Coherent soft x-ray scattering from magnetic nanostructures

Guillaume Beutier
Diamond Light Source
(previously at the CEA – Grenoble)

guillaume.beutier@diamond.ac.uk

Collaborators on the Coherent SXRMS project

Frédéric Livet (CNRS - SIMaP)
Alain Marty (CEA – SP2M)
Stefan Stanescu (ESRF – ID08, now at SOLEIL)
Peter Bencok (ESRF – ID08, now at Diamond)
Gerrit van der Laan (Daresbury Lab., now at Diamond)
Anna Haznar (Daresbury Lab., now left academic research)
Esther Dudzik (Daresbury Lab., now at HMI)
Steve Collins (Daresbury Lab, now at Diamond)
Sarnjeet Dhesi (ESRF, now at Diamond)
Virginie Chamard (CNRS – SIMaP)
Vincent Baltz (CEA – Spintec)
Stefan Landis (CEA – LETI)
Cyril Beigné (CEA – SP2M)
Frédéric Larizza (CEA – SP2M)
Karine Chesnel (CEA – SP2M – ALS)
Michel Belakhovsky (CEA – SP2M, now retired)

Outline

1. Soft x-ray resonant magnetic scattering with a coherent beam

- Motivations
- Basics of soft x-ray resonant magnetic scattering
- Basics of coherent x-ray scattering
- A quick example on magnetic stripe domains

2. Study of a grating of magnetic nanolines

- Experimental set-up
- Magnetic memory
- Reconstruction

3. XPCS for magnetic materials: brief review of recent works from other groups

Coherent SXRMS

Motivation: to develop an x-ray technique to study the exact magnetic configuration of nanostructures
→ Defects of periodicity in nearly periodic domains
→ Magnetic memory

Soft X-ray Resonant Magnetic Scattering
+
Coherent X-ray Diffraction

⇒ Magnetic imaging in the Fourier space (and possibly in the real space…)

Brand new technique for the study of magnetic systems

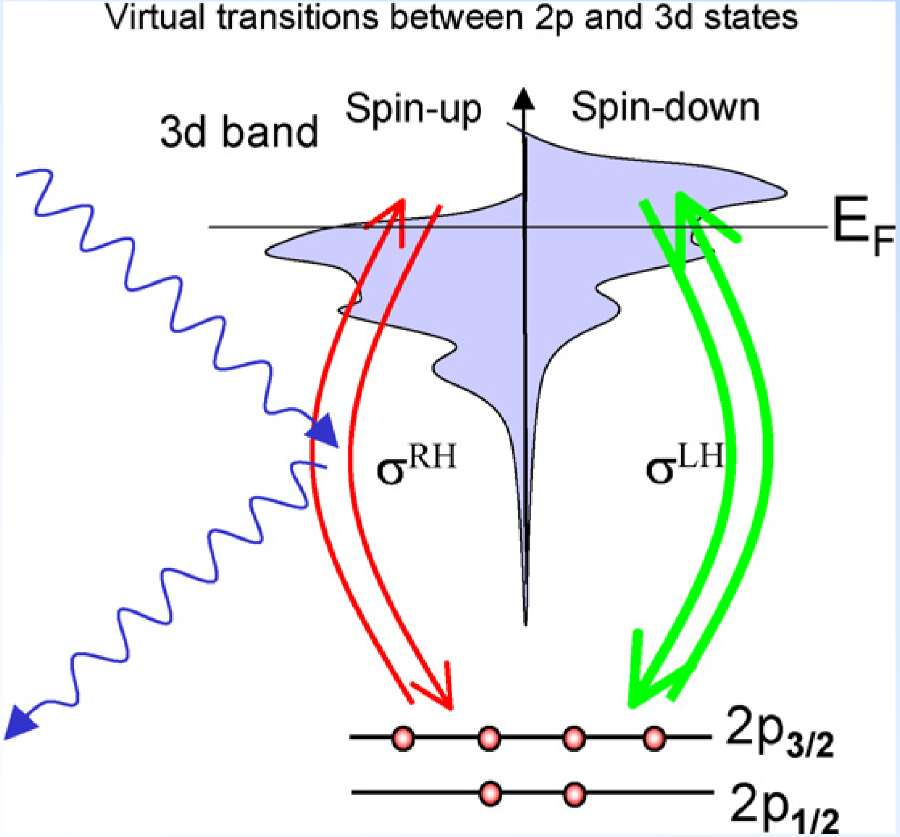
⇒ New information on well-known magnetic systems
(global processes → local processes)

⇒ Study of small magnetic objects such as patterned nanostructures

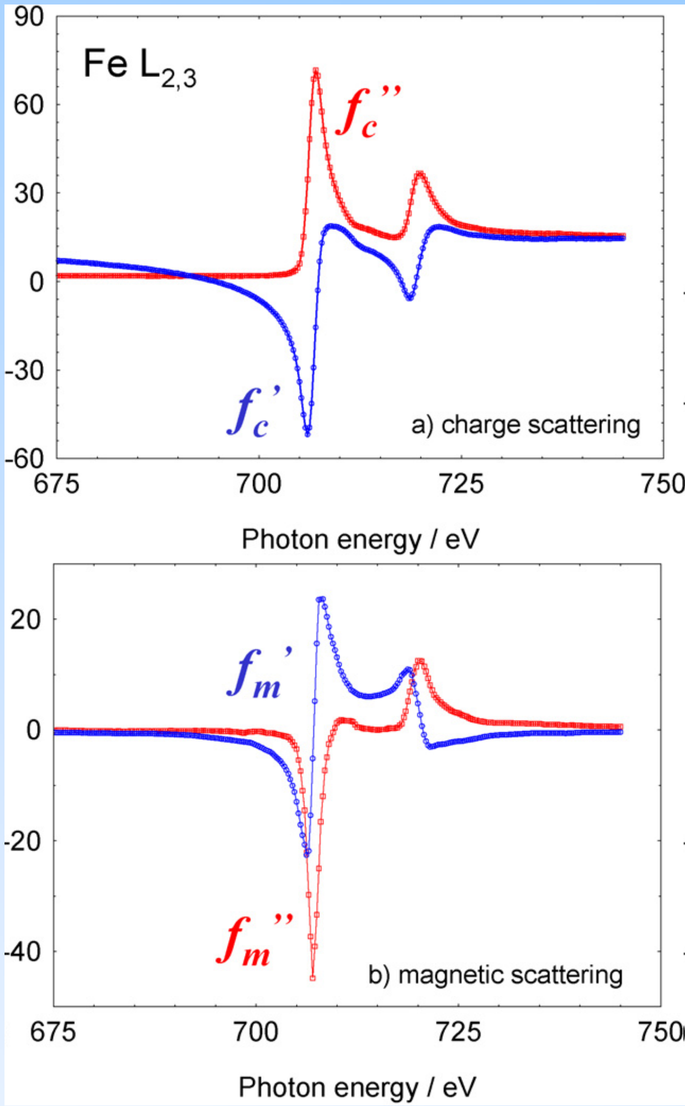
⇒ Instrumentation and methodology to be developed in 2 directions:
Intensity fluctuations
Imaging

Soft X-ray Resonant Magnetic Scattering (SXRMS)

XRMS is exactly the same process as XMCD, but XMCD measures only the imaginary part of the atomic resonant factor



⇒ chemical selectivity
⇒ shell selectivity



G. van der Laan, C.R. Physique 9, 570 (2008)

Transmission or reflection geometry?

$$f \to f^{res} = F^{(0)}\left(\hat{e}_f^* . \hat{e}_i\right) - iF^{(1)}\left(\hat{e}_f^* \wedge \hat{e}_i\right) . \hat{m}$$

charge scattering including anomalous terms

1st order magnetic scattering

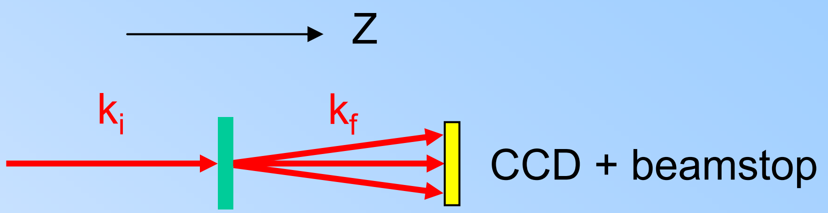
m : local magnetisation unit vector

$\hat{e}_i$: polarisation of incident photons

$\hat{e}_f$: polarisation of scattered photons

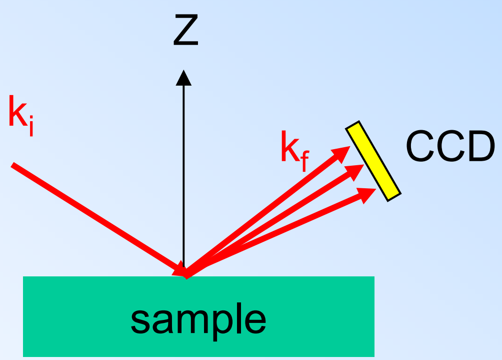
⇒ magnetic component analysis by selecting the polarizations

Transmission: f^{mag} proportional to M_Z



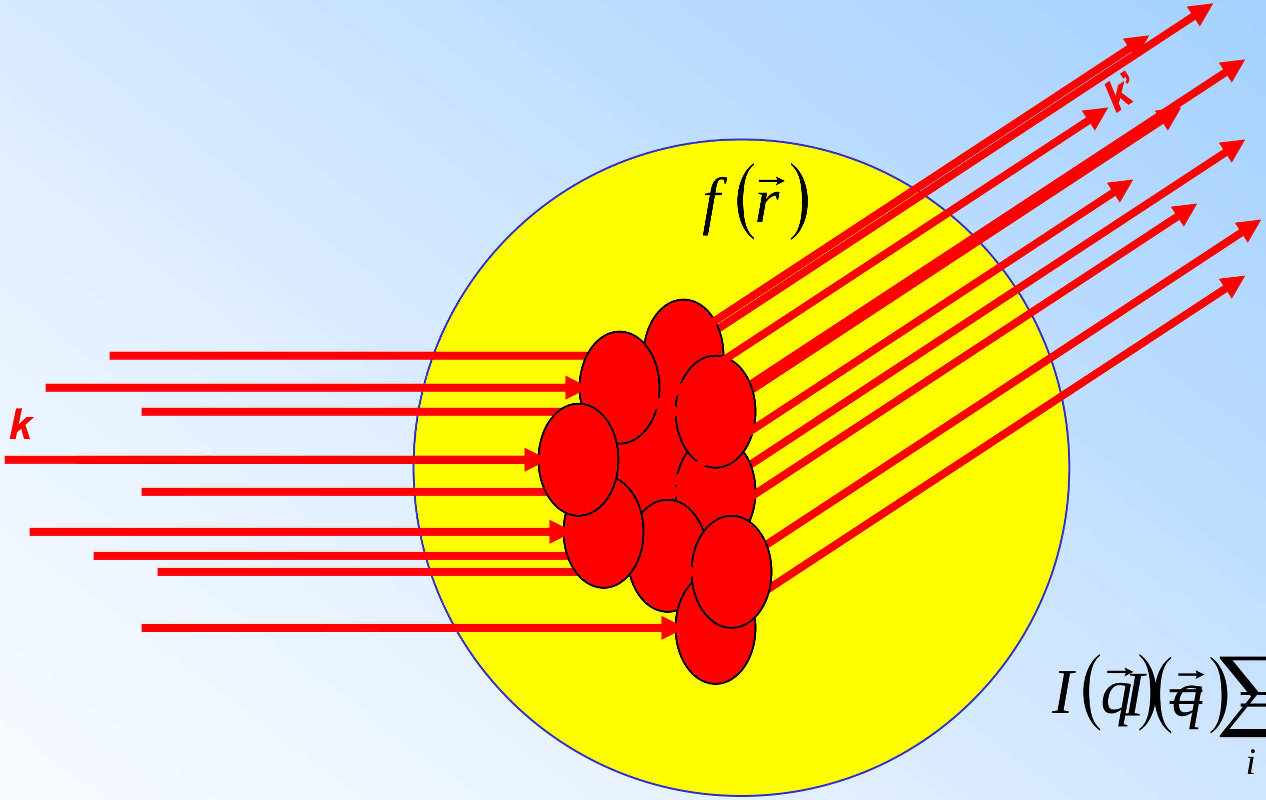
⇒ Thin films with perpendicular magnetic magnetization

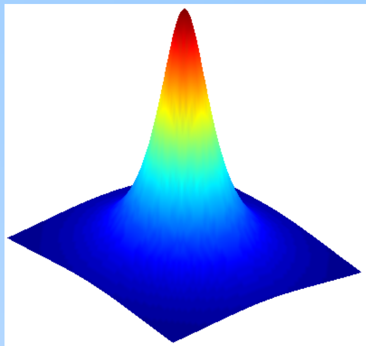
Reflection: f^{mag} mixes the magnetic components



⇒ Thick samples and/or in-plane magnetic components

Diffraction with an "incoherent" beam





$$I(\vec{q}) = \sum_i \left\| \iint_{D_i} f(\vec{r}) \exp(i\vec{q}.\vec{r})\, d\vec{r} \right\|^2$$

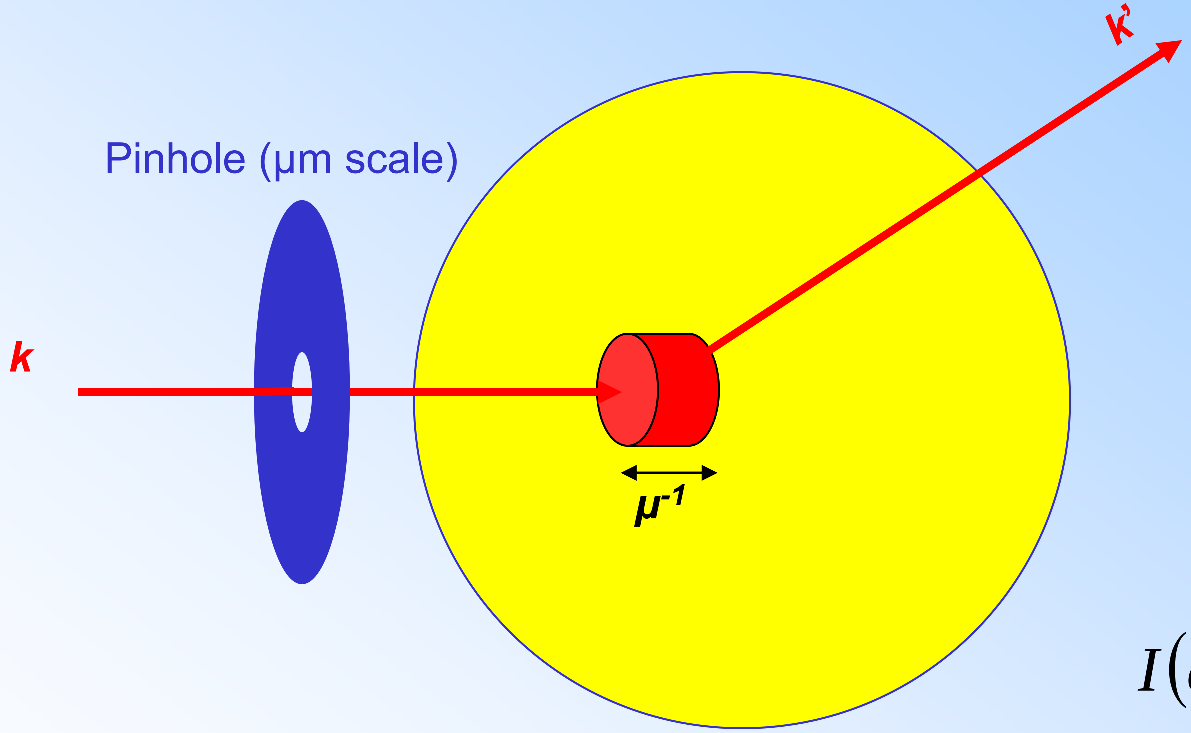
D_i : domains of coherence

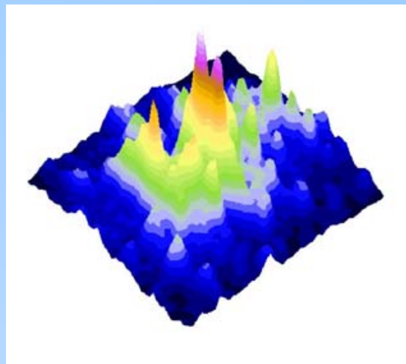
Incoherent light: **intensities** are summed

$\Rightarrow$ Properties are **averaged** over the illuminated area

$\Rightarrow$ Defects contribute to the **broadening** of the diffraction peaks

Diffraction with a coherent beam





$$I(\vec{q}) = \left| \int_{D} f(\vec{r}) \exp(i\vec{q}.\vec{r}) d\vec{r} \right|^2$$

D : domain of coherence

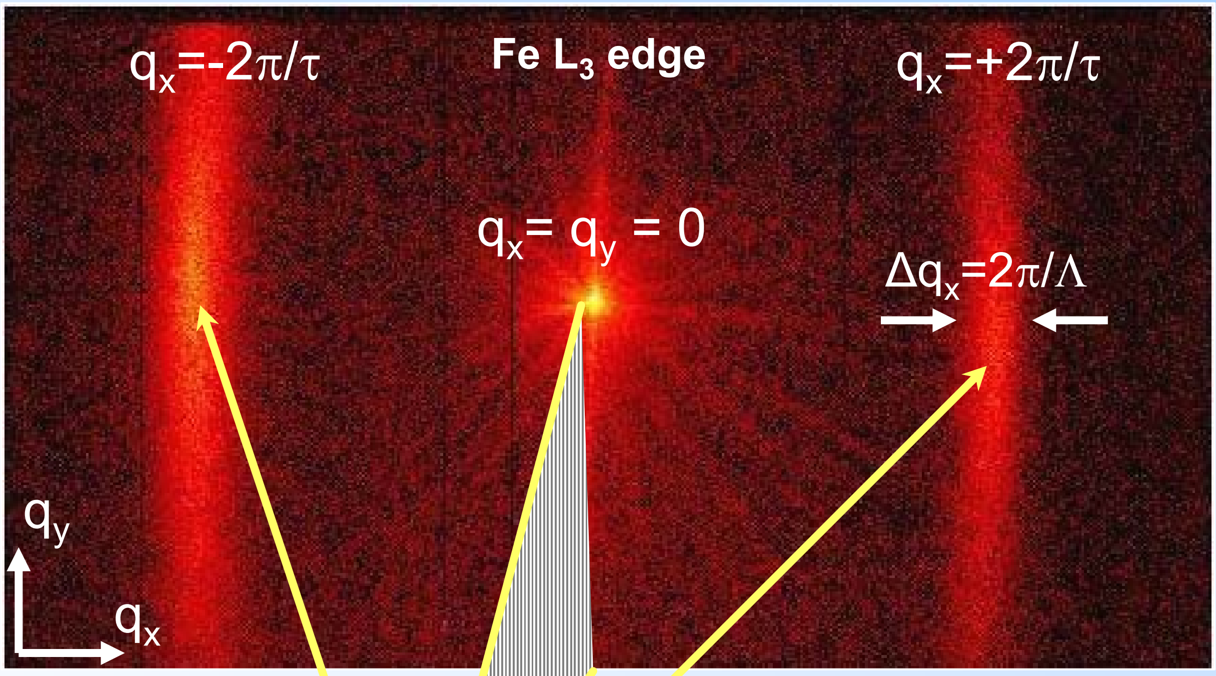
Coherent light: **amplitudes** are summed

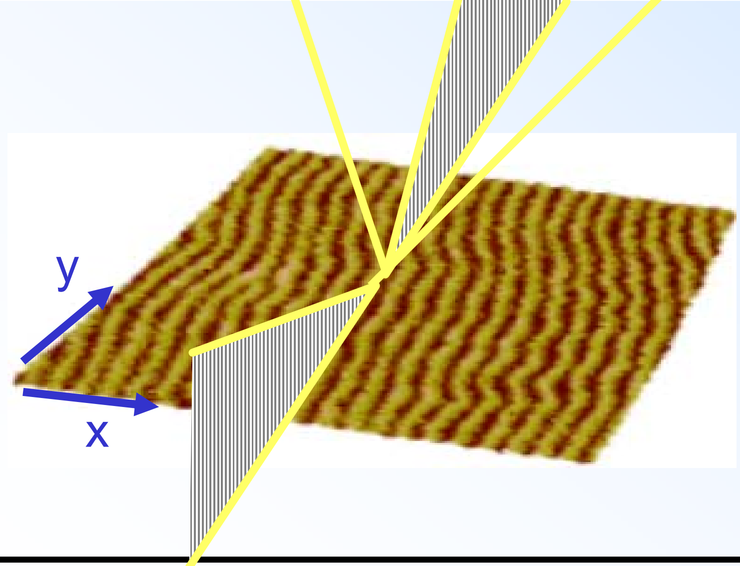
⇒ Interference over the illuminated area

⇒ Defects contribute to the **splitting** of the diffraction peaks into **speckles**

⇒ **Speckle pattern = unique signature of the diffracting object**

Example: SXRMS from stripe domains in FePd

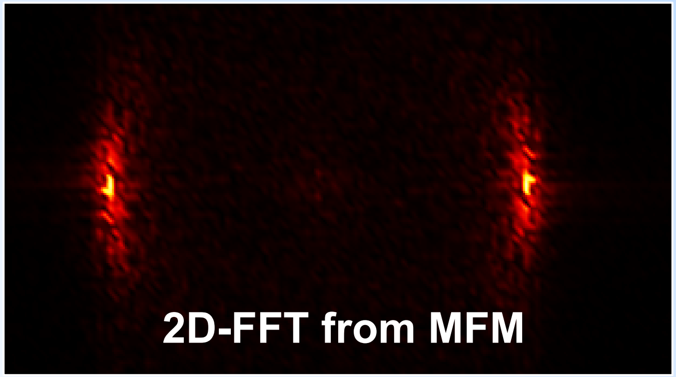




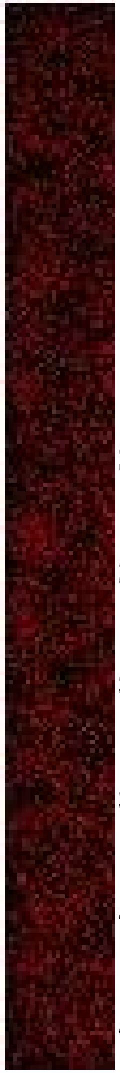
Average magnetic periodicity:
$\tau \approx 100$ nm

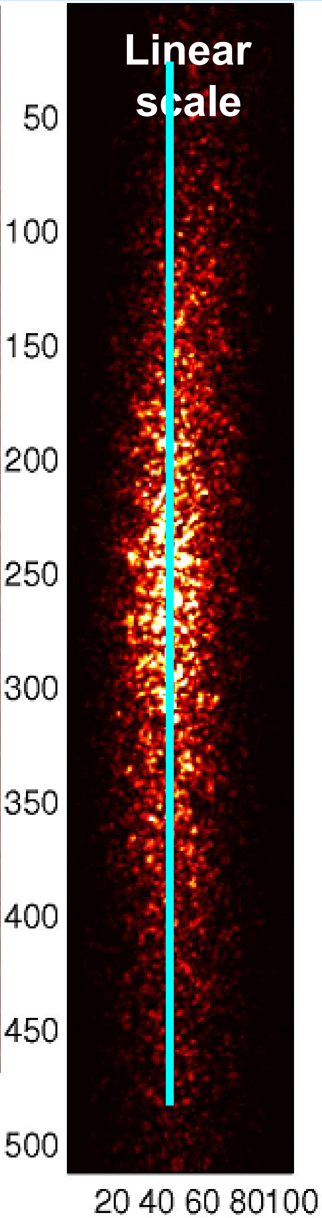
Magnetic lateral correlation length
$\Lambda \approx 1000$ nm

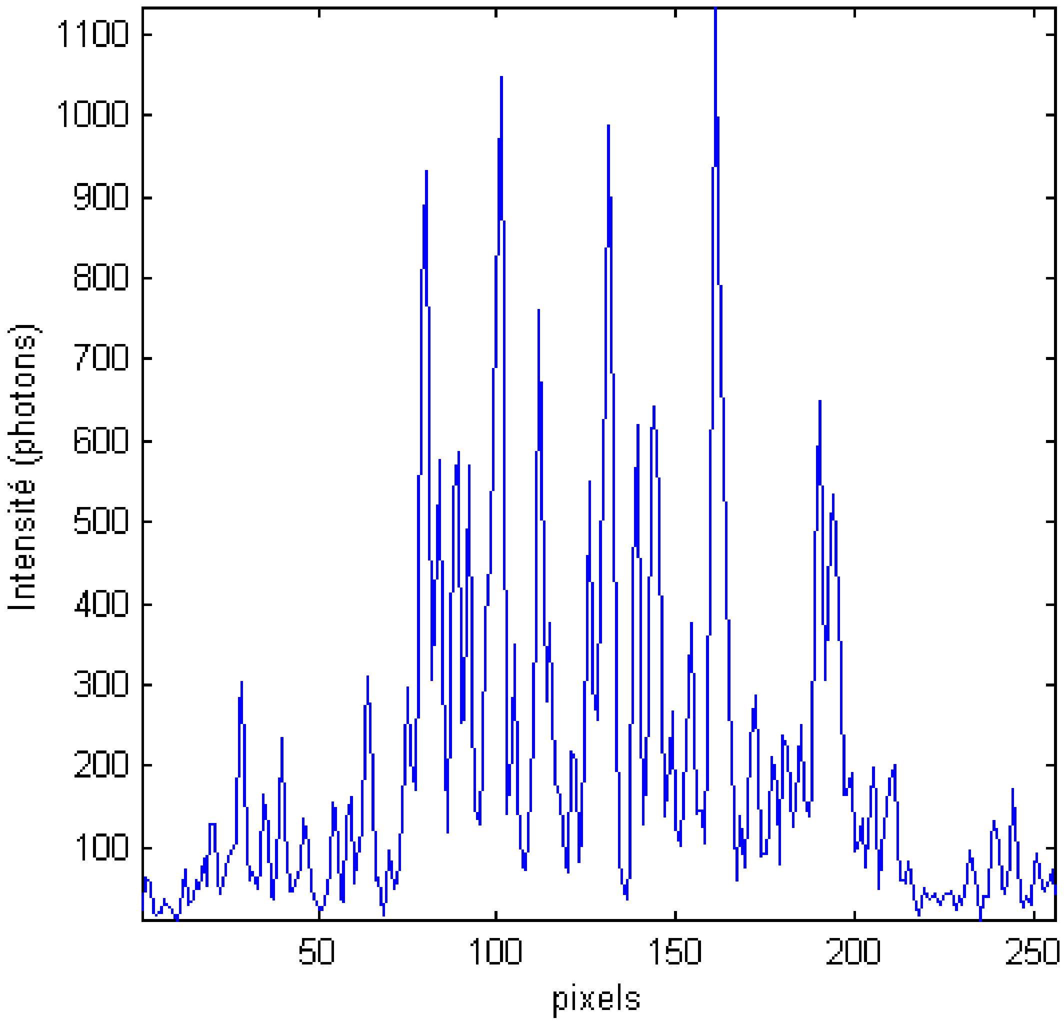
Circular dichroïsm
→ closure domains
Dürr *et al*, Science **284**, 2166 (1999)

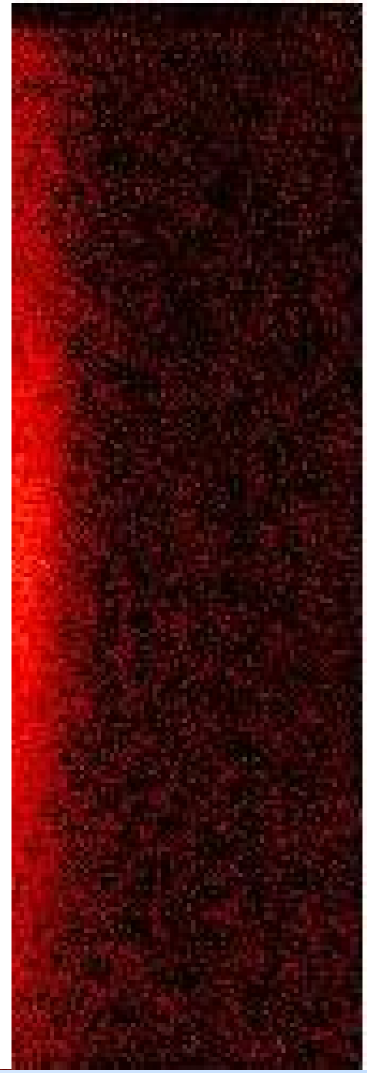


Coherent SXRMS from stripe domains

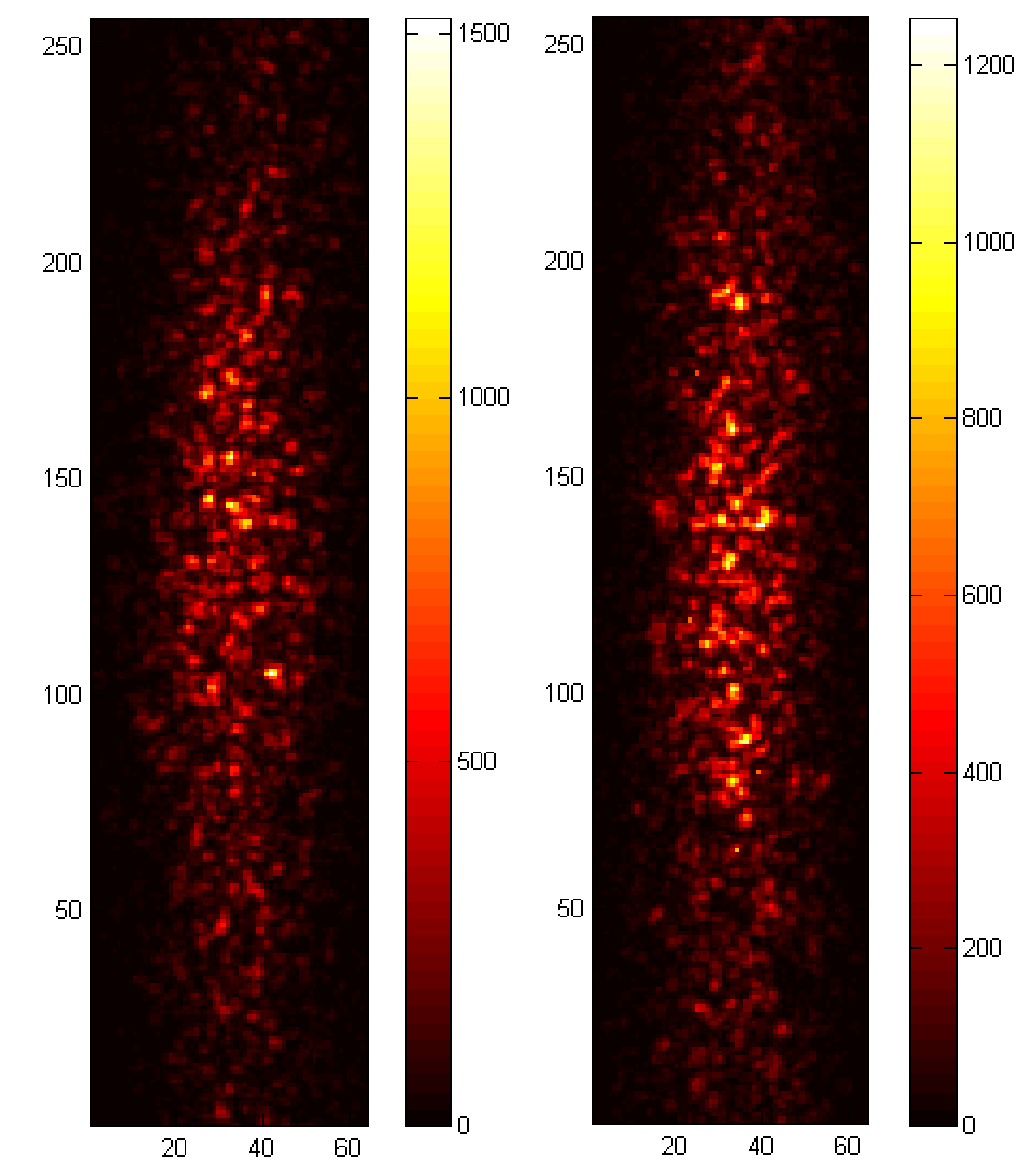






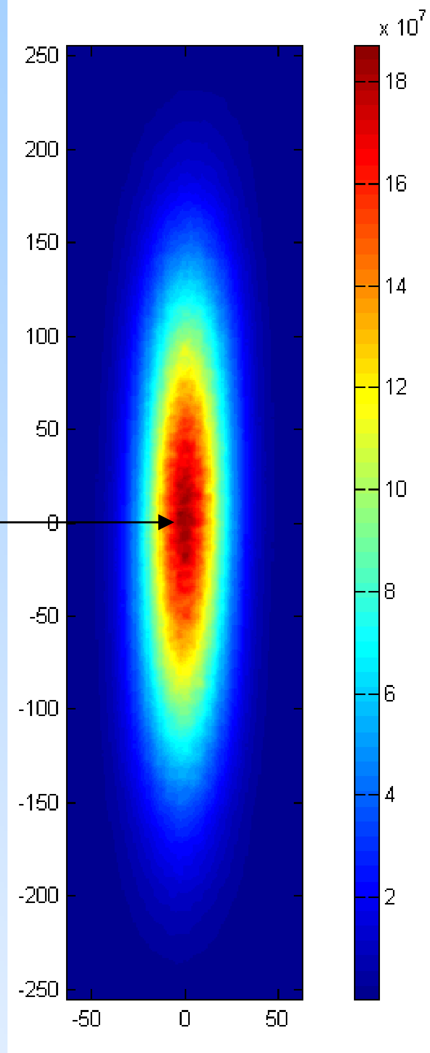


1 domain structure ↔ 1 speckle pattern



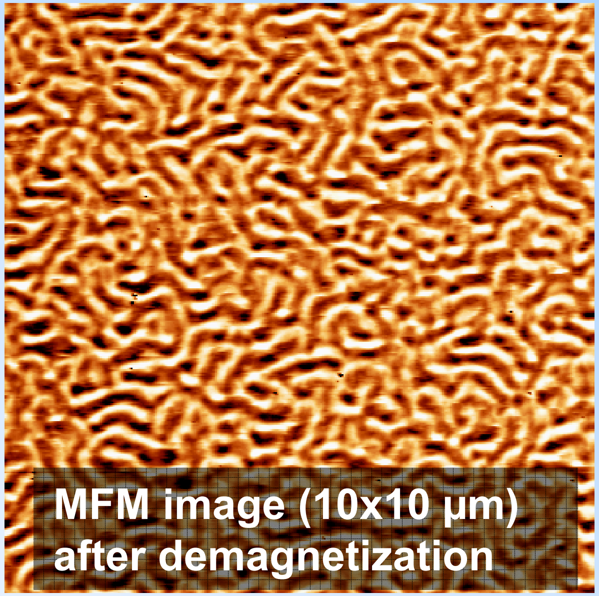
Cross-correlation function

No central spot
= no correlation

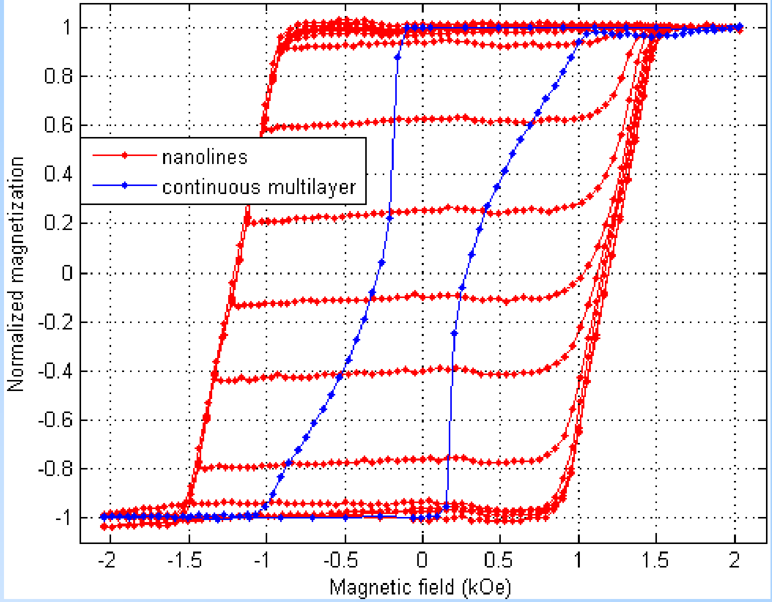


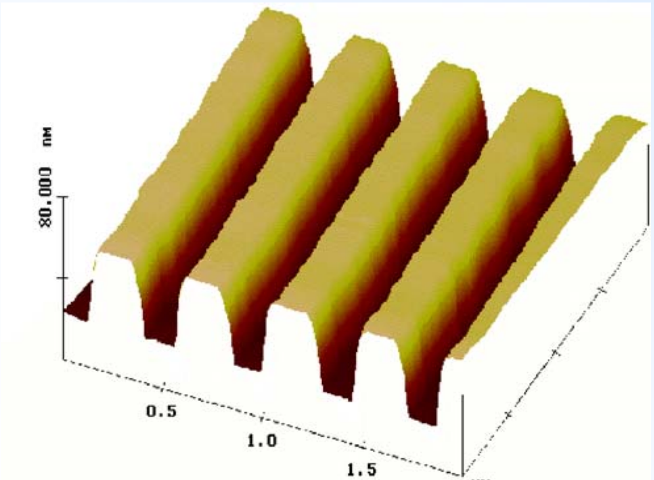
Study of a grating of ferromagnetic nanolines

$Pt_{25}/(Co_6/Pt_{25})_{12}$

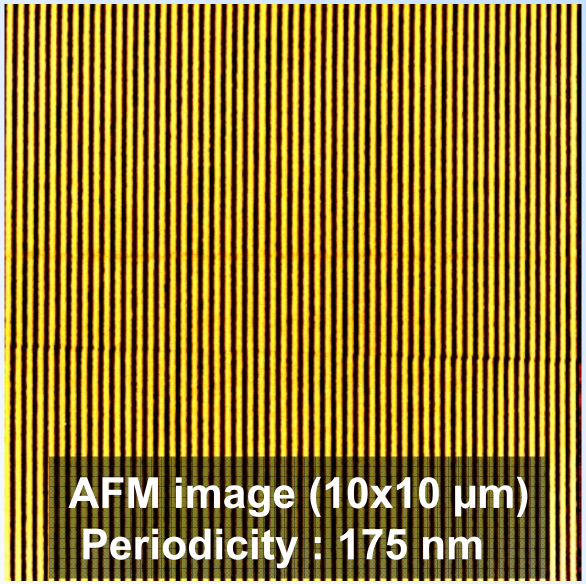


MFM image (10x10 µm)
after demagnetization

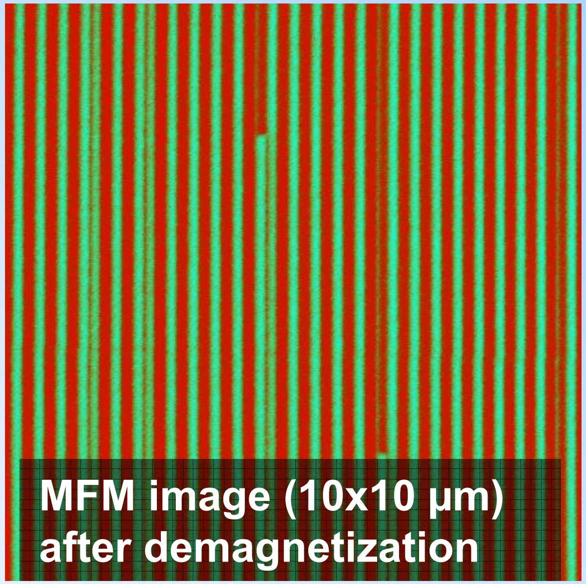




Nanolines etched in Silicon

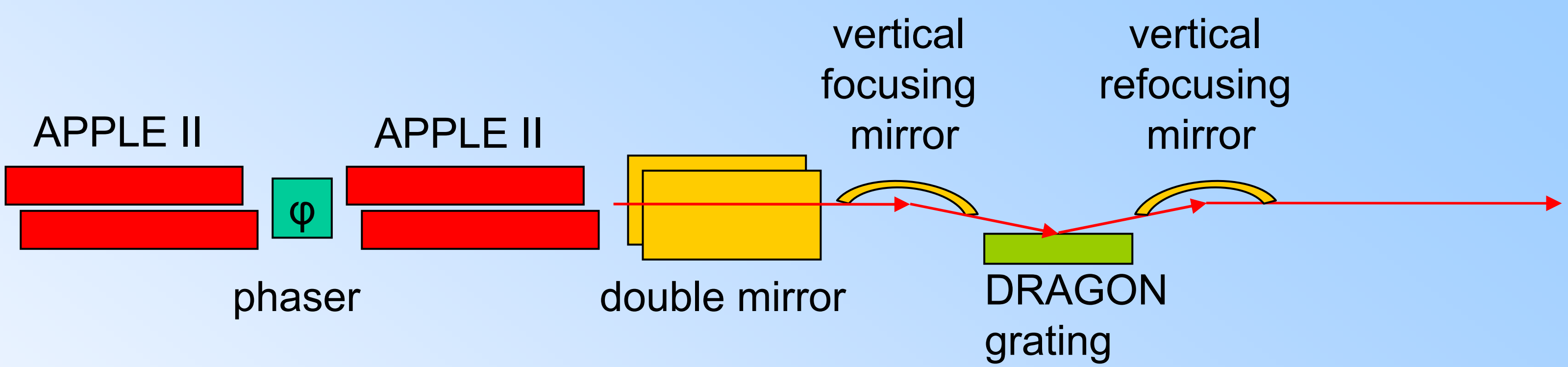


AFM image (10x10 µm)
Periodicity : 175 nm



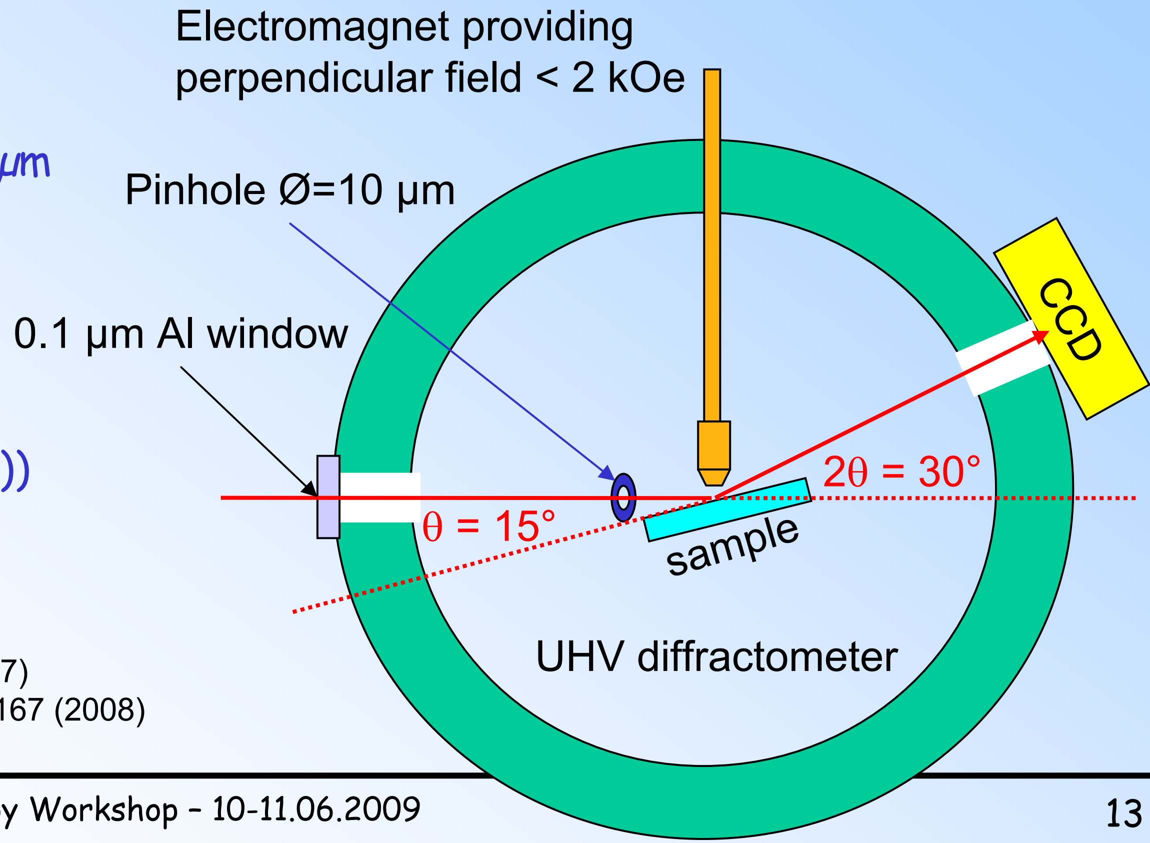
MFM image (10x10 µm)
after demagnetization

Experimental set-up for coherence at ESRF-ID08

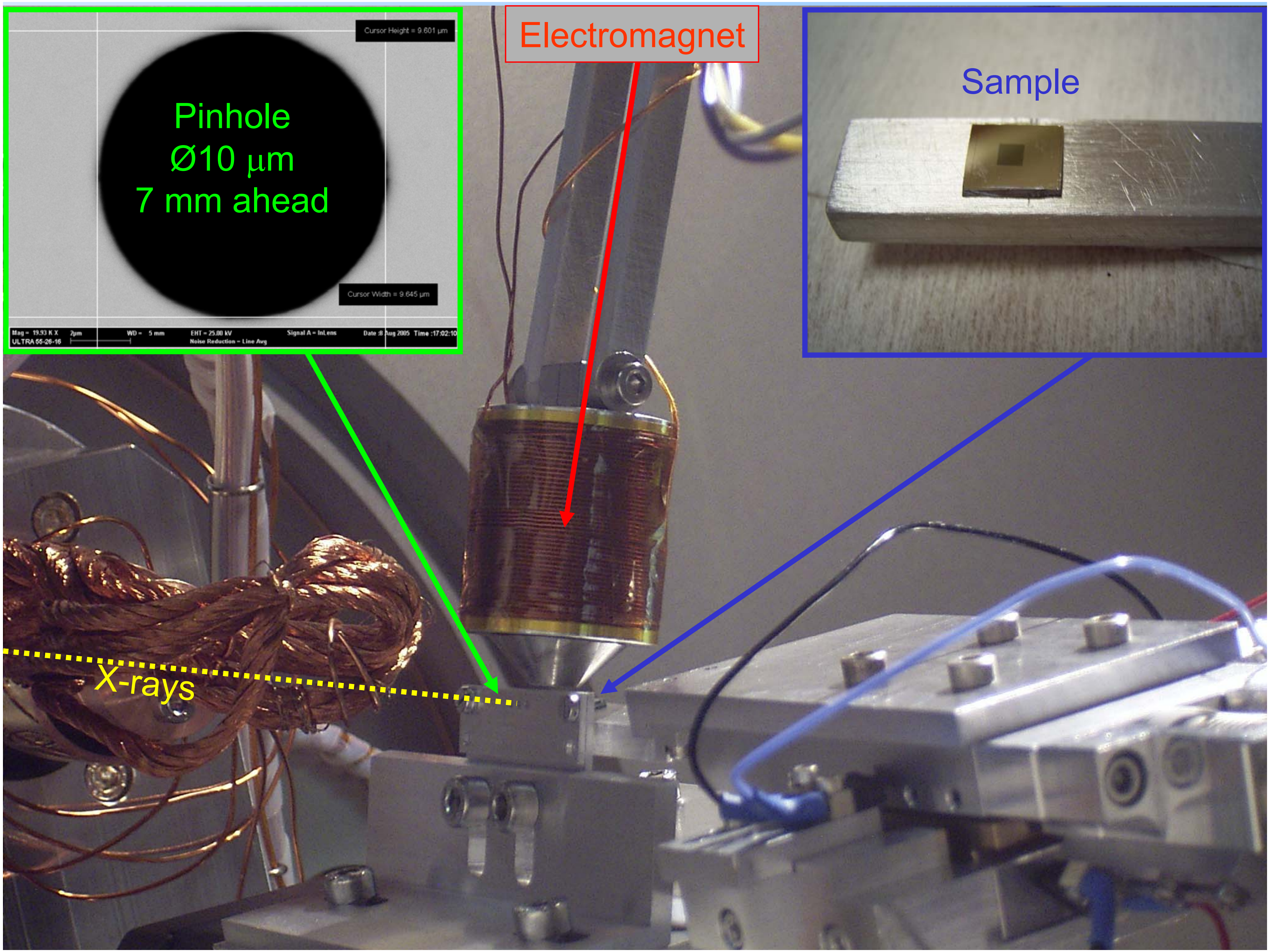


- Longitudinal coherence:
  $\xi_l = \lambda^2/(2\Delta\lambda) = \lambda/2.\,(\lambda/\Delta\lambda) \approx 2.4\ \mu m$

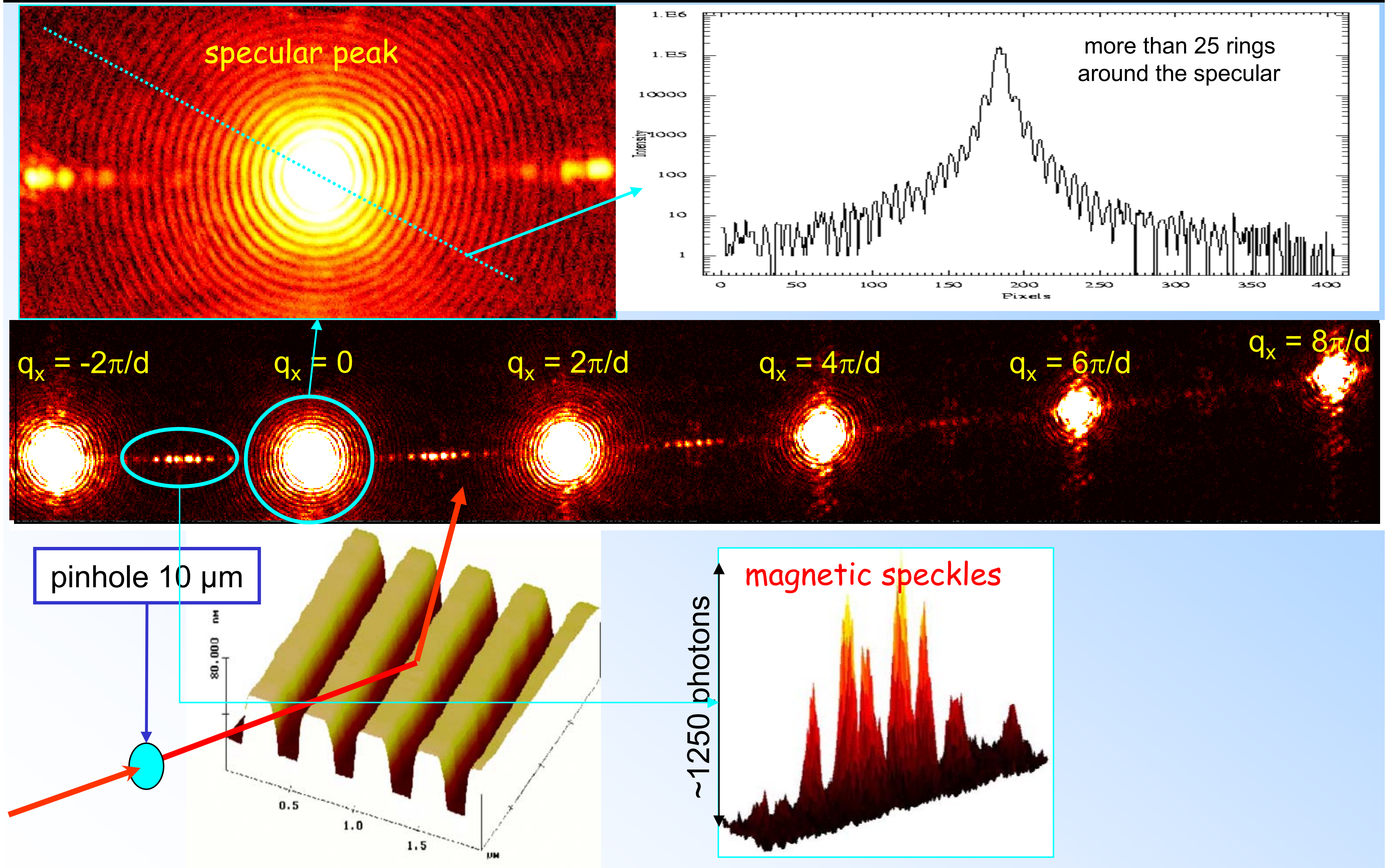
- Transverse coherence after focusing:
  vertical: ~fully coherent
  horizontal: ~20 μm > pinhole
  (beam size = 1 mm (h) x 0.3 mm (v))



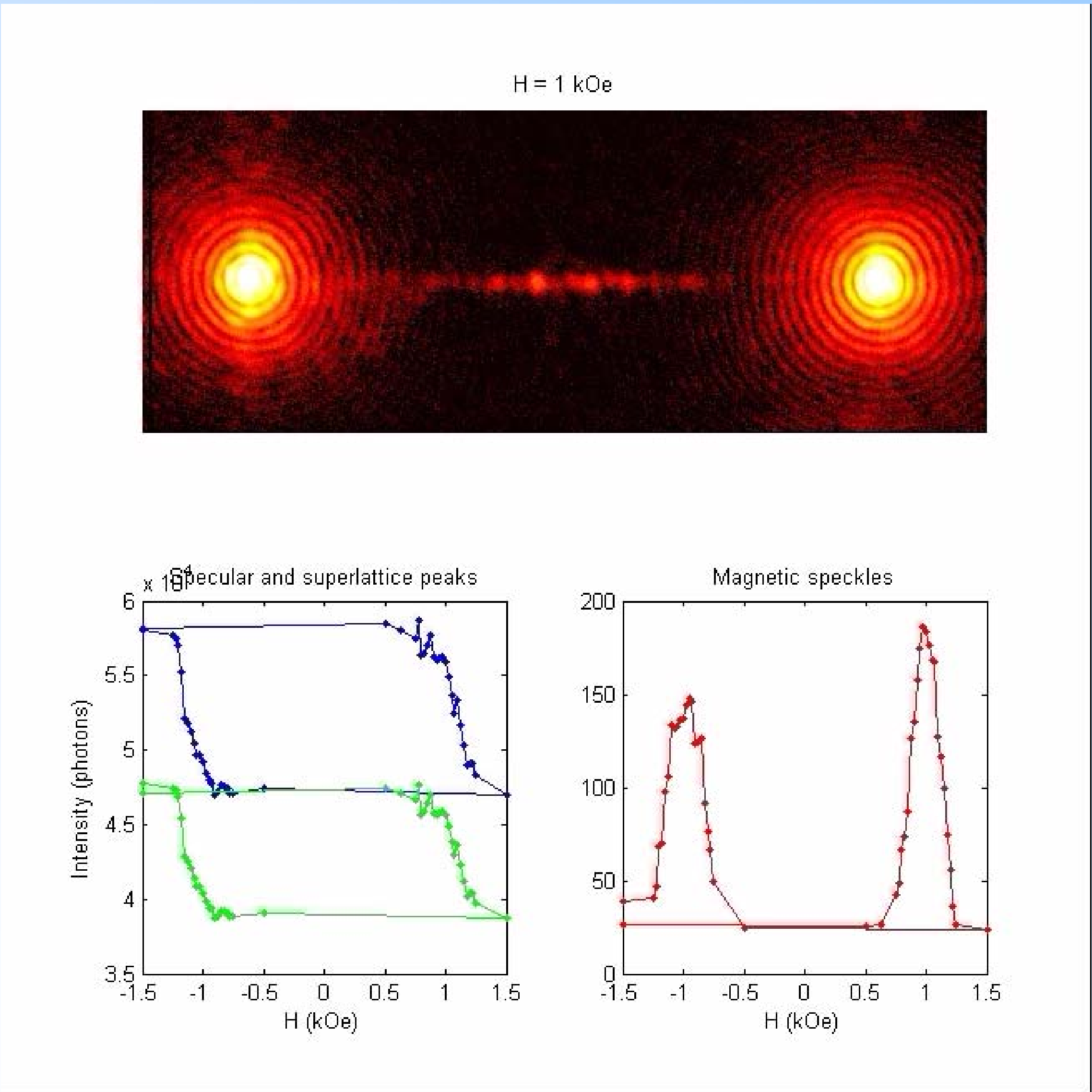
Beutier *et al*, Rev. Sci. Instrum. **78**, 093901 (2007)
Beutier *et al*, Eur. Phys. J. Appl. Phys. **42**, 161–167 (2008)


Electromagnet
Sample
Pinhole
Ø10 µm
7 mm ahead
X-rays

Magnetic speckles from nanolines

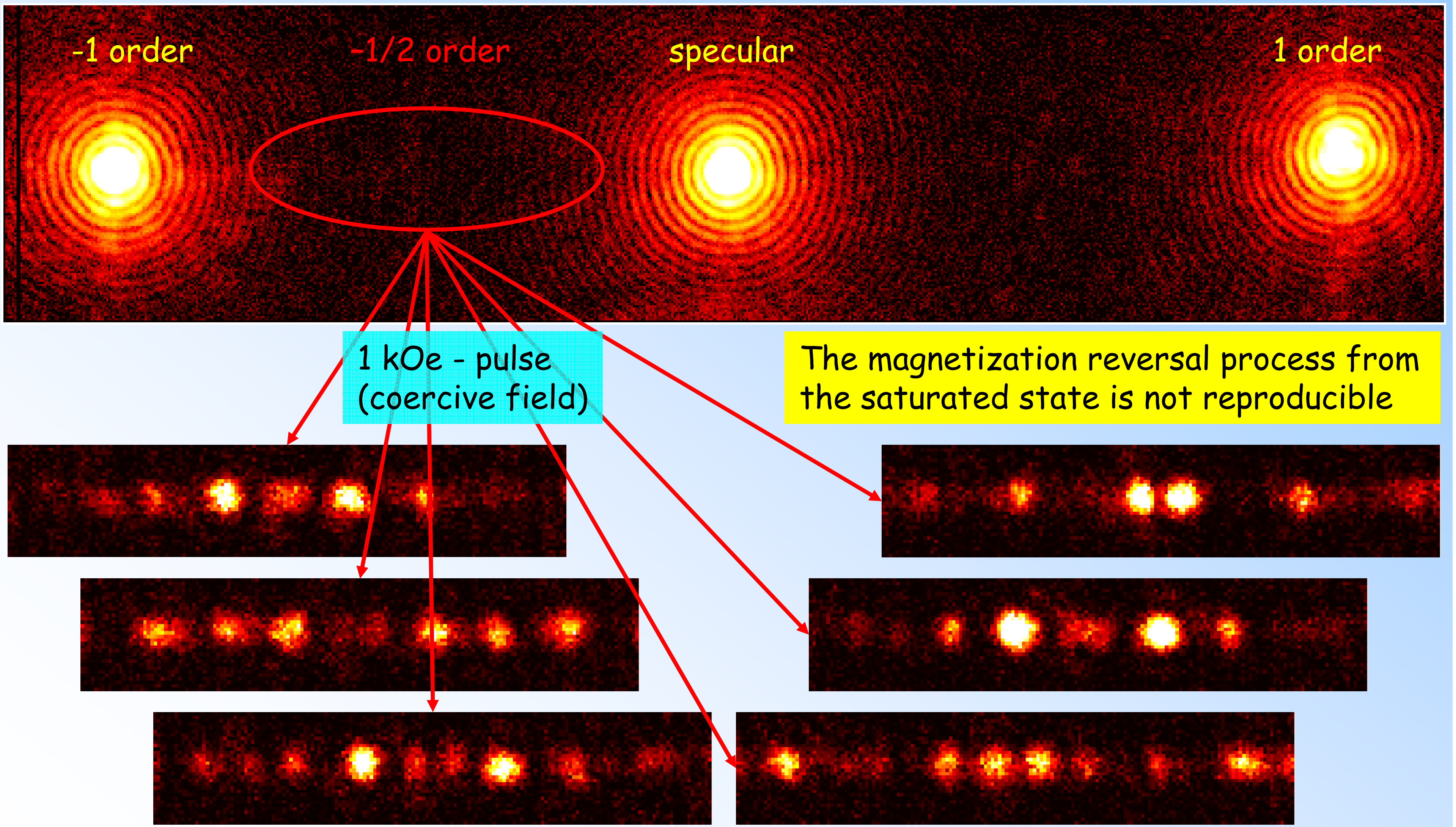


Magnetic reversal of nanolines

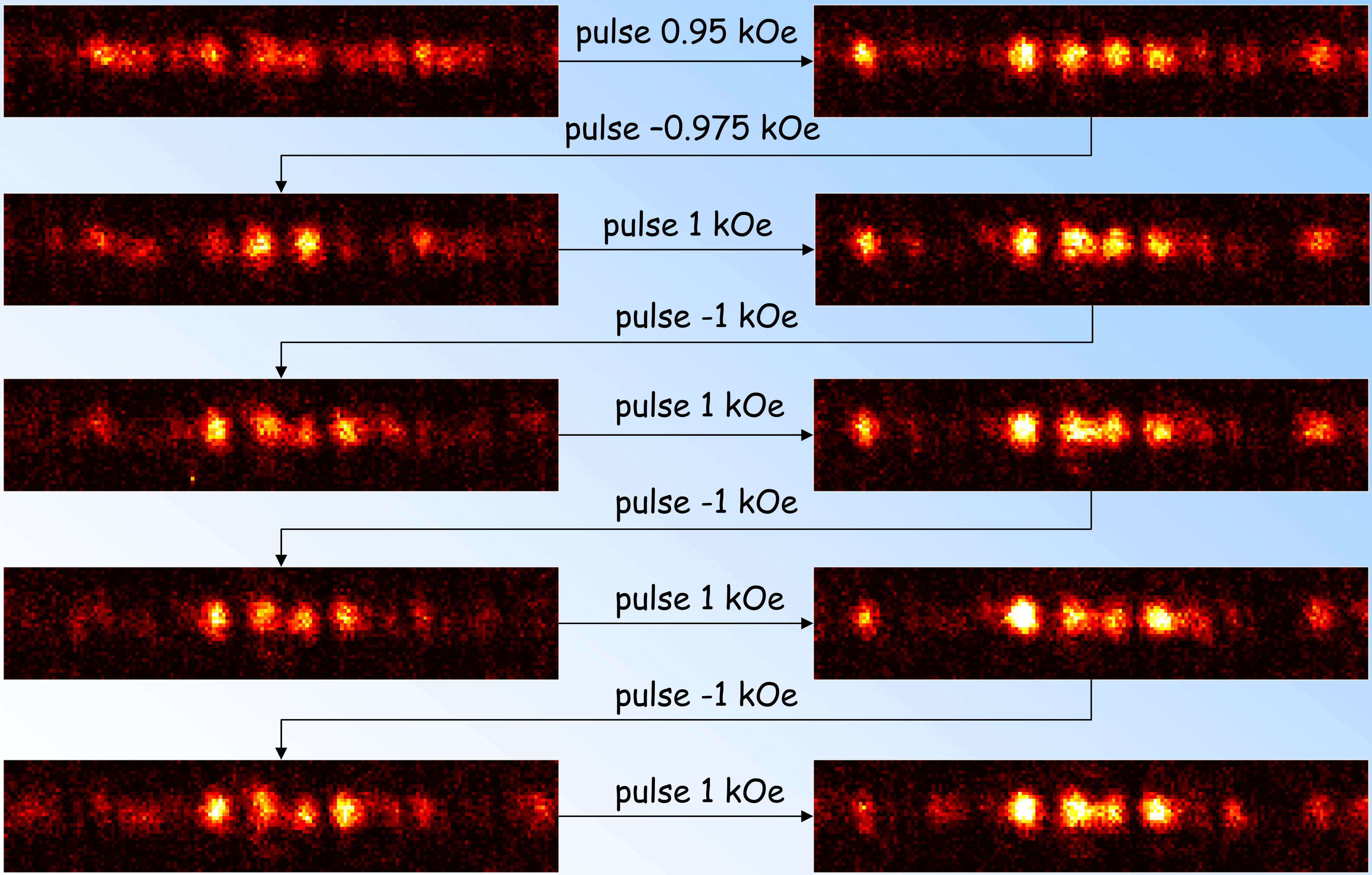


Magnetic memory after saturation

Saturated state



Magnetic memory in a minor loop



Magnetic imaging in the real space

$$\{m(\vec{r})\} \longrightarrow \left\{ I(\vec{q}) \propto \left| FT[m(\vec{r})] \right|^2 \right\}$$

?

Without holographic encoding, the phase of the FT is lost in the measurement.

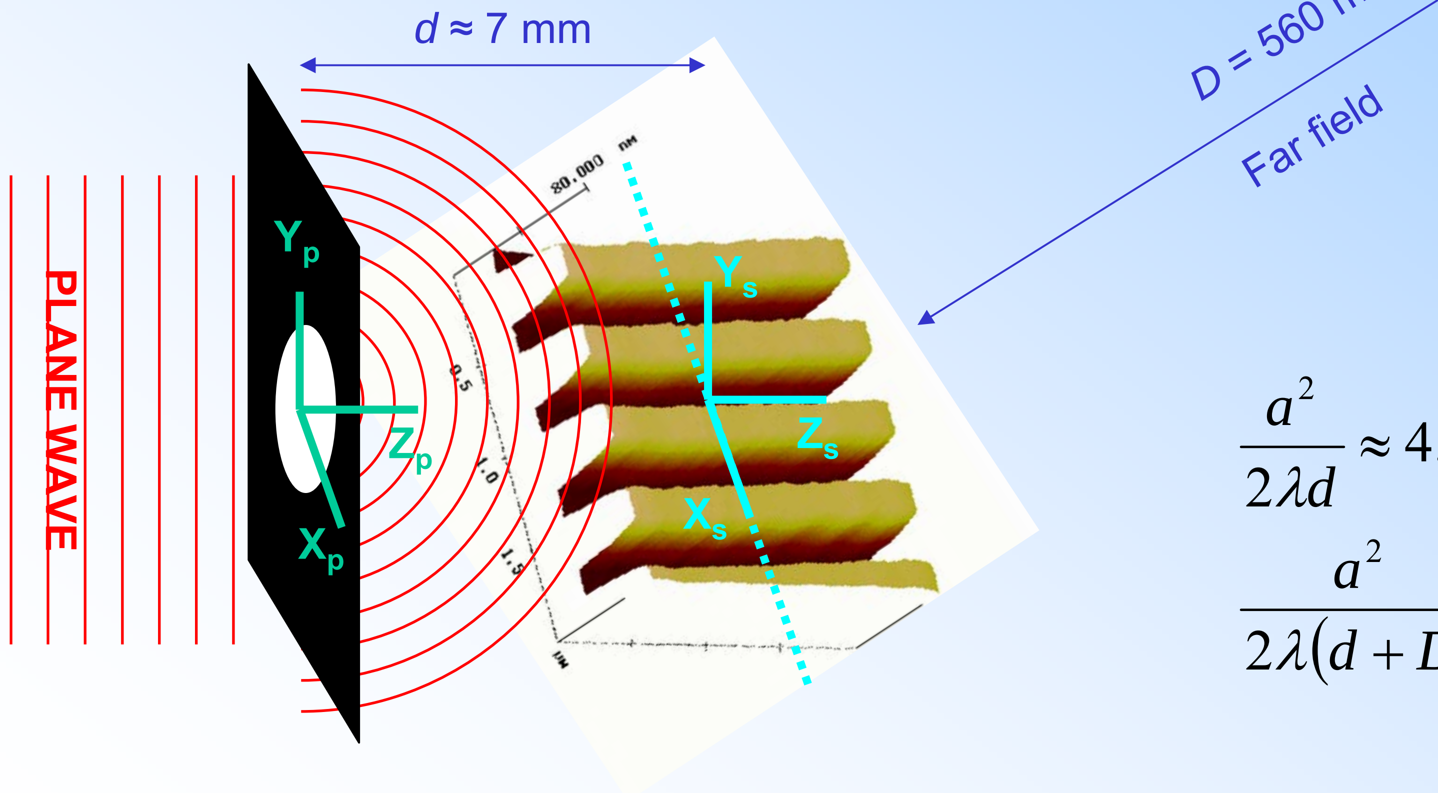
But oversampling + algorithm can in principle retrieve the phase of the FT
And thus the scattering function in the real space.

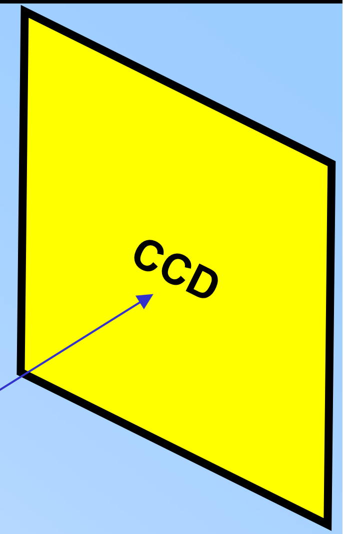
Simulation

Scattered intensity : $I(\vec{q}) = \left| \int_S A(\vec{r}) f^{res}(\vec{r}) \exp(i\vec{q}.\vec{r}) d\vec{r} \right|^2$

Scattering factor : $f^{res}(\vec{r}) = F^{(0)}(\hat{e}'^{*}.\hat{e}) - iF^{(1)}(\hat{e}'^{*} \wedge \hat{e}).\hat{m}(\vec{r})$

Incident amplitude : $A(\vec{r}) = \int_{pinhole} \exp\left[\frac{(X_p - X_r)^2 + (Y_p - Y_r)^2}{2d} \right] dX_p dY_p$

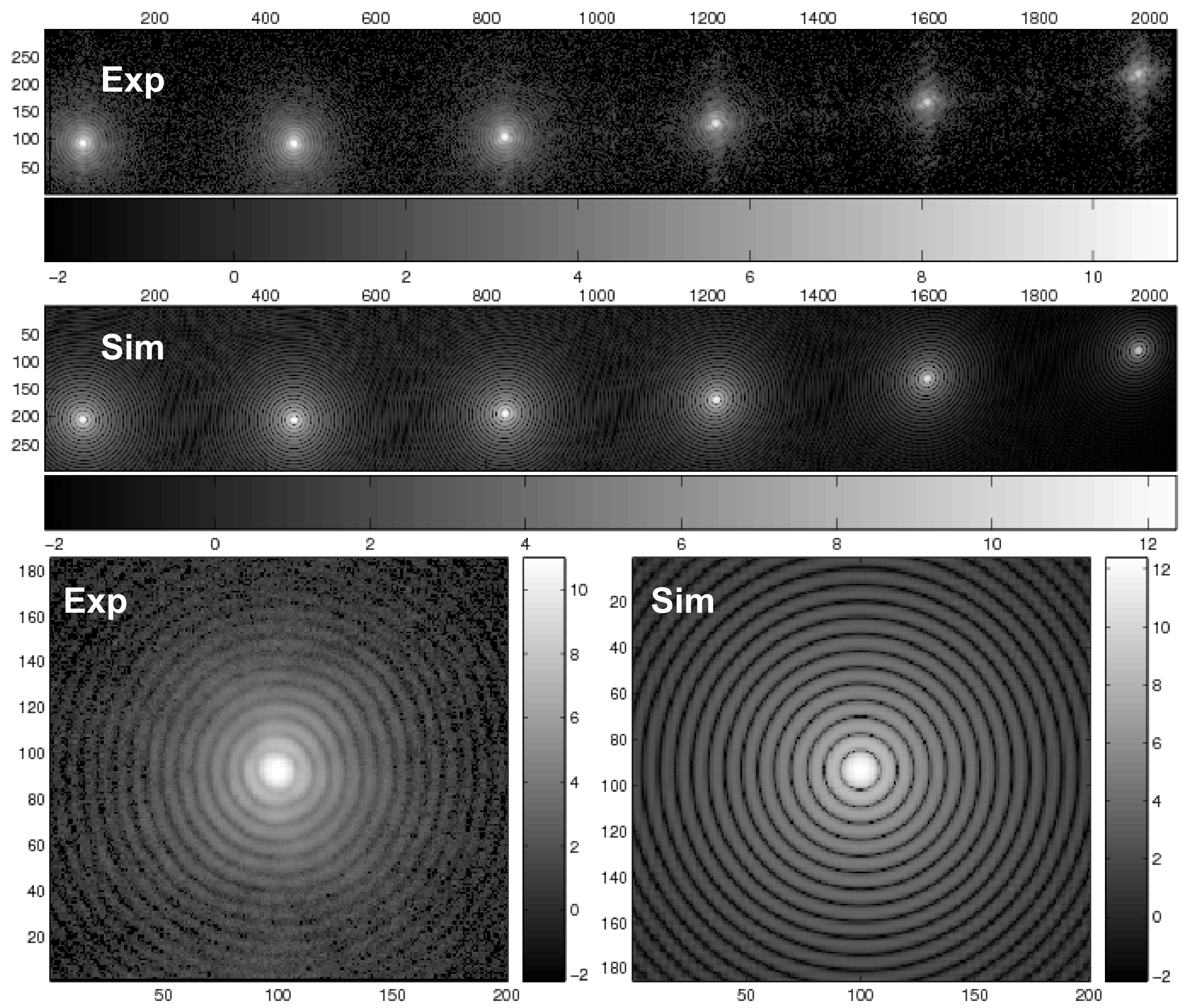




$$\frac{a^2}{2\lambda d} \approx 4.5 > 1$$

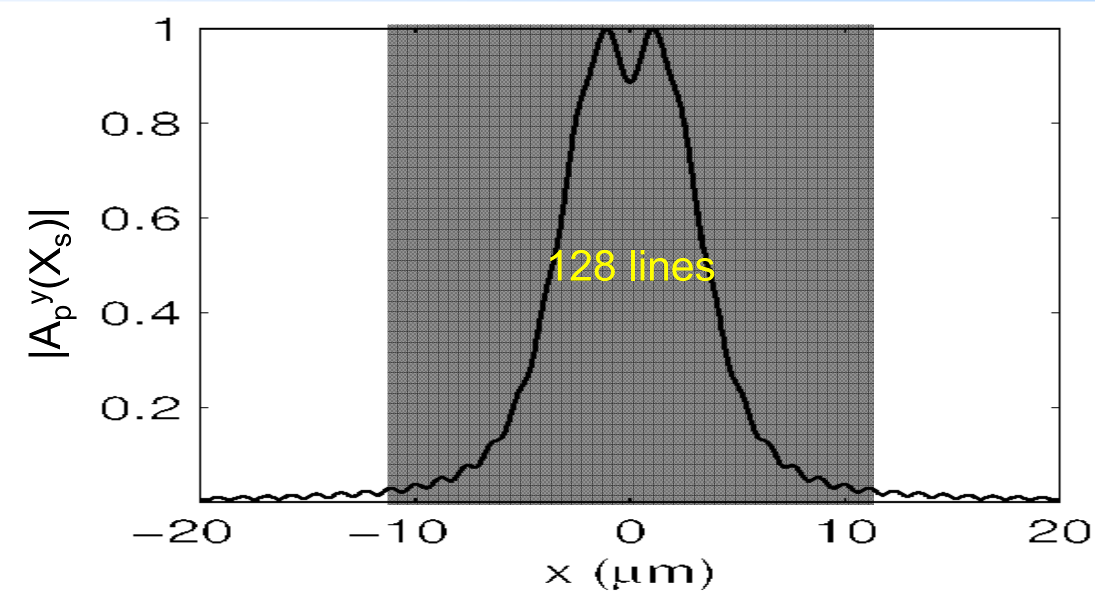
$$\frac{a^2}{2\lambda(d+D)} \approx 0.06 << 1$$

Simulation of the charge scattering

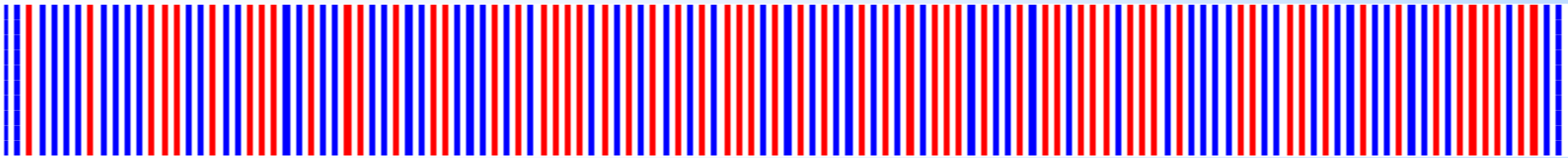


Reconstruction with a Monte Carlo method

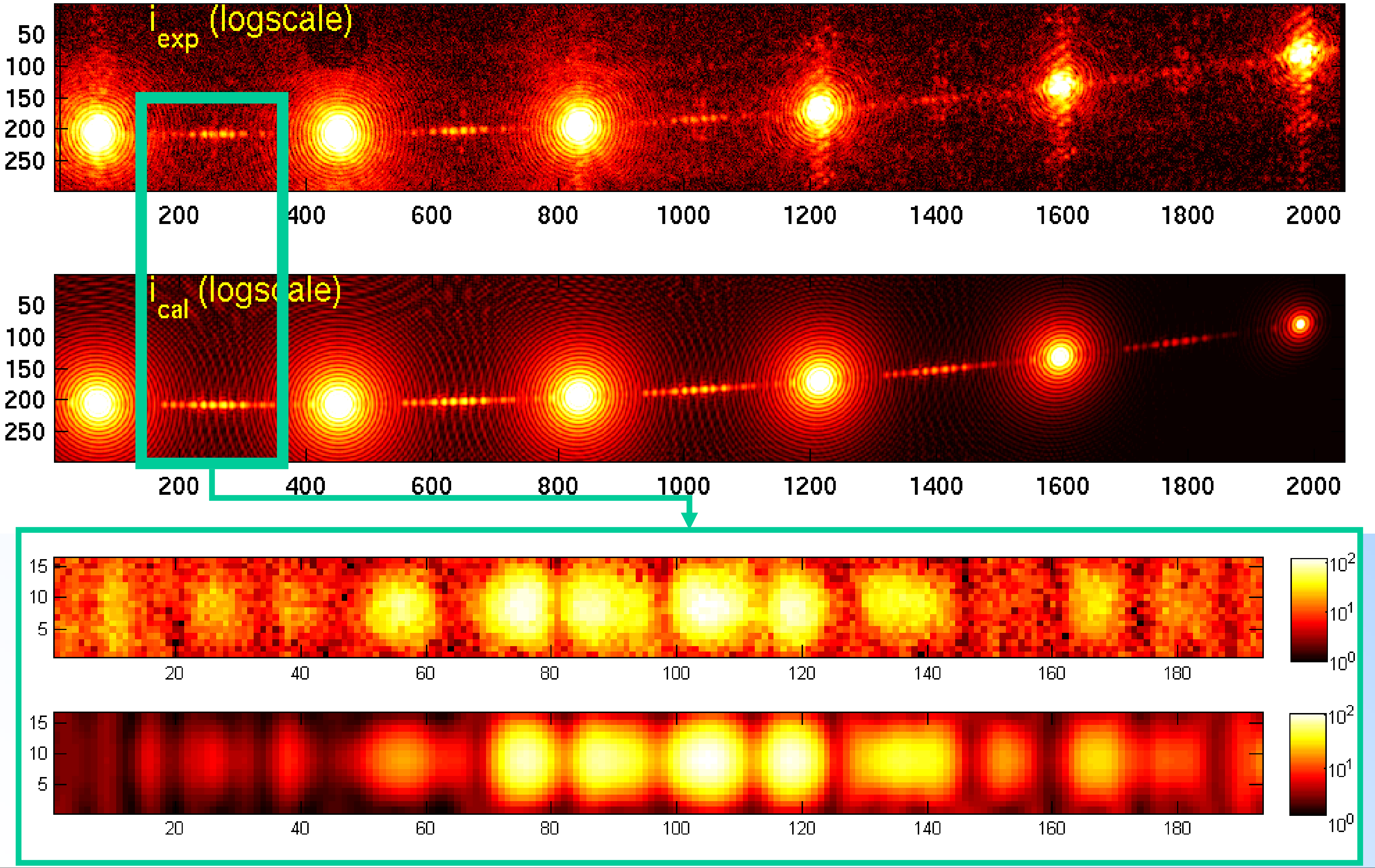
Definition of the problem
- lines monodomain ⇒ 1 dimension problem
- perpendicular magnetization ⇒ 1 unknown per line
- saturation up or down ⇒ Value +1 or –1



Simulated annealing
- Start with a random configuration
- Error criterion E
- Each step, a line is chosen randomly and its reversal probability is proportional to exp(-ΔE/kT)
- T decreases step by step

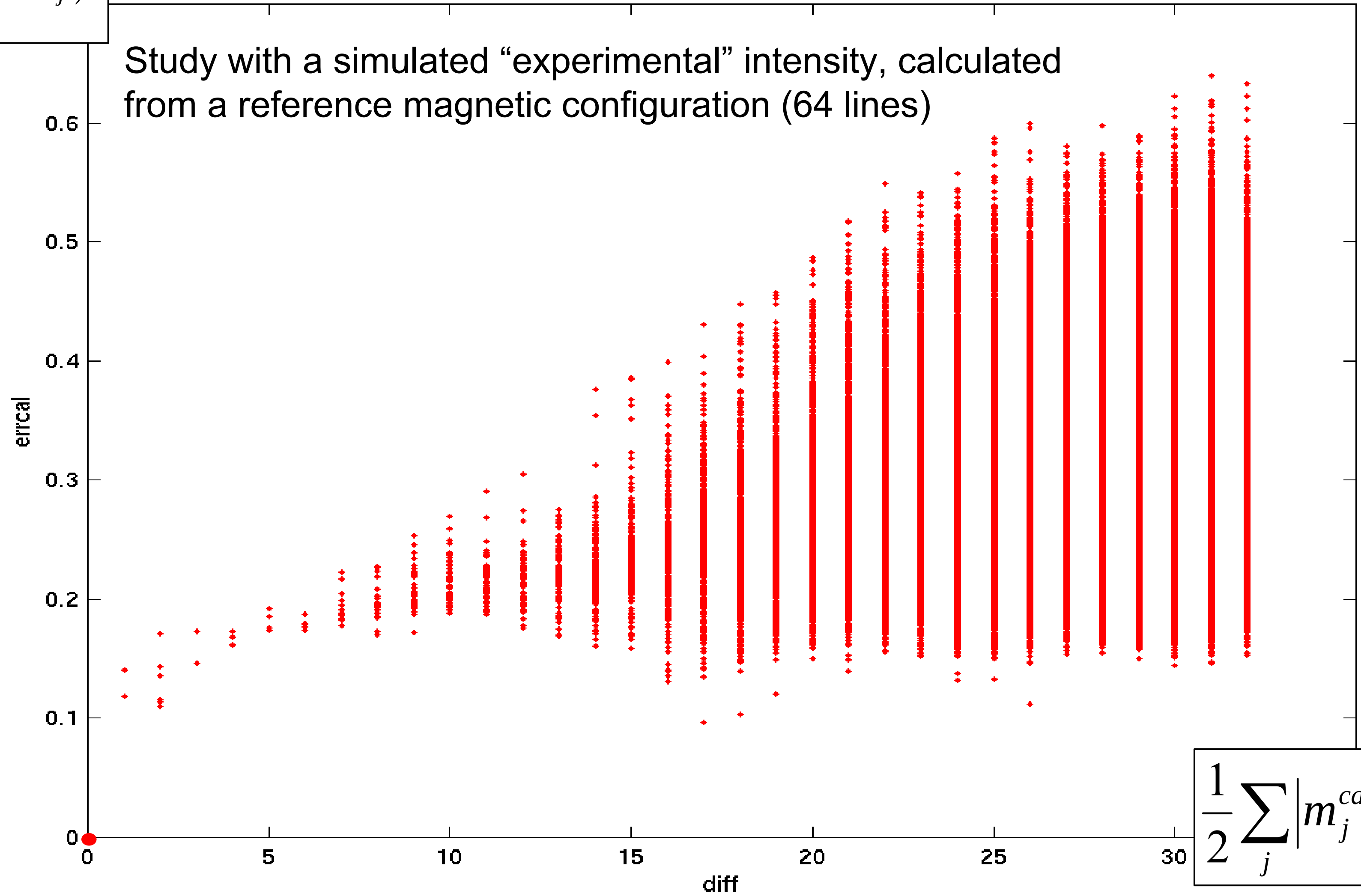


Results of reconstruction in the reciprocal space

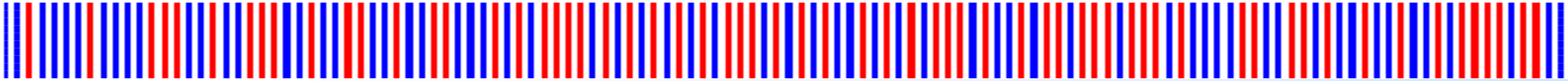


Study of the solution space

$$\sum_j \left(I_j^{cal} - I_j^0\right)^2$$



$$\frac{1}{2}\sum_j \left|m_j^{cal} - m_j^0\right|$$

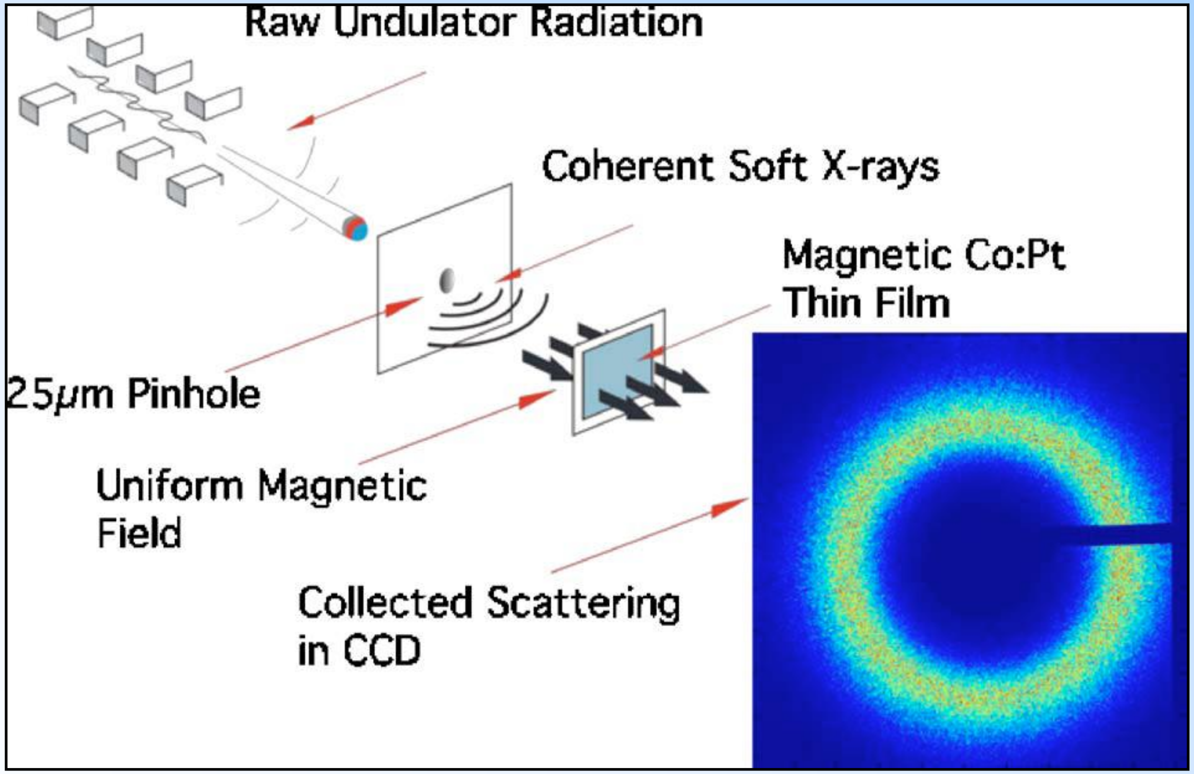


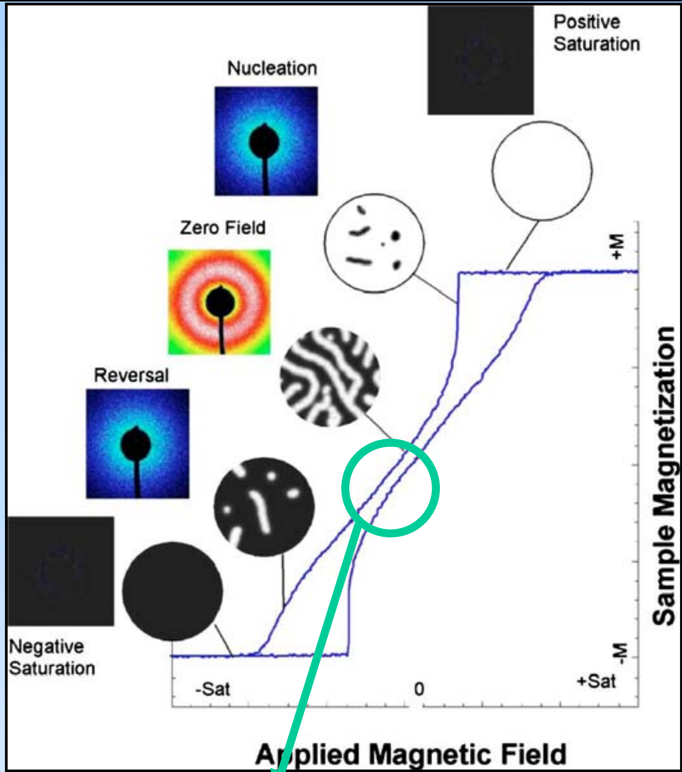
Some more recent work from other groups

- Study of the magnetic memory in Co/Pt multilayers as a function of the multilayer roughness
  Pierce et al

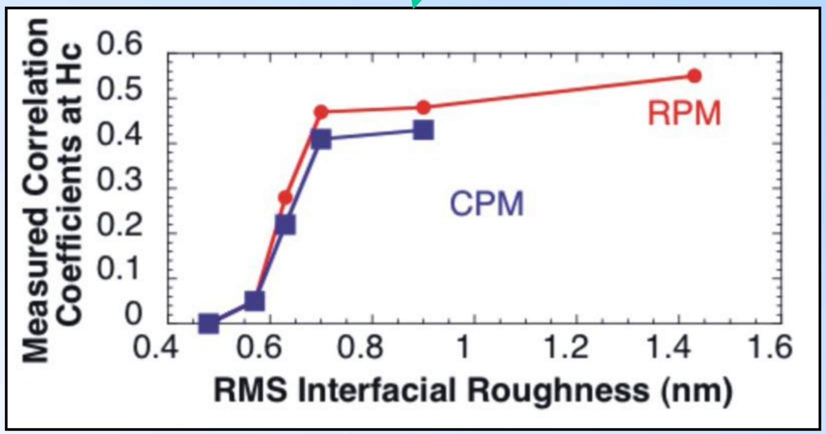
- Study of the magnetic memory induced by exchange bias in Co/Pd IrMn multilayers
  Chesnel et al

Magnetic memory vs. roughness in Co/Pt multilayers

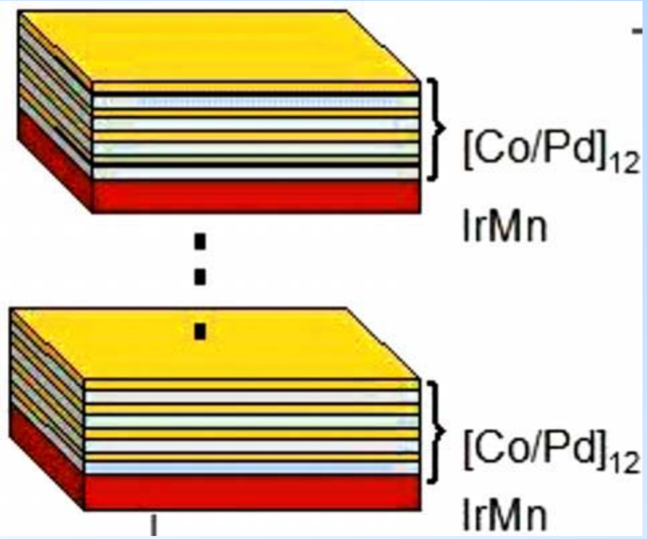


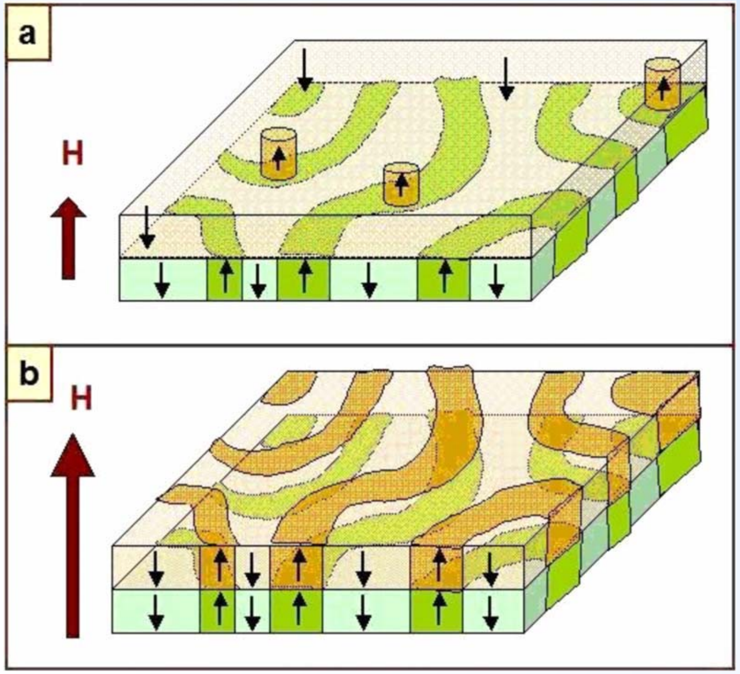


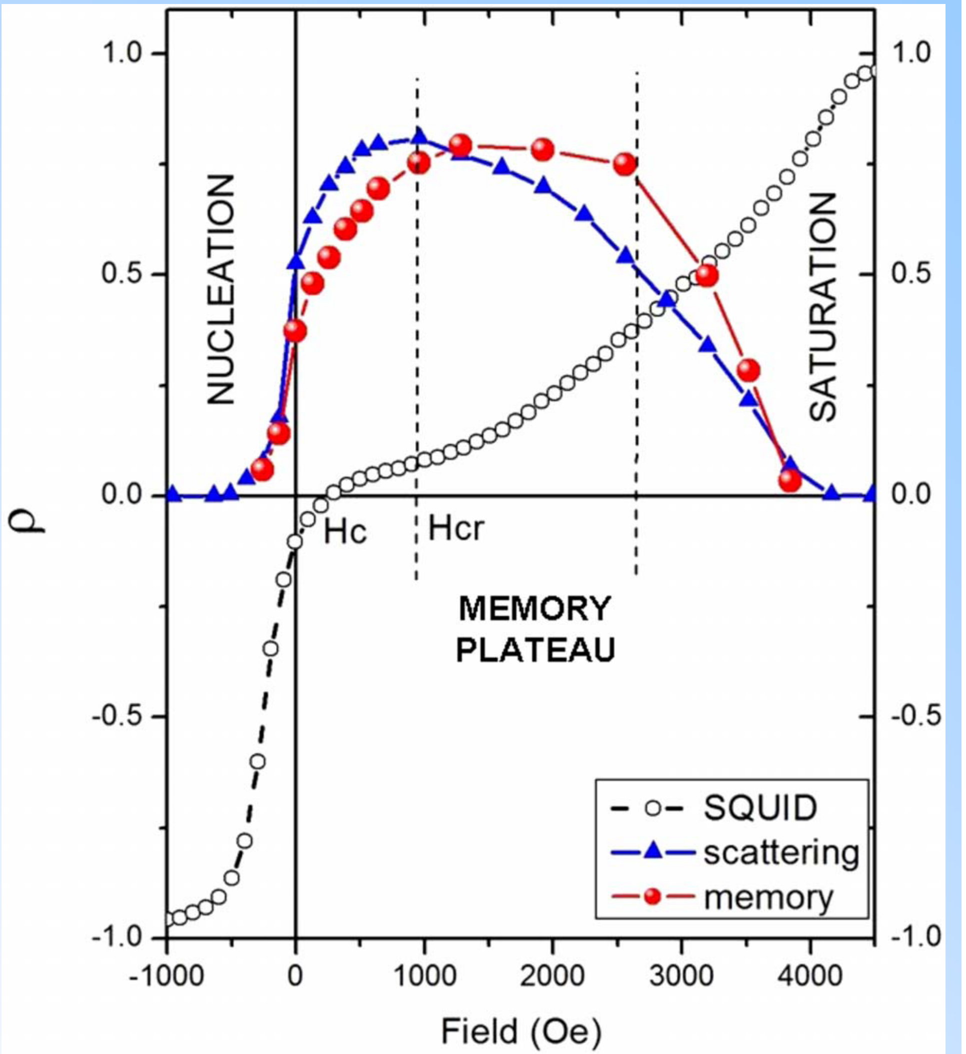
Study of the magnetic memory in Co/Pt multilayers as a function of the roughness:
Pierce *et al.*, *Phys. Rev. Lett.* **90**, 175502 (2003)
Pierce *et al.*, *Phys. Rev. Lett.* **94**, 017202 (2005)
Pierce *et al*., Phys. Rev. B **75**, 144406 (2007)



Magnetic memory via exchange coupling







Chesnel *et al.*, Phys. Rev. B **78**, 132409 (2008)

Conclusions

New information on well-known magnetic systems:
global processes → local processes

- Experimental set-up for Soft X-ray Coherent and Resonant Magnetic Scattering developed on ID08 (ESRF)

- Speckle pattern correlations
→ study of slow dynamics and response to magnetic field / electric current / temperature
→ magnetic memory induced by structural defects / exchange bias

- Algorithmic reconstruction or FT holography
→ magnetic (spectroscopic) imaging