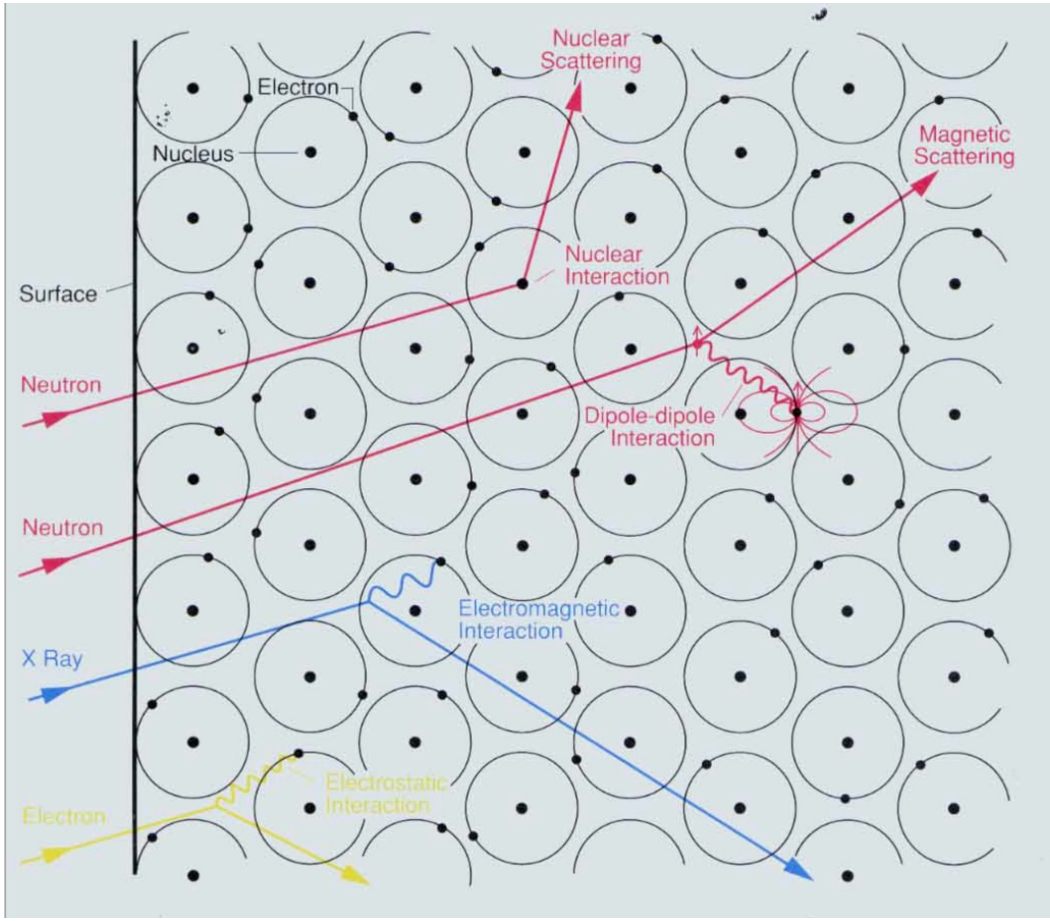
PAUL SCHERRER INSTITUT

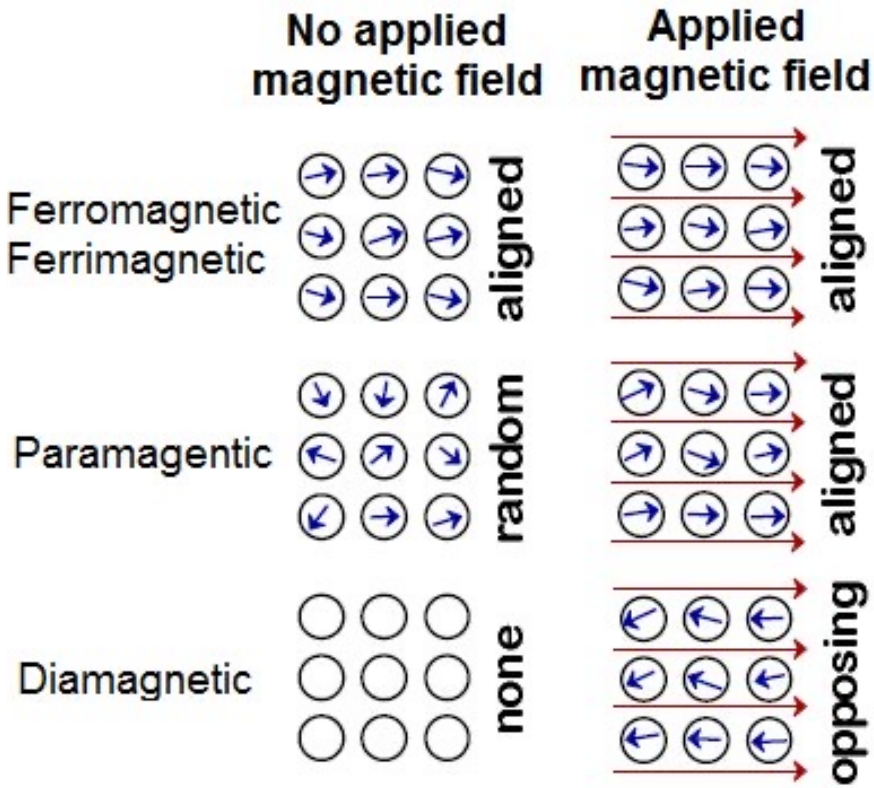
Materials Science at Large Scale Facilities

Magnetic Scattering

Contrast variation

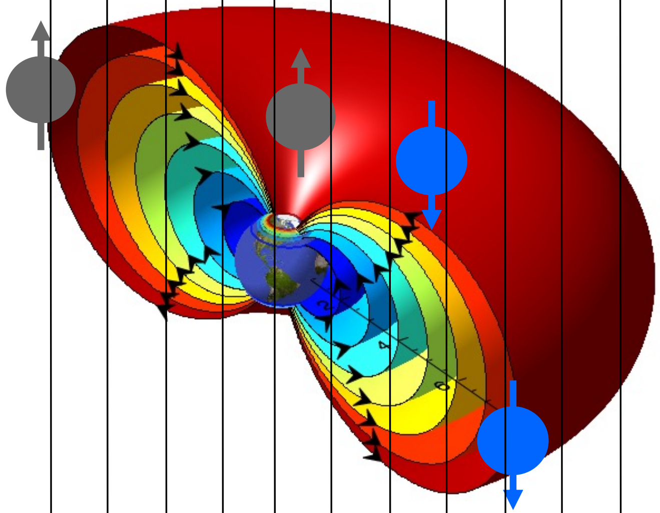
Nuclear vs magnetic interaction





Magnetic scattering

interaction potential is
NOT spherical symmetric
⇒ no scattering along ***m***



$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right)$$

$$V(\mathbf{r}) = -\boldsymbol{\mu}_N \cdot \mathbf{B}(\mathbf{r})$$

with

$$\boldsymbol{\mu}_N = \gamma \frac{e\hbar}{2m_N}\boldsymbol{\sigma}$$

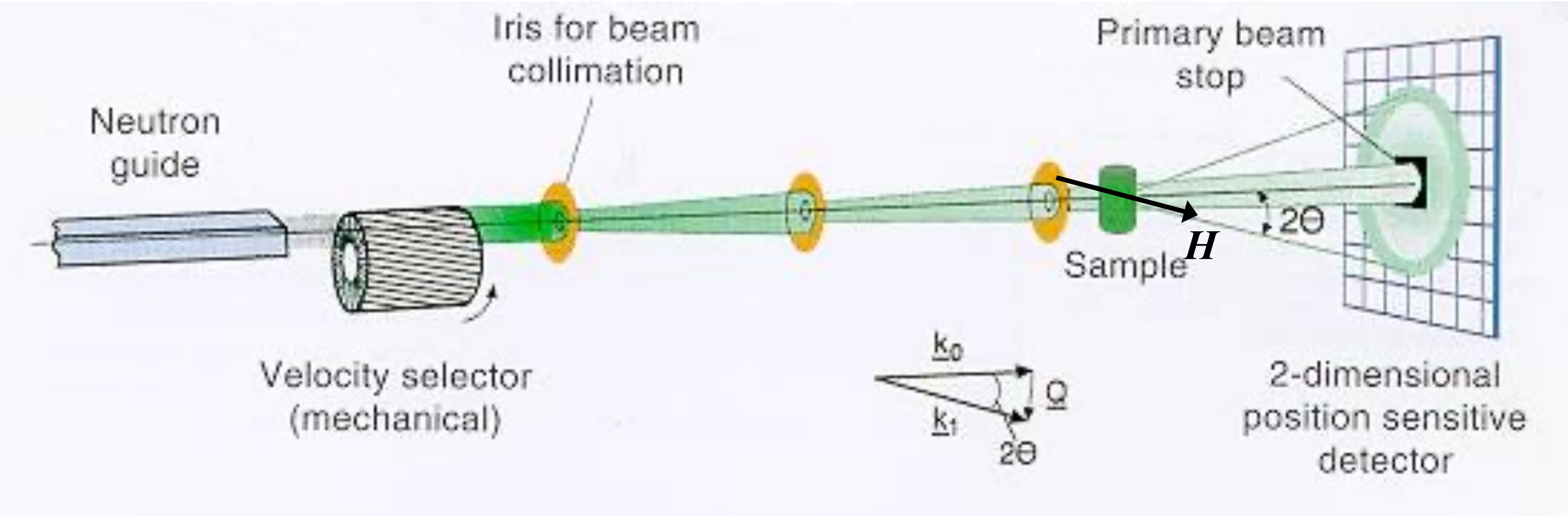
$$b_M = -\frac{m_N}{2\pi\hbar^2}\int d^3r\, e^{i\mathbf{Q}\mathbf{r}}\, \boldsymbol{\mu}_N \cdot \left(\mathbf{B}_S(\mathbf{r}) + \mathbf{B}_L(\mathbf{r})\right)$$

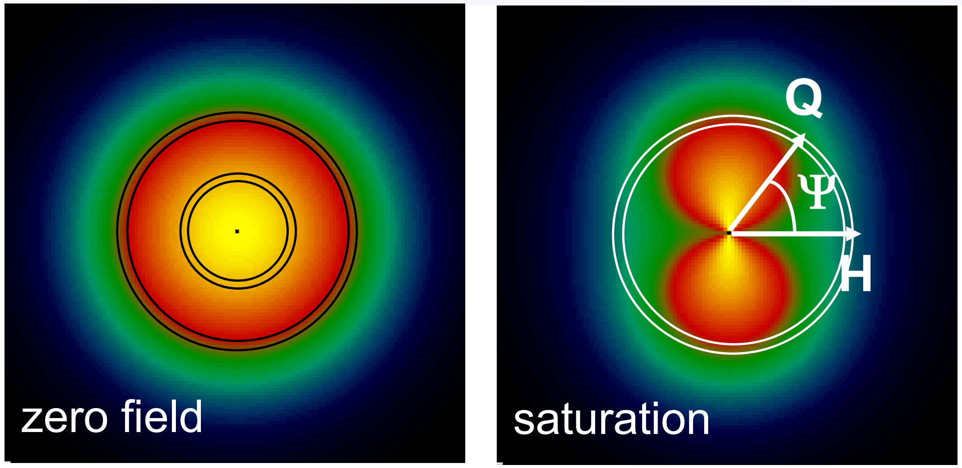
$$b_M = \frac{\gamma e \mu_0}{2\pi\hbar}\boldsymbol{\sigma}\cdot\mathbf{m}_\perp$$

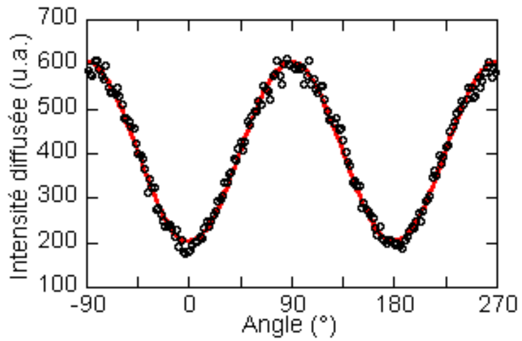
with the magnetic interaction vector

$$\mathbf{m}_\perp = \mathbf{Q}\times[\mathbf{m}\times\mathbf{Q}]/Q^2$$

Magnetic scattering

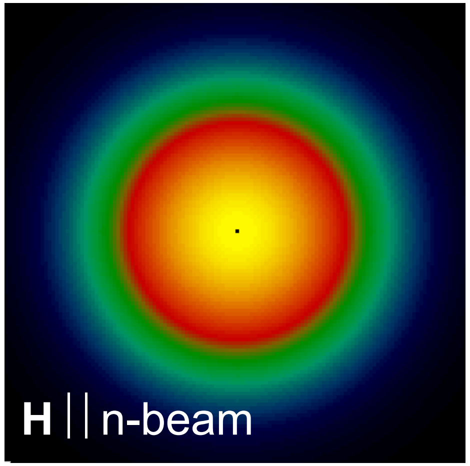






$$\frac{d\sigma}{d\Omega} = F_N^2(Q,R) + F_M^2(Q,R)\sin^2\Psi$$

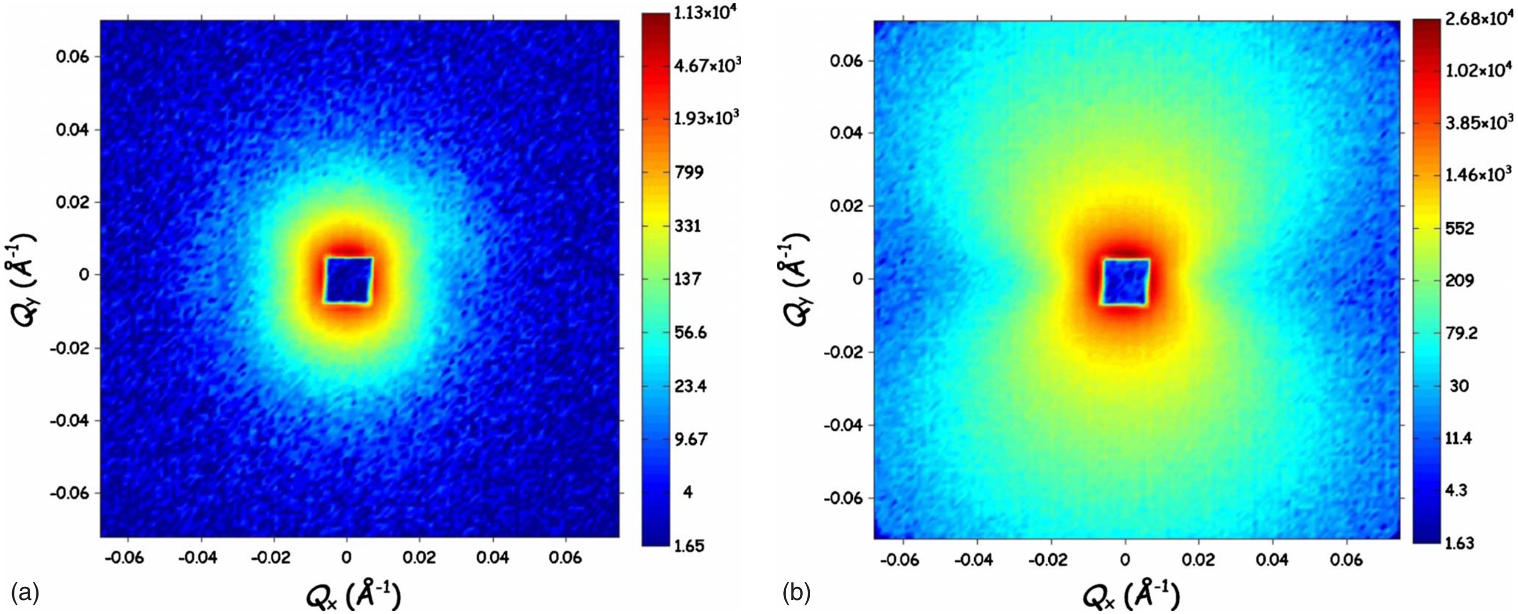
Magnetic scattering



$$\frac{d\sigma}{d\Omega} = F_N^2(Q,R) + F_M^2(Q,R)\cancel{\sin(\Psi)}$$

Application: Fe-Cu

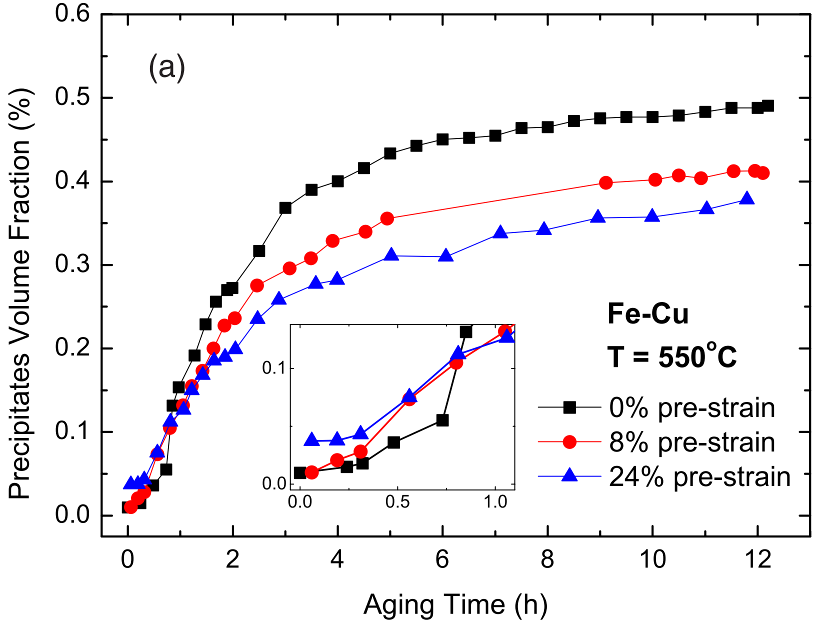
- Self-healing in ferritic steels
- Dynamic formation of precipitates
- Model system: Fe-1wt%Cu
- Comparison with and without pre-strain of 8% and 24%

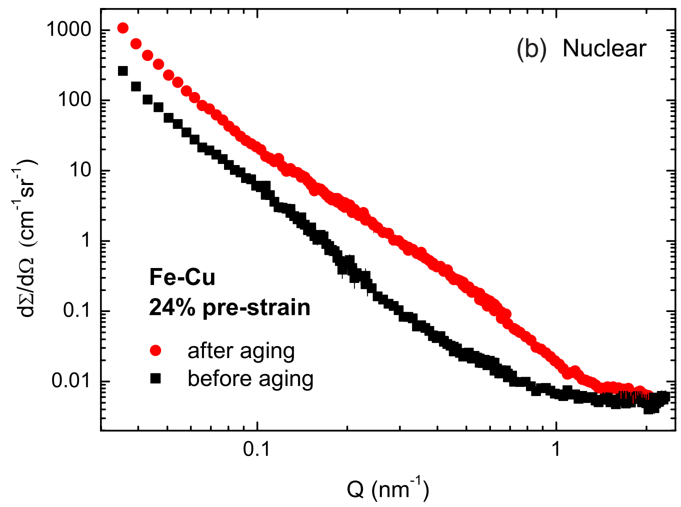


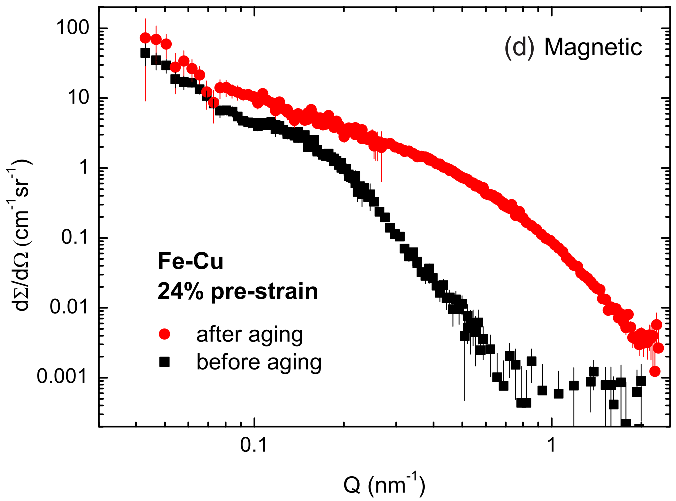
He et al. Physical Review B **82**, 174111 (2010)

Application: Fe-Cu

- Increased contrast between Fe matrix and Cu precipitates
- Precipitation kinetics can be tracked as function of time







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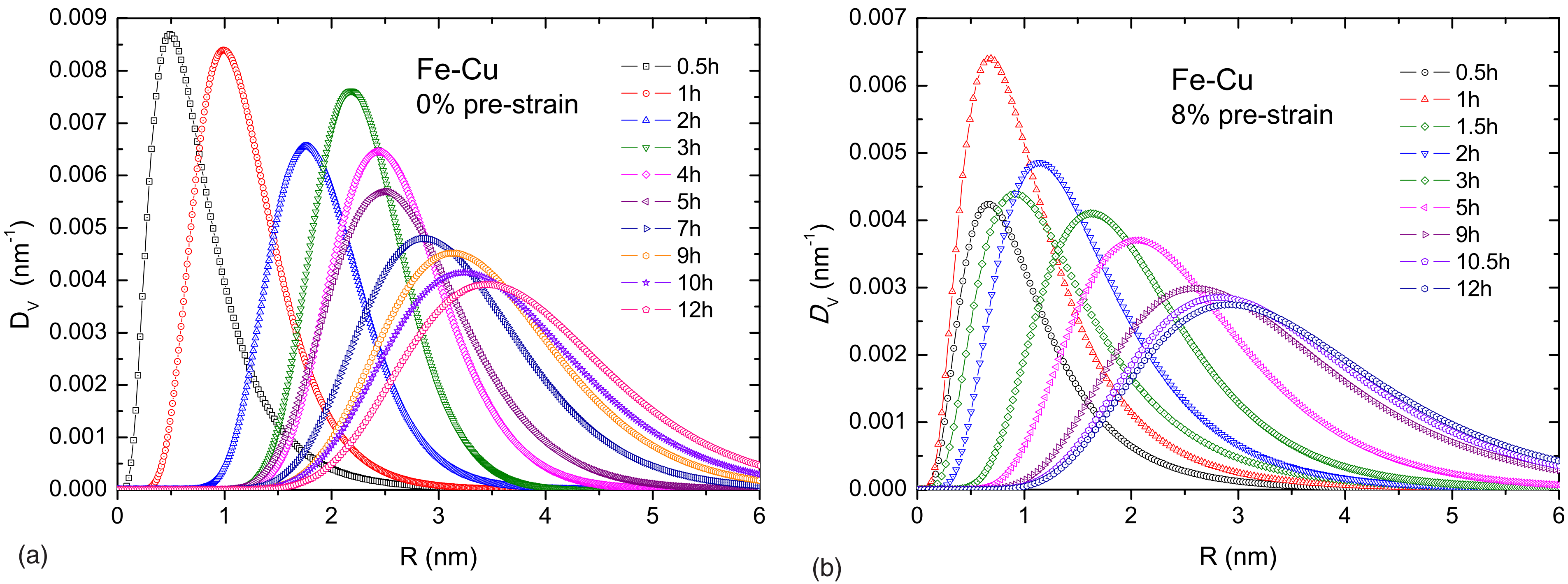
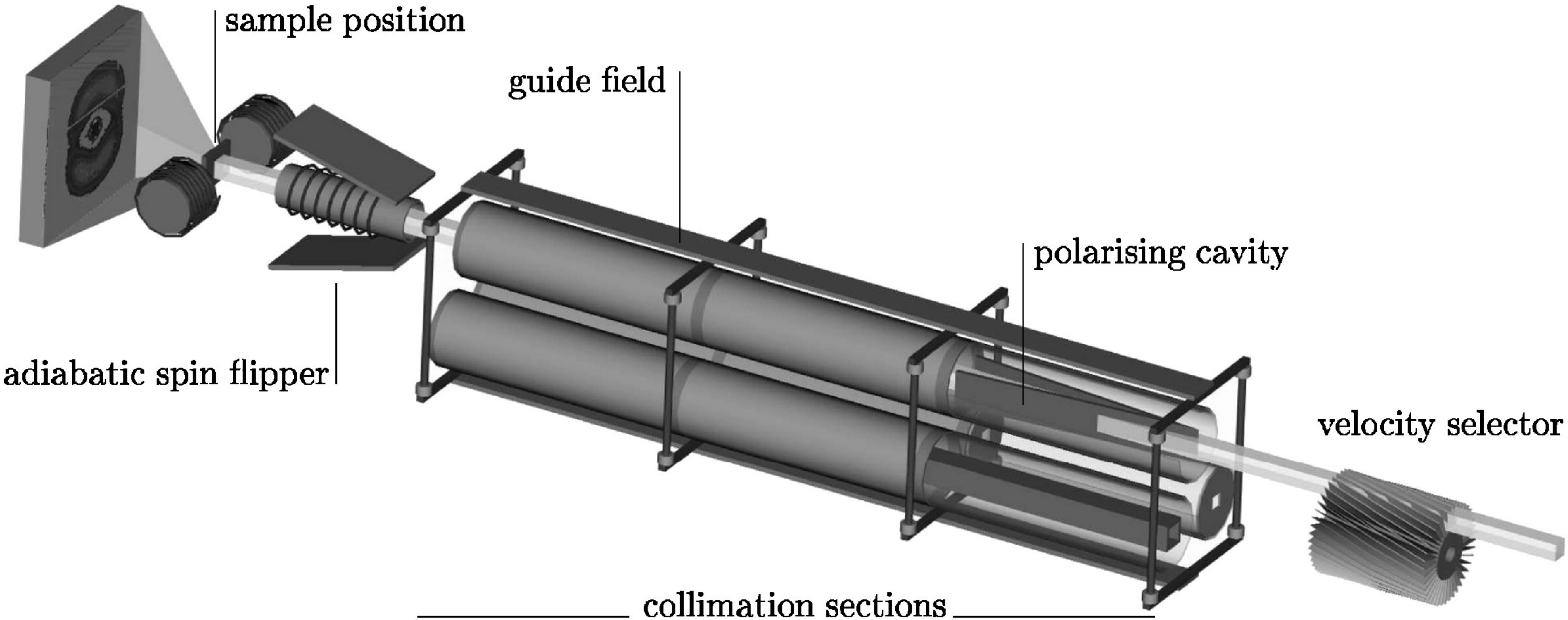
Application: Fe-Cu

- Precipitate size distribution as a function of aging time

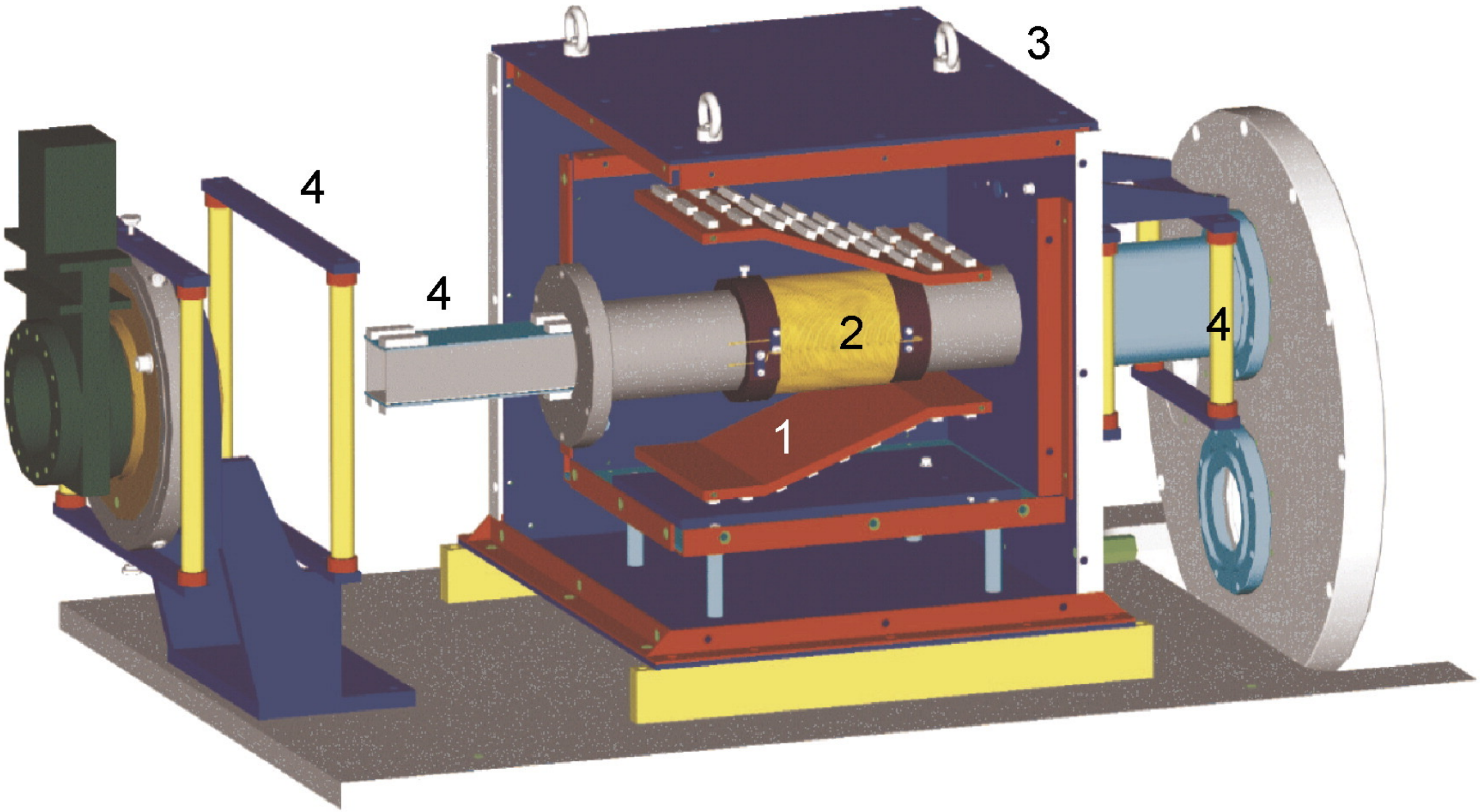


He et al. Physical Review B **82**, 174111 (2010)

Spin-polarized SANS

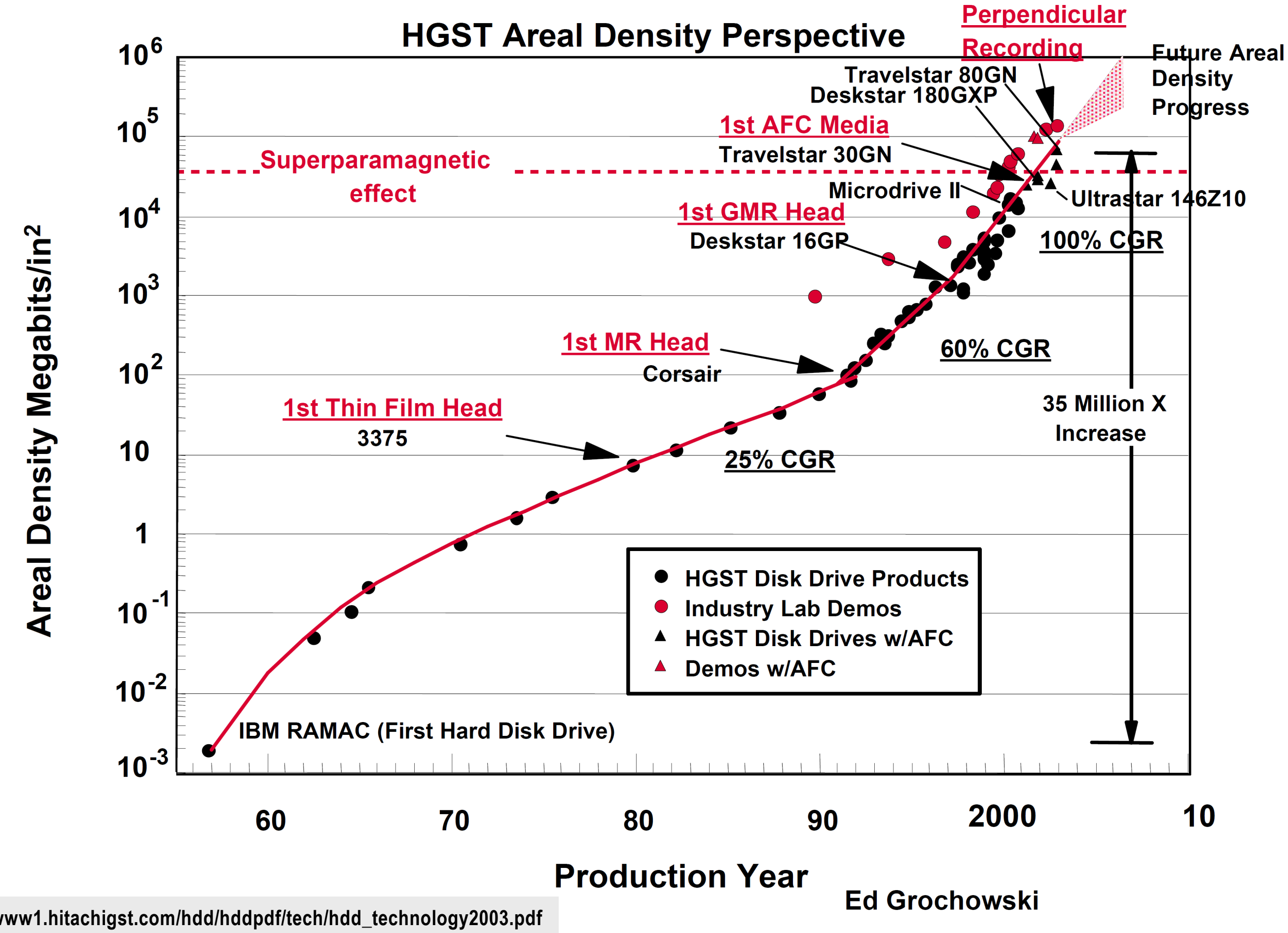


Spin flipper



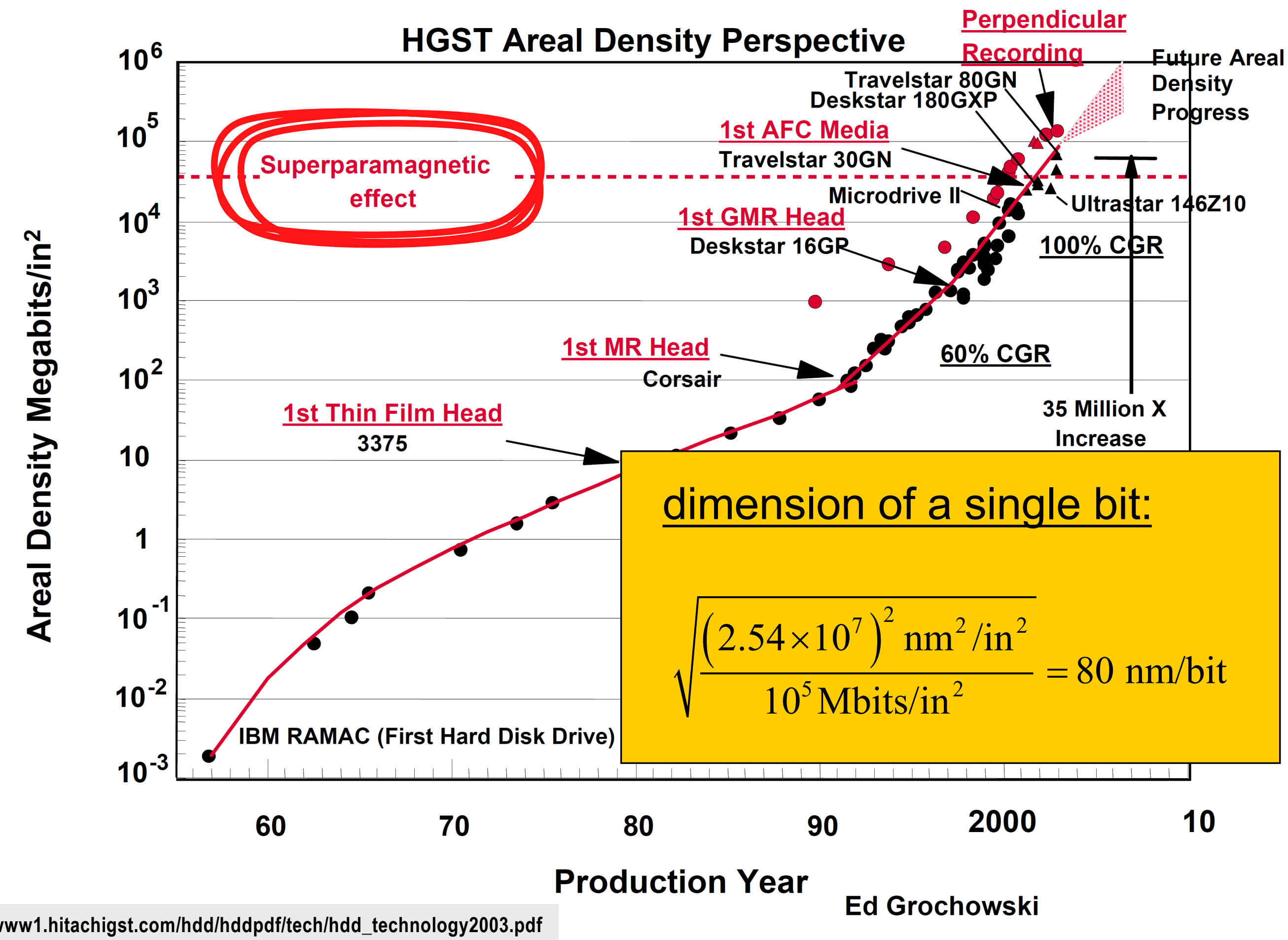
Schematic drawing of the spin flipper setup with (1) the gradient field, (2) the radio-frequency solenoid, (3) the magnetic shielding box and (4) the magnetic guiding field.

superparamagnetic effect



https://www1.hitachigst.com/hdd/hddpdf/tech/hdd_technology2003.pdf

superparamagnetic effect

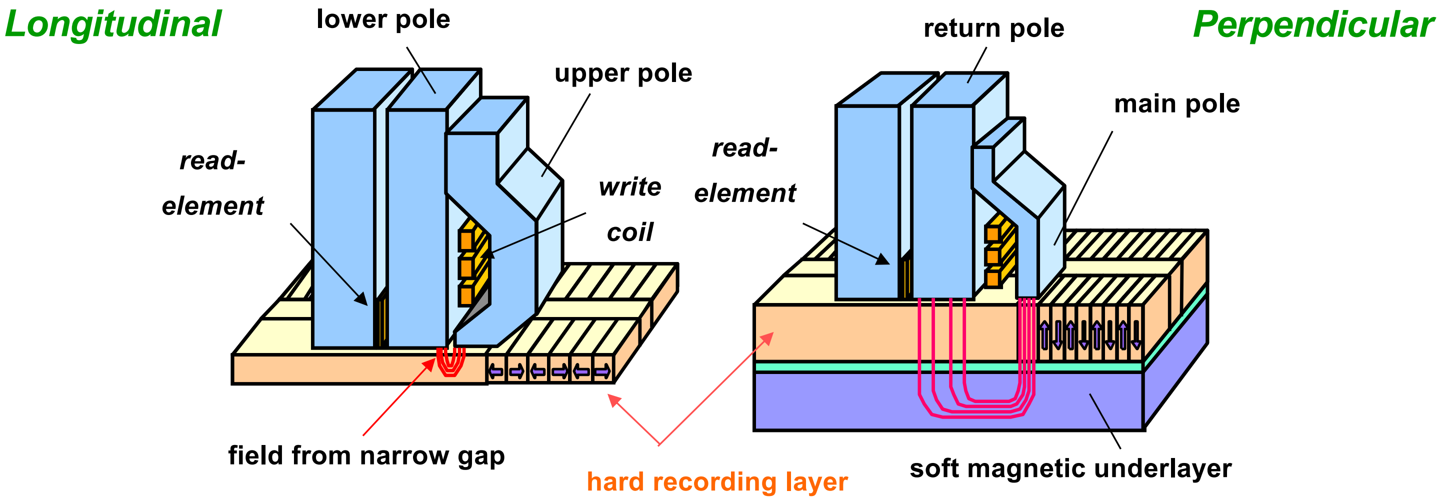


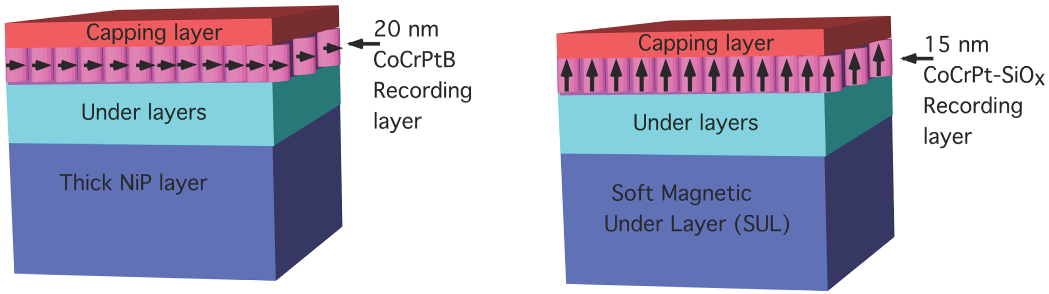
dimension of a single bit:

$$\sqrt{\frac{\left(2.54\times10^{7}\right)^{2}\ \mathrm{nm}^{2}/\mathrm{in}^{2}}{10^{5}\,\mathrm{Mbits/in}^{2}}}=80\ \mathrm{nm/bit}$$

https://www1.hitachigst.com/hdd/hddpdf/tech/hdd_technology2003.pdf

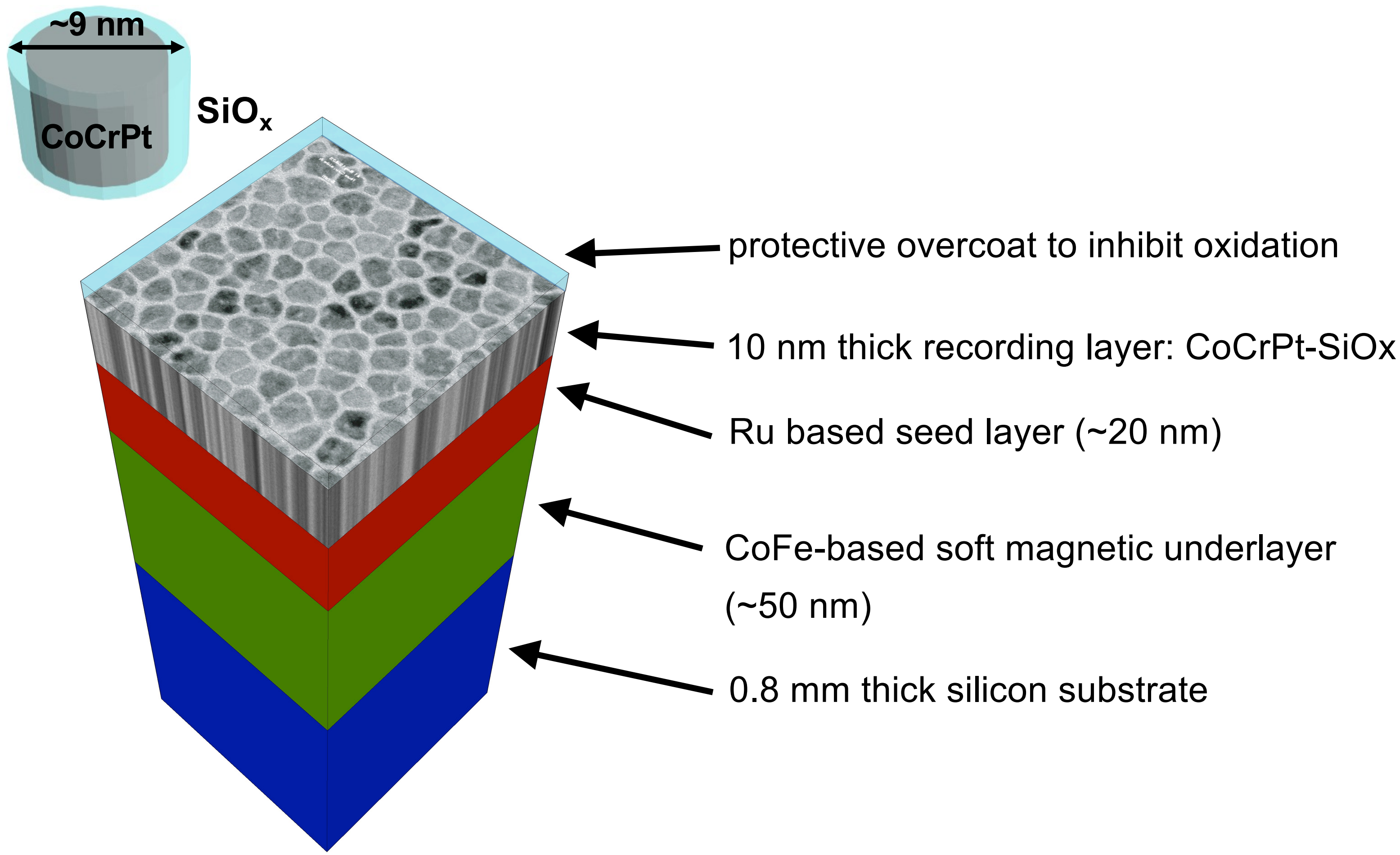
recording media



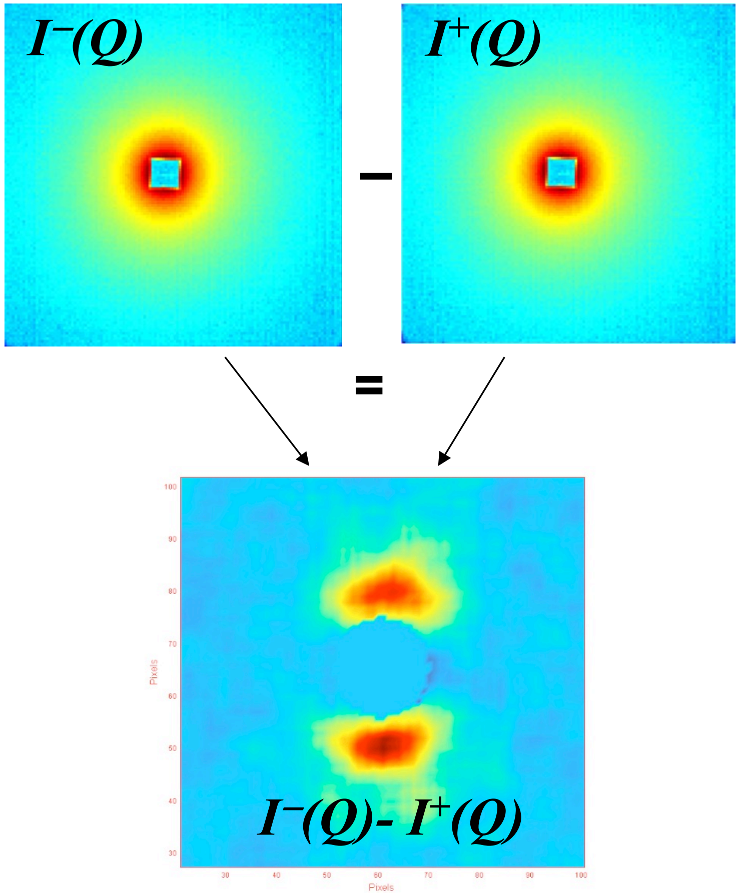


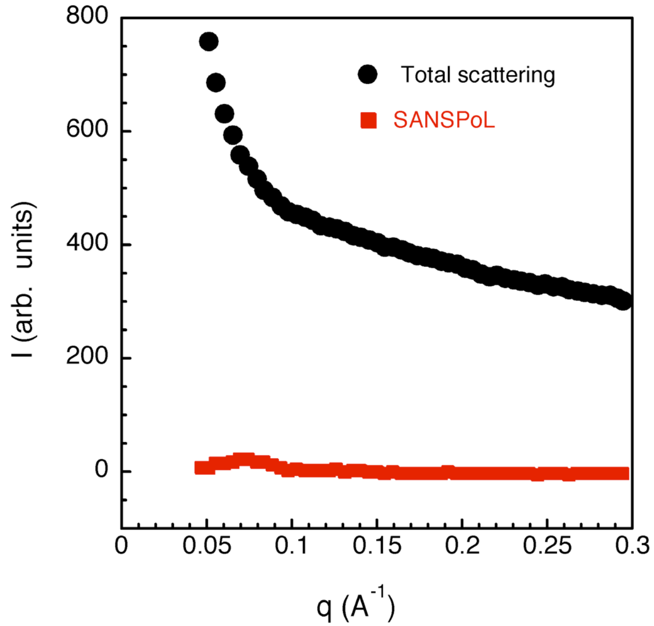
perpendicular recording allows higher head field and taller grains ➔ smaller grain area.

compositionally inhomogeneous PRM

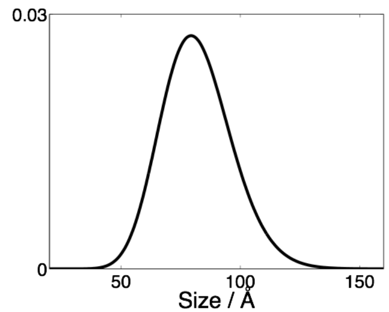


benefits of using spin-polarised SANS



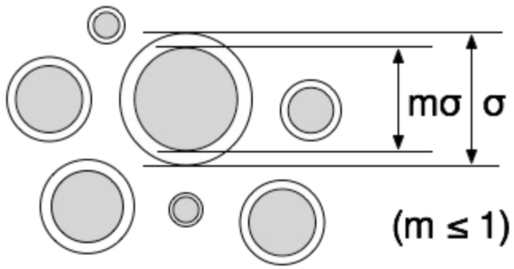


modeling of scattering data: analytic model

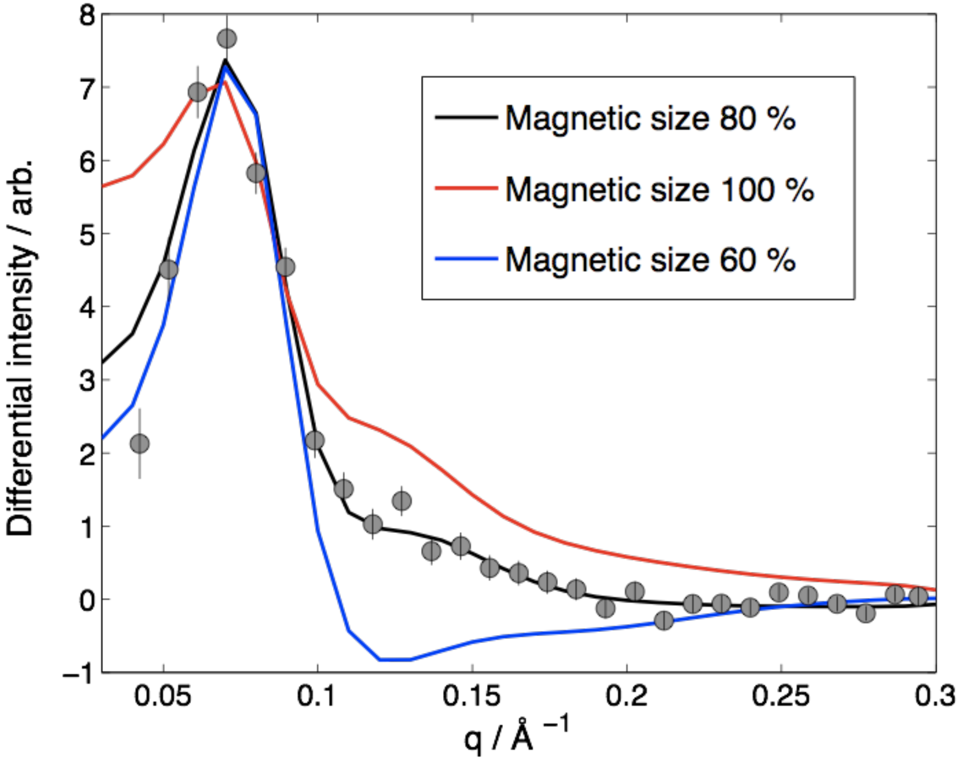


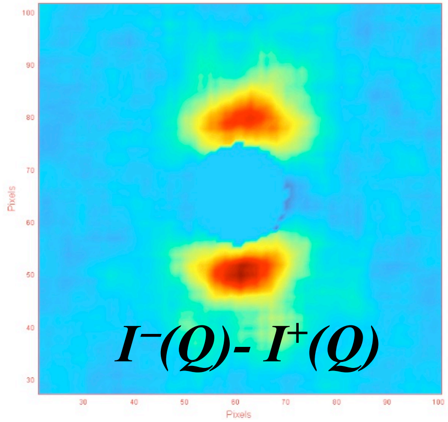
- $F(q,\sigma)$ form-factor (cylindrical, diameter σ)
- $S(q,\sigma_1,\sigma_2)$ partial structure factor for poly-disperse P-Y model
- $f(\sigma)$ size distribution (Gamma-Schulz)
- differential intensity can then be written:

  $\int F_N(\sigma)\, F_M(\sigma)\, f(\sigma)\, d\sigma + \int\int F_N(\sigma_1)\, F_M(\sigma_2)\, f(\sigma_1)\, f(\sigma_2)\, S_{12}(q,\sigma_1,\sigma_2)\, d\sigma_1\, d\sigma_2$
- for grains of given size, the size and strength of the magnetised region can then be varied freely



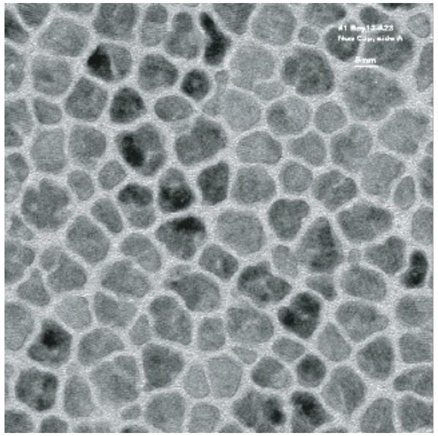
Modeling scattering data: real space images



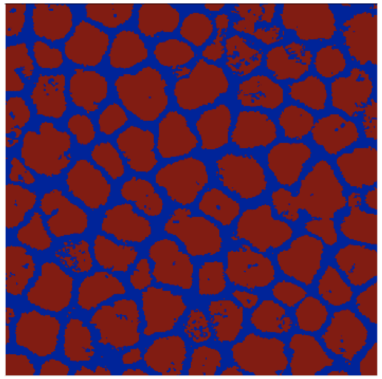


modeling scattering data: real space images

transmission electron microscope (TEM) image of surface of recording layer



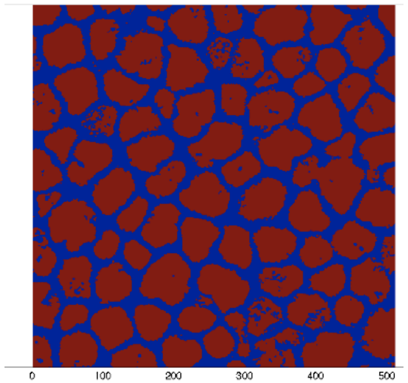
processed image to give two-level contrast



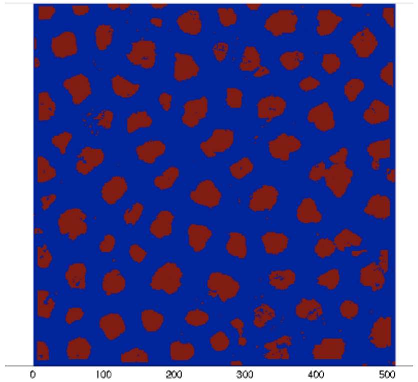
- TEM image clearly shows the heterogeneous granular structure
- nuclear scattering contrast is expected to be similar
- metallic grains are magnetised, while inter-granular medium is non-magnetic. However the full volume of the grain may not be uniformly magnetised

modeling scattering data: real space images

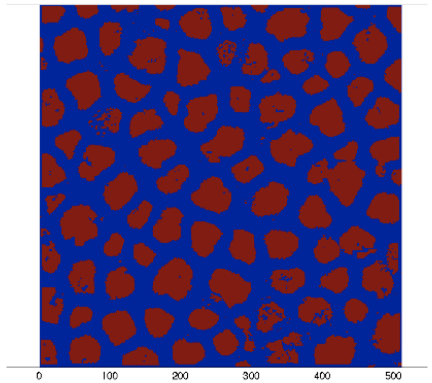
Magnetic scale 100 %

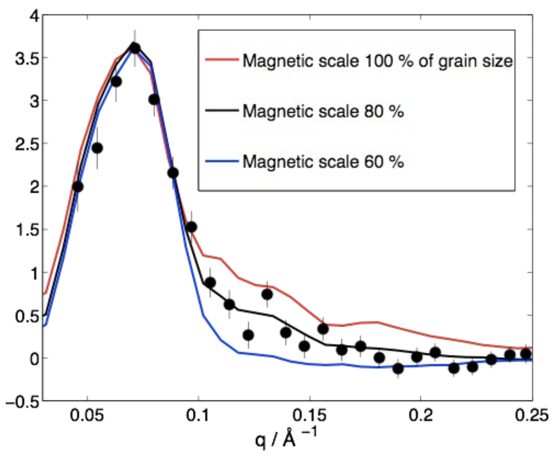


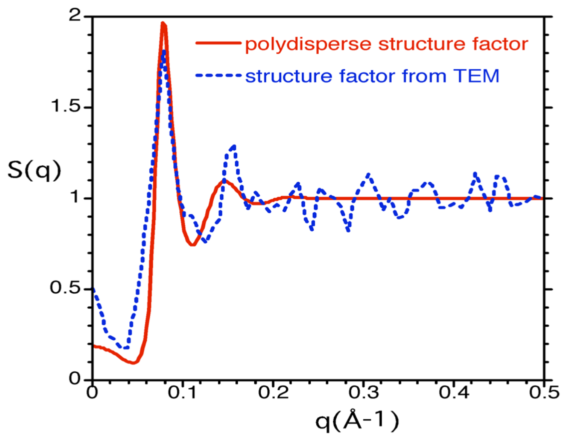
Magnetic scale 60 %



Magnetic scale 80 %



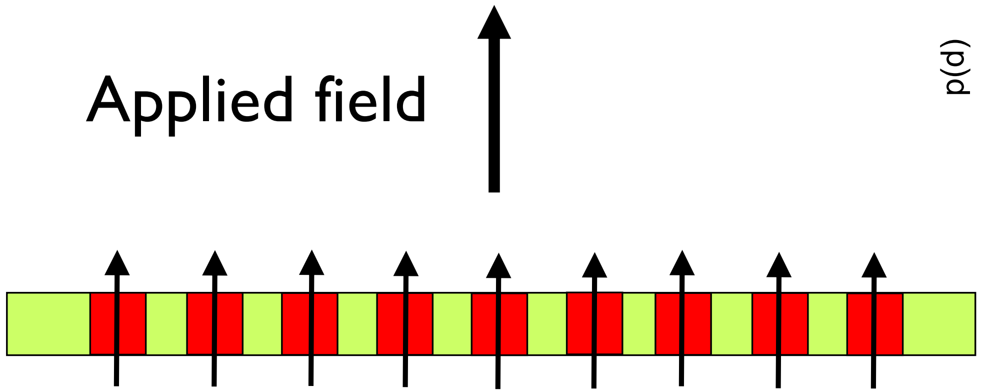


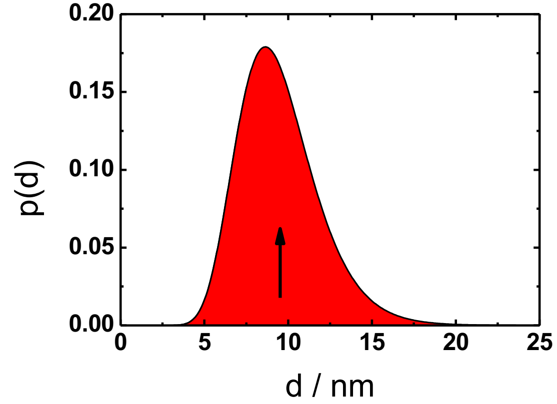


comparison of the structure factor obtained from the center of the grains in the TEM image and from the analytical model

‘Switching’ experiment

Applied field

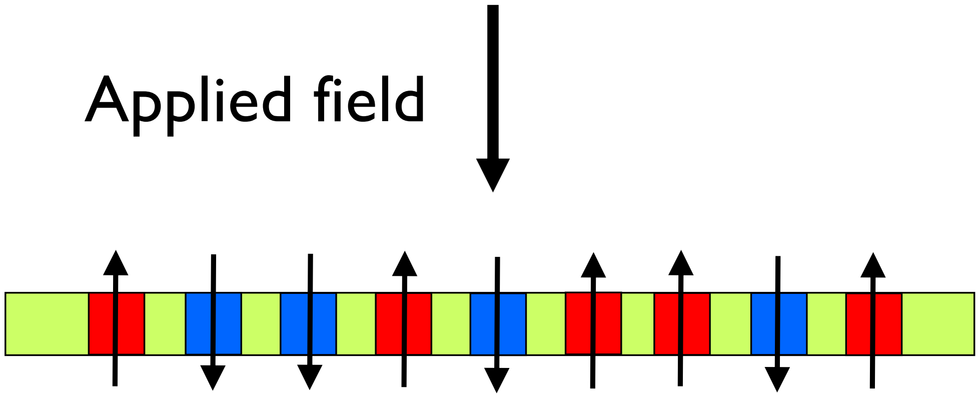


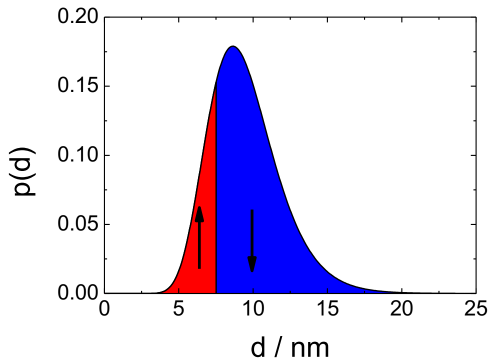


Recording layer

1. first saturate with out-of-plane field

‘Switching’ experiment



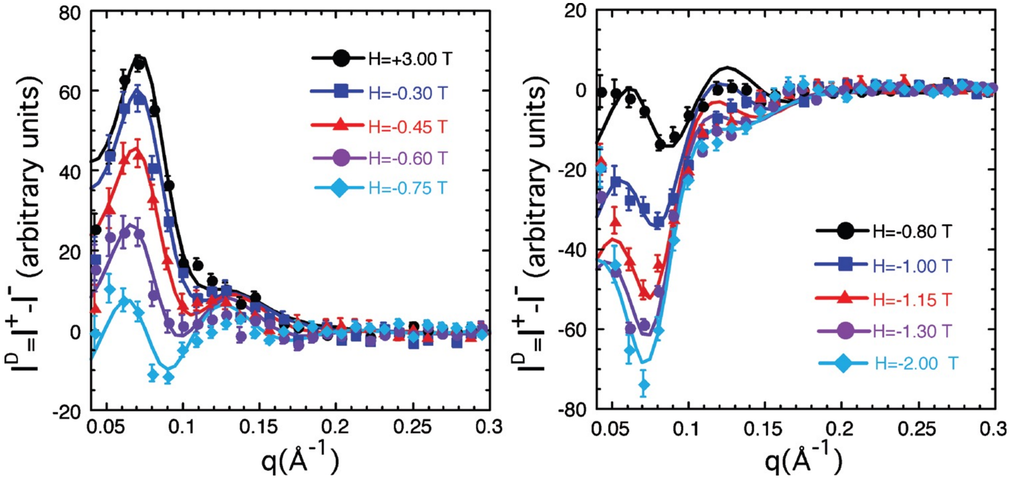


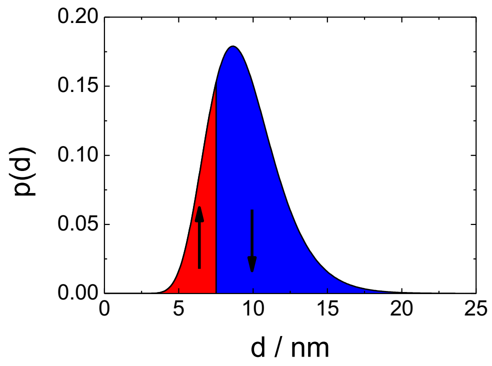
Recording layer

1. first saturate with out-of-plane field

2. then apply reverse field

'Switching' experiment



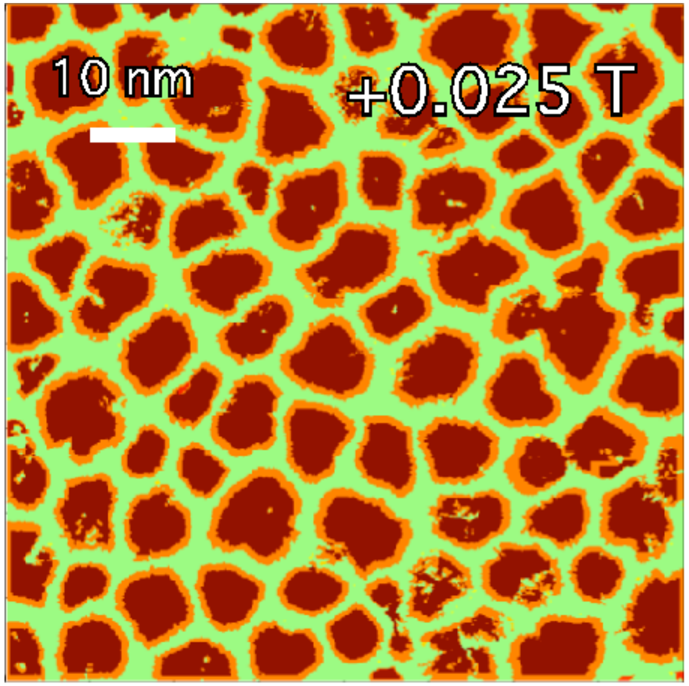


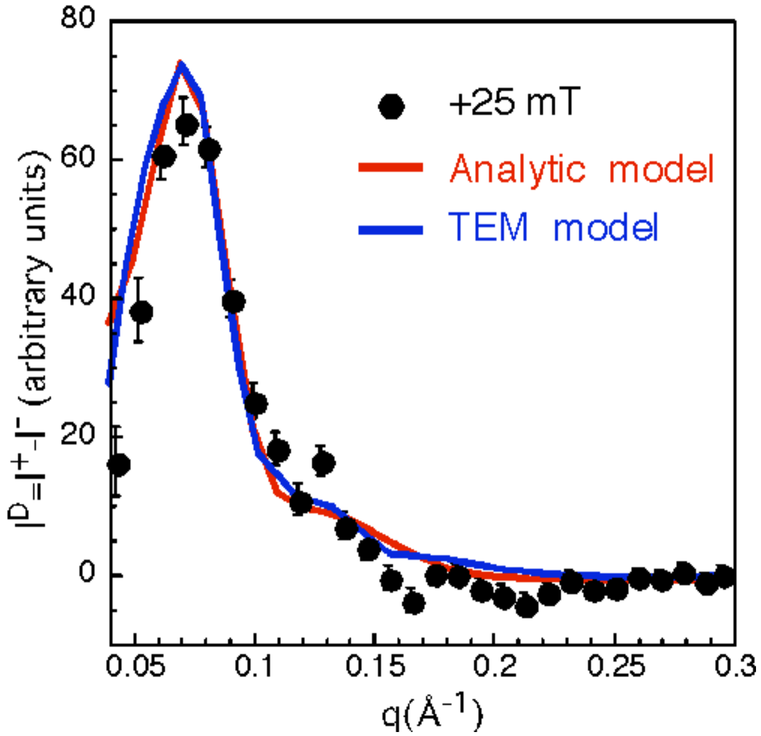
$I^-(Q)$- $I^+(Q)$ ➡ **changes sign** as grains reverse magnetisation

q-dependency ➡ **length scale** over which reversal has occurred

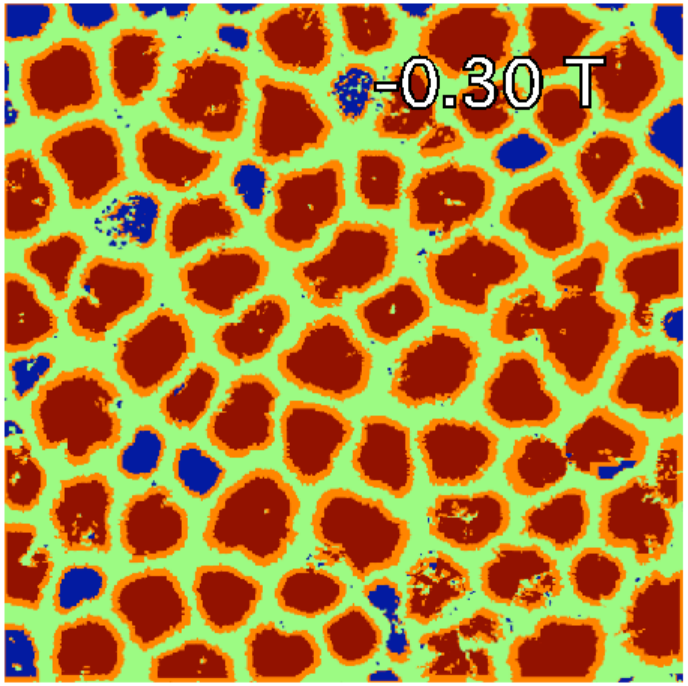
➡ **Information on which sized grains reverse at each reversal field**

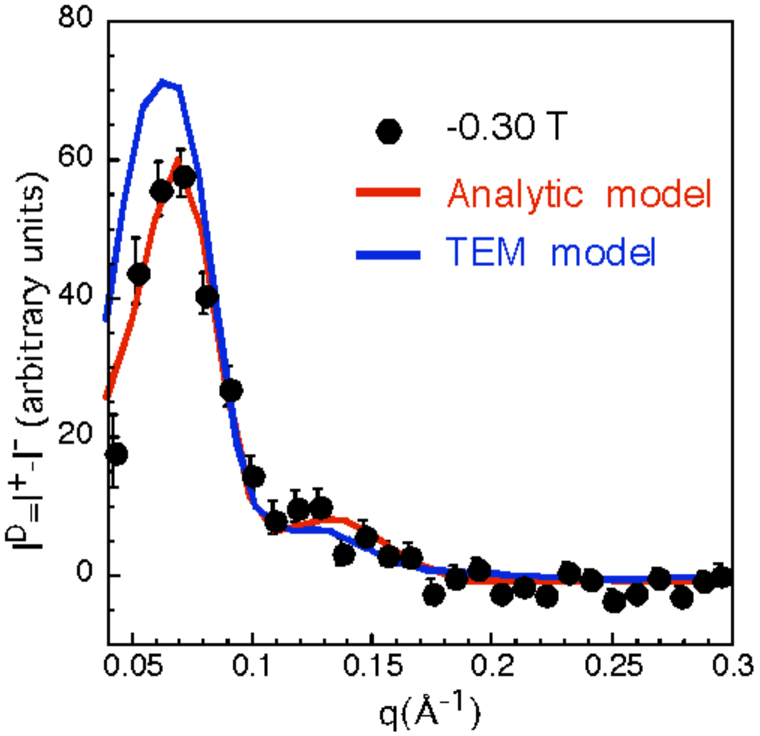
‘Switching’ experiment



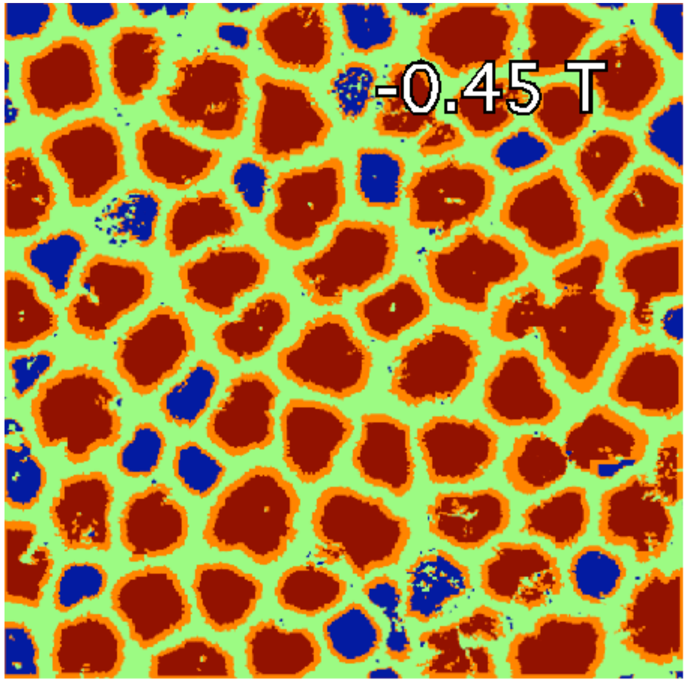


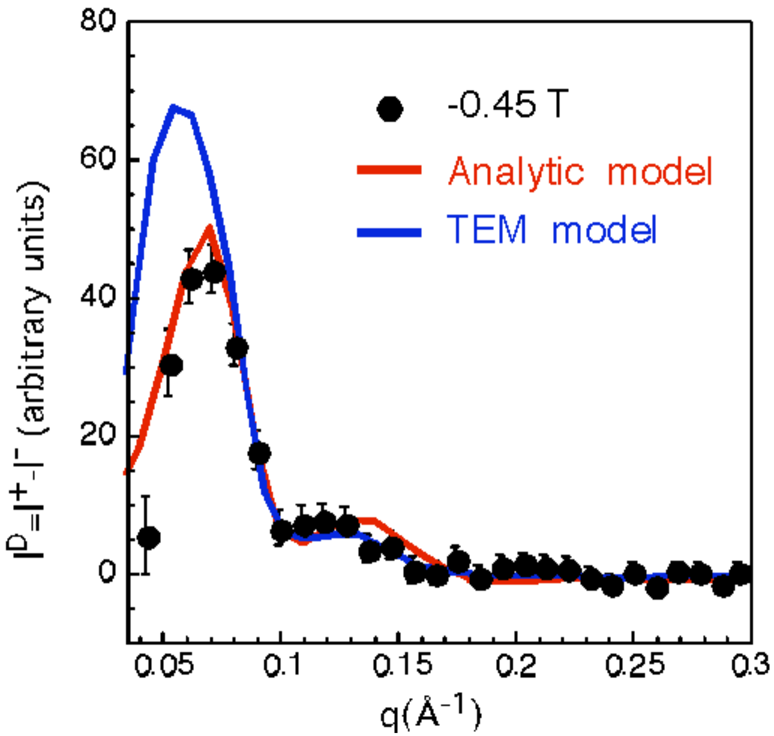
‘Switching’ experiment



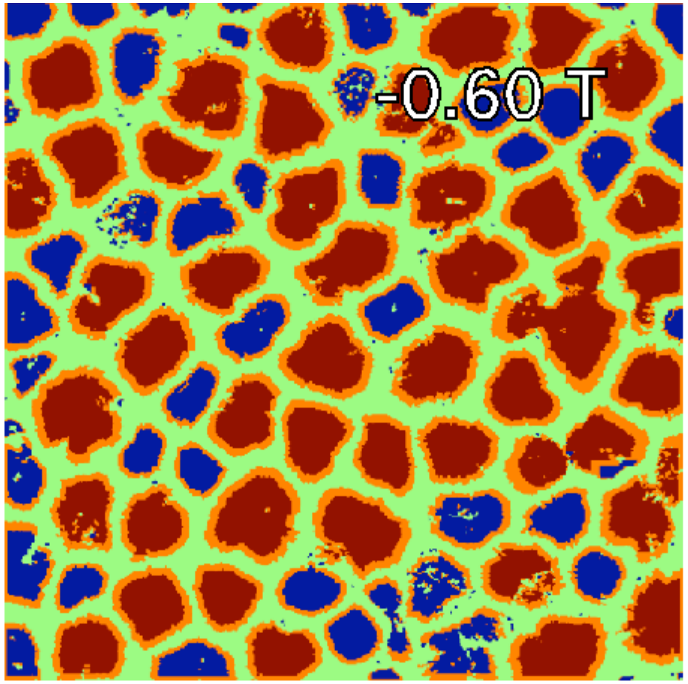


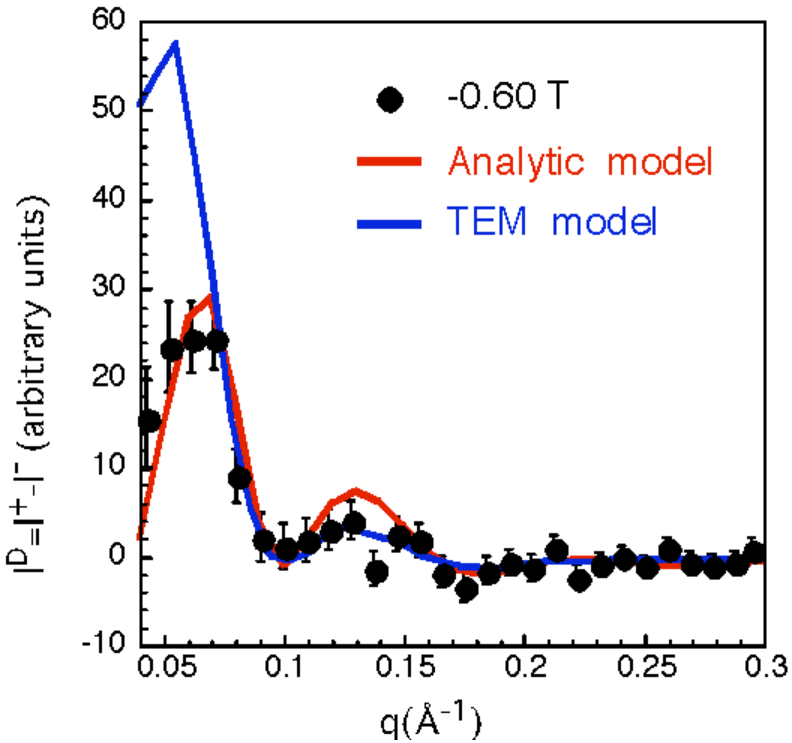
‘Switching’ experiment



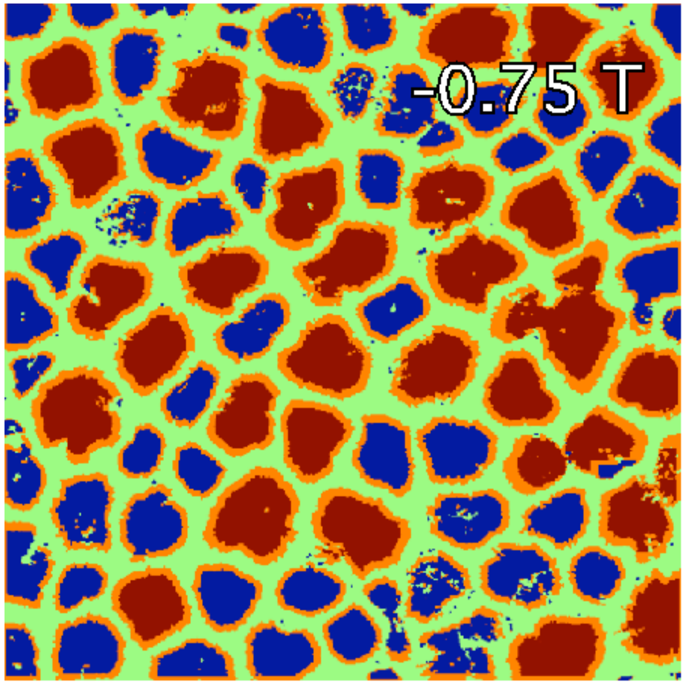


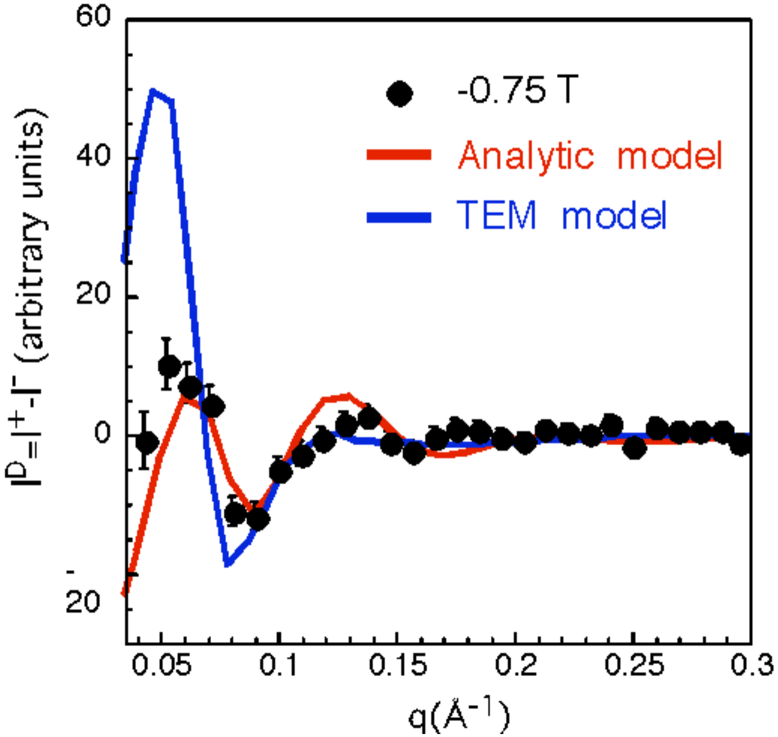
‘Switching’ experiment



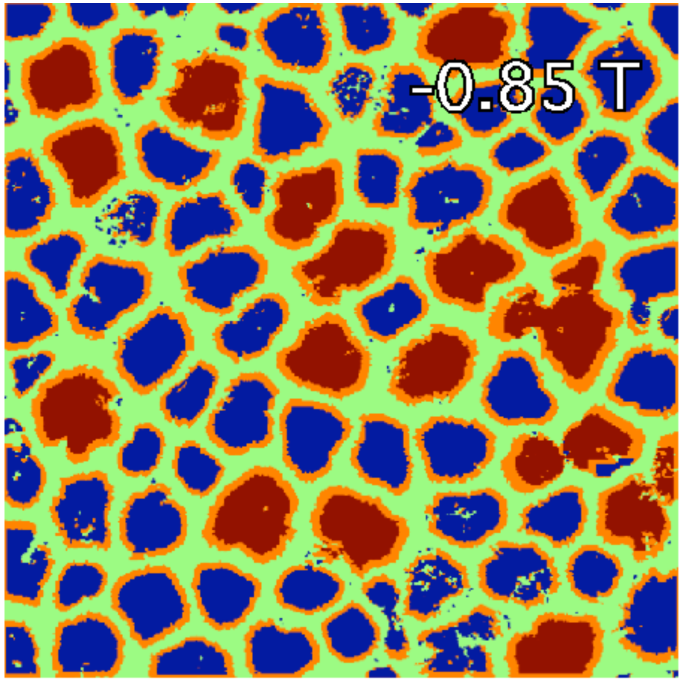


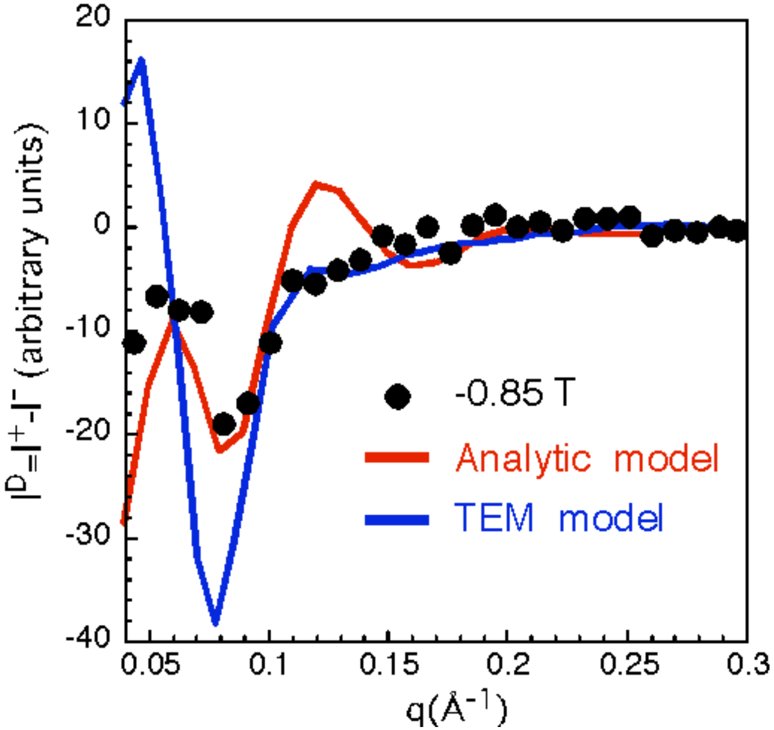
‘Switching’ experiment



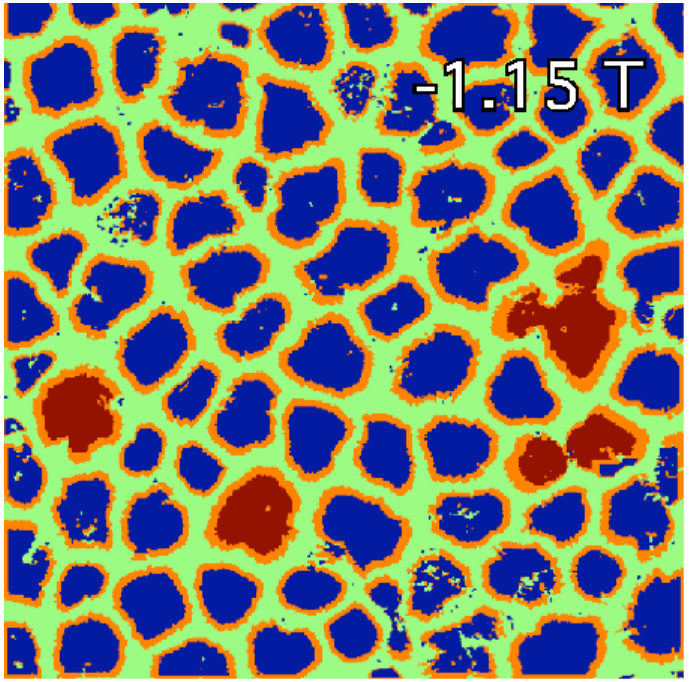


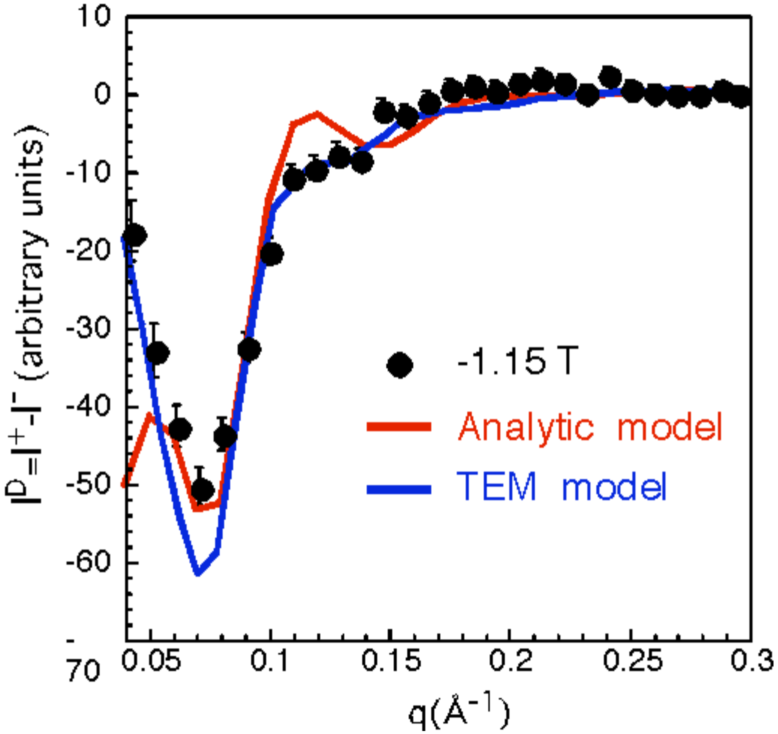
‘Switching’ experiment



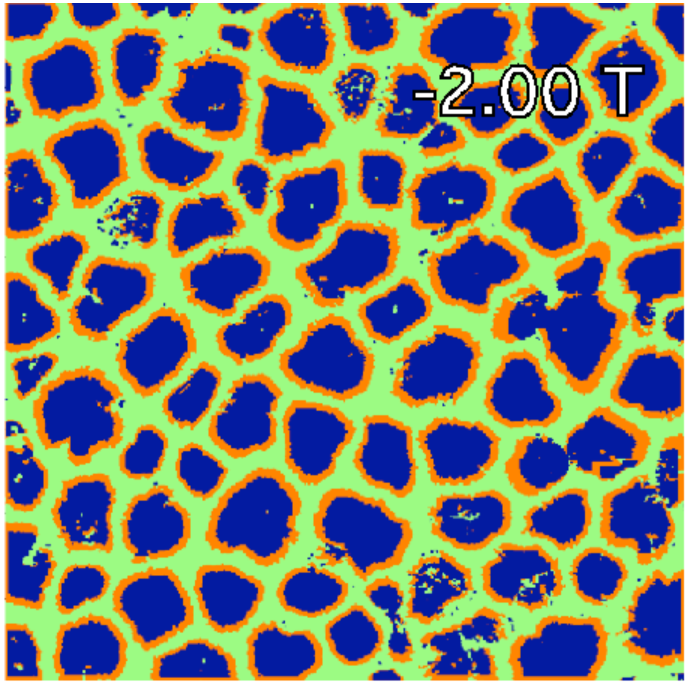


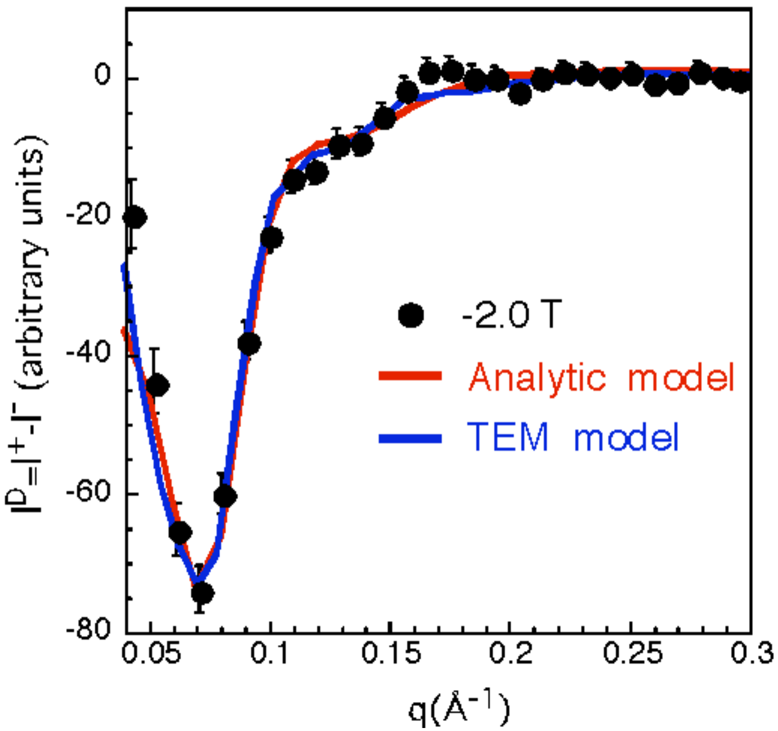
‘Switching’ experiment





‘Switching’ experiment

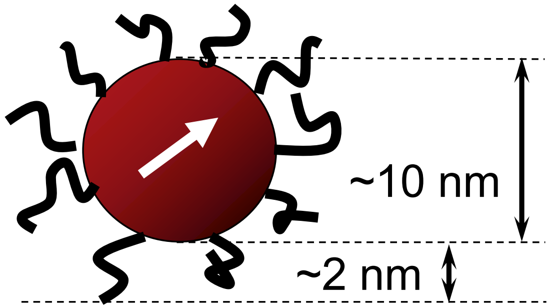




Ferrofluids

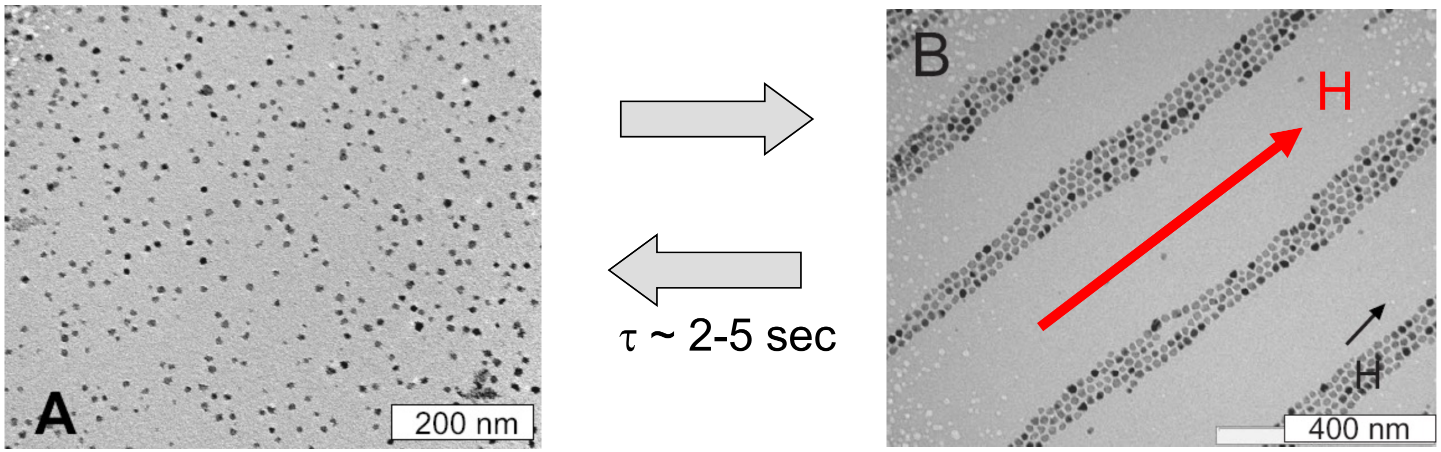
https://youtu.be/n8Zvyr2Bc5Y

Magnetic colloids



ferromagnetic core
(e.g. Co, Fe_3O_4)

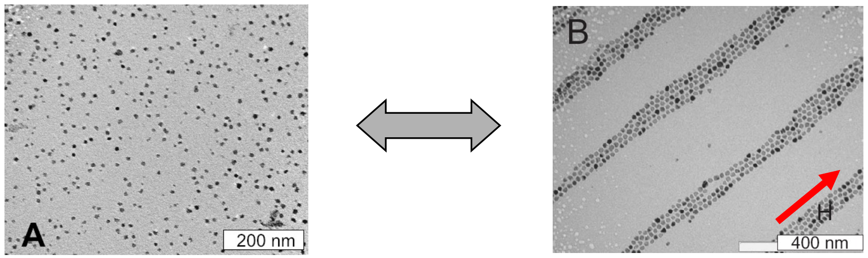
stabilizing surfactants

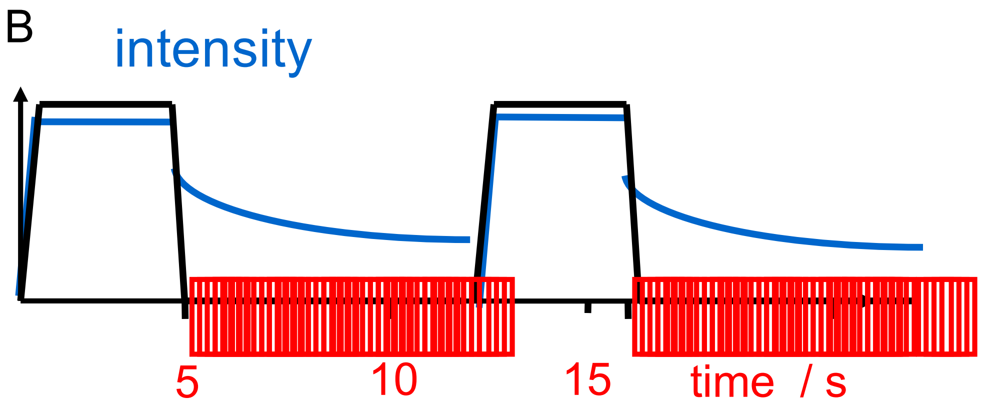


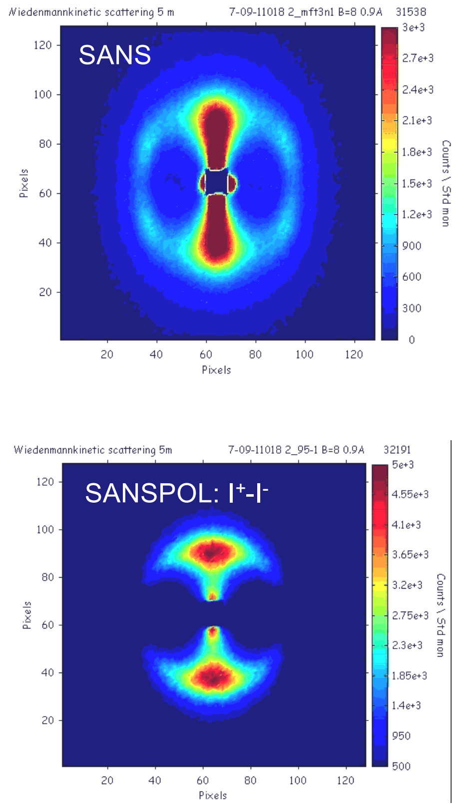
zero field

field induced ordering

time-resolved SANS and SANSPOL







decay of nuclear and magnetic

correlations measured in time

slices of 0.1 s

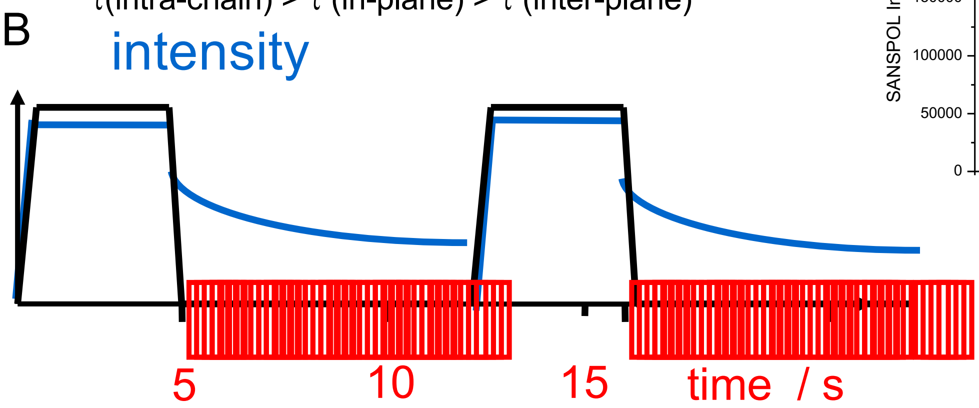
duty cycle 15-30 s

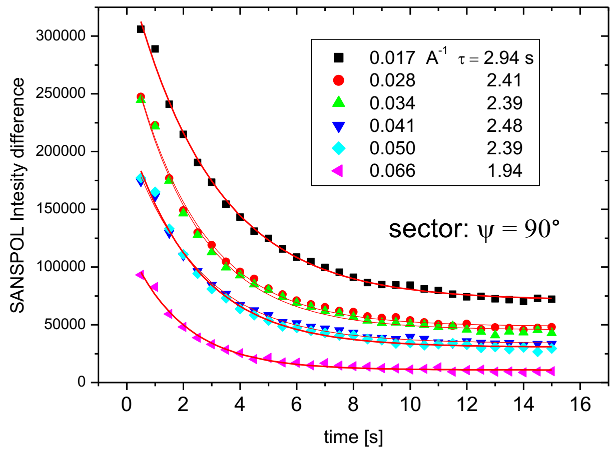
Physica B 385–386 (2006) 453–456

time-resolved SANSPOL

switch-off of B:

- slow decay of field-induced ordering (few seconds).
- fully reversible relaxation onto equilibrium
- single exponential decay:
  time constants depending on Q and B_{max}
  τ(intra-chain) > τ (in-plane) > τ (inter-plane)





Slow exponential decay

when B is switched off

$I(t)=I_0 \exp(-t/\tau)$

switch-on of B:

reordering follows B-sweep rate: process too fast!

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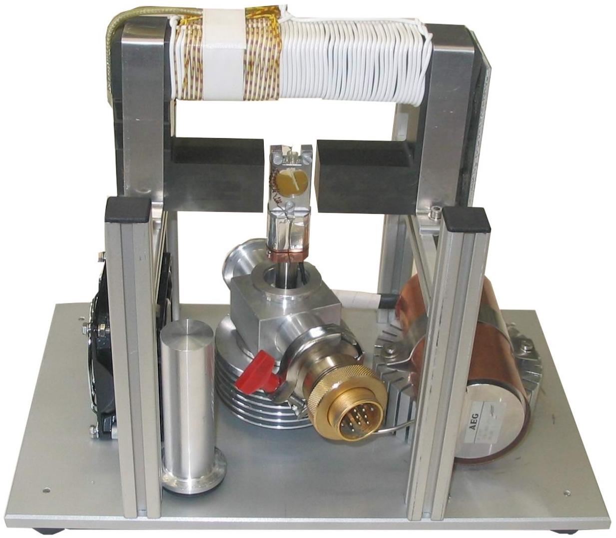
Extensions: Sample environments

small electromagnet with closed cycle refrigerator



tempertures :

70K - 300K

magnetic field:

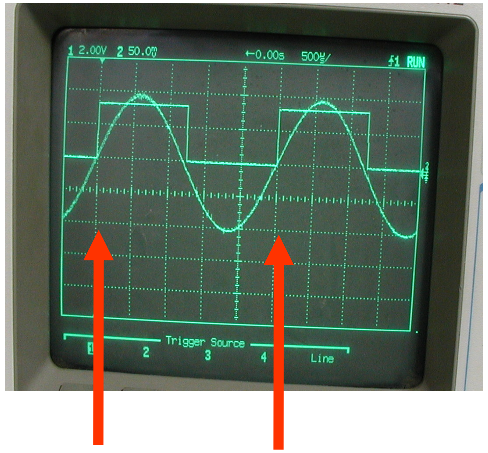
ac, dc, ac+dc :

± 40 mT

frequency:

sine-wave, square

υ : mHz… 5 kHz

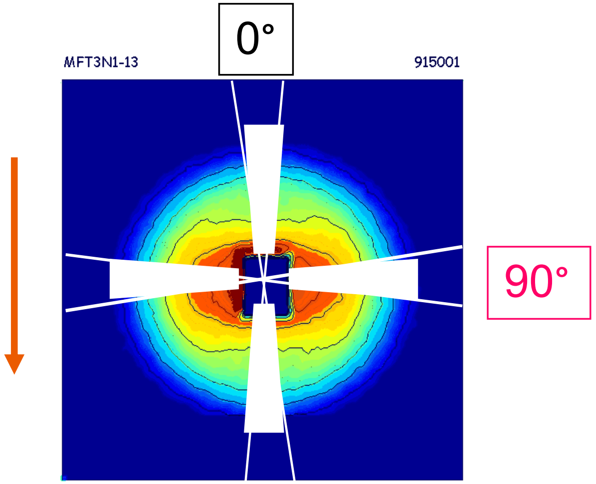


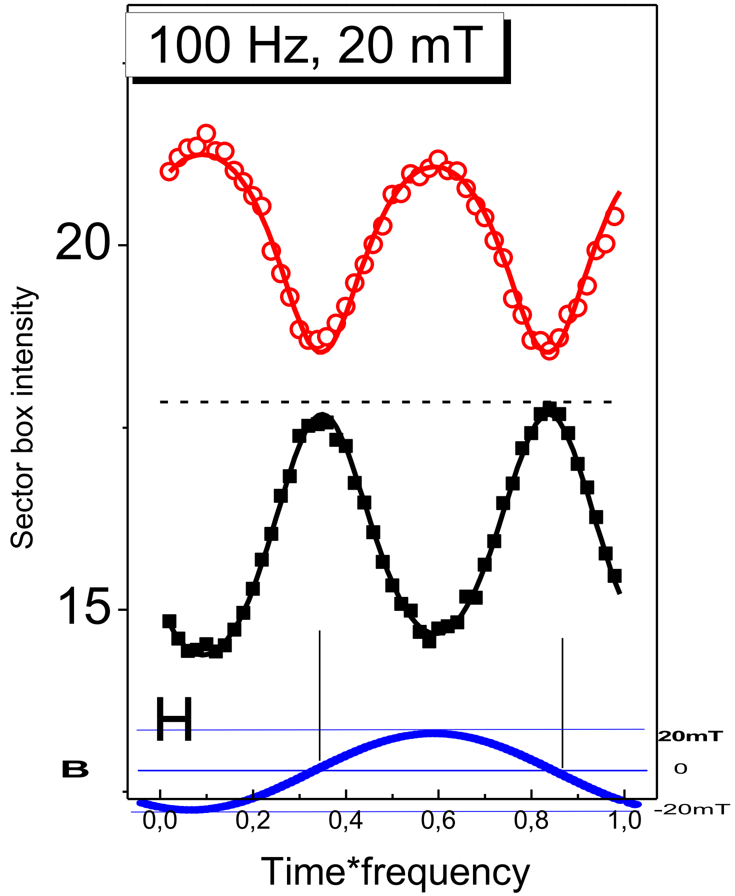
trigger for data acquisition of 2D detector

A . Wiedemann et al Physical Review B 77 (2008) 184417

stroboscopic SANS

ν_s = 100 Hz B_0= 20 mT



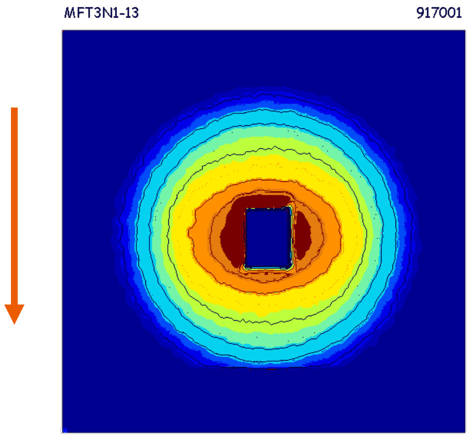


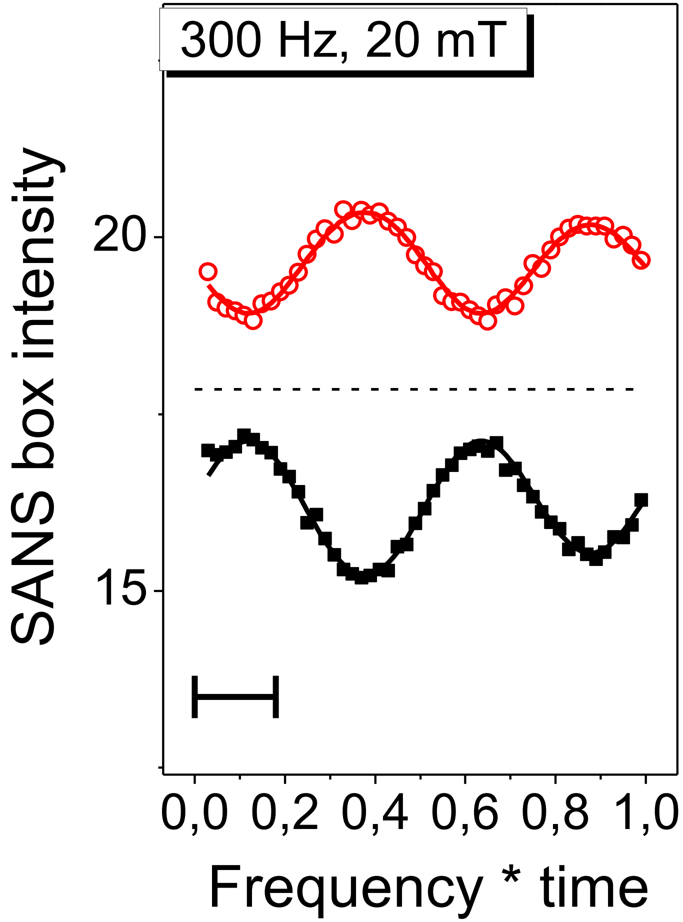
frequency of response

twice of B-field

stroboscopic SANS

ν_s = 300 Hz B_0= 20 mT



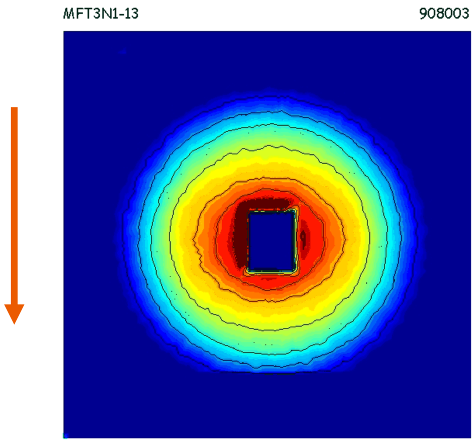


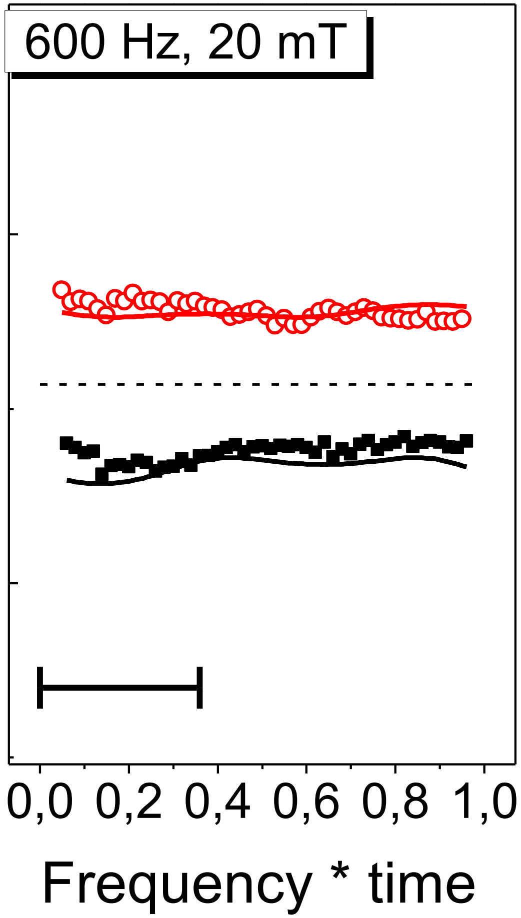
damping of oscillations

with increasing frequency

stroboscopic SANS

ν_s = 600 Hz B_0= 20 mT





damping of oscillations

with increasing frequency