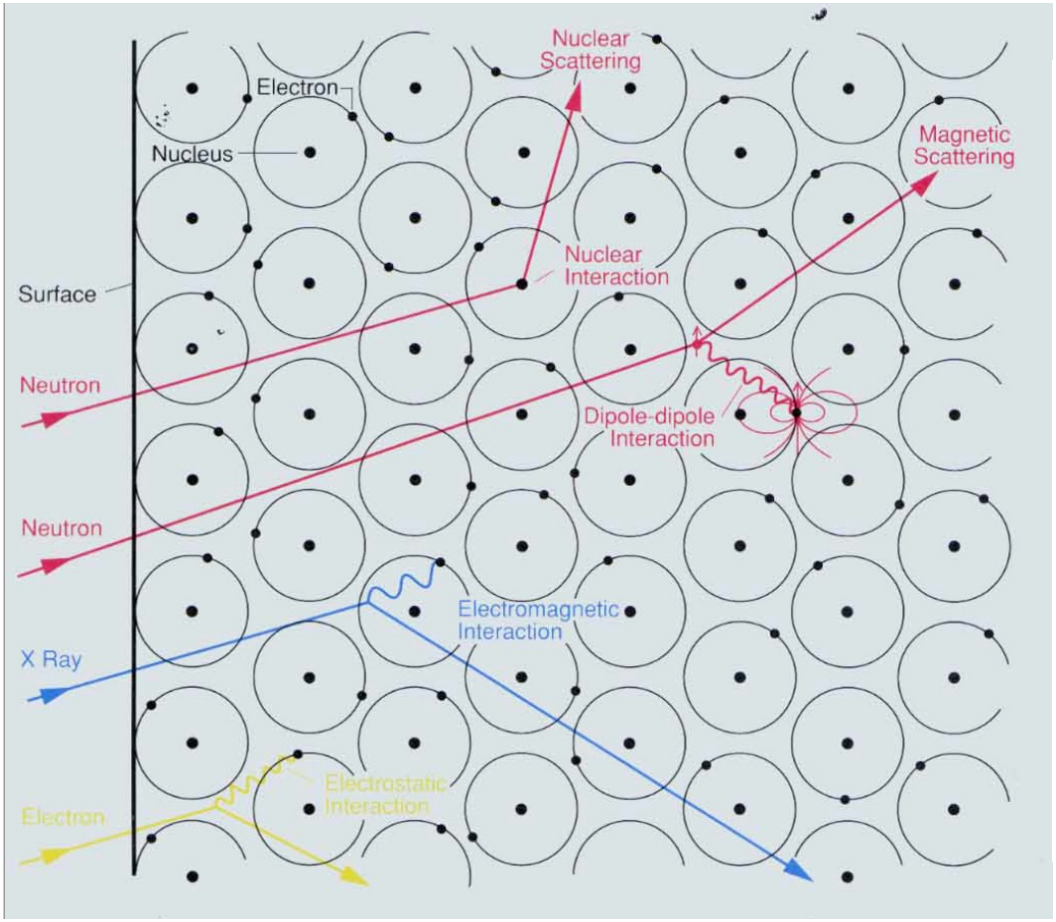
PAUL SCHERRER INSTITUT

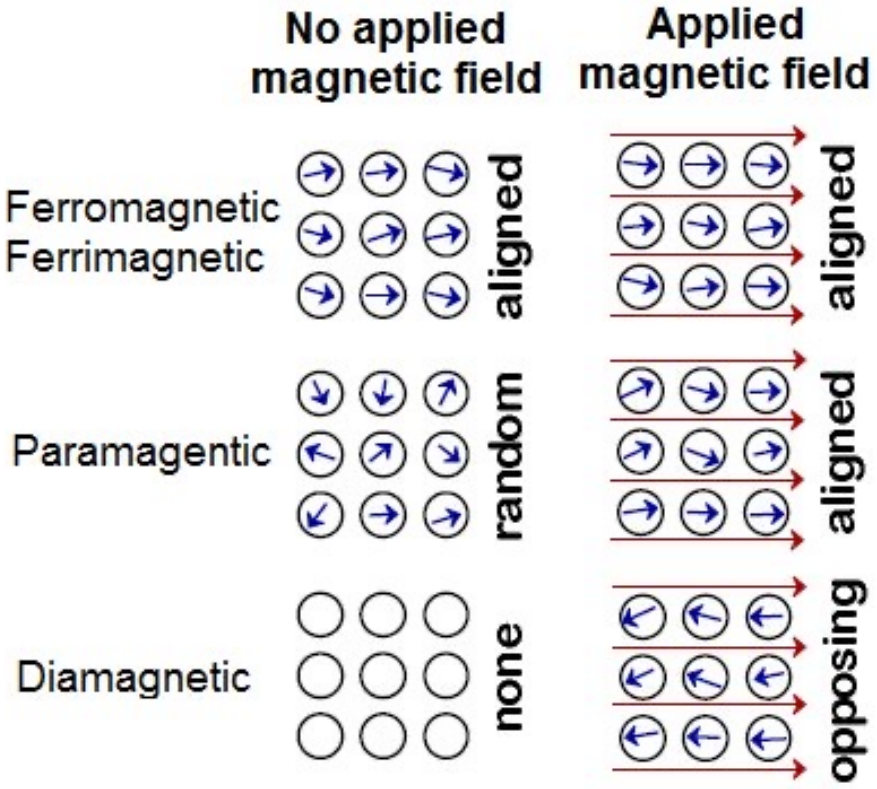
PSI

Materials Science at Large Scale Facilities

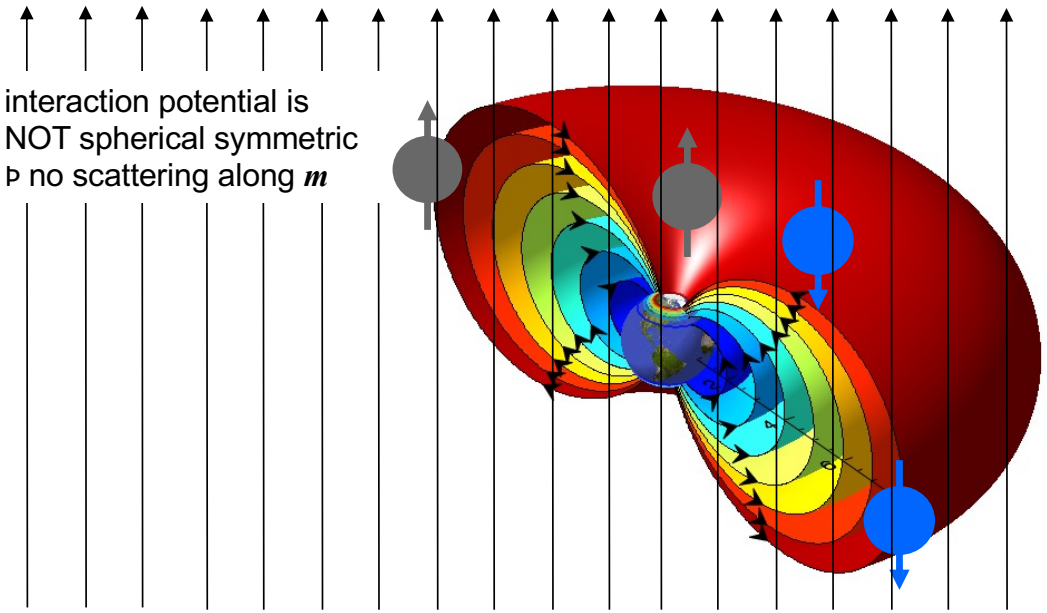
Magnetic Scattering

Nuclear vs magnetic interaction



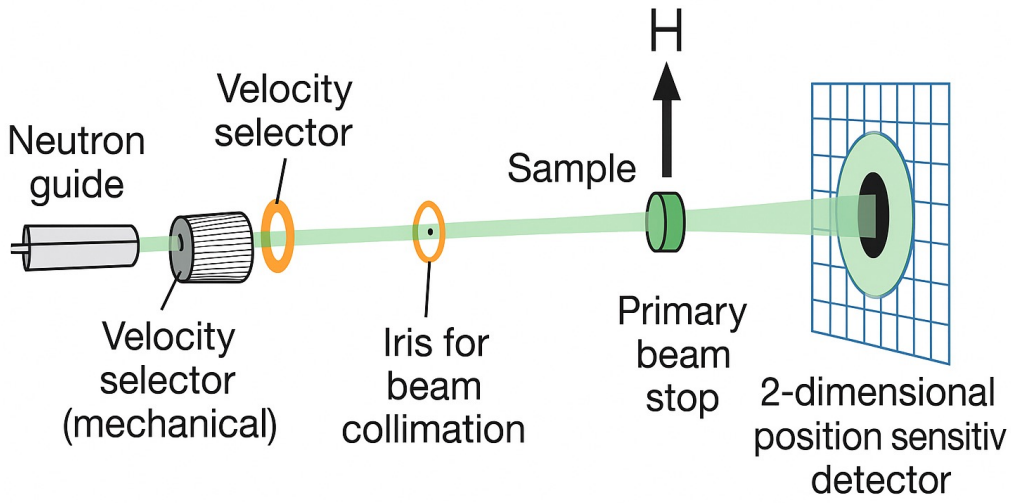


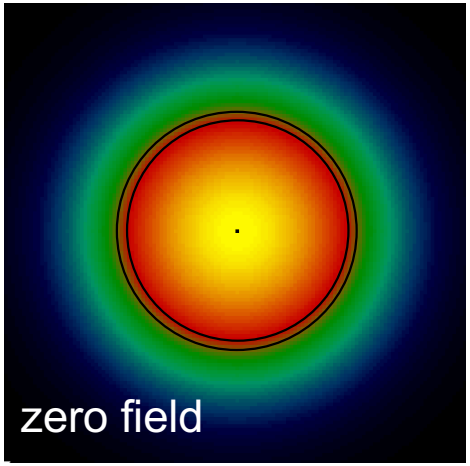
Magnetic scattering

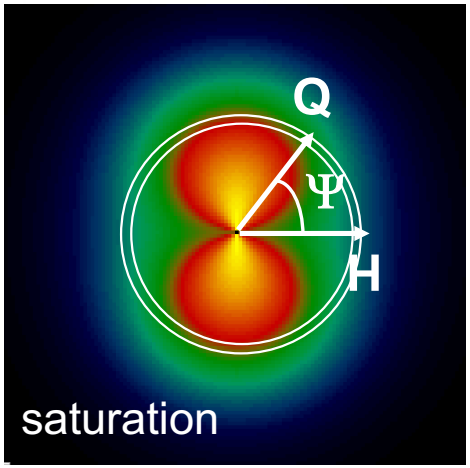


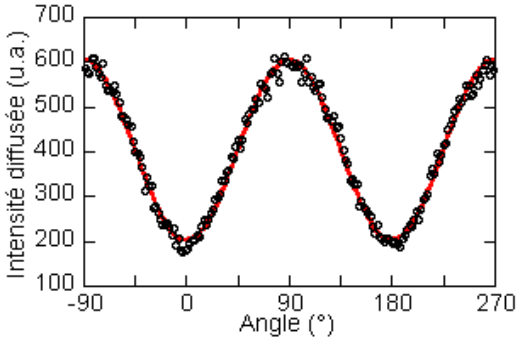
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right)$$

Magnetic scattering



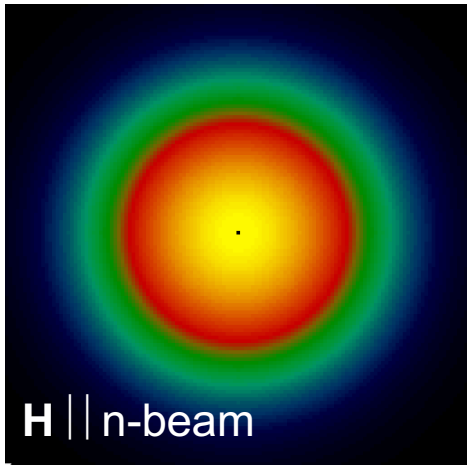






$$\frac{d\sigma}{d\Omega} = F_N^2(Q,R) + F_M^2(Q,R)\sin^2\Psi$$

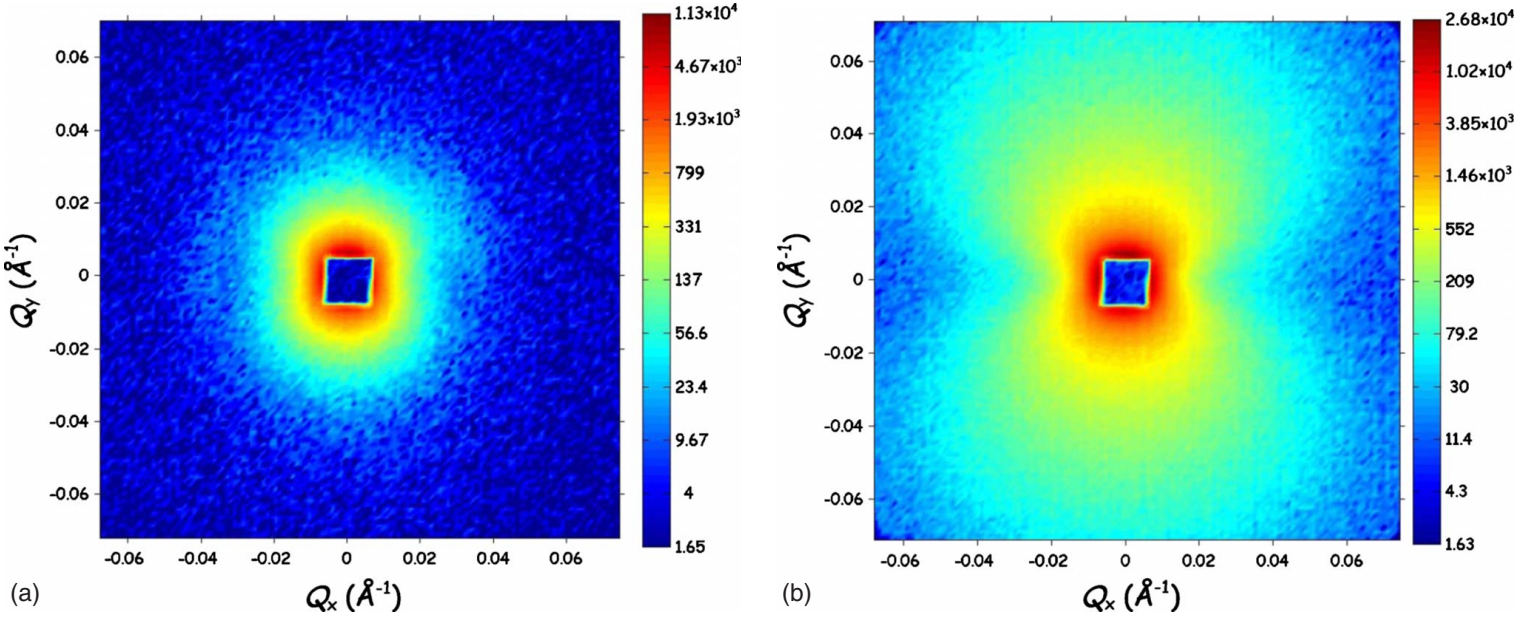
Magnetic scattering



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

Application: Fe-Cu

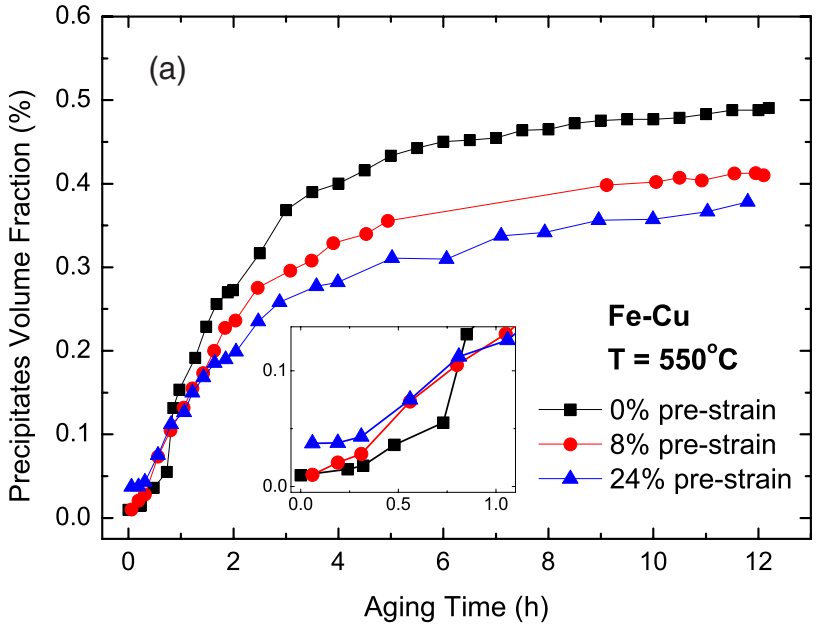
- Self-healing in ferritic steels
- Dynamic formation of precipitates
- Model system: Fe-1wt%Cu
- Comparison with and without pre-strain of 8% and 24%

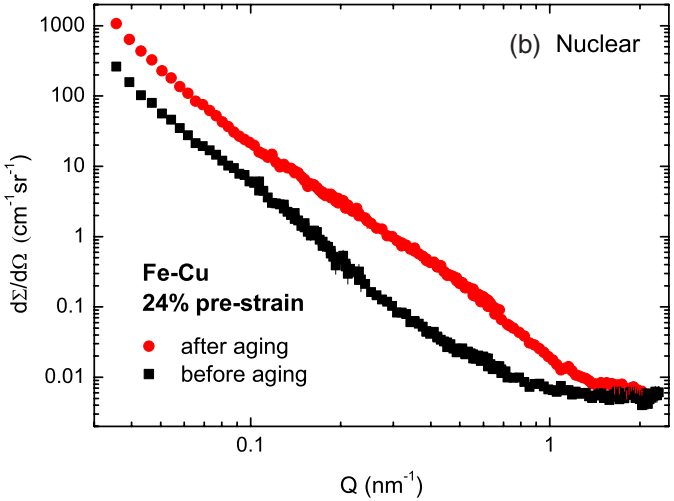


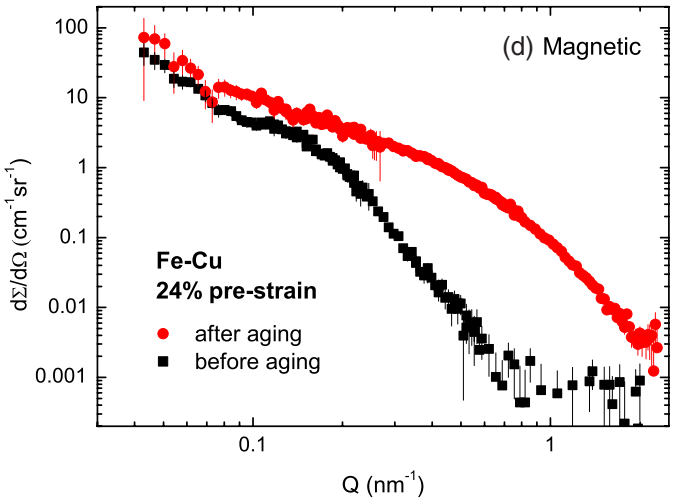
He et al. Physical Review B **82**, 174111 (2010)

Application: Fe-Cu

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



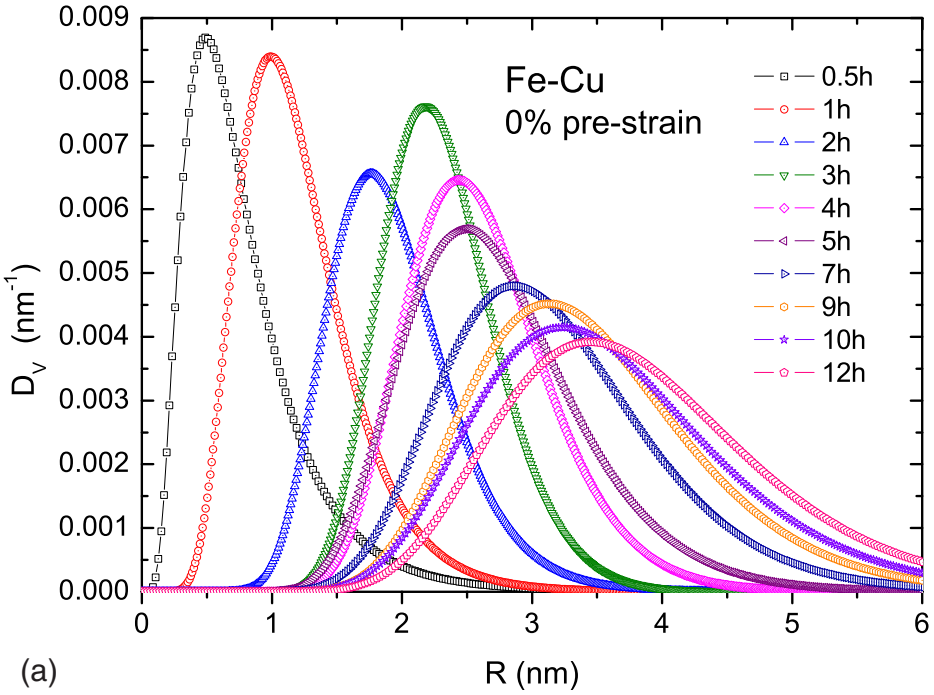


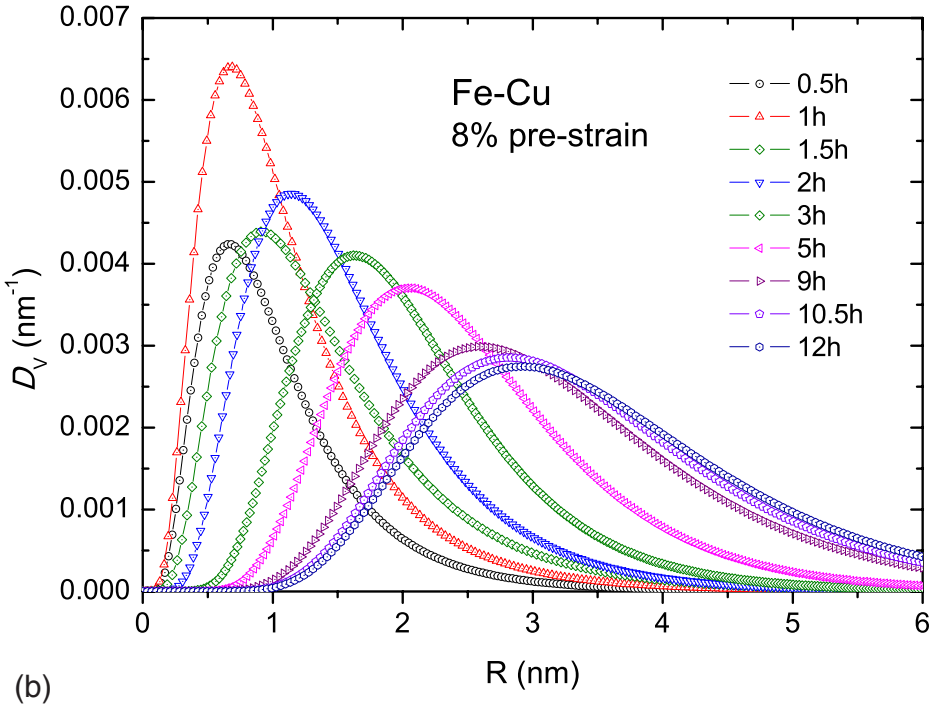


He et al. Physical Review B **82**, 174111 (2010)

Application: Fe-Cu

- Precipitate size distribution as a function of aging time





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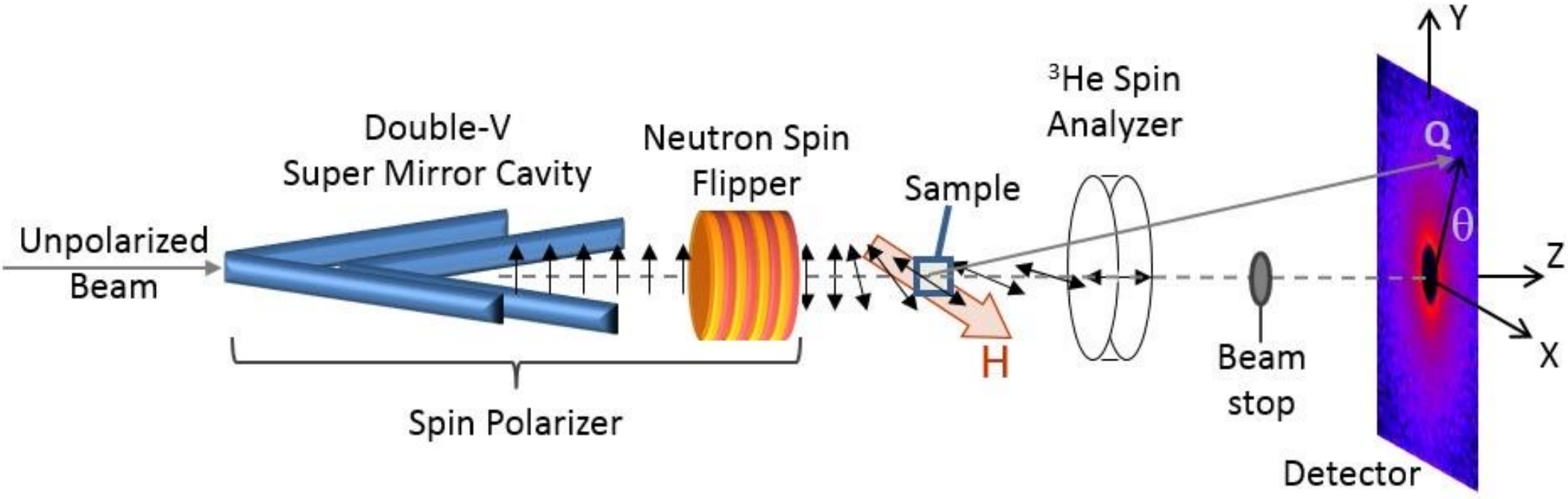
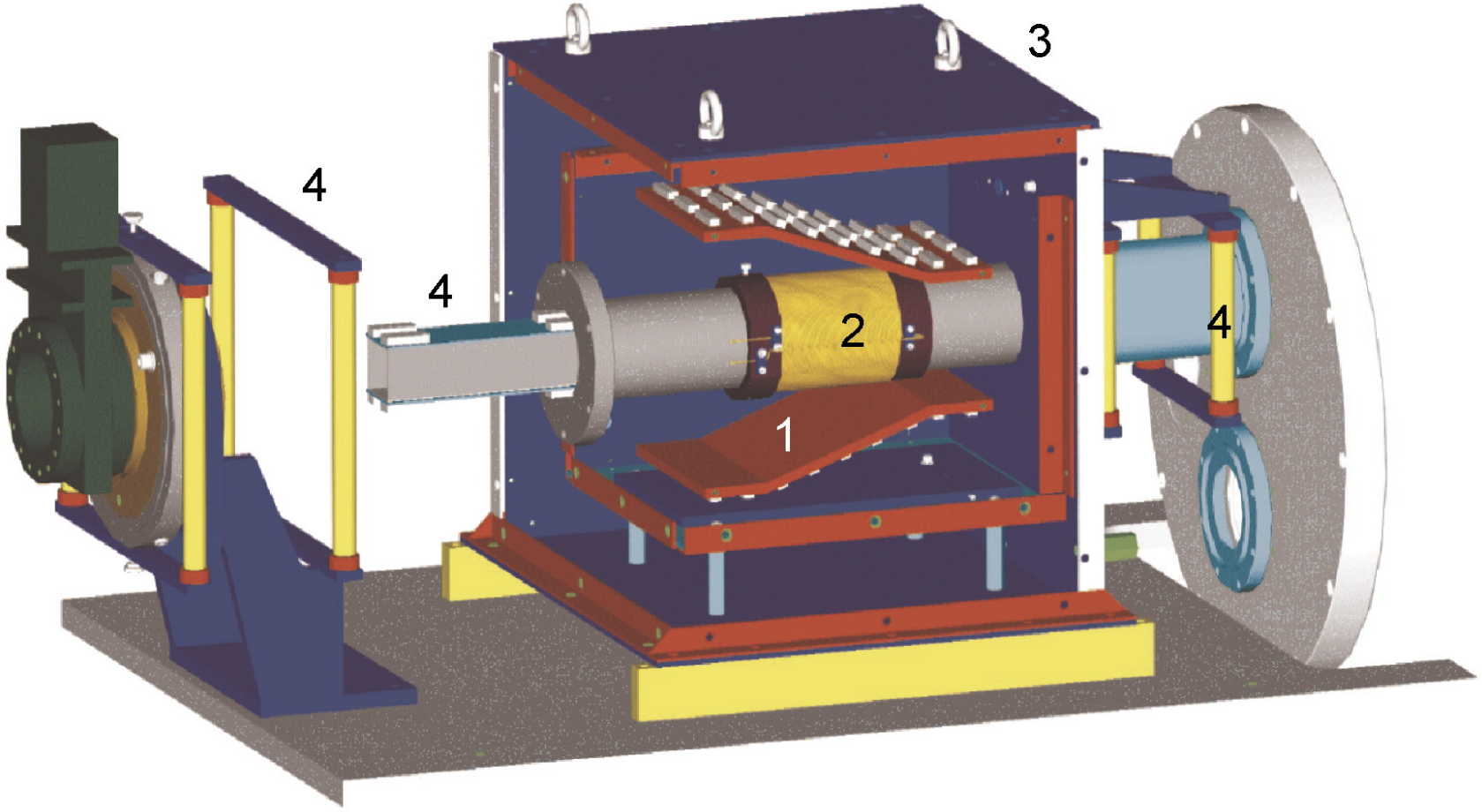
Spin-polarized SANS

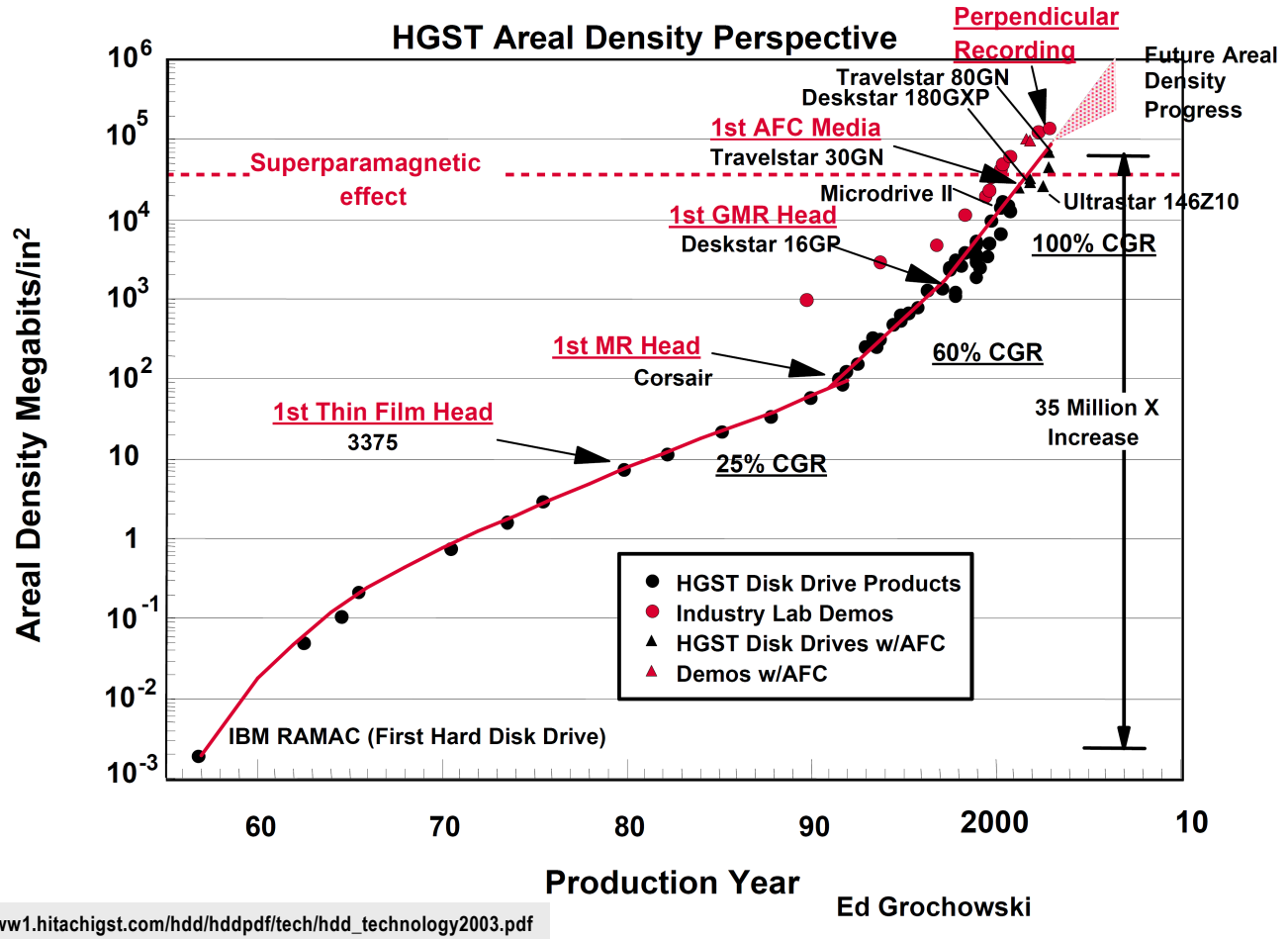


Spin flipper



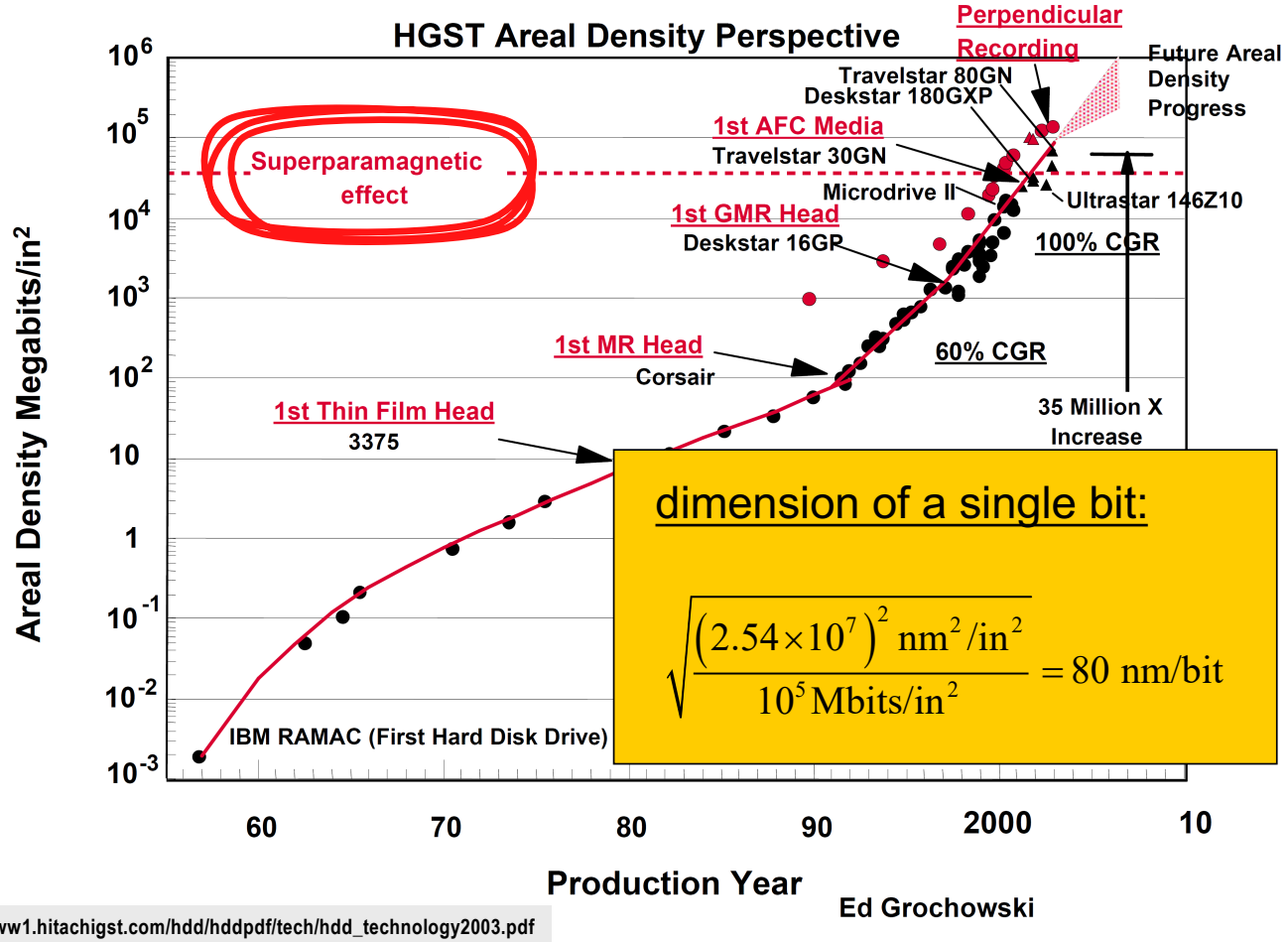
Schematic drawing of the spin flipper setup with (1) the gradient field, (2) the radio-frequency solenoid, (3) the magnetic shielding box and (4) the magnetic guiding field.

superparamagnetic effect



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

superparamagnetic effect



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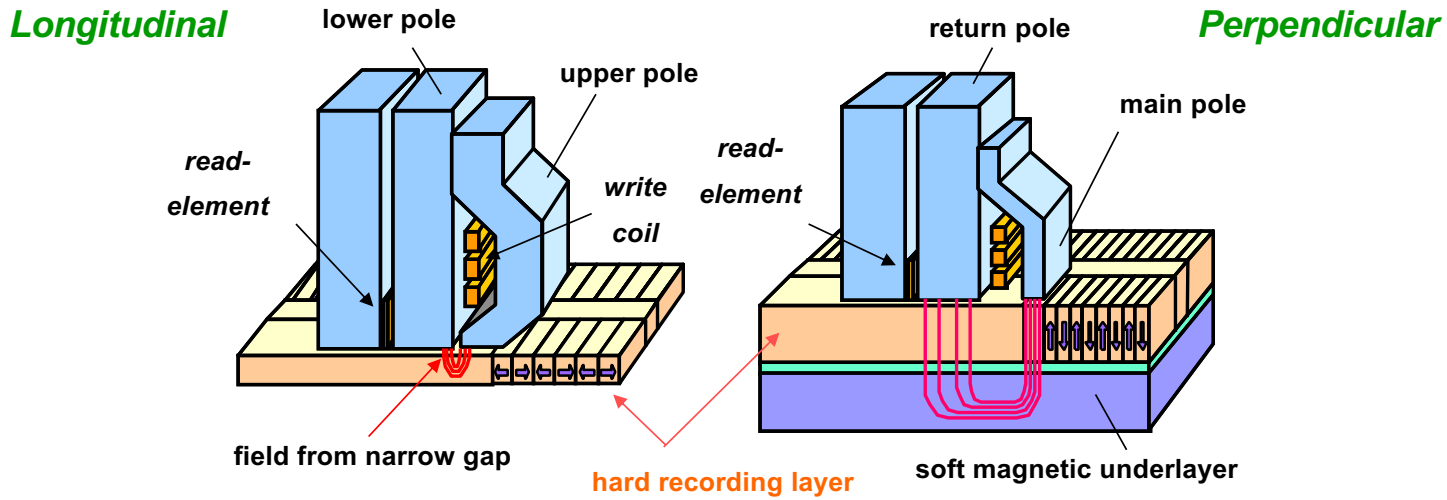
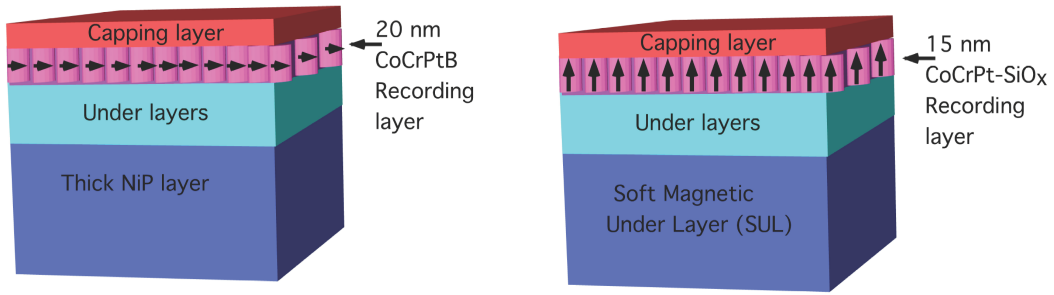
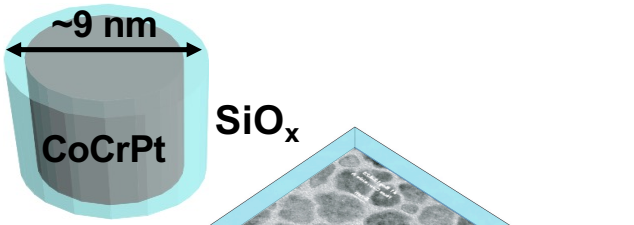
recording media

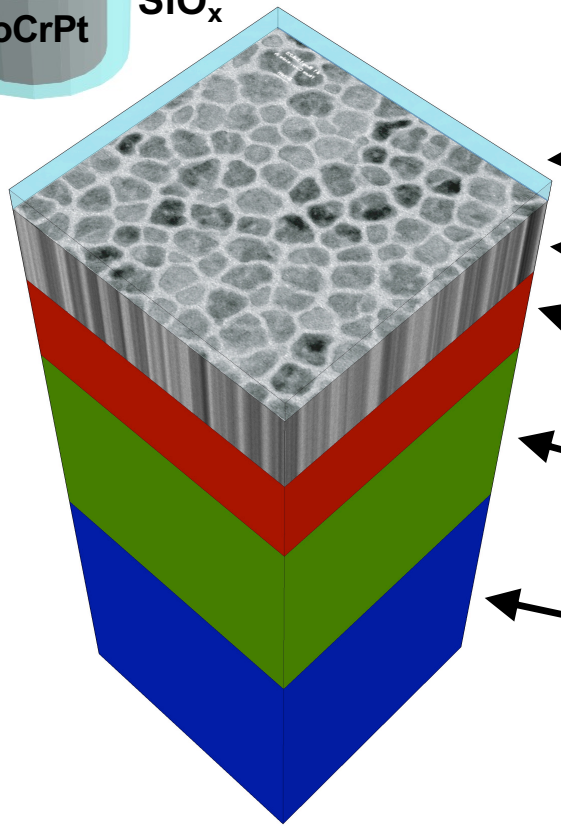




perpendicular recording allows higher head field and taller grains ➔ smaller grain area.

compositionally inhomogeneous PRM





protective overcoat to inhibit oxidation

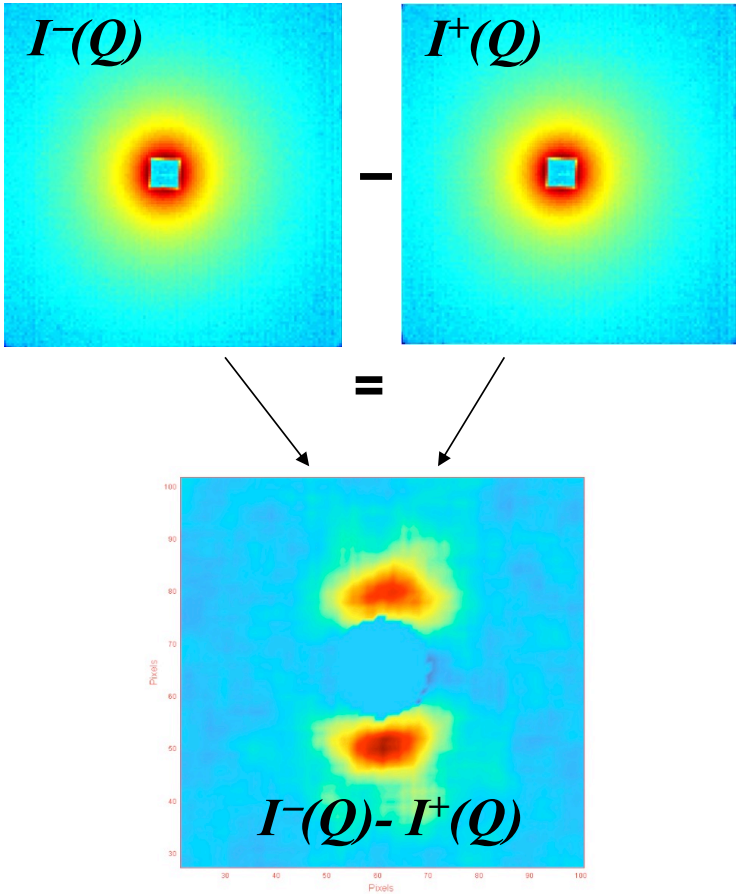
10 nm thick recording layer: CoCrPt-SiOx

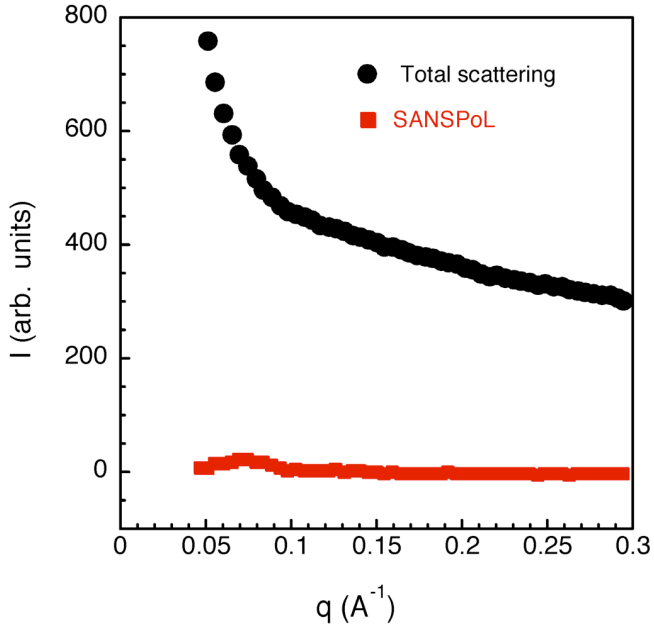
Ru based seed layer (~20 nm)

CoFe-based soft magnetic underlayer (~50 nm)

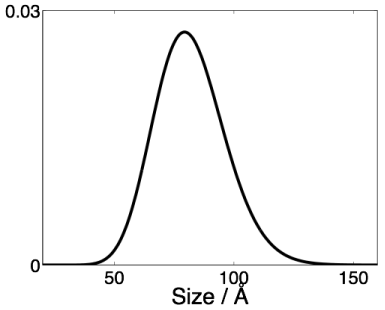
0.8 mm thick silicon substrate

benefits of using spin-polarised SANS

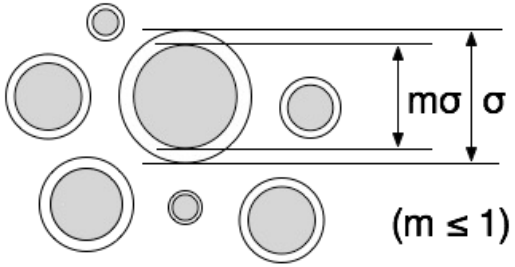




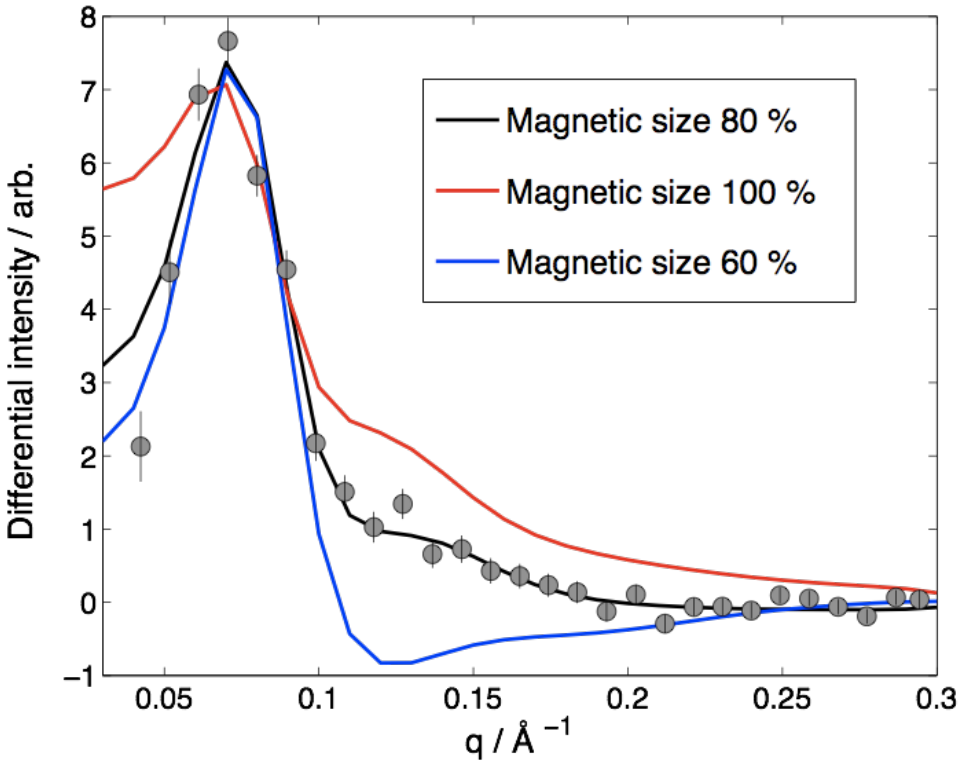
modeling of scattering data: analytic model

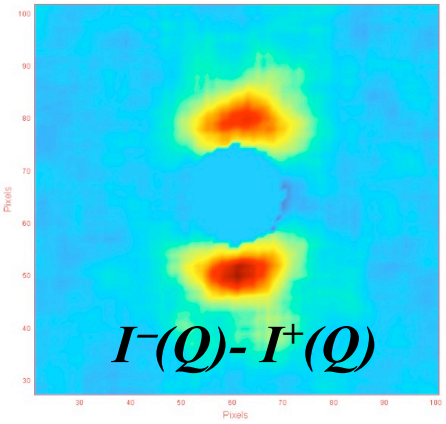


- $F(q,\sigma)$ form-factor (cylindrical, diameter σ)
- $S(q,\sigma_1,\sigma_2)$ partial structure factor for poly-disperse P-Y model
- $f(\sigma)$ size distribution (Gamma-Schulz)
- differential intensity can then be written:
  $\int F_N(\sigma)\, F_M(\sigma)\, f(\sigma)\, d\sigma + \int\int F_N(\sigma_1)\, F_M(\sigma_2)\, f(\sigma_1)\, f(\sigma_2)\, S_{12}(q,\sigma_1,\sigma_2)\, d\sigma_1\, d\sigma_2$
- for grains of given size, the size and strength of the magnetised region can then be varied freely



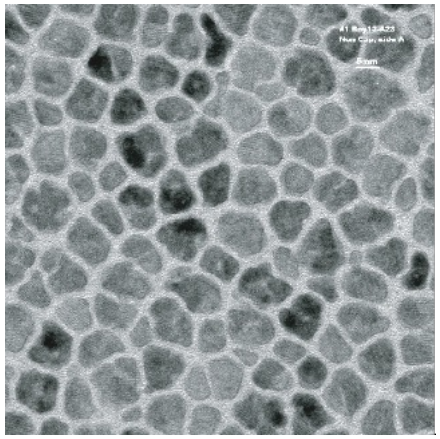
Modeling scattering data: real space images



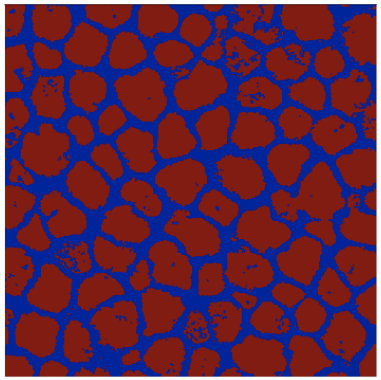


modeling scattering data: real space images

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



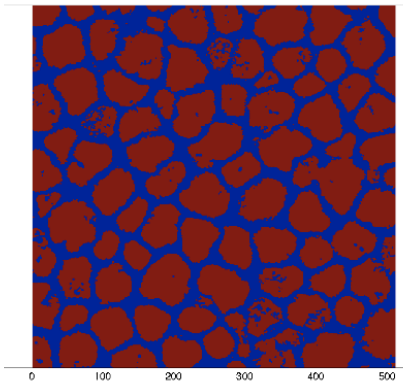
processed image to give two-level contrast



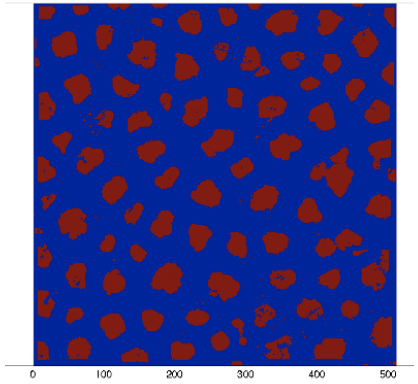
- TEM image clearly shows the heterogeneous granular structure
- nuclear scattering contrast is expected to be similar
- metallic grains are magnetised, while inter-granular medium is non-magnetic. However the full volume of the grain may not be uniformly magnetised

modeling scattering data: real space images

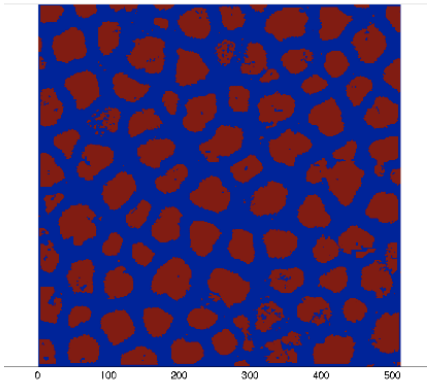
Magnetic scale 100 %

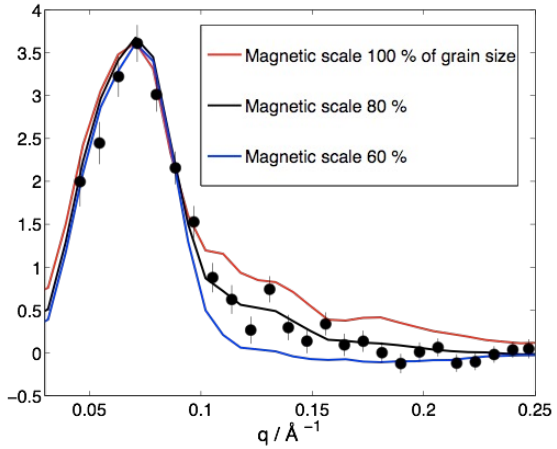


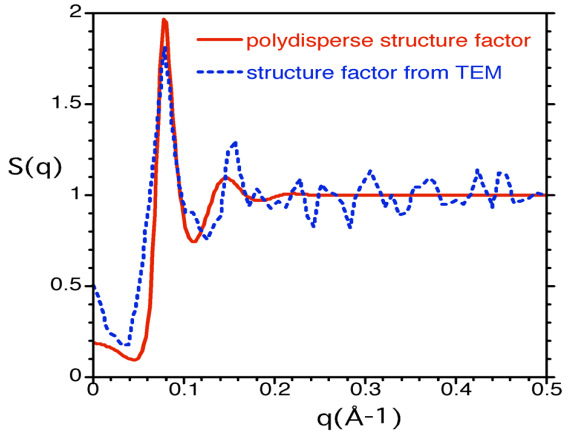
Magnetic scale 60 %



Magnetic scale 80 %

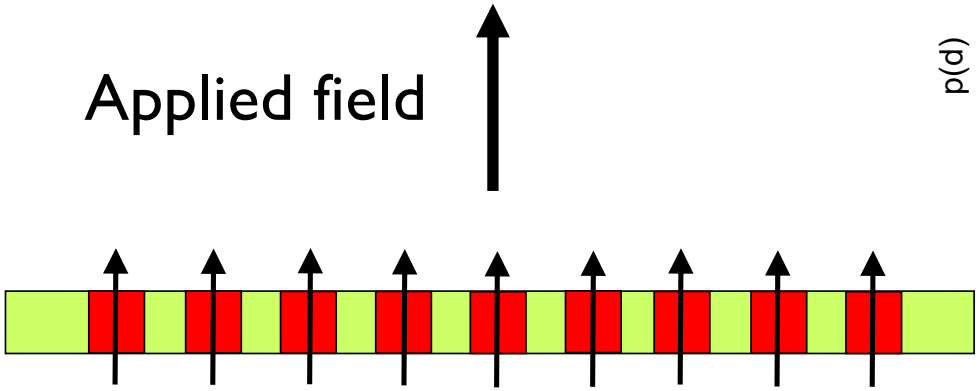


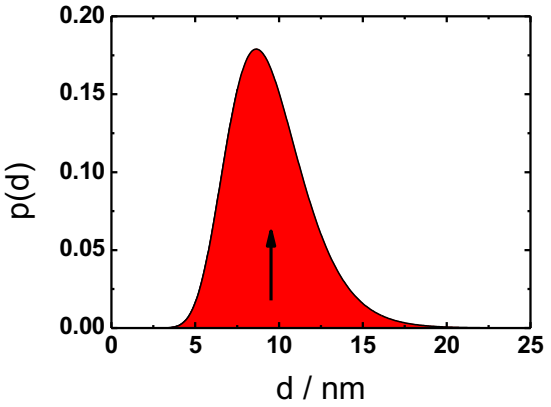




comparison of the structure factor obtained from the center of the grains in the TEM image and from the analytical model

‘Switching’ experiment

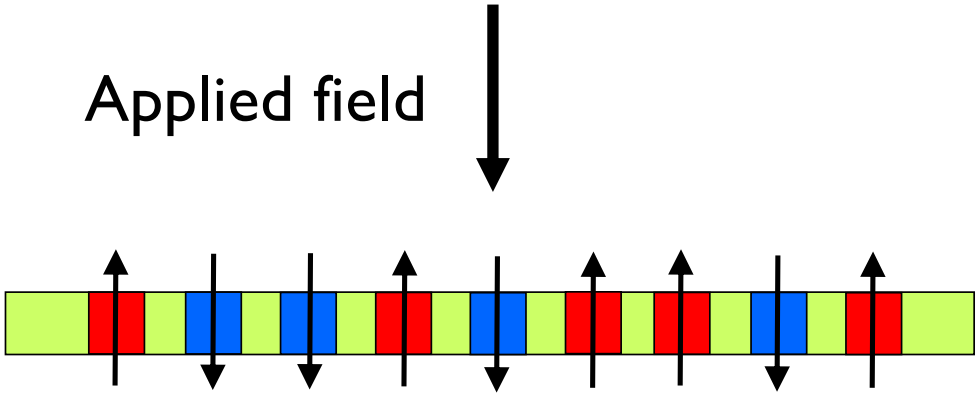


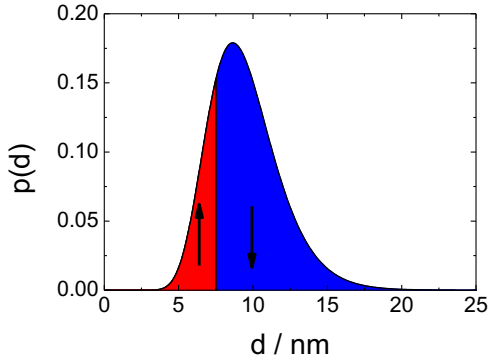


Recording layer

1. first saturate with out-of-plane field

‘Switching’ experiment

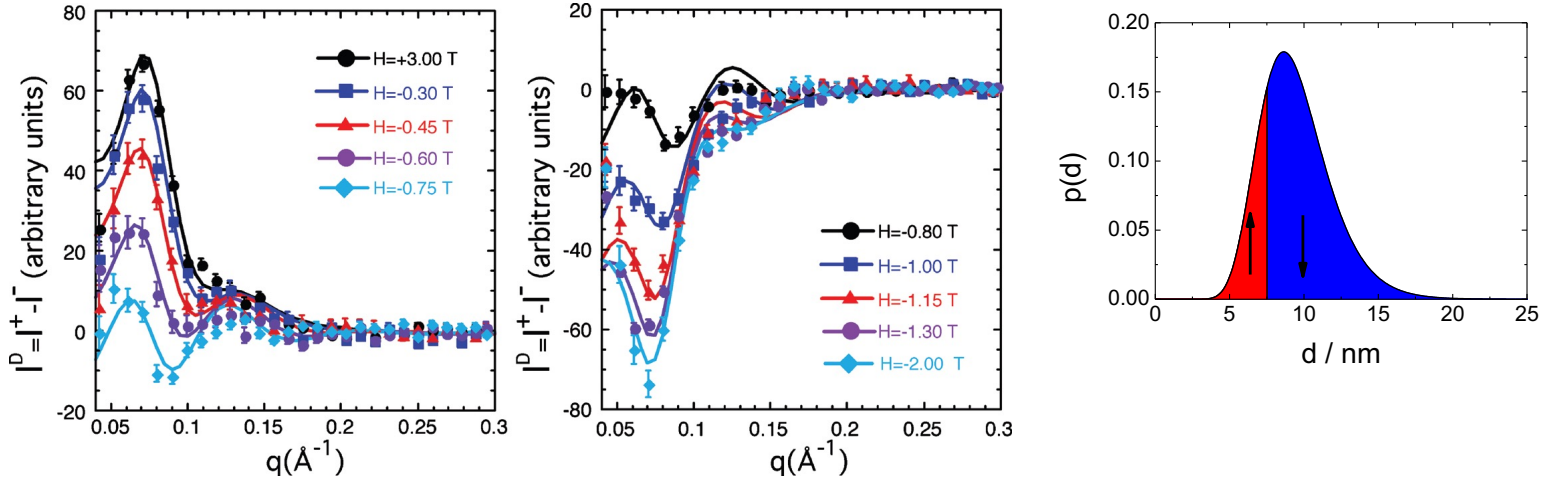




Recording layer

1. first saturate with out-of-plane field
2. then apply reverse field

‘Switching’ experiment

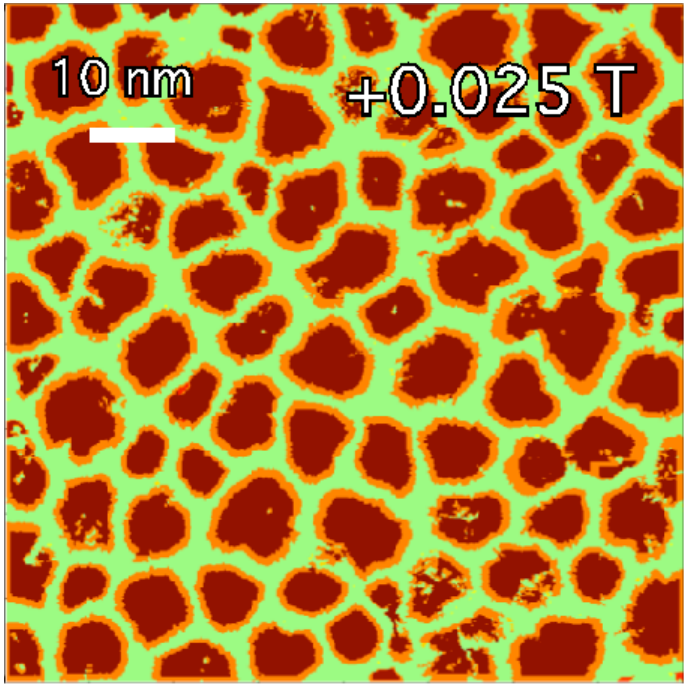


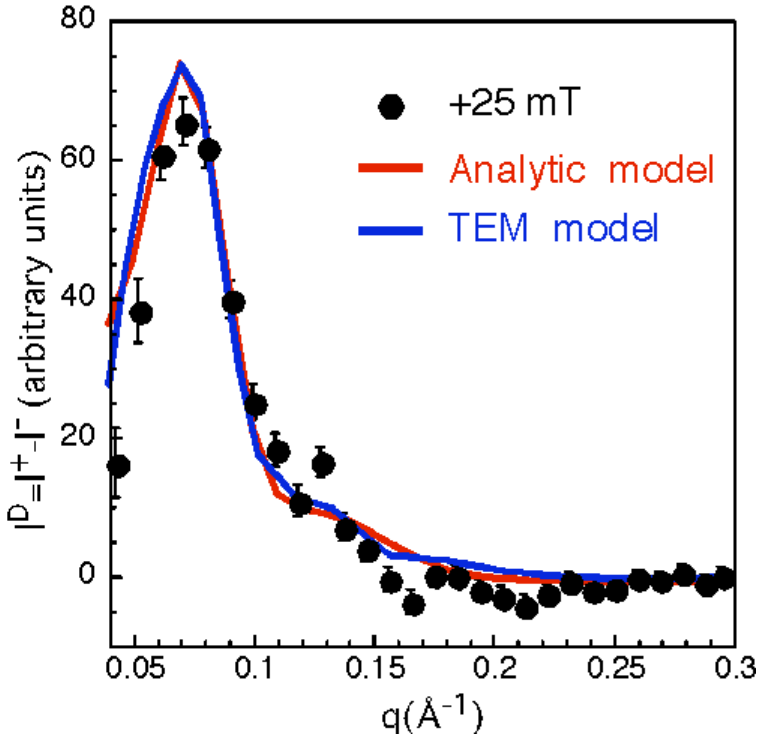
$I^-(Q) - I^+(Q)$ → **changes sign** as grains reverse magnetisation

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

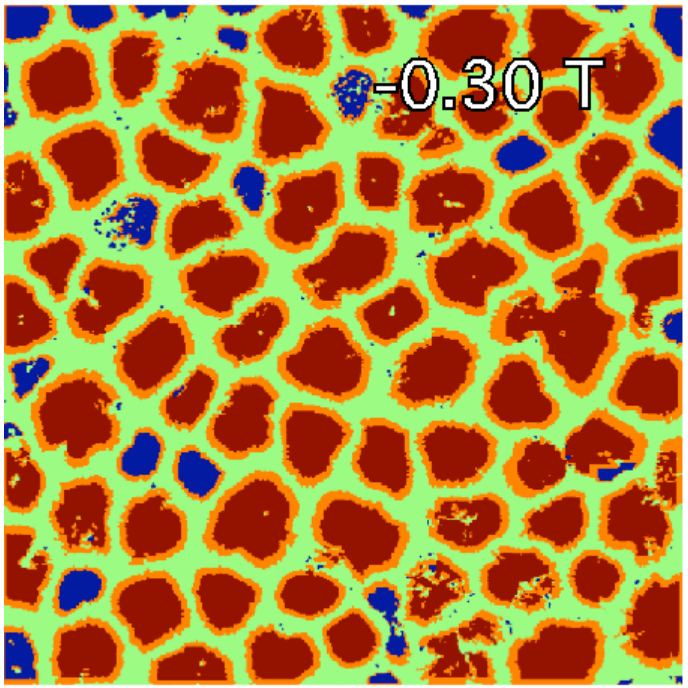
→ **Information on which sized grains reverse at each reversal field**

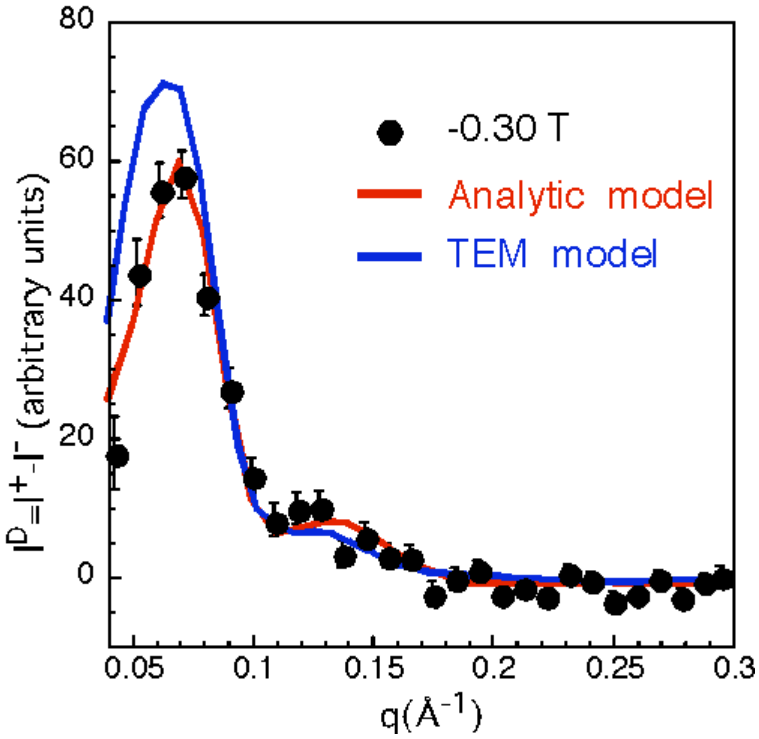
‘Switching’ experiment





‘Switching’ experiment





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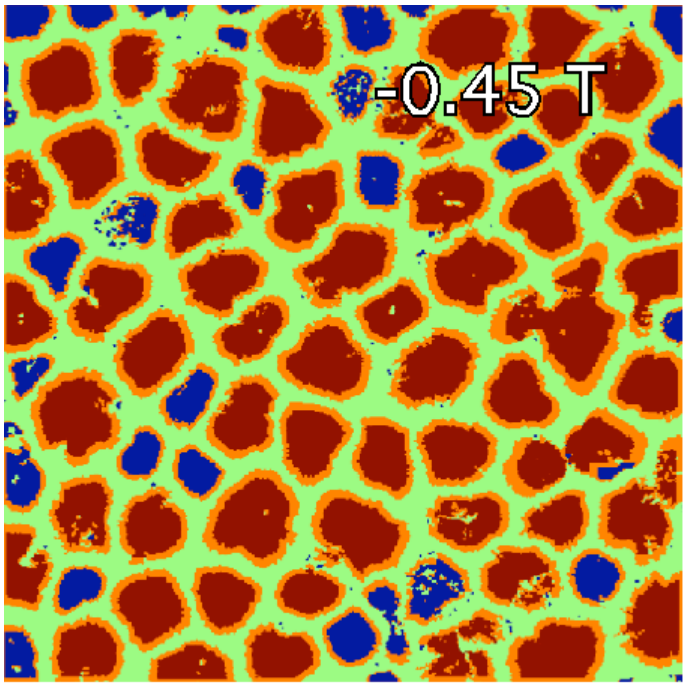

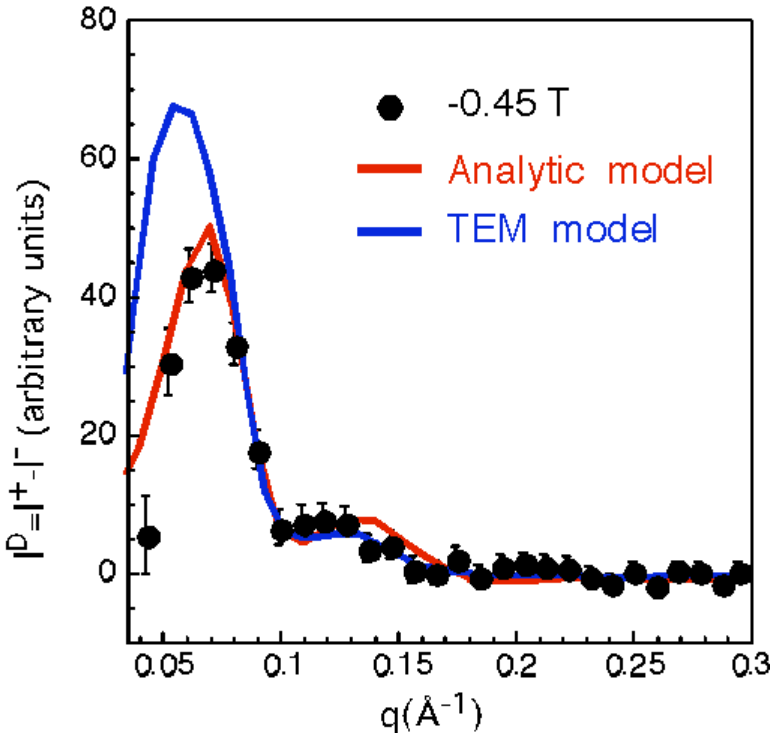

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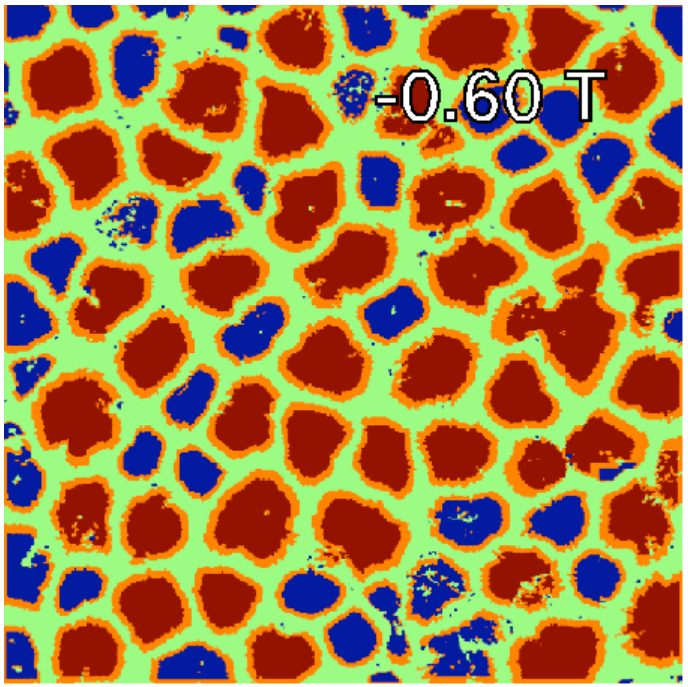
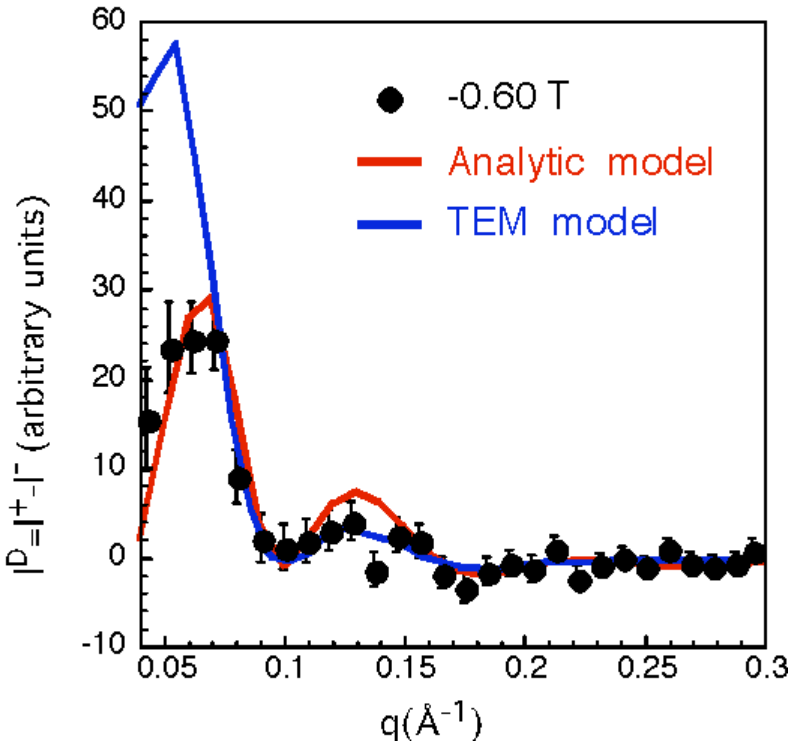
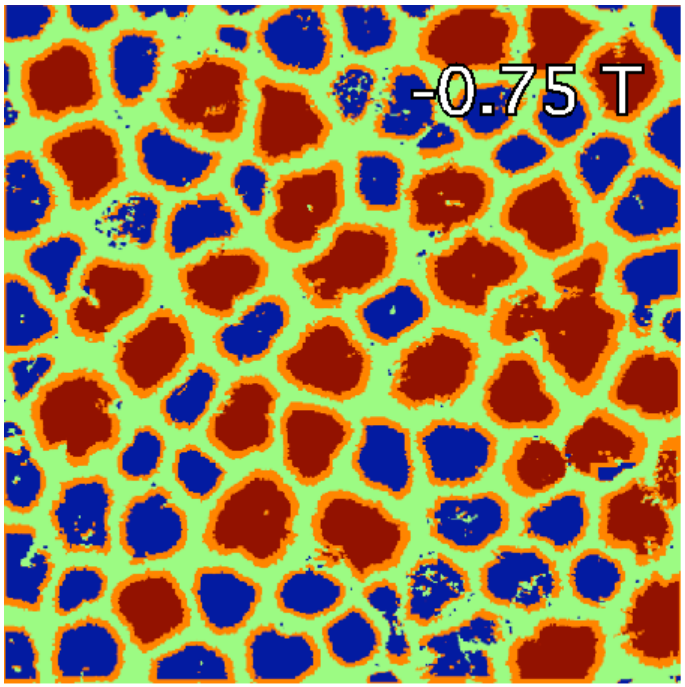
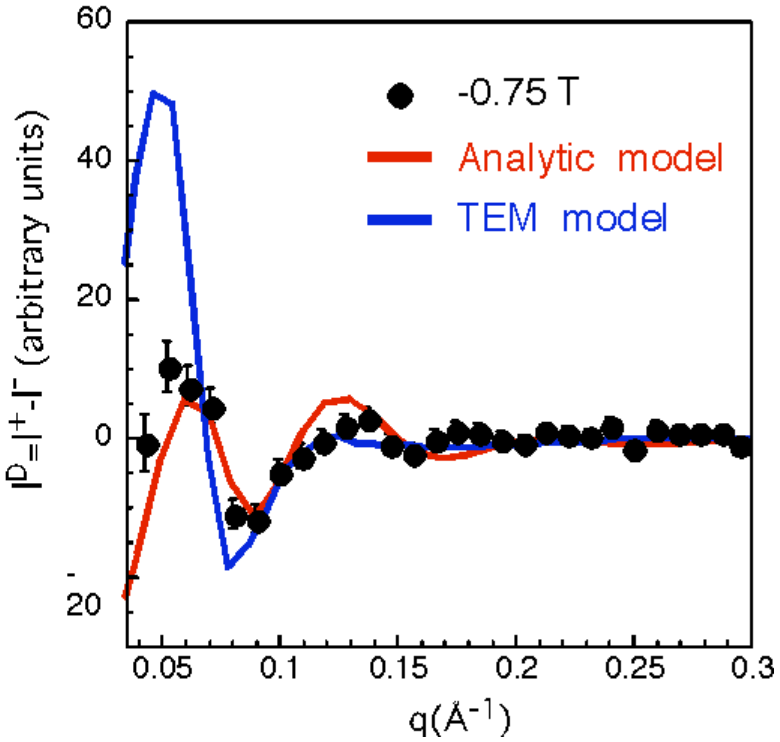


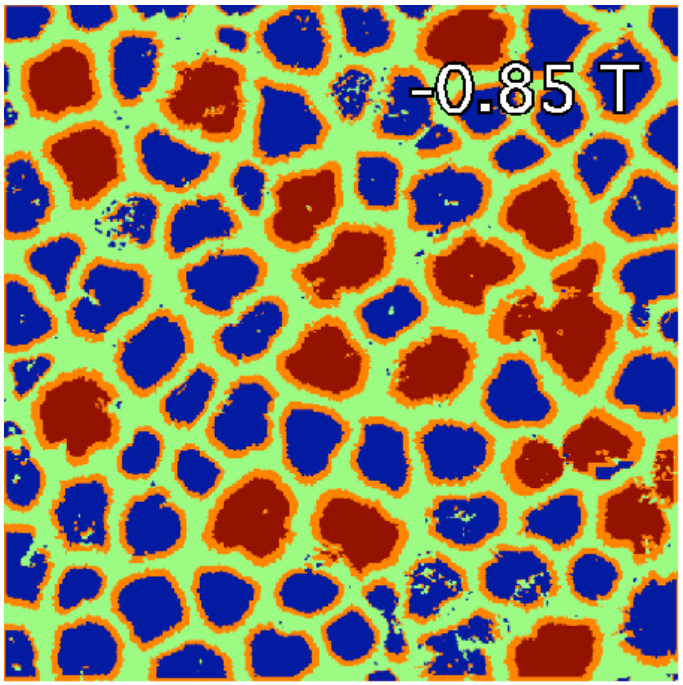


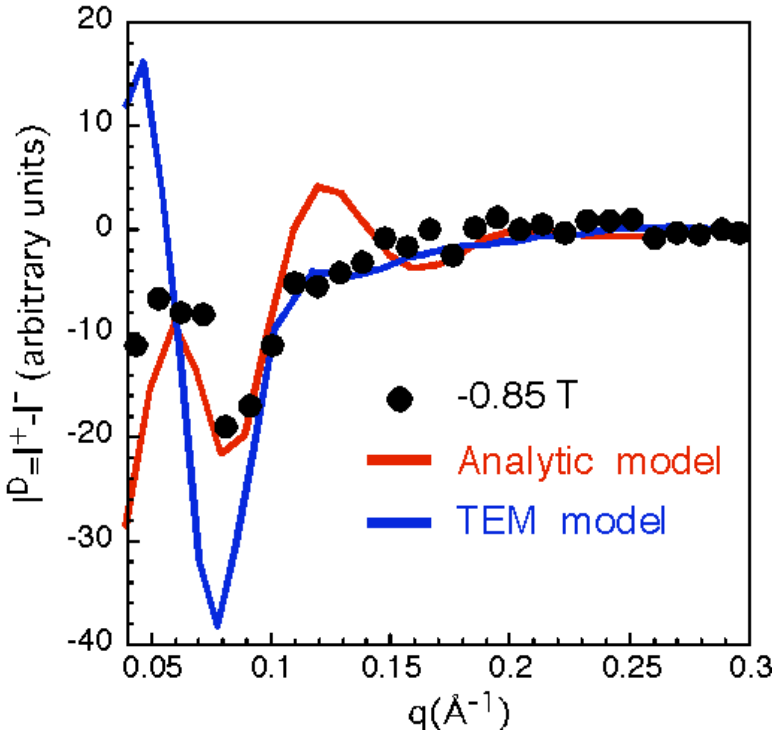
‘Switching’ experiment



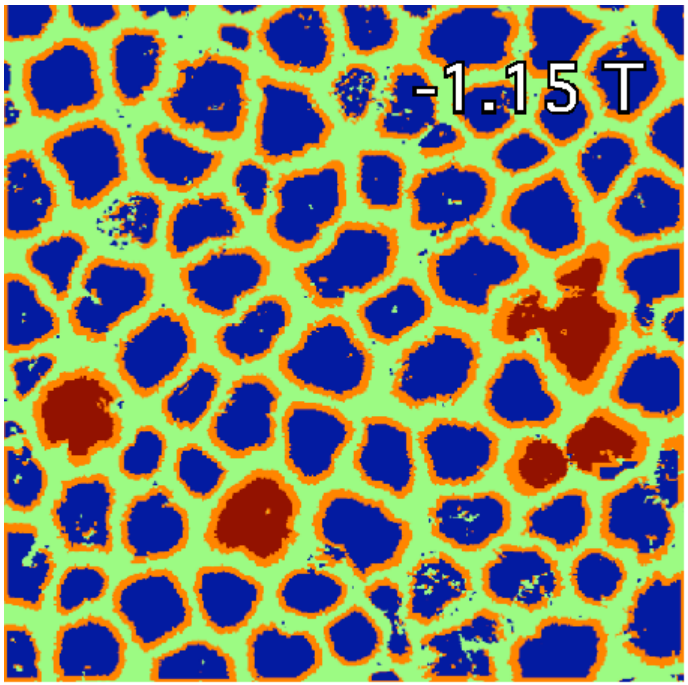


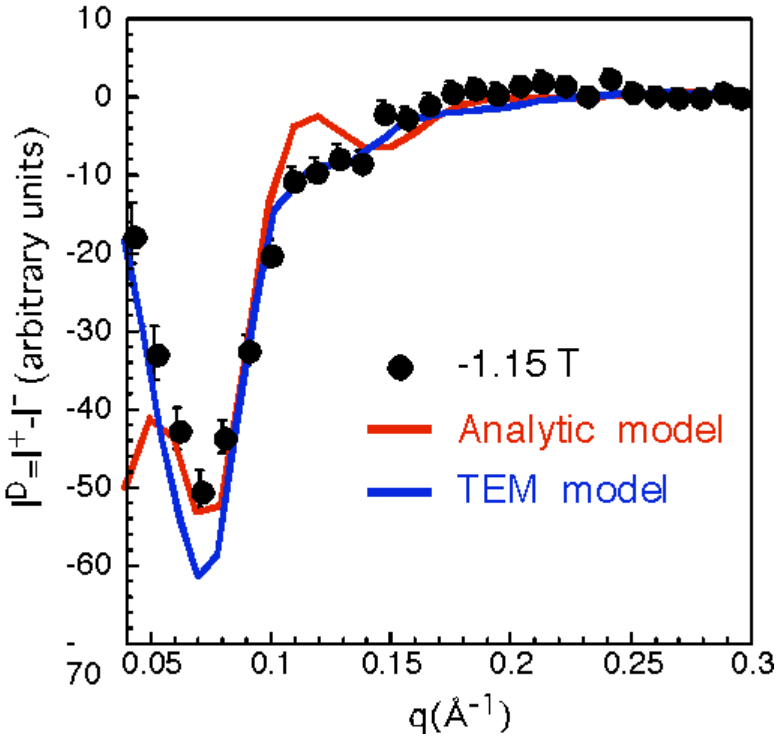
‘Switching’ experiment



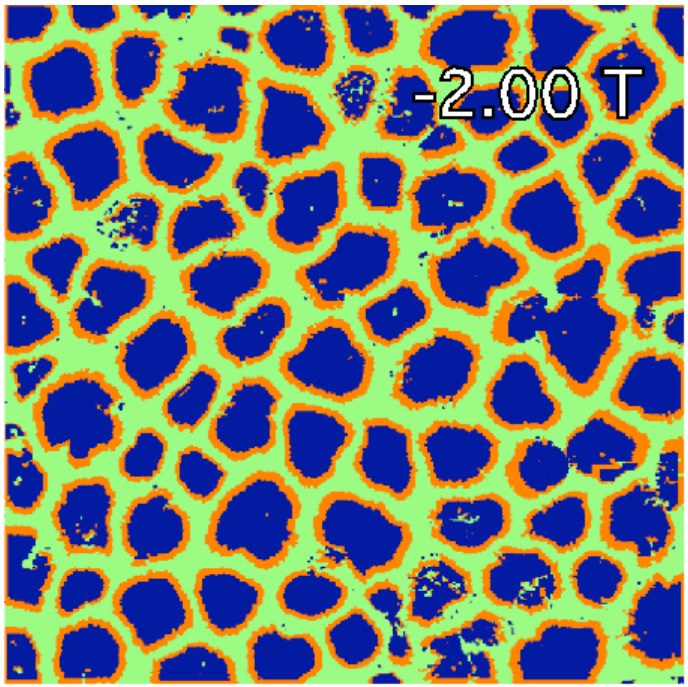


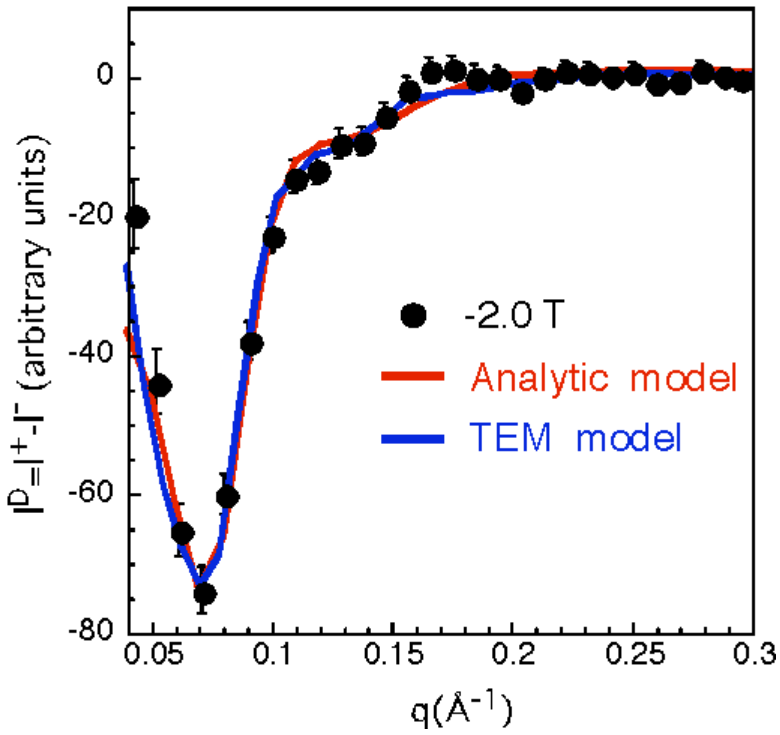
‘Switching’ experiment





‘Switching’ experiment

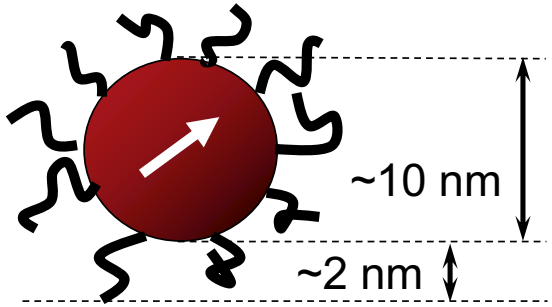




Ferrofluids

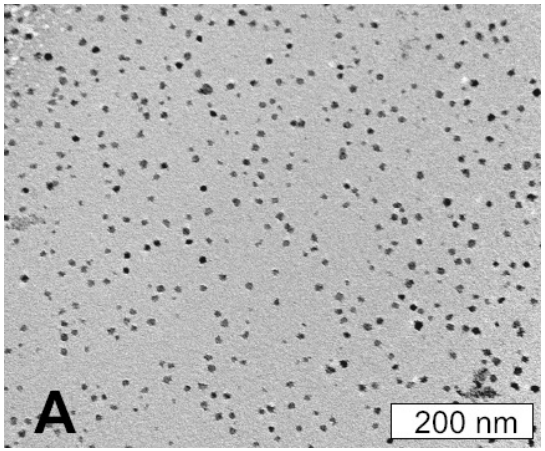
https://youtu.be/n8Zvyr2Bc5Y

Magnetic colloids



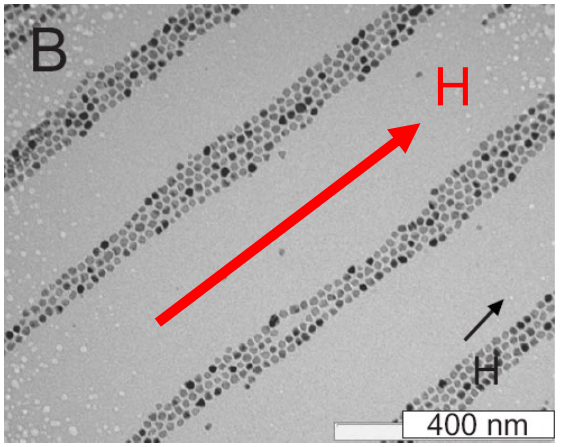
ferromagnetic core
(e.g. Co, Fe_3O_4)

stabilizing surfactants



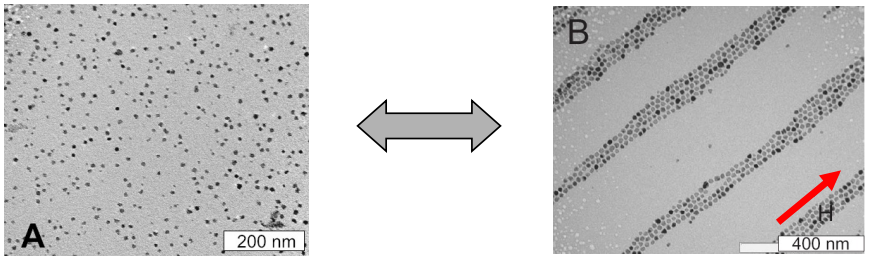
zero field

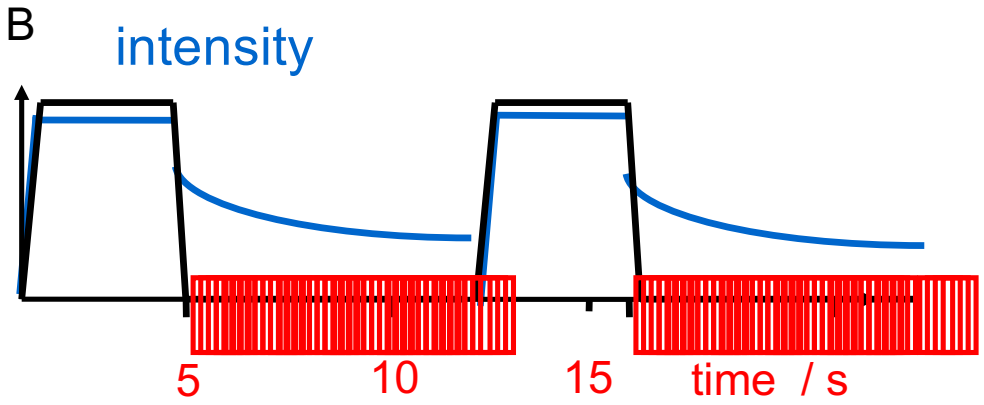
τ ~ 2-5 sec



field induced ordering

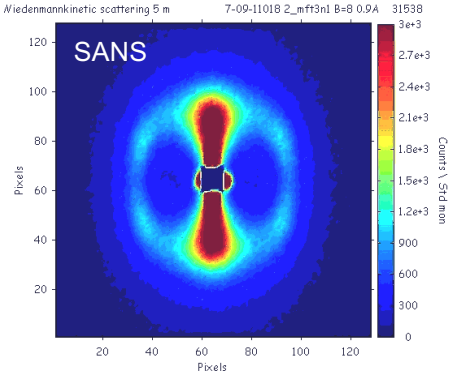
time-resolved SANS and SANSPOL

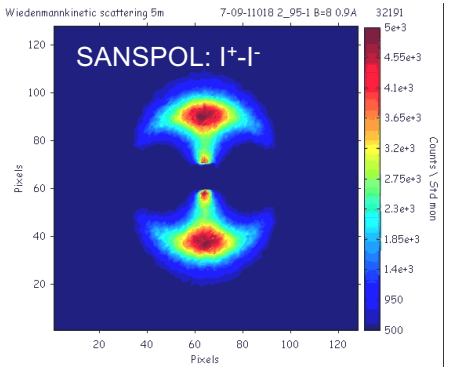




decay of nuclear and magnetic correlations measured in time slices of 0.1 s

duty cycle 15-30 s





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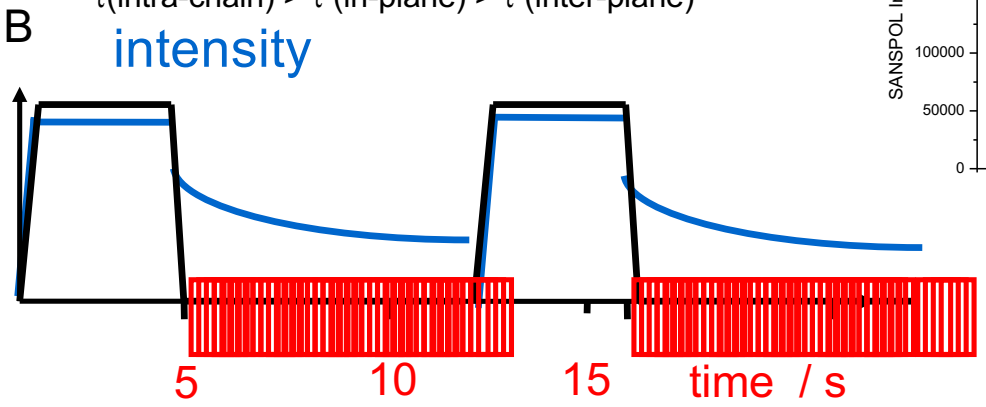
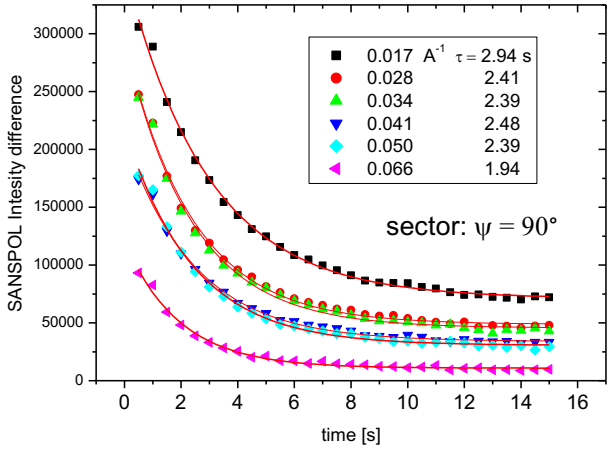
time-resolved SANSPOL

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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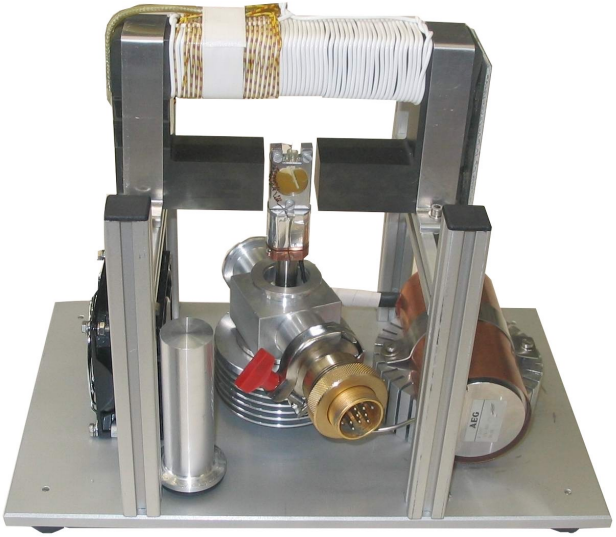
Extensions: Sample environments

small electromagnet with closed cycle refrigerator



tempertures :

70K - 300K

magnetic field:

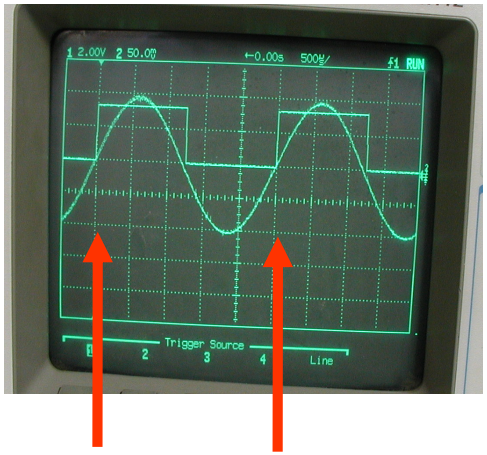
ac, dc, ac+dc :

± 40 mT

frequency:

sine-wave, square

υ : mHz… 5 kHz

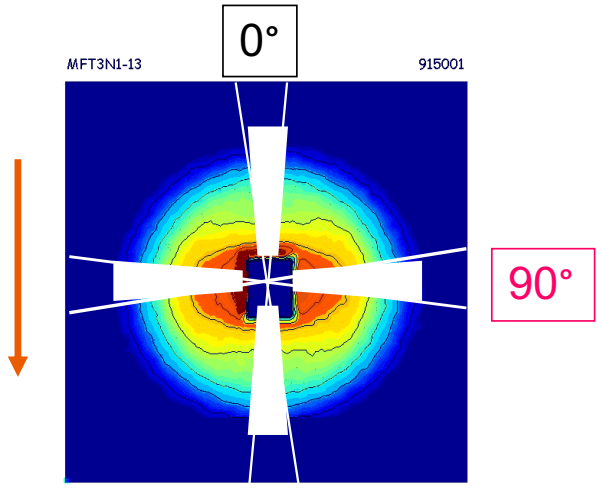


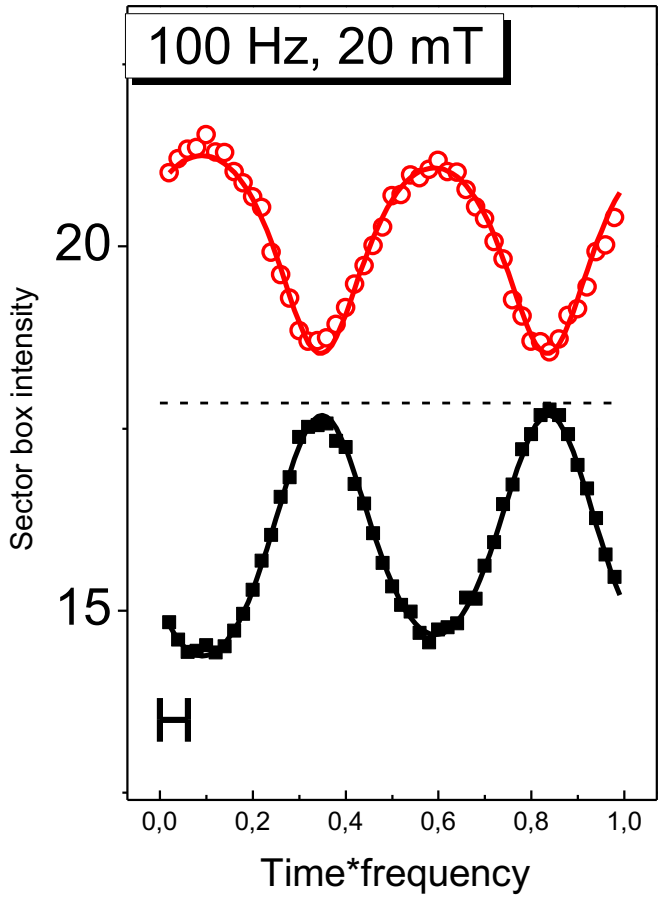
trigger for data acquisition of 2D detector

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

stroboscopic SANS

ν_s = 100 Hz B_0= 20 mT



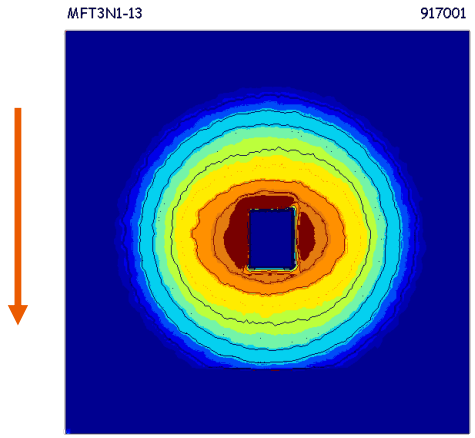


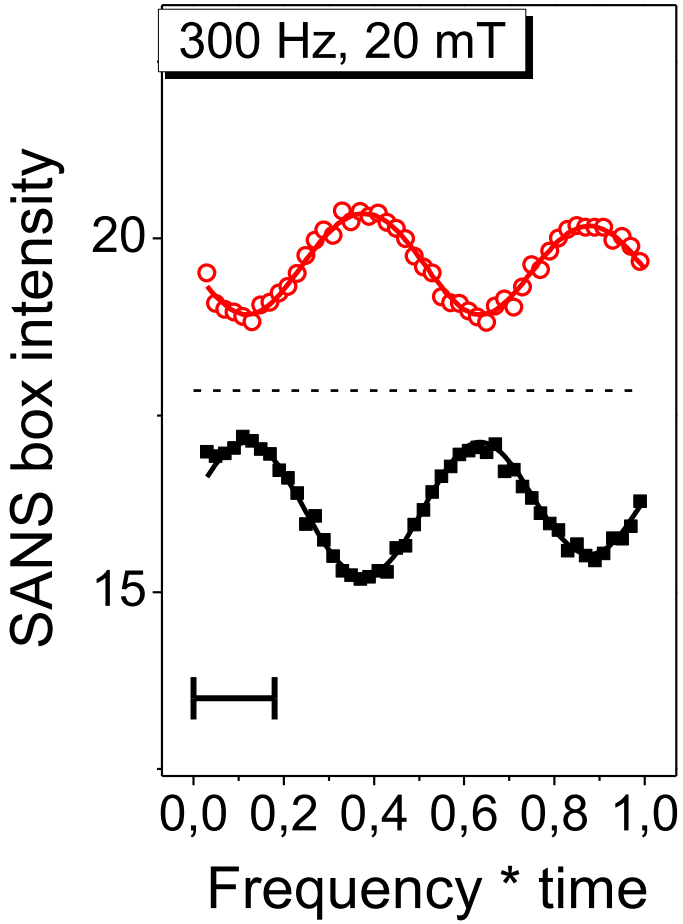
frequency of response twice of B-field

the magnetic scattering intensity is proportional to the square of the magnetization vector.

stroboscopic SANS

ν_s = 300 Hz B_0= 20 mT



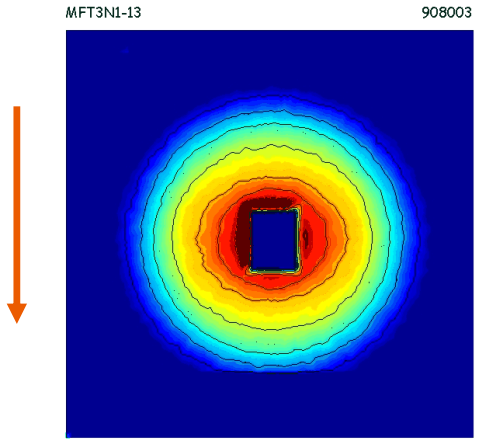


damping of oscillations

with increasing frequency

stroboscopic SANS

ν_s = 600 Hz B_0= 20 mT



damping of oscillations

with increasing frequency