X-ray imaging, spectroscopy and diffraction: a user's ultrafast dream

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Vetenskapsrådet

Knut och Alice Wallenbergs Stiftelse

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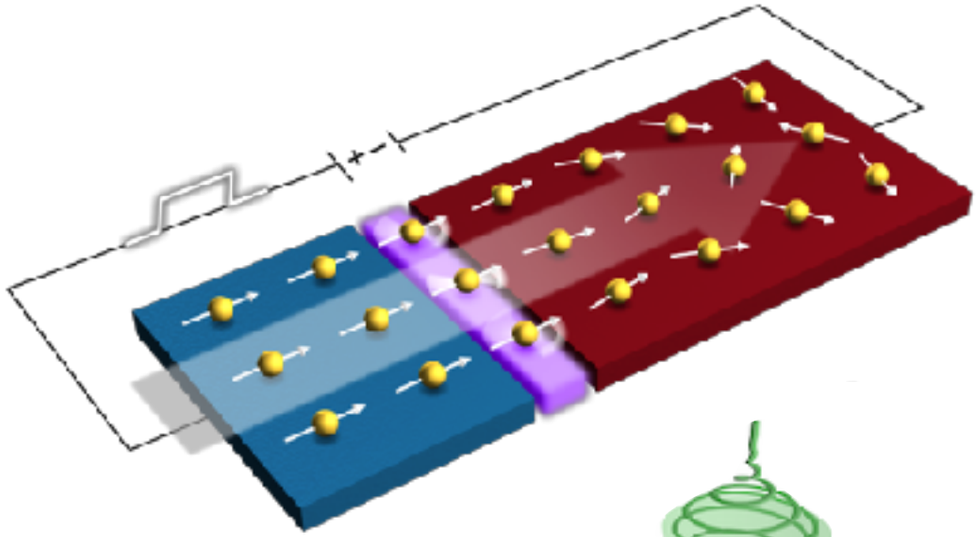
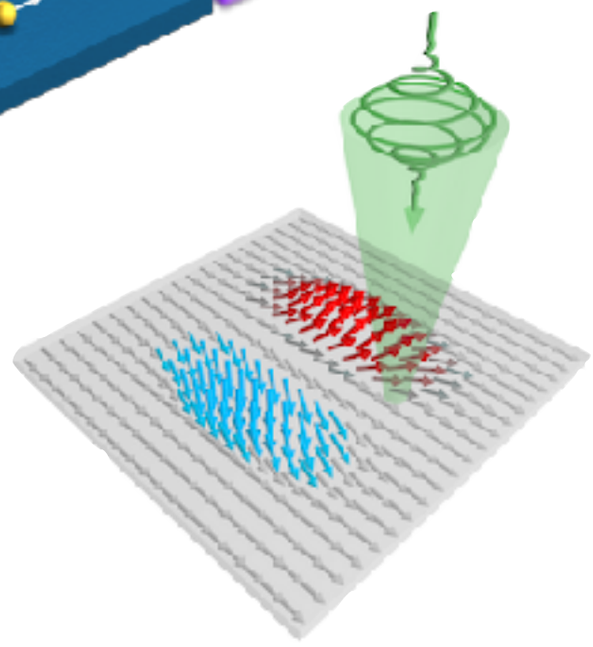
Outline

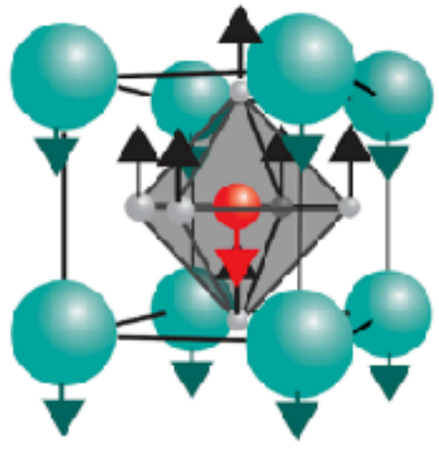
- Transient (magnetic) spectroscopy of interfaces



- Time-resolved imaging of gigahertz (spin) dynamics



- Femtosecond x-ray diffraction of terahertz phonons



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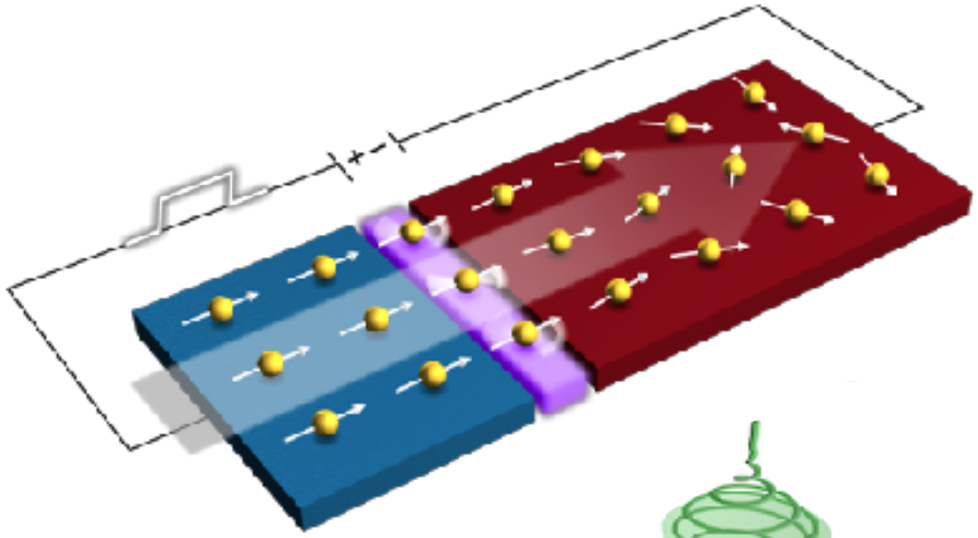

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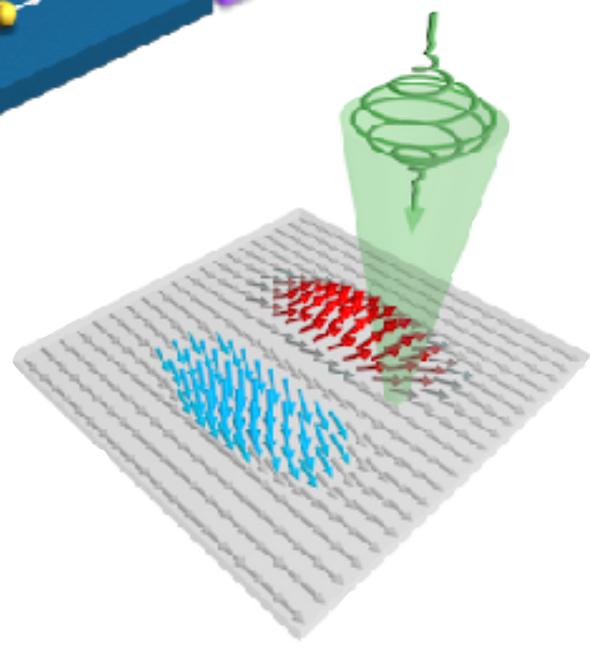

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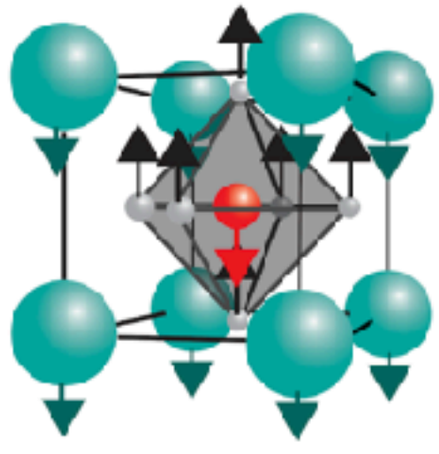
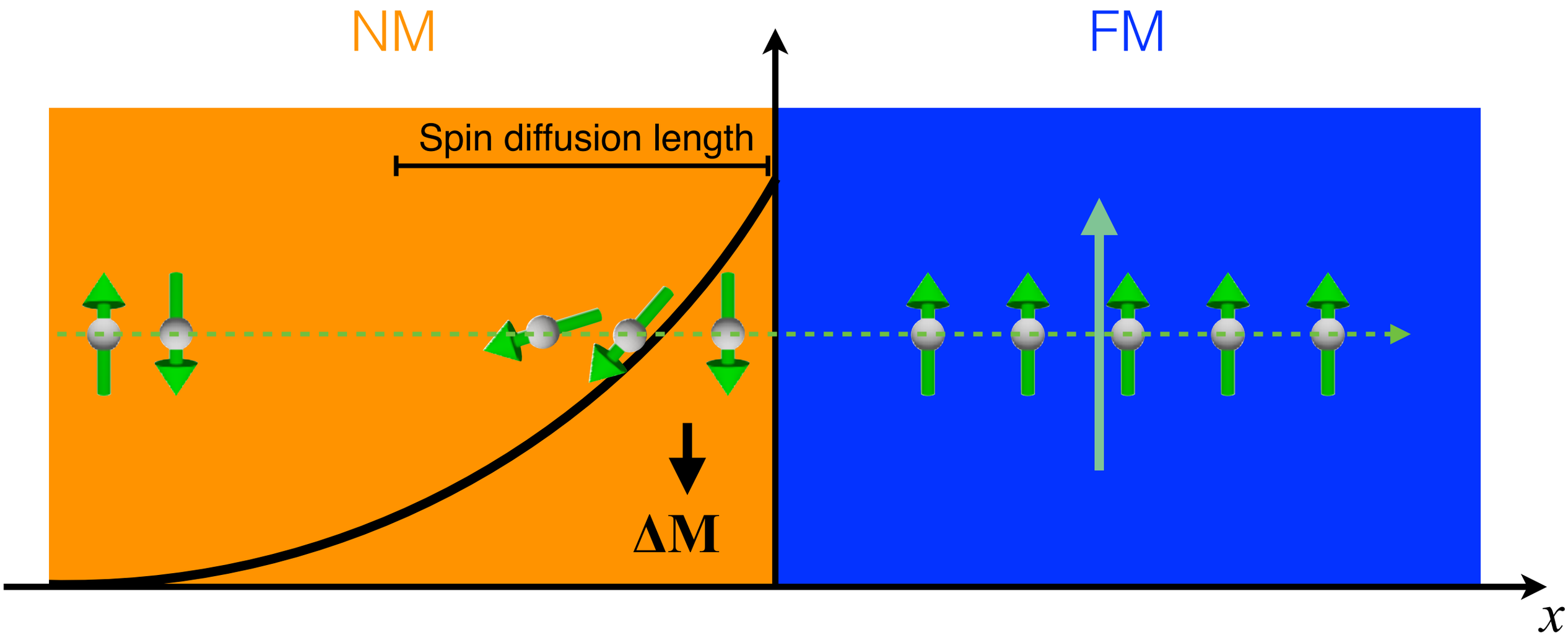


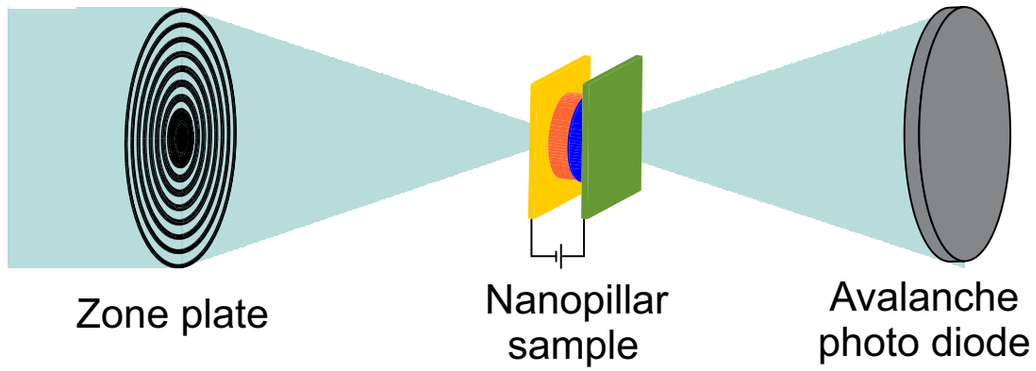
Spin accumulation

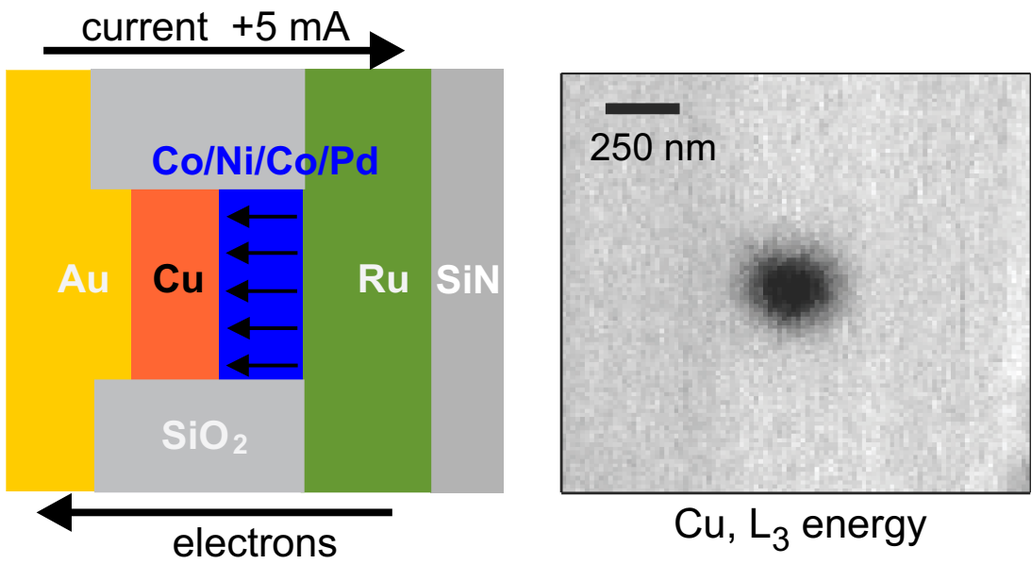


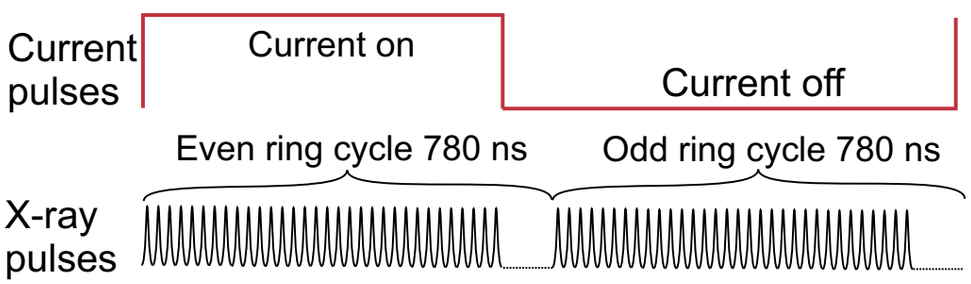
Spin accumulation at the interface:

- Spin-polarized current induces small magnetization in the normal metal
- Great technological relevance (magnetic memories)

Experimental set-up and sample description







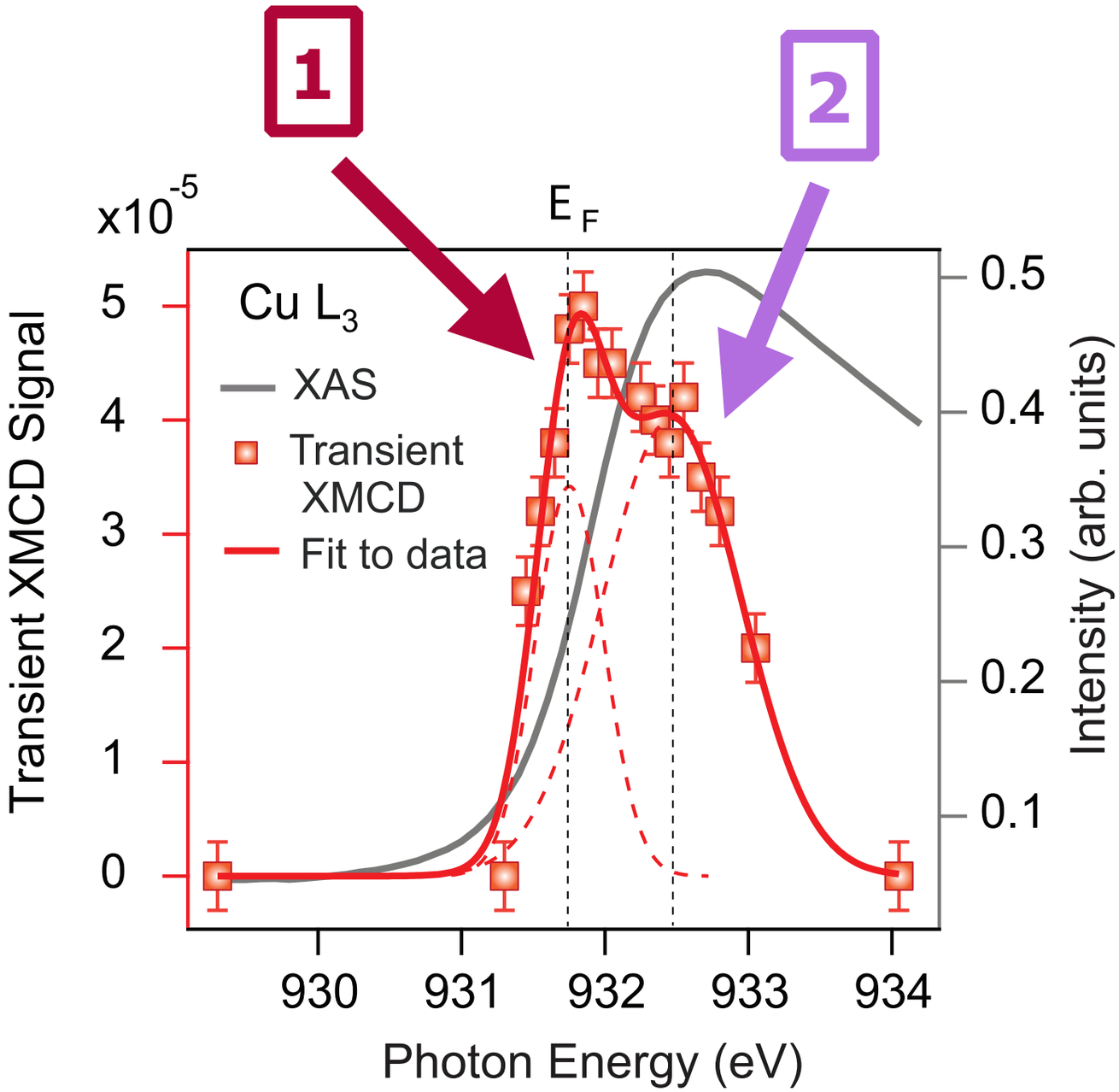
- Nanopillar sample with Cu/Co interface
- Circularly polarized x-rays around the Cu L_3 edge (932.7 eV)

Image current-induced XMCD

($I \sim 10^7$ A/cm^2)

- Possible to switch both current polarity and x-ray helicity

X-ray energy dependence



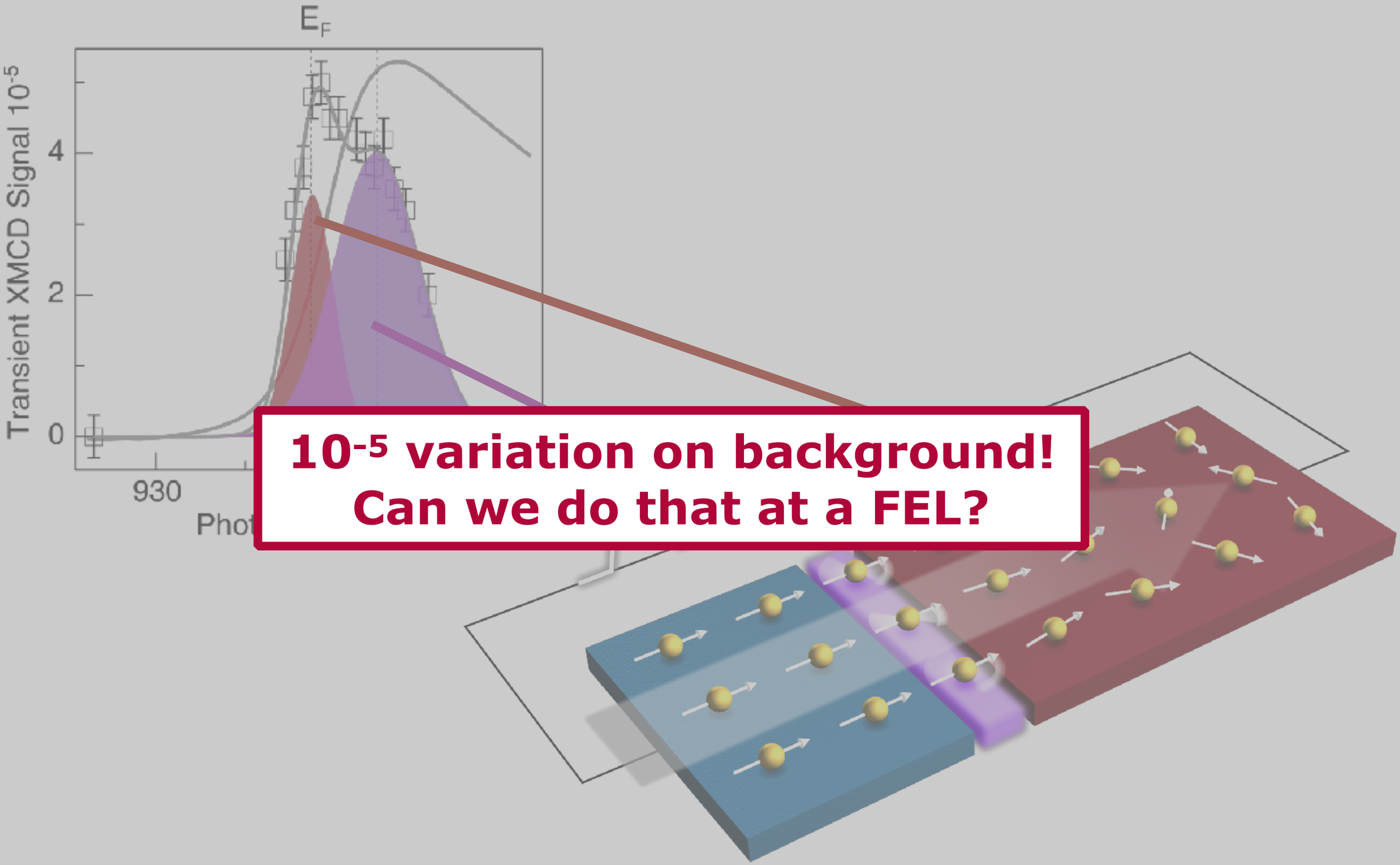
- Peak at the Fermi level: **spin accumulation**

- **Unexpected second peak** at the XAS peak energy: same x-ray energy of *static* moments at hybridized Cu/Co interface

- Joule heating reduces the **net interface moment,** spin-torque re-aligns it

Samant et al., PRL **72**, 1112 (1994)
Nilsson et al., Phys. Rev. B **54**, 2917 (1996)

Imaging spin injection into Cu



10^{-5} variation on background!
Can we do that at a FEL?

R. Kukreja, S. Bonetti, Z. Chen, D. Backes, Y. Acremann, J. A. Katine, A. D. Kent, H. A. Dürr, H. Ohldag, and J. Stöhr, *Phys. Rev. Lett.* **115**, 096601 (2015)

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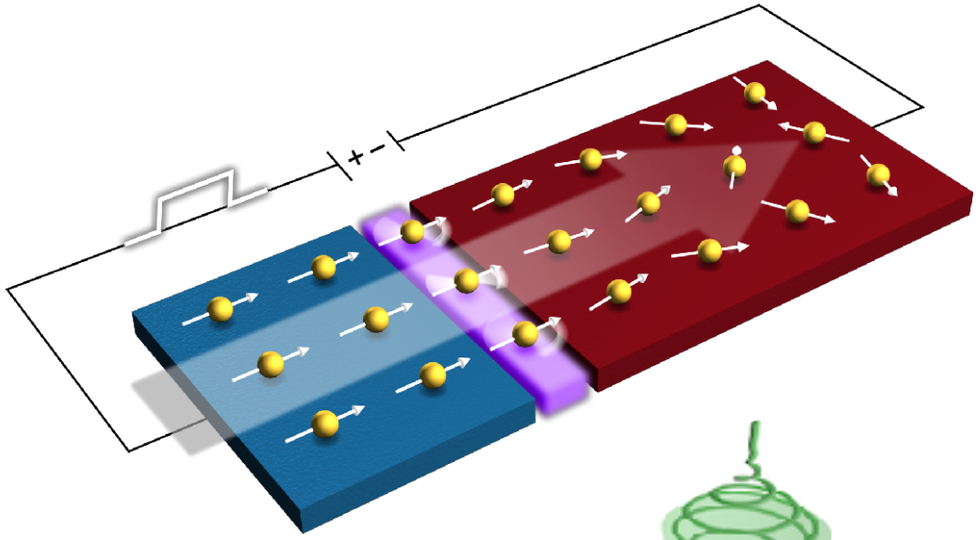
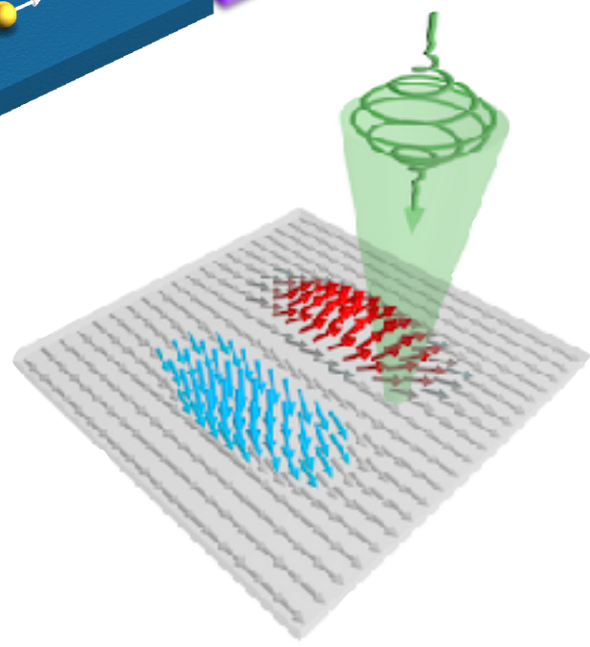
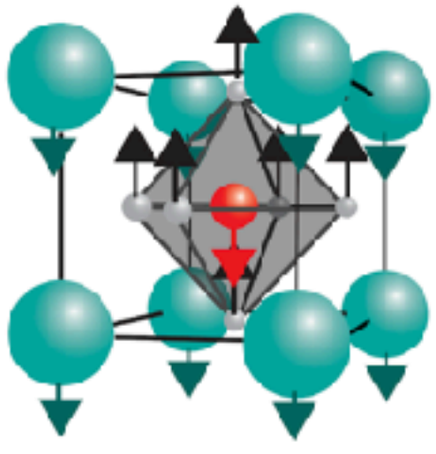


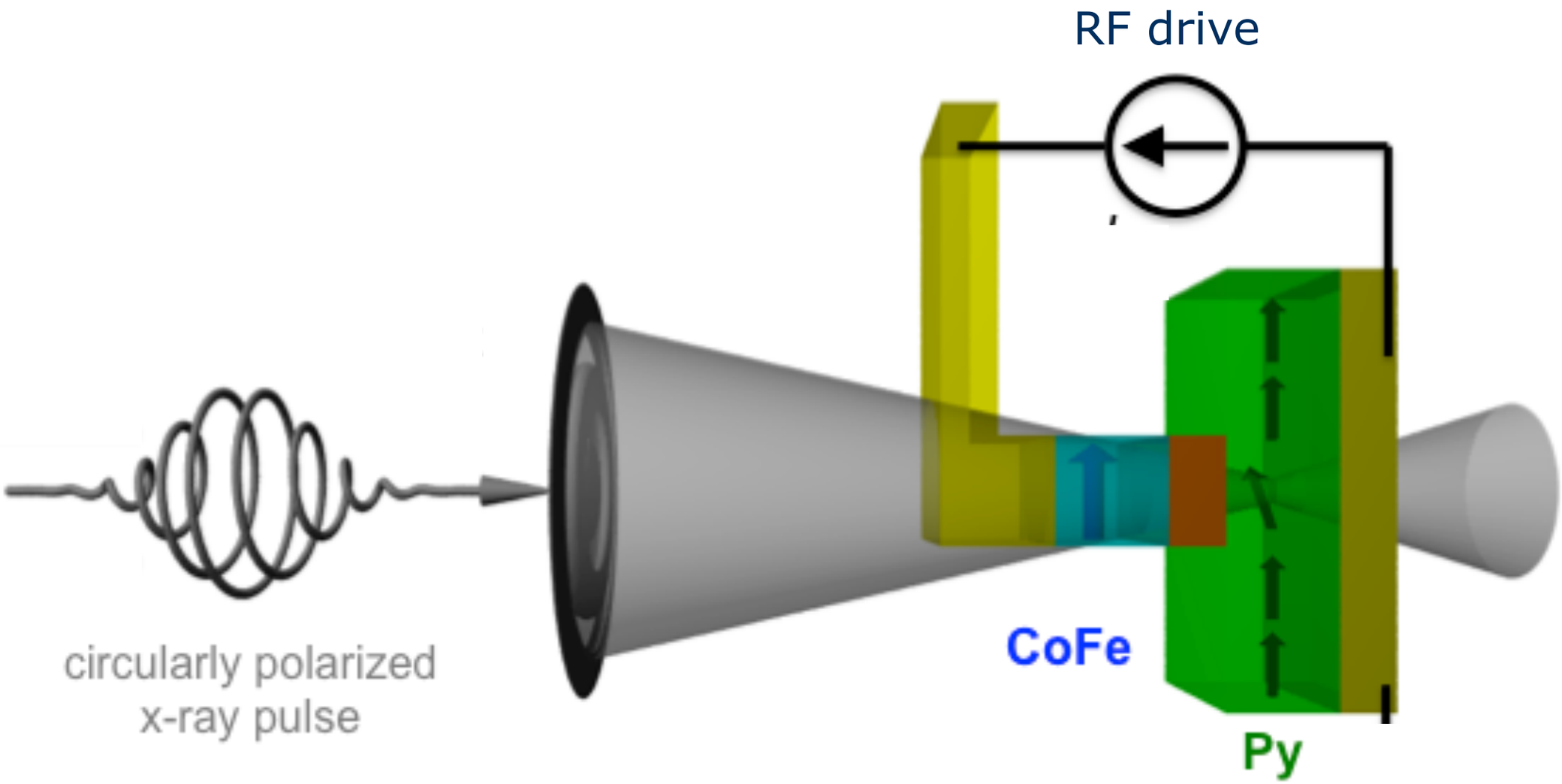
- Time-resolved imaging of gigahertz (spin) dynamics



- Femtosecond x-ray diffraction of terahertz phonons



Imaging of spin waves in nanocontacts

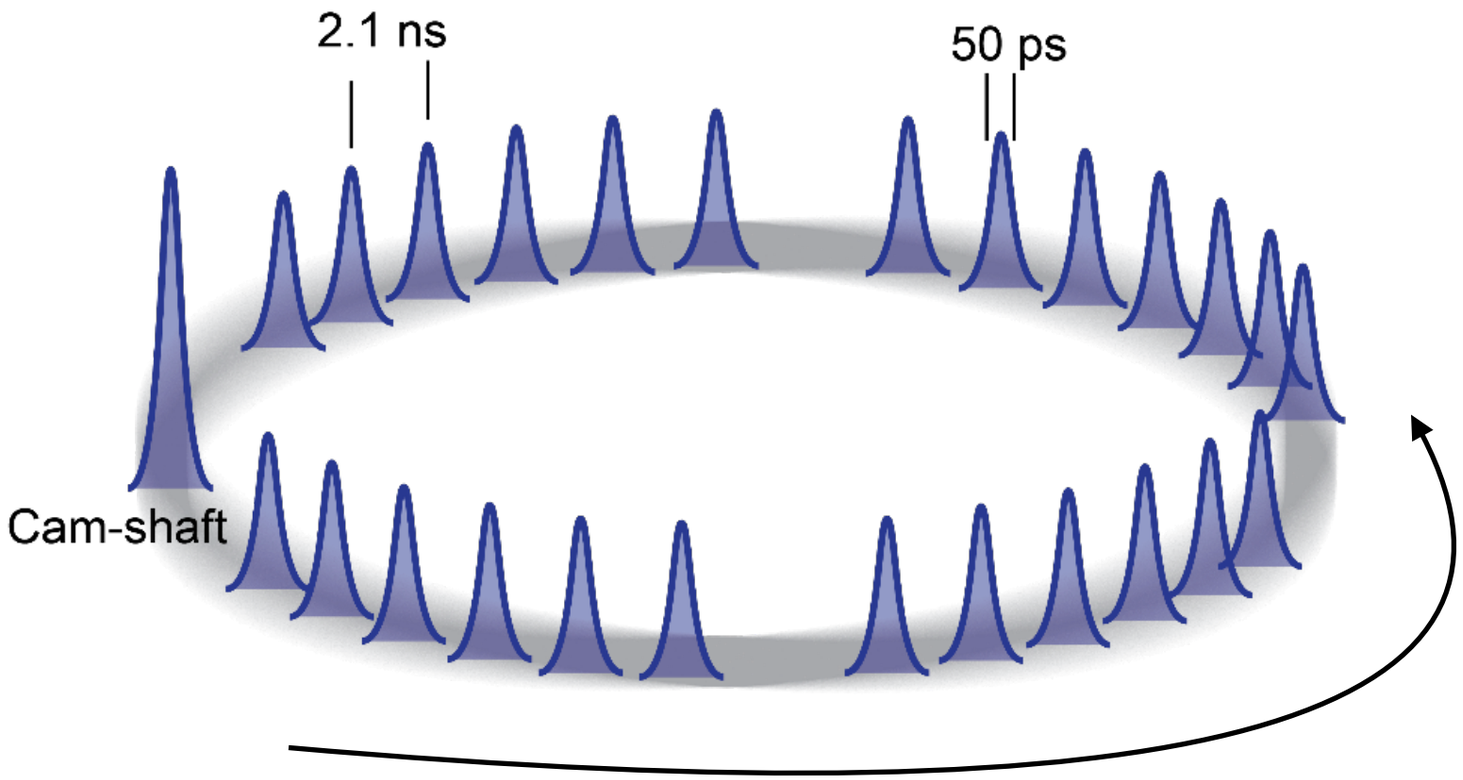


$\sin\theta = \Delta M/M$

M: static XMCD
ΔM: time resolved XMCD

“Pump/probe” experiments at synchrotrons for increased sensitivity

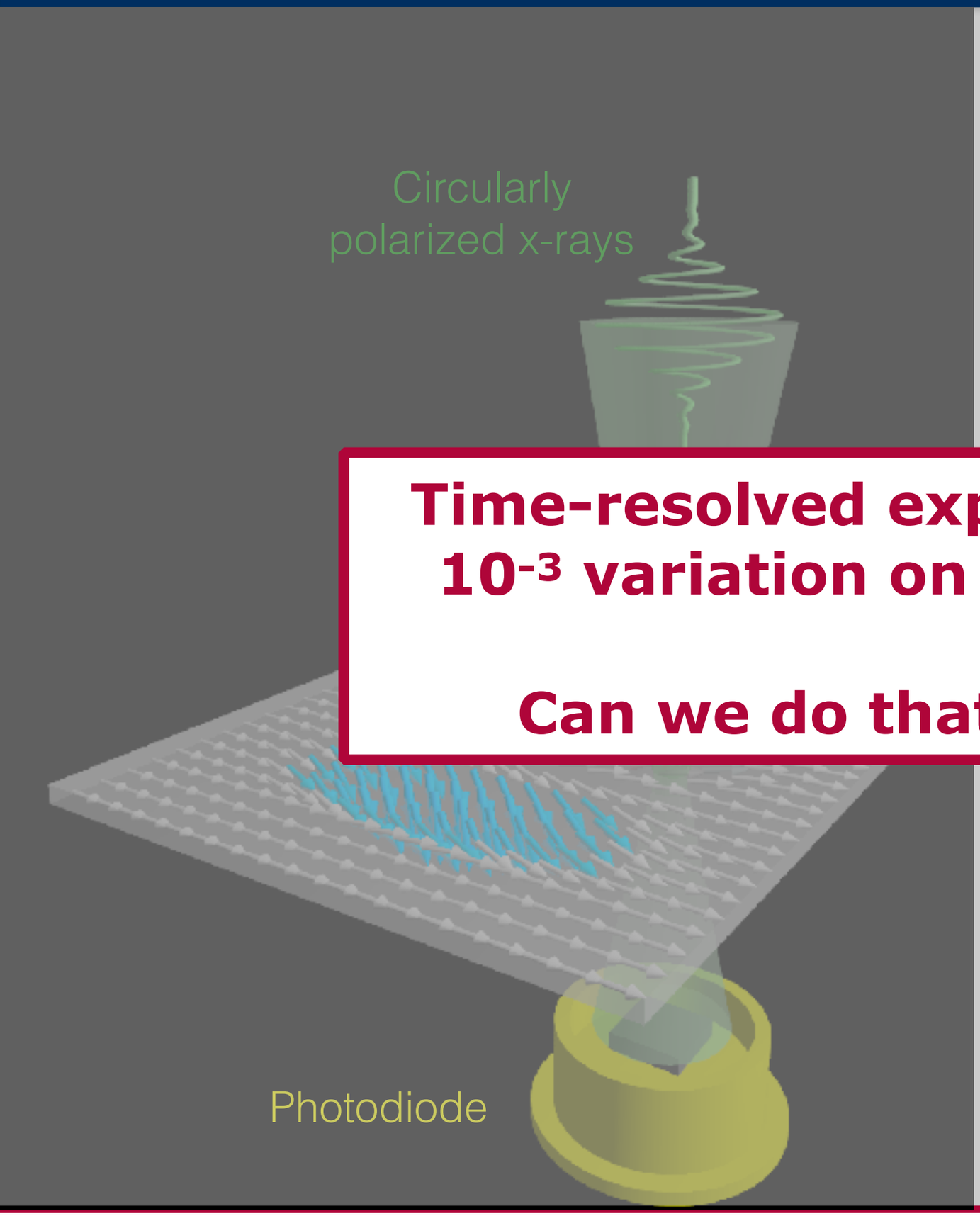
SSRL

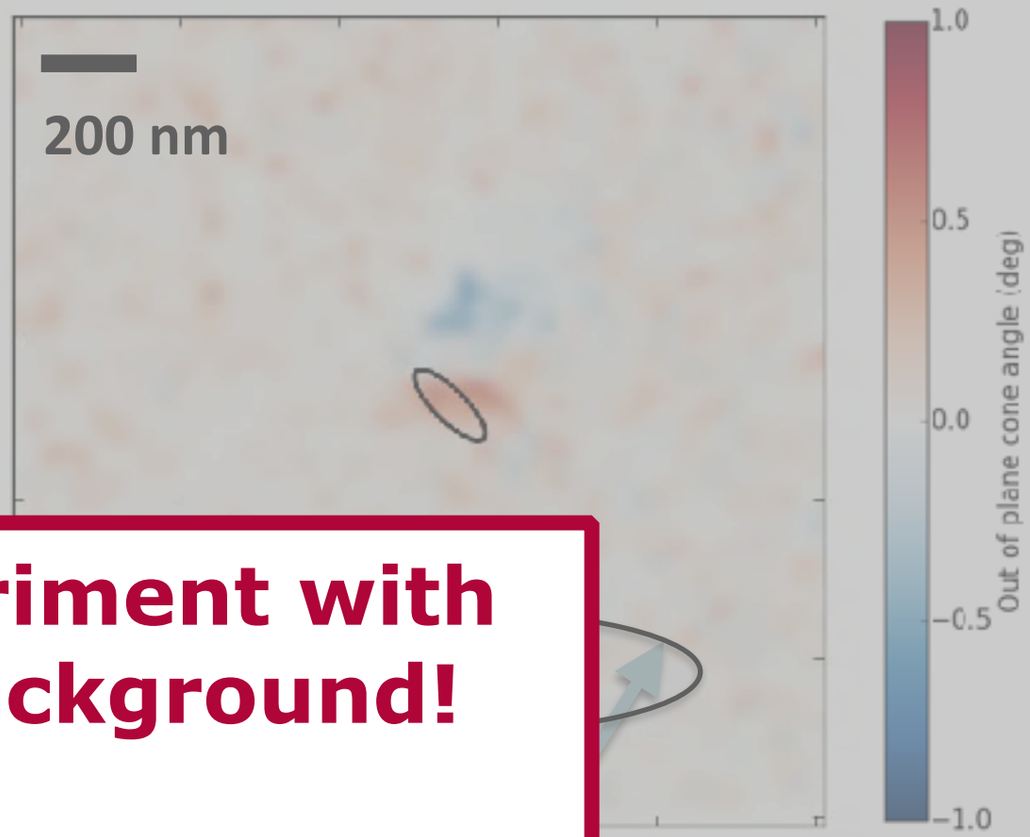


Storage ring orbit period: 780 ns (1.28 MHz)

- 476 MHz modulation: noise reduction (“lock-in”)
- 1.28 MHz modulation: normalization

State of the art time-resolved magnetic imaging at synchrotrons





Time-resolved experiment with 10^{-3} variation on background!

Can we do that at a FEL?

1 precession period: 160 ps

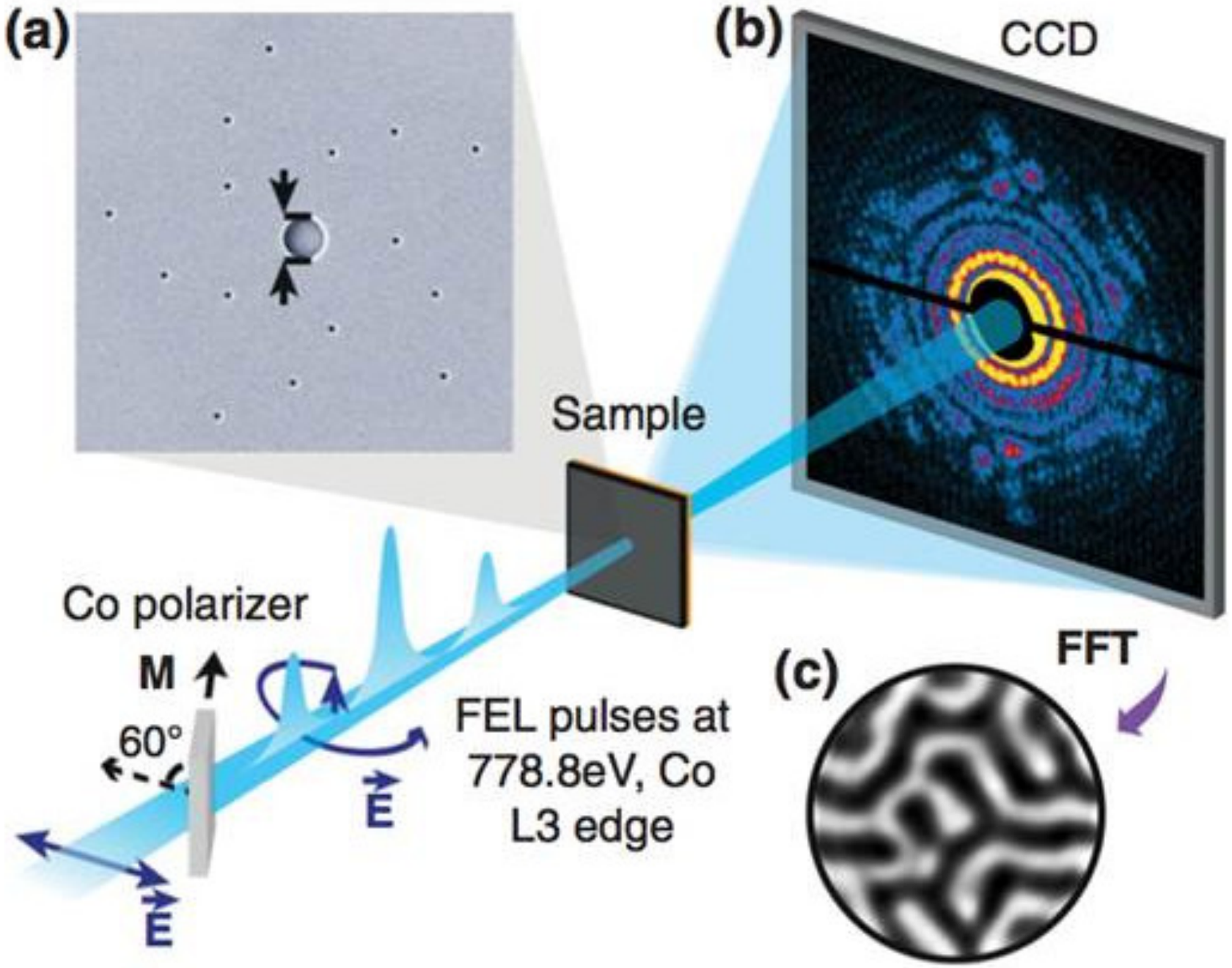
30 nm, 20 ps resolution

1 deg precession, 10^{-3} variation

S. Bonetti *et al*, *Nature Comm.* **6**:8889 (2015)

S. Bonetti, *J. Phys.: Cond. Matt.* **29**, 133004 (2017)

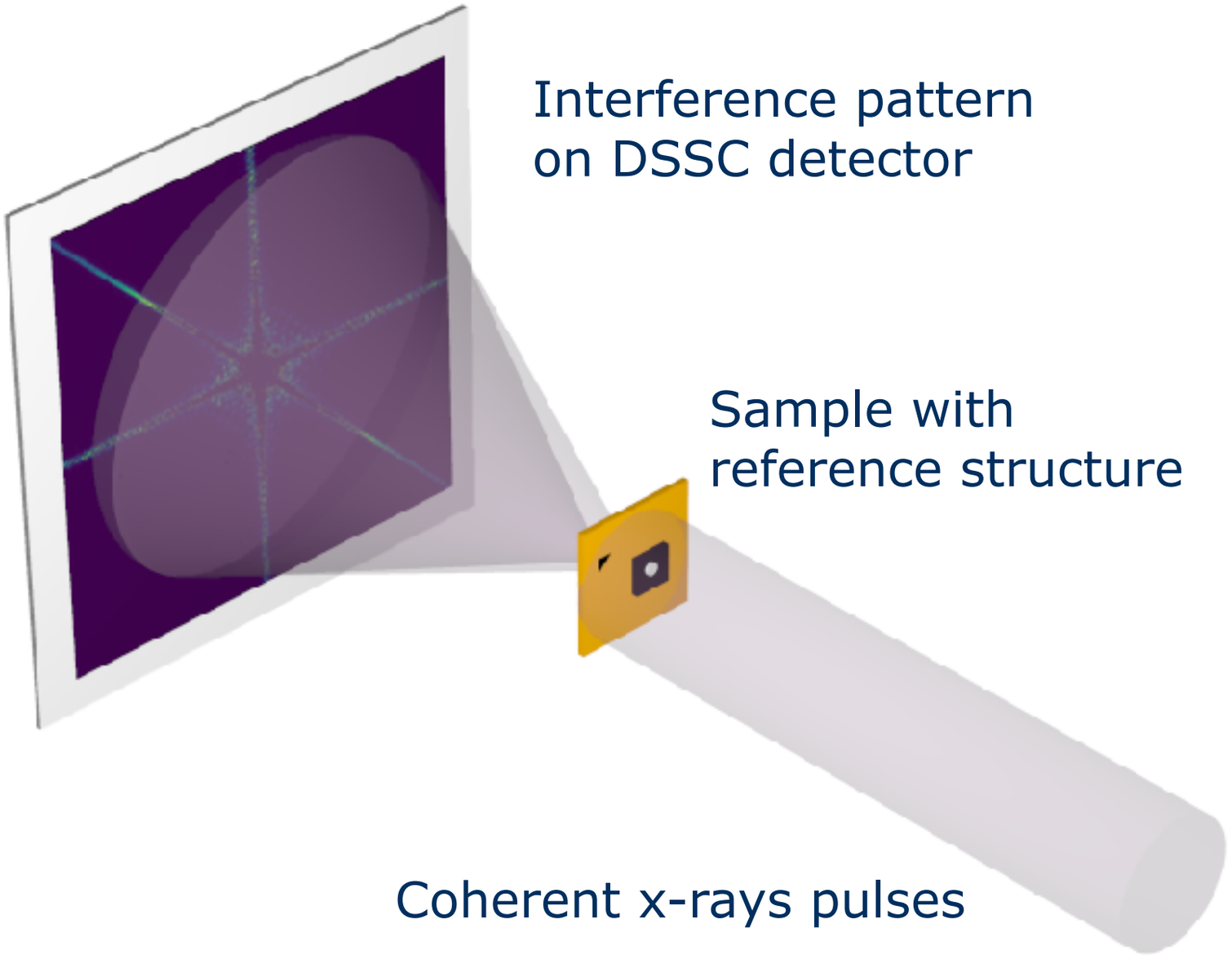
Spatial resolution: x-ray holography



Demonstrated: 15 nm resolution, soft x-rays, circular polarization

Community proposal at European XFEL - accepted

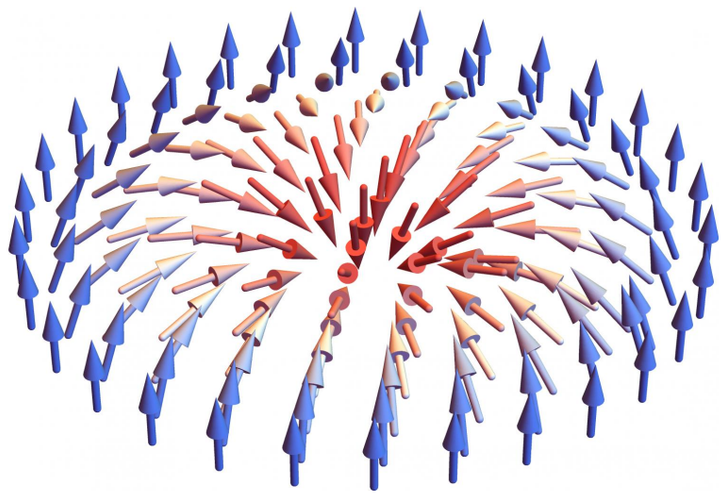
X-ray holography of ultrafast magnetism: femtosecond movies at the nanoscale



Interference pattern
on DSSC detector

Sample with
reference structure

Coherent x-rays pulses



Skyrmion

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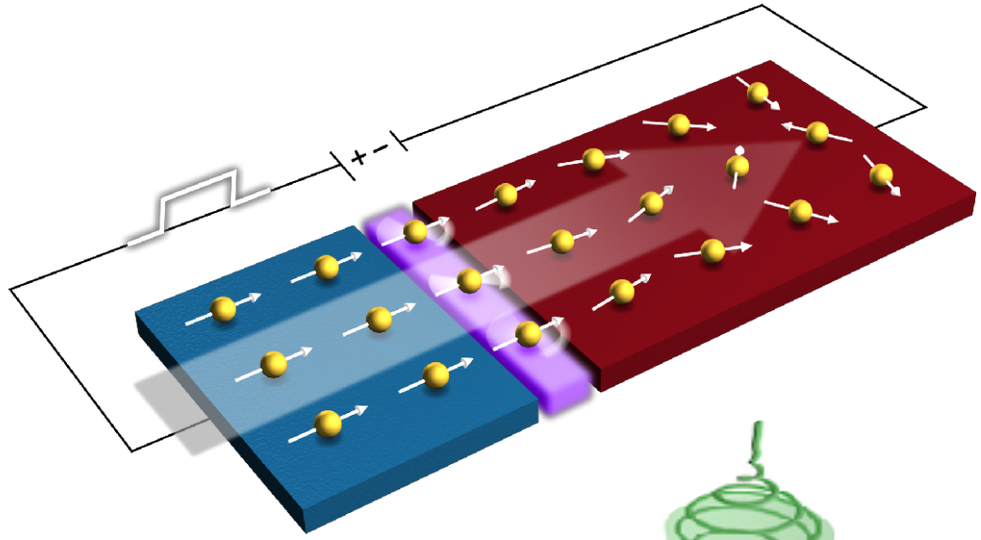

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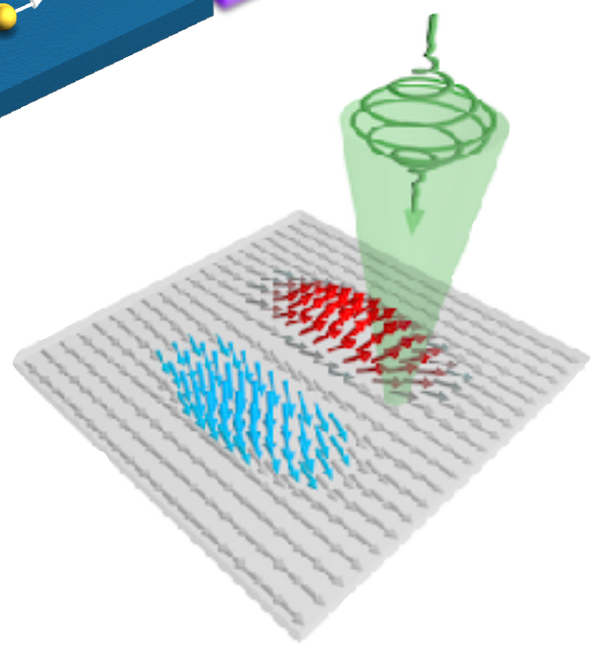

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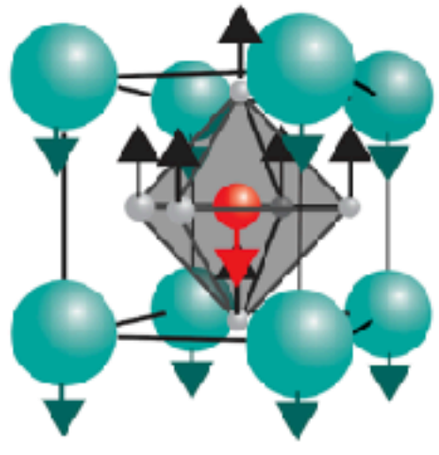


Temporal resolution: FELs

- 20-50 fs “good”, so far the least problematic parameter

- But:
  - Fermi electron velocities in metals are ***1 nm / fs***
  - Phonons and magnons at ***~10 THz (100 fs period)*** determines fundamental properties of many materials

- ***Need 10 fs or better soon!***

- Timing tool at XPP/LCLS: observation of 8 THz oscillations, probably the limit. Better synchronization will be needed.

Excitation strength: the repetition rate dilemma

- More pulses: better statistics and resolution
- But: measurements often ***stroboscopic***, need to reset after each pulse.
- Pump-probe experiments: need to thermalize back to same state before next pulse; 1 µs (***1 MHz***) not enough?
- In laser experiments (***1 kHz***), ballpark numbers for solid state:
  - Pump: 10-100 mJ/cm^2, 10 - 100 uJ, **10 - 100 mW**
  - Probe: 0.01 - 0.1 mJ/cm^2, 0.1 - 1 uJ, **0.1 - 1 mW**

Challenges

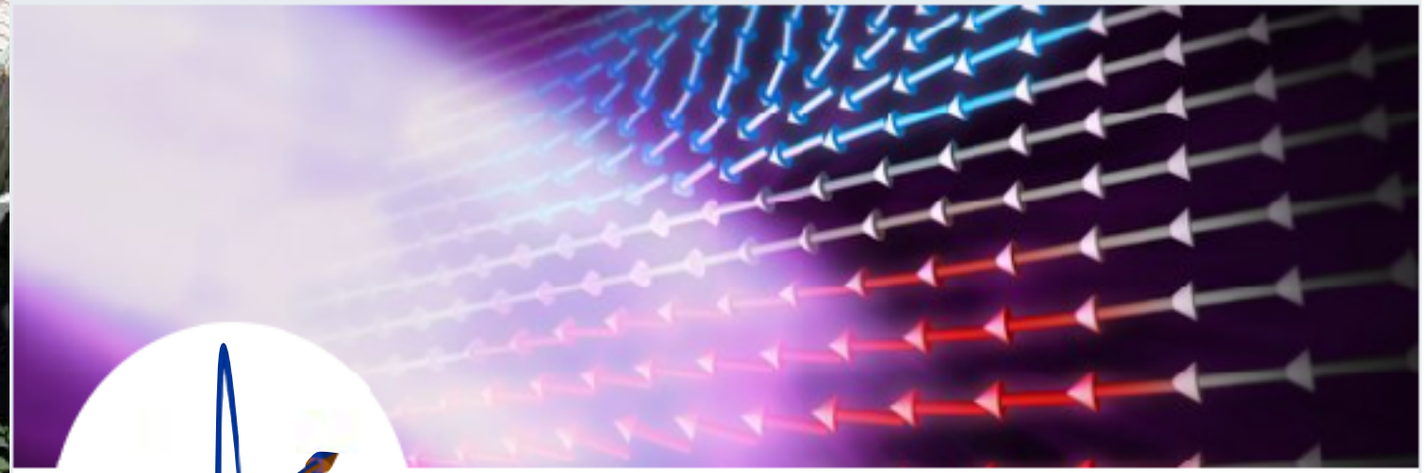
- Can we measure ultrafast resonant x-ray spectroscopy with **high sensitivity** (10^{-5} or better)?

- Can we create **femtosecond movies at the nanoscale**?

- Can we easily combine **pump pulses** of arbitrary wavelengths (from terahertz to XUV)?

- Can we tune the FEL between sensitive spectroscopy and stroboscopic imaging (high **rep-rate**, low energy/pulse), and single-shot and pump-probe (low rep-rate, high energy/pulse) settings?

Thank you for your attention!



Ultrafast Dynamics…

@UltrafastSU