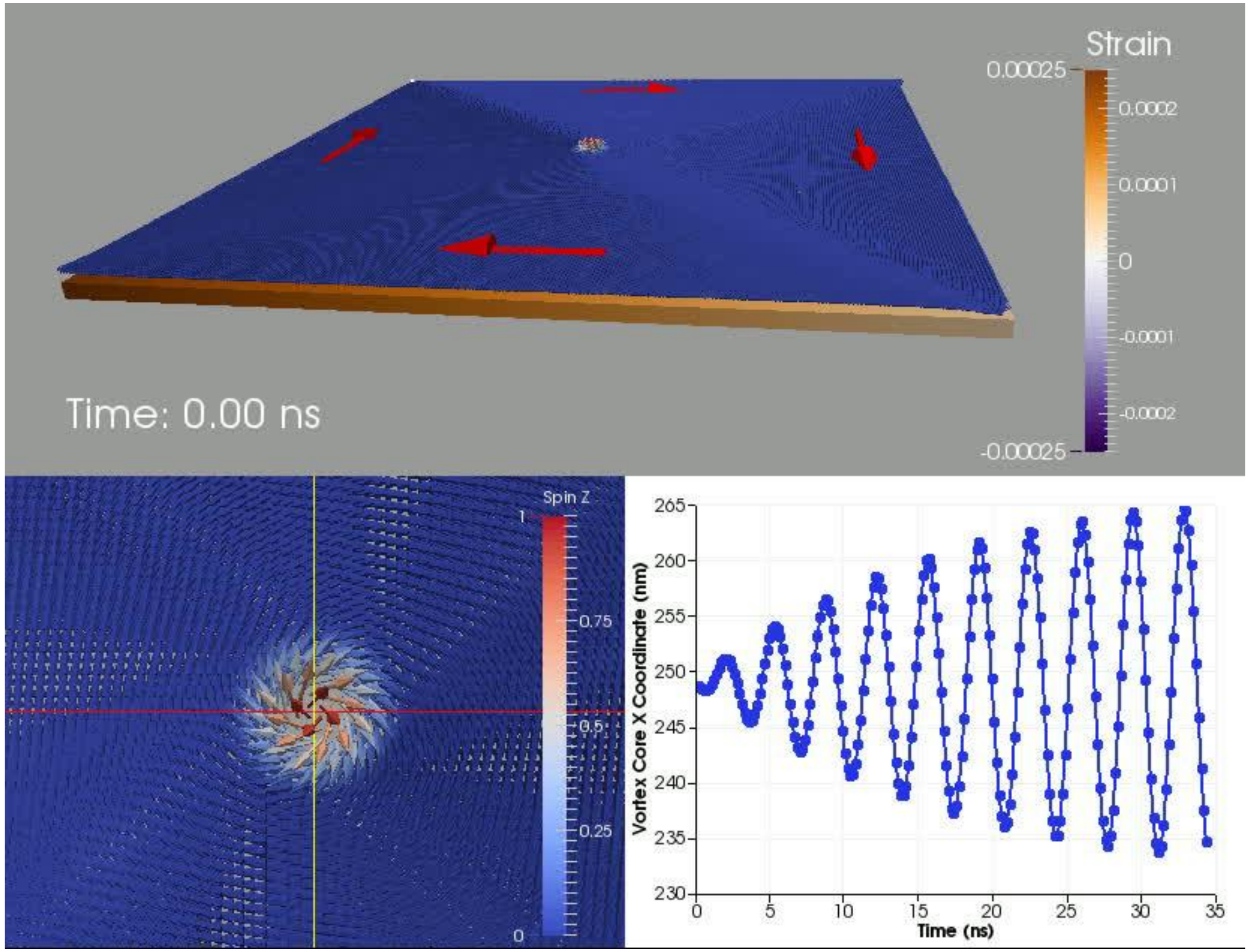

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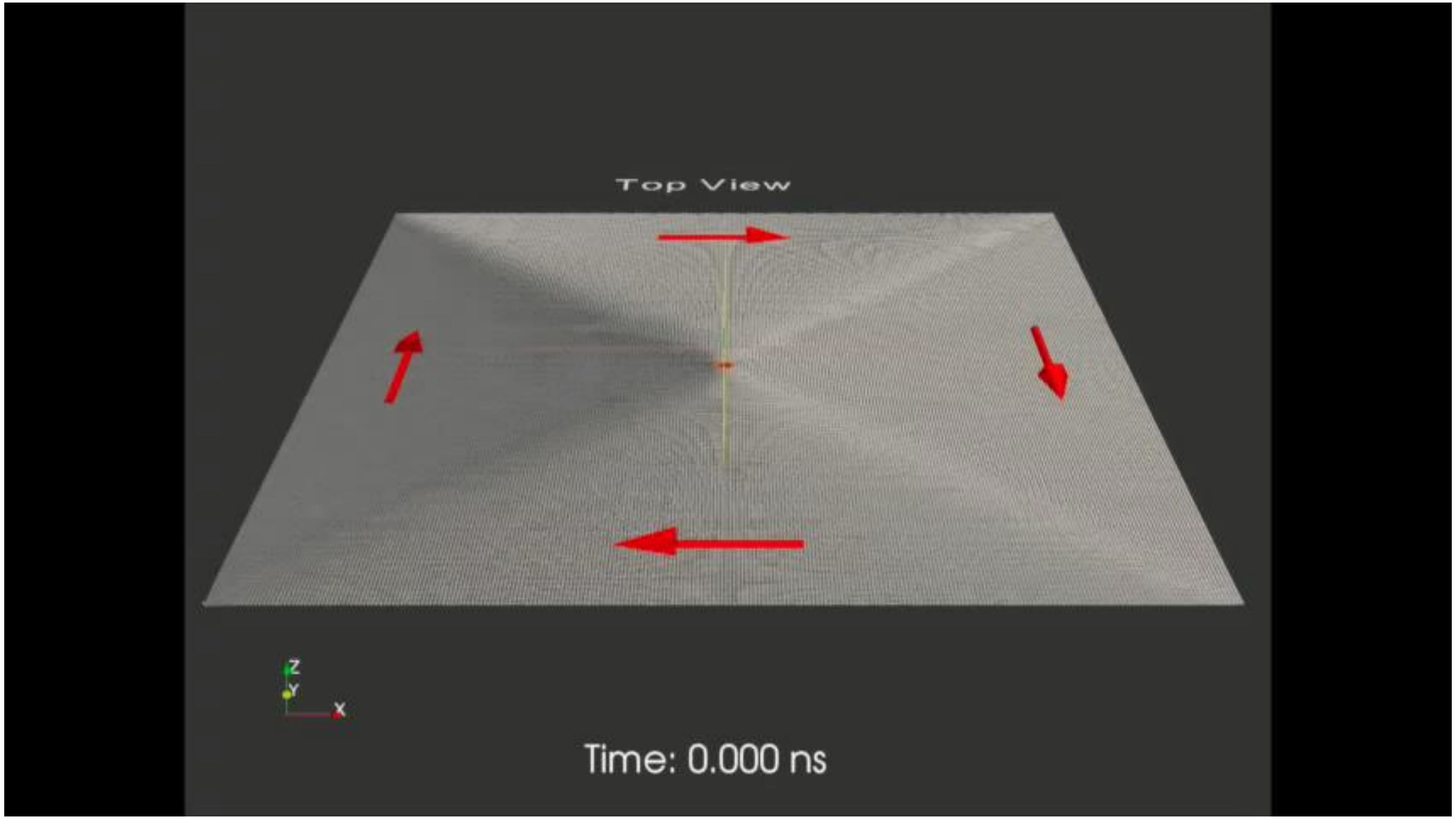

Acknowledgments

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Thankyou for your attention