Going Small, Fast and Dilute With Soft X-ray Microscopy

10 GHz, 10 nm and 10 ppm

(pico) (nano) (micro)

Hendrik Ohldag

SLAC National Accelerator Laboratory

January 10, 2017 at the meeting of the SCV section of the IEEE Magnetics Society

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

IEEE Magnetics Society
IEEE

- **IEEE Magnetics Society Home Page:** ***www.ieeemagnetics.org***
  - 3000 full members
  - 300 student members

- **The Society**
  - Conference organization (INTERMAG, MMM, TMRC, etc.)
  - Student support for conferences
  - Large conference discounts for members
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  - **Distinguished lectures**

- **Journals (Free Electronic Access for Mambers)**
  - *IEEE Transactions on Magnetics*
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- **Online applications for IEEE membership:** ***www.ieee.org/join***
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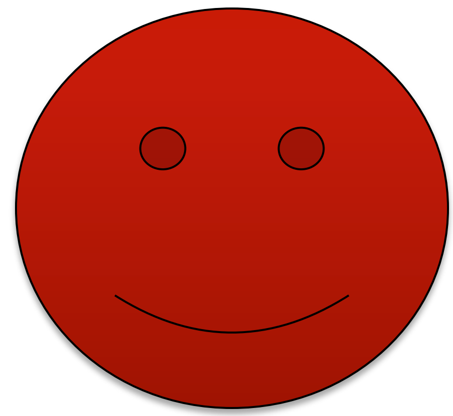

THANK YOU !!!

The Team

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The Royal Institute of Technology:	Anders Eklund, Gunnar Malm
Emory University:	**Sergei Urazdhin**
Oakland University:	Vasyl Tyberkevich, Andrei Slavin
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SLAC At A Glance – DOE/University

- SLAC is a U.S. DOE-funded National Laboratory, operated by Stanford University; Established in 1962
- 426 acres of Stanford land.
- ~50 Stanford faculty, ~1,500 employees + 3,000 users, visiting scientists per year
- In the past operated SPEAR, PEP, SLC for high energy physics.
- Today operates 2 major DOE-BES scientific user facilities (LCLS and SSRL) – light sources
- SLAC is not only operated by Stanford University it is also a part of the University. SU students and faculty work at SLAC

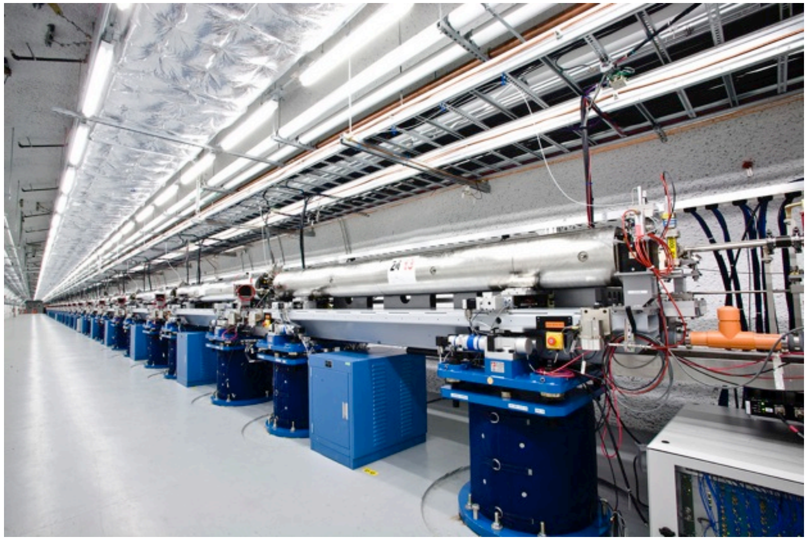
SLAC Now And Then – A Changing Mission

Stanford Linear Accelerator Center (SLAC), *started out as dedicated high energy physics laboratory* (1960 – mid 2000s)

SLAC National Accelerator Laboratory *today, enables accelerator based experiments* (including cosmological accelerators) in general, with a particular focus on Photon Science.

SLAC is a multidisciplinary user facility e.g.
- Life Sciences
- Applied Physics
- Astrophysics
- Chemistry

…..



Right: The LCLS undulator hall

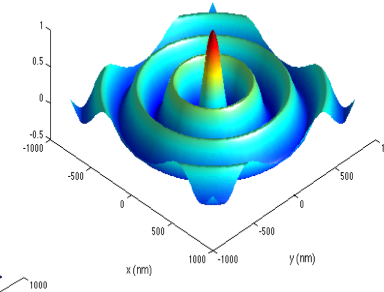
Outline

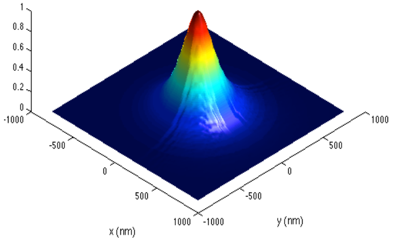
1.) Why synchrotron based x-ray microscopy?

2.) A quick primer into soft x-ray absorption

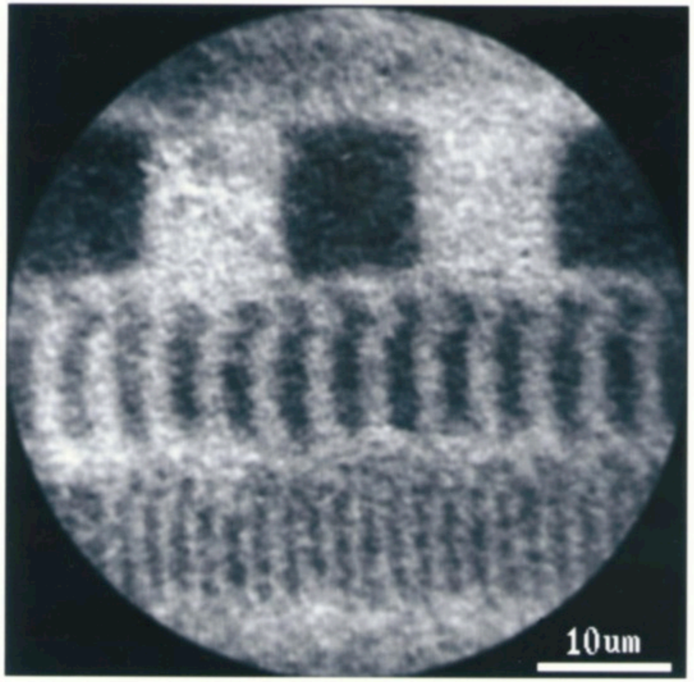
3.) Examples:

- Chemical and magnetic sensitivity — **LSMO**
- High sensitivity microscopy: — **Spin Injection**
- High temporal and spatial resolution: — **Spin Waves**





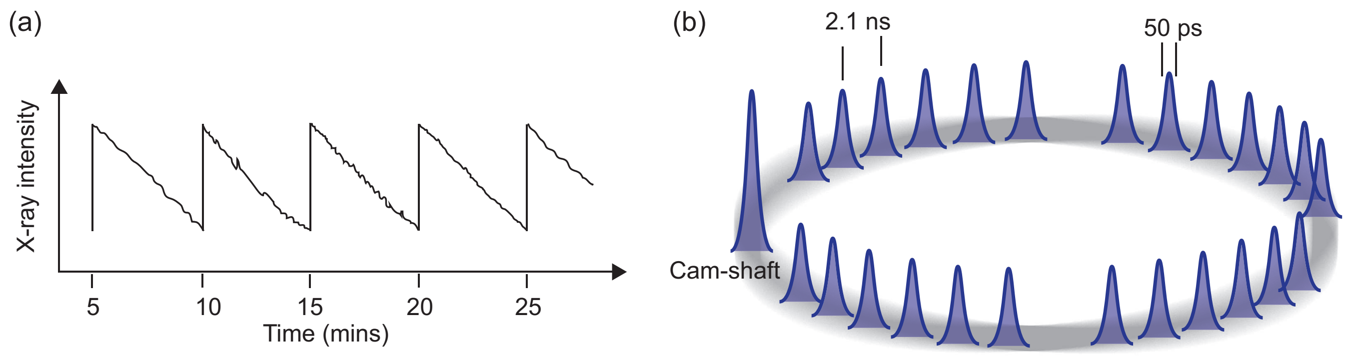
A Very Brief History Of X-ray Microscopy



The "power" of X-rays:

- X-rays provide SEE-THRU vision.
- The incredible intensity allows nanometer resolution in three dimensions

A Synchrotron Is A Pulsed X-ray Source



… it is a wonderful tool for time resolved studies with a few 10s of picosecond time resolution.

… produces wide spectrum of polarized radiation (eV – keV)

… but it also varies in intensity over time (~2%) due to electron loss

→ Normalization is crucial for high sensitivity
→ real time normalization, lock in to pulse structure

X-ray Microscopy At The Nanometer and Picosecond Scale

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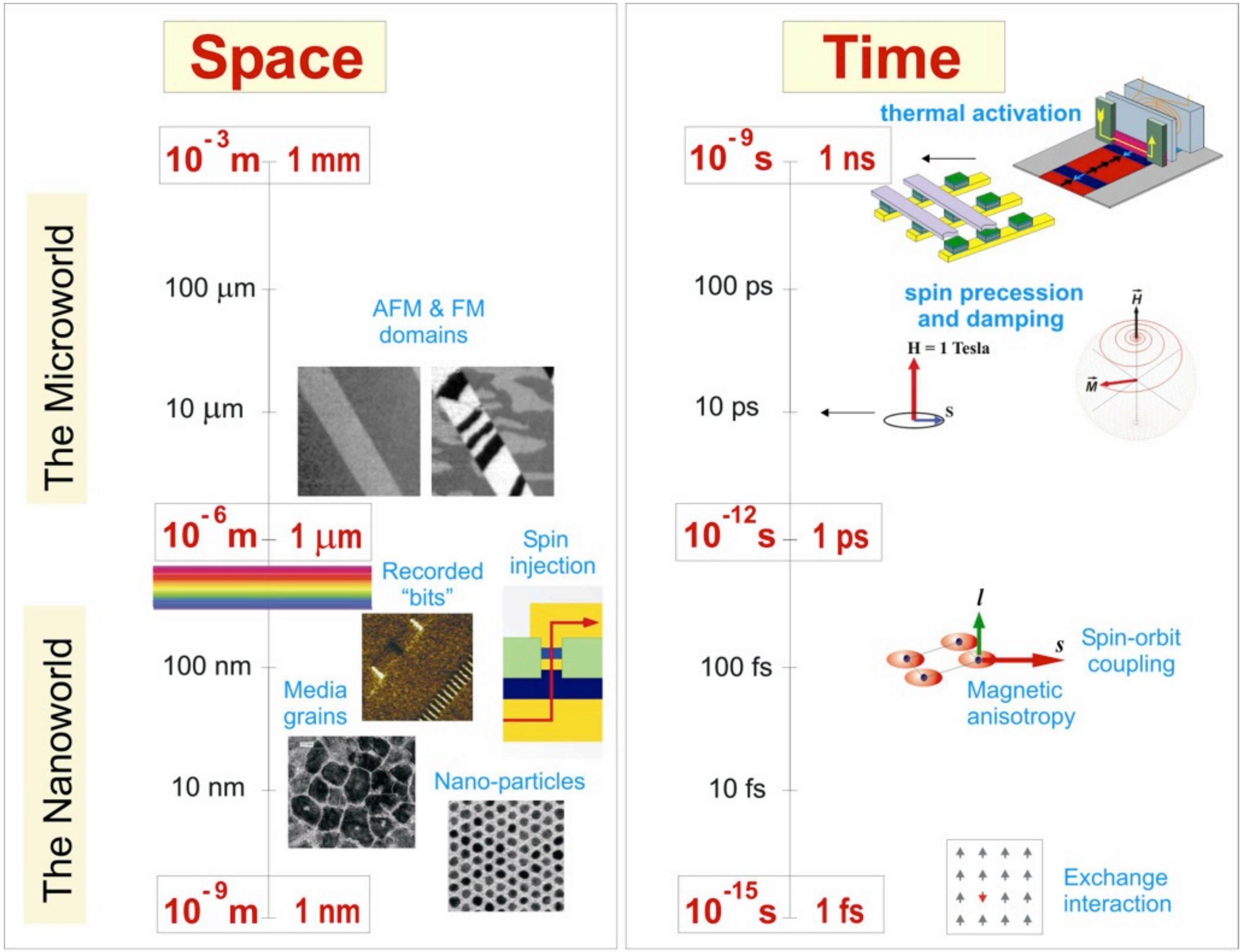
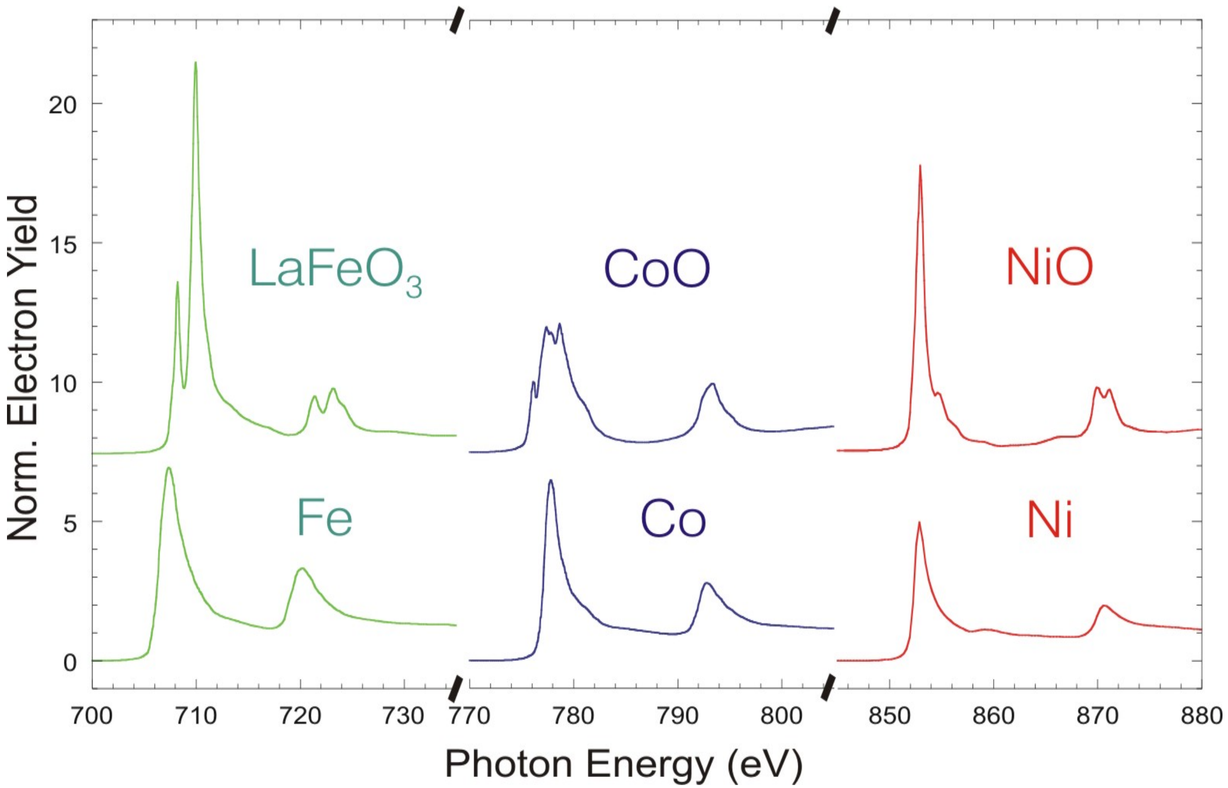
The time structure and wavelengths of synchrotron radiation is uniquely suited to study the fundamental processes behind technologically relevant magnetic devices .

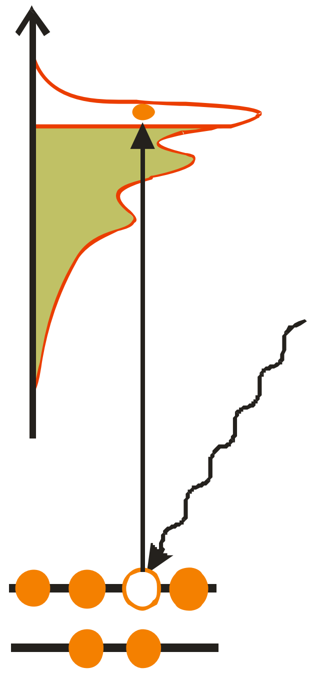


Note: Δt (fs) = 4 / ΔE (eV)

A quick primer to Soft X-ray Absorption Microscopy

Elemental And Chemical Sensitivity

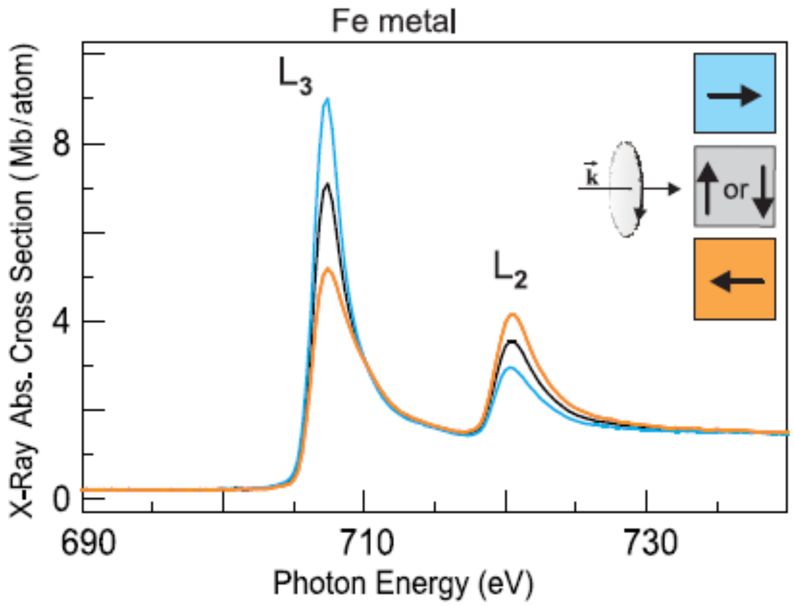


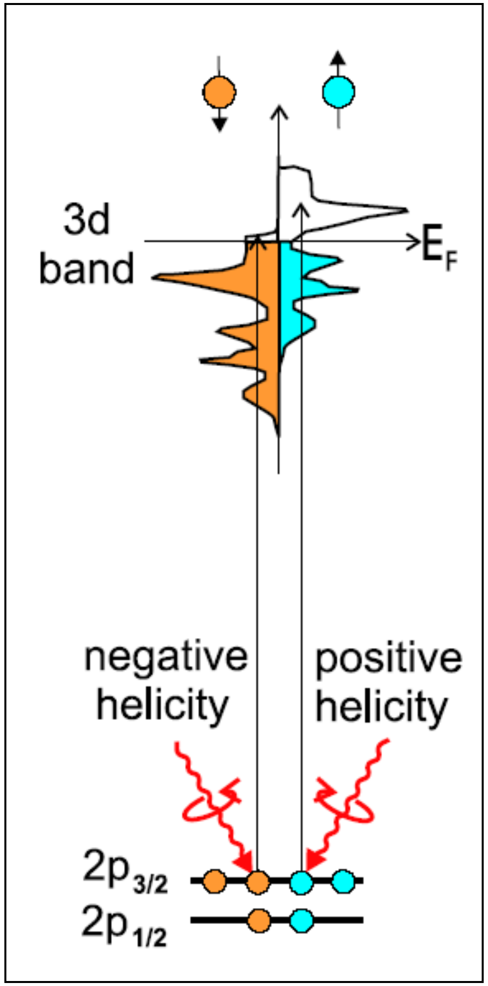


Energy of absorption resonance (binding energy of core level)→ Elemental specificity

Shape of resonance DOS(E) of final states → Chemical sensitivity

Polarization Dependence: XMCD

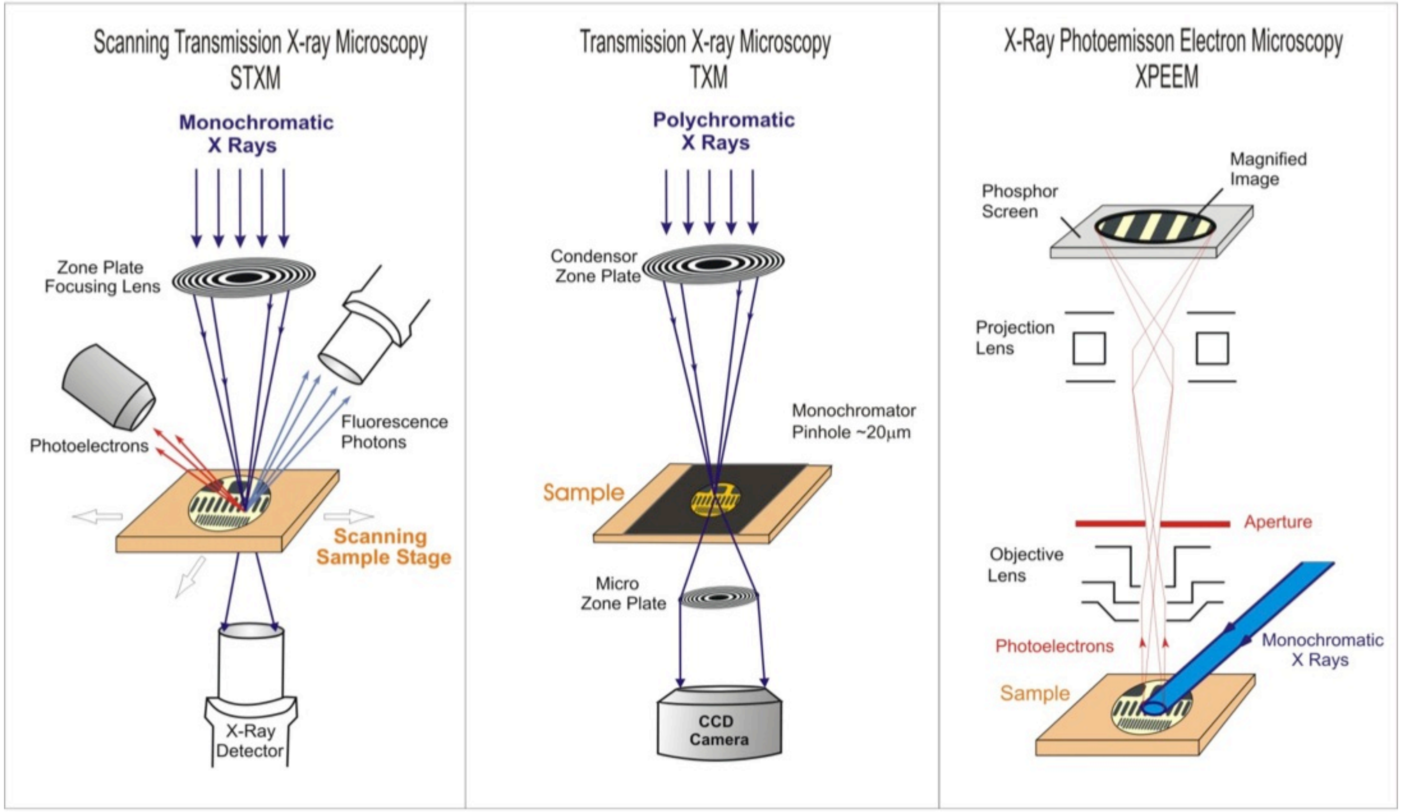




- Optical transition conserve the electron spin
- Selection rules limit the number of possible transitions effectively generating spin polarized electrons as a probe

Spin asymmetry in ferromagnets leads to
→ X-ray Magnetic Circular Dichroism (XMCD)

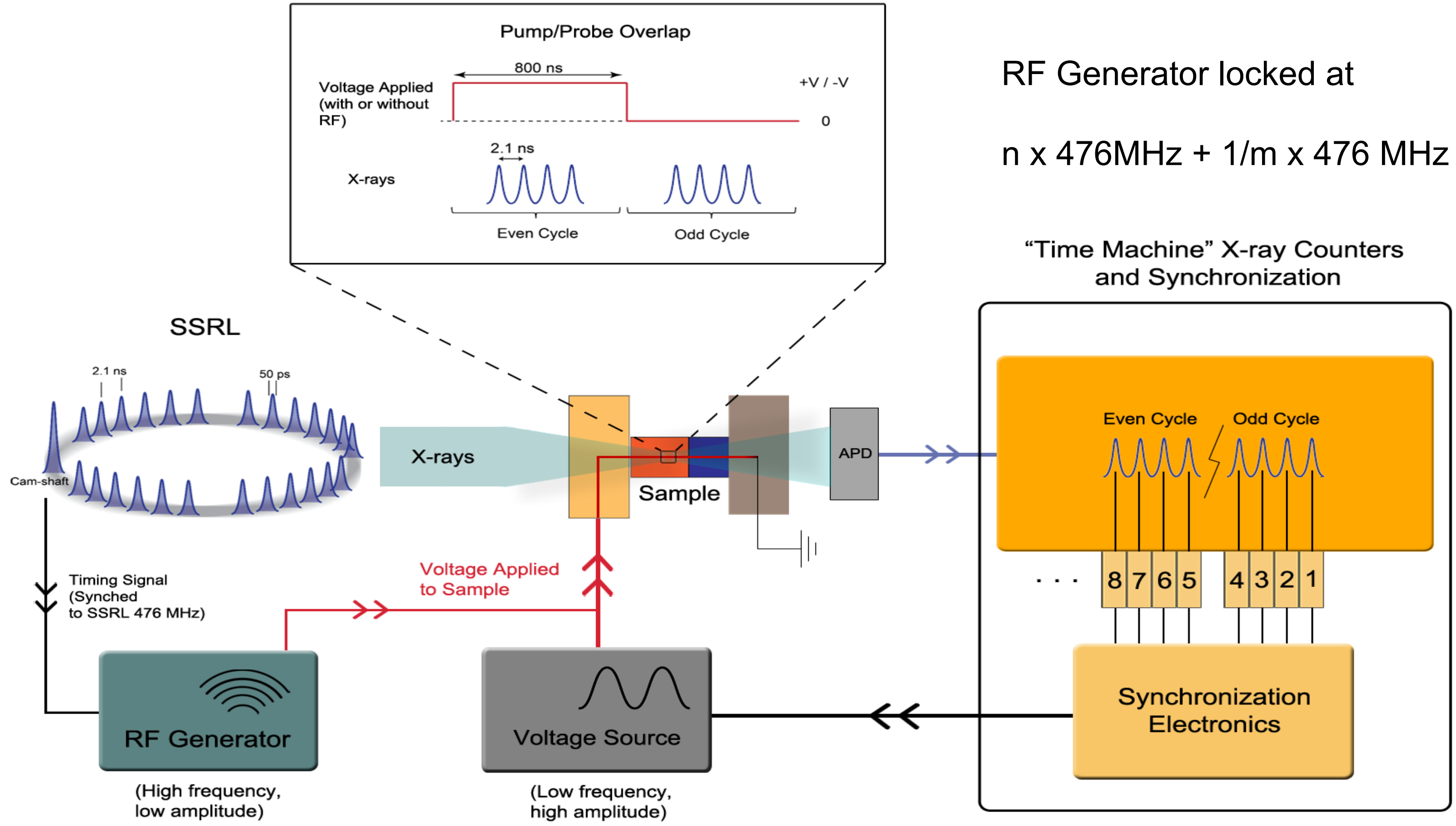
X-ray Microscopy



X Ray absorption can be detected in transmission, fluorescence or electron yield

→ X-ray and electron microscopy is possible with high spatial resolution.

The SSRL Scanning X-ray Microscope



RF Generator locked at

n x 476MHz + 1/m x 476 MHz

→ Effective double lock-in at 476 MHz and 1.28 MHz with 24hr stability ~ 1ps
→ Enables useful normalization in STXM and SNR of 10^5 - 10^6 after seconds

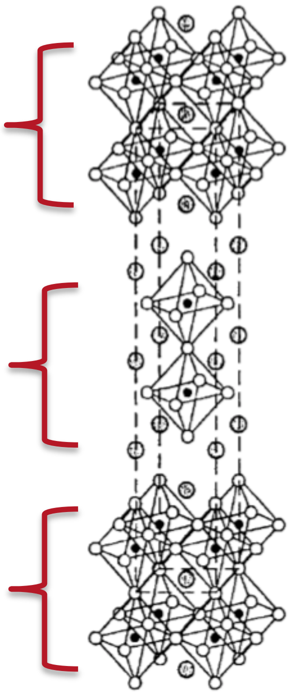
S. Bonetti et al. Rev. Sci. Instr. 093703, 86 (2015)

The Mystery Of Two Transitions in LSMO

A “static” example

The Mystery Of Two Transitions in LSMO

Investigate the microscopic origin of two transition temperatures in $La_{1+x}Sr_{2-x}Mn_2O_7$ - Extensively studied by ARPES !!



n=2

$(R,A)_3M_2O_7$

Bi layered LSMO with x~0.25 shows
(Ling et al. PRB **62** 15096 (2000))

- a metal to insulator transition
- a ferromagnet to paramagnet transition

around 120K

Note: cubic LSMO is a ferromagnetic metal at RT

Conduction above T_C? Magnetism above T_C?

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A local metallic state in globally insulating $La_{1.24}Sr_{1.76}Mn_2O_7$ well above the metal–insulator transition

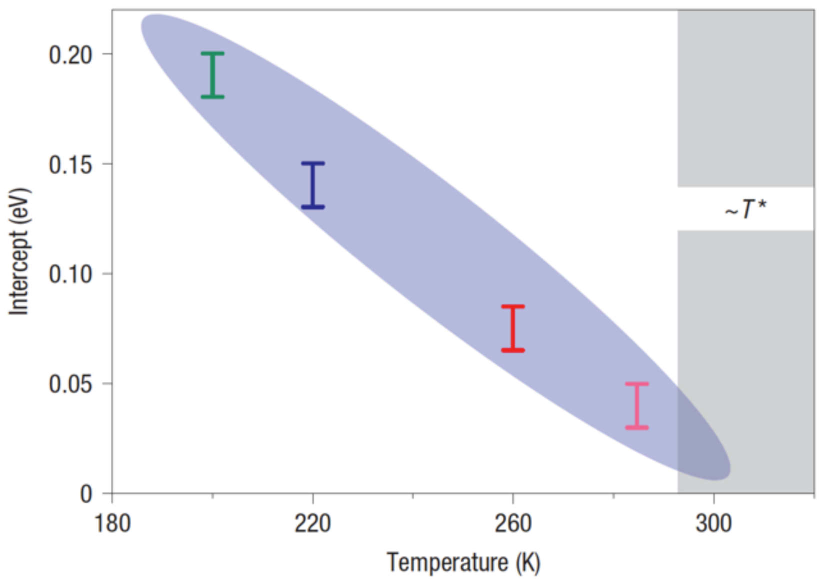
Z. SUN[1,2]*, J. F. DOUGLAS[1], A. V. FEDOROV[2], Y.-D. CHUANG[2], H. ZHENG[3], J. F. MITCHELL[3] AND D. S. DESSAU[1]*

Two-dimensional intrinsic and extrinsic ferromagnetic behavior of layered $La_{1.2}Sr_{1.8}Mn_2O_7$ single crystals

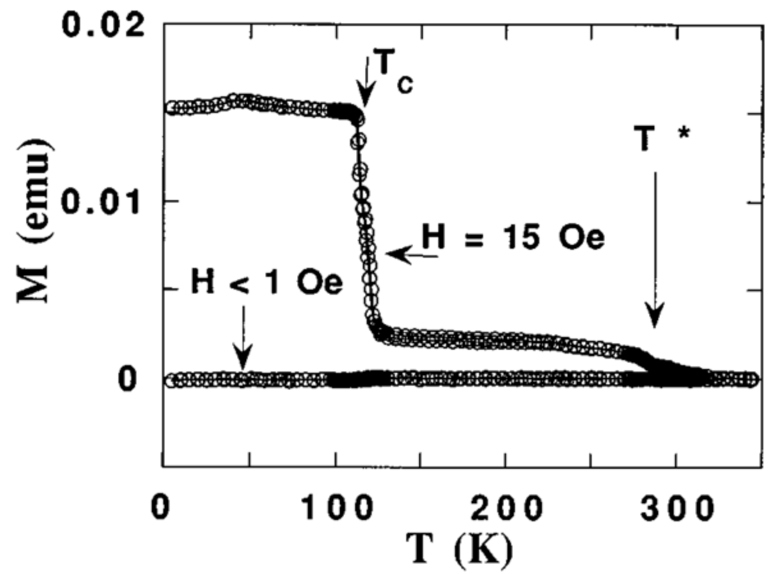
C. D. Potter,* Maribeth Swiatek,† and S. D. Bader
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

D. N. Argyriou‡
Science and Technology Center for Superconductivity, Argonne National Laboratory, Argonne, Illinois 60439

J. F. Mitchell, D. J. Miller, D. G. Hinks, and J. D. Jorgensen

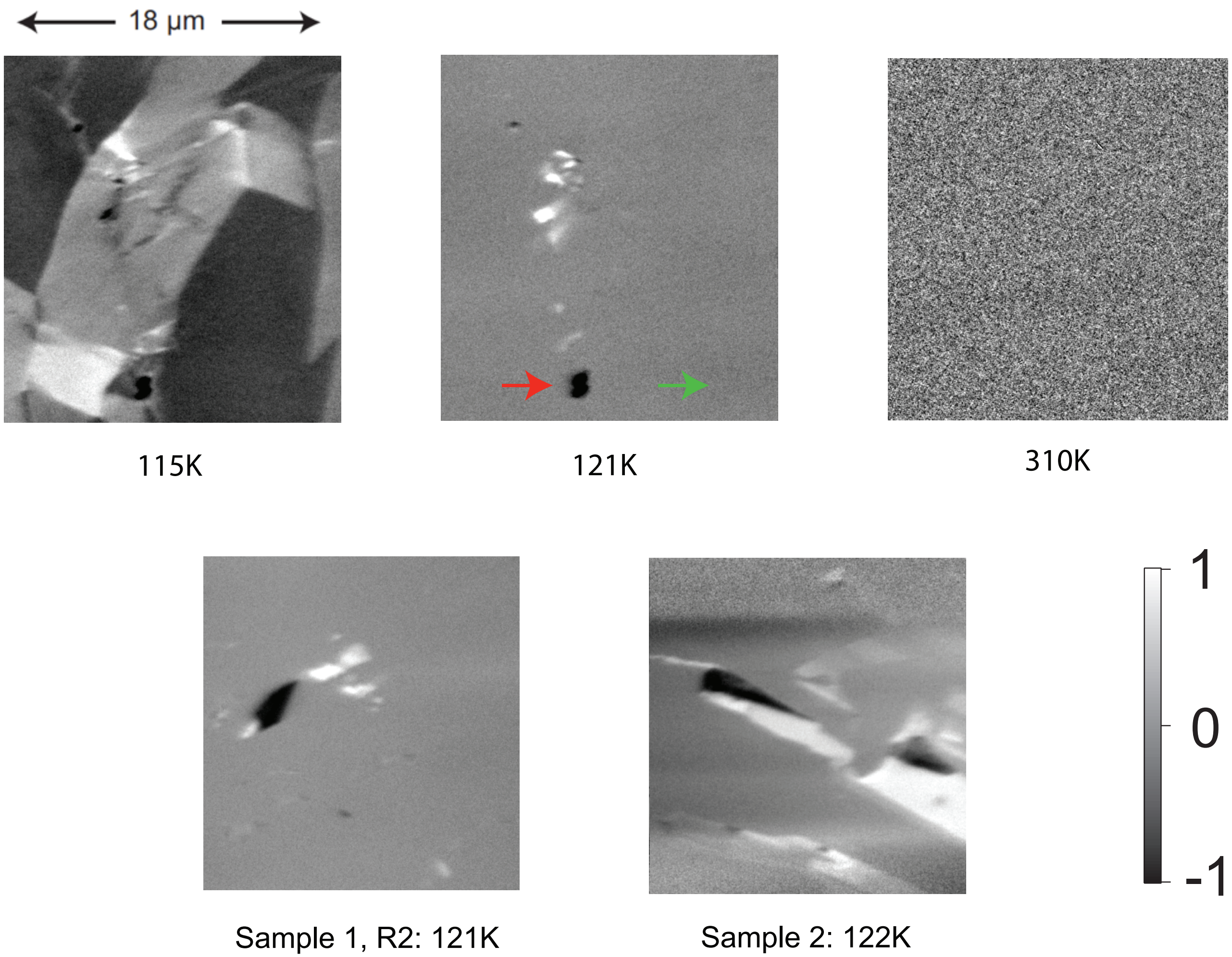


Nature Physics 2007

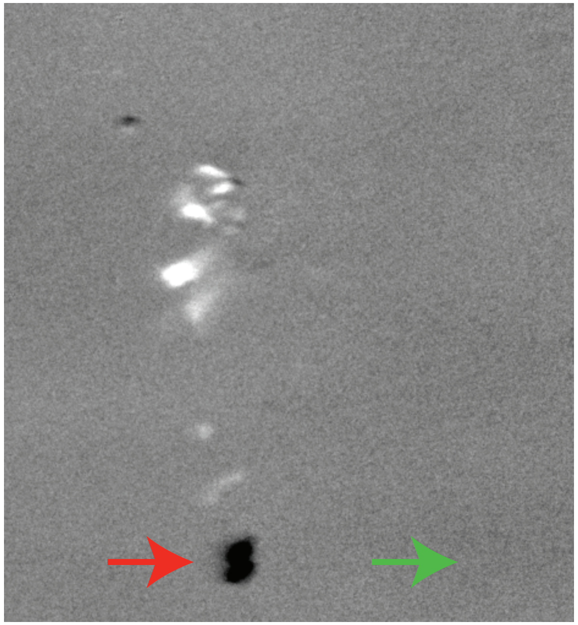


Phys Rev B 1998

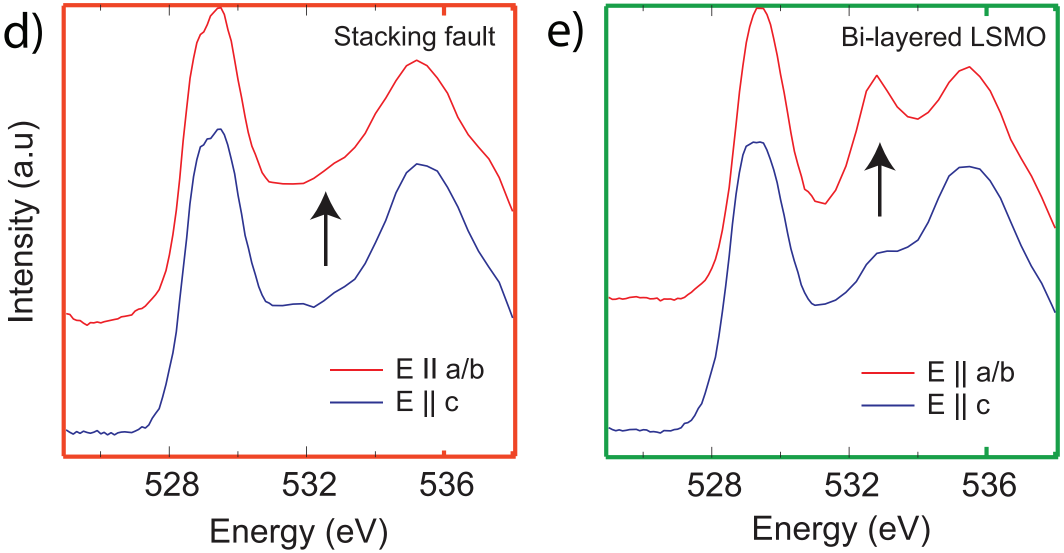
PEEM Reveals Magnetic Contrast Above 120K



Magnetic Inclusions And Linear Dichroism

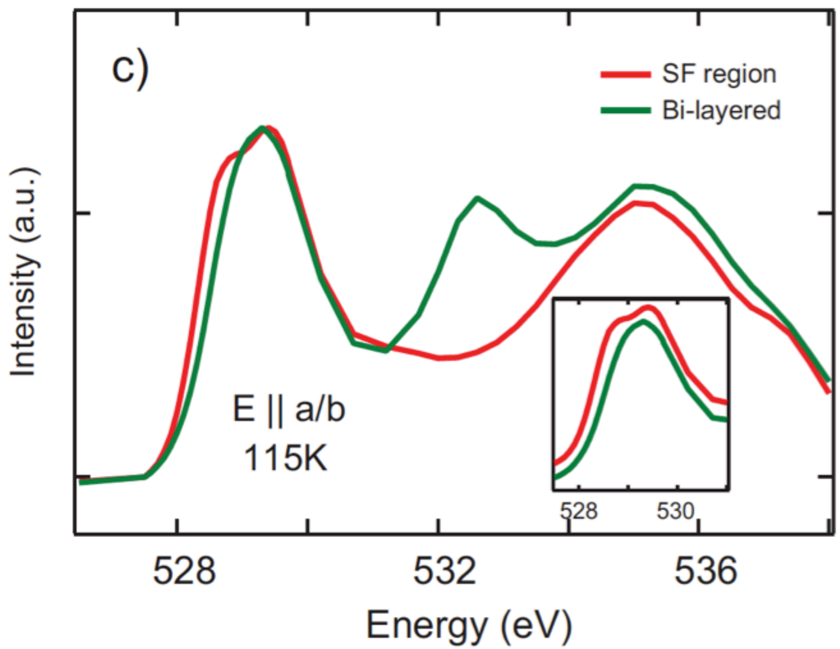


121K

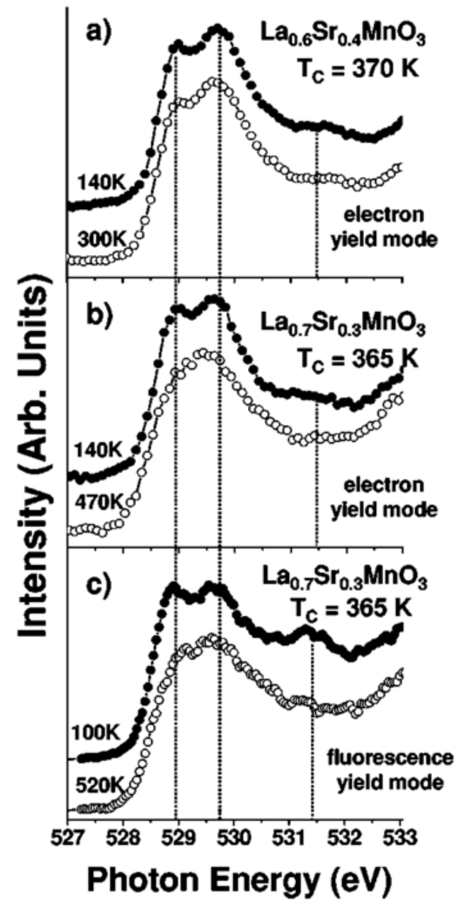


- Layered sample exhibits linear dichroism
- Magnetic Impurities do not → 3D structure like cubic, metallic, ferromagnetic LSMO phase
- Stacking Faults !!!

Stacking Faults Exhibit Metallic Signature



XAS intensity at peak onset
→ Indicates DOS at E_F

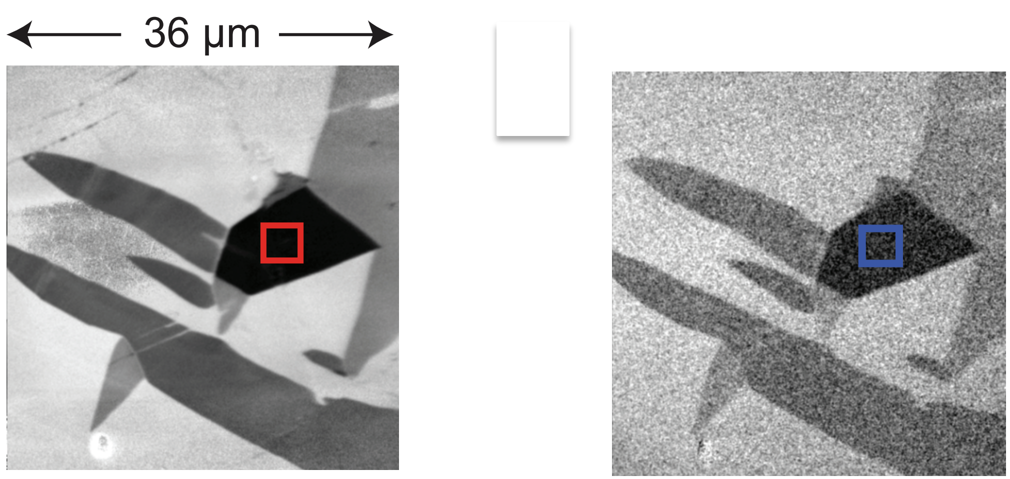


Mannella et al. PRB 2005

Summary Example 2

1. PEEM can be used to reveal effects from intergrowths in “real” samples
2. T* is due to stacking faults that are structurally more 3D like
3. Stacking faults are more metallic than the bi-layered host

M. Hossain et al., Appl. Phys. Lett. **101**, 132402 (2012).

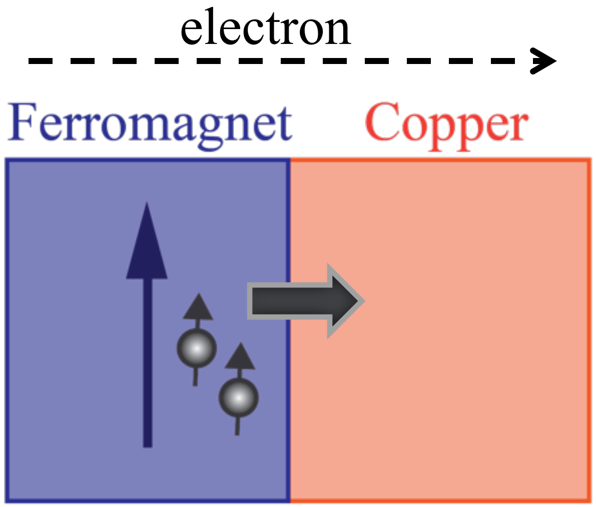


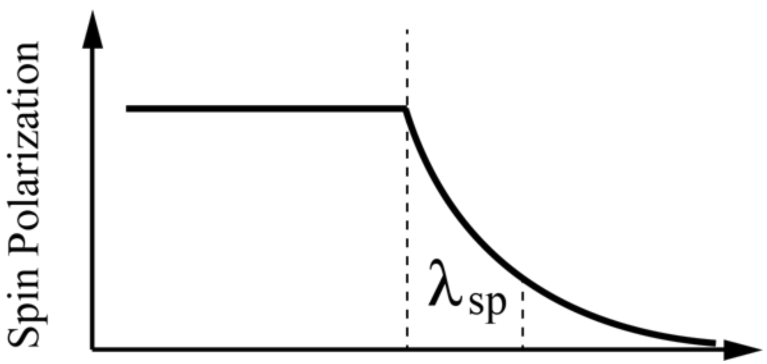
Mn XMCD versus O XMCD in LSMO at 25 K

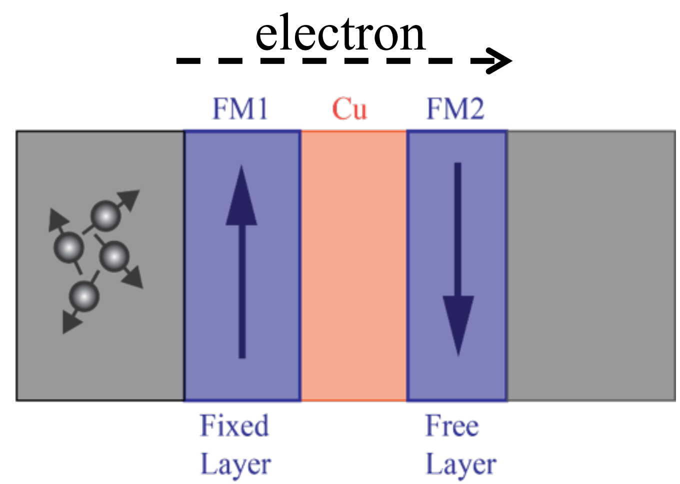
Observing spin accumulation at interfaces and in the bulk

Measuring tiny magnetic moments via high frequency lock in techniques

Transient Magnetization and Giant Magneto Resistance







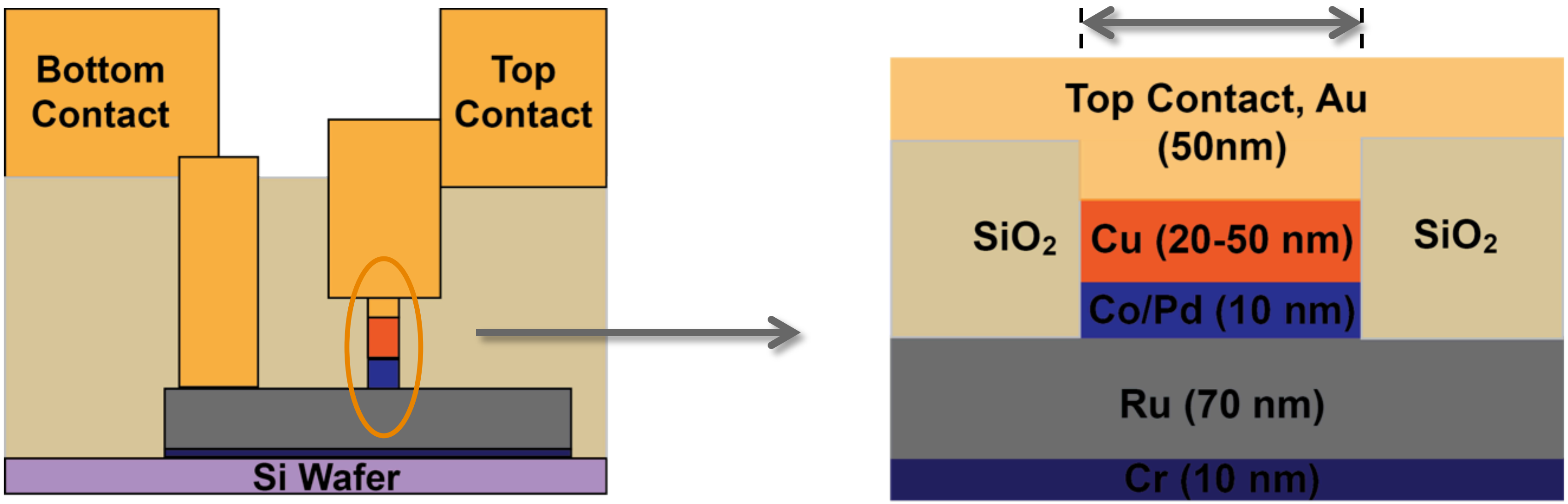
Spin polarization in Cu can be used to switch second FM

Predicted less than 0.001 Bohr Magneton per Cu atom

Complex Sample – Buried Cu – High Current Density

Lithographically fabricated Pillars

150 x 150 nm^2,
250 x 250 nm^2

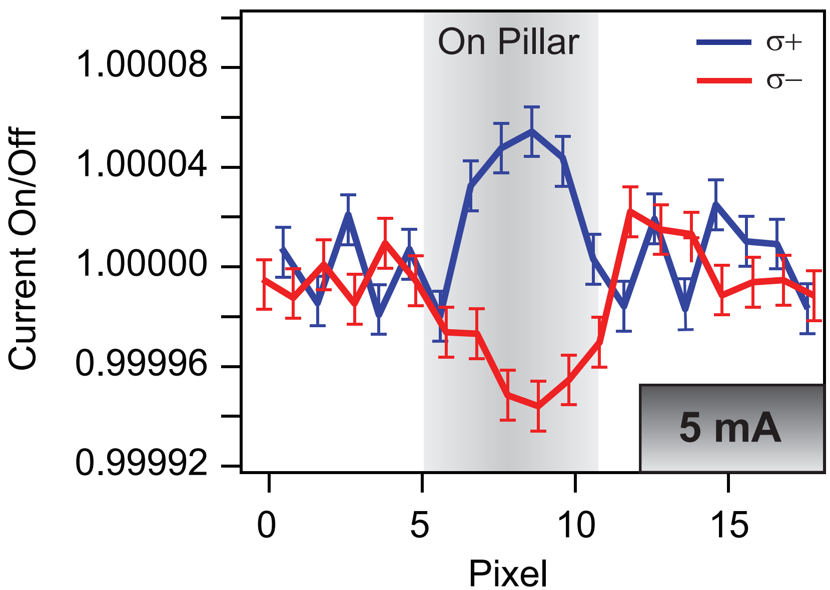


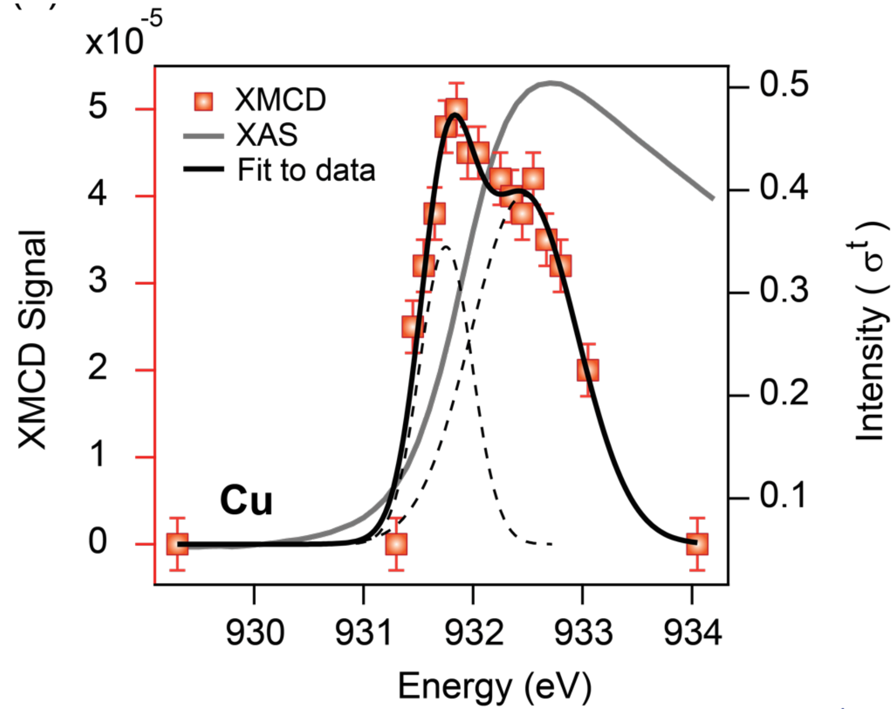
Lithography done by J. Katine from HGST

Stack Layers grown by A. Kent group from NYU

Stack – Ta(3)/Ru(30)/Ta(3)/Ru(30)/Ta(3)/CoPd(10nm)/NiCo(2nm)/**Cu(27 nm)**/Au(50nm)

XMCD of a Nanopillar



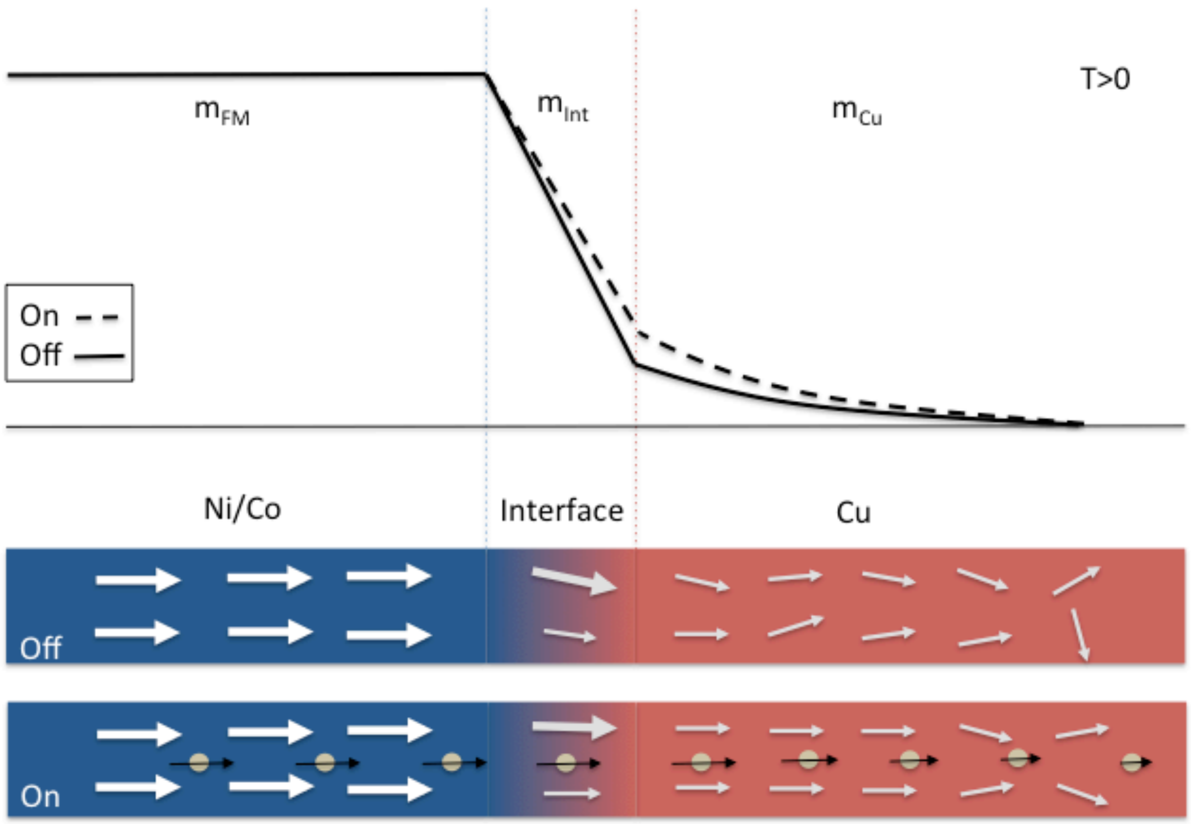


Estimated 3x10^{-5} μ_B per Cu atom due to spin injection.

Spectroscopy shows ~ ½ of the scattering at the interface.

R. Kukreja et al., Phys. Rev Lett. 115, 096601 (2015)

Magnetic Interface and Chemical Interface



1.) Significant alignment via spin torque at interface
2.) Small spin accumulation per atom in Cu bulk

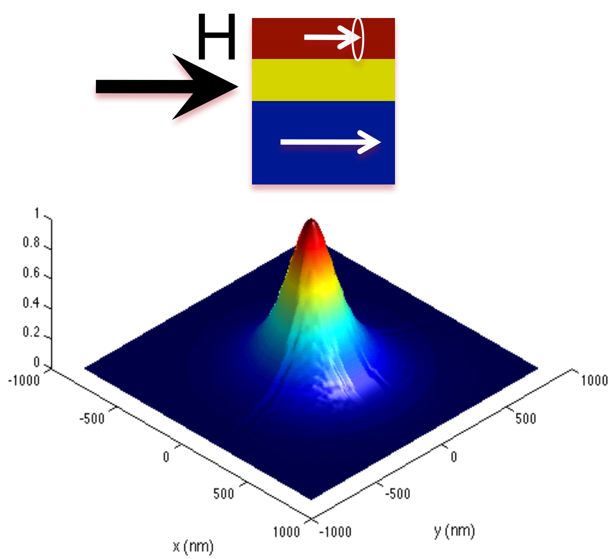
OK – let's ride some (spin) waves now

Spin Torque Oscillator and Spin Waves

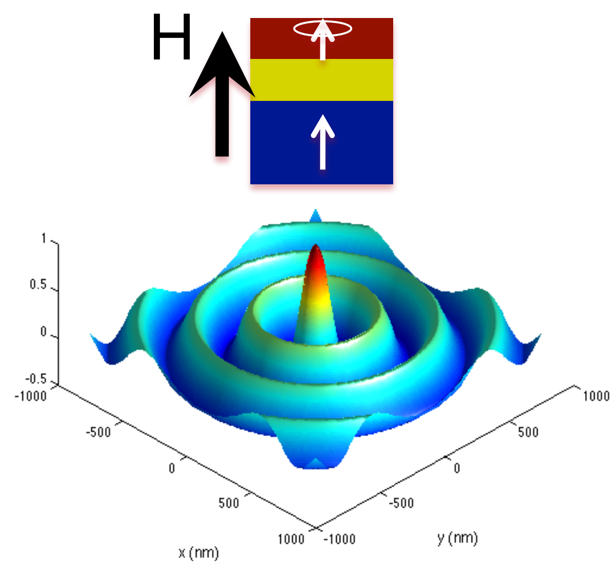
PRL **105,** 217204 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

Experimental Evidence of Self-Localized and Propagating Spin Wave Modes in Obliquely Magnetized Current-Driven Nanocontacts

Stefano Bonetti,[1,*] Vasil Tiberkevich,[2] Giancarlo Consolo,[3,4] Giovanni Finocchio,[4] Pranaba Muduli,[5] Fred Mancoff,[6] Andrei Slavin,[2] and Johan Åkerman[1,5]



A. Slavin and V. Tiberkevich, Phys. Rev. Lett. **95**, 237201 (2005)



J. Slonczewski, J. Magn. Magn. Mater. **195**, 261 (1999)

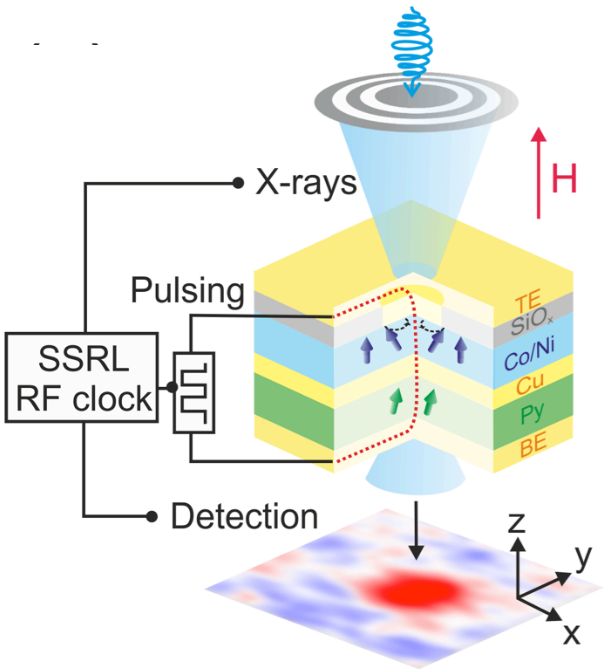
Case 1: Out of plane anisotropy

Free layer: (0.2Co|0.6Ni) x 6

Spacer: Cu 10 nm

Fixed layer: Py 10 nm

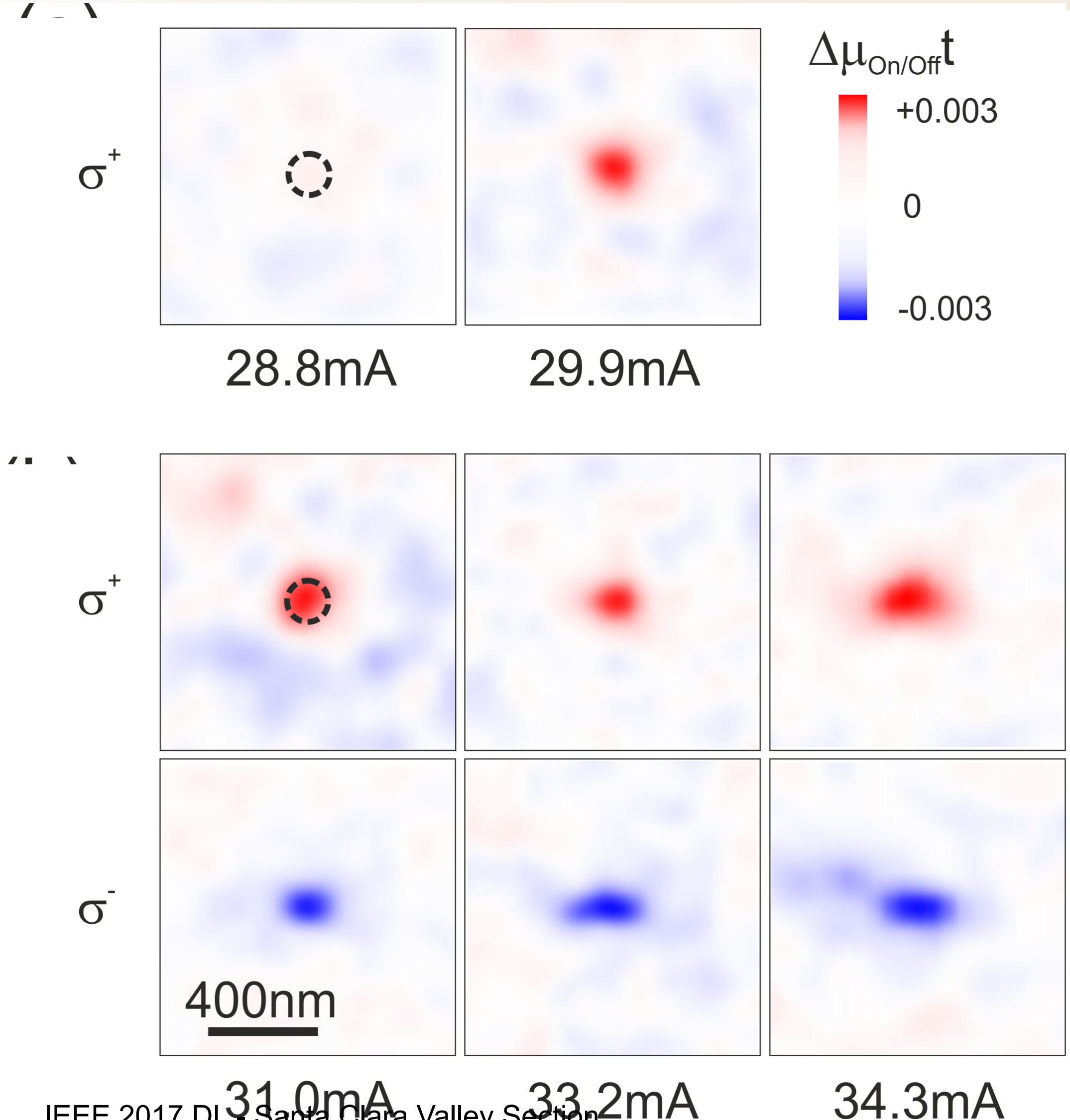
External field:	700 mT
Current:	24-30 mA
Contact:	~150 nm
Photon Energy:	778.2eV (Co L_3)



- Precession of the magnetization will reduce **M** along x-rays
- Acquire images with current on/current off

→ Images of the envelope of the excitation

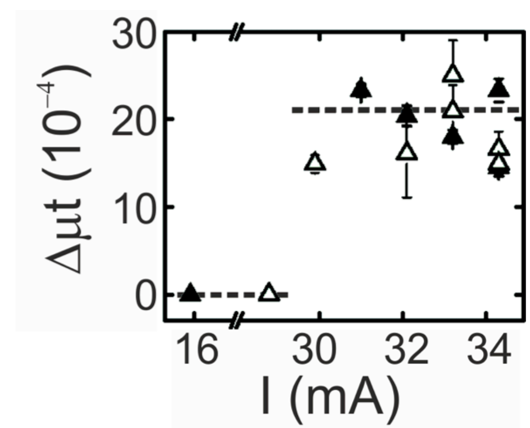
Observations



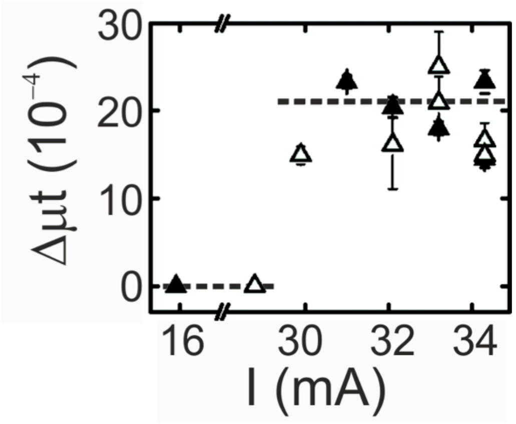
No changes up to 29mA

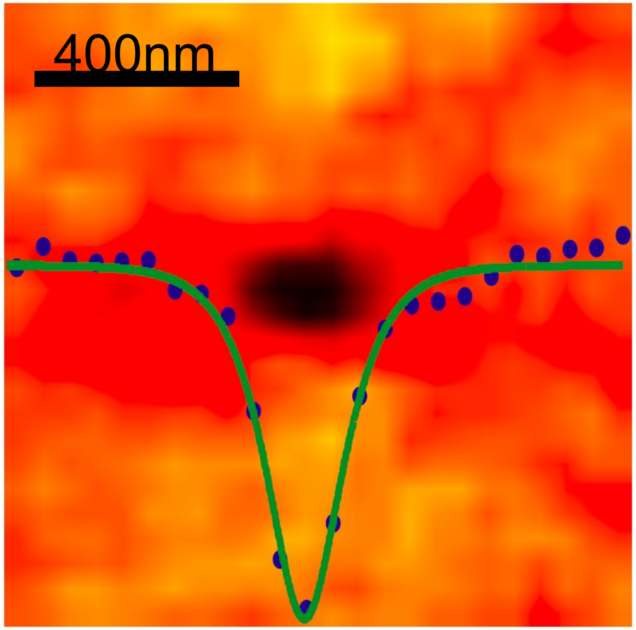
Onset of magnetic excitation at ~ 30 mA

Excitation persists up to at least 34 mA



Conclusions – What is this?





→ Sudden onset of excitation
→ Stability range of excitation
→ Line profile and width (~175 nm) cannot be fitted with propagating mode

Consistent with real space image of a localized magnetic soliton.

[D. Backes et al. Phys. Rev. Lett. 127205 (115), 2015]

Now We Rotate The Film And Magnetization In Plane ….

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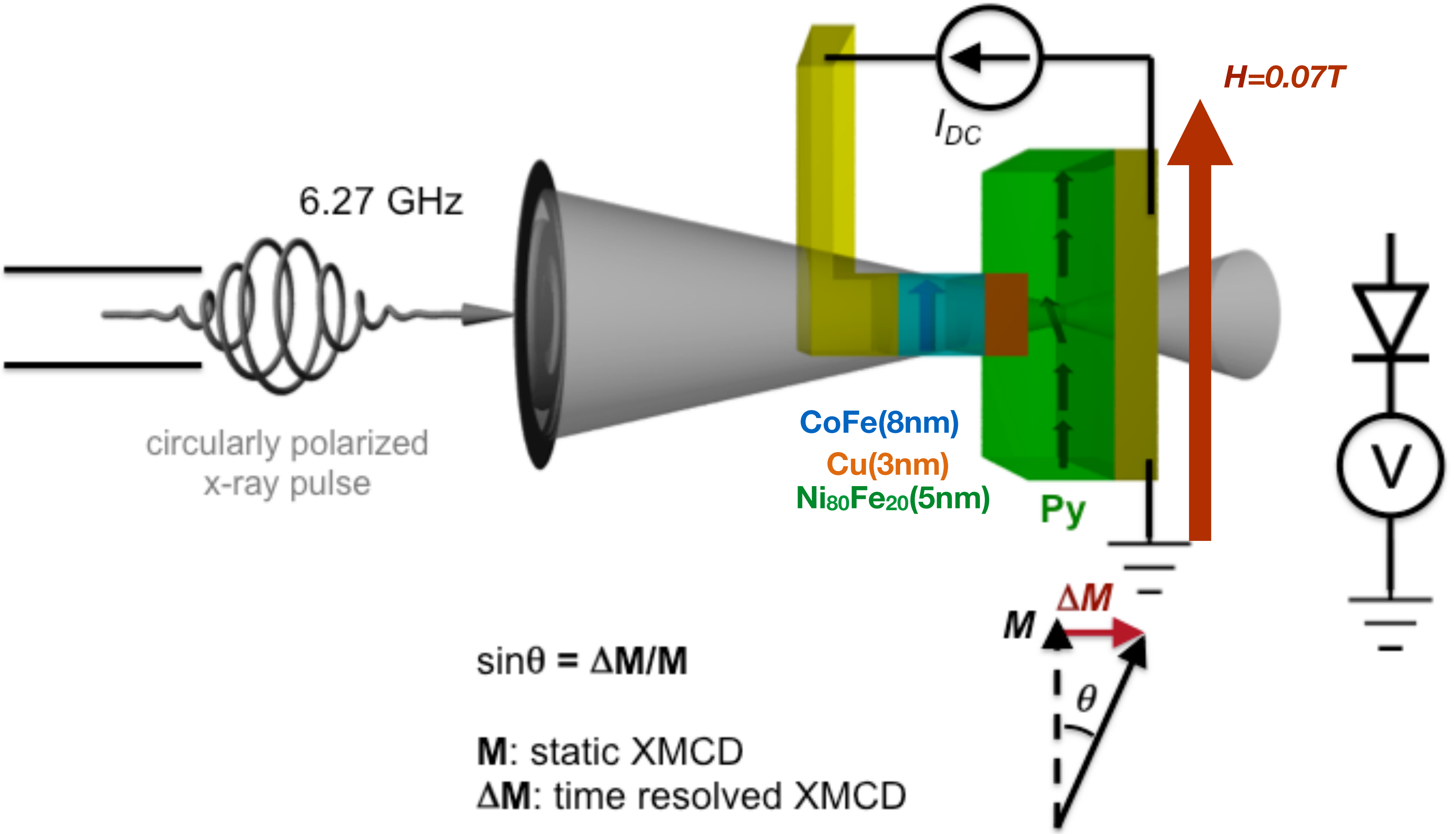


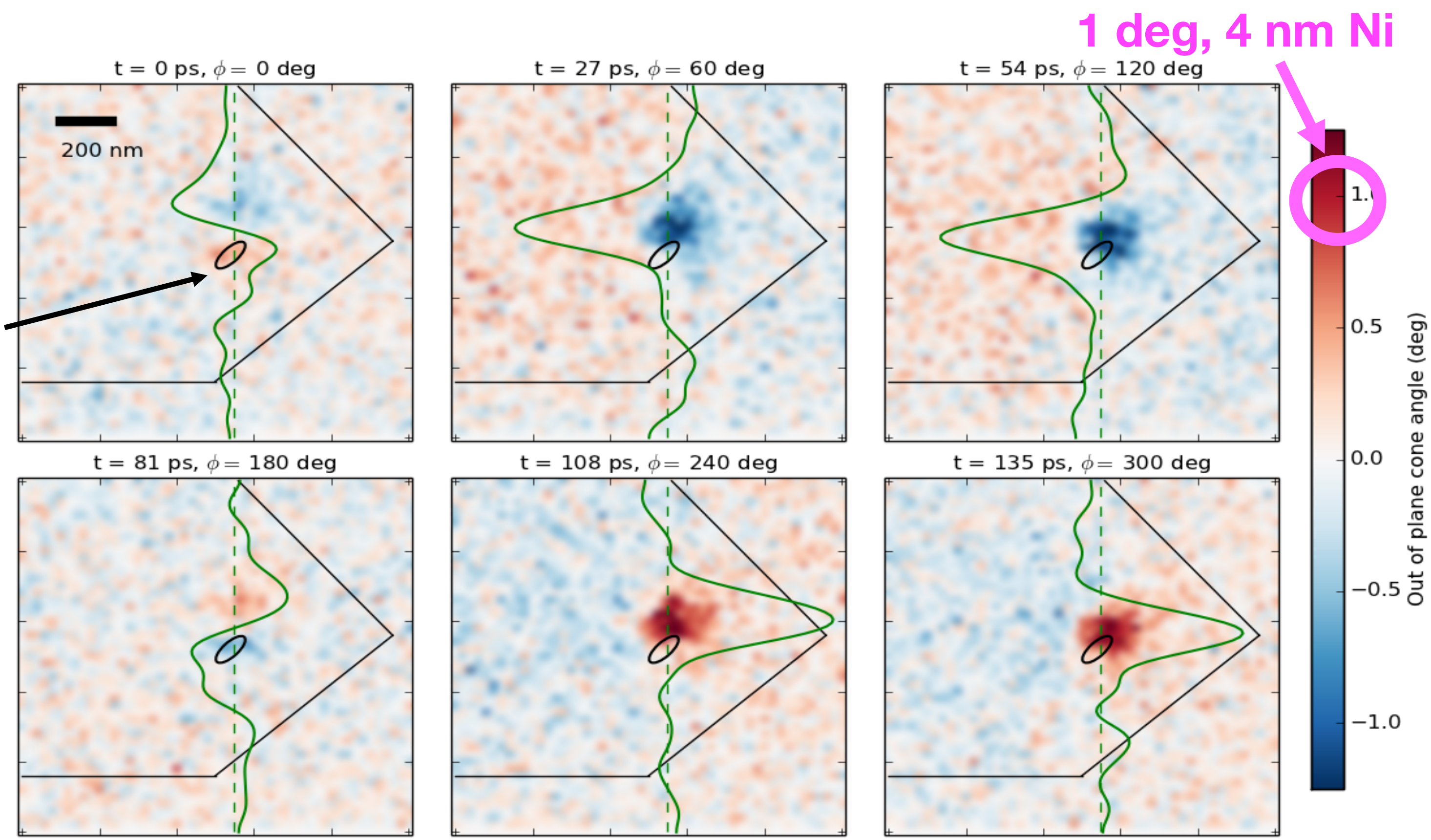
$\sin\theta = \Delta M/M$

M: static XMCD
ΔM: time resolved XMCD

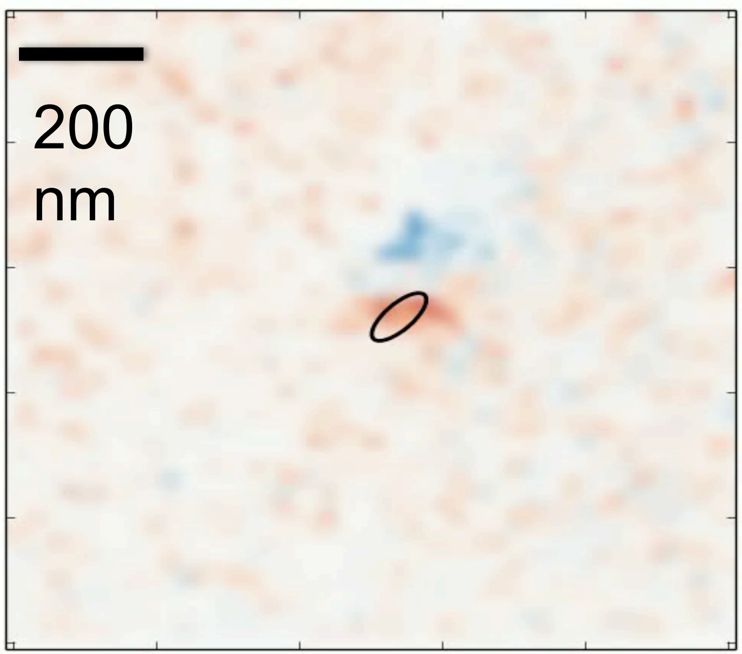
Following the Excitation in Time

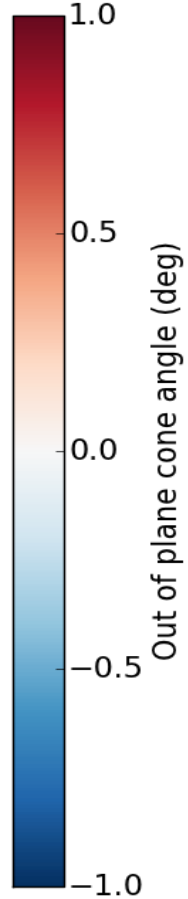
Nano Contact

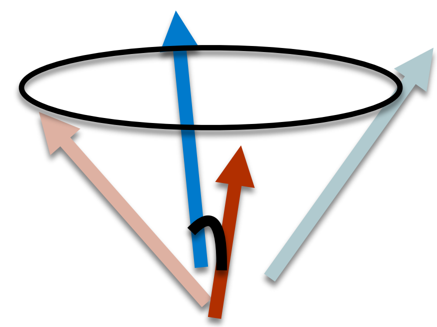
50 nm x 130 nm



Spin Wave Movie

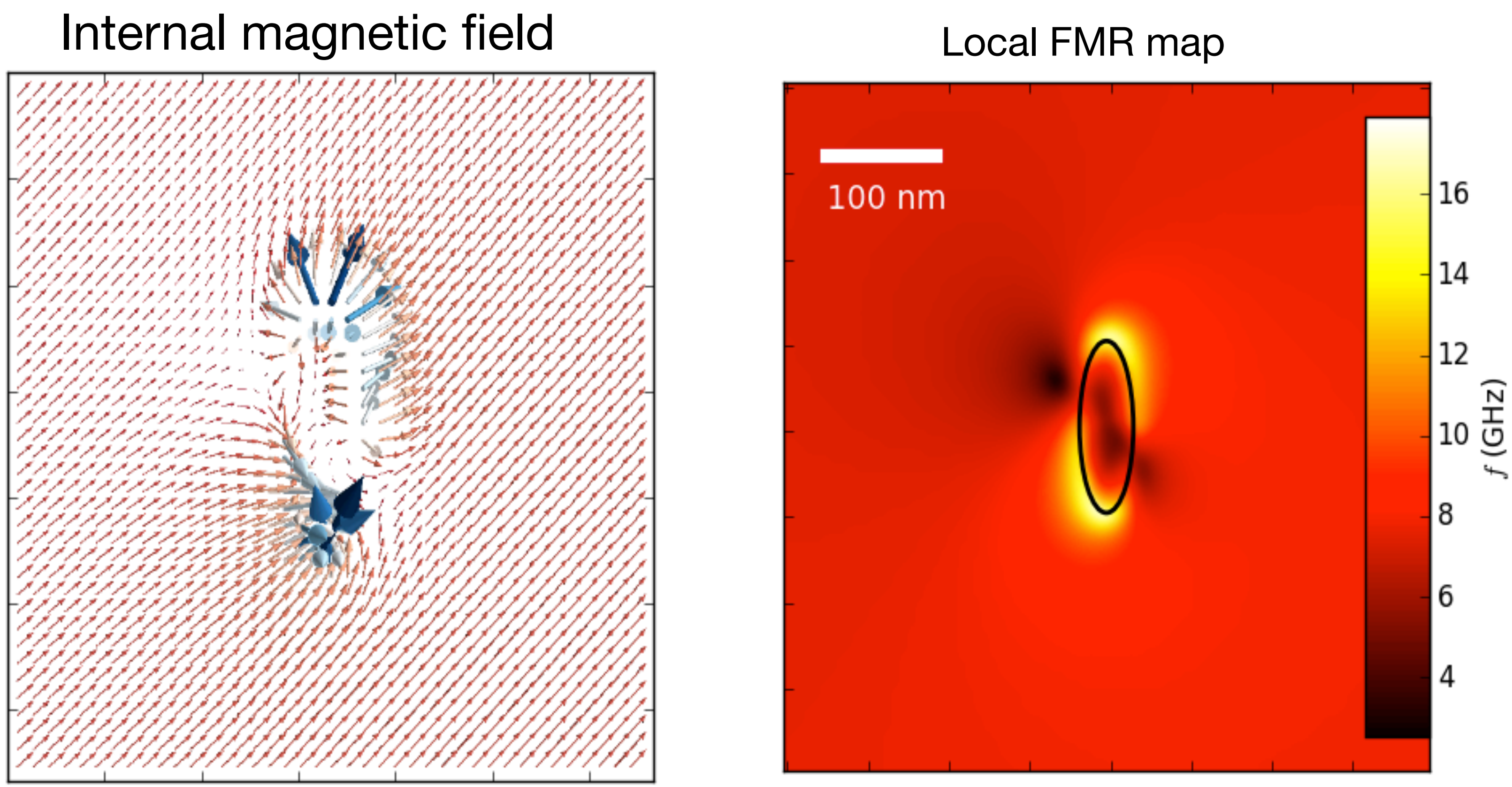






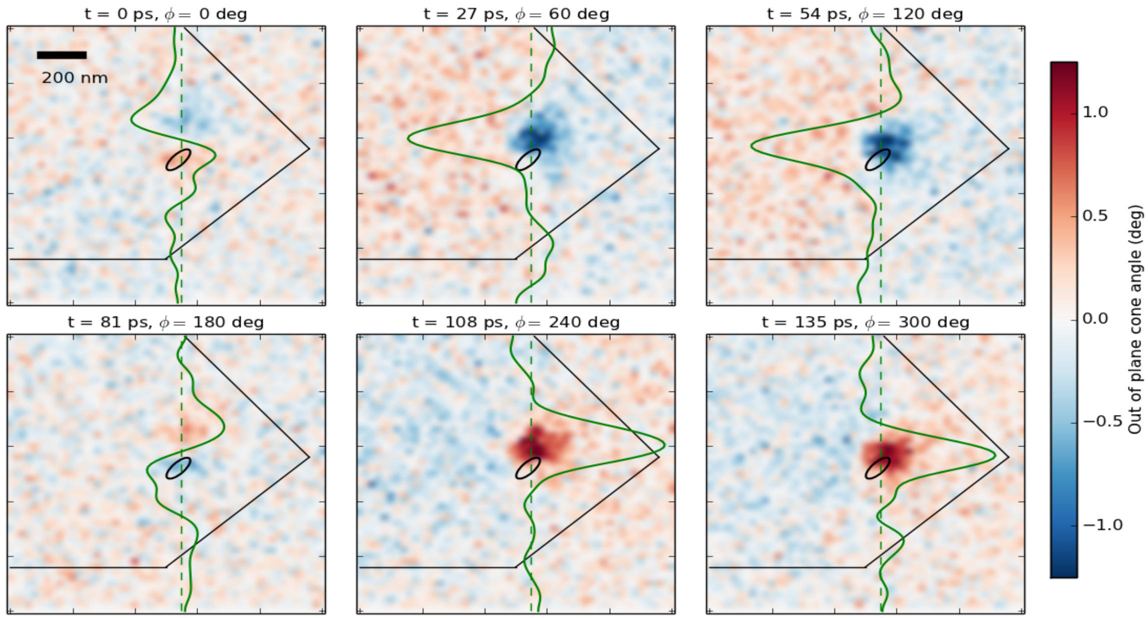
Out-of-plane
cone angle

Variation of Internal Fields → Asymmetric FMR



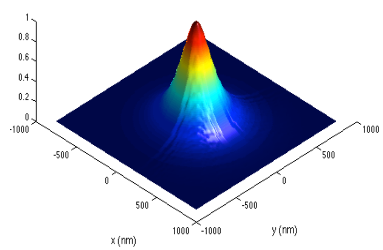
Internal Field = Oersted field + External field + Dipolar field from polarizing layer

Conclusion: Symmetry is Important



Oersted and Dipolar field create potential well and a localized spin wave

(Slavin and Tiberkevich)

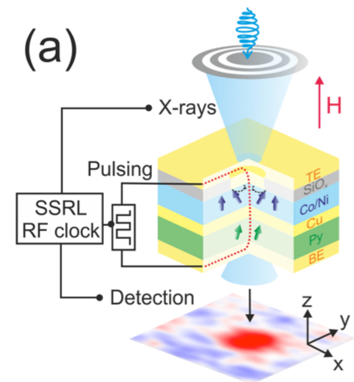


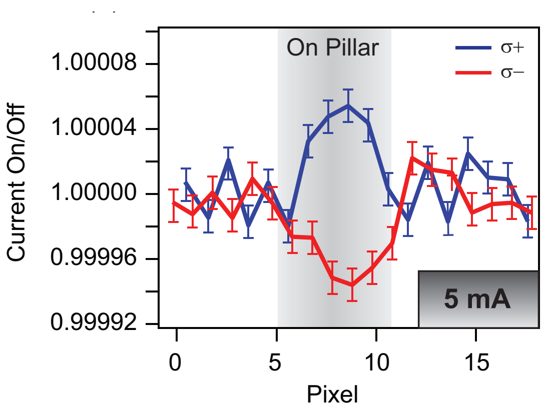
But: the real potential landscape is asymmetric
→ Asymmetric dynamics around nanocontact
→ Additional nodes in excitation

[S. Bonetti et al, Nature Comm. 8889, **9**, (2015)]

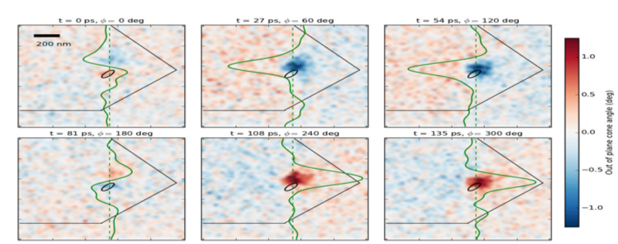
Summary

X-ray microscopy is able to image the dynamics of spin current driven devices in operations and realistic environment on the Nanoscale.

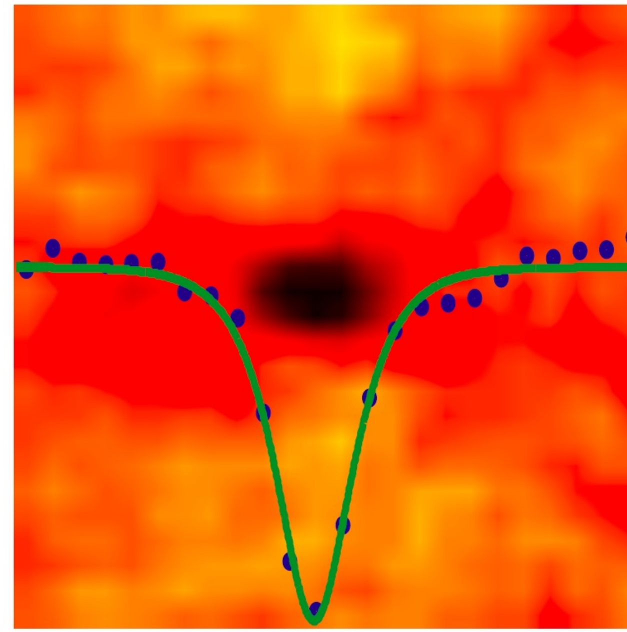




Sensitivity sufficient for spectroscopic characterization of dynamically induced changes in the electronic structure.



Complex dynamics behavior can be observed in basic device structure taking into account the “real” geometry and boundary conditions.



Thank you !