Reflectometry at the IBR-2 and Science

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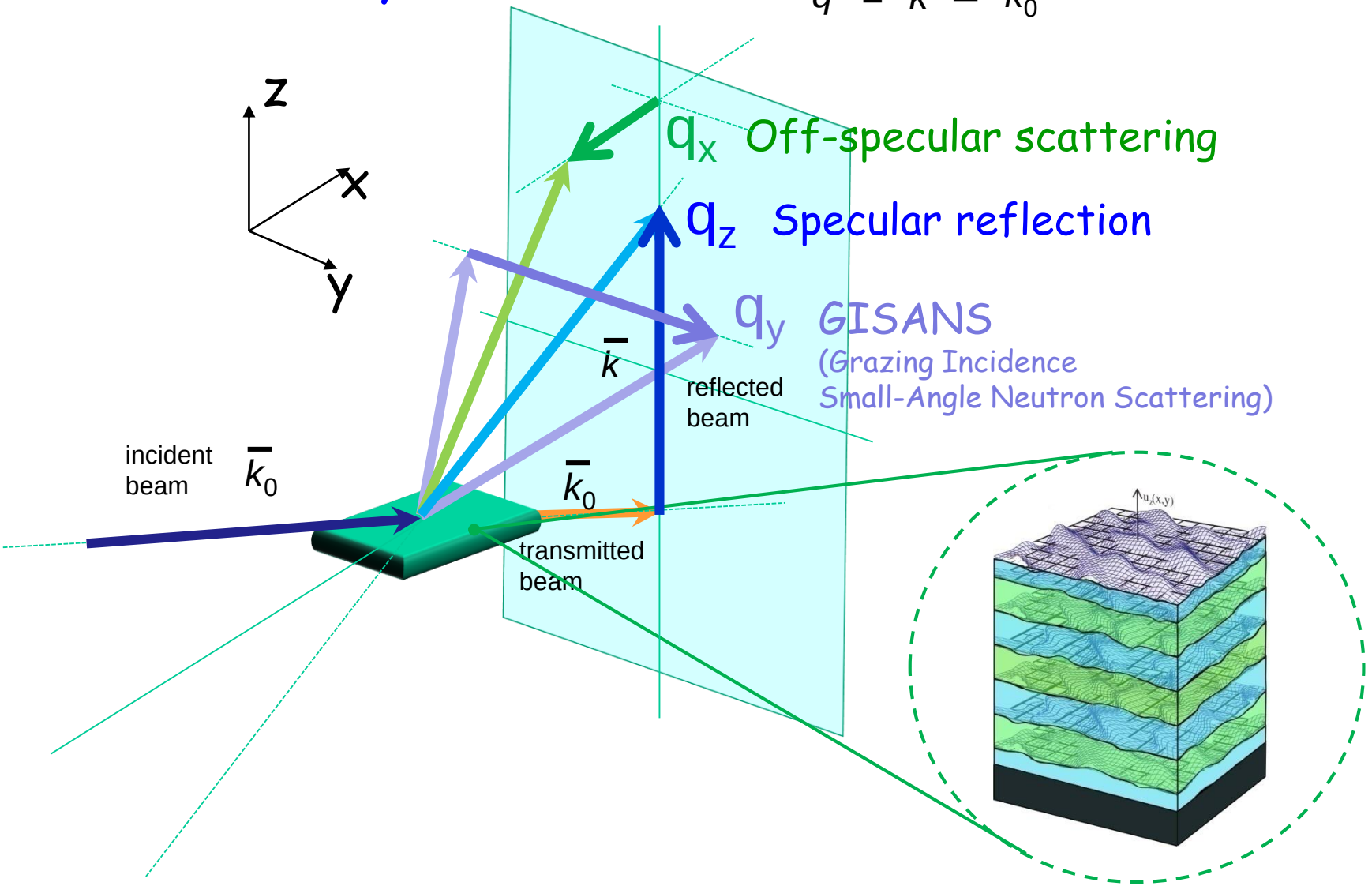
3D Reflectometry

$$\bar{q} = \bar{k} - \bar{k}_0$$



$q_x\ q_y\ q_z$

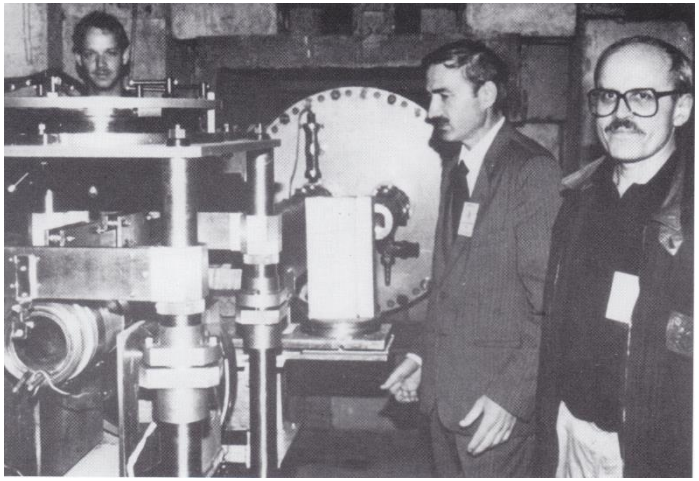
$\mathbf{u_z(x,y)}$ – vertical surface displacement

Development of optics of thermal neutrons at FLNP JINR

- Devices for neutron reflectometers, Korneev's spin-flipper, 1979
- Production of neutron guides, 1980s
- Neutron reflectometers:

spectrometer of polarized neutrons (SPN), 1988

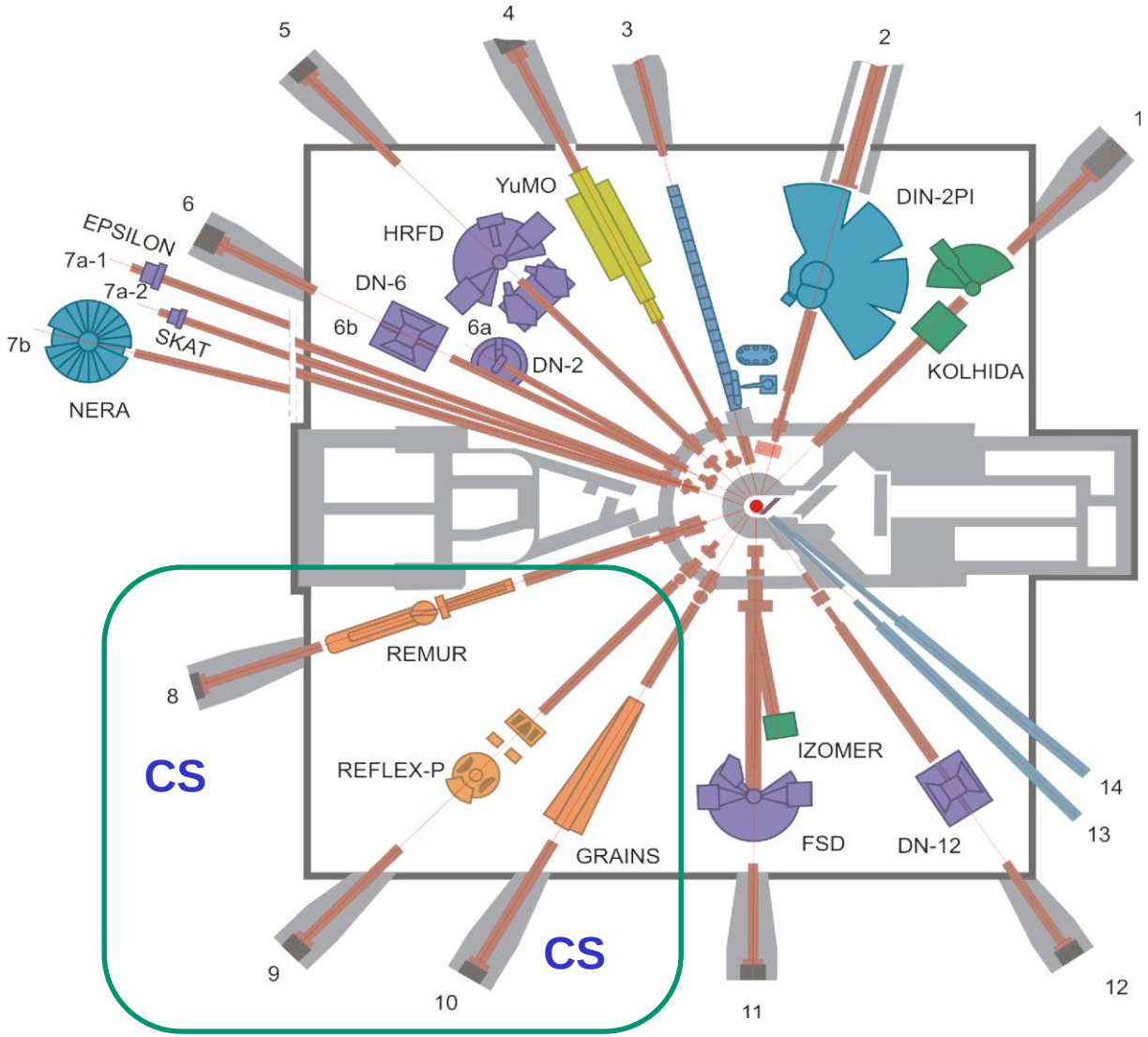
reflectometer REFLEX, 1992



reflectometer REMUR, 2003

reflectometer GRAINS, 2012

Reflectometry Suite at IBR-2

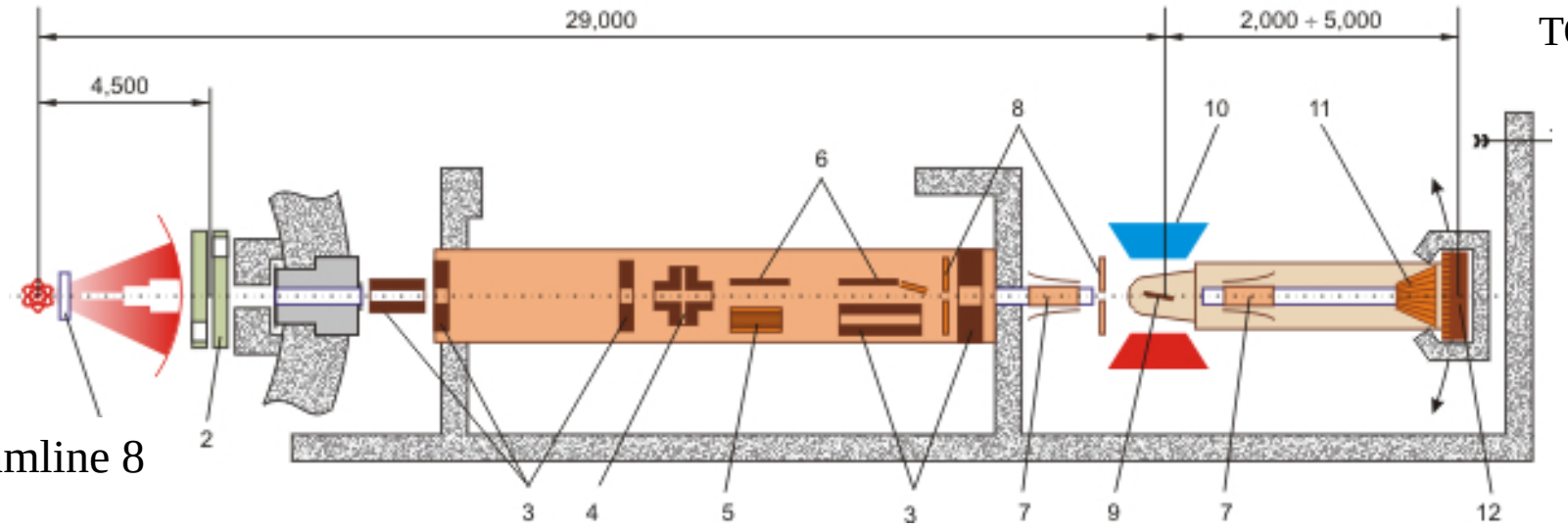


Sector of Neutron Optics

TOF reflectometers:

REMUR (beamline 8)
REFLEX (beamline 9)
GRAINS (beamline 10)

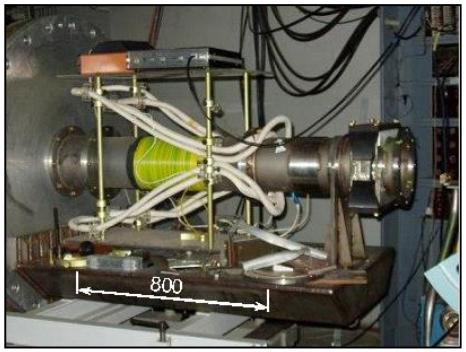
REMUR - Reflectometer with Polarized Neutrons



Parameter	
Total flux at sample position	$3 \cdot 10^4$ n/(s·cm^2)
Wavelength range	1 - 15 Å
Grazing angle	1-100 mrad
q-range	$2 \cdot 10^{-3}$ - 1 Å^{-1}
Detector system	2D PSD, ^{3}He, 20 × 20 cm, spatial resolution 2×2 mm
Temperature range	1.5 - 300 K
Q-resolution	$2 \cdot 10^{-3}$ at 10 Å
Magnetic field range	20 Oe - 3 T

https://flnp.jinr.int/en-us/main/facilities/ibr-2/remur

Polarized neutrons detection channel at REMUR

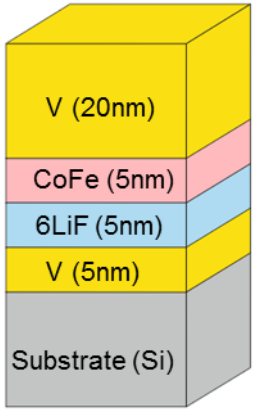


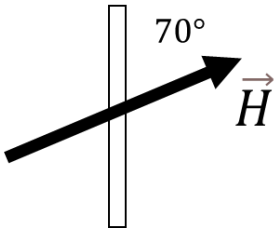
Spin-flipper

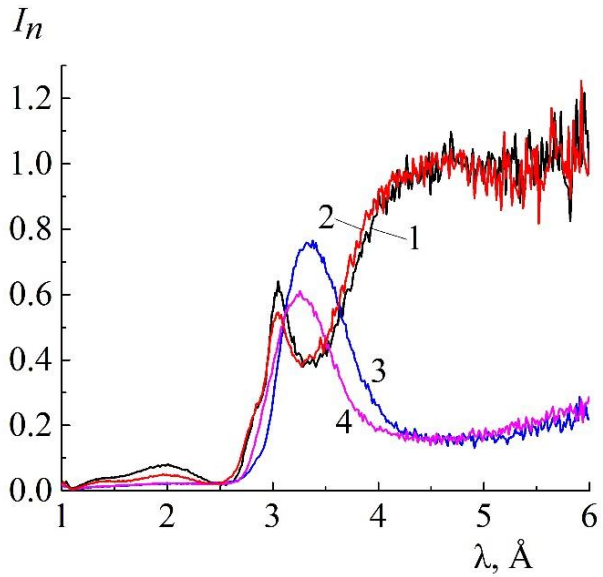
Wide-aperture analyzer

PSD in background protection chamber

Electromagnet



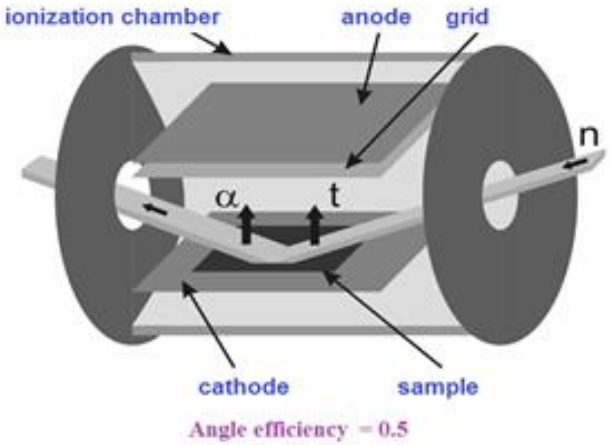




$1 - I_{off,off}$; $2 - I_{on,on}$; $3 - I_{off,on}$; $4 - I_{on,off}$

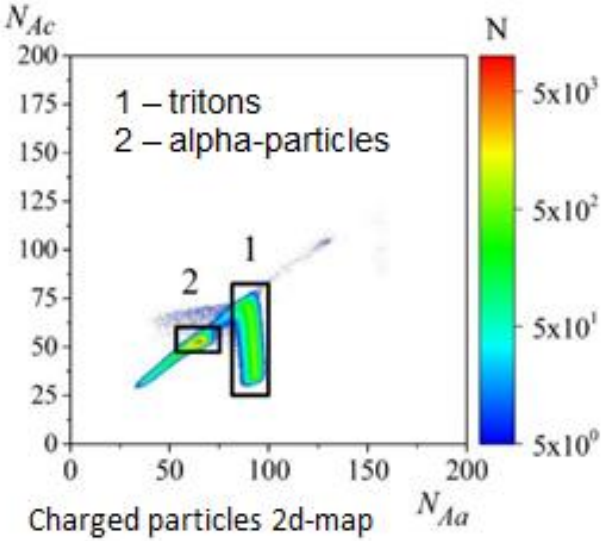
$H = 295\ Oe$ 70 degrees 3.11 $mrad$

Charged particles detection channel at REMUR

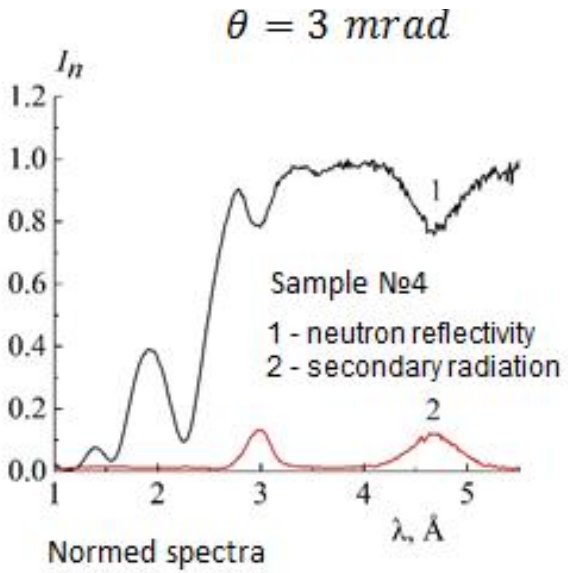


Measurements scheme

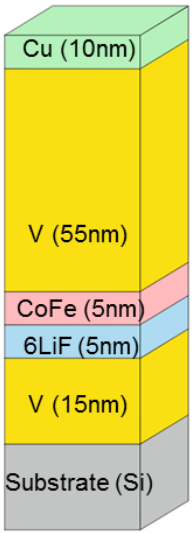
1 – ionization chamber
2 – goniometer



Charged particles 2d-map



Normed spectra

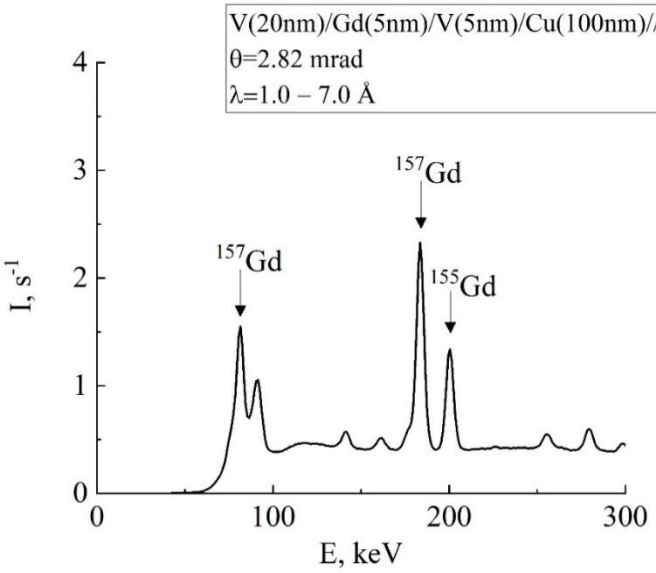


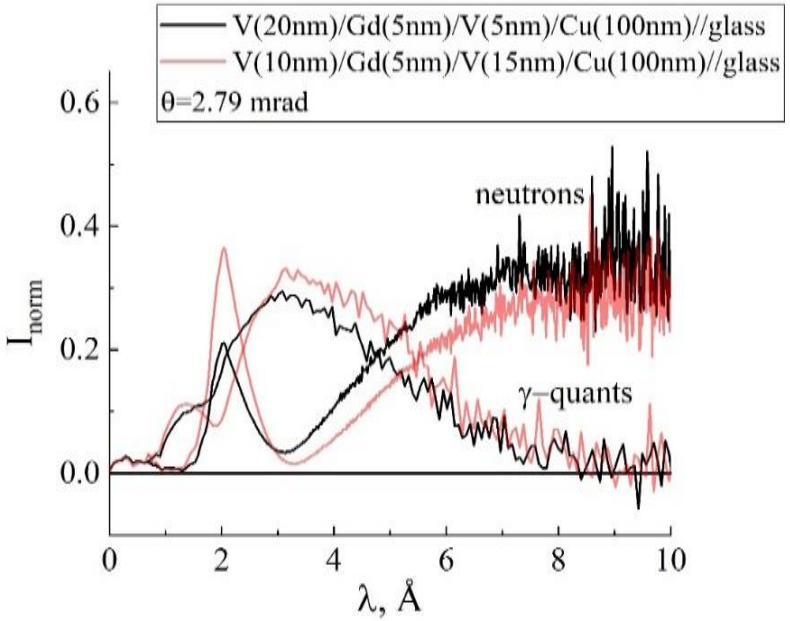
Sample №4

Gamma quanta registration channel at REMUR

Gamma-detector

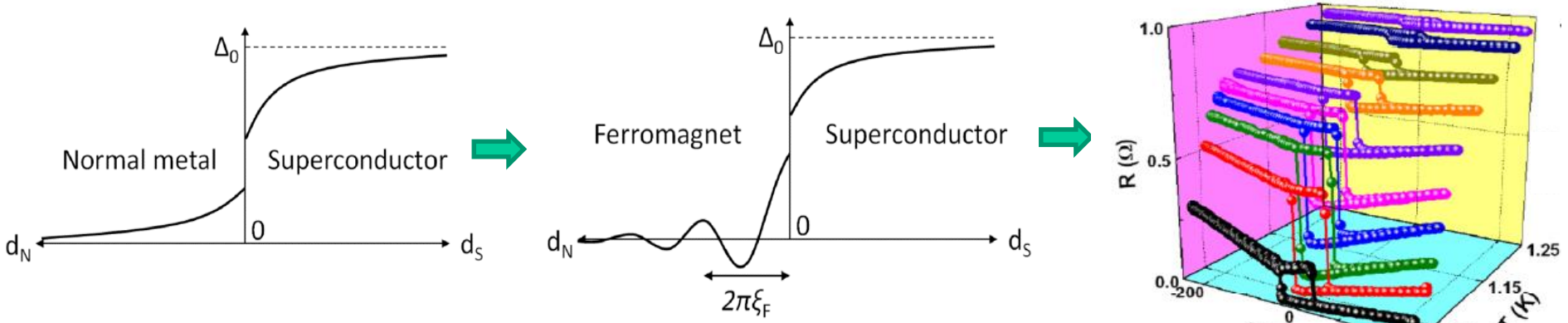
Gamma detector at sample position





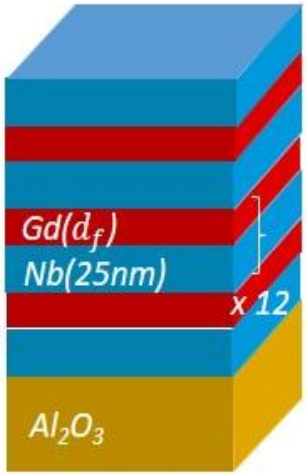
Ferromagnet-Superconductor Layered Heterostructures

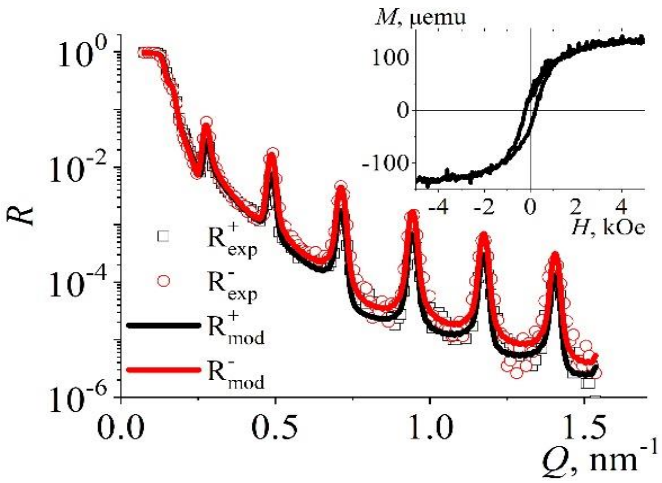
spin valve effect in Fe/V/Fe

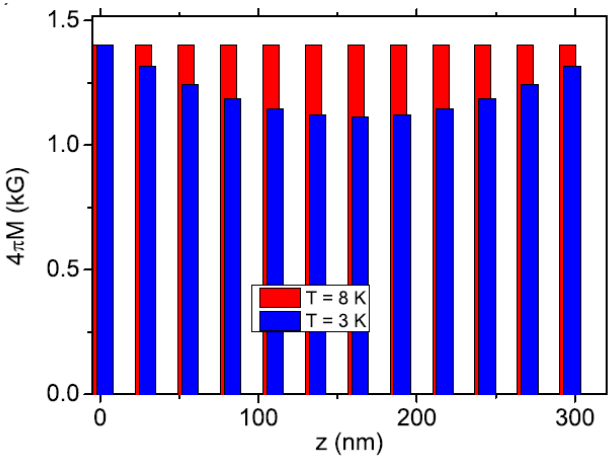


G. Miao, Spintronics Driven by Superconducting Proximity Effect, Chapter 7, in A. Gabovich (Ed.) Superconductors - New Developments, IntechOpen, 2015

Magnetic proximity effect in Nb/Gd superlattice

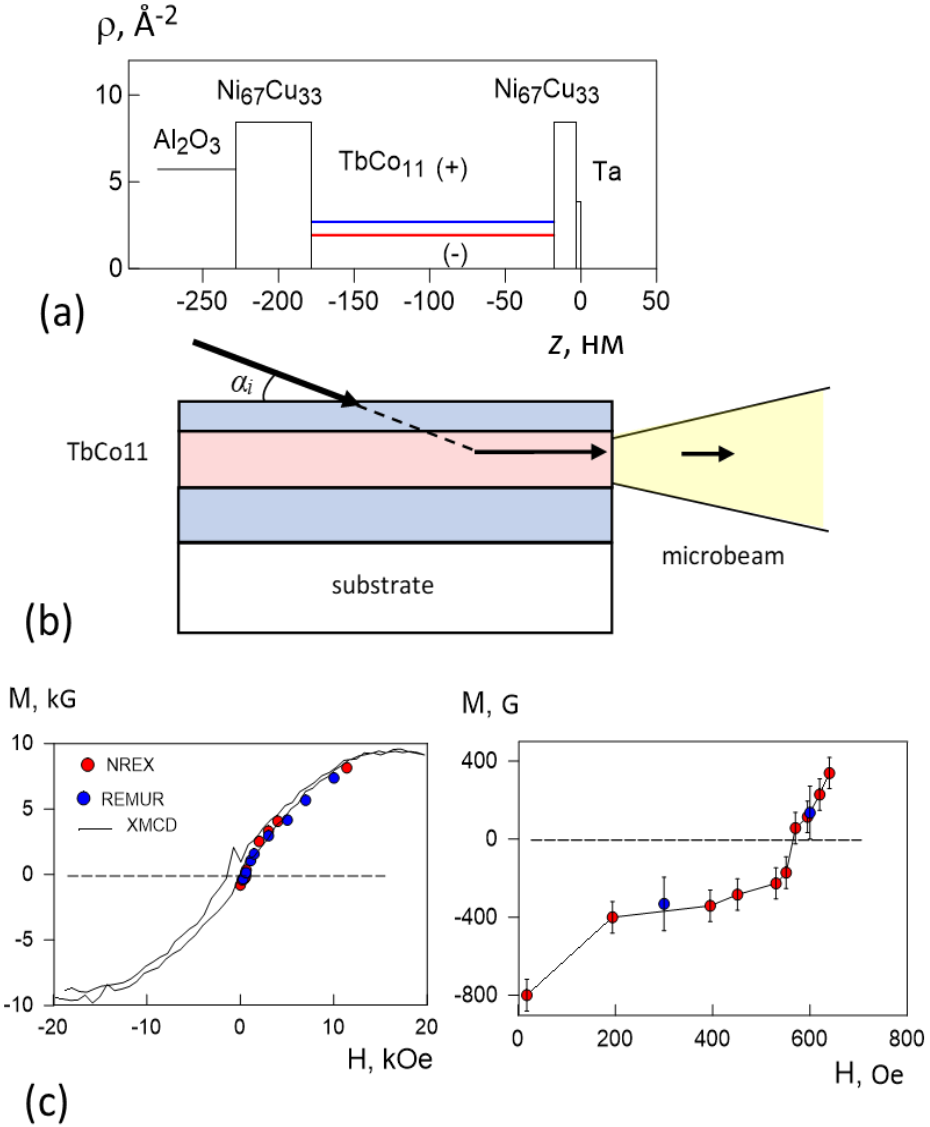






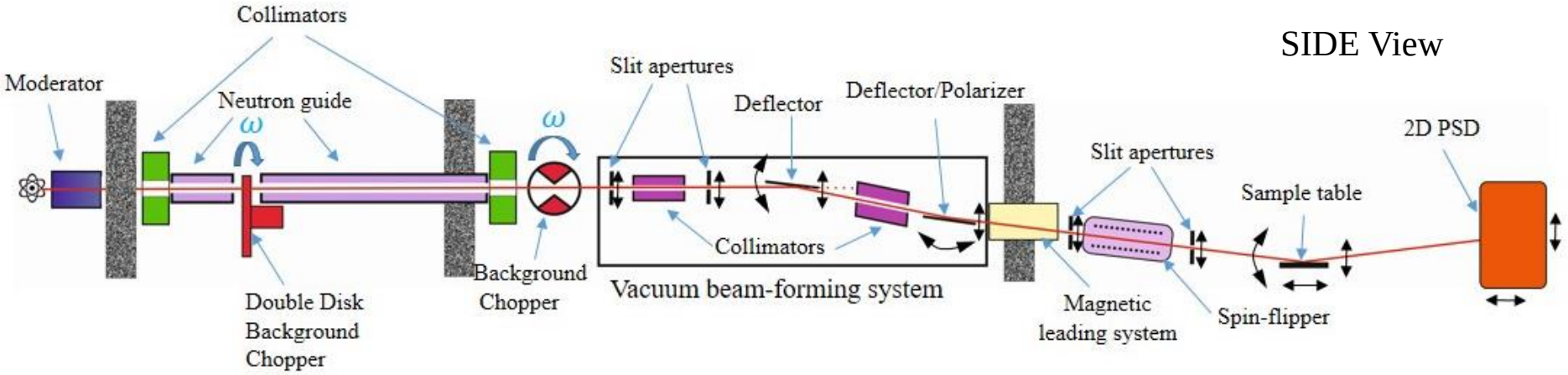
Yu.N. Khaydukov, E. A. Kravtsov, V. D. Zhaketov, Phys. Rev. B 99 (2019) 140503.

Polarized neutron channeling



Kozhevnikov, S.V., Zhaketov, V.D., Keller, T., et al., NIM A 915 (2019) 54-64
Kozhevnikov, S.V., Zhaketov, V.D., Keller, T., et al., NIM A 927 (2019) 87-100

GRAINS time-of-flight reflectometer with horizontal geometry

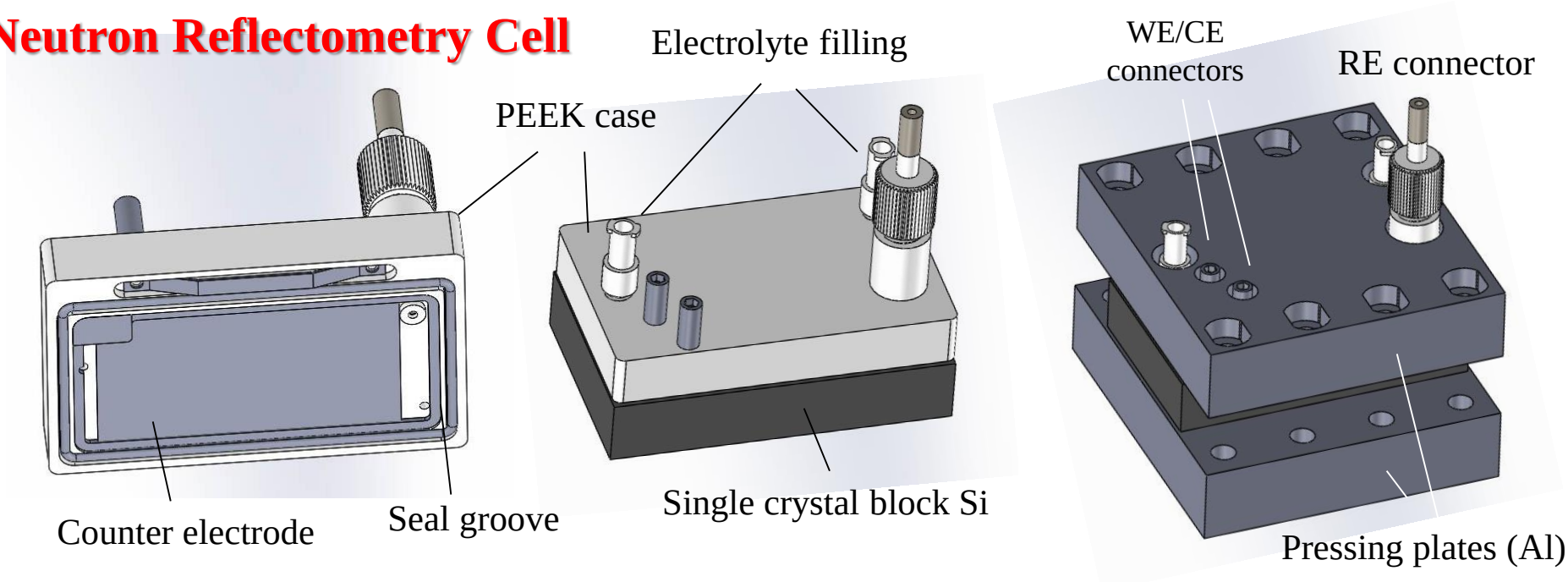


Beamline 10B

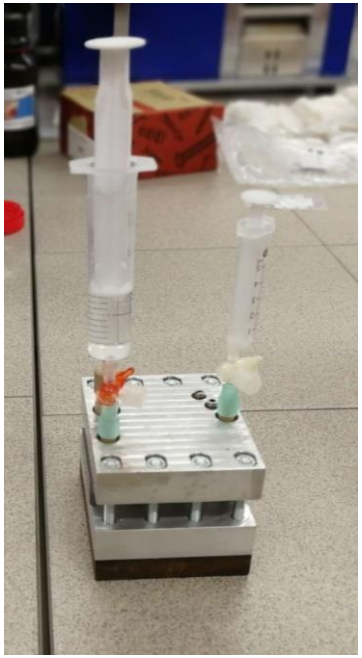
Neutron wavelength range, nm	0.05 - 1.0 (cold) 0.05 - 0.7 (thermal)
Grazing angle, mrad	0 - 25
q_z-interval covered, nm^{-1}	0.05 - 2
Angle resolution, %	2 - 10
Neutron flux at sample position, $cm^{-2} \cdot s^{-1}$	1 (cold) - 2 (thermal) $\times 10^6$
Sample dimensions, cm	(2 × 2) - (7 × 15)
Deflecting mirror	Supermirror NiTi, m = 2, L = 1 m
Detectors	2D PSD, ^{3}He, 20 × 20 cm, spatial resolution 2×2 mm 1D cylindrical counter, ^{3}He, ∅ 18 mm, L = 190 mm

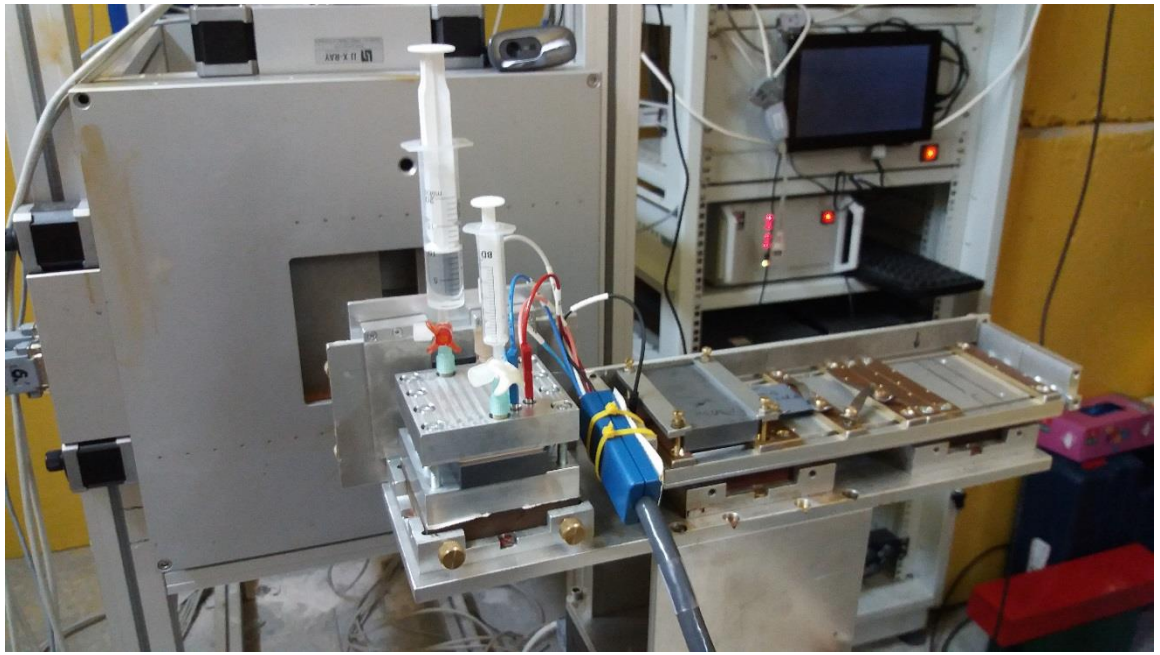
https://flnp.jinr.int/en-us/main/facilities/ibr-2/grains

Neutron Reflectometry Cell

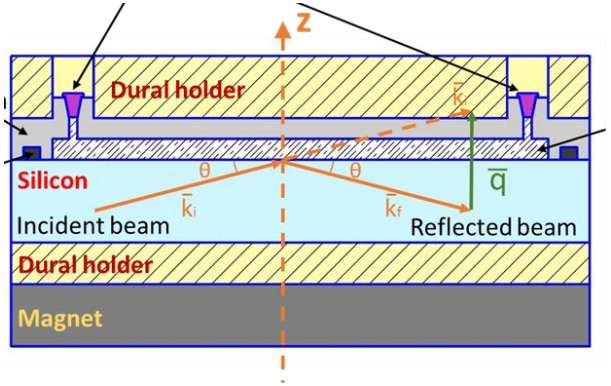


GRAINS Reflectometer, IBR-2 (Dubna)





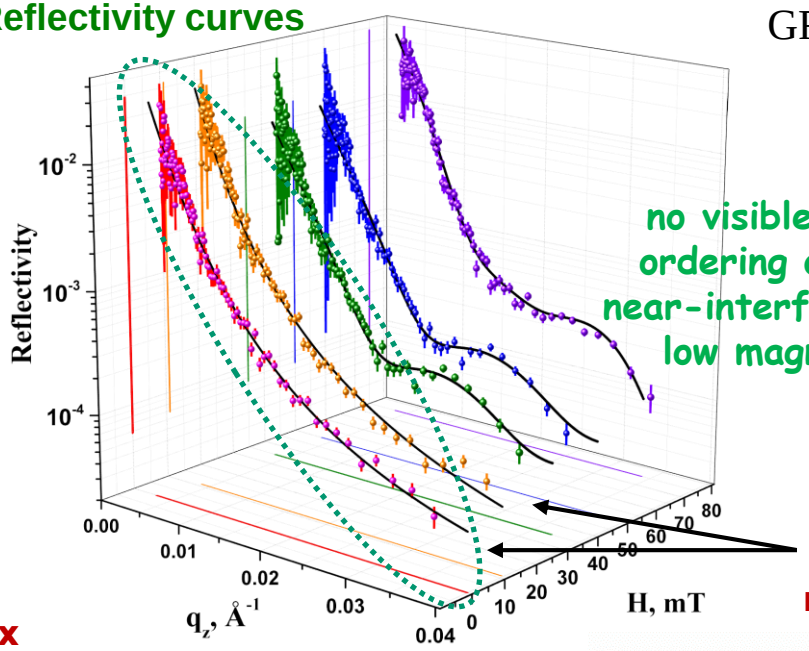
Nanoparticles at interfaces: ferrofluid under magnetic field



Principal scheme of a sample cell for NR experiments on the ferrofluid/silicon interface under an external magnetic field

Reflectivity curves

GRAINS

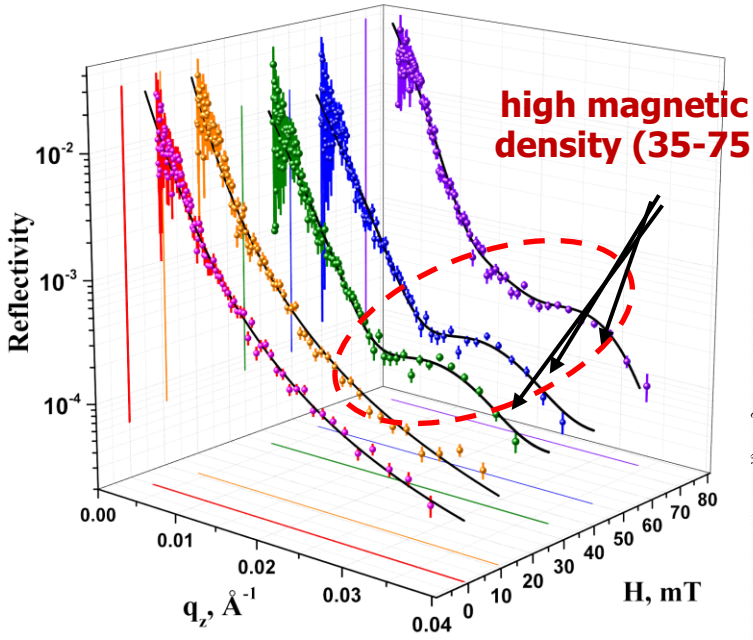


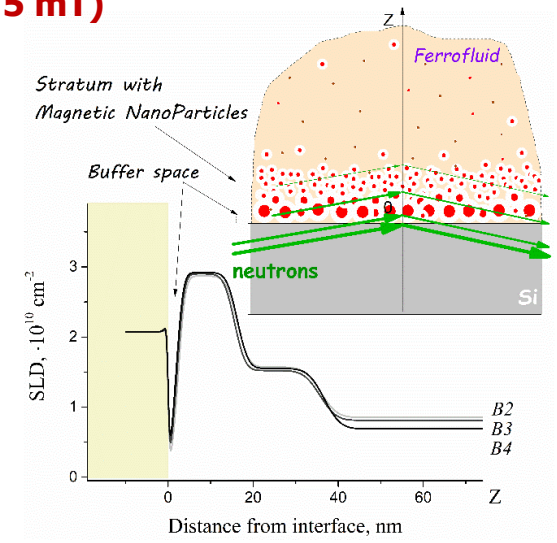
no visible structural ordering of MNPs at near-interface region at low magnetic field

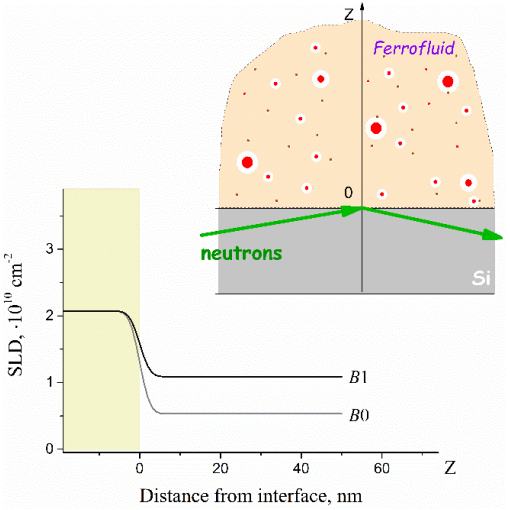
zero and weak magnetic fields

Reflectivity curves

high magnetic flux density (35-75 mT)

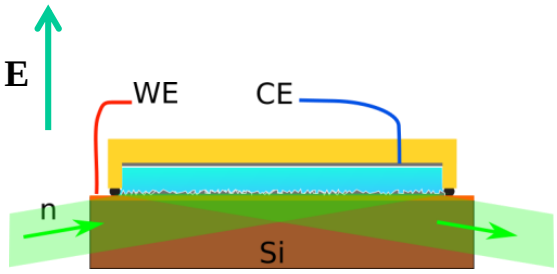


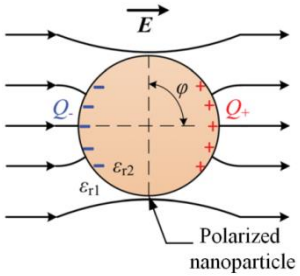


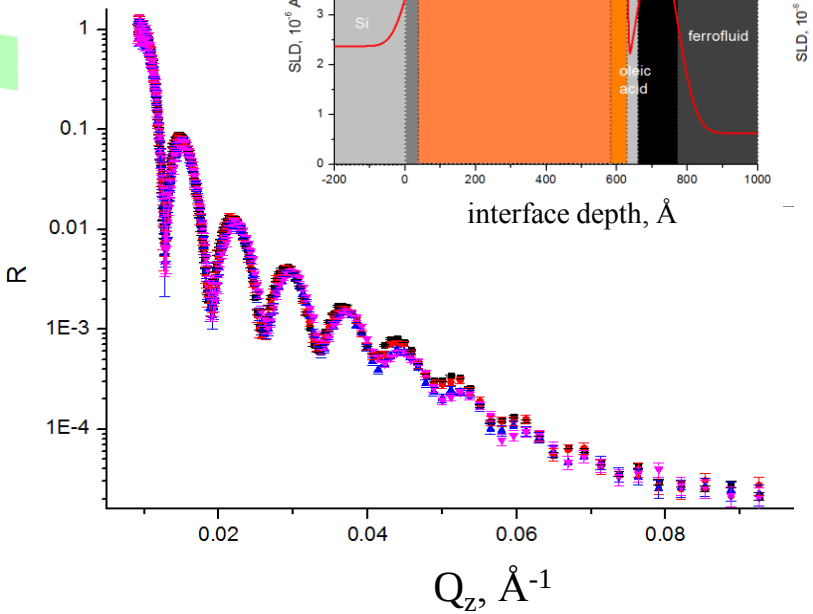


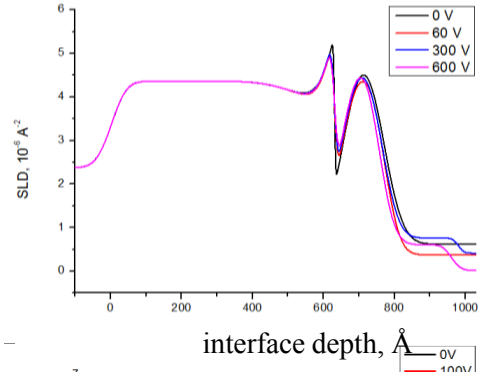
Nagornyi A.V., Petrenko V.I., Rajnak M., Gapon I.V., Avdeev M.V., et al., *Applied Surface Science* 473 (2019) 912–917.

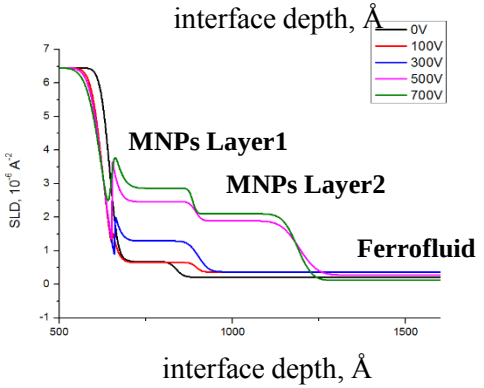
Nanoparticles at interfaces: ferrofluid under electric field

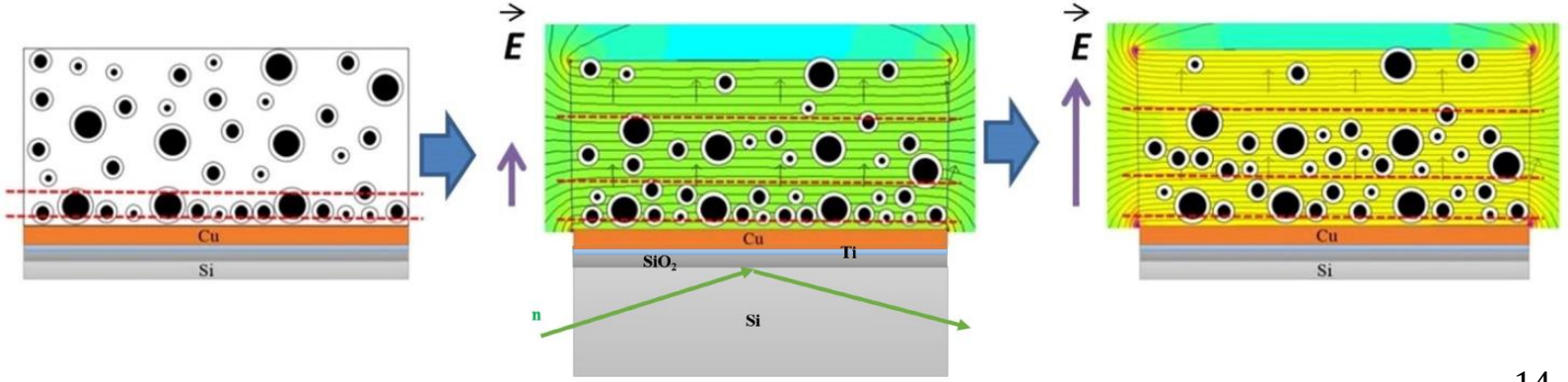








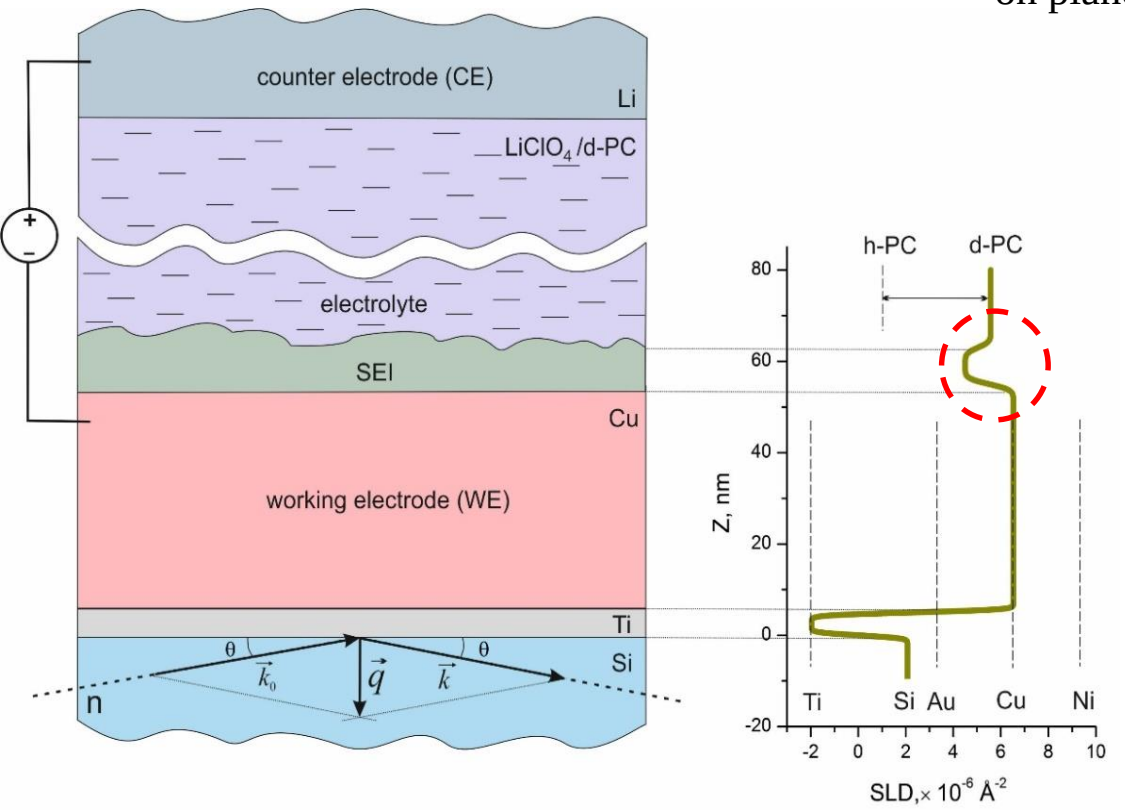


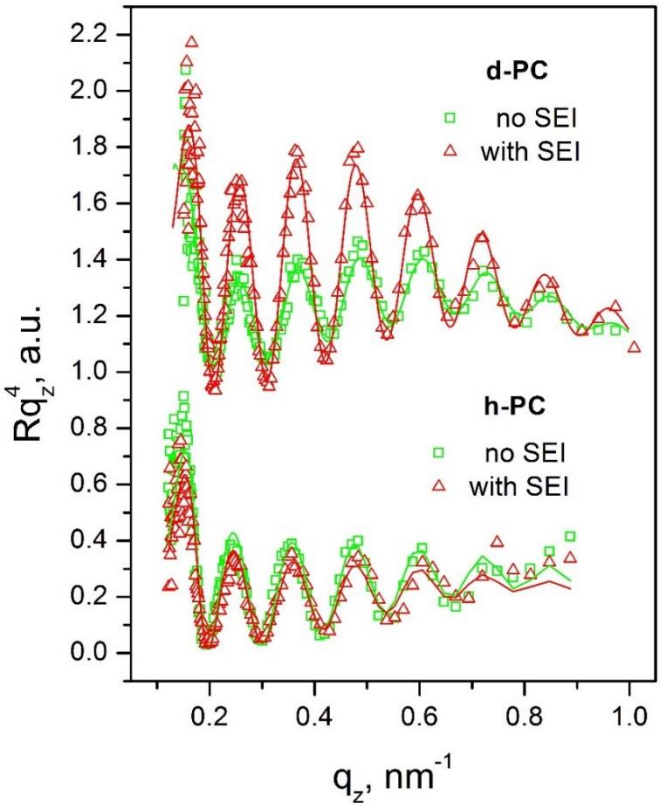


M. Rajnak, V.I. Petrenko, M. Karpets, et al., *J. Mol. Liq.* 362 (2022) 119773

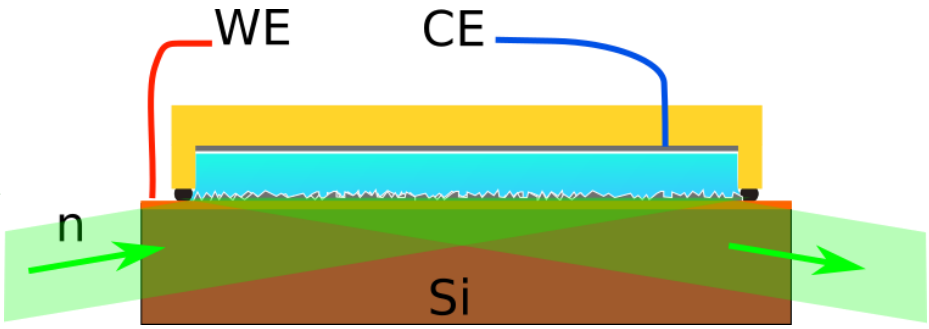
Electrochemical interfaces

Formation of Solid Electrolyte Interphase (SEI)
on plane metal anodes

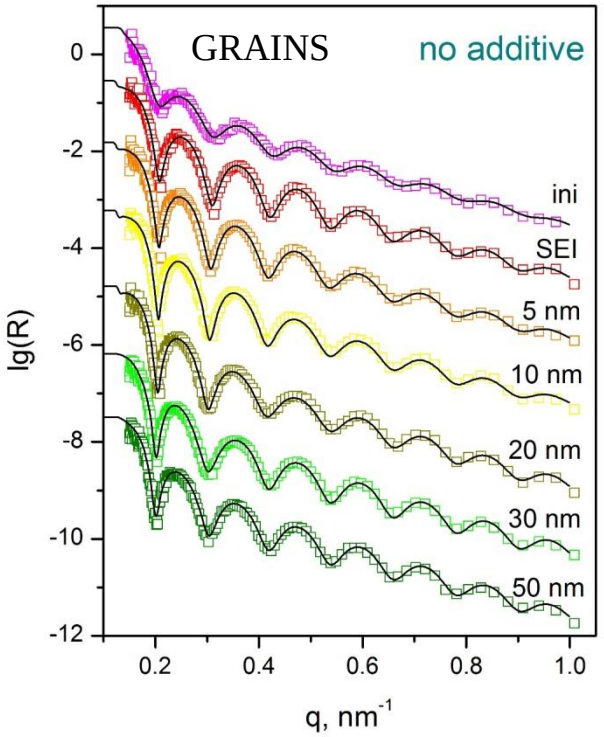


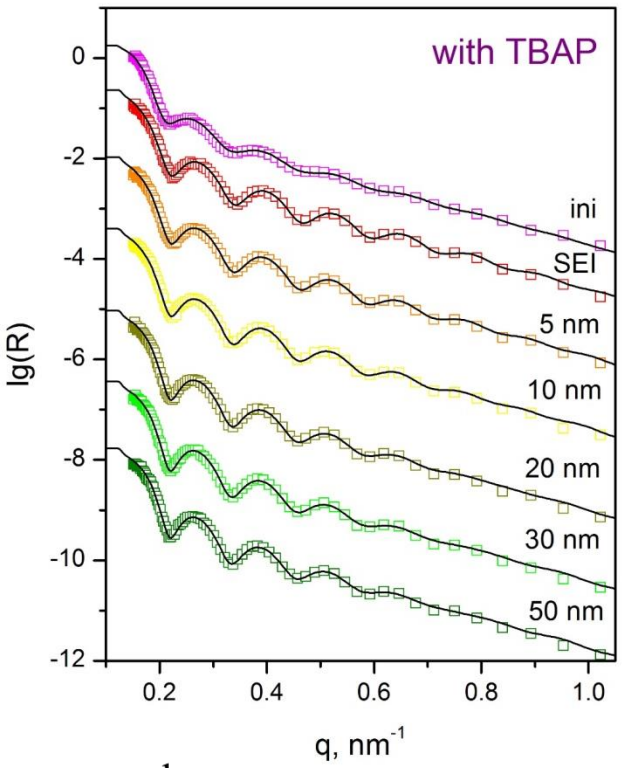


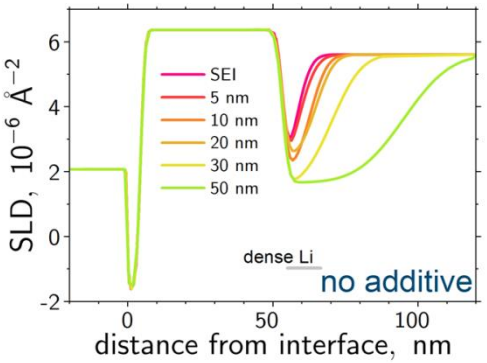
Electrochemical cell

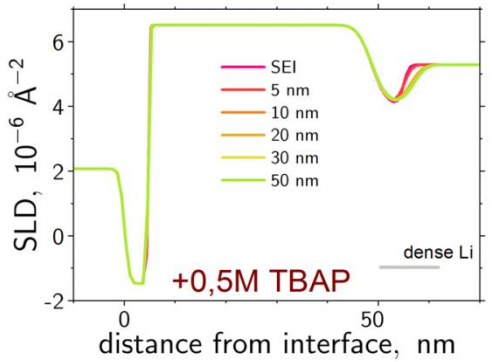


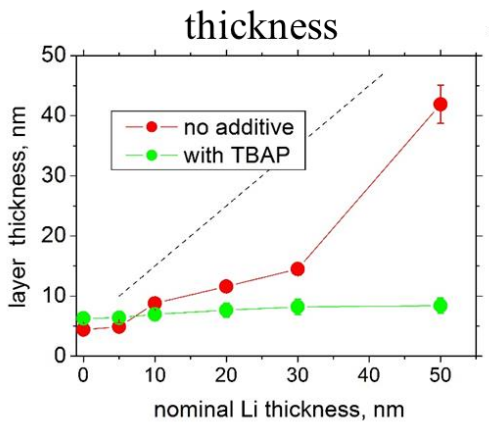
Electrochemical interfaces

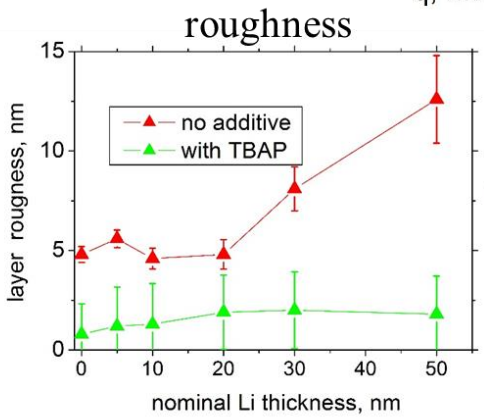


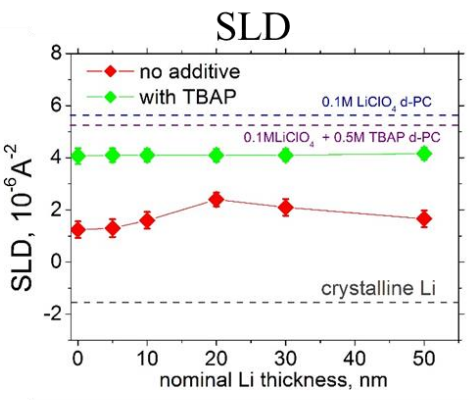






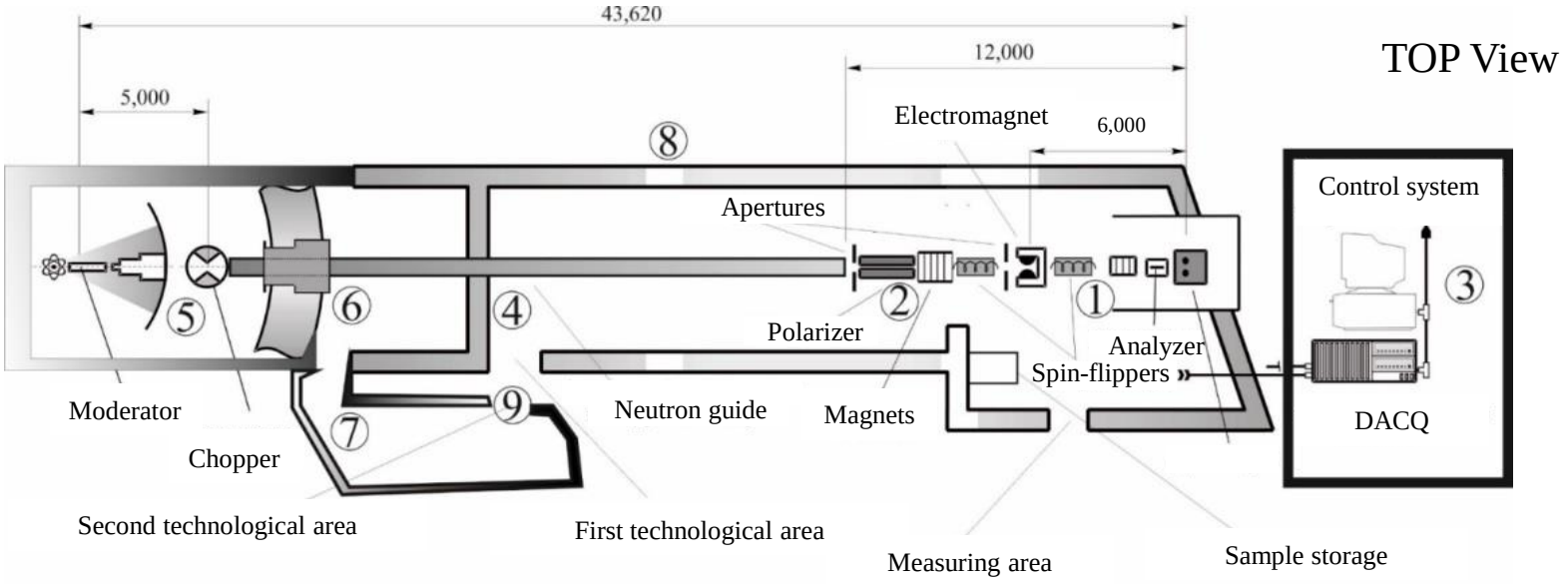






M.V. Avdeev, A.A. Rulev, E.E. Ushakova, Ye.N. Kosiachkin, V.I. Petrenko, I.V. Gapon, E.Yu. Kataev, V.A. Matveev, L.V. Yashina, D.M. Itkis, *Appl. Surf. Sci.* 486 (2019) 287-291

REFLEX - Reflectometer with Polarized Neutrons

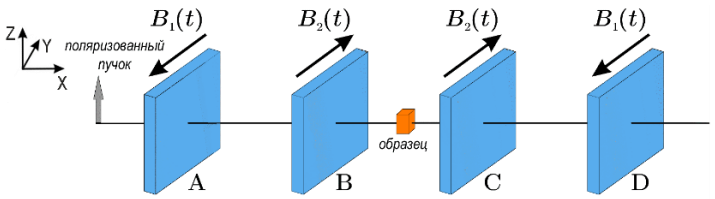


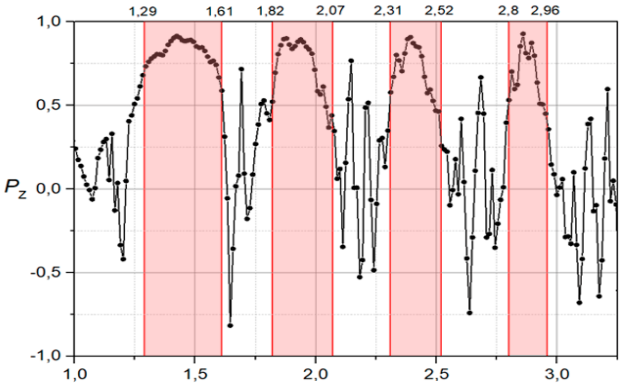
Beamline 9

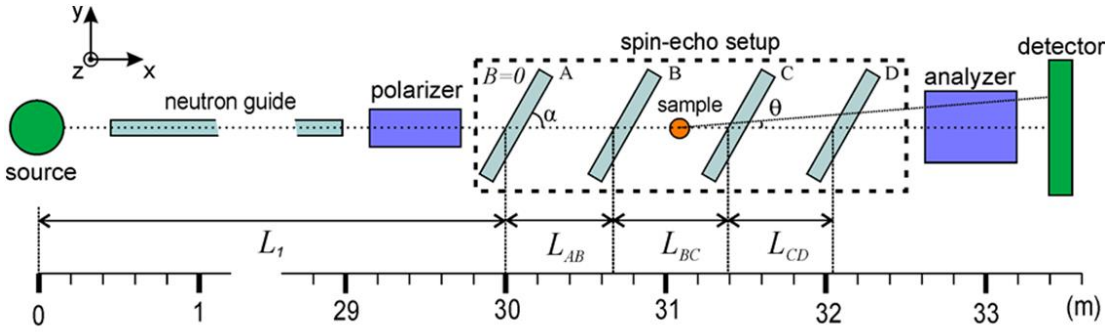
Beam-forming system	supermirror (m=1.2) neutron guide 27 m long, 10×80 mm^2
Wavelength range	1.4 - 10 Å
Q-range	0.001- 0.13 $Å^{-1}$
Neutron flux at sample position	10^5 $s^{-1}cm^{-2}$
Q-resolution	3 - 10 %
Sample-to-detector distance	2 - 6 m
Minimum sample dimensions	20×20 mm^2
Magnetic field at sample position	<0.4 T
Spin-flippers	2 radio-frequency adiabatic spin-flippers
Polarizer	Transmission type, V-shape, Fe/Si, m=5
Analyzer	Transmission type, Fe/Si, m=3.6 (also FeCo/TiZr supermirror, m=2, is available)
Detectors	2D PSD 200×200 mm^2, ^3He; ^3He proportional counter

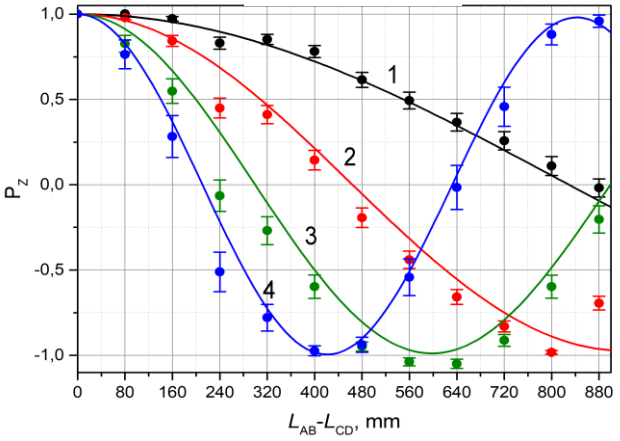
https://flnp.jinr.int/en-us/main/facilities/ibr-2/reflex

Spin-Echo-SANS option at REFLEX

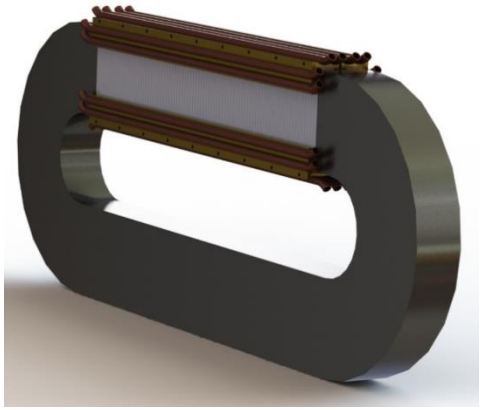








$$Z = \gamma B_{max} f \frac{2\hbar a L ctg(\alpha)}{m_n v_n^3 \sin(\alpha)}$$



Wavelength range, Å	1.2 - 6
Spin-echo length range, Å	100 - 15000
Magnetic field gradient, G/s	$3.75 * 10^5$
Pulse frequency, Hz	200
Tilt angle of coils, degrees/deg./°	10 - 15
Dimensions of spin rotator coil, mm × mm × mm	350 × 80 × 40
Distance between spin-rotators, m	1

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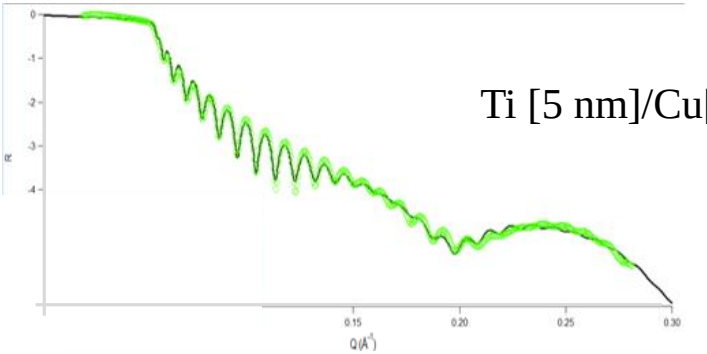
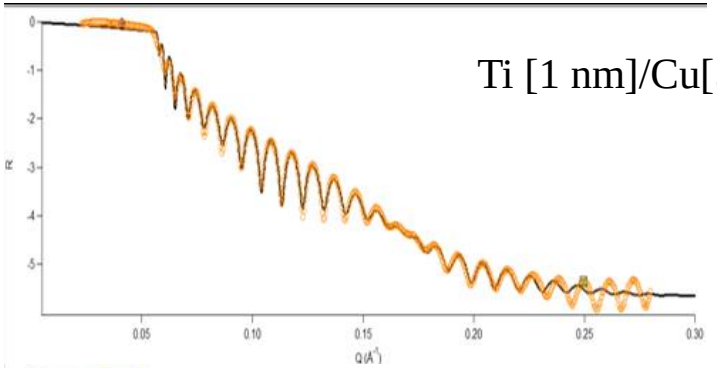
Special coatings for electrochemical experiments by XRR

Malvern PANalytical Emyrean

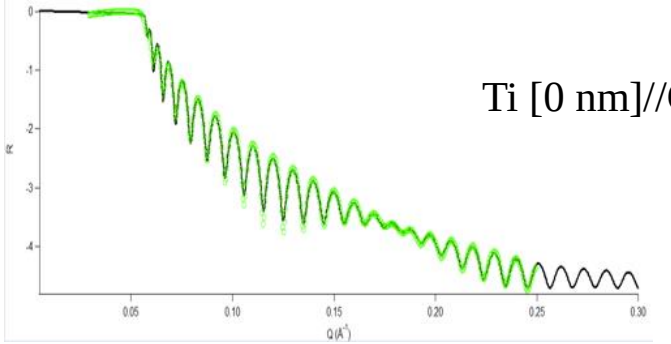
Si(crystal)/Ti [0-10 nm]/Cu[10-50 nm]



Ti [5 nm]/Cu[50 nm]



Ti [1 nm]/Cu[50 nm]



Ti [0 nm]//Cu[50 nm]

Y.N. Kosiachkin, I.V. Gapon, A.A. Rulev, E.E. Ushakova, et al., *J. Surf. Investigation* 15 (2021) 787-792

Main areas of research for NR at FLNP JINR

Polarized neutrons

- *Magnetic layered heterostructures*
- *New optical devices*

Pulsed source

- *In situ experiments for soft and liquid interfaces*
- *Extended methods based on Larmor precession*