Combining high time and spatial resolution of magnetic microscopy with X-ray ptychography

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Shopping list to perform time-resolved microscopy

A microscope

- Spatial resolution
- Field of view / Number of pixels
- Linearity and bit dynamics
- Noise and sensitivity, time for an image

A source of excitation of the sample

- Bandwidth
- Type of excitation (pulse, ac, arbitrary…)
- Repetition rate

A fast (stroboscopic) sampling

- Duration
- Repetition rate
- Jitter

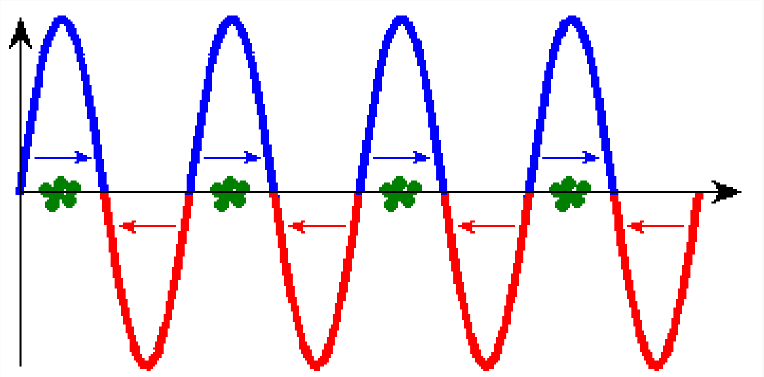
- Many techniques with different parameters
- No "best technique"

Time structure of (X-ray light) bunches at synchrotrons

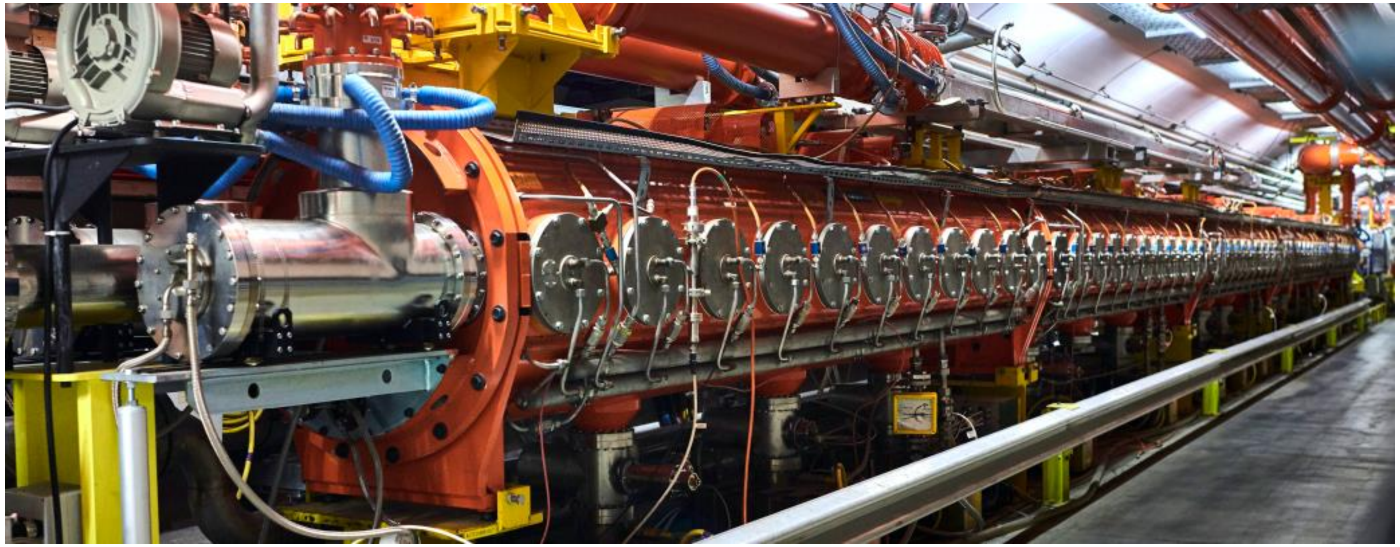
Particles in a linear accelerator or storage ring come as bunches

- **Linear accelerator**: electrostatic potential of GV cannot be sustained
- **Storage ring**: a circular uniform electric field does not exist

➡ The charged particles come in bunches, accelerated by the E-field of resonating cavities



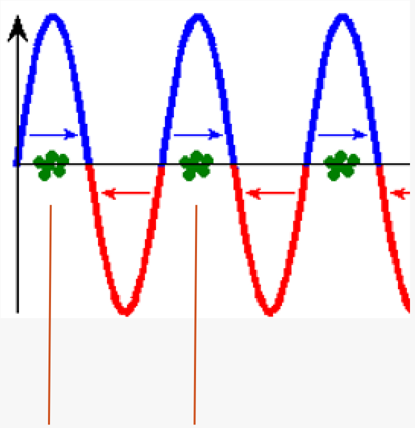
https://en.wikipedia.org/wiki/Linear_particle_accelerator



RF cavities in series at LHC – CERN

Time structure of (X-ray light) bunches at synchrotrons

Time and frequency figures at SOLEIL



$$f_{\text{SOLEIL}} = 352.202 \text{ MHz}$$

$$f_{\text{ALBA,SLS,BESSY,Diamond}} = 500 \text{ MHz}$$

$$f_{\text{ESRF}} = 352.37 \text{ MHz}$$

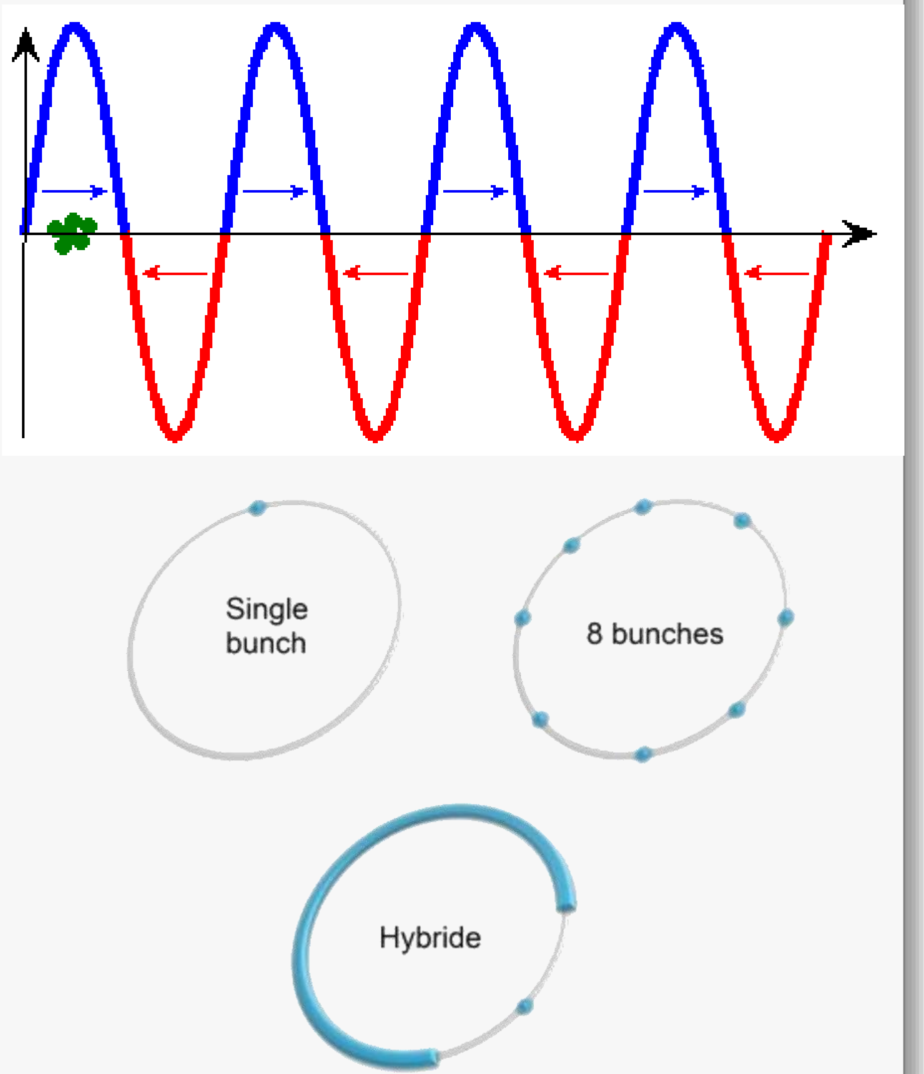
$$d = \frac{c}{f} \approx 1 \text{ m}$$

Hundreds of bunches circulating in the ring

- Bunch length@SOLEIL: 47 ps
- Jitter: a few ps

Time structure of (X-ray light) bunches at synchrotrons

Low-filling modes at SOLEIL

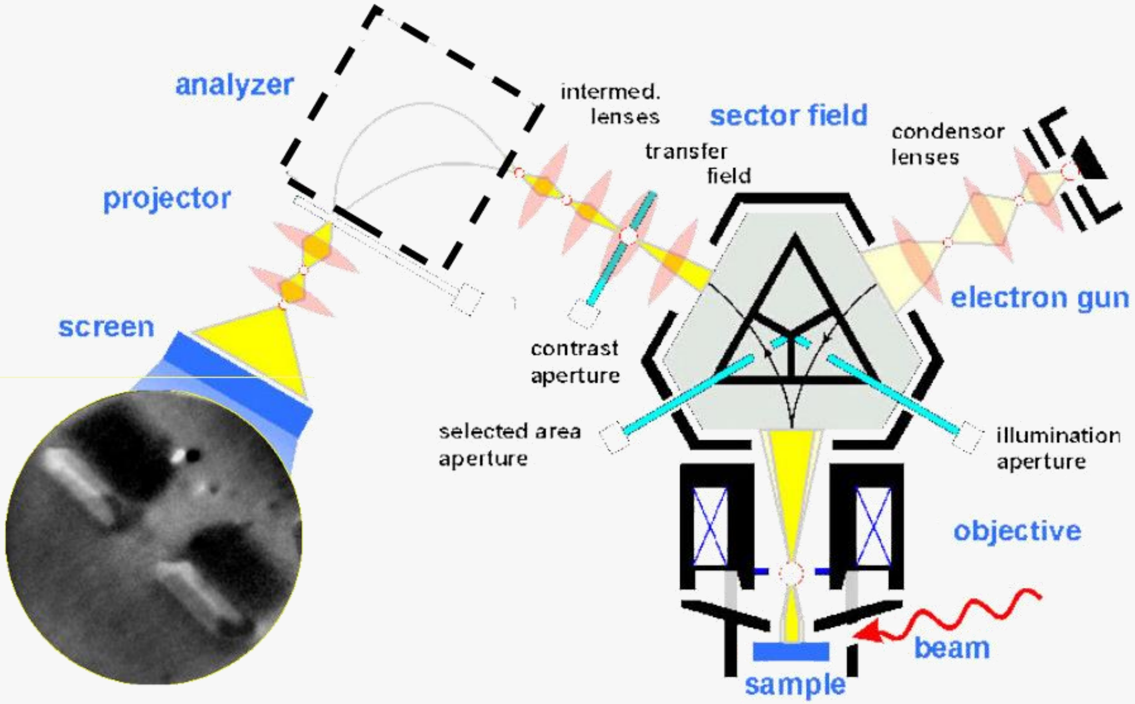


Mode	Current	Pulse frequency	Pulse period
Full	500 mA	352.202 MHz	2.8 ns
8-bunch	100 mA	6.773 MHz	148 ns
Single bunch	20 mA	846.64 kHz	1.181 µs
Hybrid	400 mA	353.202 MHz 846.64 kHz	2.8 ns 1.181 µs

PEEM : Photo-Emission Electron Microscope

Principle

- Based on LEEM: Low-Energy Electron Microscope
- Photon-in Electron-out



Assets

Spatial resolution ≈25nm

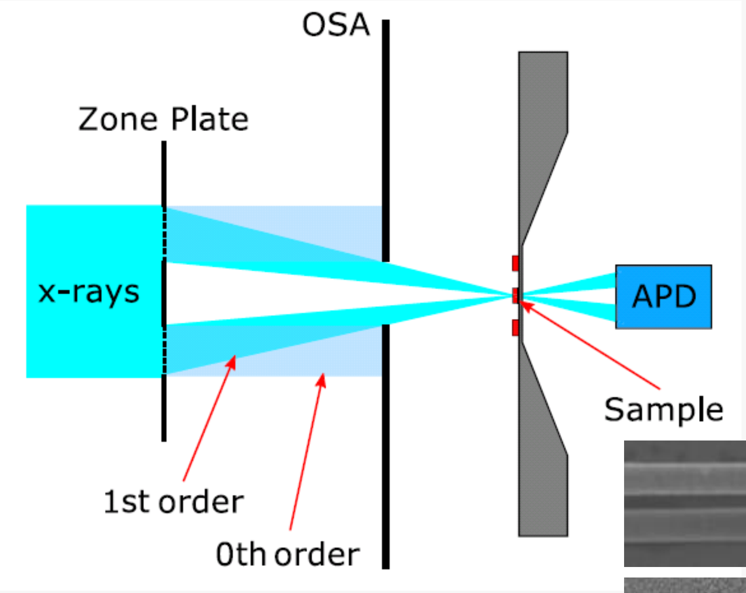
- Full-field: **real time** LEEM/PEEM
- Variable field-of-view
- Reflection, surface-sensitive
- Sample at **high voltage** (>10 kV), an issue for spintronics
- **Little space** available around sample
- **Tricky to combine with magnetic field**

Magnetic imaging at synchrotrons

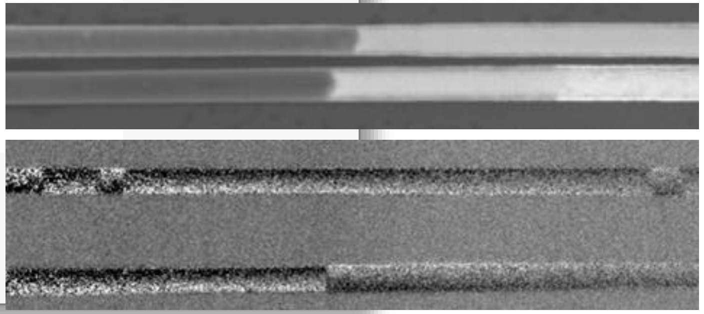
STXM : Scanning Transmission X-ray Microscope

Principle

- Focusing with a Fresnel zone plate
- X-ray detector (photomultiplier tube / Avalanche Photodiode)



Courtesy: S. Finizio



450nm-diameter core-shell wires

Assets

Spatial resolution ≈25nm

- **Sample grounded**: good for spintronics
- **Variable field-of-view**
- Compatible with **magnetic field**
- Reasonable **space available** for sample environment
- **Scanning**: somewhat slow
- **Transmission**: sample preparation, volume averaging, less sensitive for ultrathin films

Note:

Variant TXM = Transmission X-ray Microscope

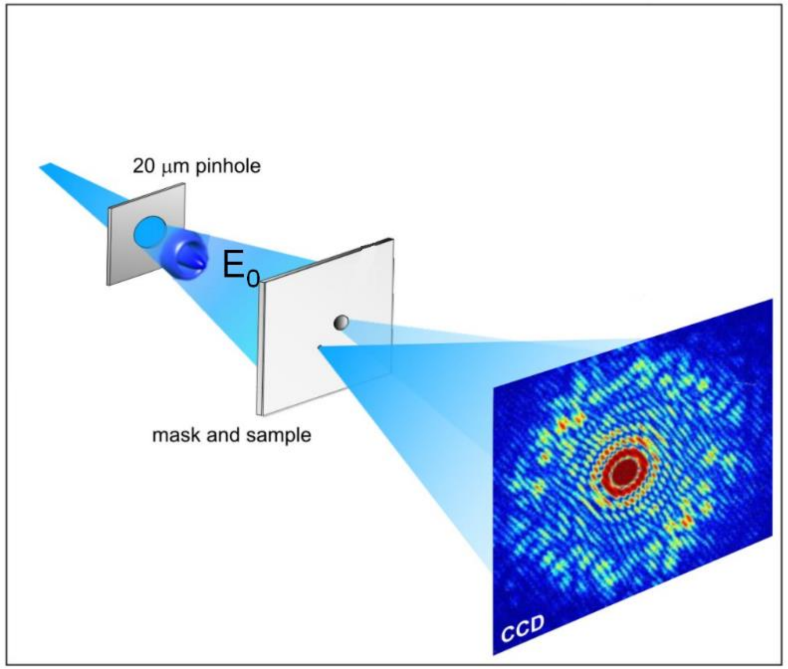
→ A second ZP after sample makes an image

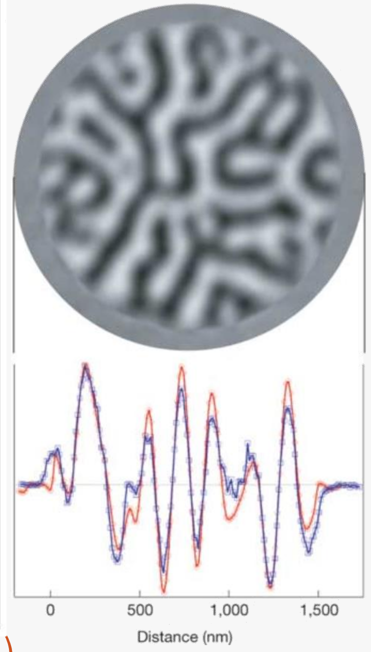
→ Full field

Holography techniques

Principle

- Holography between an object and a reference
- The Fourier transform of the hologram provides the real-space image





S. Eisebitt et al., Nature 332, 885 (2004)

Assets

Spatial resolution <20 nm

- **Sample grounded**: good for spintronics
- Compatible with **magnetic field**
- Reasonable **space available** for sample environment

- **Fixed** field-of-view and position
- **Transmission and reference**: sample preparation, volume averaging, less sensitive for ultrathin films

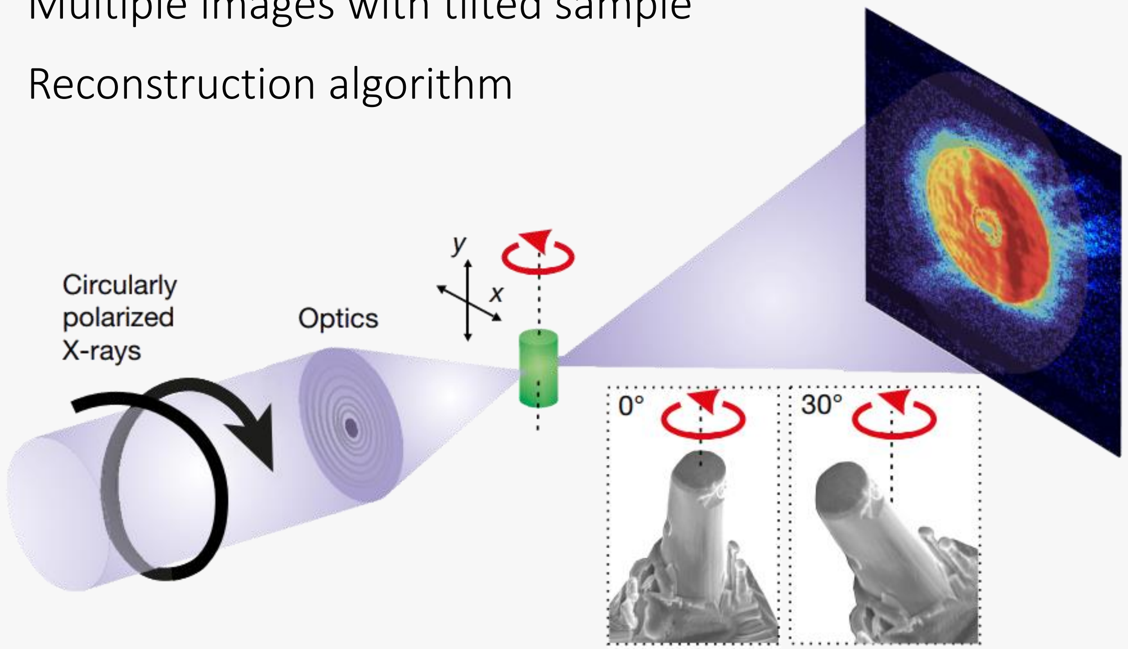
Note:

A number of variants exist for the reference beam

Vector tomography (or variations)

Principle

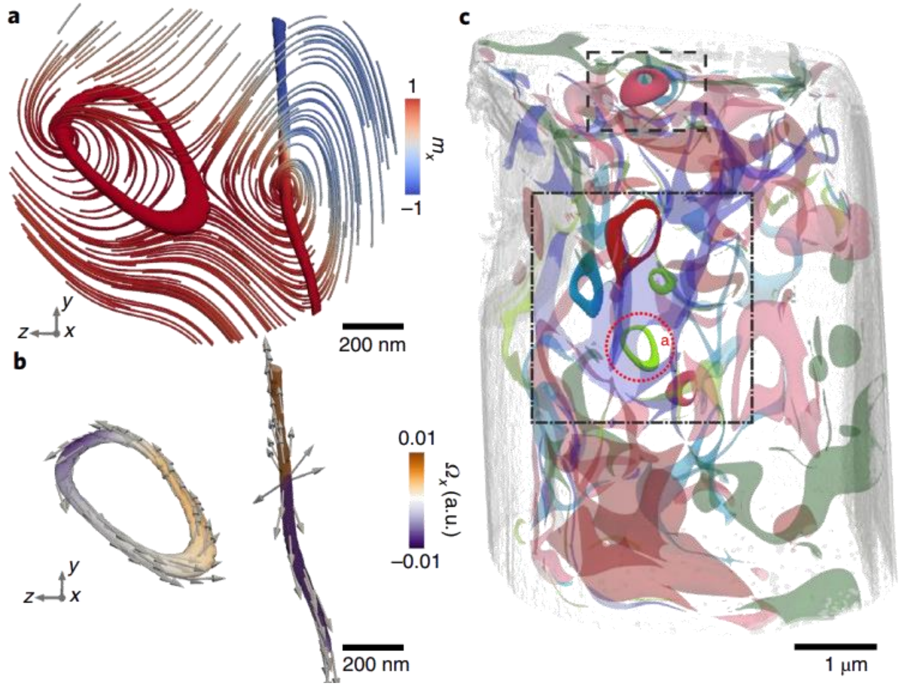
- Multiple images with tilted sample
- Reconstruction algorithm



C. Donnelly et al., Nature 547, 238 (2017)

Assets Spatial resolution ≈25nm

- 3D vectorial information
- Long acquisition time



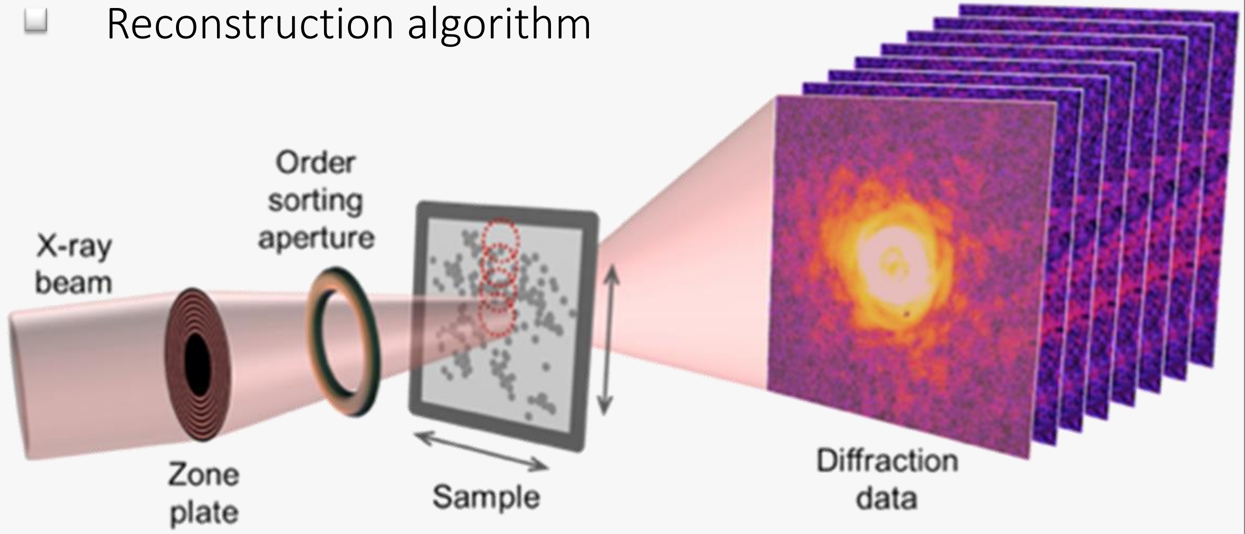
C. Donnelly et al., Nature Phys. 17, 316 (2020)

Magnetic imaging at synchrotrons

Ptychography: combine STXM and scattering

Principle

- 2D series of scattering with overlapping FoVs
- Reconstruction algorithm

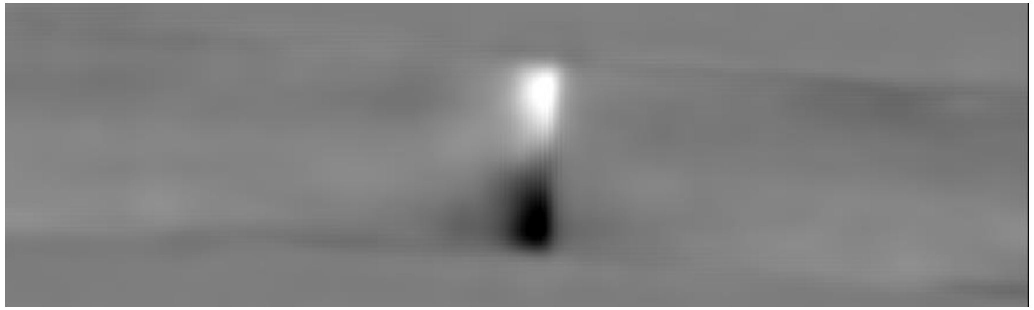


Courtesy: R. Belkhou

Assets

Spatial resolution ≈10nm

- **Sample grounded**: good for spintronics
- Compatible with **magnetic field**
- Reasonable **space available** for sample environment
- **4D data set** -> Huge data and reconstruction time
- **Transmission**: sample preparation, volume averaging, less sensitive for ultrathin films



Chemical modulation in a 200nm-diameter wire

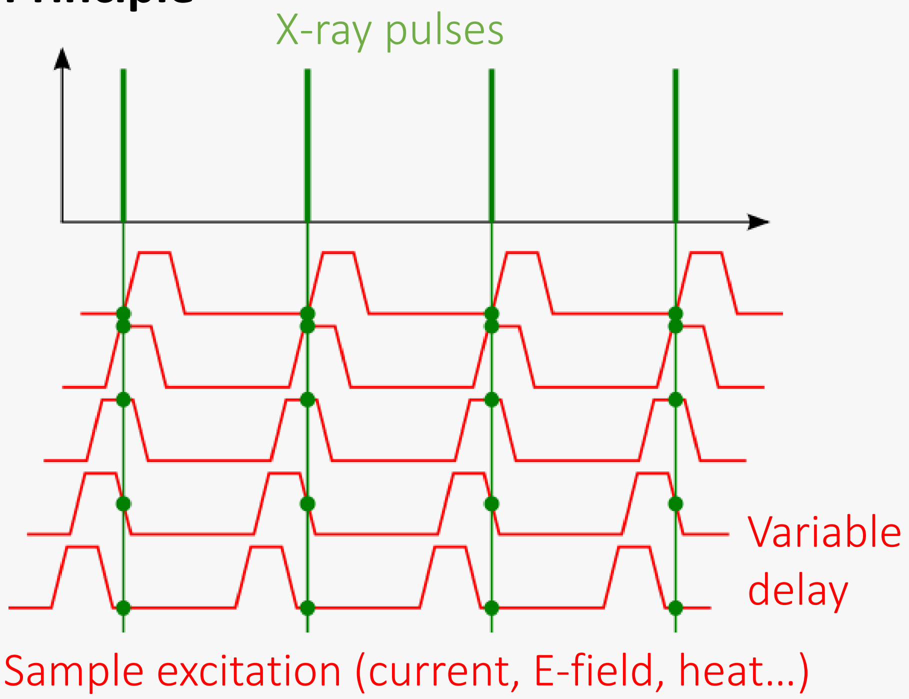
F. Pfeiffer, Nat. Photon. 12, 9 (2018)

X. Shi, Appl. Phys. Lett. 108, 094103 (2016)

Time-resolved magnetic imaging at synchrotrons

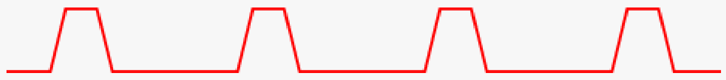
Excitation periodic with the bunch frequency

Principle

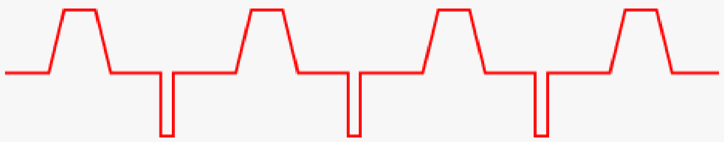


Variations

- Pulses/Patterns: magnetization reversal, excitation…



- Need for a reset if irreversible: wall motion, skyrmion nucleation…



Low-bunch mode may be desirable:

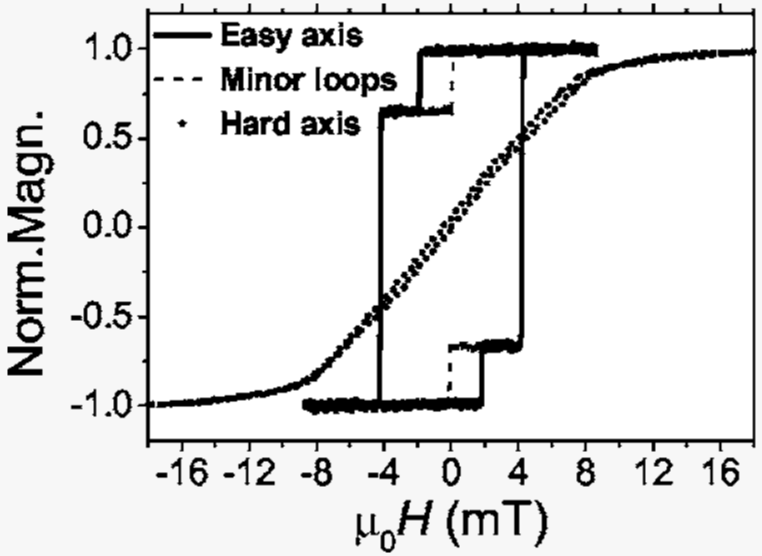
- Capacity of electronics to **repeat pattern** with power
- Need of sample to **cool down**

Take-away

- Requires suitable generator, delay and machine clock
- No requirement on the measurement: can be applied to all techniques

Low-filling mode – Pioneering Example

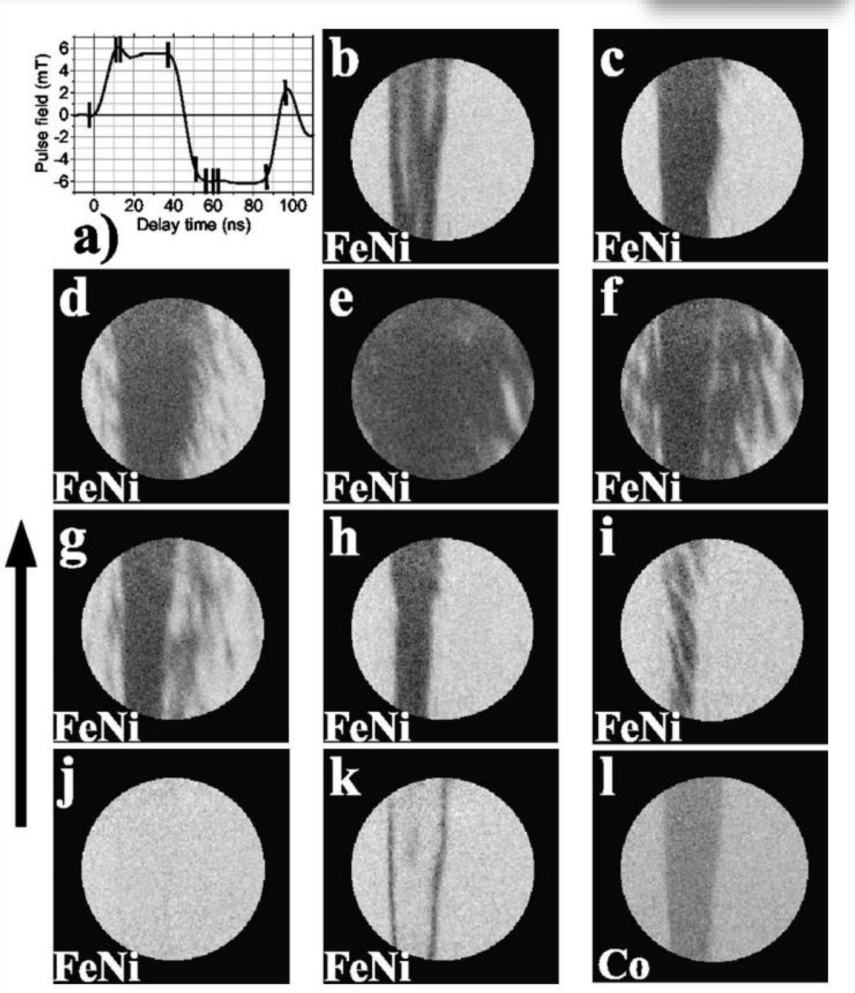
System



- $FeNi/Al_2O_3/Co$ trilayer
- Exchange-bias observed

Measurement

PEEM



Take-away

- Non-uniform switching of FeNi
- Bias arises atop domain walls in Co

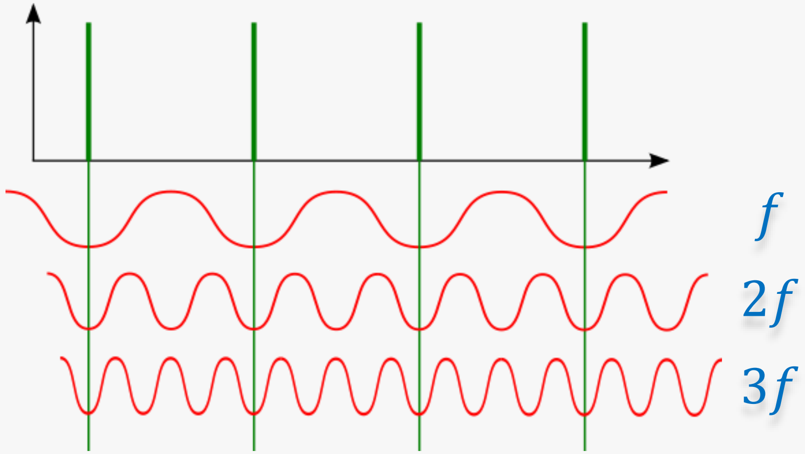
J. Vogel, W. Kuch et al.
Appl. Phys. Lett. 82, 2299 (2003)

J. Vogel, W. Kuch et al.,
Phys. Rev. B 72, 220402(R) (2005)

Time-resolved magnetic imaging at synchrotrons

Excitation periodic with the bunch frequency – ac excitation for FMR, spin waves etc.

Principle

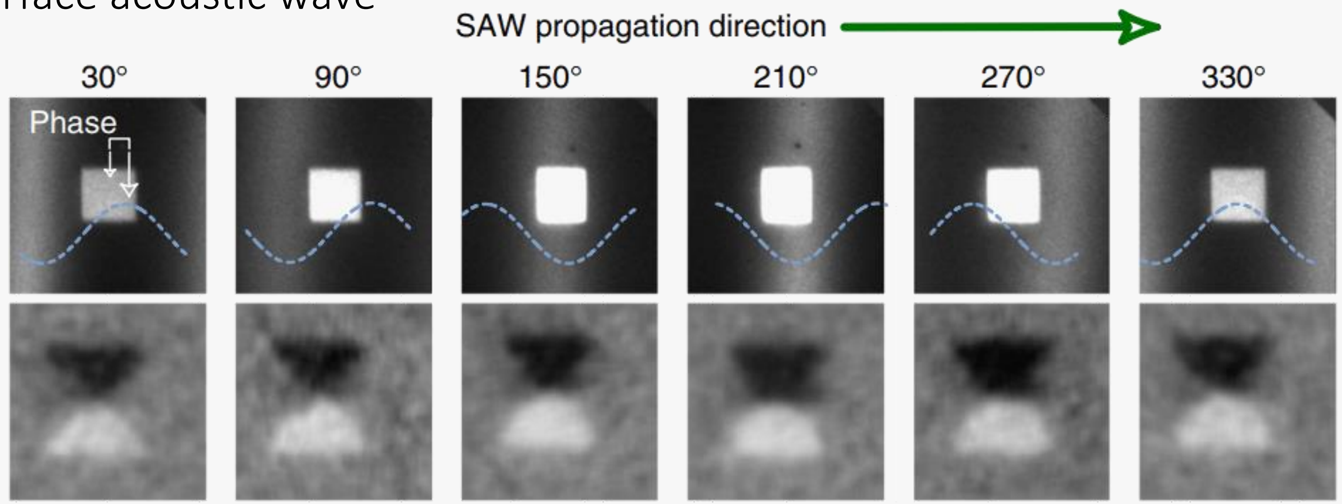


- FMR and spin waves “for free” on any setup
- Only RF frequency and harmonics available

Example

PEEM

Strain-driven magnetization dynamics induced by a surface acoustic wave



M. Foerster et al., Nature Comm. 8, 407 (2017)

Time-resolved magnetic imaging at synchrotrons

Pump-probe with temporal sorting of data

Principle

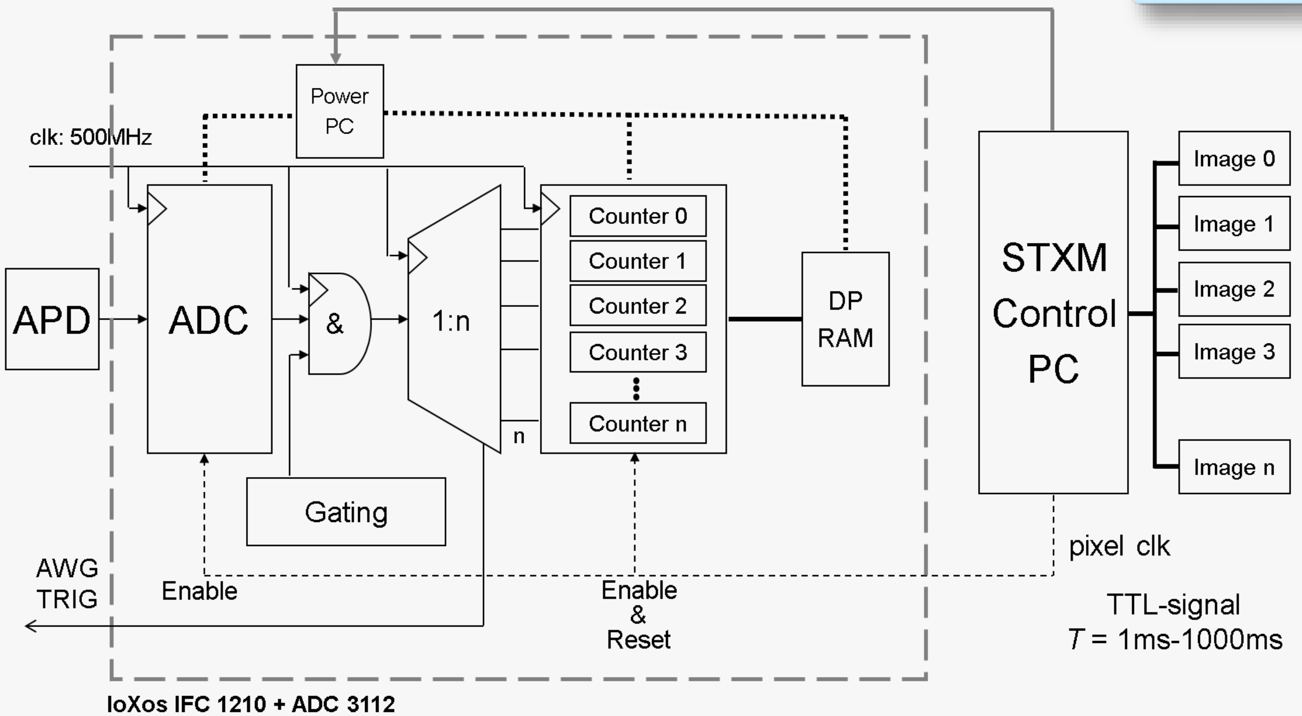
- Photon bunches detected on fast detector
- Temporal sorting with FPGA electronics
- Excitation frequency must be rational but not a multiple of the bunch frequency
  → All photons of the 500 MHz RF mode can be used independently of the excitation

- All photons used: fast
- Requires **dedicated electronics**
- Not suitable for full-field imaging

Available: SLS & Bessy

Full scheme

STXM



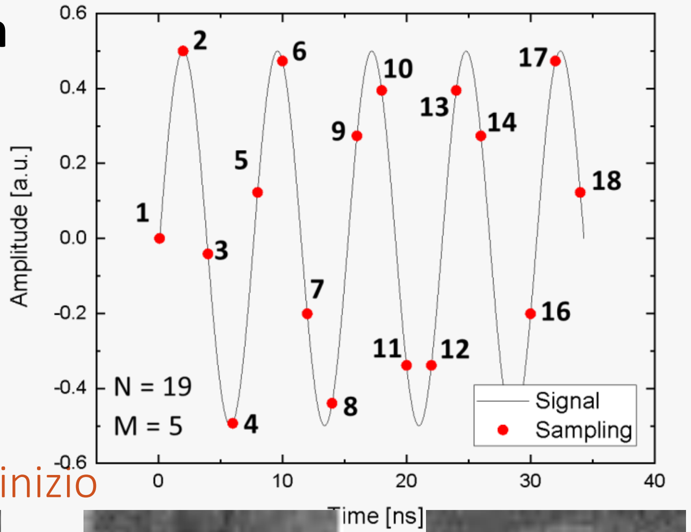
Courtesy: S. Finizio

Note: more elaborate schemes exist with time-of-flight for arbitrary excitations

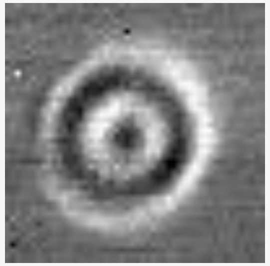
Time-resolved magnetic imaging at synchrotrons

Pump-probe with temporal sorting of data – Examples

RF excitation

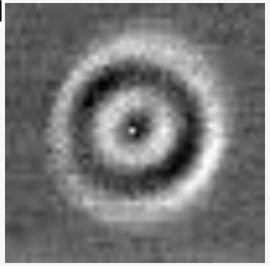


Courtesy: S. Finizio



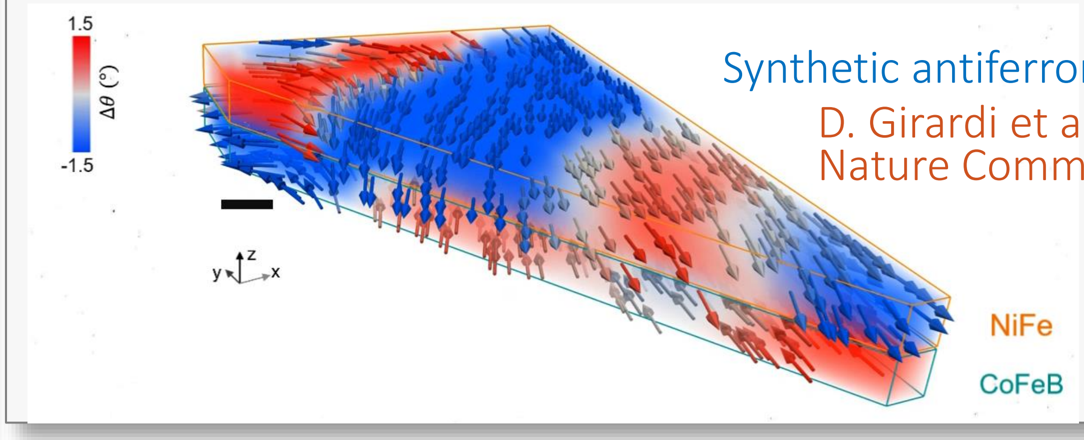
142 MHz
Gyration

285 MHz
Gyration



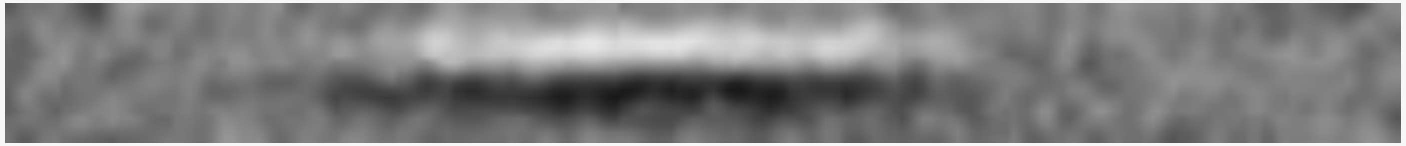
785 MHz
Breathing

Spin wave in 3D (laminography)



Synthetic antiferromagnet
D. Girardi et al.,
Nature Comm. 15, 3057 (2024)

Fast pulse -> Domain-wall switching



Bloch-point wall switching in 125nm-diameter nanowire
O. Fruchart et al., unpublished

Notes

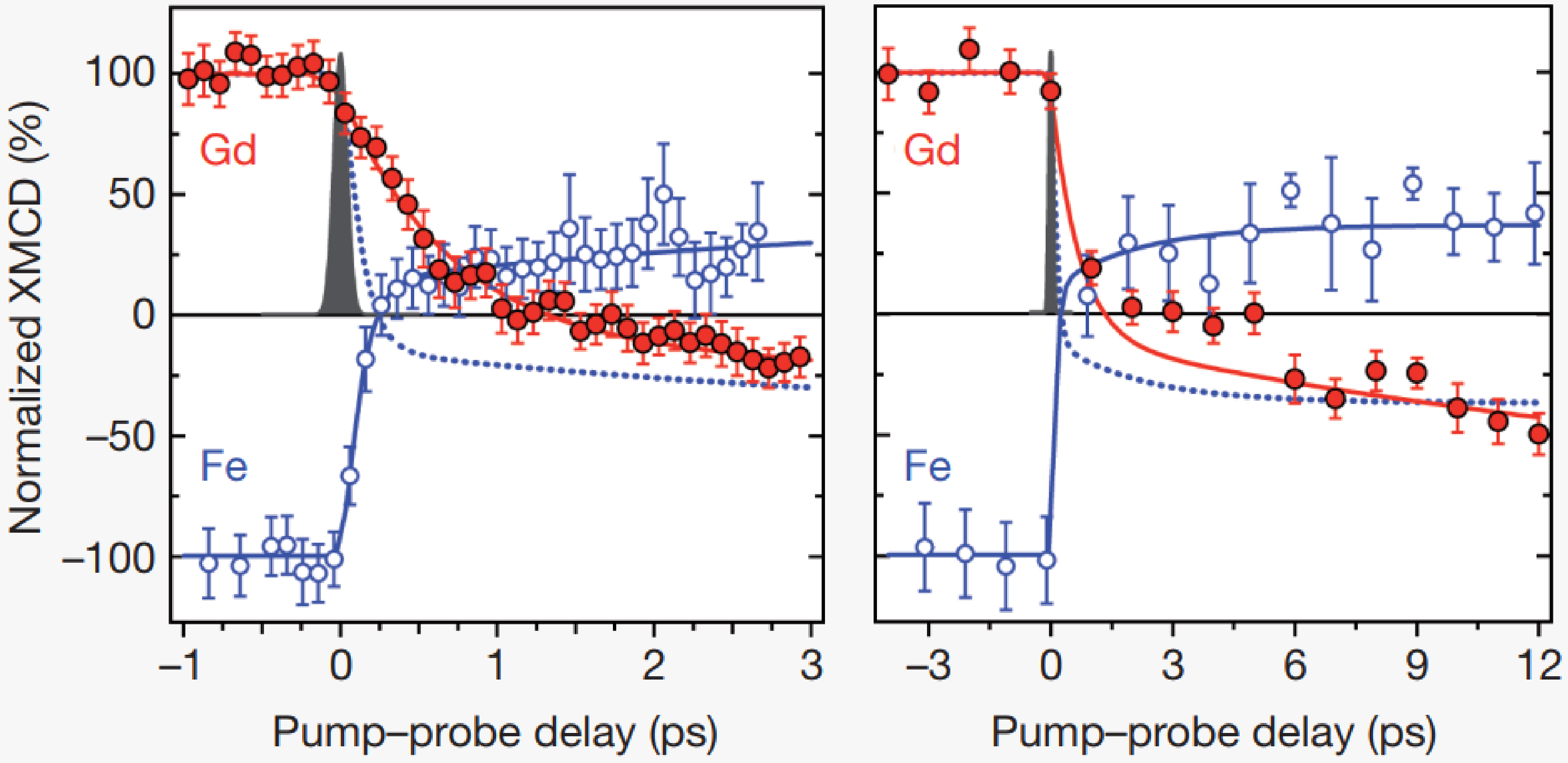
- Cannot be applied for 2D detectors (not fast enough & FPGA pixel-controlled)
- Spatial resolution determined by zone plate (circa 25nm)

Time-resolved magnetic imaging at synchrotrons

Ultrafast magnetization processes – Requires free electron laser or slicing (available Bessy)

All-optical switching in ferrimagnets

$Gd_{25}Fe_{65.6}Co_{9.4}$



I. Radu at el., Nature 472, 205 (2011)

Physics

- (All-)optical switching
- Ultrafast demagnetization
- THz dynamics

Time-resolved magnetic imaging at synchrotrons

Ultrafast magnetization processes (FEL & slicing) – From scattering to holographic imaging

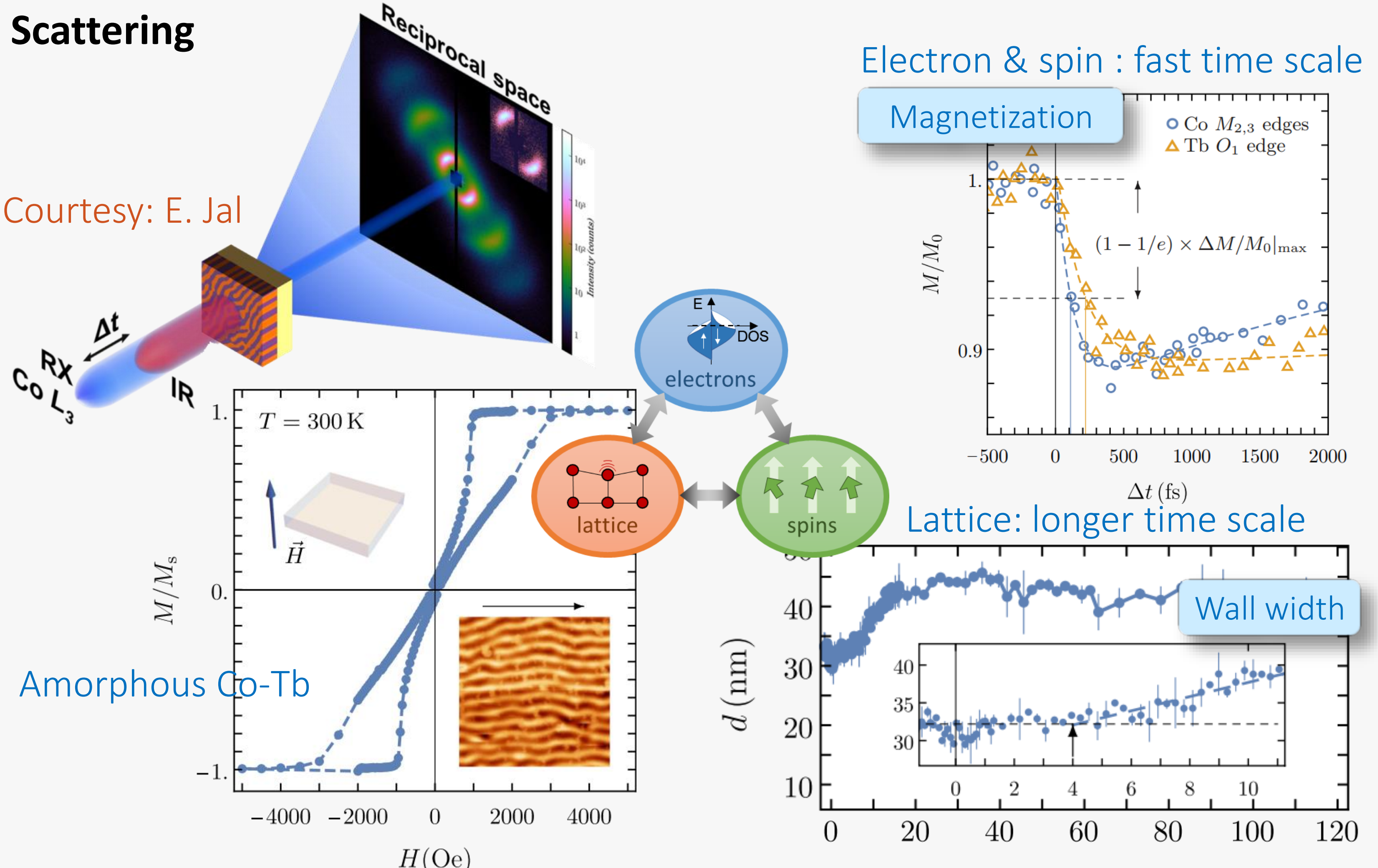
Scattering

Courtesy: E. Jal

Electron & spin : fast time scale

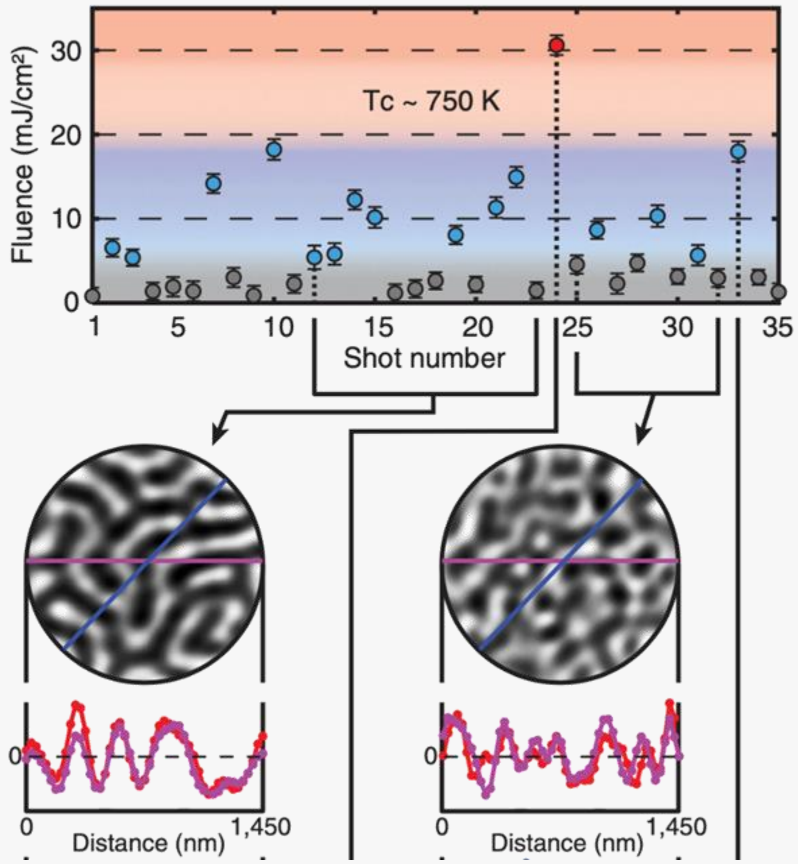
Lattice: longer time scale

Amorphous Co-Tb



M. Hennes, Phys. Rev. B 102, 174437 (2020)

Imaging down to single-shot



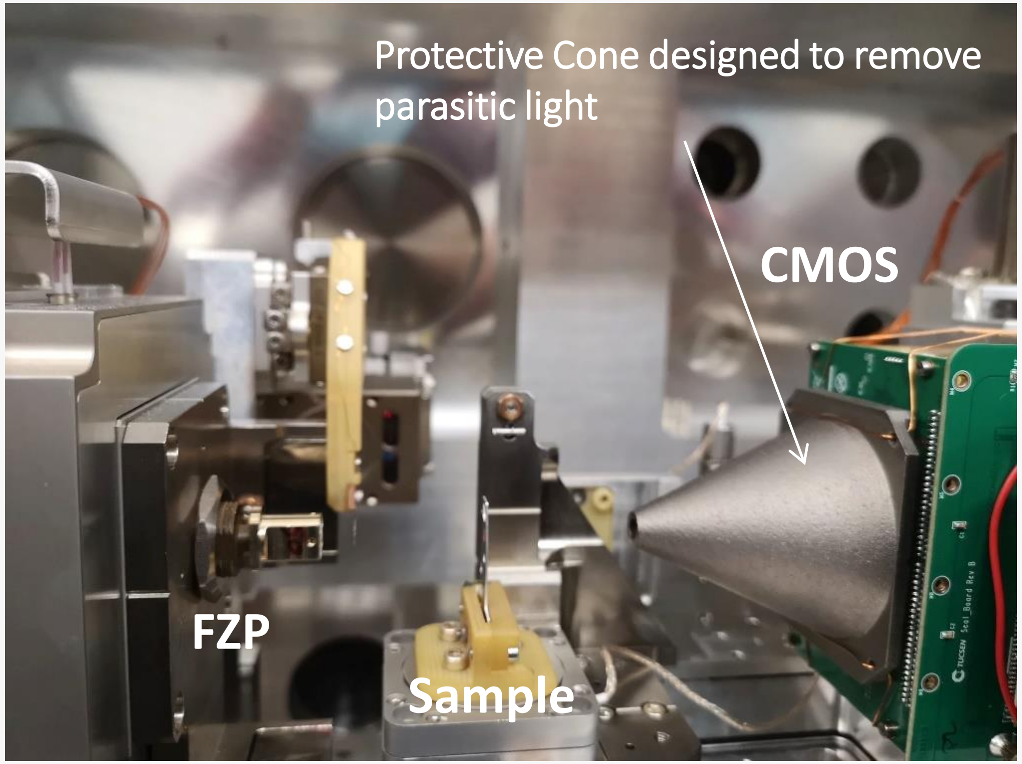
T. Wang et al,
Phys. Rev. Lett. 108, 267403 (2012)

Time resolved magnetic imaging at SOLEIL

HERMES beamline – Rachid Belkhou

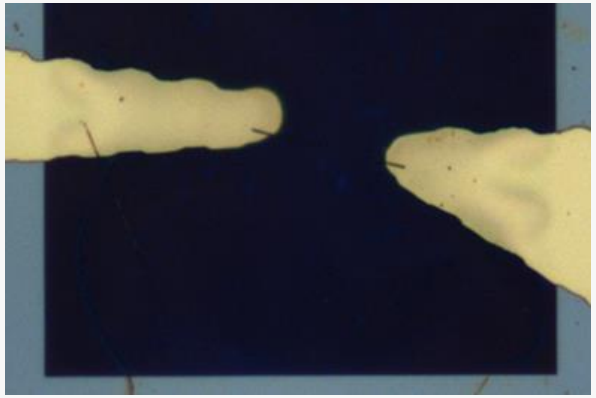
Commissioning experiments 2024/12

Setup for STXM & Ptychography

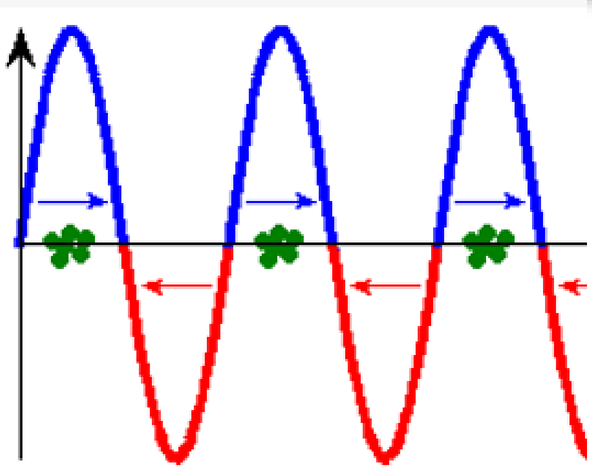


Test case for time resolution

Soft-magnetic cylindrical nanowires



Pump: Œrsted field



Probe: multi-bunch, 352MHz, period 2.8ns

Time resolved magnetic imaging at SOLEIL

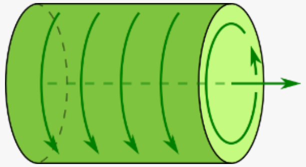
SOLEIL SYNCHROTRON — spintec SPIN IN ELECTRONICS

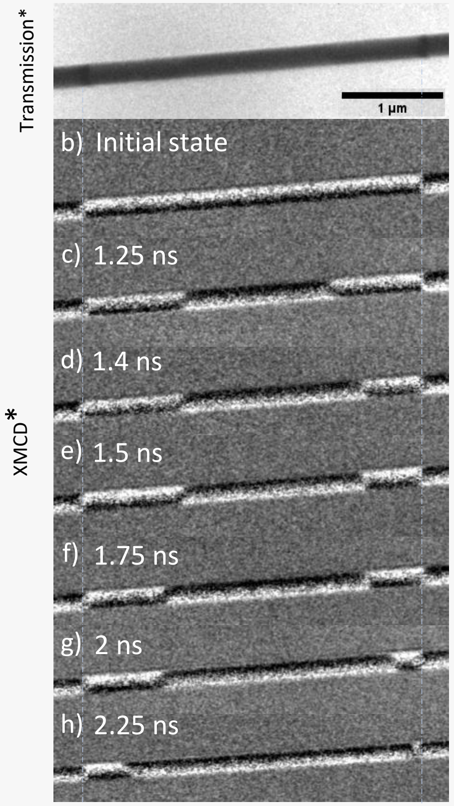
Domain-wall motion

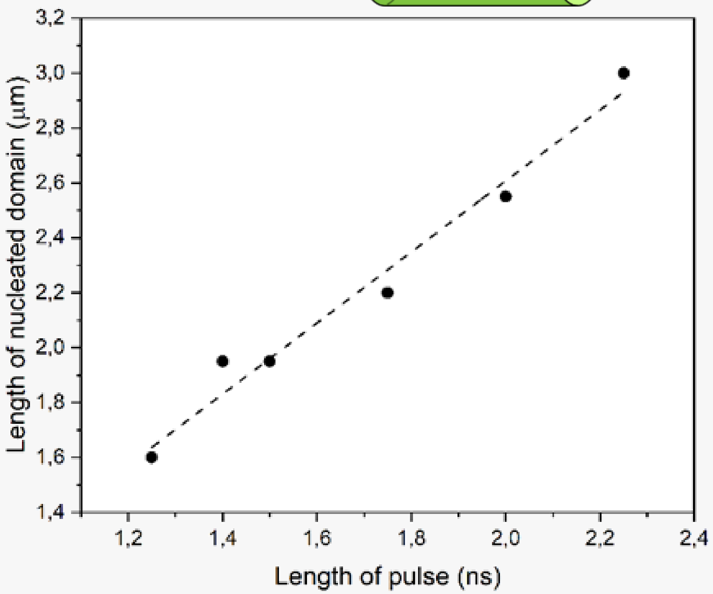
200nm-diameter nanowires with azimuthal domains

Static imaging after short pulses

$J = 1.1 \times 10^{11}\ \mathrm{A/m^2}$





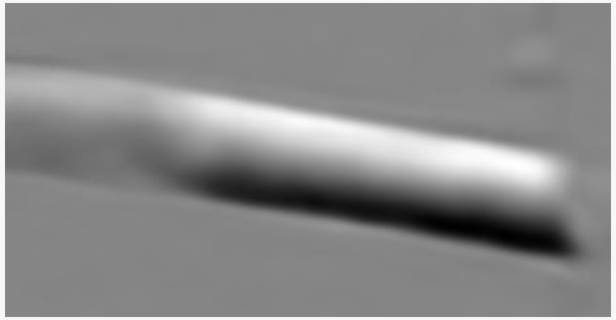


Conclusion

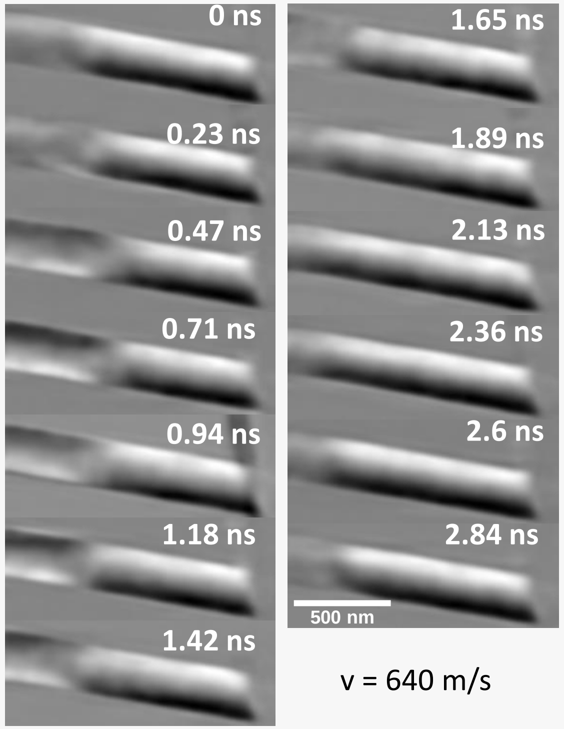
Domain-wall speed 600m/s

Time-resolved imaging

$J = 3.9 \times 10^{10}\ \mathrm{A/m^2}$



Time frame 2.8ns



v = 640 m/s

Conclusion

Domain-wall process confirmed

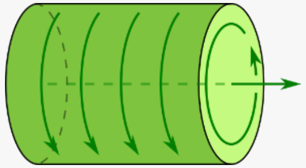
L. Gomez-Cruz, to be submitted – **Thursday 28, HZ4, 11:30**

Time resolved magnetic imaging at SOLEIL

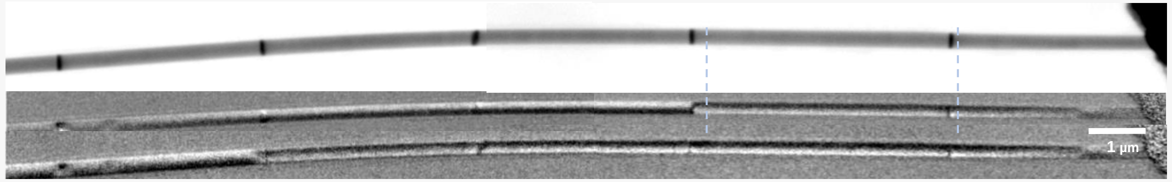
Domain-wall motion

200nm-diameter nanowires with azimuthal domains

Static imaging after short pulses



$J = 6.5 \times 10^{10}\ \mathrm{A/m^2}$



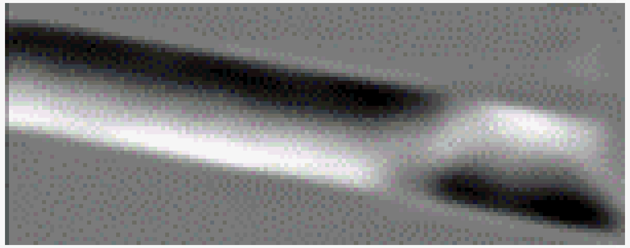
Conclusion (?)

Domain-wall speed 3.5 km/s

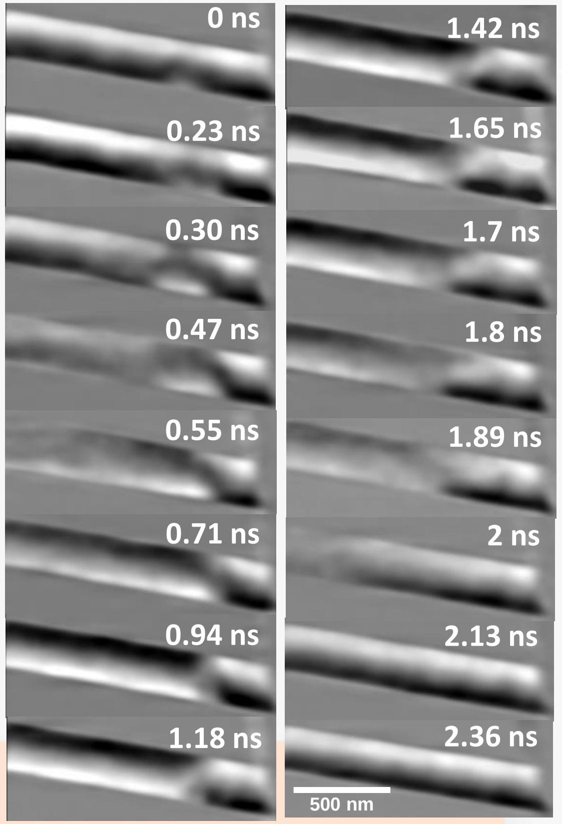
What is the underlying physical process ?

Time-resolved imaging

$J = 7.8 \times 10^{10}\ \mathrm{A/m^2}$



Time frame 2.8ns



Conclusion

Underlying process = coherent switching

High-speed domain-wall motion cannot be claimed

L. Gomez-Cruz, to be submitted

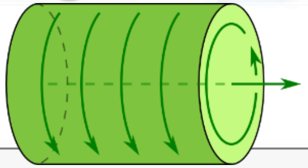
Talk Thursday 28, HZ4, 11:30

Time resolved magnetic imaging at SOLEIL

SOLEIL SYNCHROTRON

spintec SPIN IN ELECTRONICS

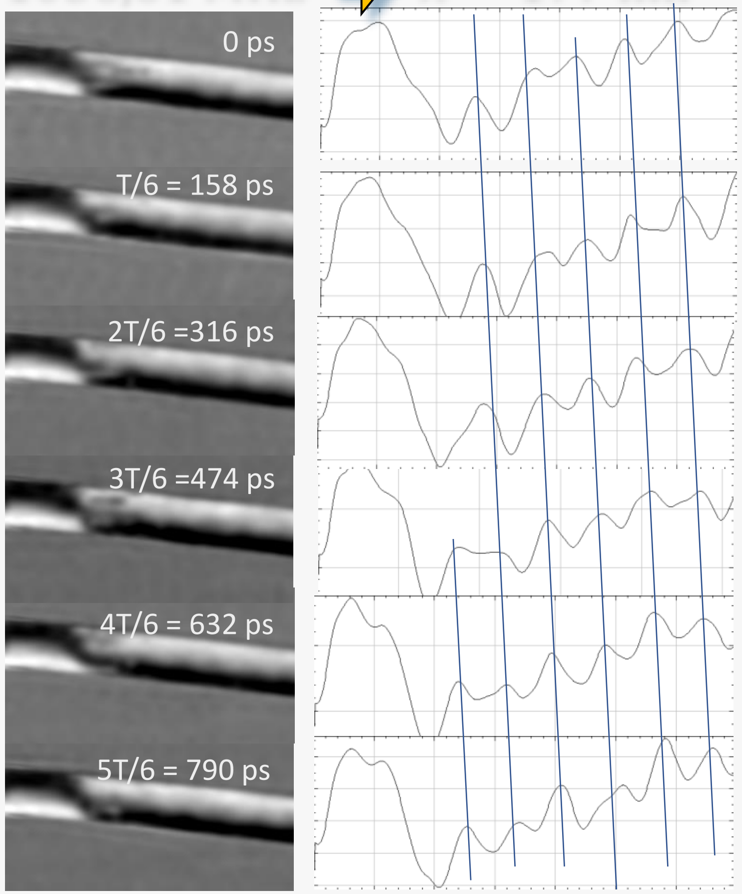
Spin wave emission and propagation



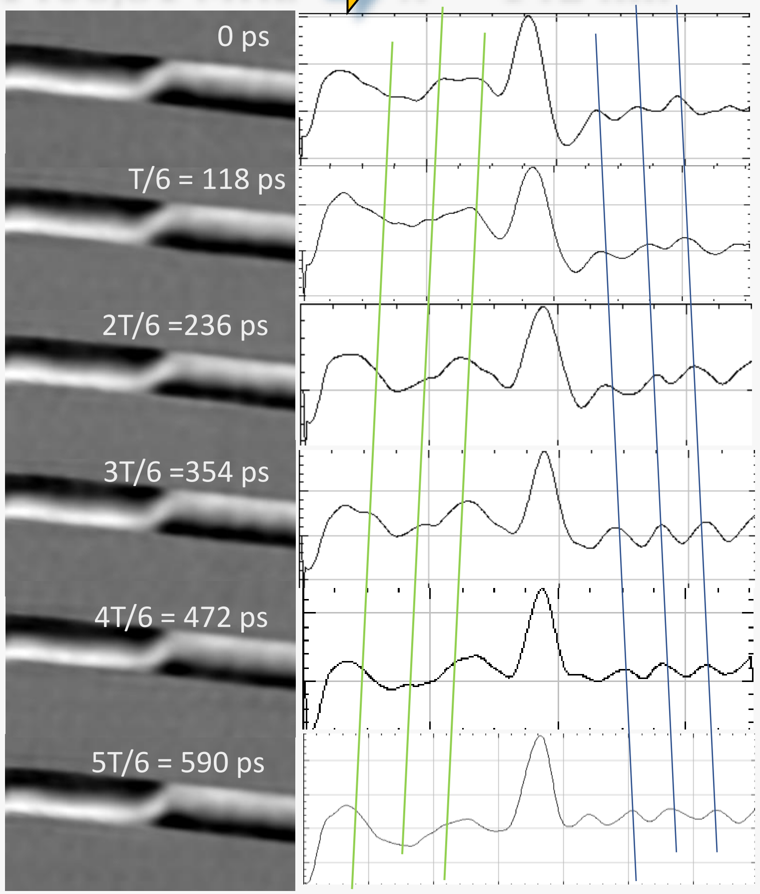
200nm-diameter nanowires with azimuthal domains

Spin waves emitted by oscillating domain wall

1056,61 MHz ➔ $\lambda = 177$ nm

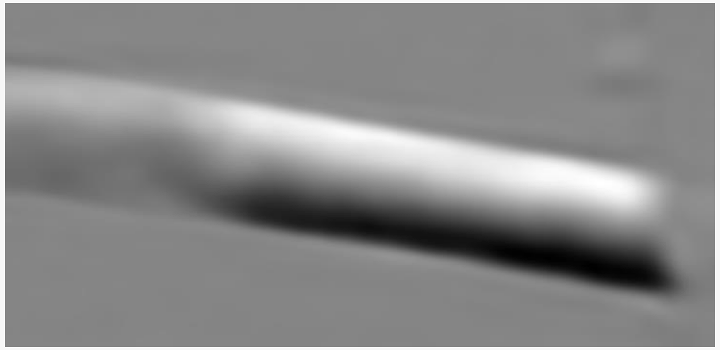


1408,81 MHz ➔ $\lambda = 142$ nm



-> Dispersion curve $\omega(k)$ can be determined

Spin waves emitted by moving domain wall (?)

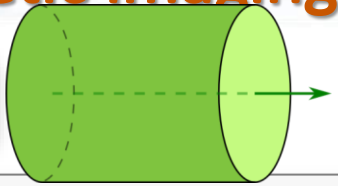


Time frame 2.8ns

N. Martin et al., to be submitted

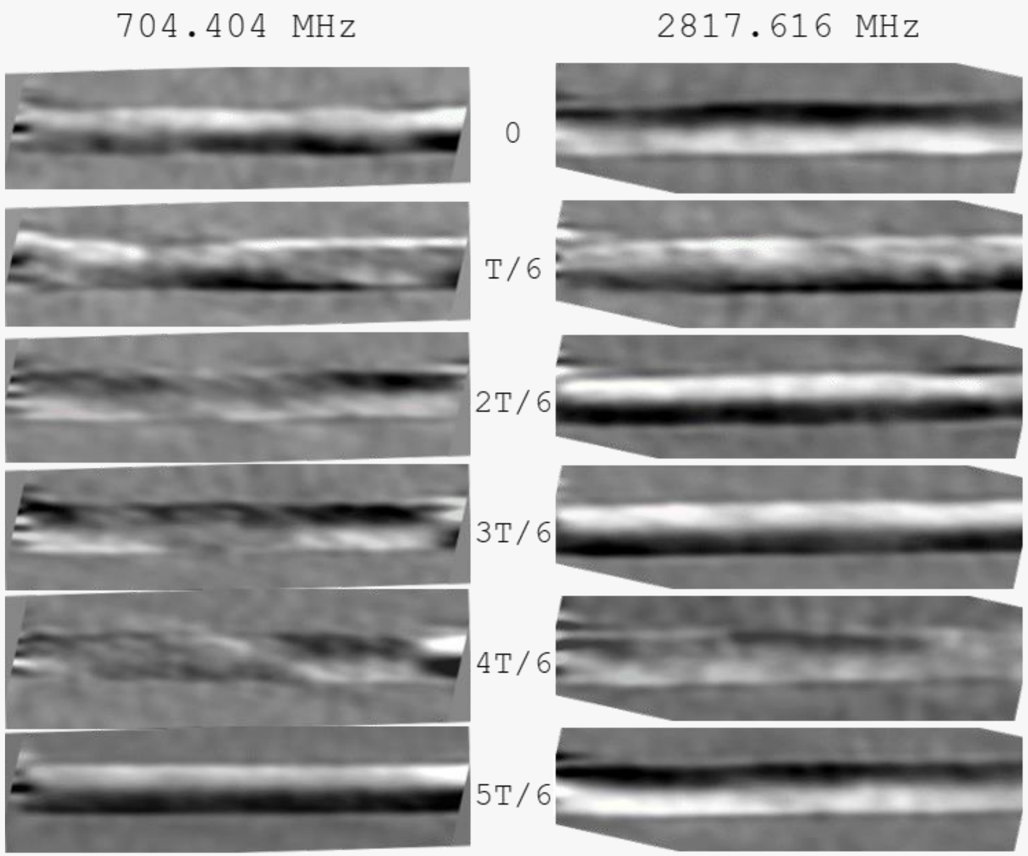
Time resolved magnetic imaging at SOLEIL

Ferromagnetic resonance

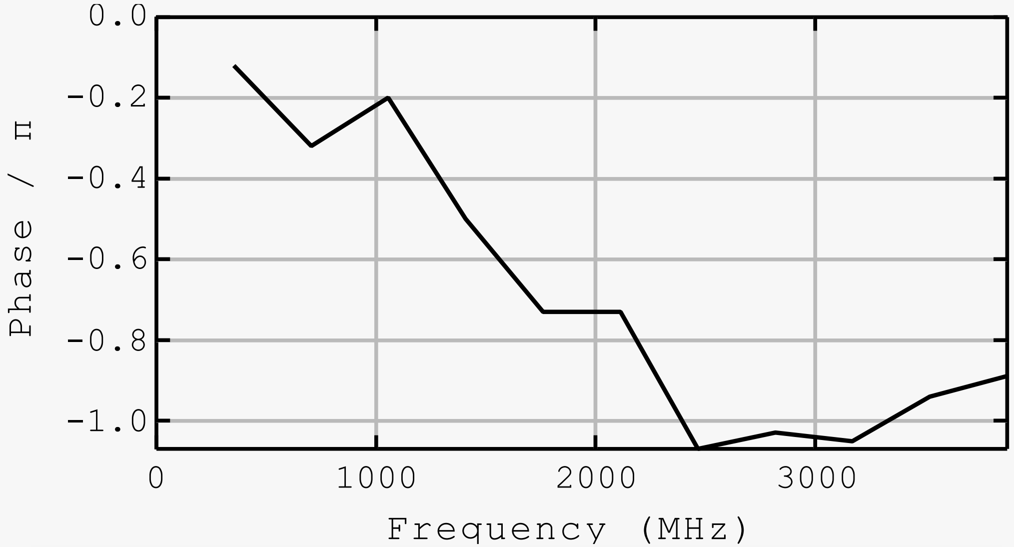


140nm-diameter nanowires with longitudinal magnetization

Imaging domain response



Tracking phase response



Conclusion

- Phase can be tracked
- Analysis requires care (phase shift of pump versus frequency …)

N. Martin et al., to be submitted

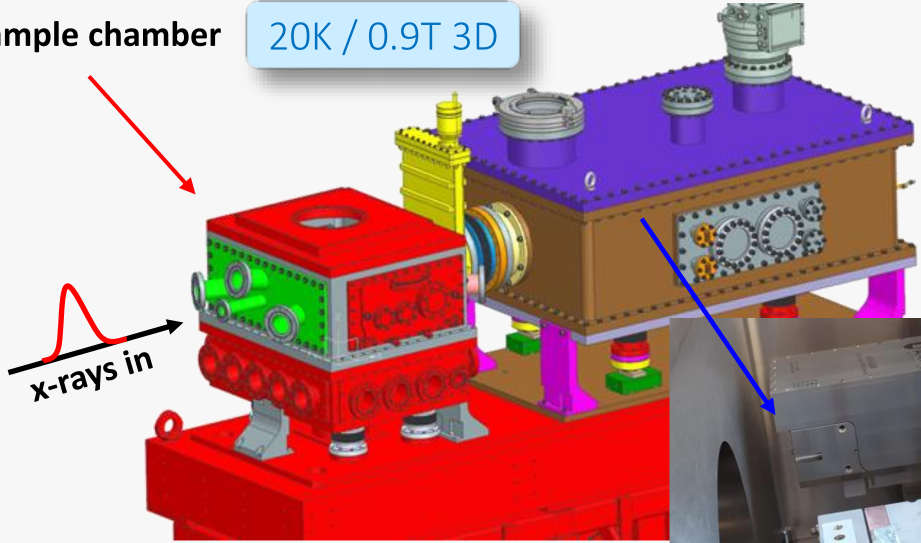
Time-resolved magnetic imaging at SOLEIL

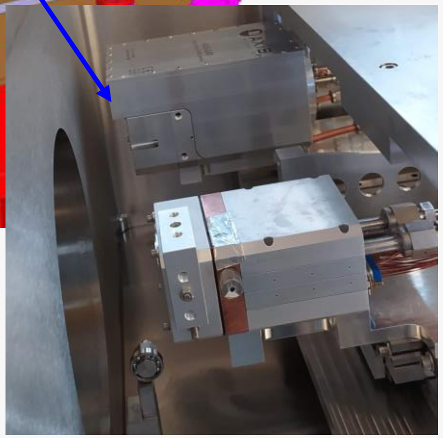
SEXTANTS beamline – Current status
Nicolas Jaouen

Setup for Fourier-Transform Holography

sample chamber

20K / 0.9T 3D

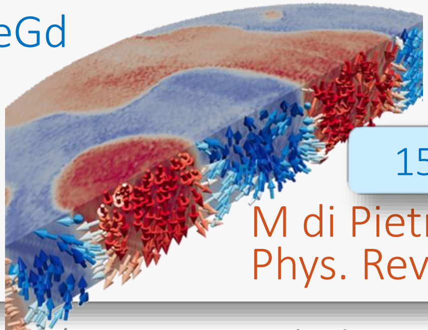




Switchable 2D detectors

- 2048x2048 sCMOS
- 6144x6144 sCMOS (update)

FeGd

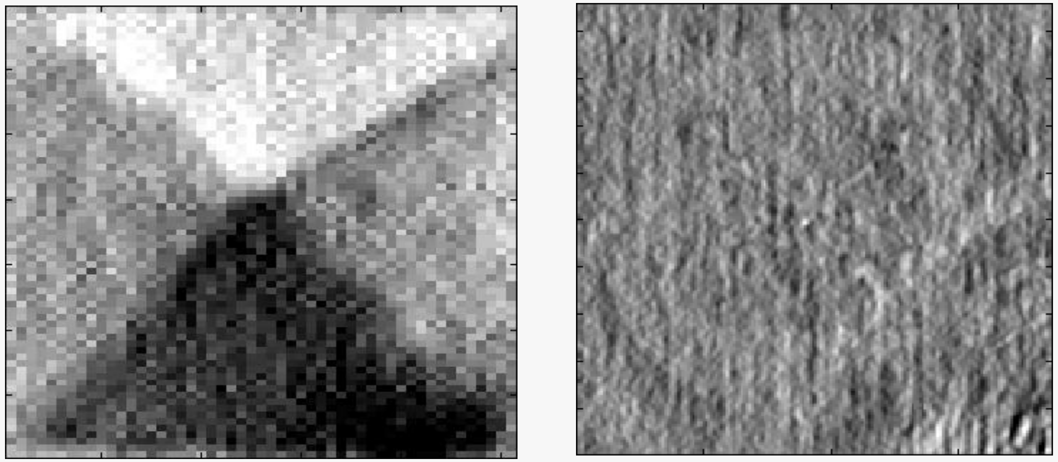


15x15x80nm spatial resolution

M di Pietro Martinez et al.,
Phys. Rev. B 107, 09445 (2023)

Time-resolved

- Flux-closure in dots with in-plane magnetization
- Excitation with strip-line at 8-bunch harmonics



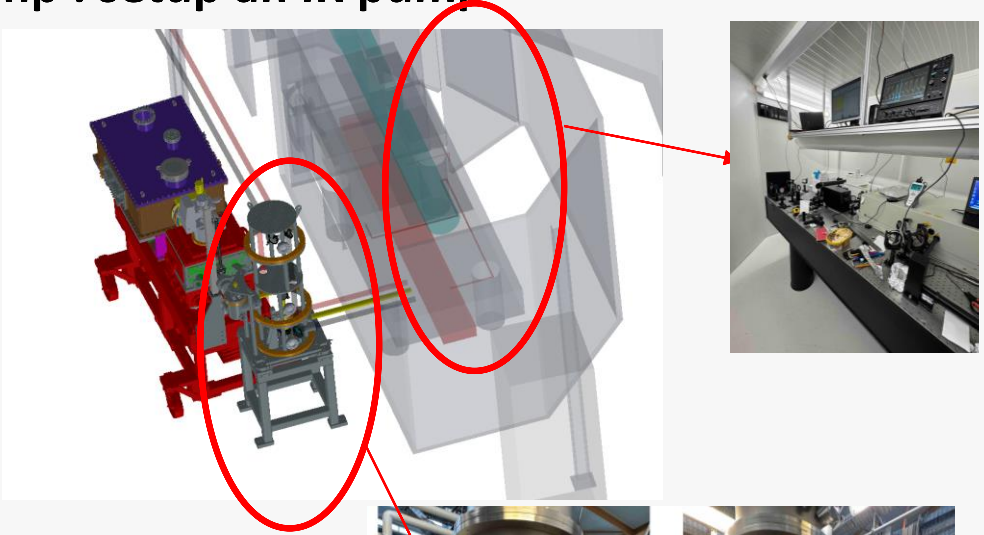
N. Bukin et al, Sci. Rep. (2016)

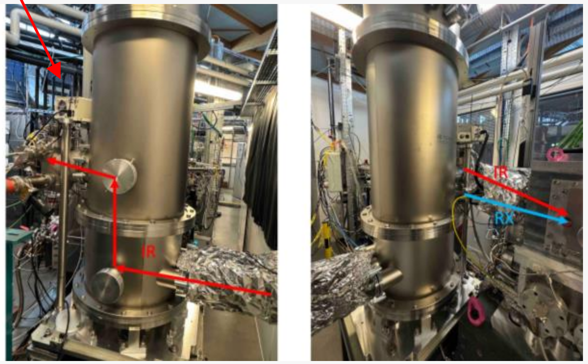
Coll. F. Ogrin (Exter, UK); G. van der Laan (DLS, UK);
G. Beutier (Grenoble, France)

Time-resolved magnetic imaging at SOLEIL

SEXTANTS beamline – Prospects
Nicolas Jaouen

Pump : setup an IR pump





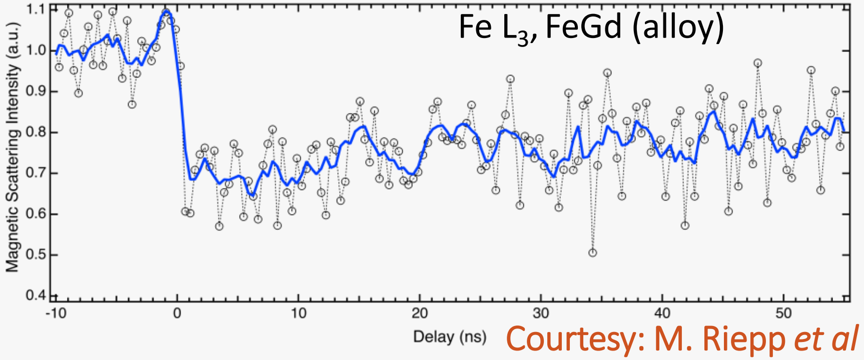
Repetition rate 1 kHz

Pulse duration 120 fs

Wavelength 80 nm

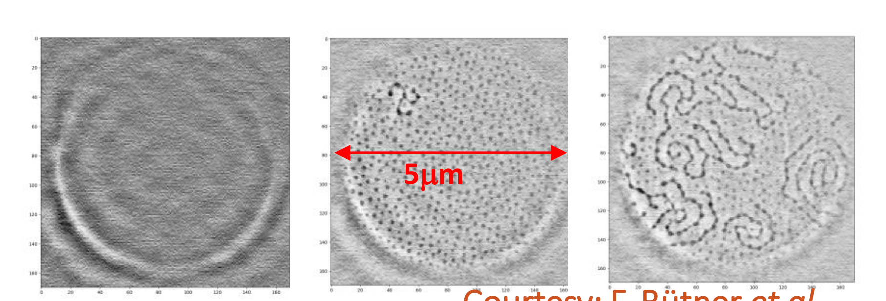
Probe

- XRMS: MCP+delayline (first commissioning)



Courtesy: M. Riepp *et al*

- Holography: IR nucleation of magnetic texture



Courtesy: F. Bütner *et al*

- **Future: Ultra-fast pixelized X-ray detector** designed at SOLEIL, for SEXTANTS and HERMES (mid-term)

Take-away message

- **Proof of principle** for time-resolved magnetic ptychography, 50ps / 10nm
- **Demonstrated**: domain-wall motion, spin-wave propagation, their interaction, FMR
- **Prospect**: 8-bunch filling as good compromise between beam flux (20%) and flexibility for continuous mapping of frequency and sample cooling
- **Time resolution open to users** on HERMES (ptychography) and SEXTANTS (reciprocal space). 100MHz power pulse generator, 10 GHz AWG, 10 GHz oscilloscope available.

Call deadline 15th Sep

Combining high time and spatial resolution of magnetic microscopy with X-ray ptychography

N. Martin, L. Gomez-Cruz, L. Perez, C. Thirion, O. Fruchart, A. Masseboeuf, R. Belkhou

To be submitted

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spintec-lab