Свободная поверхность феррожидкости в нормальном магнитном поле: внутренняя структура и поверхностная неустойчивость

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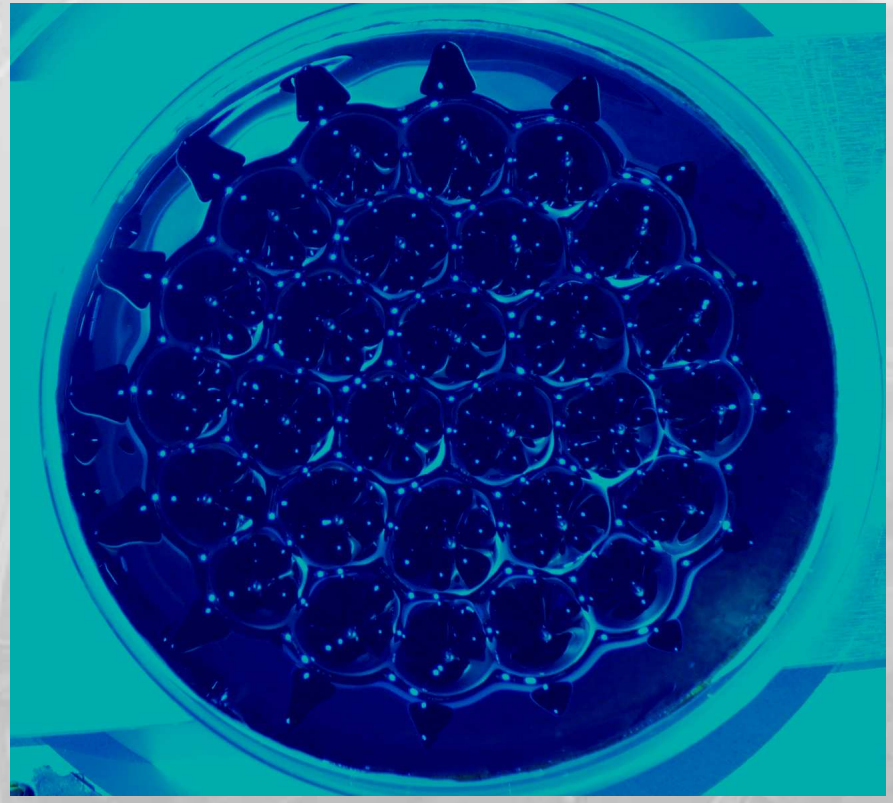
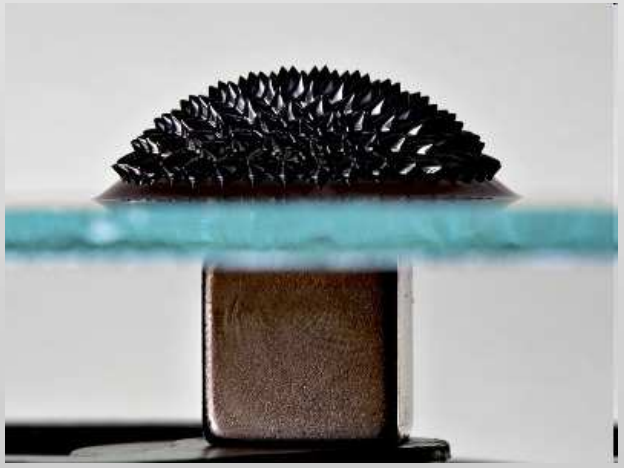


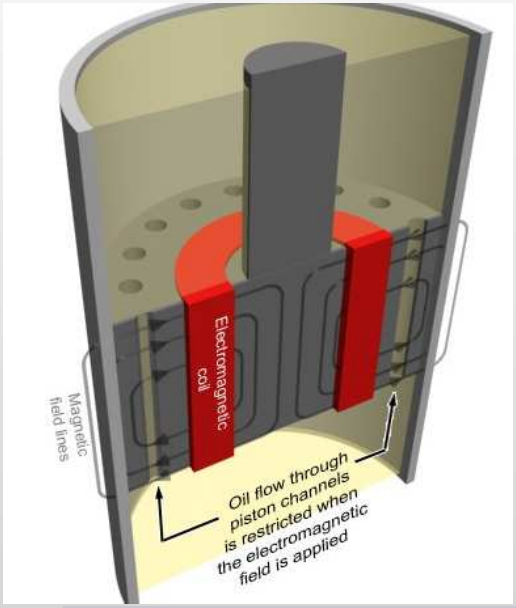
- introduction to ferrofluids
- structure of air-ferrofluid interface as obtained by X-ray scattering
- conclusion
- outlook

FERROFLUID LIKE A LIQUID MAGNET

FERROFLUIDS or **MAGNETIC FLUIDS** or **MAGNETIC COLLIDS** were developed in the 1960's through the sponsorship of NASA, to address the unique requirements of moving liquid fuel in a gravity-free outerspace environment.



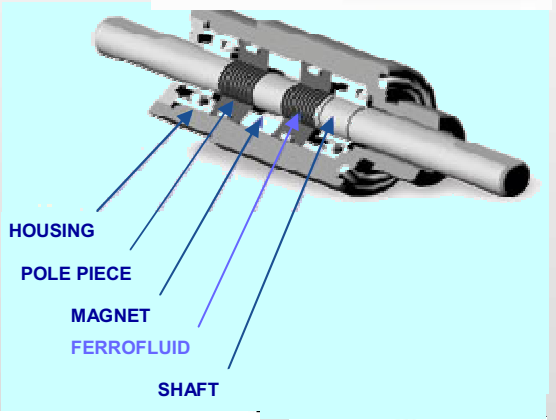
PRACTICAL APPLICATIONS



- sealing of shafts and rods
- magneto-fluid lubrication
- supports, bearing
- dampers, shock-absorbers
- drag reduction and flow separation control
- heat transfer enhancement
- densimeters
- accelerometers
- pressure transducers
- displacement transducers
- slope angle-data transmitters
- electromechanical converters
- electrical contacts
- displays
- level detectors
- linear pumps
- printers
- loud speakers
- hard disks

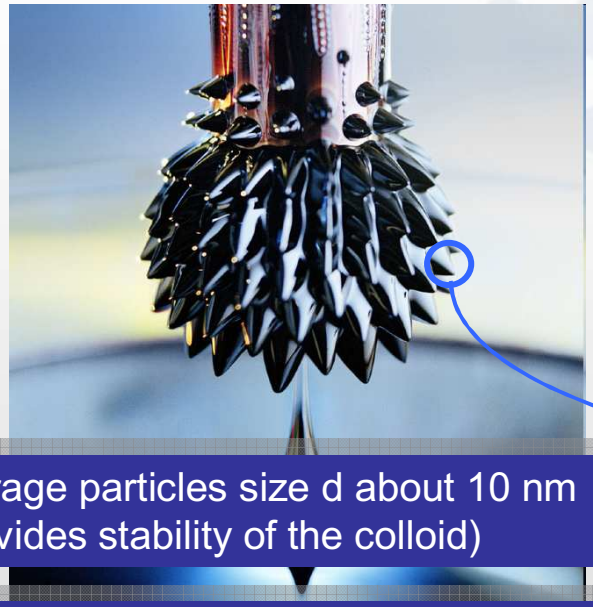
…

~ 3500 patents



R.E. Rosensweig: Ferrohydrodynamics. University Press, Cambridge (1985)
E. Blums, A. Cebers, M. M. Maiorov: Magnetic Fluids. de Gruyter, Berlin (1997)

FERROFLUID – WHAT IS INSIDE?



average particles size d about 10 nm
(provides stability of the colloid)

each particle is usually coated with a stabilizing dispersing agent
(excluding ionic ferrofluids)

MAGNETIC NANO-FLUIDS
NANO-MAGNETIC FLUIDS

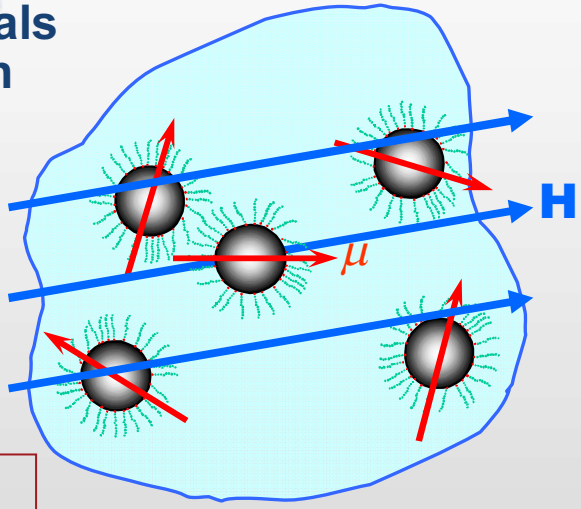
each particle comprises a single domain
$\mu = VM_S = 10^3 \div 10^4\ \mu B$
(superparamgnetism)

gravity

thermal motion

van der Waals attraction

steric repulsion



magnetic interaction

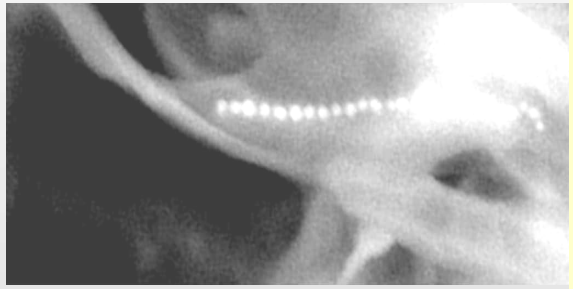
dipole-dipole interaction

$$E_m = \eta_0 MHV$$

Local interpartical correlations change macroscopic properties of the whole system

FERROFLUIDS IN MODERN LIFE

biomedic … pplications



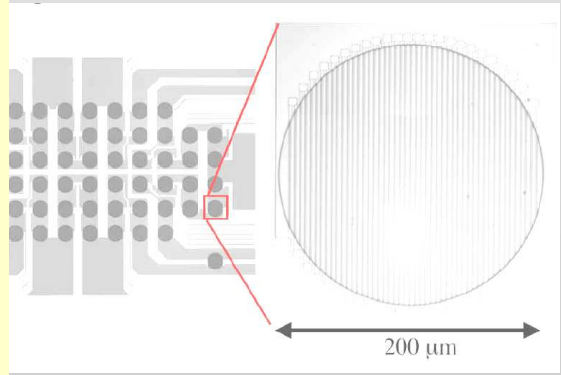
… ible superparamagnetic
… rgeted drug delivery
…
… esonance imaging
… gnostic and treatment
…

$$E = -\vec{\mu} \cdot \vec{B}$$

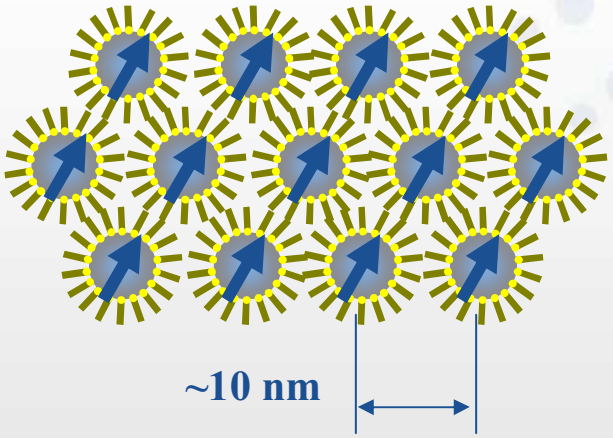
micromag … al systems

- electro-magnetic micro-…
- magnetic micro-wire ma…
- ultra-high gradient mag…
- advanced data storage …

…



THE AIM OF OUR STUDY



Produce 2d magnetic nano-structure preferably by self-ordering or with help of magnetic fields

In bulk ferrofluid?

PHYSICAL REVIEW E **68**, 031203 (2003)

Field-induced pseudocrystalline ordering in concentrated ferrofluids

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(Received 13 December 2002; published 17 September 2003)

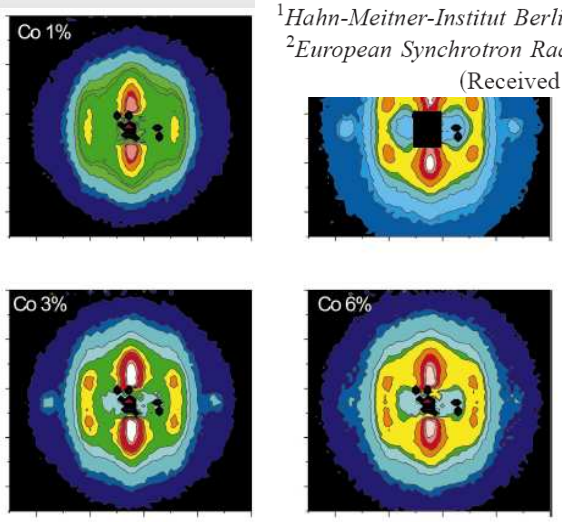
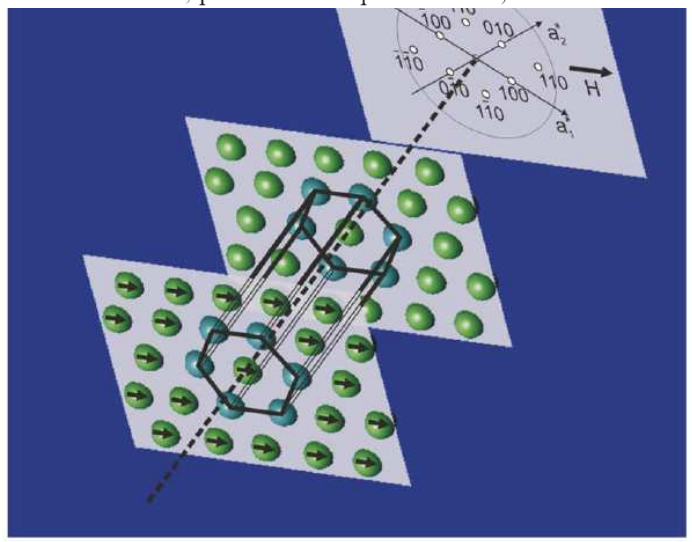


FIG. 1. (Color) 2D isointensity SANS pattern of Co-FF samples DS1, DS2, DS3, and DS6 for nonpolarized neutrons measured in a horizontal magnetic field of $H = 1.1$ T, applied perpendicular to the incident neutrons.



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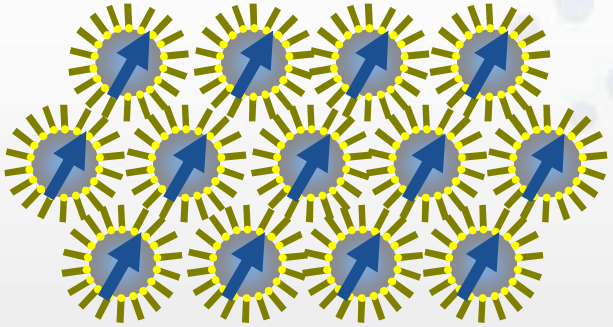
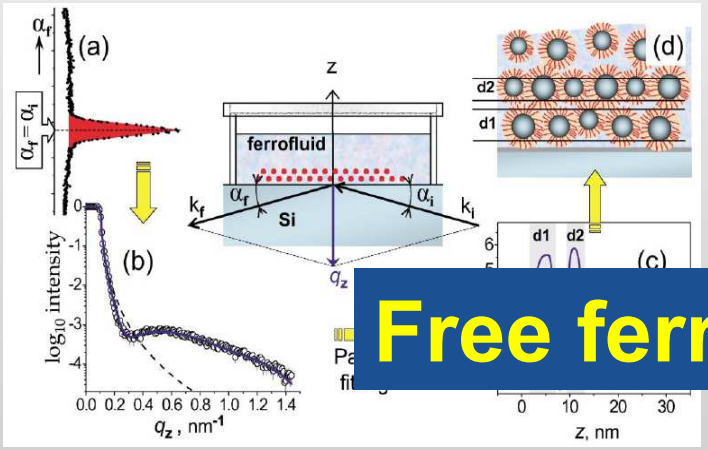


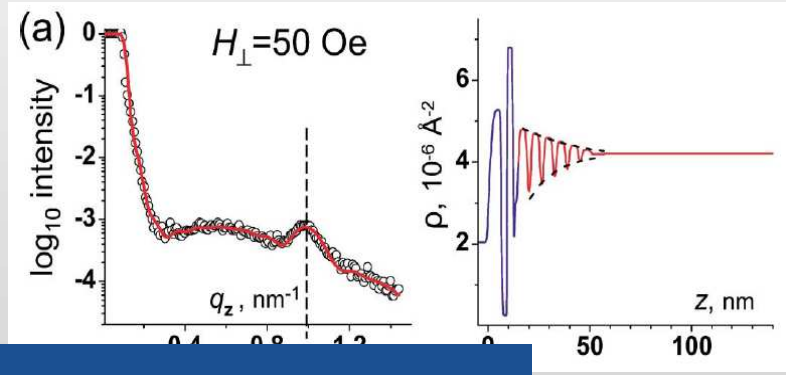
Produce 2d magnetic nano-structure preferably by self-ordering or with help of magnetic fields

Solid-liquid interface?

neutron reflectometry

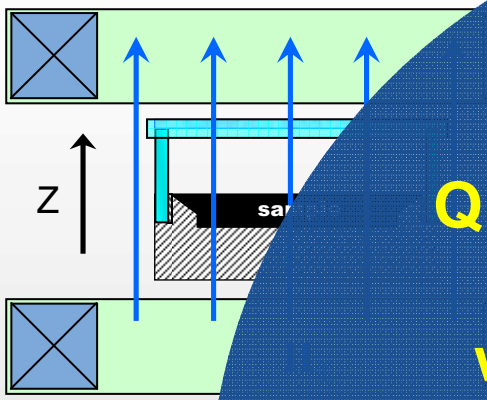


Free ferrofluid surface?



ordeev, D. Orlova
in Ferrofluids at
SiO_2 Interfaces. PRL **93,** 267203 (2004)

ROSE[illegible]ABILITY



$$\lambda^2 = \frac{8\pi\left(\chi_i + 2\right)}{\chi_i^2\left(\chi_i + 1\right)}\sqrt{\rho\sigma g}$$

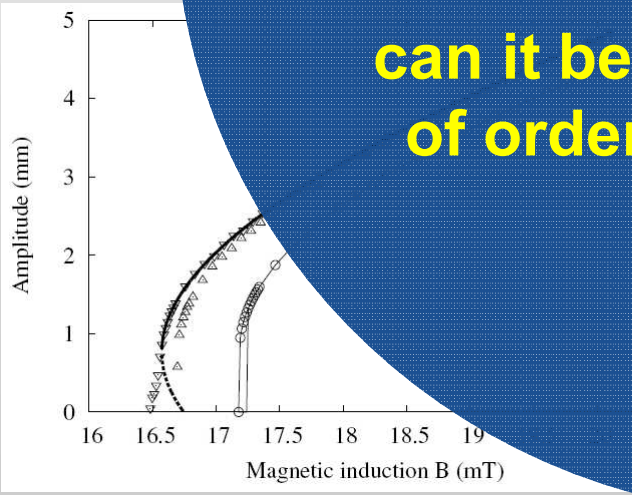
$$\lambda_c = 2\pi\sqrt{\frac{\sigma}{\rho g}}$$

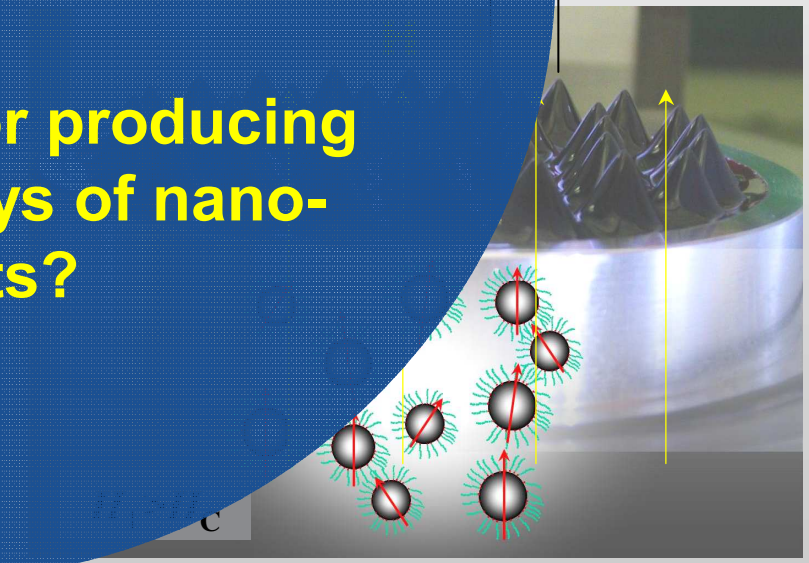
Bifurcat[illegible]
ferroflui[illegible]
magneti[illegible]

QUESTIONS TO ANSWER:

what is the microscopic structure of the FF surface in subcritical fields?

can it be used for producing of ordered arrays of nano-magnets?

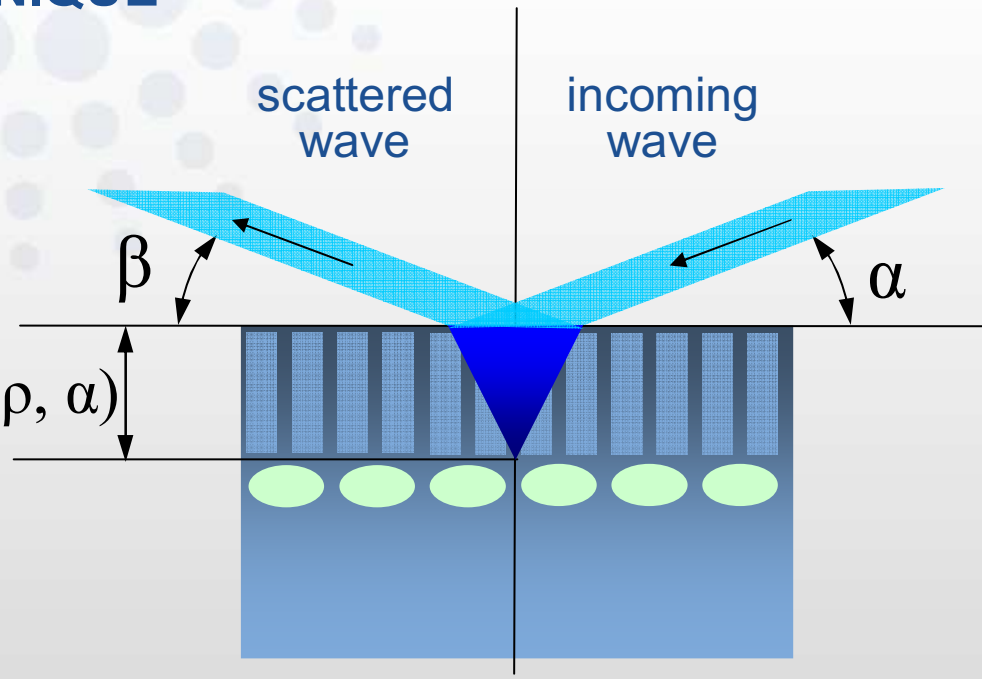


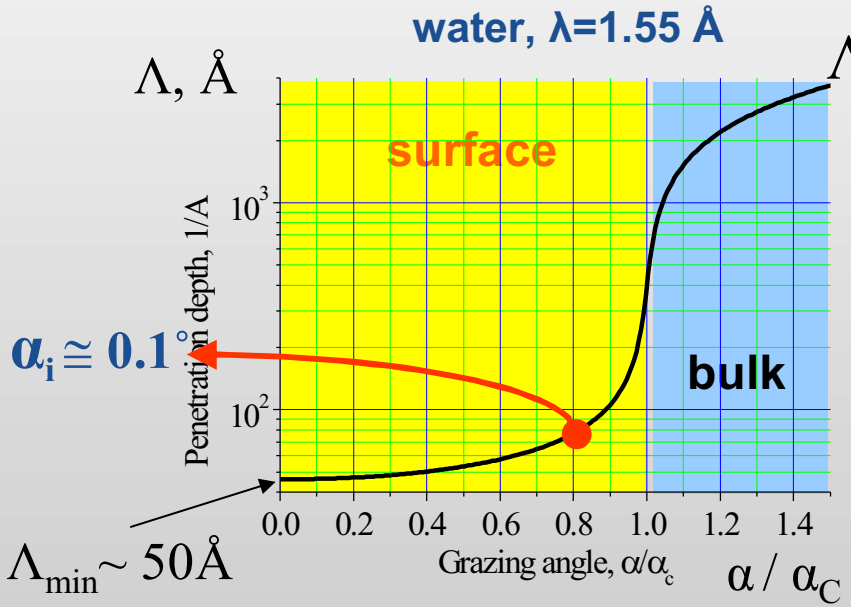


GRAZING INCIDENCE SCATTERING – SURFACE SENSITIVE TECHNIQUE

$$n = 1 - \delta - i\beta$$

$$\delta = \frac{\lambda^2 \rho r_e}{2\pi} \qquad \delta \approx 10^{-6} \qquad \alpha_c = \sqrt{2\delta}$$

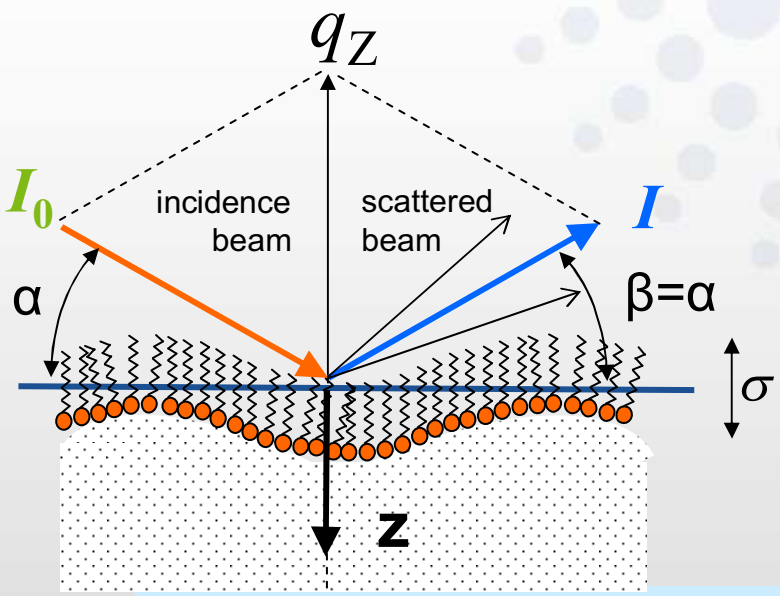


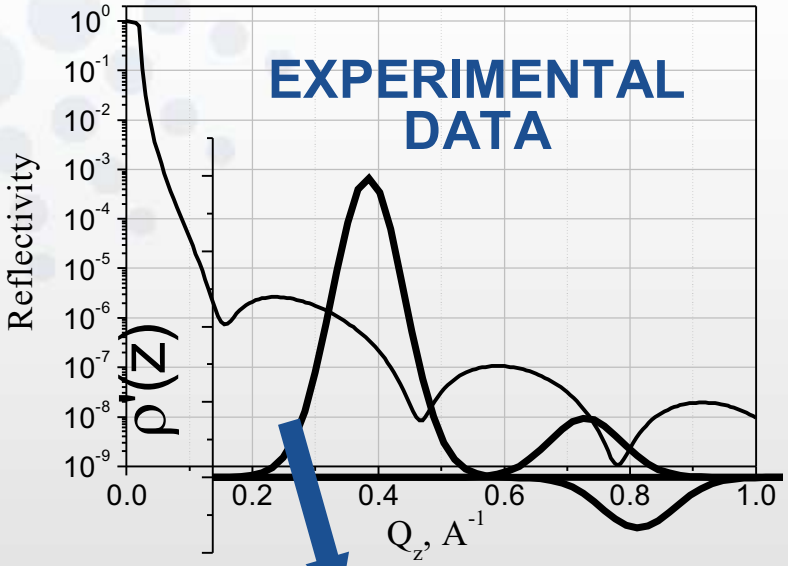


$$\Lambda(\alpha) = \frac{\lambda}{2\sqrt{2}\pi\left(\sqrt{\left(\alpha^2 - \alpha_C^2\right) + 4\beta^2} - \left(\alpha^2 - \alpha_C^2\right)\right)^{1/2}}$$

λ[Å]=12.4 / E[keV]
8 keV → 1.55 Å

REFLECTIVITY METHODE





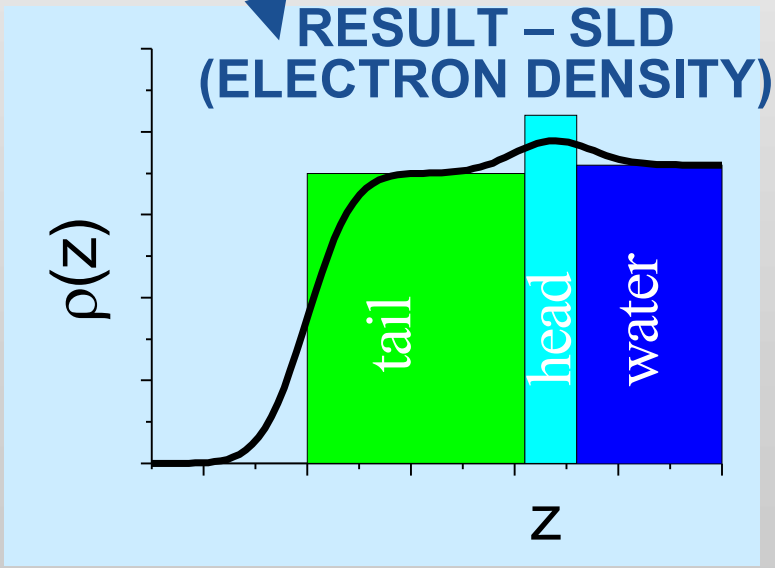
$$I/I_0 = R_F(q_Z)\,|F(q_Z)|^2 \exp(-(q_Z\sigma)^2)$$

where

$$q_z = \frac{4\pi}{\lambda}\sin\alpha$$

$$R_F(q_z) = \left(\frac{2\pi}{\lambda}\right)^2 \left|\frac{\sin\alpha - \sqrt{\sin^2\alpha - \sin^2\alpha_C}}{\sin\alpha + \sqrt{\sin^2\alpha - \sin^2\alpha_C}}\right|^2$$

$|F(q_Z)|$ = Fourier transform of $\partial\rho(z)/\partial z$

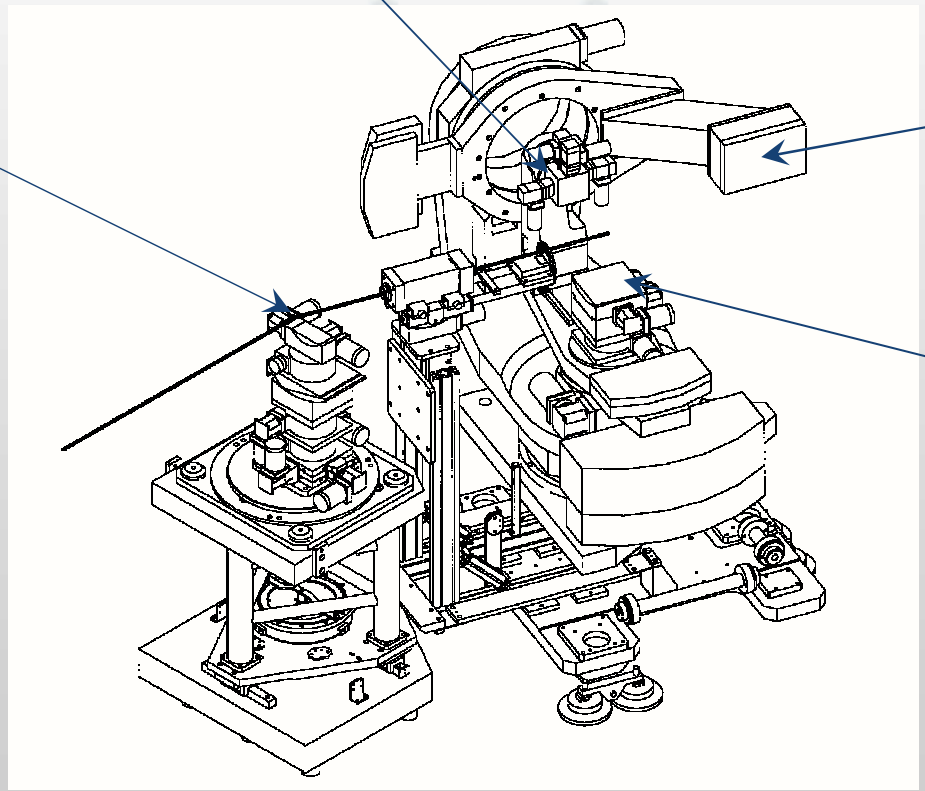


ID10B DIFFRACTOMETER FOR GRAZING INCIDENCE X-RAY SCATTERING ON LIQUID SURFACES

Vertical Sample Stage

Beam Deflector

Ge(111) deflector
Si(111) analyzer
Si(333) analyzer
Focusing
[mirror, Be-CRL, FZP]

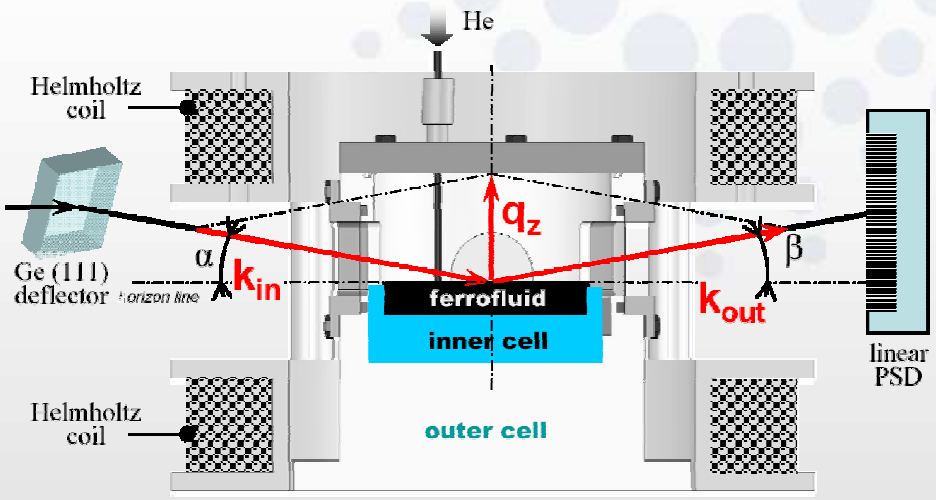


Detector arm

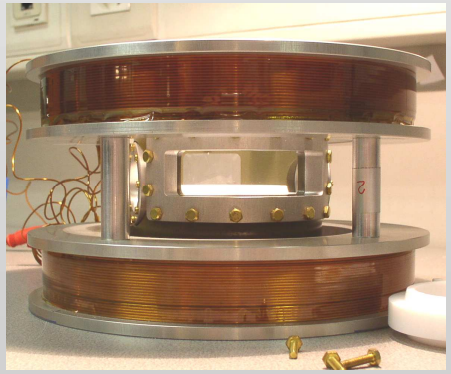
Collimation
Slits
Sollers
Analyzer
Detectors
D0, D1, D2

Horizontal Sample Stage

SAMPLE CELL

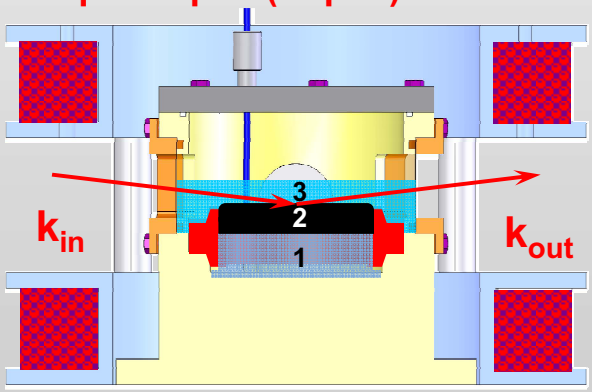


Sketch of the free surface experiment showing the incident and reflected X-ray beams (k_{in}, k_{out}) and the sample environment.



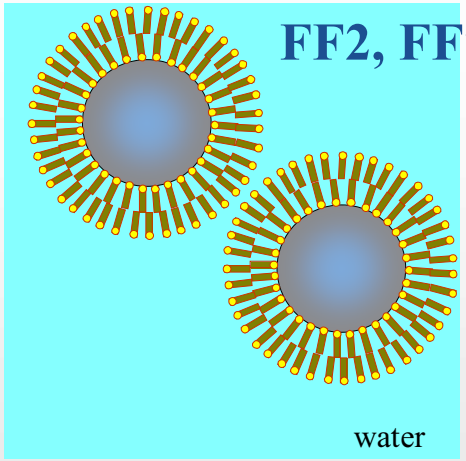
- vertical input/output angle up to 18°
- horizontal output angle up to 60°
- sample diameter up to 70 mm
- maximum field strength 20 mT
- hermetic closure
- 100% Teflon coating inside

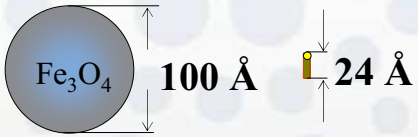
liquid-liquid (-liquid) interface

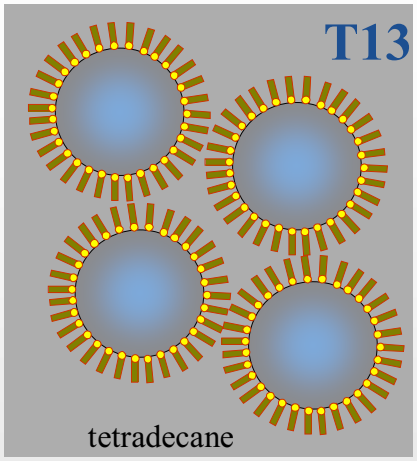


E ≈ 22 keV

FERROFLUID SAMPLES





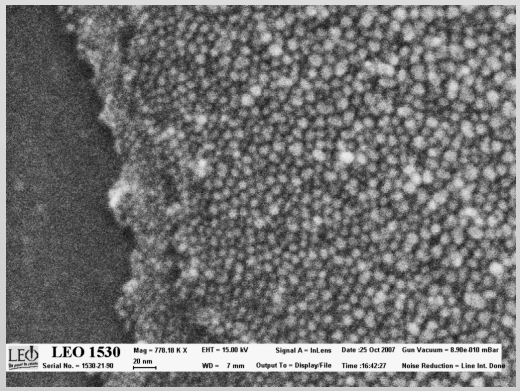


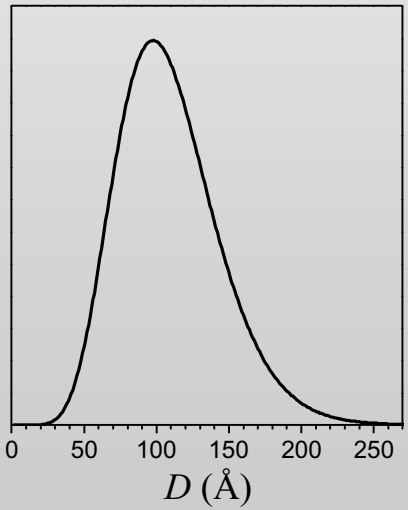
Water-based ferrofluid
Magnetite (Fe_3O_4) cores
Concentration C= 2 and 7 % vol.
Surfactant – sodium oleate ($C_{18}H_{33}NaO_2$)
double layer.

Oil-based ferrofluid
Tetradecane $CH_3(CH_2)_{12}CH_3$
Surfactant – oleic acid ($C_{18}H_{33}OOH$)
single layer.
C= **13** % vol.

SEM

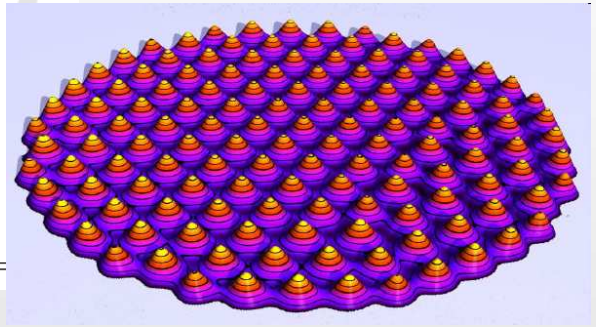
500 Å





CORE SIZE DISTRIBUTION

Sample or compound	γ (mN/m)	ρ_m (g/cm^3)	χ_i	H_c (Oe)	ρ (10^{-6} Å^{-2})
FF2	32	1.11	0.33	275	10.0
FF7	30	1.26	1.16	74	11.4
T13	23	1.35	2.15	36	11.6
Fe_3O_4		5.0			40.5
$C_{18}H_{33}COOH$		0.89			8.5
$C_{18}H_{33}NaO_2$	37	1.02			9.6
H_2O	72.8	1.00			9.5
$C_{14}H_{30}$	26.6	0.76			7.5



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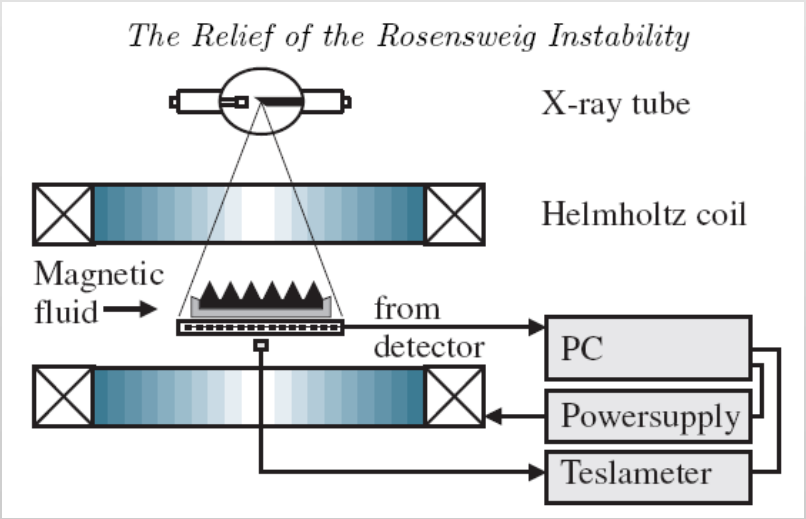
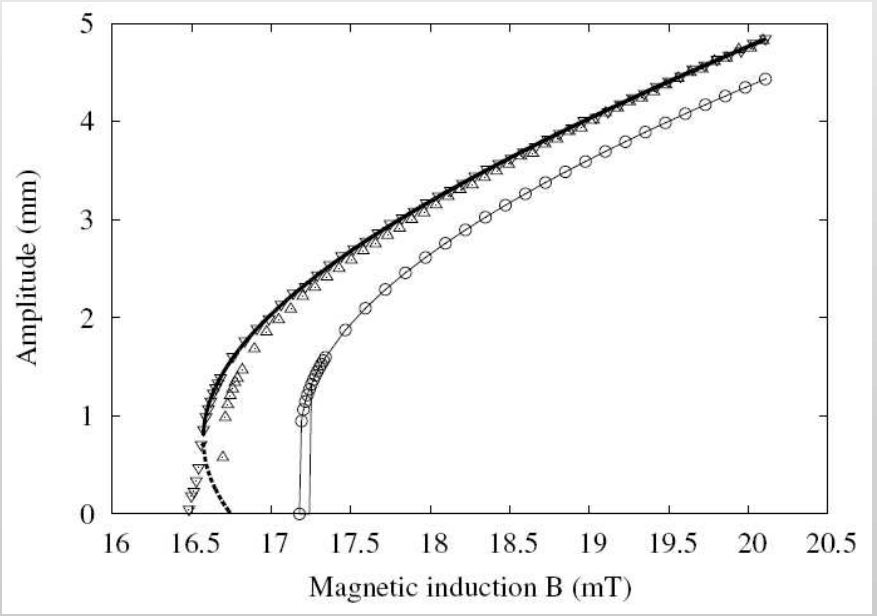
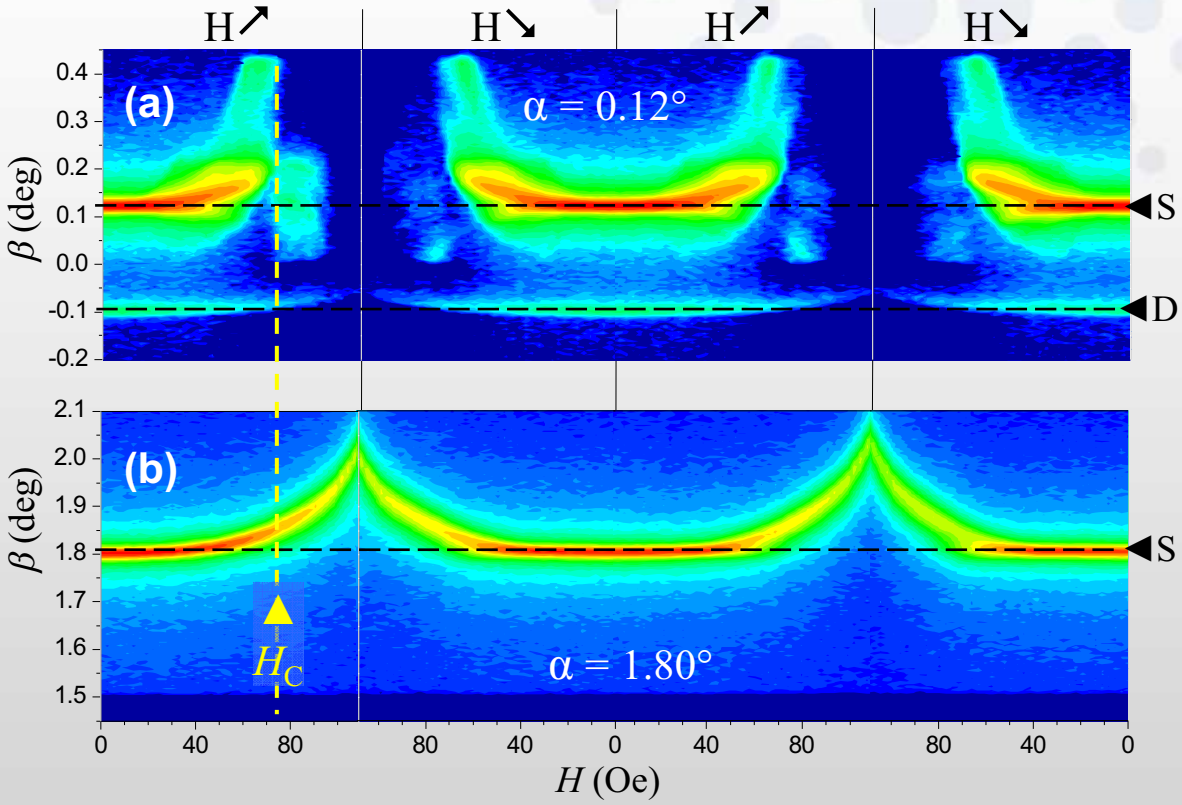
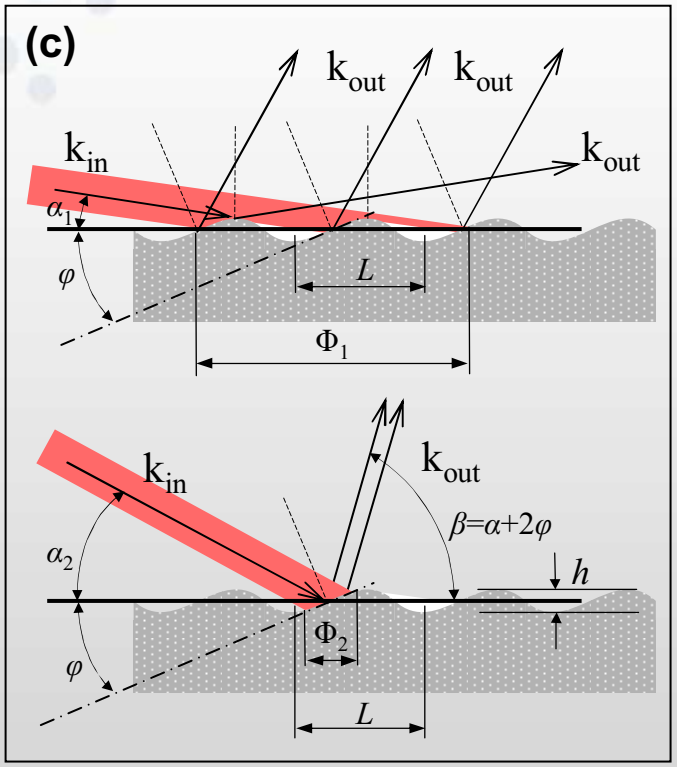




MACROSCOPIC DISTORTION OF FREE FF SURFACE IN NORMAL MAGNETIC FIELD





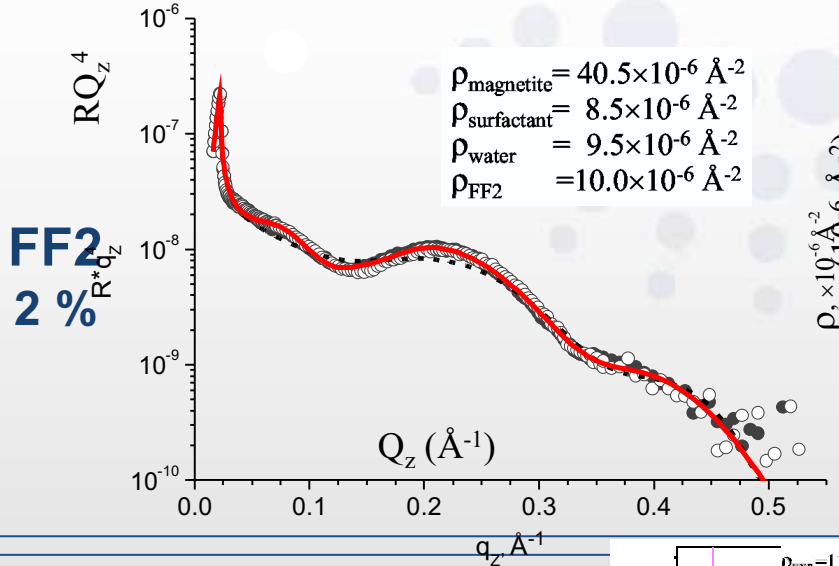
Exit-angle intensity distribution obtained during two field increasing-decreasing cycles

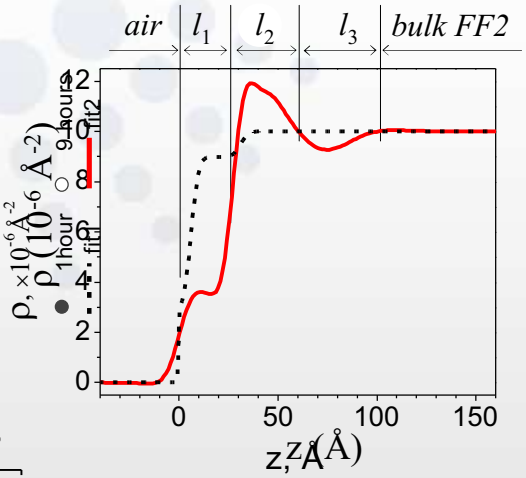
Surface distorted already at $H<H_C$

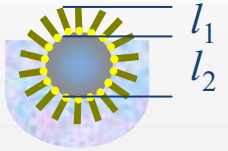
REFLECTIVITY FROM WATER FERROFLUID

S8 TIME EFFECT AT ZERO FIELD

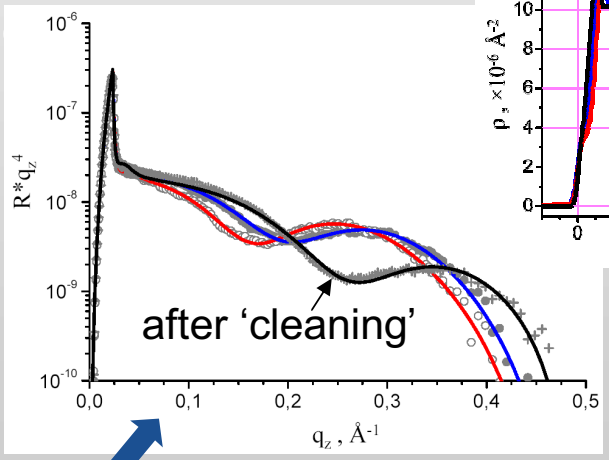
FF2
2 %

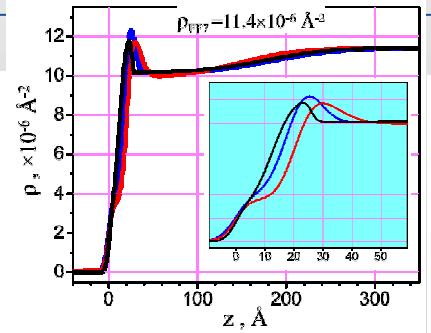


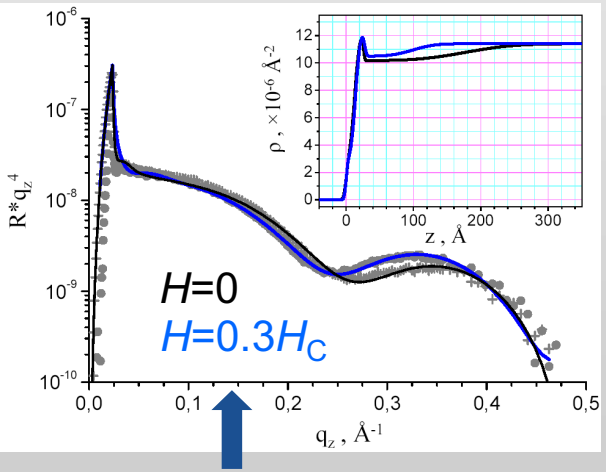




FF7
7 %



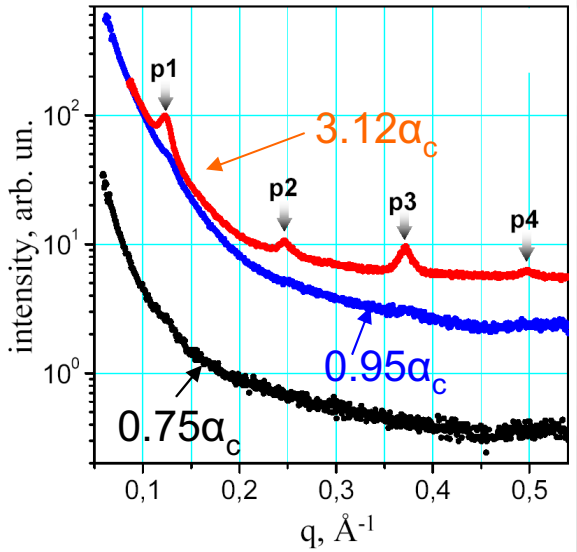




surface structure recreates from the bulk material

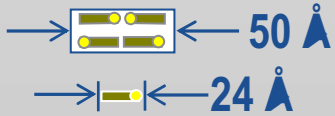
field brings more particles from the bulk to the surface

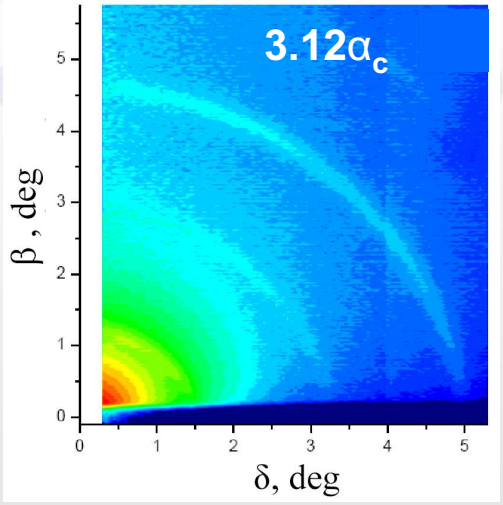
GID FROM WATER FERROFLUID FF2



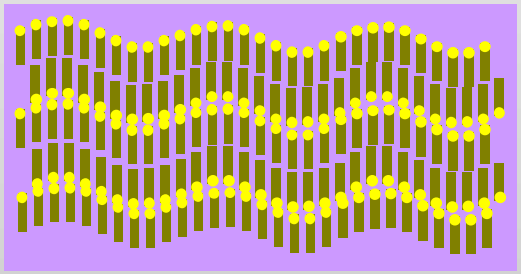
equidistant peaks ⇒ ordering of monodisperse objects of a size L_d =50Å

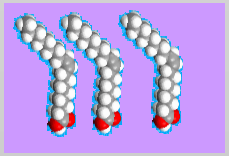
intensity of the odd peaks is higher than intensity of even peaks ⇒ more basic structural unit with $L_d/2$





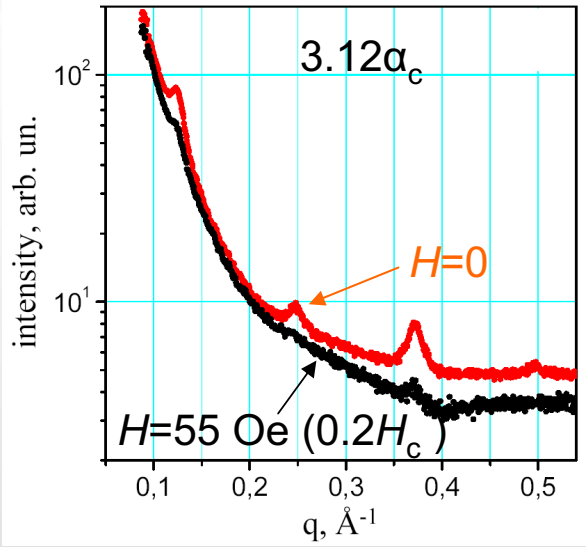
powder rings ⇒ 3d multilamellar structure





no order inside of the oleic acid monolayer

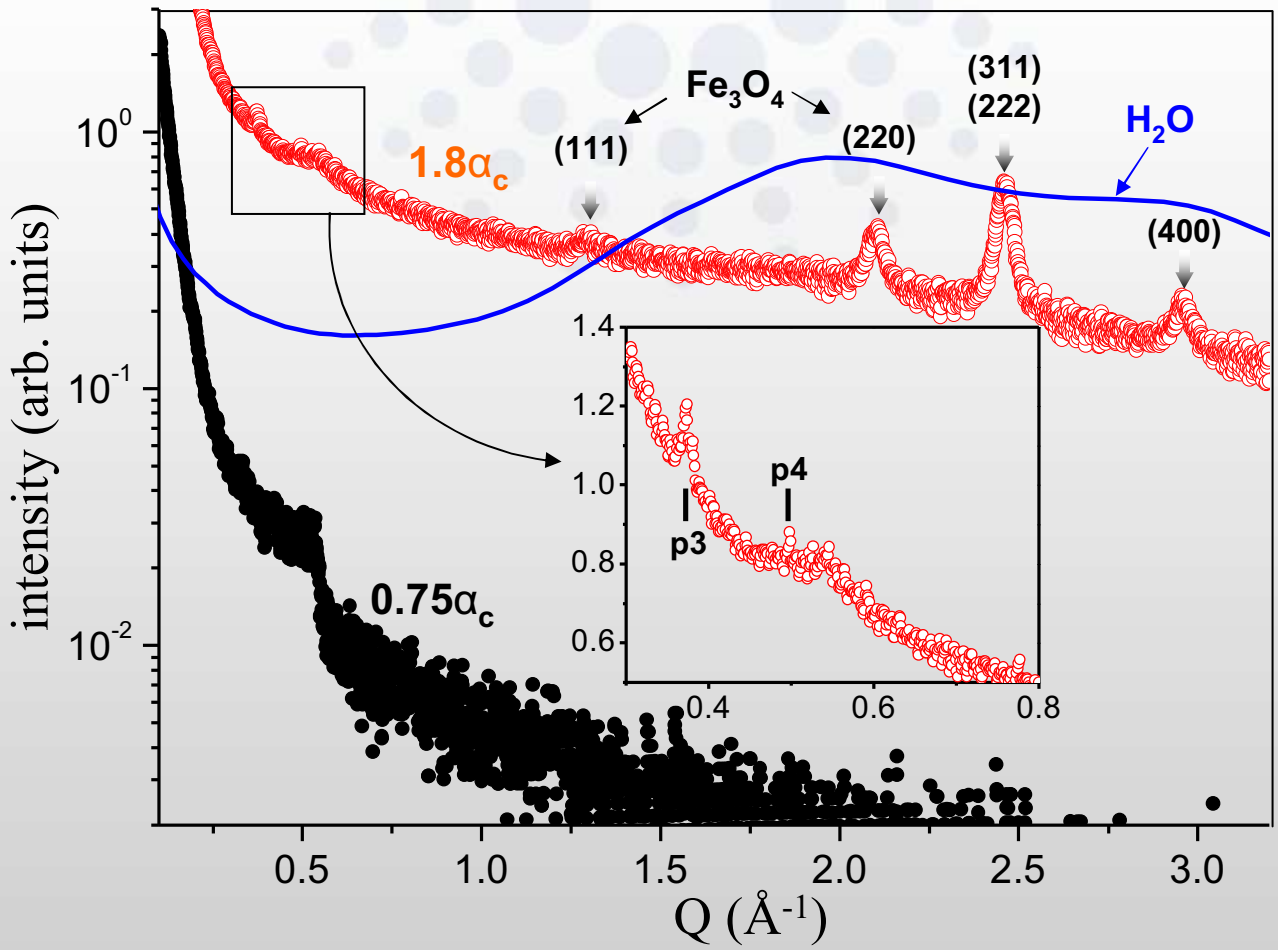
stearic acid is straight



field-induced degradation of the peaks ⇒ dissipation of the ordering
or
less objects at the surface

GID ON WATER-BASED FERROFLUID

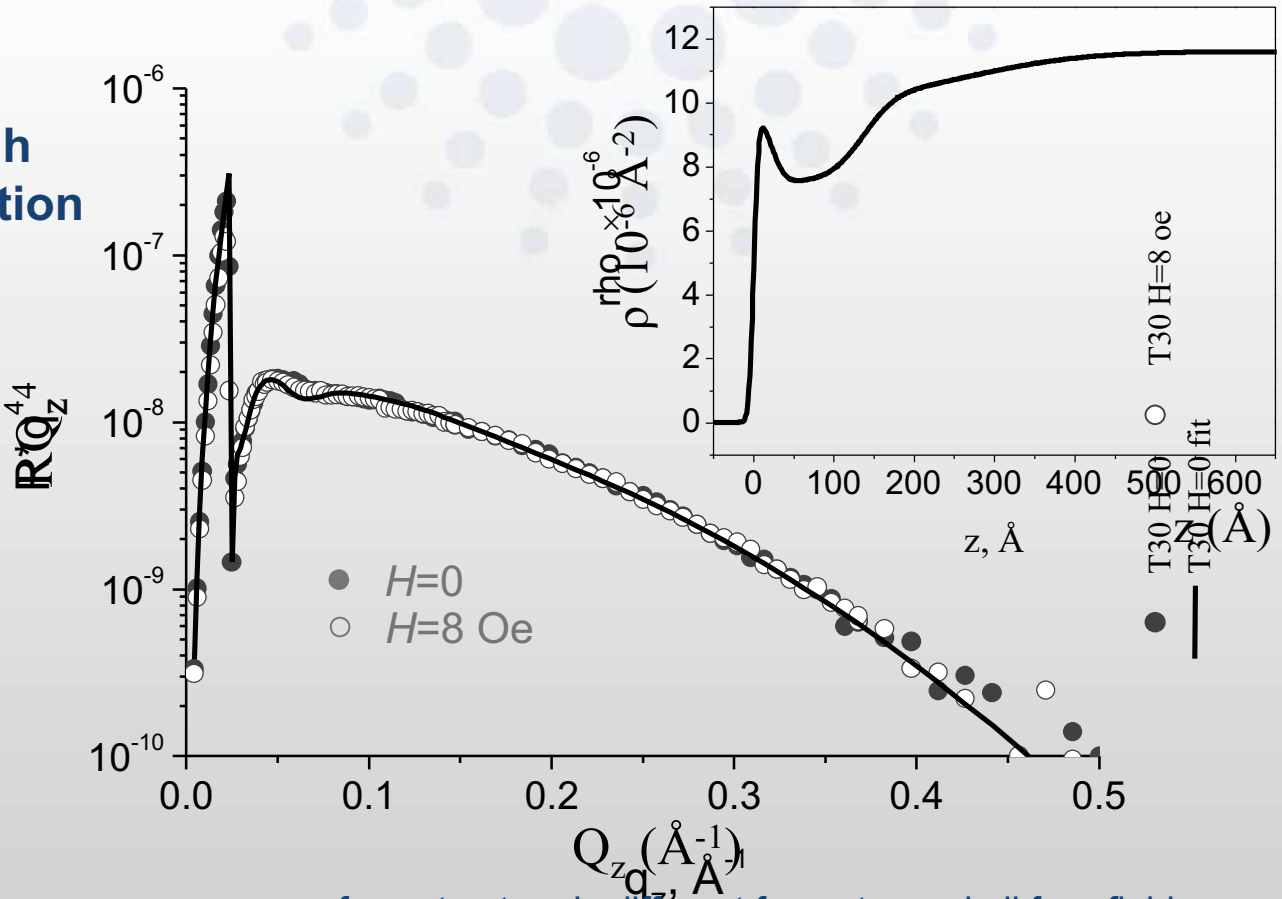
FF7
7%



similar GISAXS peaks but with low intensity
magnetite peaks at high q
no trace of water

REFLECTIVITY FROM OIL FERROFLUID

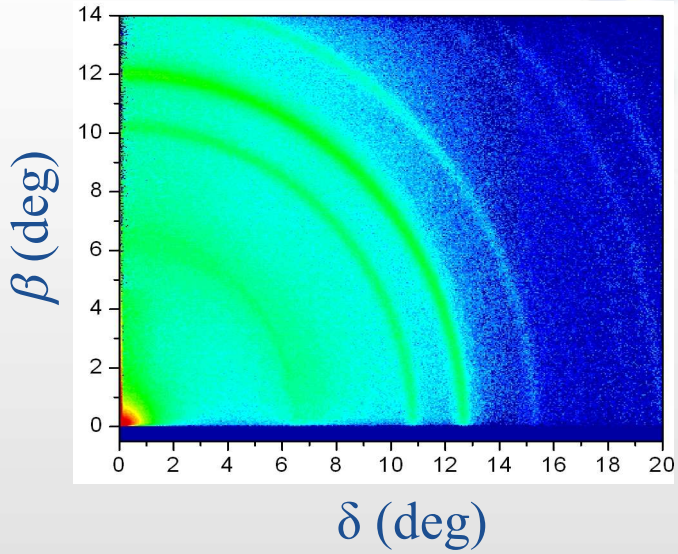
T13
very high concentration



surface structure is different for water and oil ferrofluid

sharp border between ferrofluid and air
depleted layer is almost pure oil
surface is very sensitive to the field ⇒ maximum 10 Oe can be used

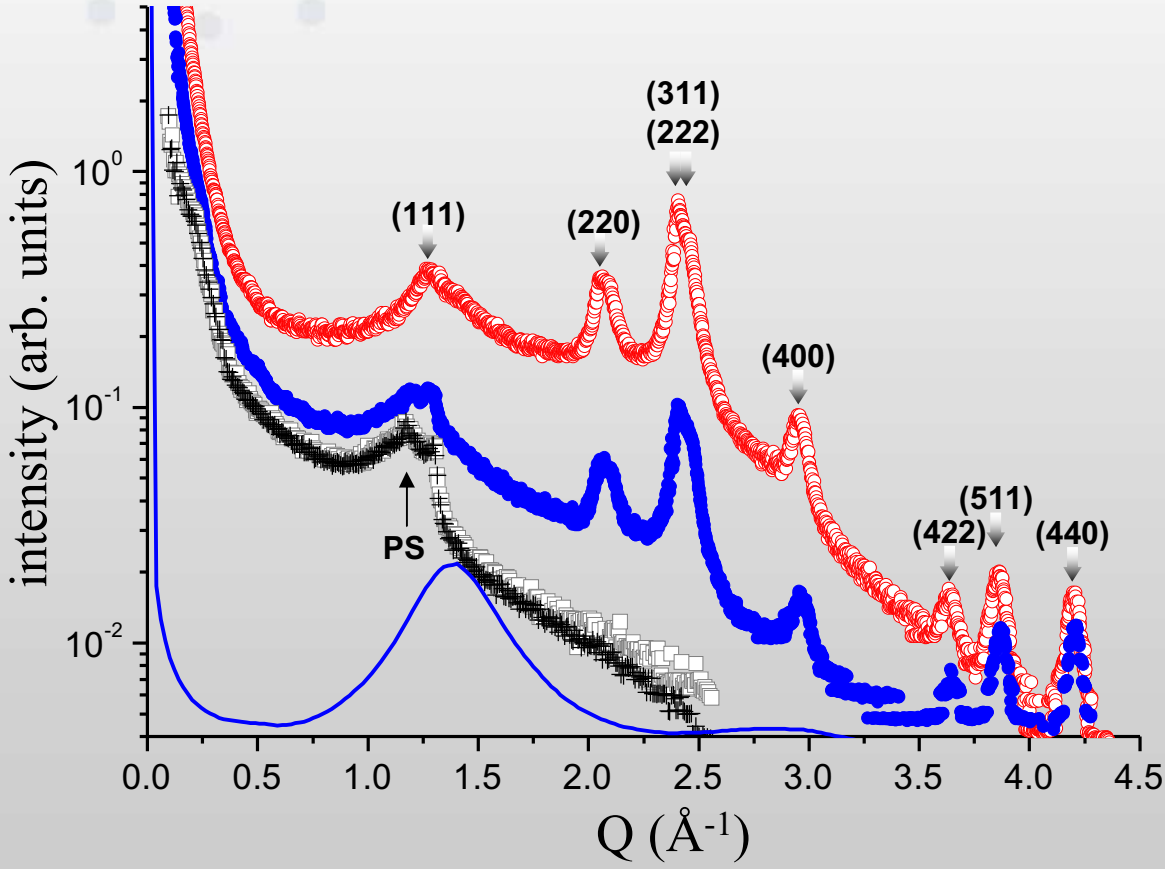
GID FROM OIL FERROFLUID T13



tetradecane peak

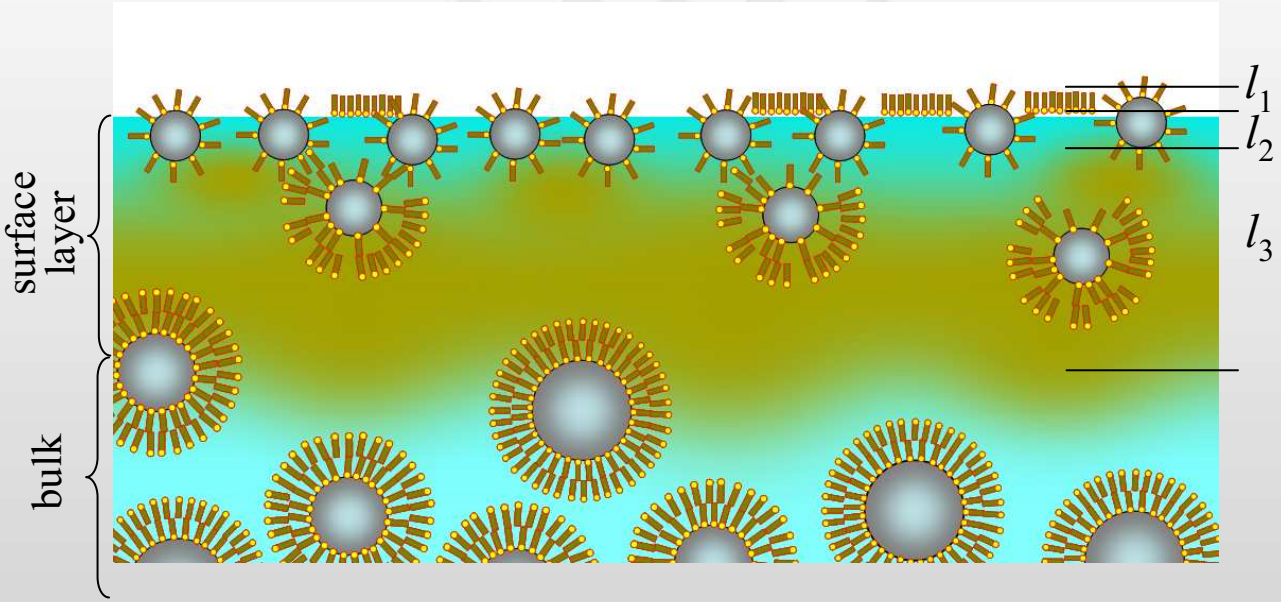
no 50 Å periodicity

Fe_3O_4 peaks at high q



RECONSTRUCTION OF THE FF SURFACE STRUCTURE

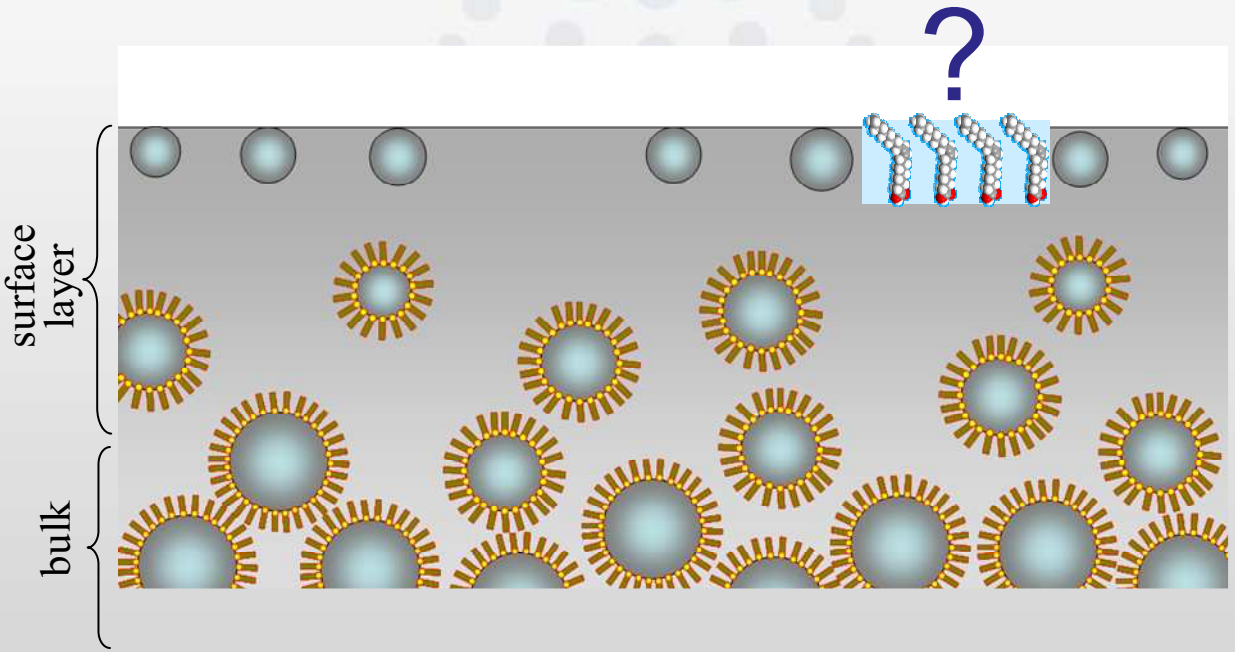
WATER FERROFLUID



l_1 – surfactant layer (~ 25 Å)
l_2 – small particles with a single hydrophobic surfactant shell (30÷40 Å)
l_3 – surfactant enriched layer with Na oleate multilamellar structure (100÷250 Å)

RECONSTRUCTION OF THE FF SURFACE STRUCTURE

OIL FERROFLUID

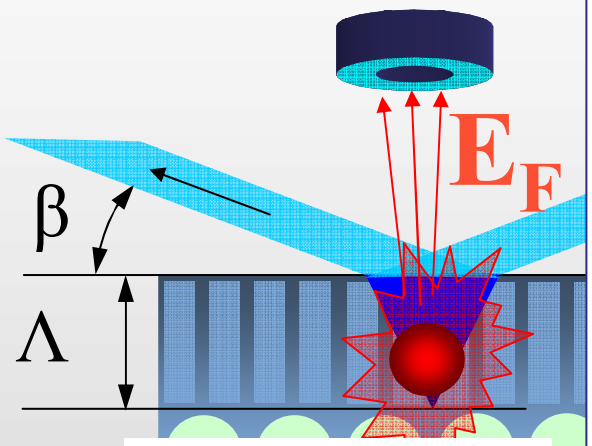


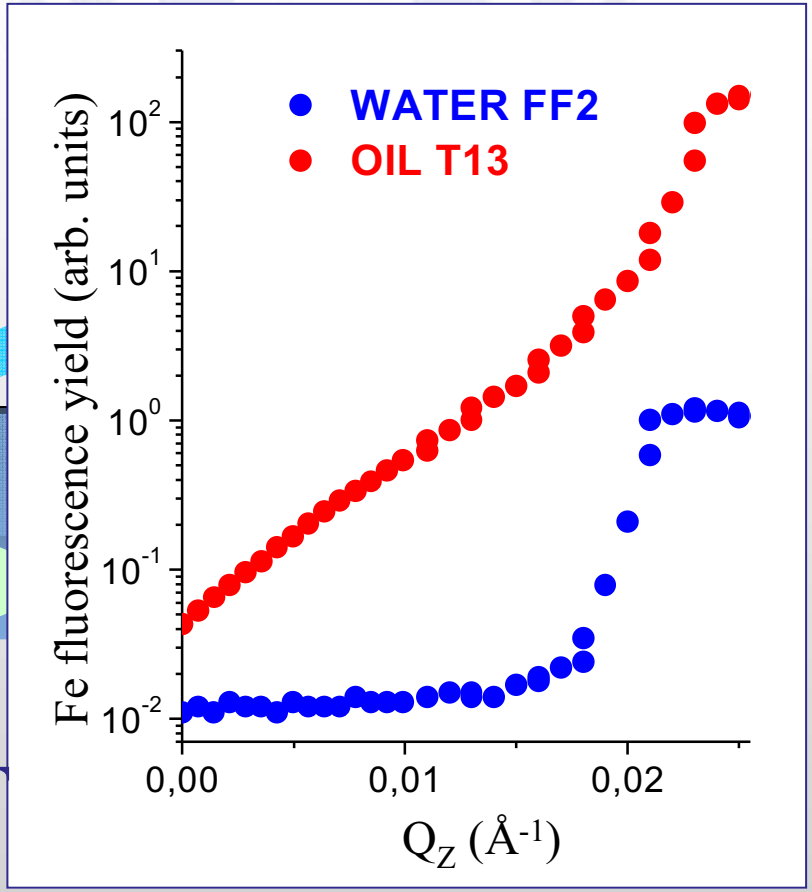
l_1 – layer with small particles or oleic acid Gibbs layer
l_2 – layer of pure oil (300÷500 Å)
no oleic acid ordering

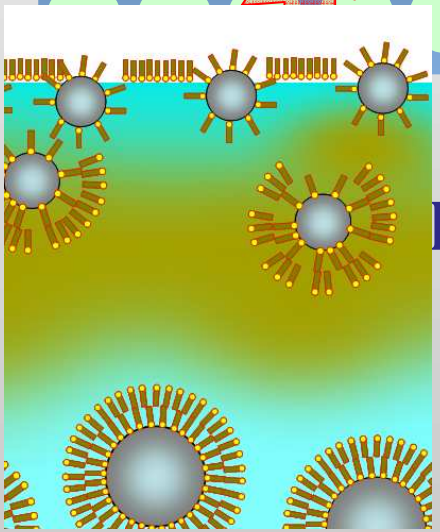
structure is more simple
oil ferrofluid is more promising for practical applications

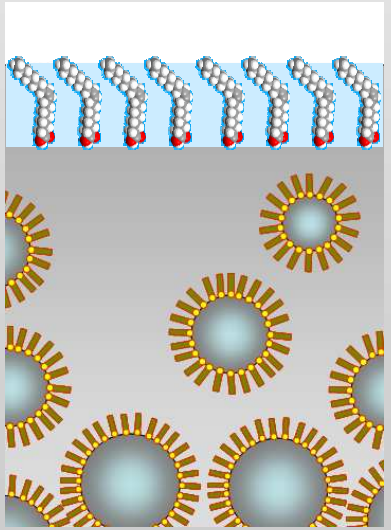
COMPLEMENTARY TECHNIQUE – X-RAY FLUORESCENCE

energy-dispersive





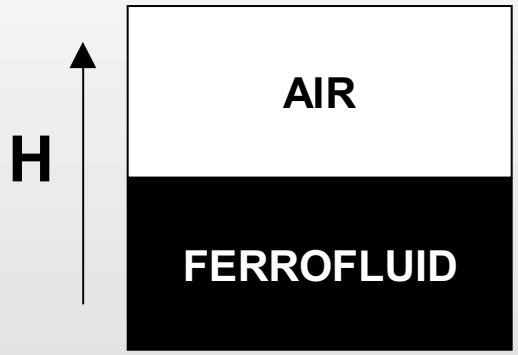




TO BE CONTINUED

QUESTION

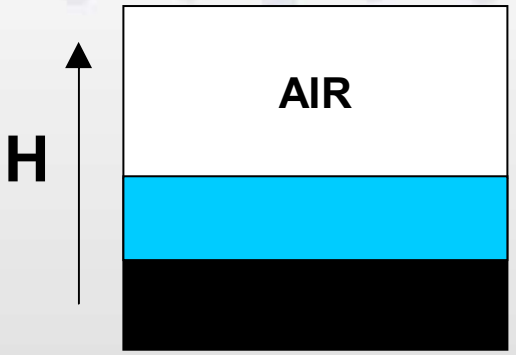
How to calculate RI parameters for the real surfaces of the surfacted ferrofluids?



Ideal 'pure' case:
gas – homogeneous magnetic media

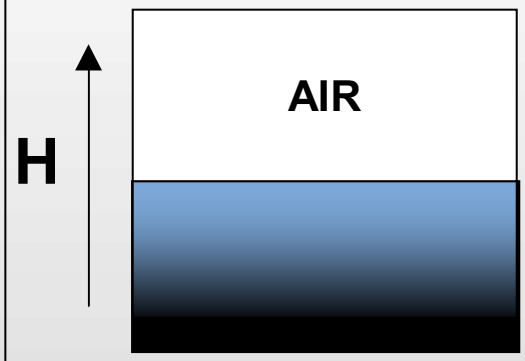
$$H_c^2 = \frac{8\pi(\chi_i + 2)}{\chi_i^2(\chi_i + 1)}\sqrt{\rho\sigma g}$$

$$L = 2\pi\sqrt{\frac{\sigma}{\rho g}}$$



Water-based ferrofluid:
gas –
non-magnetic layer –
magnetic media

?



Oil-based ferrofluid:
gas –
layer with gradient concentration

?

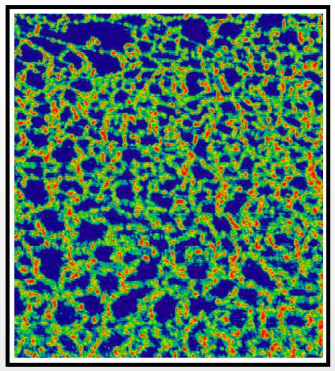
CONCLISION

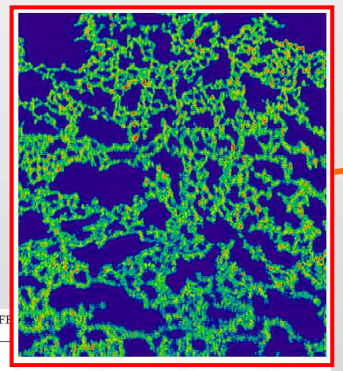
- Producing of desired structure on the free ferrofluid surface will be difficult

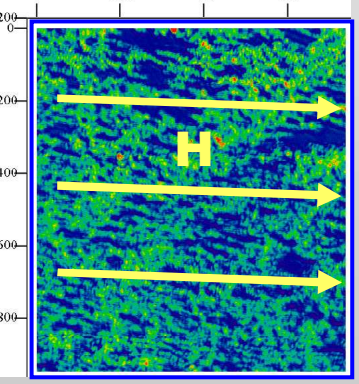
- One must look for another way to provide ordering of the particles

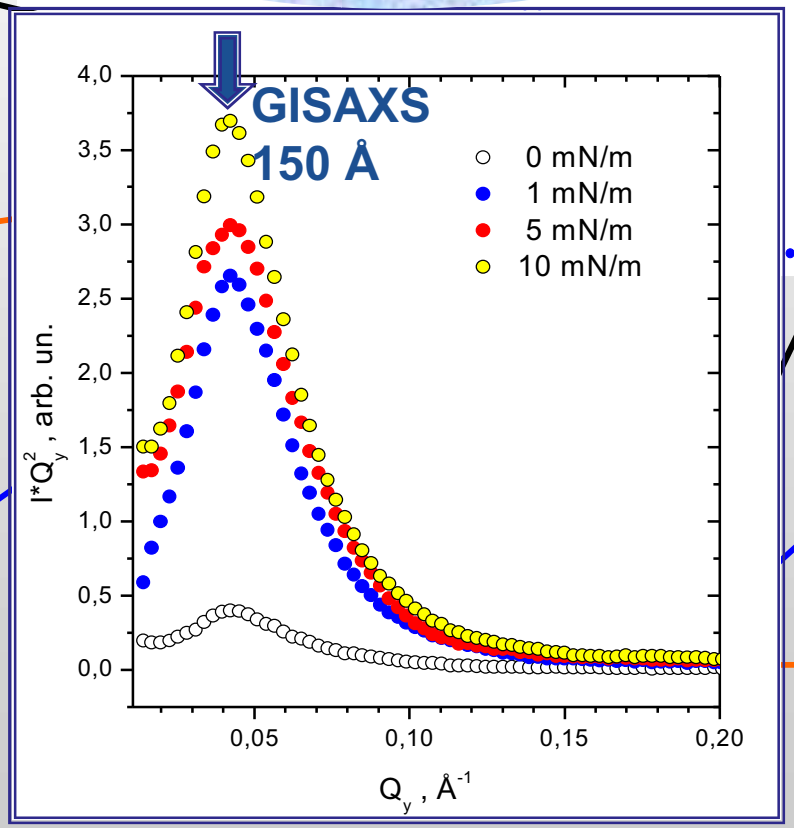
OUTLOOK: ORDERING ON LIQUID SURFACE LANGMUIR TECHNIQUE

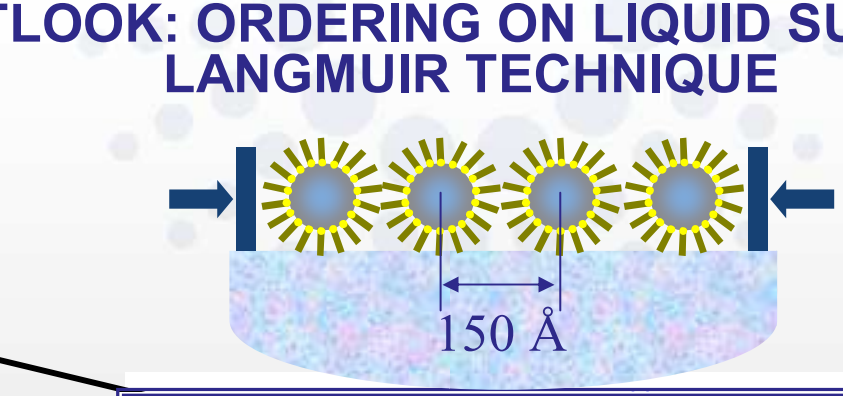
images from Brewster angle microscope

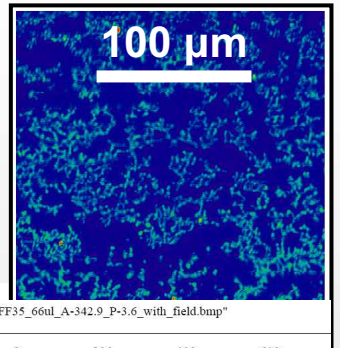


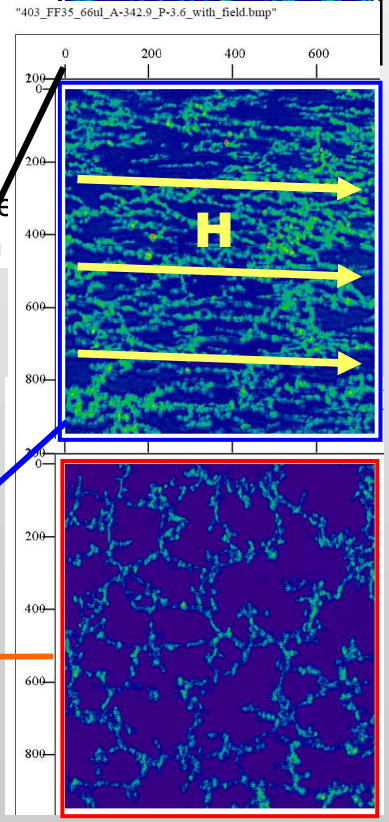




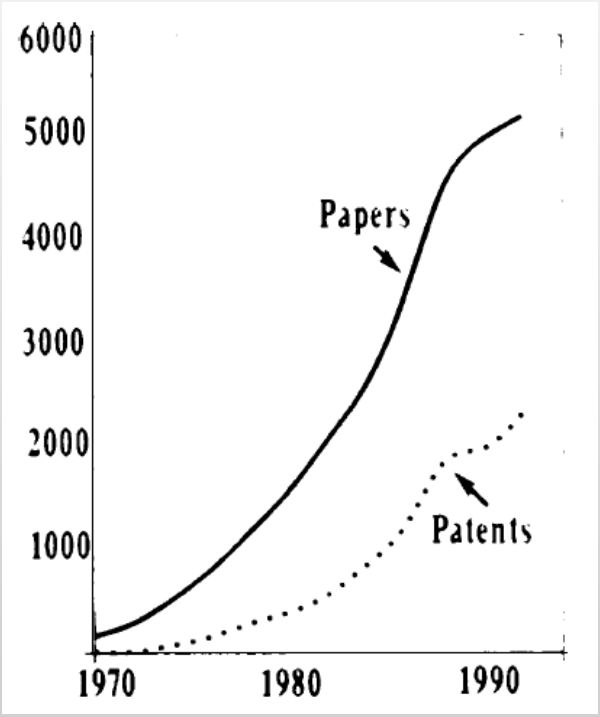


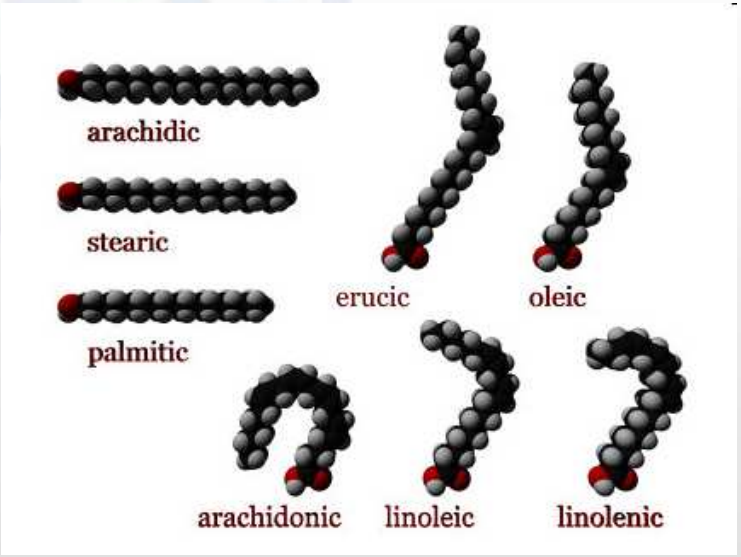






THANK YOU FOR YOUR ATTENTION





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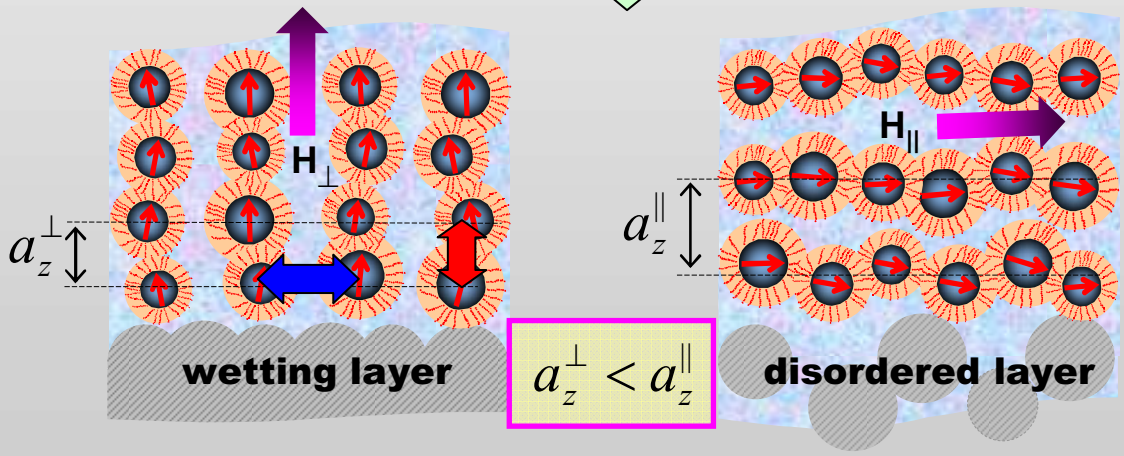
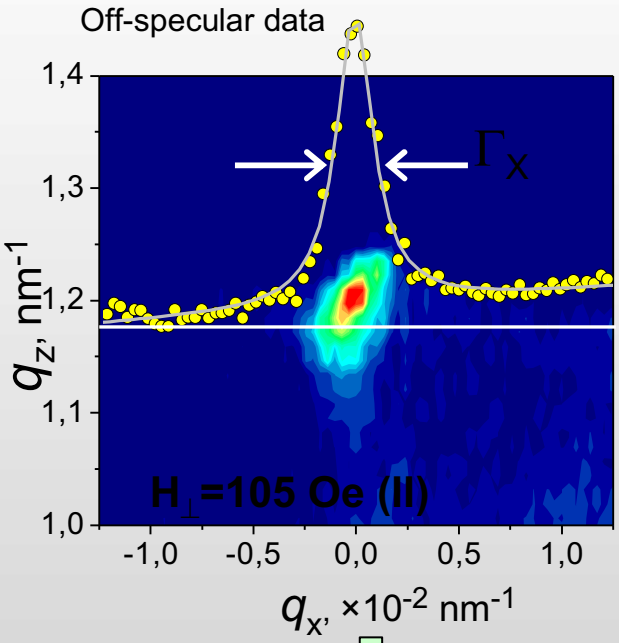
EXPERIMENTAL: MAIN RESULTS

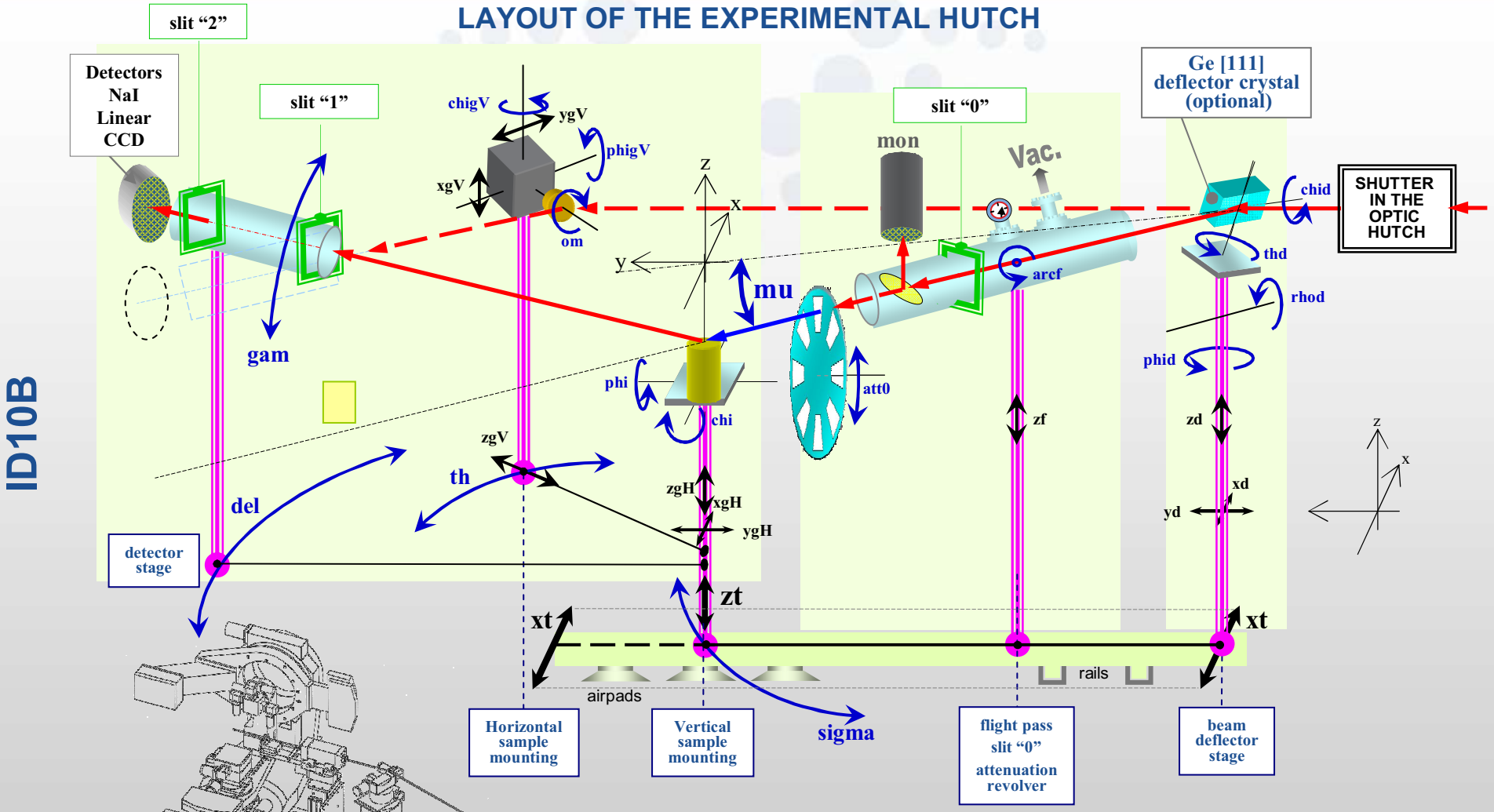
field	N	a_z [nm]	ζ_z [nm]
H = 0	0	-	-
$H_\perp$ = 50 Oe	6	6.3 ± 0.1	17 ± 3
$H_\perp$ = 105 Oe (I)	9	6.2 ± 0.1	21 ± 3
$H_\perp$ = 105 Oe (II)	30	5.2 ± 0.1	43 ± 3
$H_\parallel$ = 105 Oe	15	7.3 ± 0.1	33 ± 3





lateral correlation length
$L_X = 2\pi/\Gamma_X$ = 3 μm
(domain size)

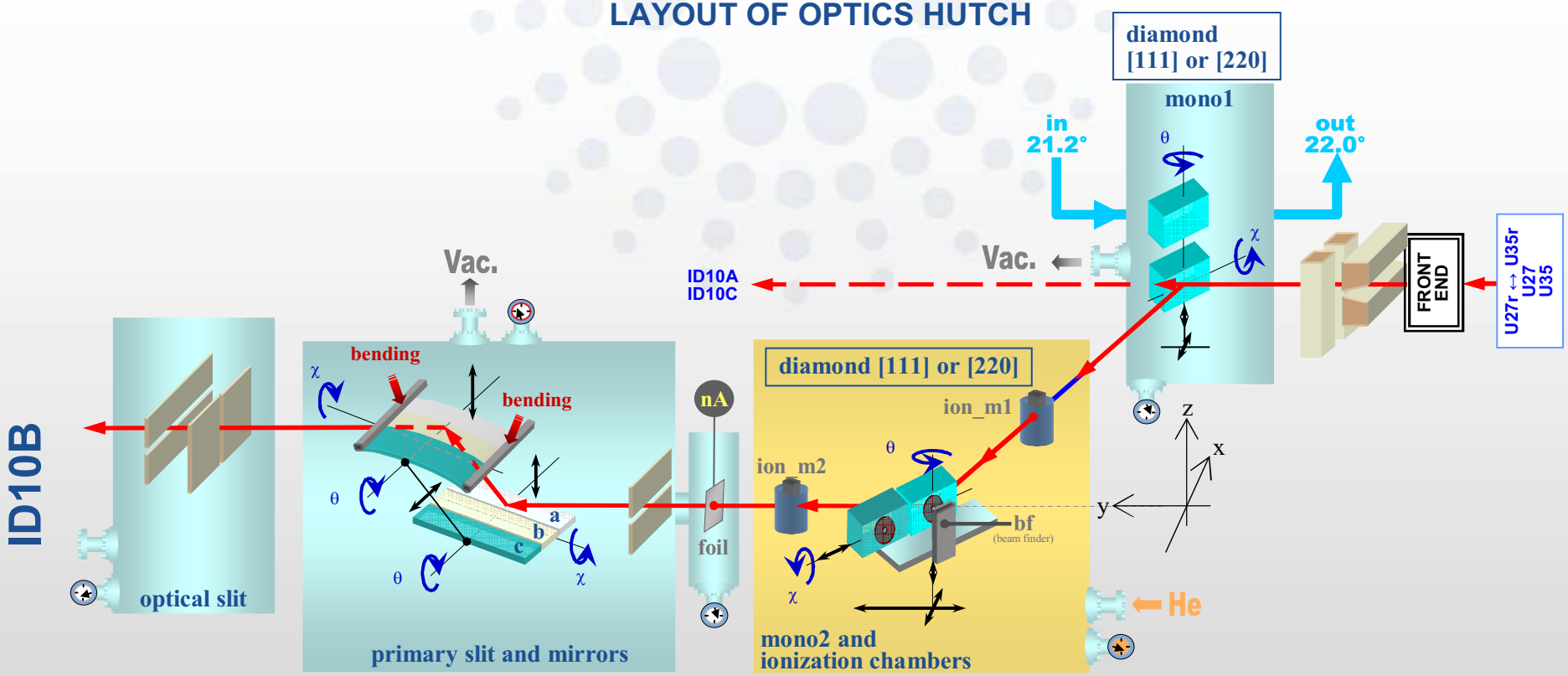
LAYOUT OF THE EXPERIMENTAL HUTCH



Elements position from the source [mm].

Deflector	39885
Goniometer (COR)	40885

LAYOUT OF OPTICS HUTCH



Energy range [keV]
7.75-13.83 with C(111)
12.66-22.59 with C(220)

Elements position from the source [mm].

Monochromator 1	30500
Monochromator 2	31322 - 32248
Foil monitor	33097
Primary Optics Slit	33733
Mirror 1	34384
Mirror 2	34784
Optics Slit	38377