Ultrafast and Very Small.

Discover Nanoscale Magnetism with Picosecond Time Resolution and High Sensitivity

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June 20th 2017, IEEE summer school

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

IEEE Magnetics Society

- **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
  - Graduate Student Summer Schools
  - Local chapter activities
  - **Distinguished lectures**

- **Journals (Free Electronic Access for Members)**
  - *IEEE Transactions on Magnetics*
  - *IEEE Magnetics Letters*

- **Online applications for IEEE membership:** ***www.ieee.org/join***
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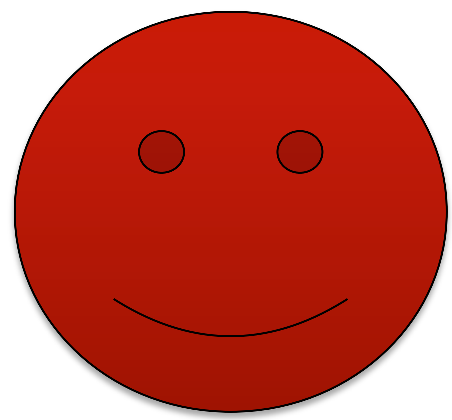


THANK YOU !!!

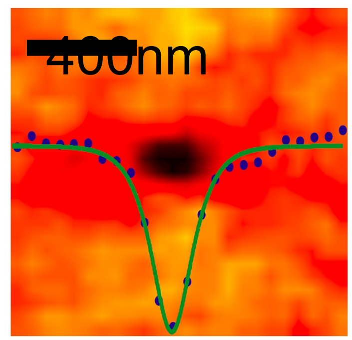
Outlook

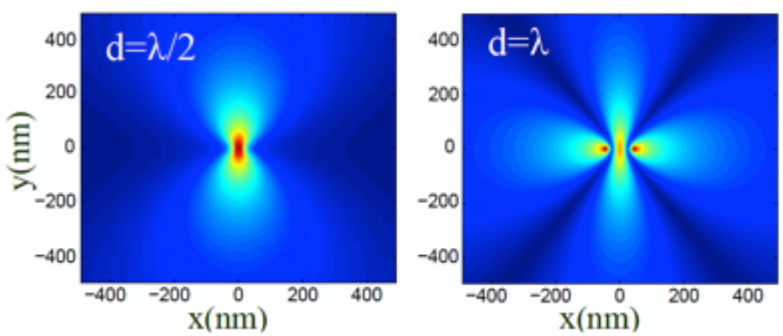
1.) State of the art devices and the need for soft x-ray spectromicroscopy

2.) Antiferromagnetic – Ferromagnetic exchange coupling

3.) Spin transfer across interfaces

4.) Imaging spin waves





Some Dinner Conversation Starters.
Why is Magnetic Storage Still Relevant and Interesting?

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If a hard drive read head would be a Boeing 747 and the disk the size of the earth, the 747 would fly at Mach 800, one inch above the ground and register every blade of grass without error.

It takes 6-9 months from the first steps to produce a read head until it leaves the factory in a fully – meaning bit by bit – tested hard drive.

Technology based on science awarded a Nobel prize in 2008.
Costs, comparable to a toaster – with vastly different profit margins !!!

Like lasers, magnetic information storage is at the back bone of the modern economy. Between 50-100% of the worldwide GDP would vanish without it.

AND: The science is fascinating and actually fun !!!

Example: Classical Engineering vs. Nano Engineering

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1956 IBM RAMAC
5 MB, 2000 lbs, $30.000 per month

→ 60 years

Capacity 10^6
"Density" 10^9
Cost efficiency10^{10}

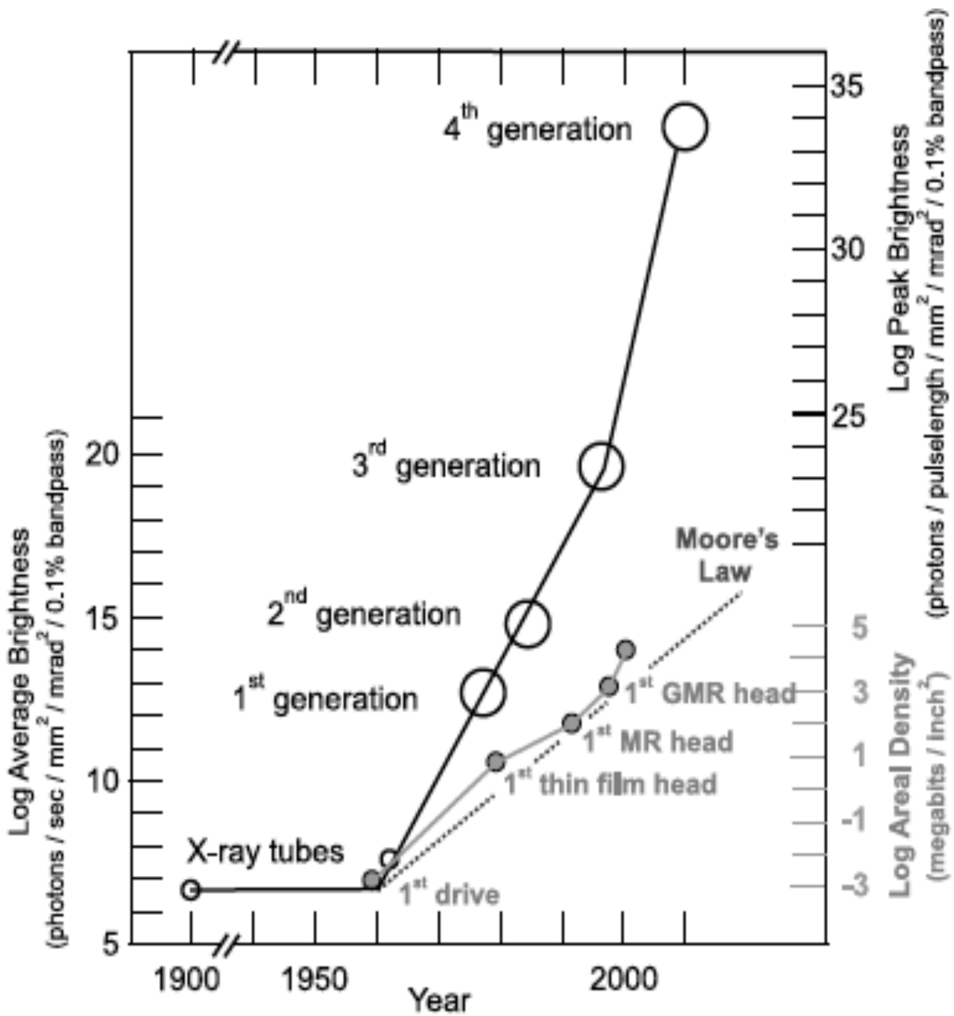
2016 Seagate Portable
5 TB, 0.5 lbs, $200 once

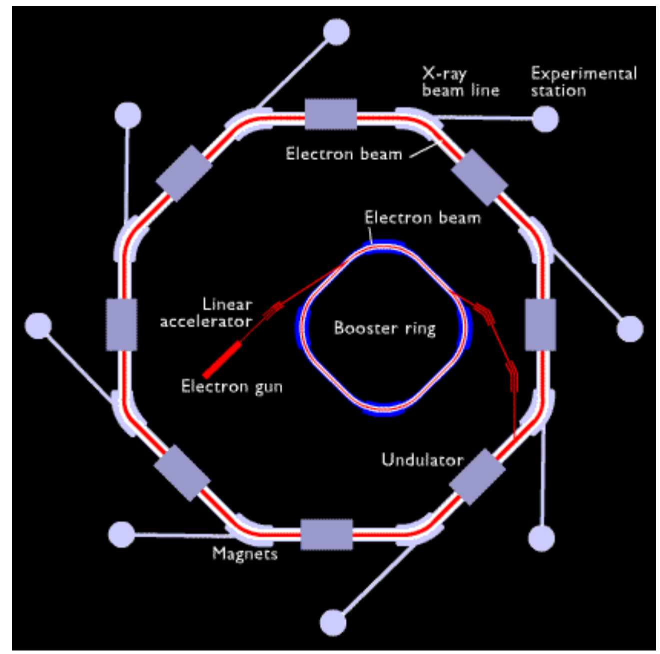
Modern devices rely on functionalized alloys and multilayers, **engineered on fundamental length scales**,

Characterization tools need to be able to **"SEE-THRU"** to the atomics scale

→ Soft X-rays provide this ability

Development of X-ray Sources





The brightness of x-ray sources has increased by >15 orders of magnitude allowing us to follow technological advances on the nanoscale

X-ray Microscopy At The Nanometer and Picosecond Scale

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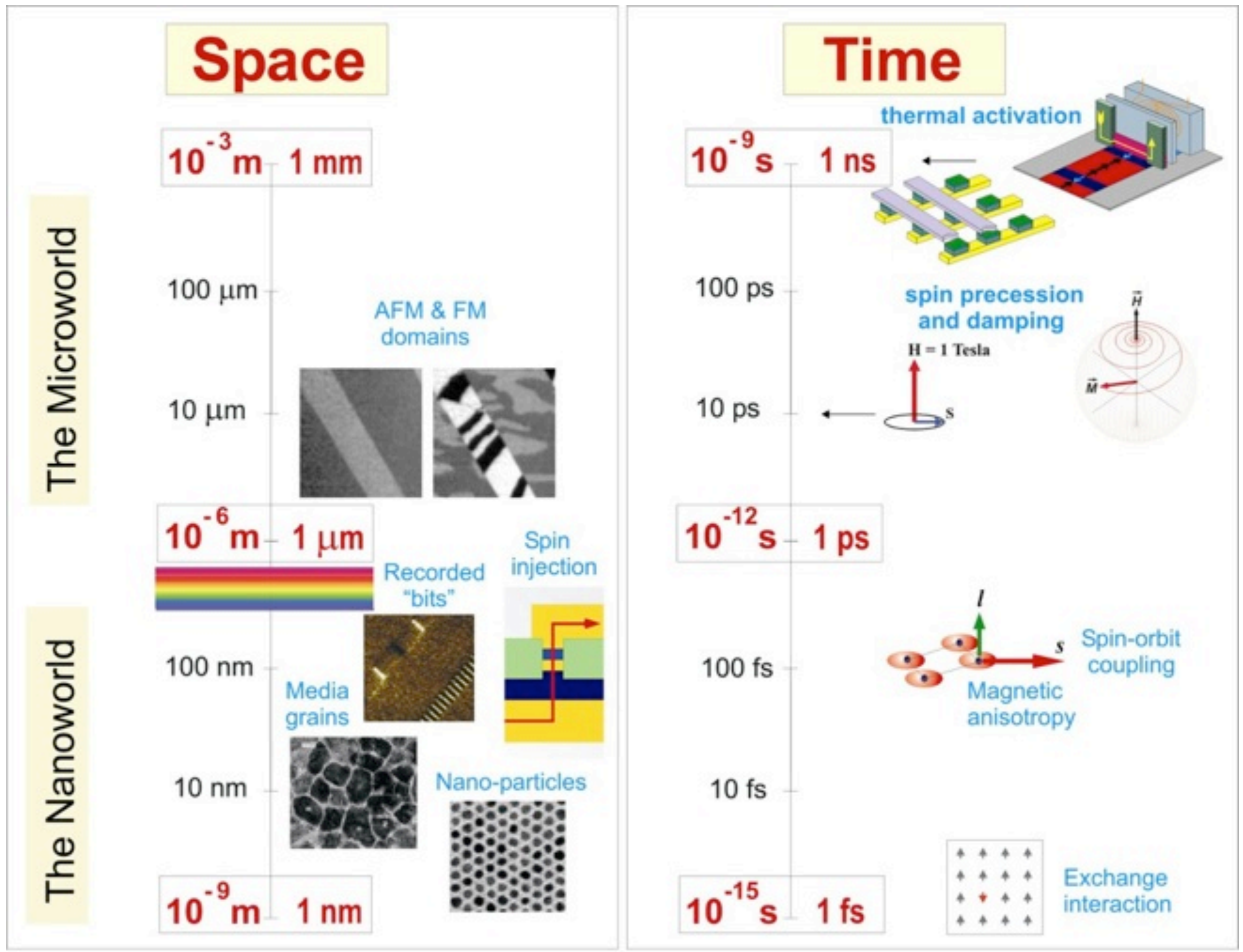
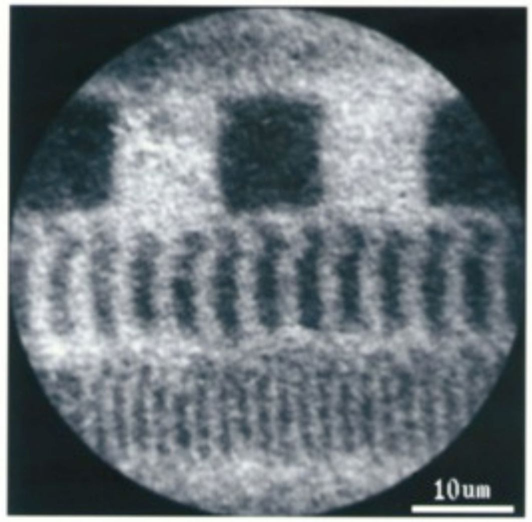
The time structure and wavelengths of synchrotron radiation is uniquely suited to study the fundamental processes behind technologically relevant magnetic devices .



Note: Δt (fs) = 4 / ΔE (eV)

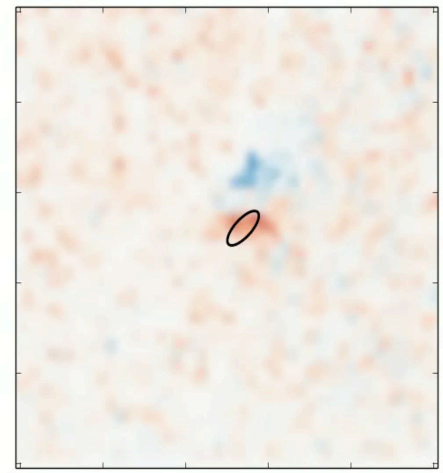
A Very Brief History Of X-ray Microscopy

1895



1995

2001



2016

The "power" of X-rays:

→ Synchrotrons provide very bright, tunable and polarized x-rays.
→ Chemical and magnetic microscopy in 4D (x,y,z,t) is possible
→ Sensitive to buried interfaces and very small changes in M

What Is SLAC And What Does A Synchrotron Do?

SLAC Now And Then – A Changing Mission

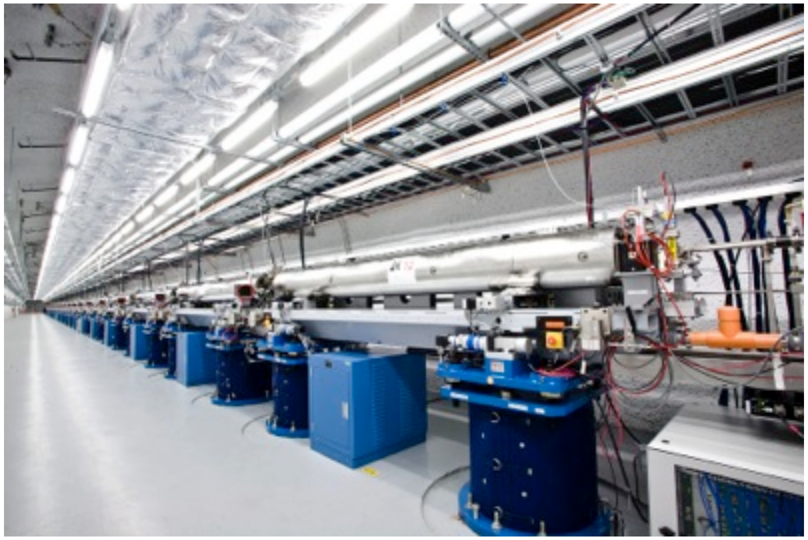
Stanford Linear Accelerator Center (SLAC), *started out as dedicated high energy physics laboratory* (1960 – mid 2000s)

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.

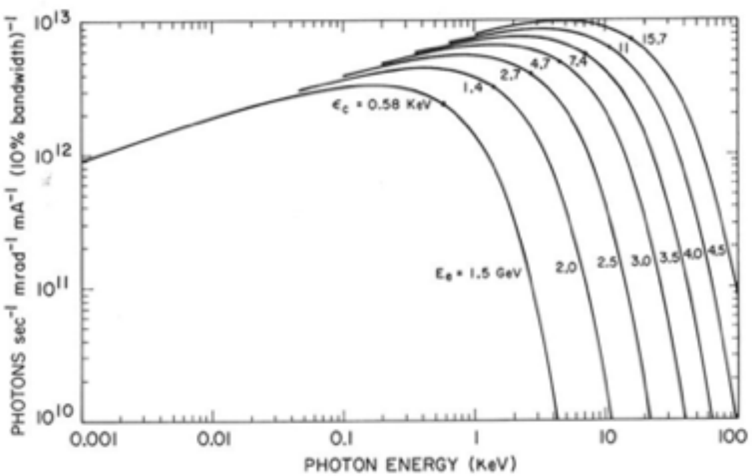
- Life Sciences
- Applied Physics
- Astrophysics
- Chemistry

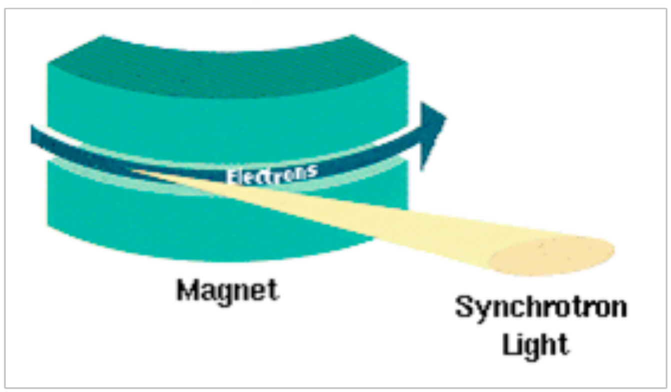
…..

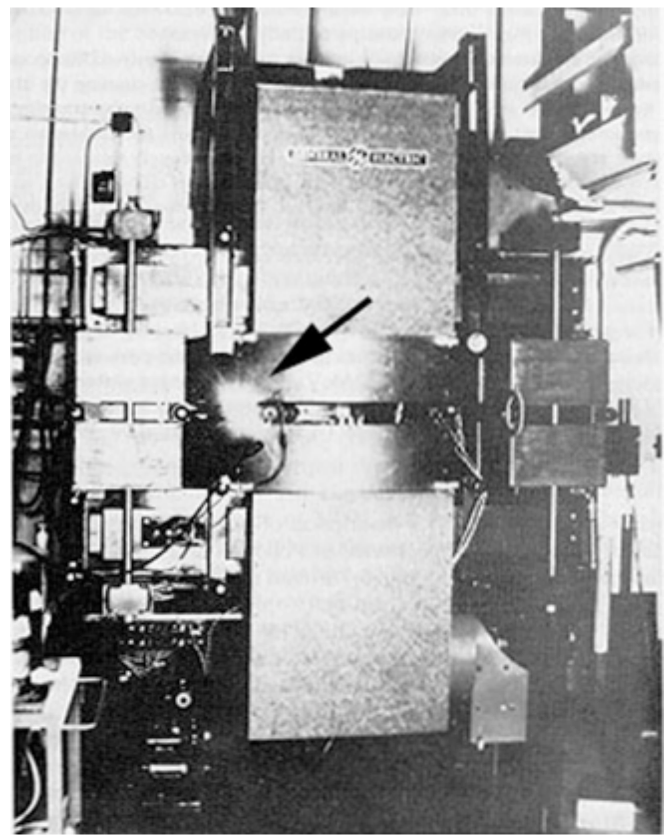


Right: The LCLS undulator hall

Storage Rings Produce Radiation

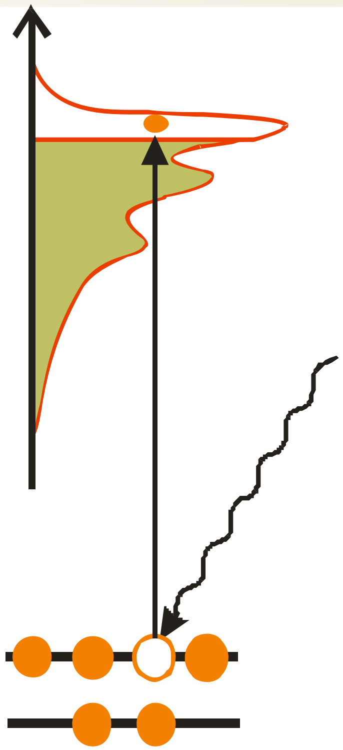






Synchrotrons produce directed, tunable, polarized and very intense x-rays using relativistic particle beams

The X-ray Absorption Process



|<f|H|i>| = transition matrix element
~ overlap of 2p and 3d wavefunctions

$$T_{i\to f} = \frac{2\pi}{\hbar} \left|\langle f|H'|i\rangle\right|^2 \rho_f$$

ρ = density of (valence) state

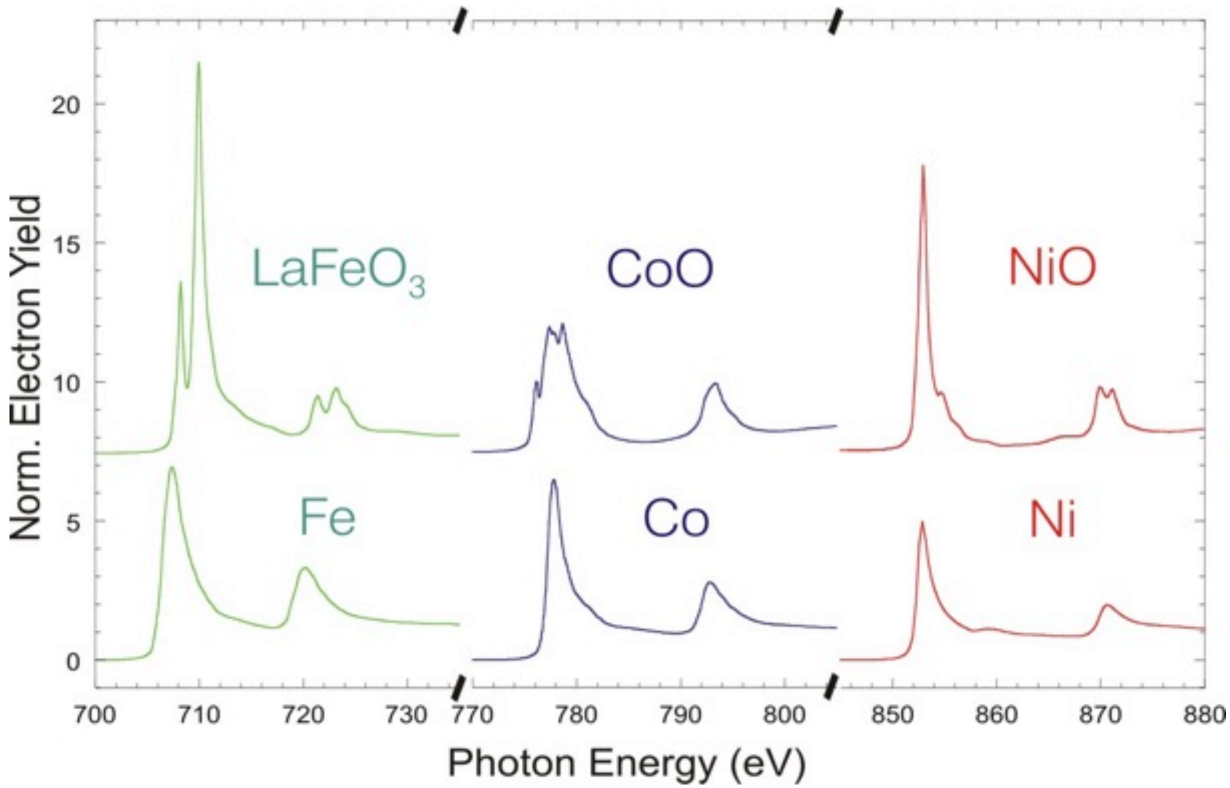
Fermi's golden rule

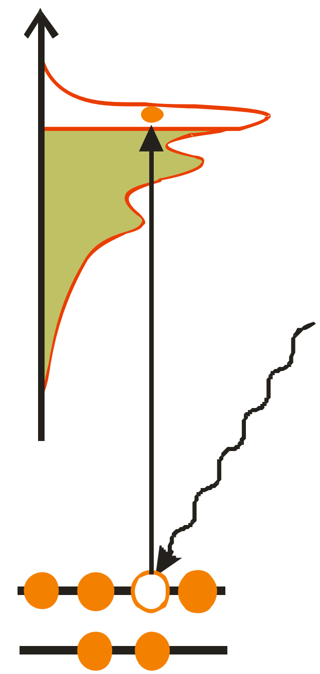
Resonant core level soft x-ray absorption directly probes the local electronic valence structure.

Note: Hard x-rays probe strcuture since wavelength is of the order of Angstrom.

The electronic valence structure depends on local symmetry and bonding

Elemental And Chemical Sensitivity

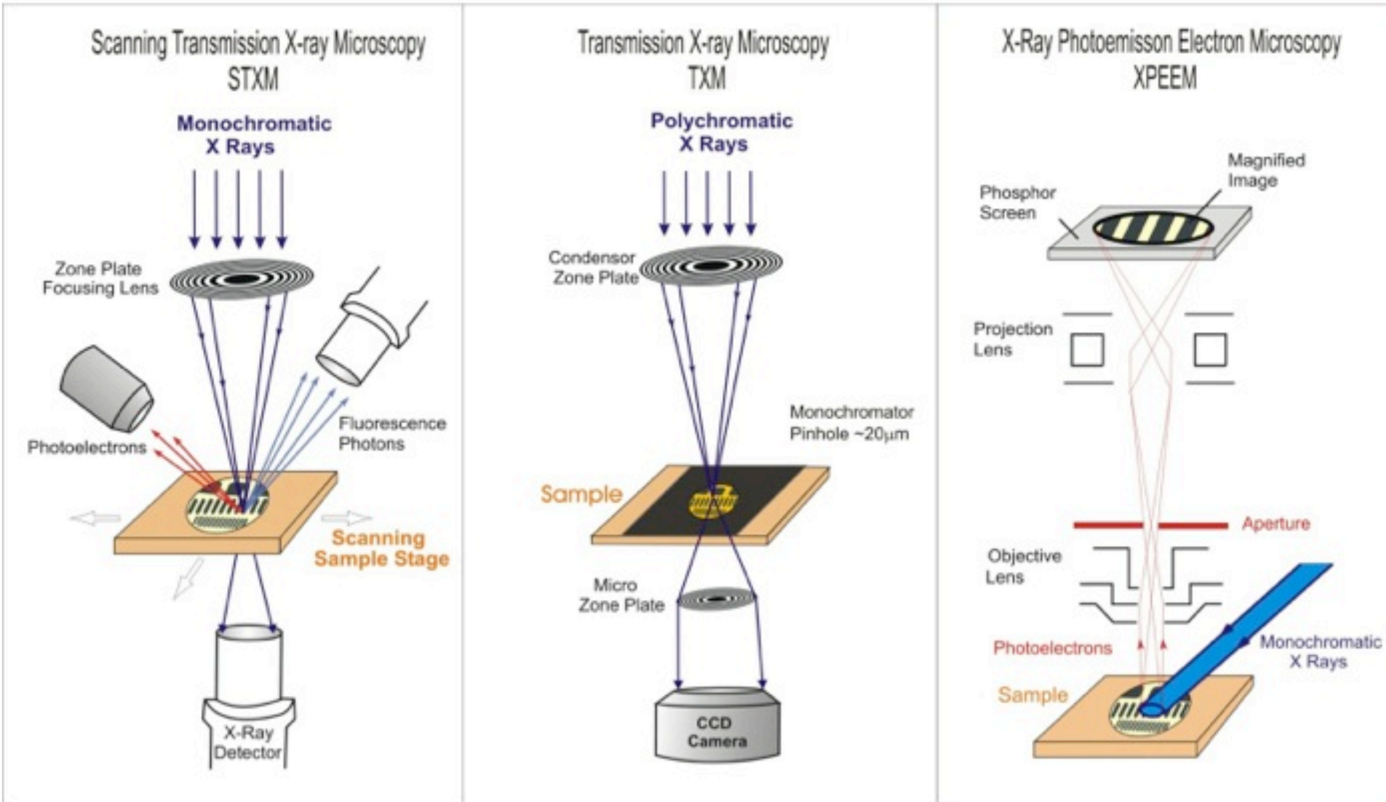




Energy of absorption resonance (binding energy of core level)→ Elemental specificity

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

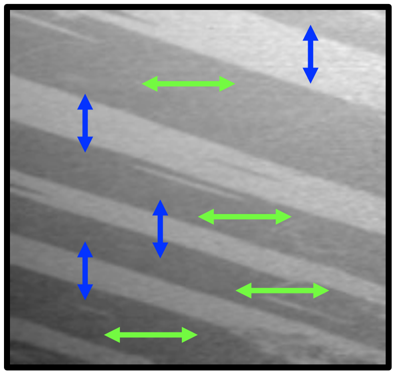
Spatial Resolution: X-ray Microscopy

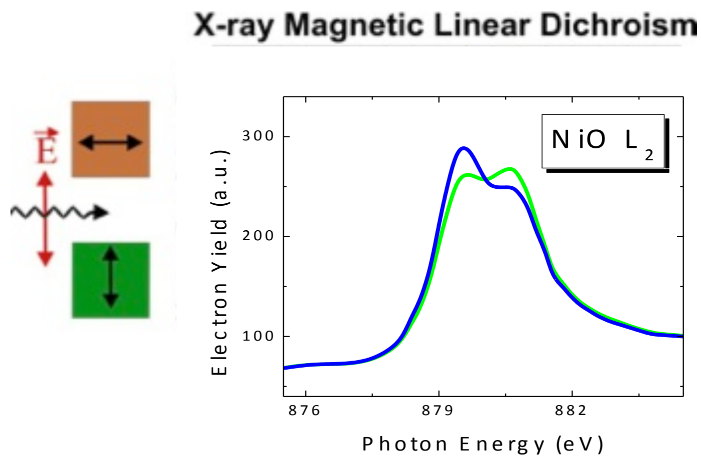


X Ray absorption can be detected in transmission, fluorescence or electron yield

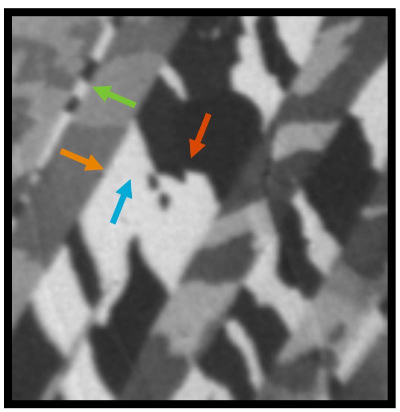
→ X-ray and electron microscopy is possible with high spatial resolution.

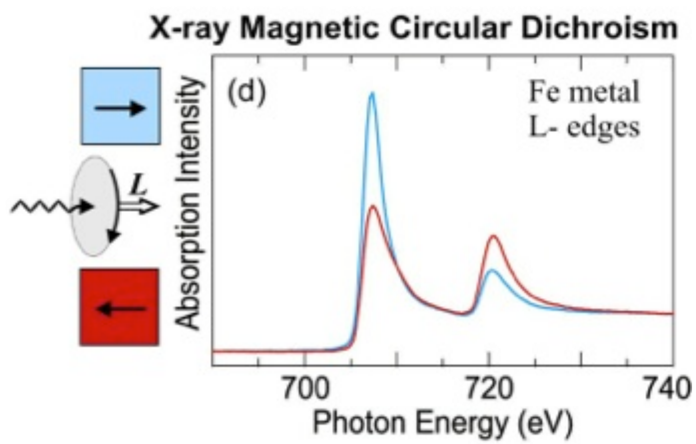
Element Specific Magnetic Contrast → Dichroism





XMLD



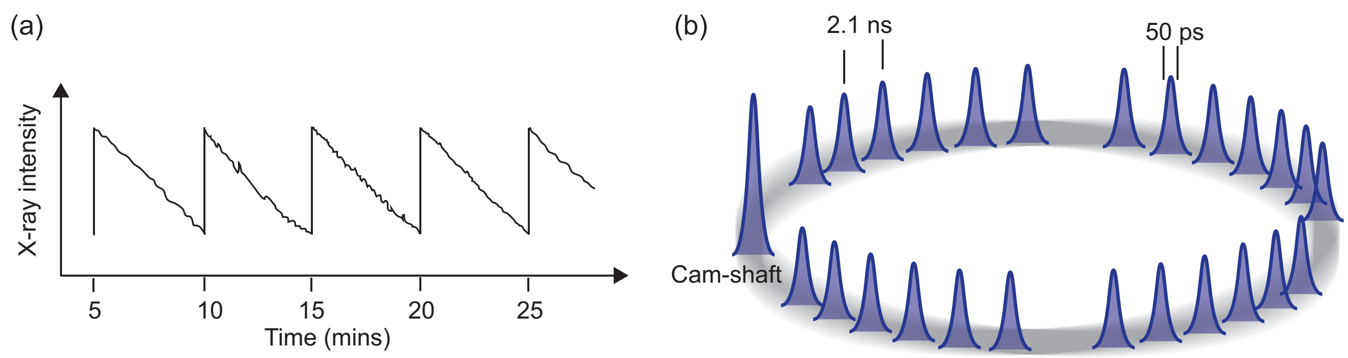


XMCD

PRL 86, pp. 3419 (2001),
PRB 64, pp. 4422 (2001),
PRL 86, pp. 2878 (2001),
PRL 87, pp. 7201 (2001),

PRL 91, art. no. 017203 (2003),
PRL 92, art. no. 247201 (2004),
PRL 96, art. no. 027203 (2006),
PRB 79, art. no. 052403 (2009),

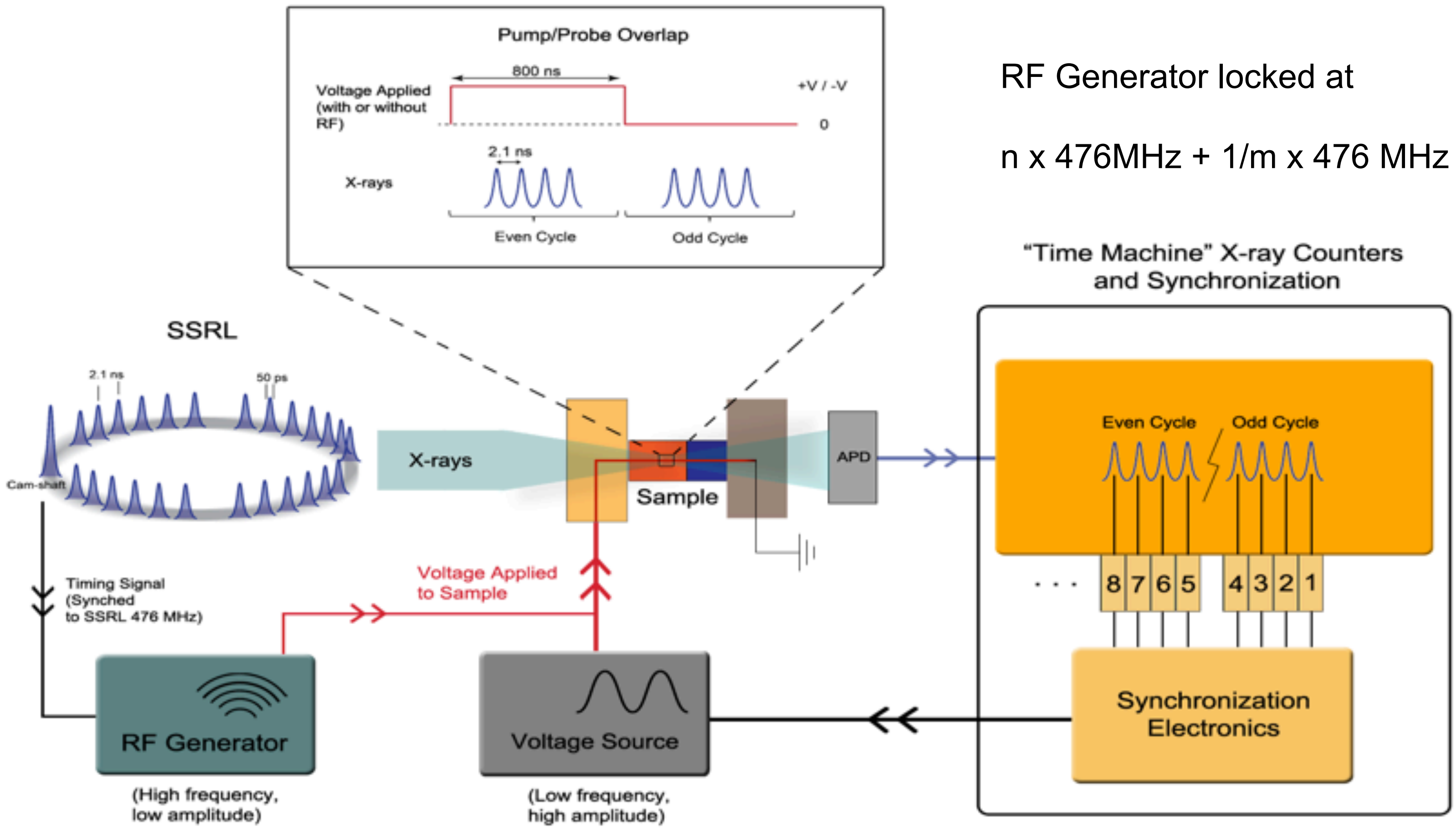
A Synchrotron Is A Pulsed X-ray Source → Temporal Resolution



The radiation is pulsed like a **strobe light** enabling pump probe experiments with 50 ps.

Significant intensity variations require normalization procedure to achieve high SNR

"Real Time" Normalization Scanning X-ray Microscope



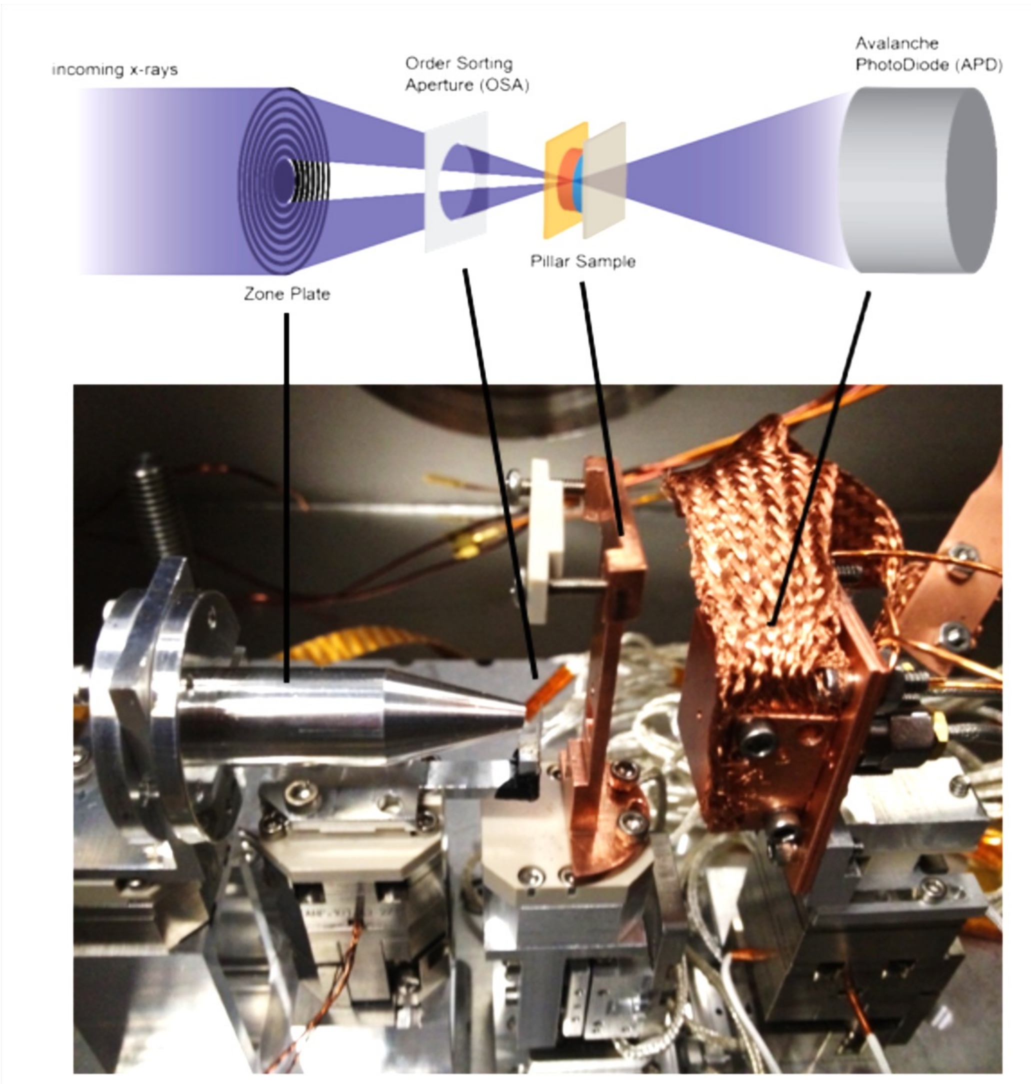
RF Generator locked at

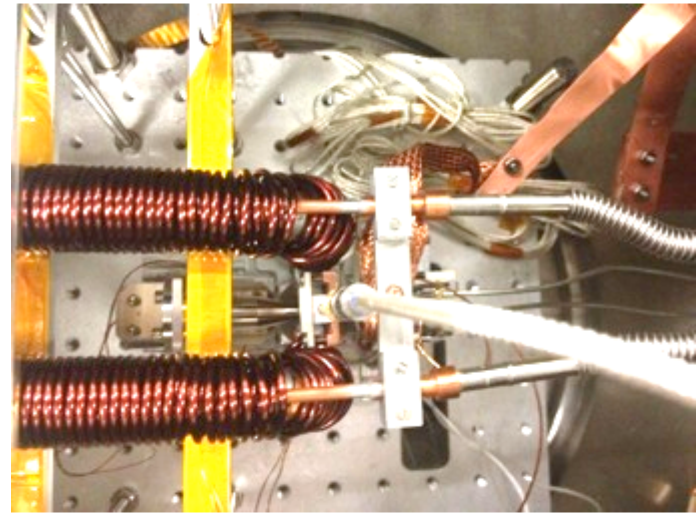
n x 476MHz + 1/m x 476 MHz

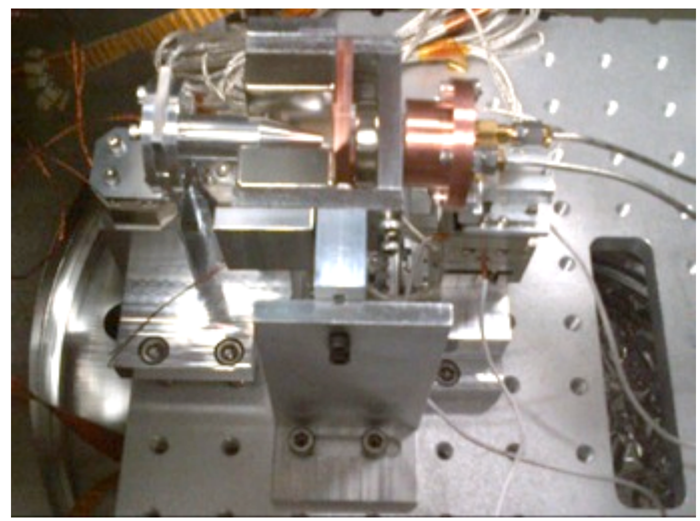
→ Effective double lock-in at 476 MHz and 1.28 MHz with 24hr stability ~ 1ps
→ Enables useful normalization in STXM and SNR of 10^5 - 10^6 after seconds

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

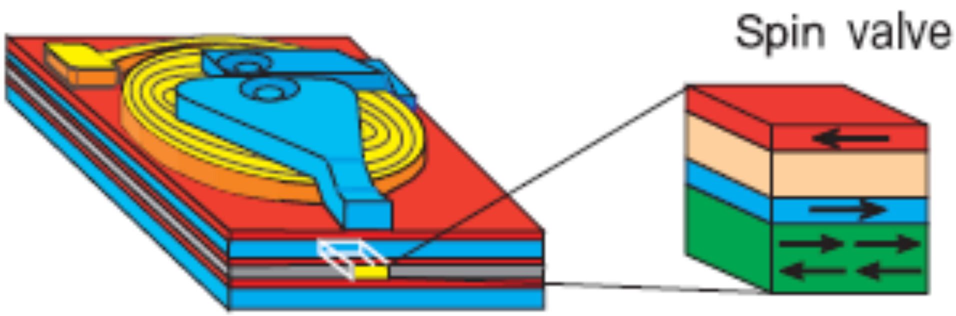
The SSRL STXM - Overview





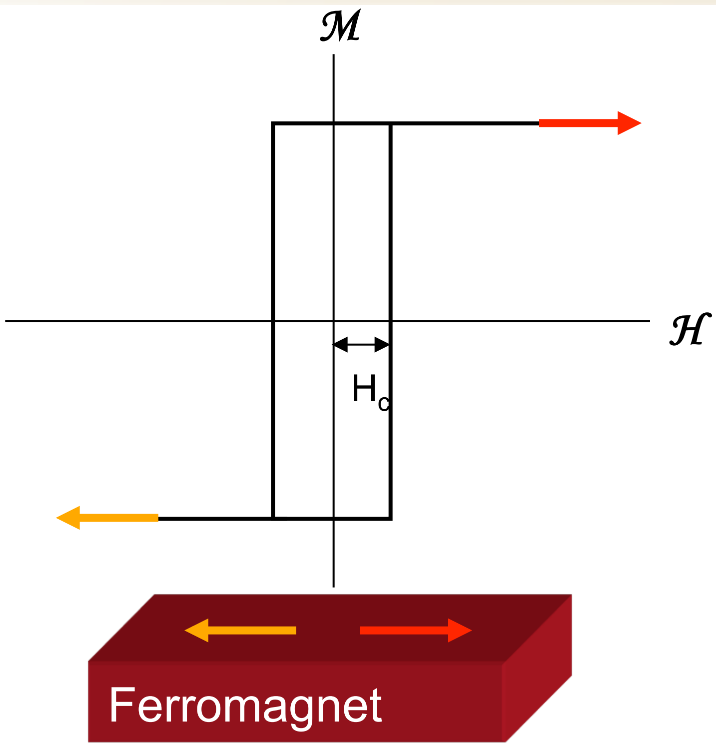


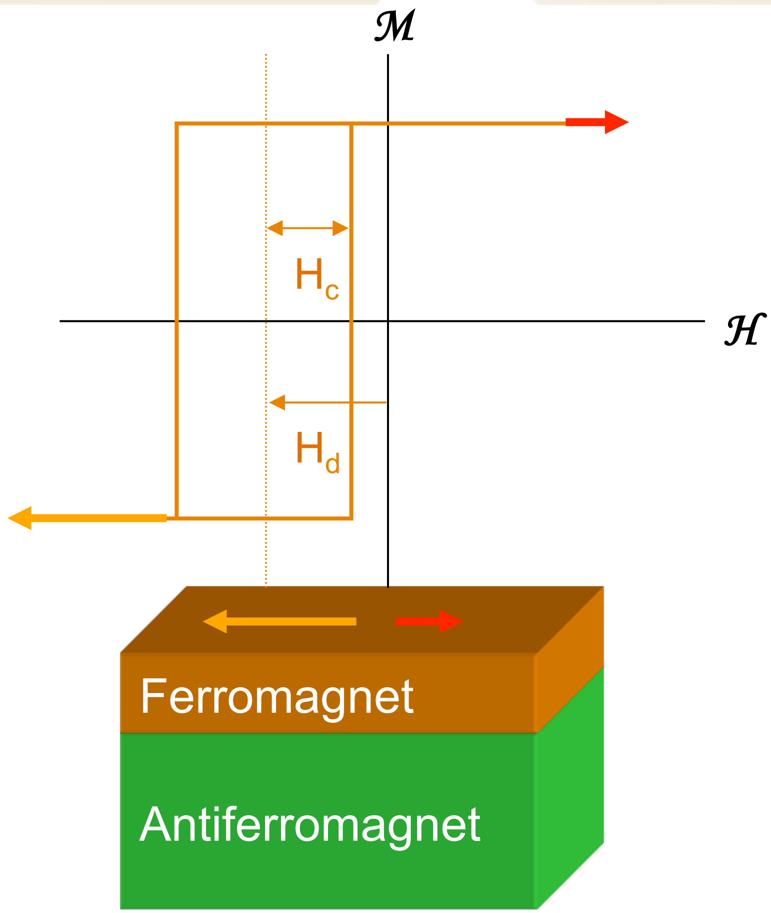
Step 1: AFM → FM Interface



Exchange Bias
AFM/FM Exchange Coupling

Exchange Bias

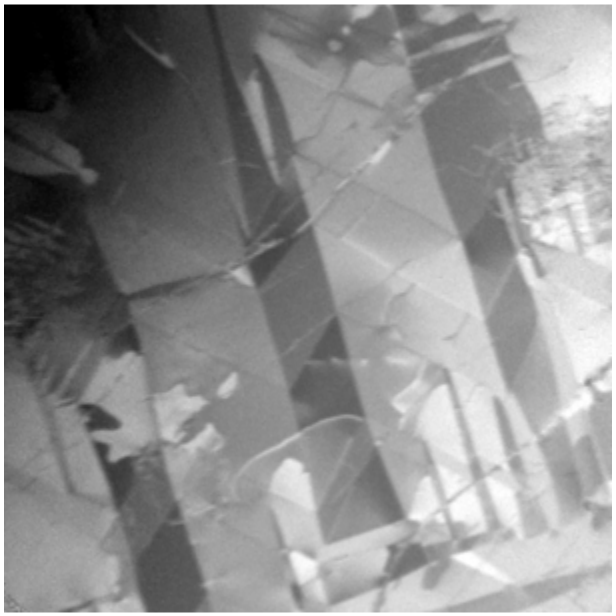




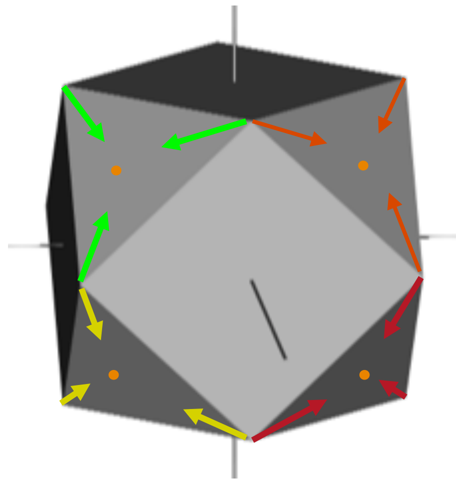
Exchange bias can be used to establish magnetic reference layers in devices.
Assume that AFM is not changed by presence of FM or fields

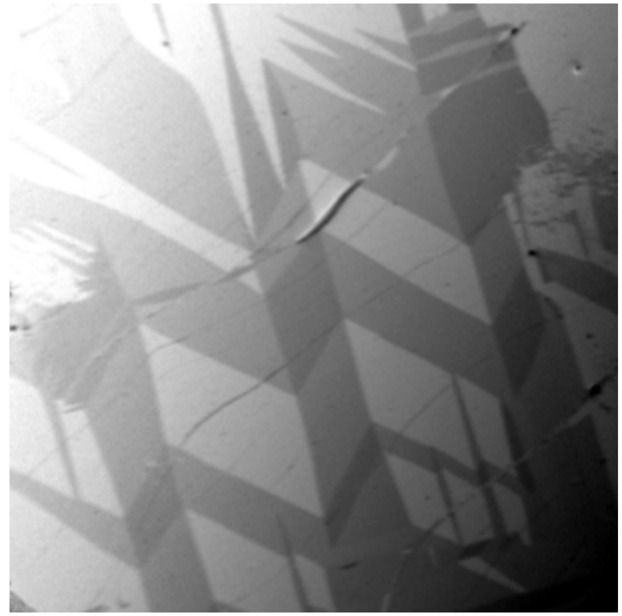
Spins and Twins – Nickel and Oxygen !!!

Field of view: 27μm



Ni 2p linear dichroism





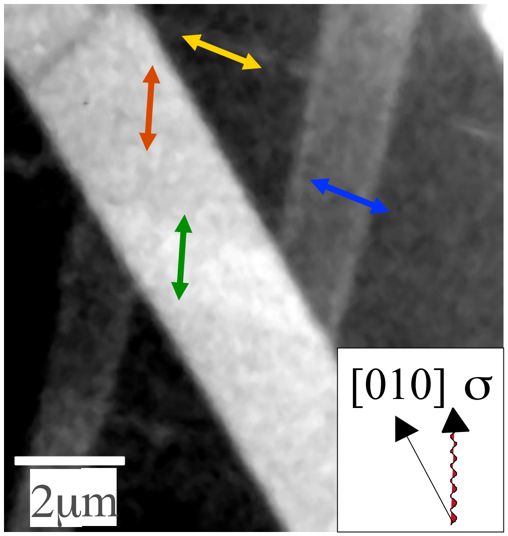
O 1s linear dichroism

Magnetic moment of Nickel causes XMLD (Spin Domains)

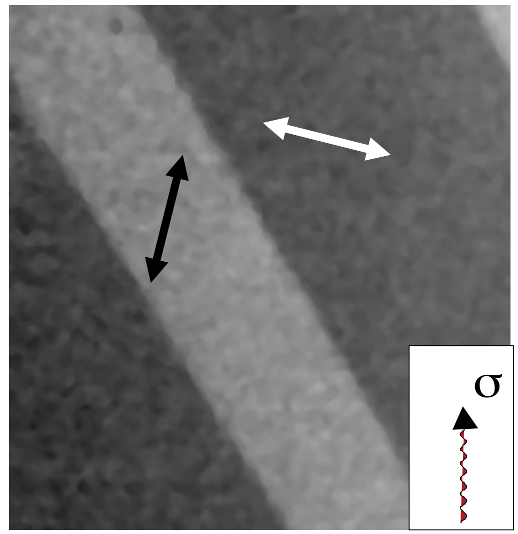
Non-cubic coordination around (non-magnetic) Oxygen causes XNLD(Twin Domains)

Separation of magnetic and crystallographic order !!!

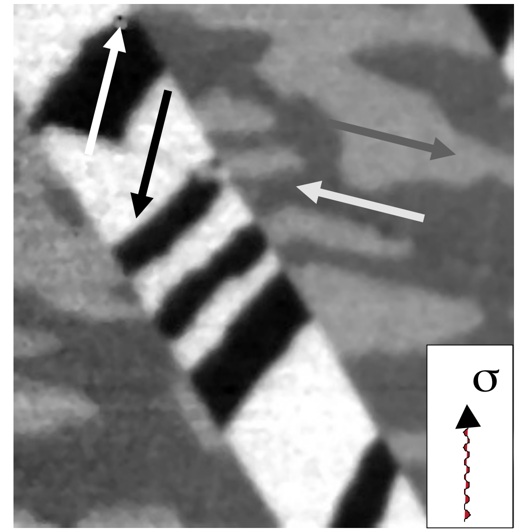
Now we add a bit of FM Co on top.



Bare NiO(001)



NiO after Co deposition

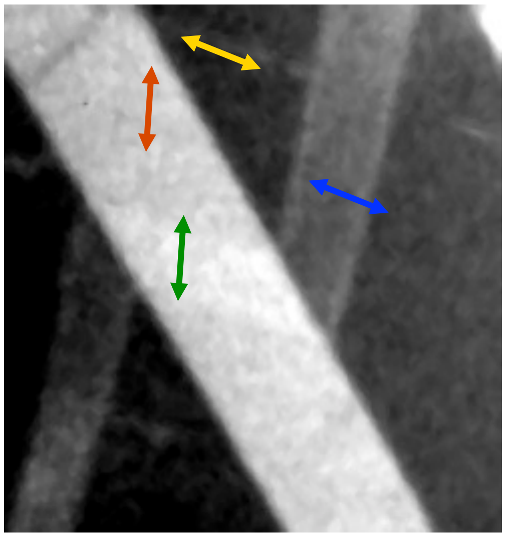


2nm Co on NiO(001)

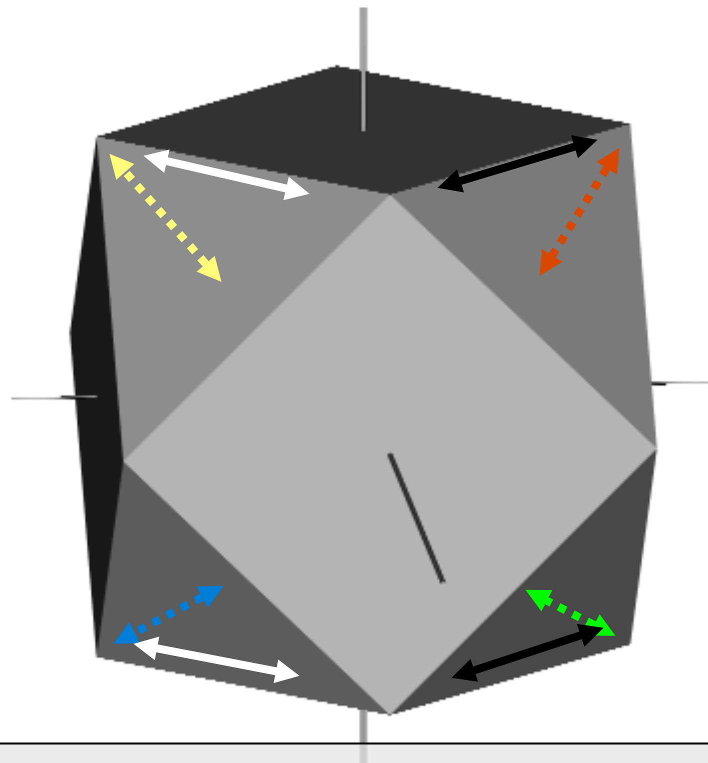
AFM surface domain pattern.

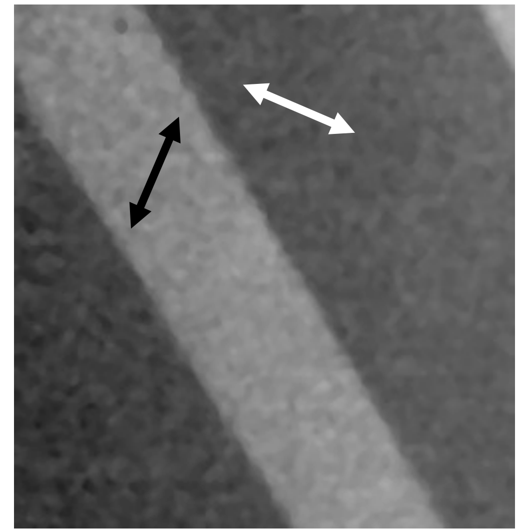
Reorientation of AFM spin axis upon deposition of Co due to **exchange** coupling.

Spin reorientation in NiO in response to Co



NiO before

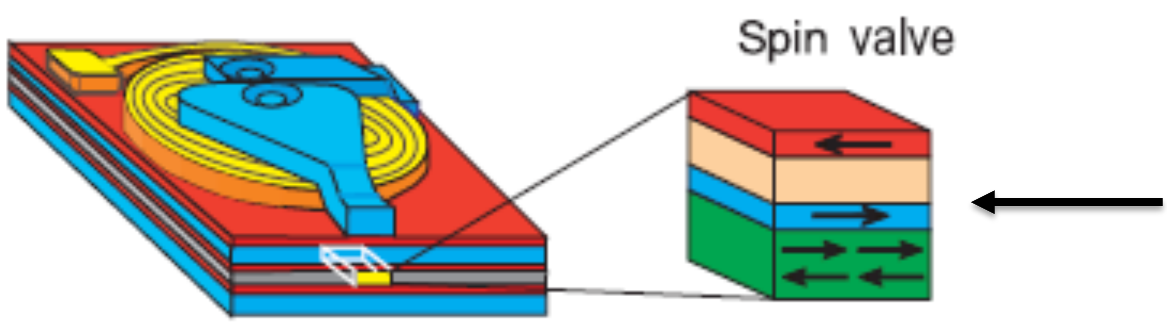




NiO after

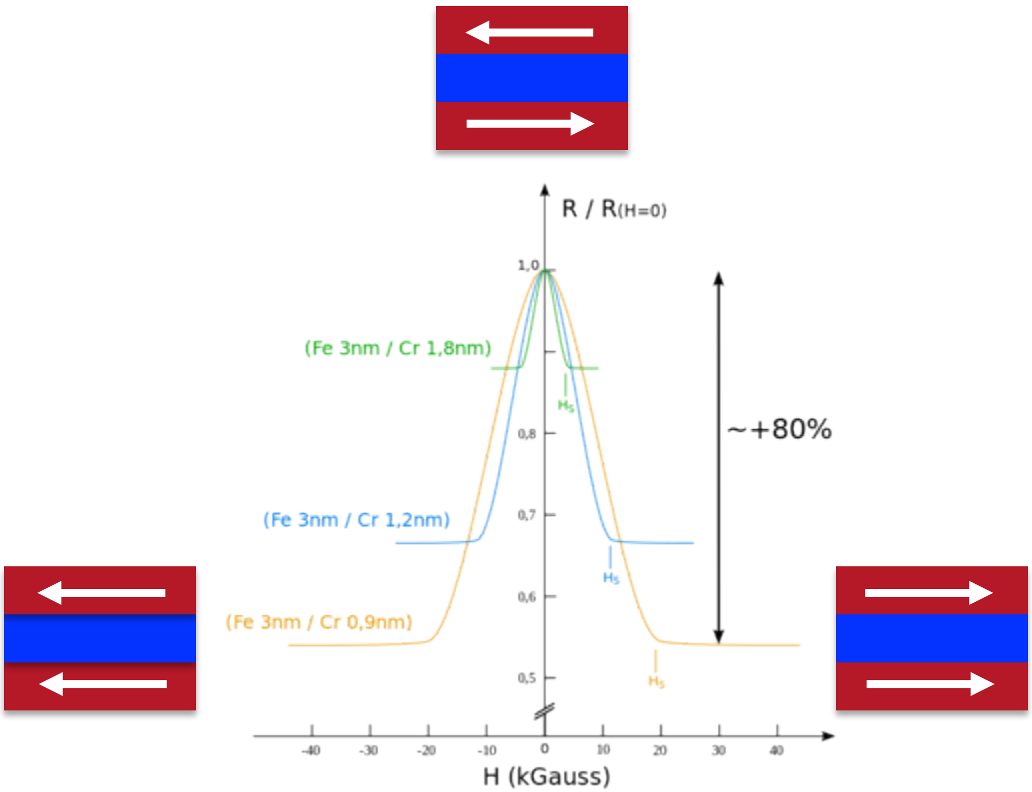
Upon Co deposition the FM spins align the AF spins parallel to the surface.
The AF does change at the interface !!!

Step 2: FM → NM Interface

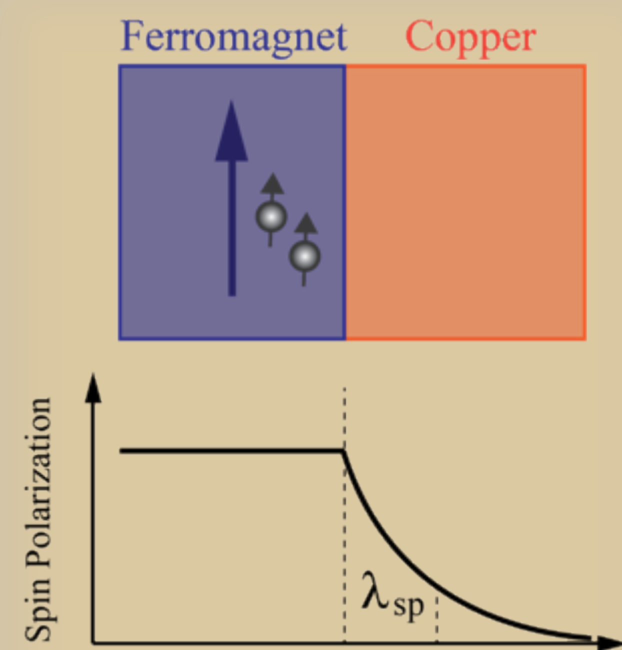


Spin Injection

Giant Magneto Resistance and Transient Magnetization

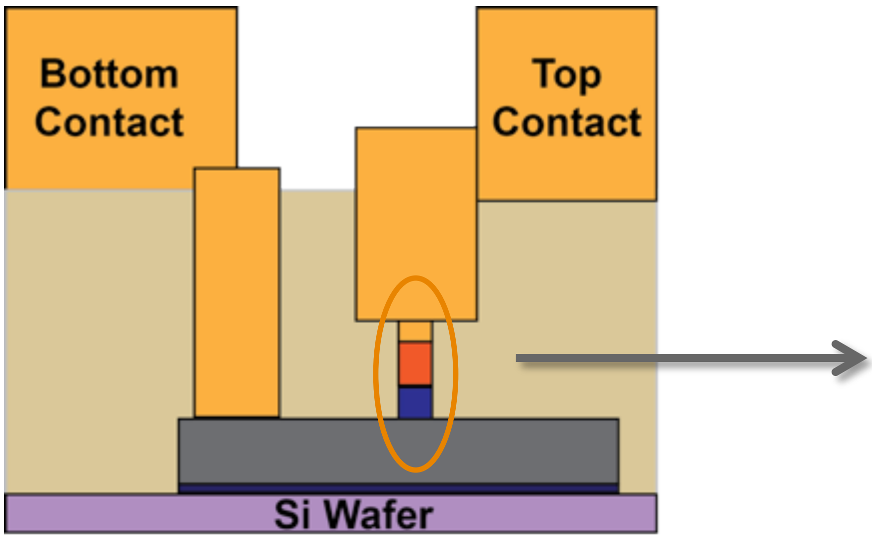


Albert Fert and Peter Grünberg (1988)
Nobel Prize (2007)

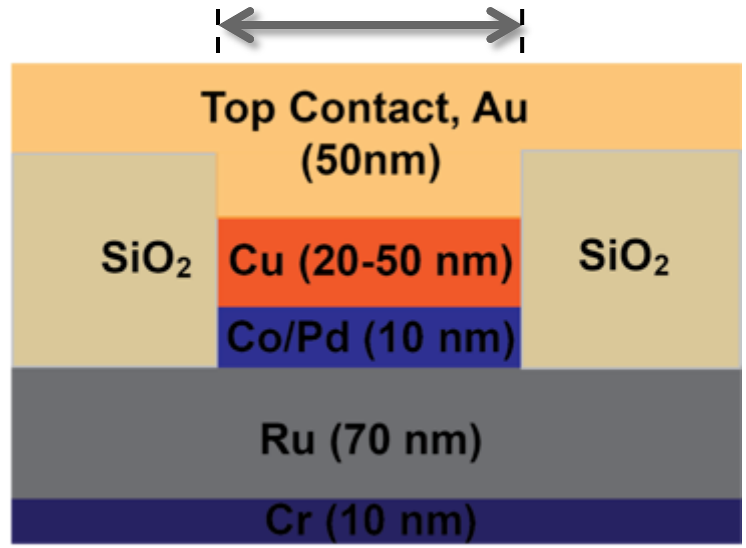


Current from FM to NM across an interface induces magnetization in NM

Spin Injection Sample - Dynamic XMCD at 1.28 MHz



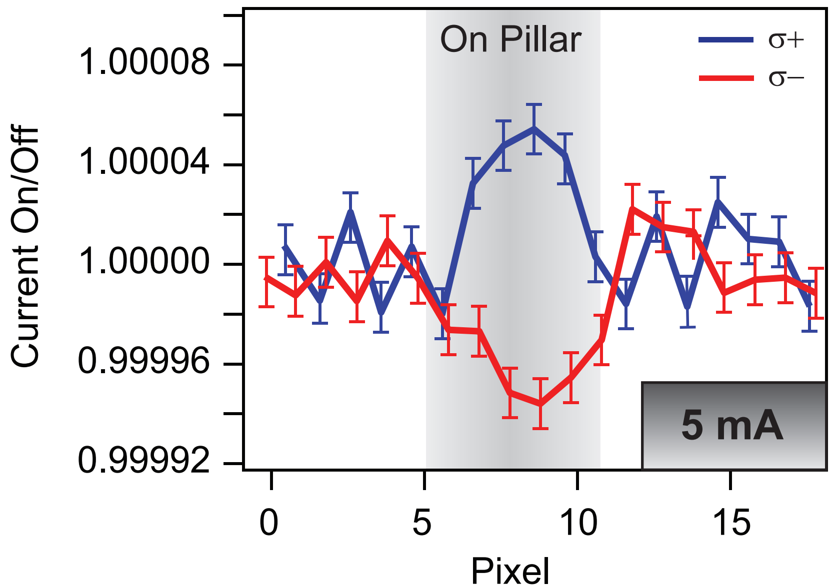
Lithography J. Katine (HGST)

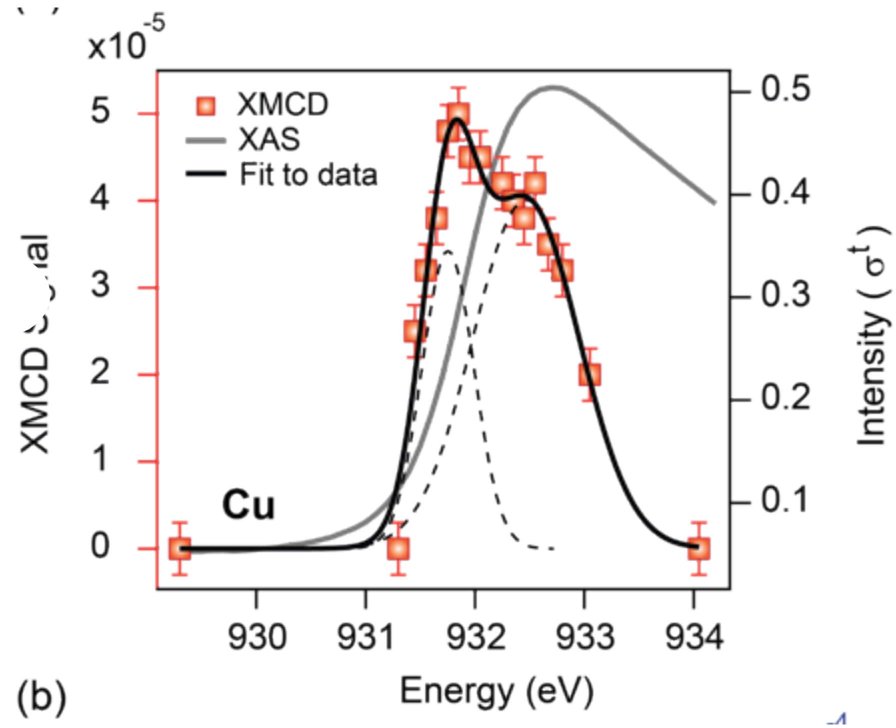


Stack growth A. Kent (NYU)

Approach: Measure Cu XMCD while modulating the current

XMCD of a Nanopillar Due To Spin Injection in STXM





<5x10^{-5} μ_B per Cu atom due to spin transfer from Co → Cu.
Note: Sign reverses for Fe → Cu (weak vs. strong FM)

Spectroscopy shows two (!!) peaks in XMCD at E_F and max. DOS

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

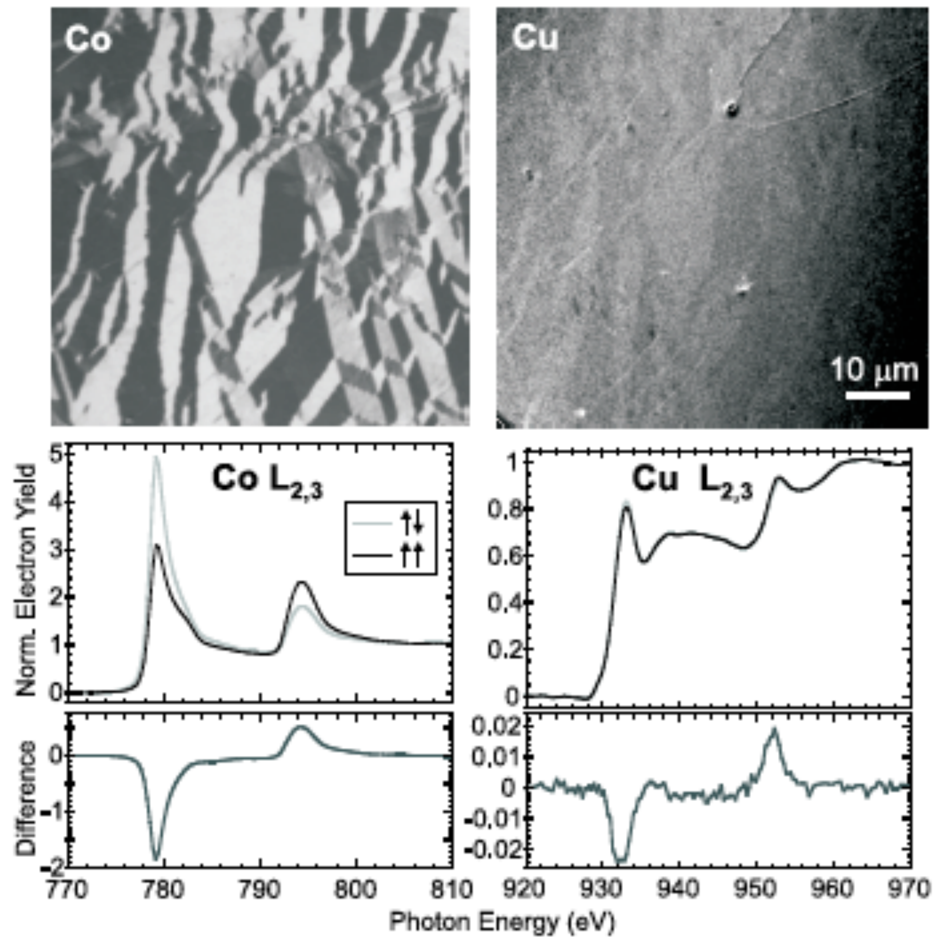
Proximity Magnetization is Key

Example: 1nm Cu/Co

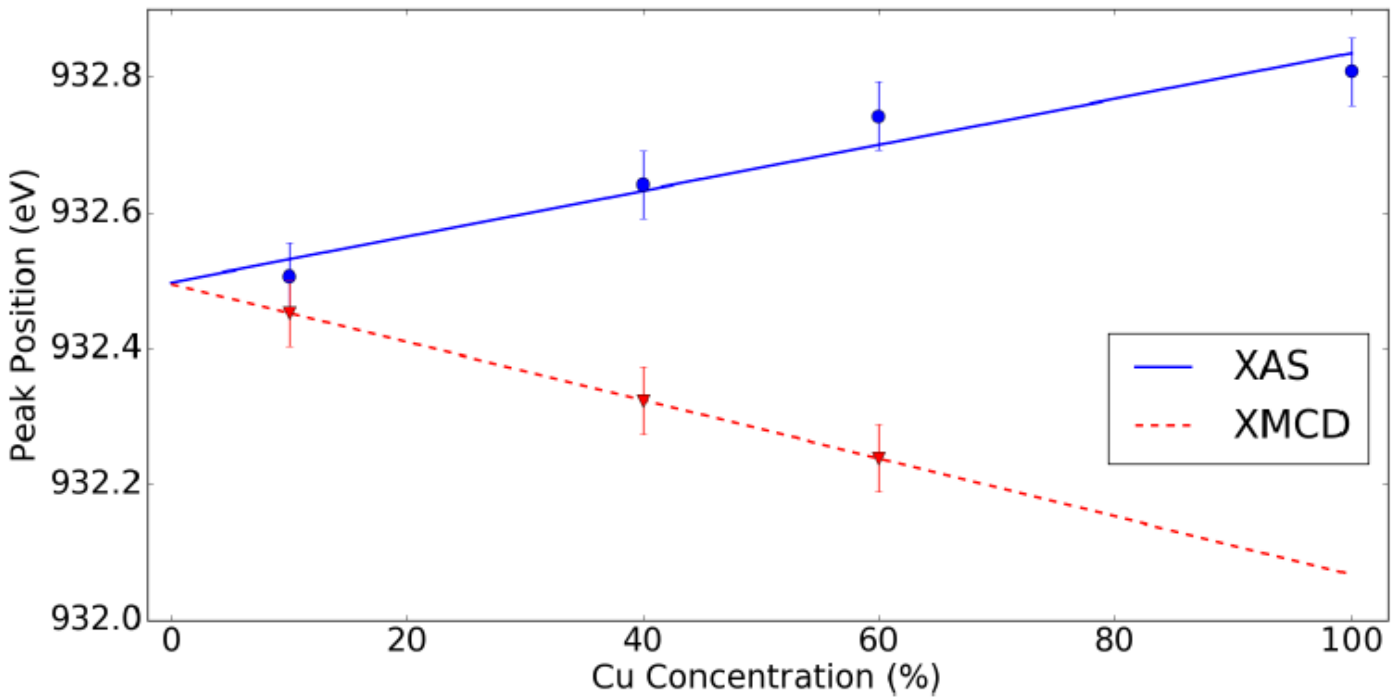
Non magnetic Cu becomes FM in proximity to FM Co

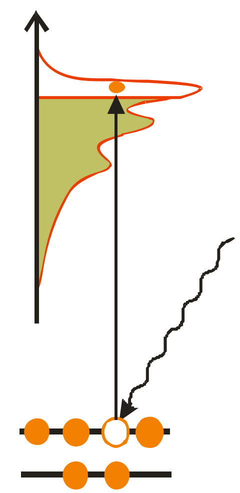
Cu XMCD corresponds to ~0.01-0.05 μB

→ Cu XMCD of proximity magnetization appears right at the Cu XAS edge



Concentration Dependence of Static XMCD in Alloys



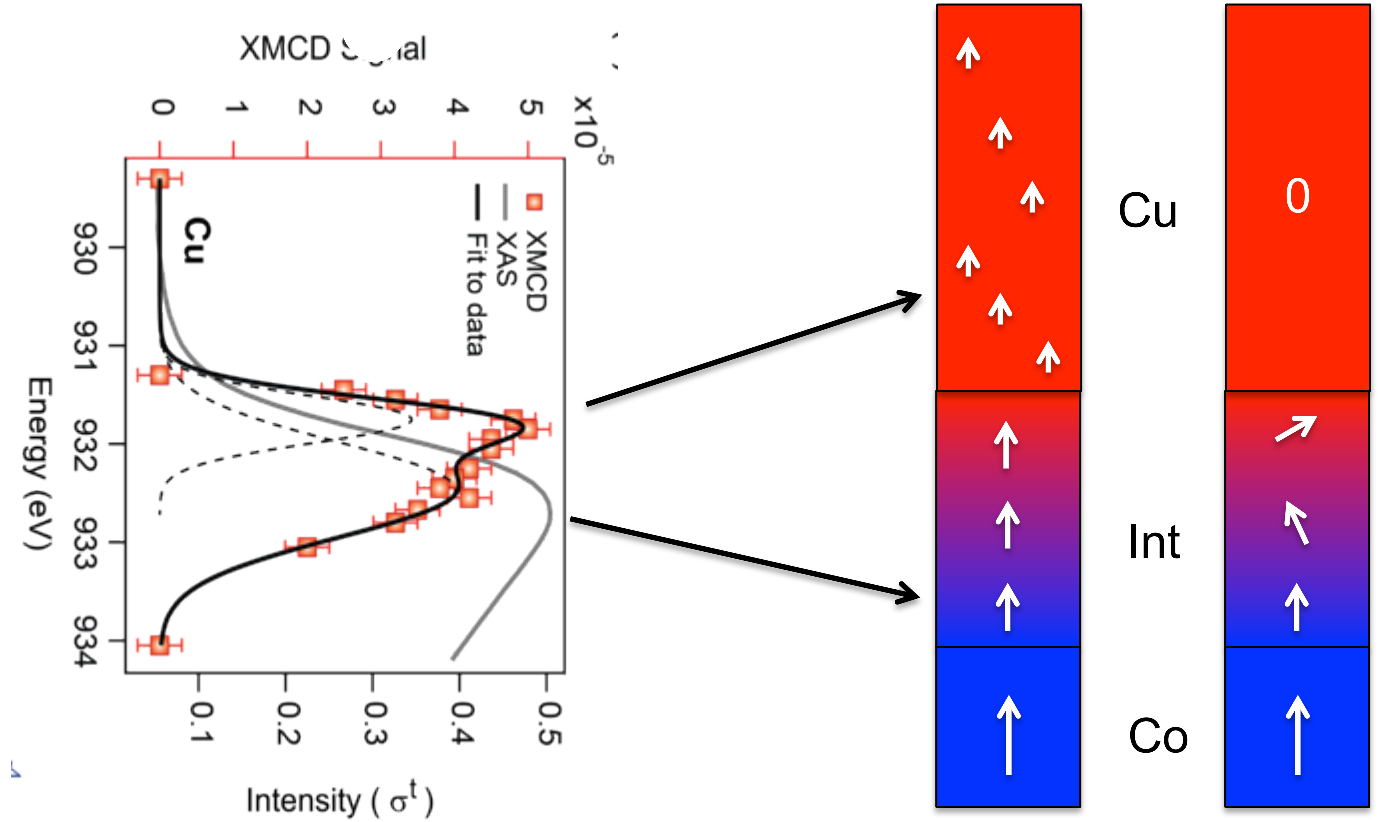


Cu strong d-DOS about 0.5-1 eV above $E_{F,}$ Co strong d- DOS at E_F - Co d-orbitals drive Cu d-orbitals towards E_F the more Co is added (left side)

Isolated Cu atoms next to Co atoms show XMCD at the XAS peak

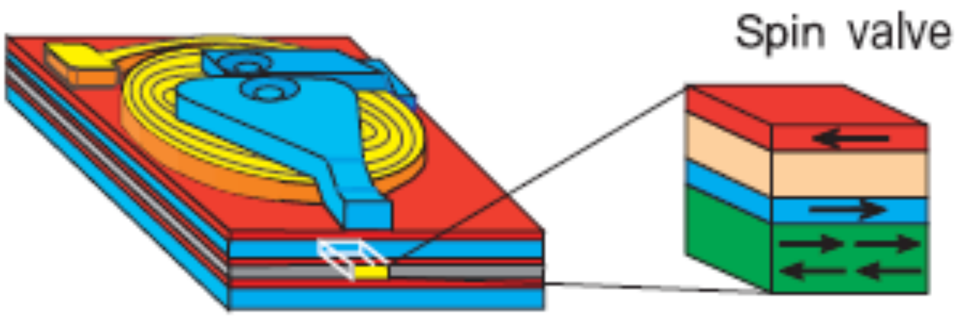
Z. Chao et al. to be submitted

Summary: Interfacial vers. Bulk XMCD



Injecting a spin polarized current from Co → Cu leads to realignment of interfacial moment via spin torque which limits spin accumulation in Cu bulk

Step 3: Spin Injection + Spin Dynamics = Spin Waves from Spin Torque



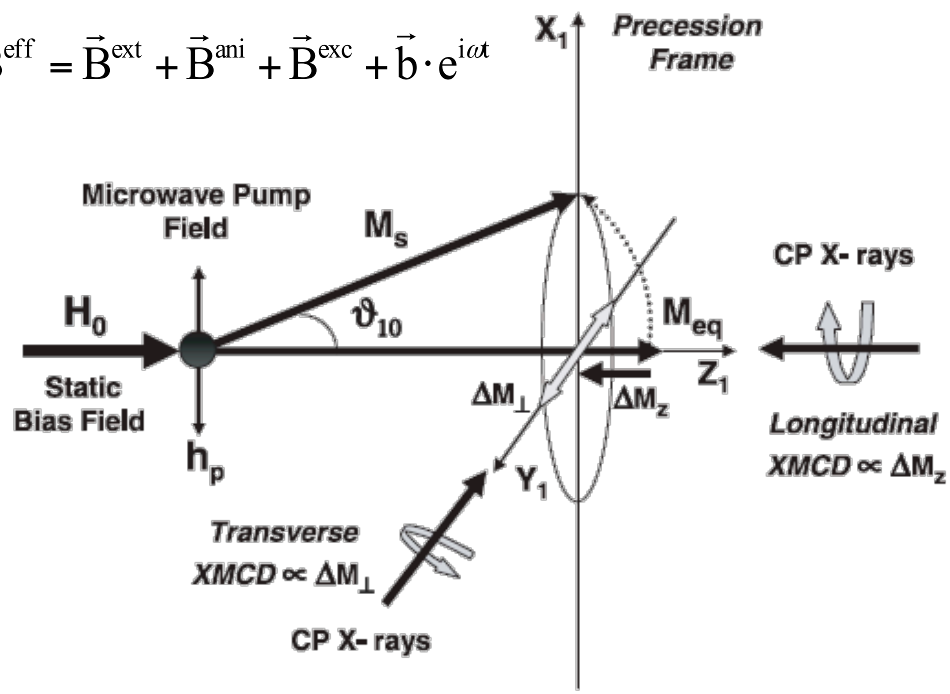
Spin Torque Oscillations
Spin Waves

How to Detect Magnetization Dynamics – e.g. FMR

$$\vec{B}^{eff} = \vec{B}^{ext} + \vec{B}^{ani} + \vec{B}^{exc} + \vec{b} \cdot e^{i\omega t}$$

$$\frac{d\vec{M}}{dt} = -\gamma\left(\vec{M} \times \vec{B}^{eff}\right) + \frac{\alpha}{M^2}\left(\vec{M} \times \left(\vec{M} \times \vec{B}^{eff}\right)\right)$$

LLG equation
Magnetization dynamics

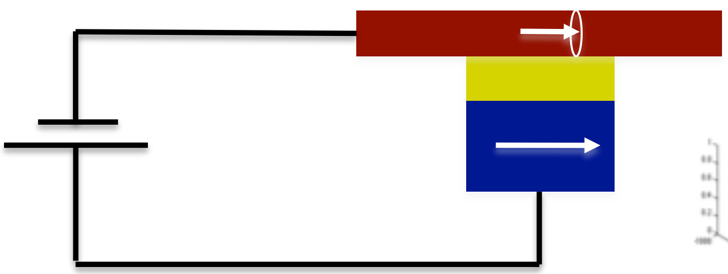


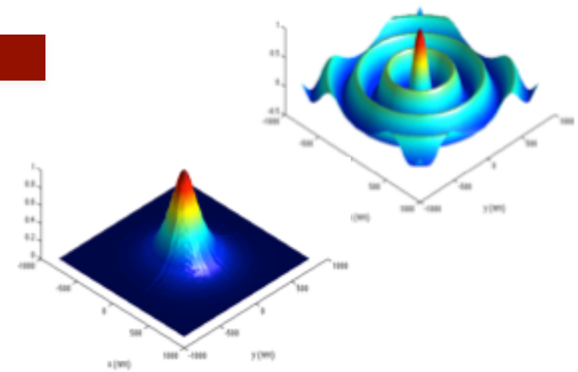
Ferromagnetic resonance is the method of choice for a quantitative analysis of relaxation rates, magnetic anisotropy, magnetic exchange and susceptibility in a single experiment.

STXM XFMR capable of doing this with elemental and spatial resolution, addressing fundamental dynamic properties of technologically relevant devices and structures.

Spin Transfer Torque Into a Ferromagnet

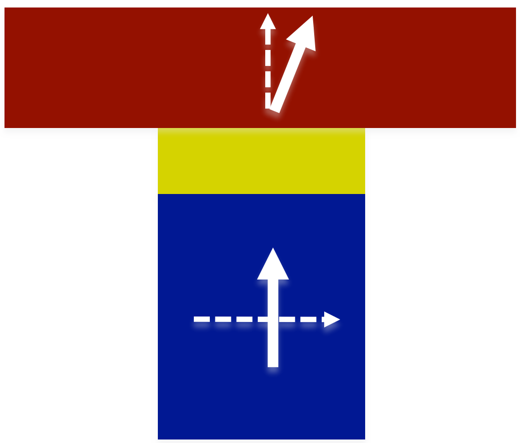
A DC spin polarized current generated in the blue FM excites spin wave excitation in the second red FM, much like a bow exciting the string of a violin.





Propagation or localization of dynamics excited at the NM-FM interface depend on the exact local geometry and field

Case 1: Longitudinal Geometry



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

Spacer: Cu 10 nm

Fixed layer: Py 10 nm

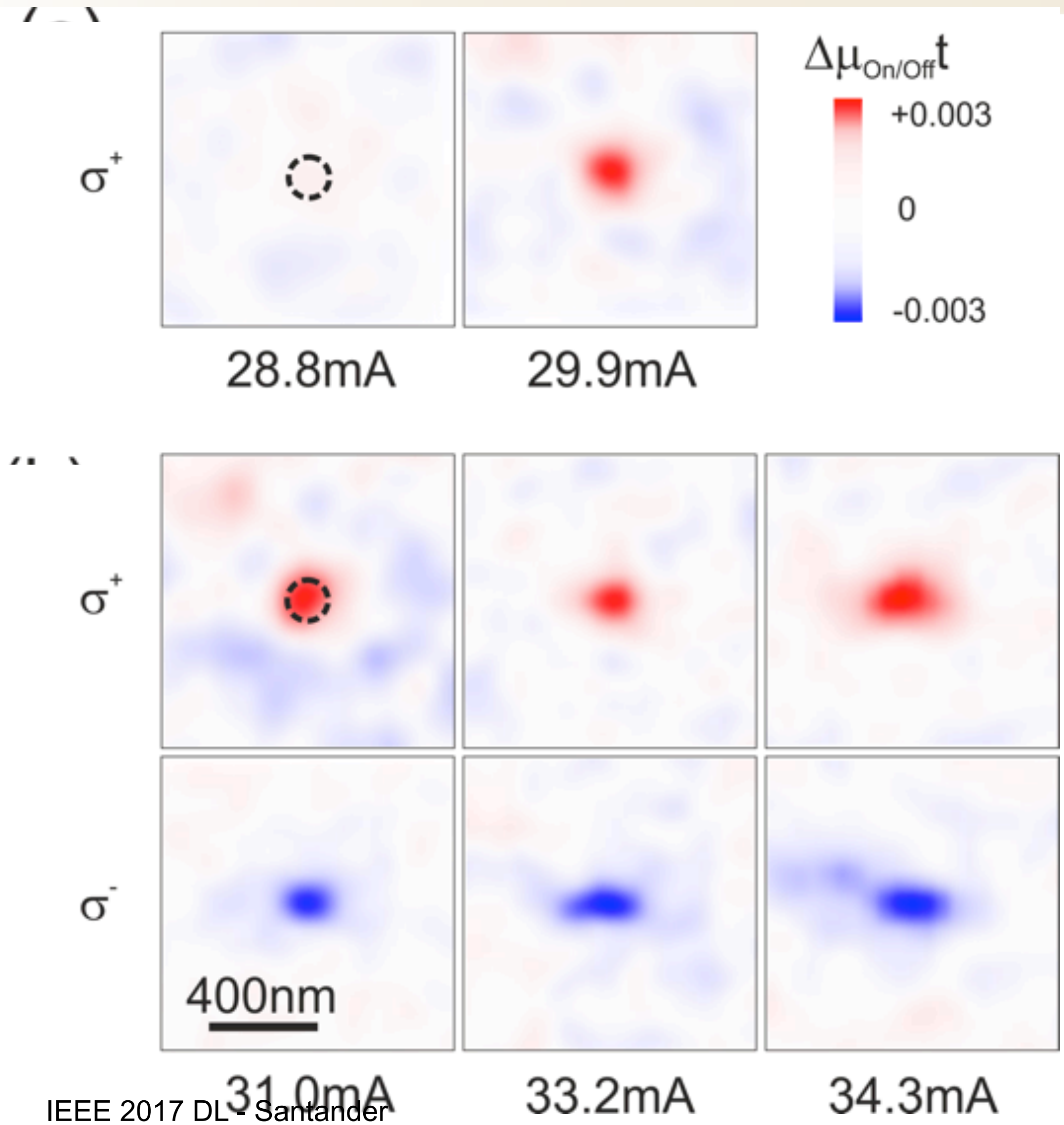
External field: 700 mT, out of plane

Contact: ~150 nm

- Current induced precession of the magnetization will reduce **out of plane M**

→ Images of the envelope of the excitation can be obtained with x-rays parallel M

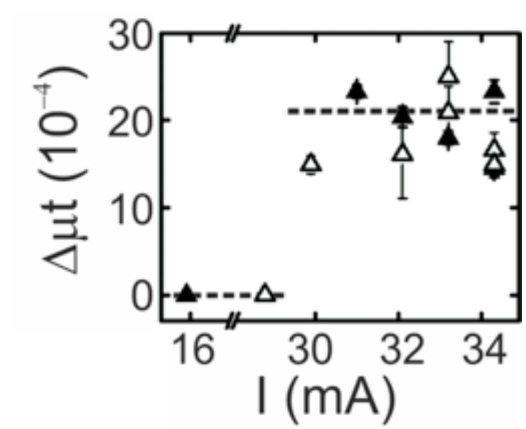
Observations



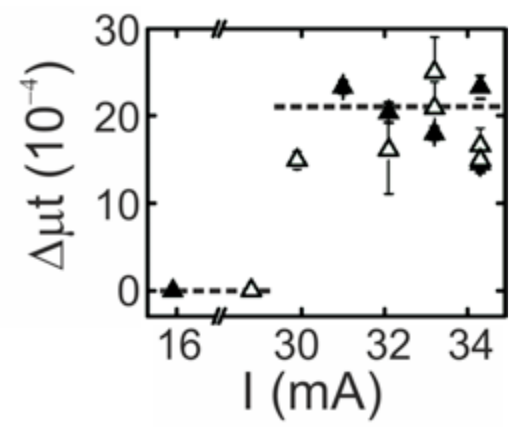
No changes up to 29mA

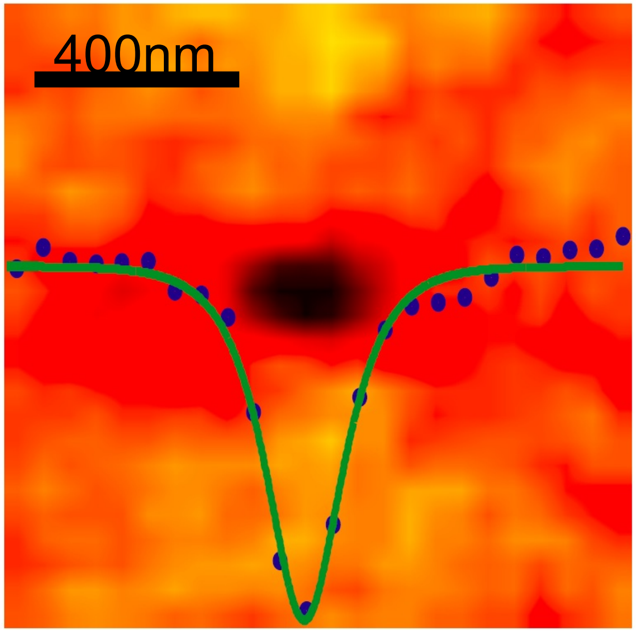
Onset of magnetic excitation at ~ 30 mA

Excitation persists up to at least 34 mA



Conclusions – What is This?



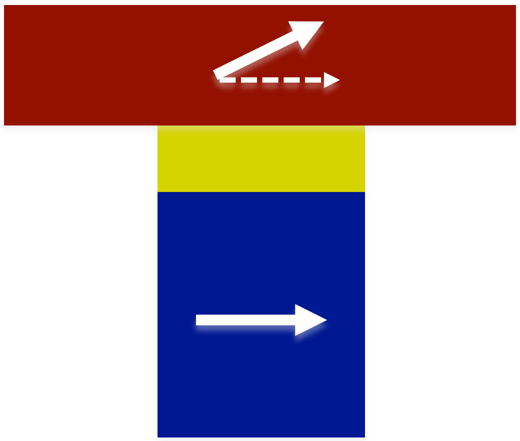


→ Sudden onset of excitation
→ Stability range of excitation
→ Line profile and width (~175 nm) cannot be fitted with propagating mode

Consistent with real space image of a localized magnetic soliton.

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

Case 2: Transverse Geometry



Free layer: 5nm Py

Spacer: Cu 10 nm

Fixed layer: CoFe 20 nm

External field: 70 mT, in plane

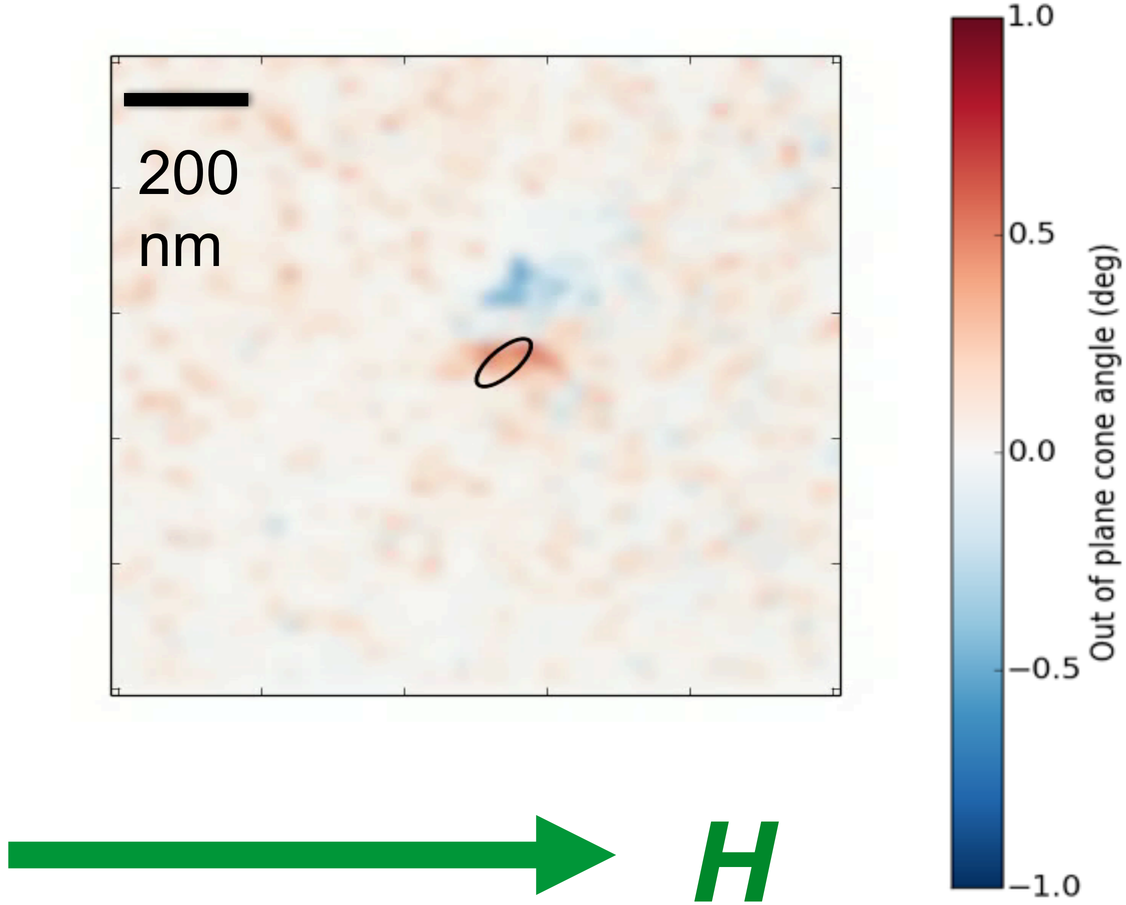
Contact: ~50x130 nm

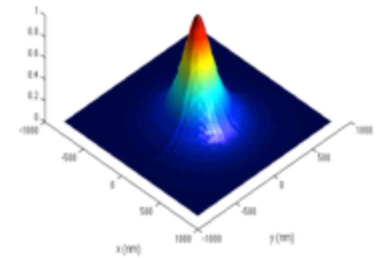
Frequency: ~6.2 GHz

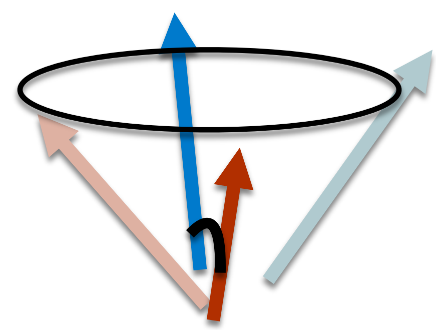
- Current induced precession of the in plane magnetization

→ Time resolved images of the excitation (Δ**M**) can be obtained at the exciation frequency

Spin Wave Movie



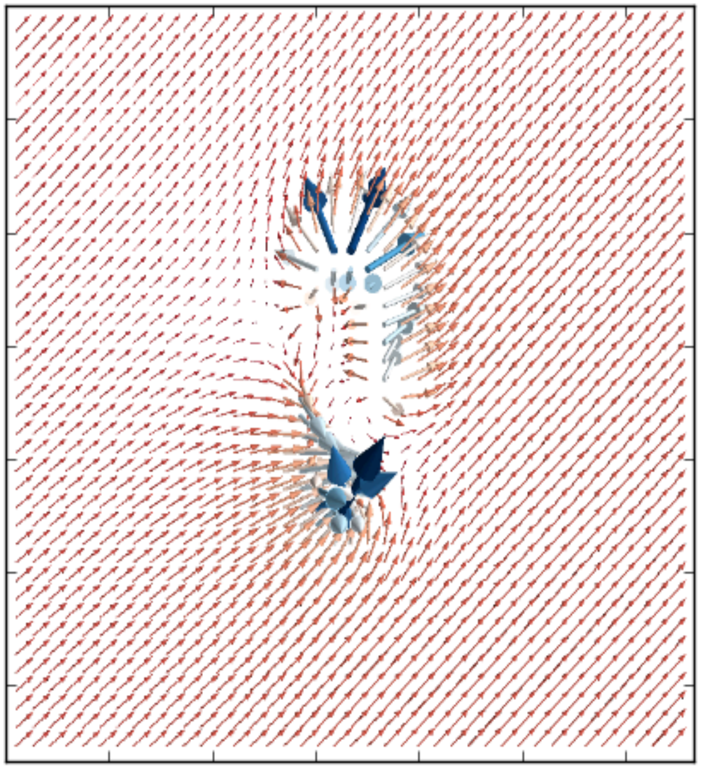




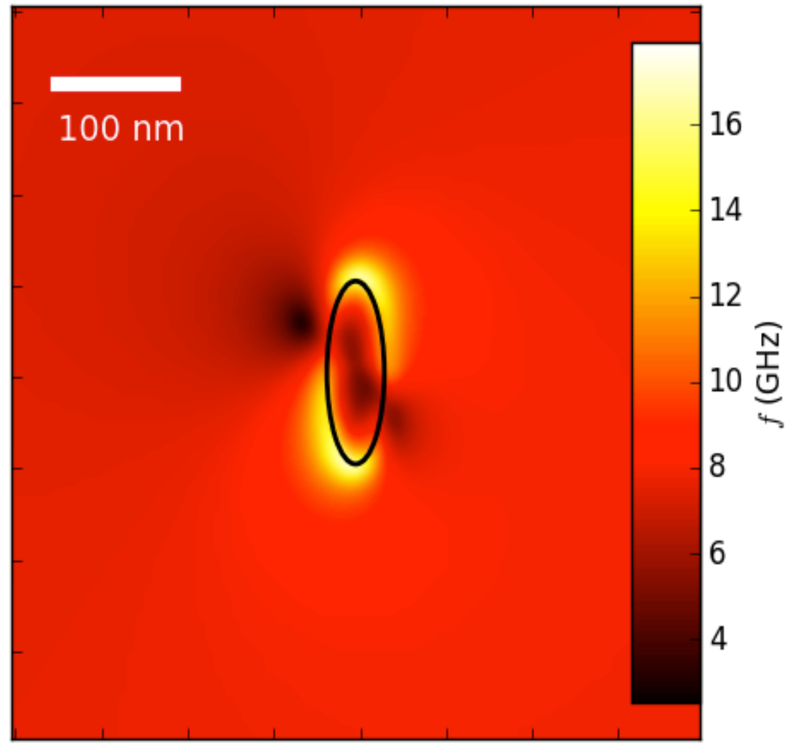
Out-of-plane cone angle

Variation of Internal Fields → Asymmetric FMR

Internal magnetic field

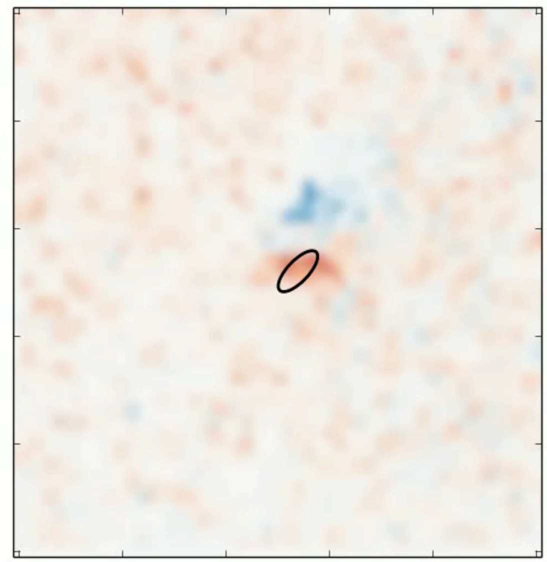


Local FMR map



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

Summary



<u>Over the past 20 years x-ray dichroism has shed light on every aspect in a spin transfer device</u>

→ Exchange bias, AFM/FM exchange anisotropy
→ Spin accumulation and spin transfer at NM/FM interfaces
→ Spin transfer torque dynamics

The Team

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