Neutrons in solid state physics

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Outline

1. Basic requirements for an application of neutron beam in the solid state physics

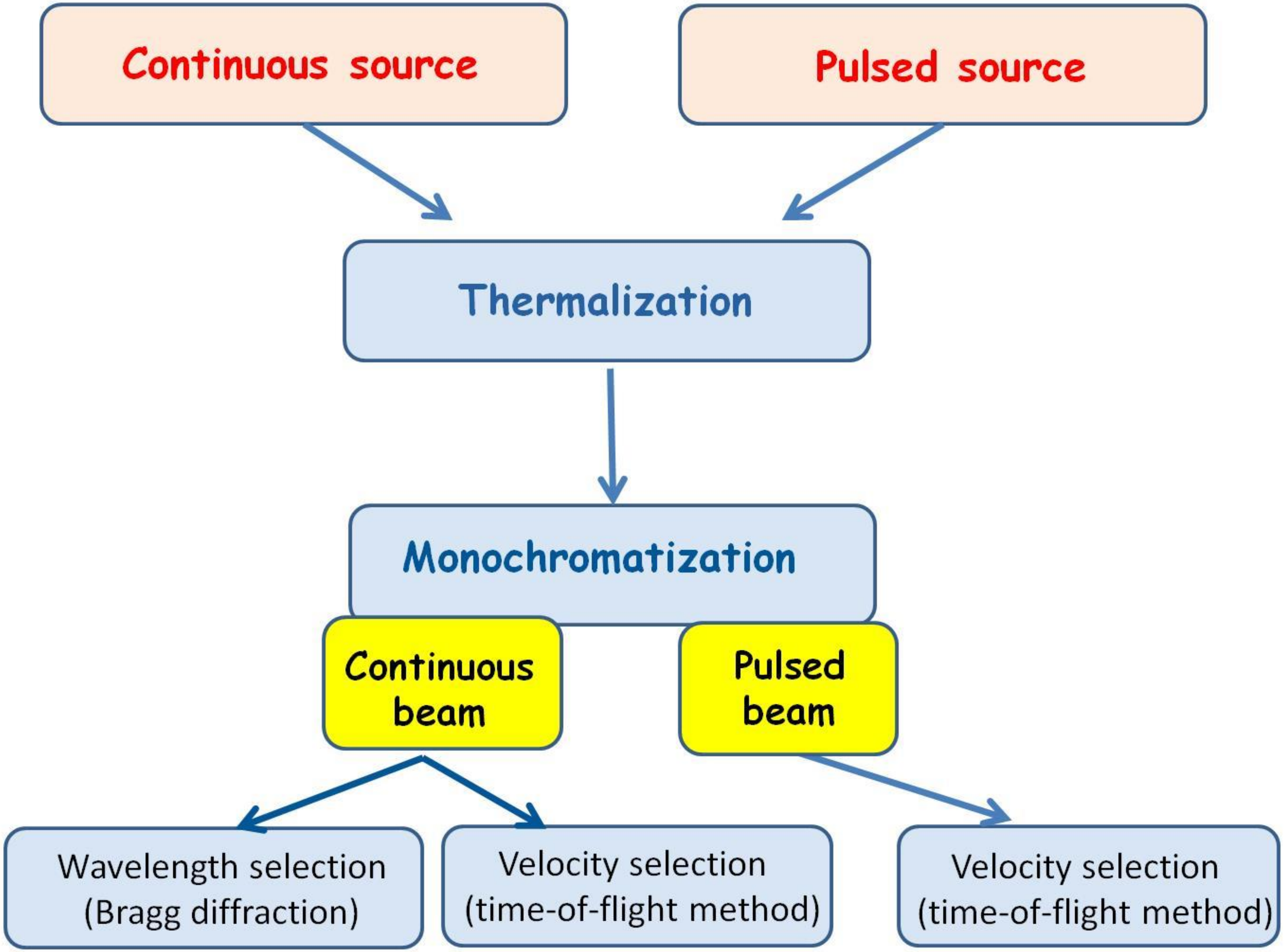
2. Important neutron properties

3. Inelastic neutron scattering (PbTe)

4. Polarized neutron reflectivity – Pt/Co/Pt multilayer

5. Neutron facility landscape

6. Conclusions



Continuous source
Pulsed source
Thermalization
Monochromatization
Continuous beam
Pulsed beam
Wavelength selection (Bragg diffraction)
Velocity selection (time-of-flight method)
Velocity selection (time-of-flight method)

Neutron properties important when investigating solids

Neutron scattering sensitive to light elements

Magnetic neutron scattering as effective as the nuclear one

Long neutron penetration length

~~Non descructive experimental tool~~ (except high-energy neutrons)

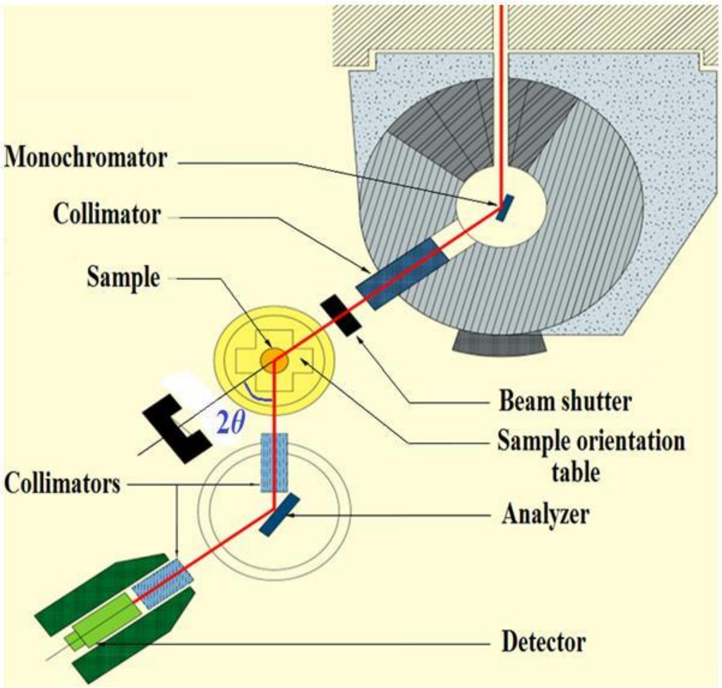
Experiments which do not require extreme neutron flux: mostly diffraction methods (elastic scattering)

- Powder diffraction
- Small angle scattering
- Imaging
- ...

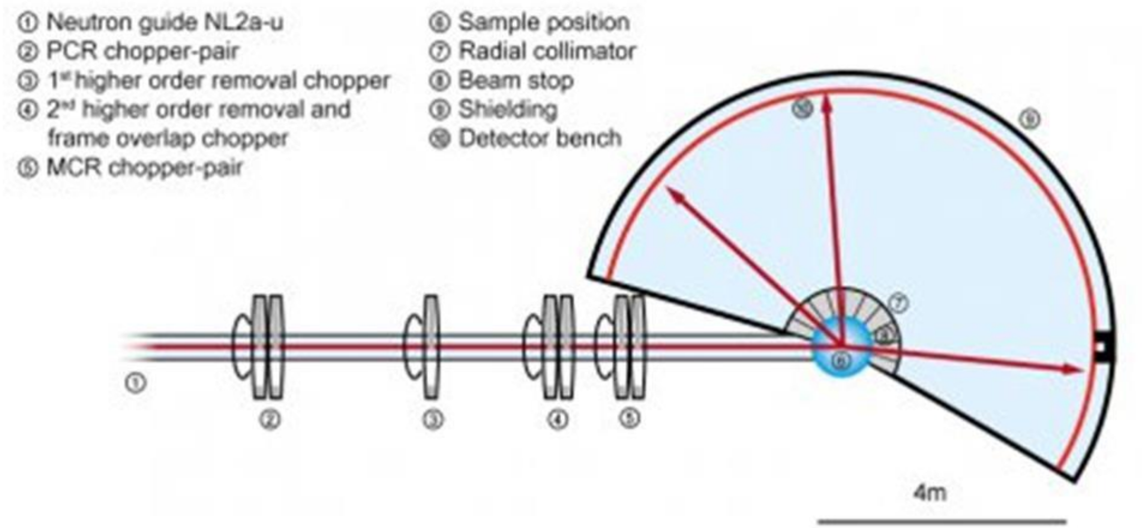
High neutron flux is required for:

- Inelastic scattering (excitations)

Idea of neutron spectrometer for elastic or inelastic scattering



http://www-llb.cea.fr

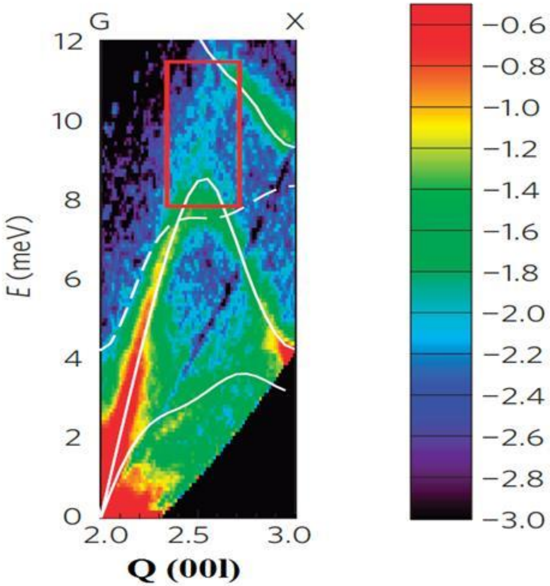


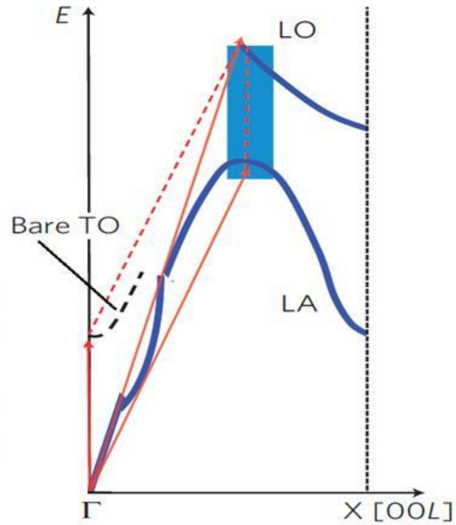
www.mlz-garching.de

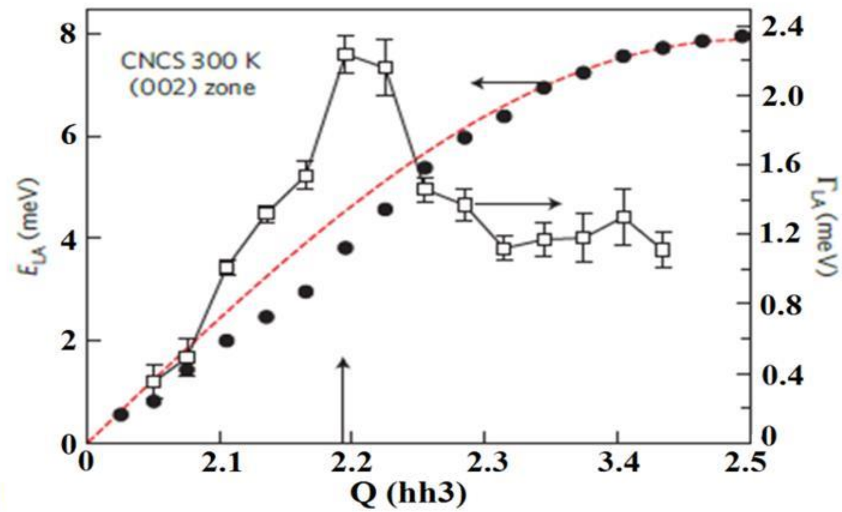
Triple-axis spectrometer

Time-of-flight spectrometer

Strong acoustic-optic phonon coupling the reason for low thermal conductivity in PbTe







Due to TO-LA phonon interaction LA phonon dispersion is modified and strong damping of LA (peak in FWHM) is observed

O. Delaire, J. Ma, K. Marty et al., *Nature Materials* **10**, 614 (2011)

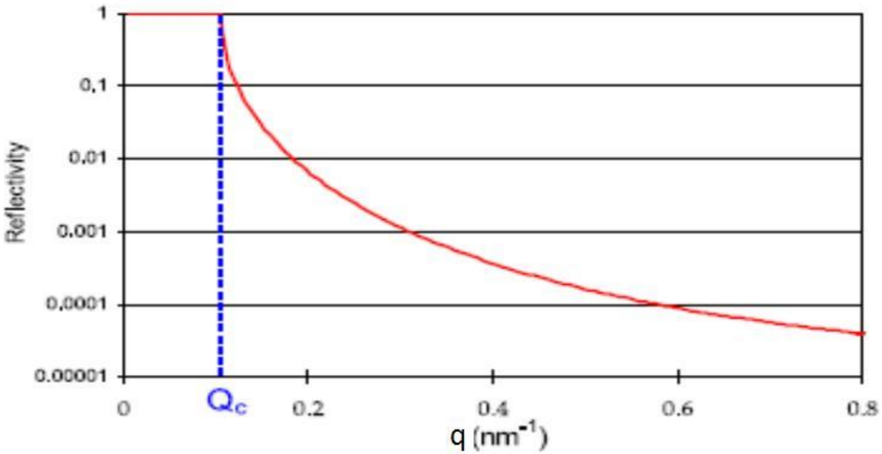
time-of-flight Cold Neutron Chopper Spectrometer, Spallation Neutron Source Oak Ridge (USA)

Some details are not reproduced by measurements performed with the use of continuous source and triple-axis spectrometer

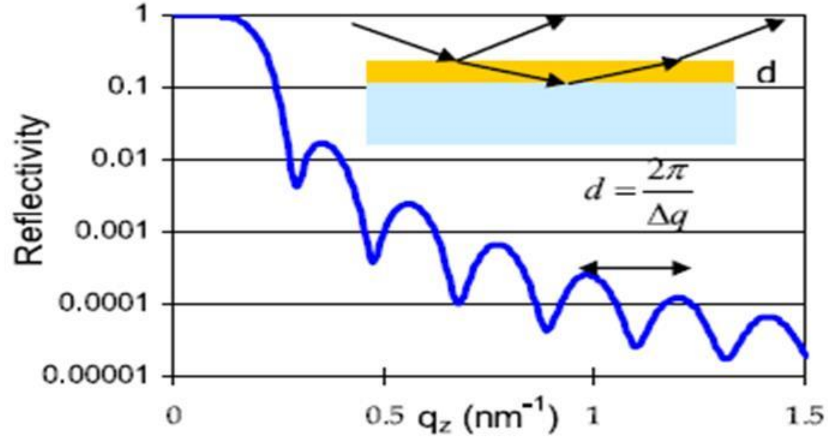
(disadvantage – time consuming experiment)

Polarized neutron reflectivity (PNR)

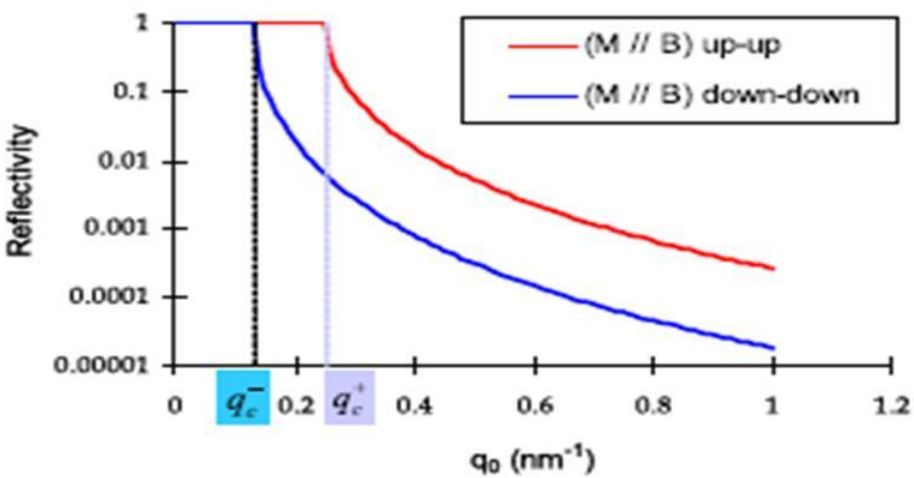
bulk crystal

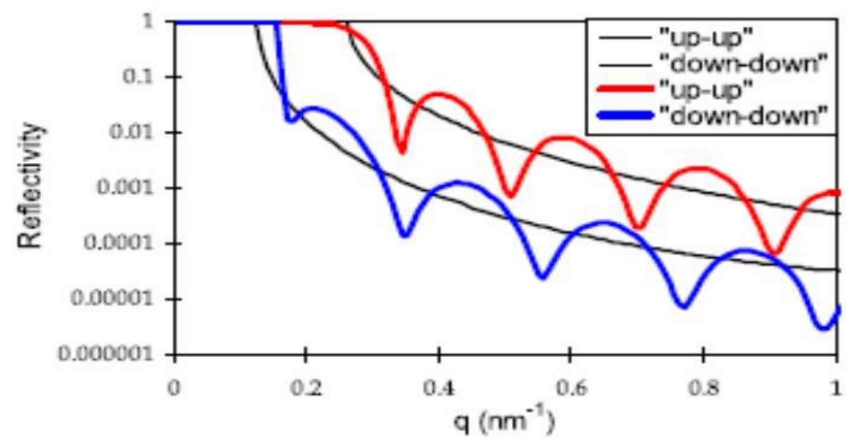


thin layer

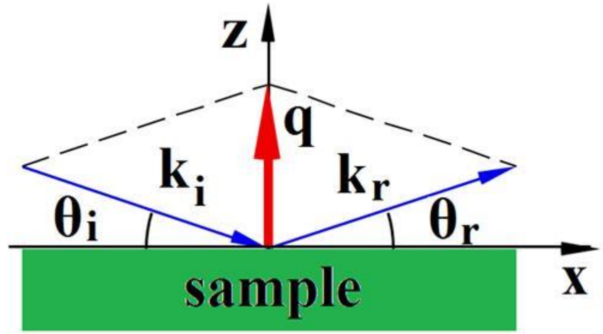


FM order (M component in plane)





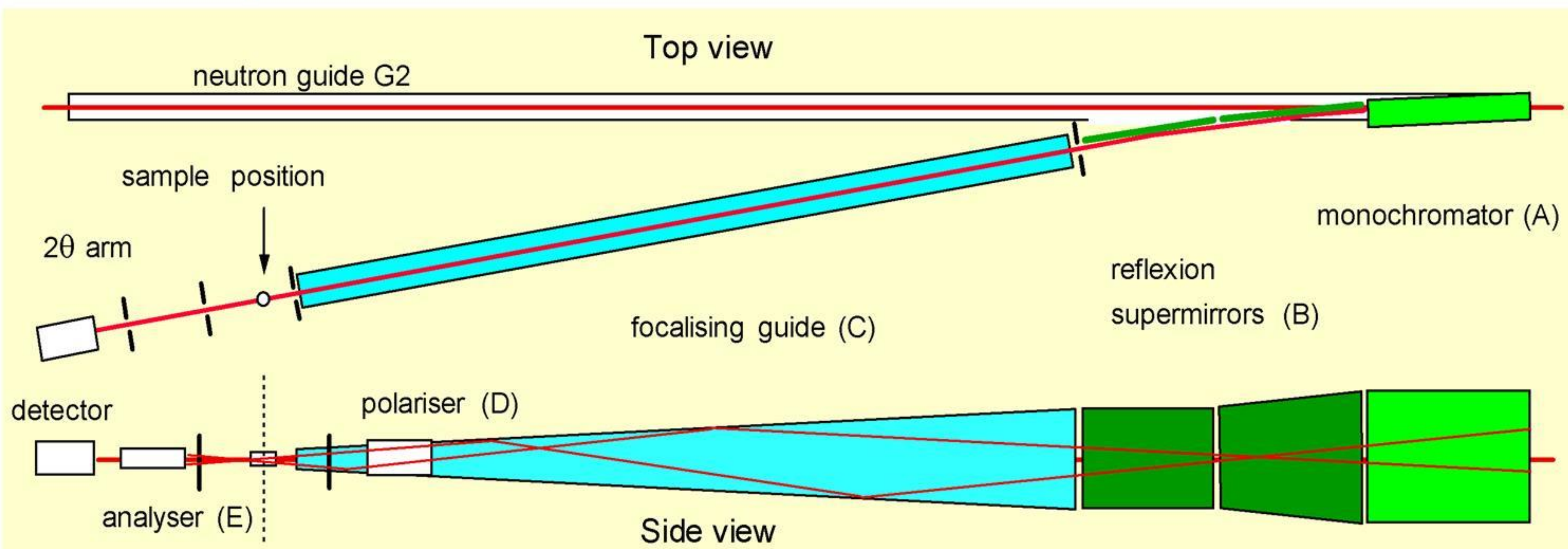
refraction index $n = 1 - \delta \pm \delta_M$



momentum transfer q

$$q = k_r - k_i = \frac{4\pi}{\lambda}\sin\theta$$

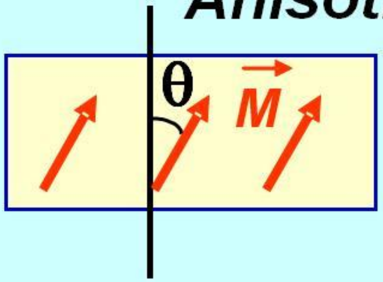
Neutron spectrometer PRISM : λ = 4.0 Å, T = 295 K, B < 2 T



http://www-llb.cea.fr

Post-growth modification of magnetic anisotropy

Anisotropy energy $E_A(\theta) = K_{1eff}\sin^2(\theta)$



$$-2\pi M^2 + K_{1V} + (2K_{1S})\,/\,d$$

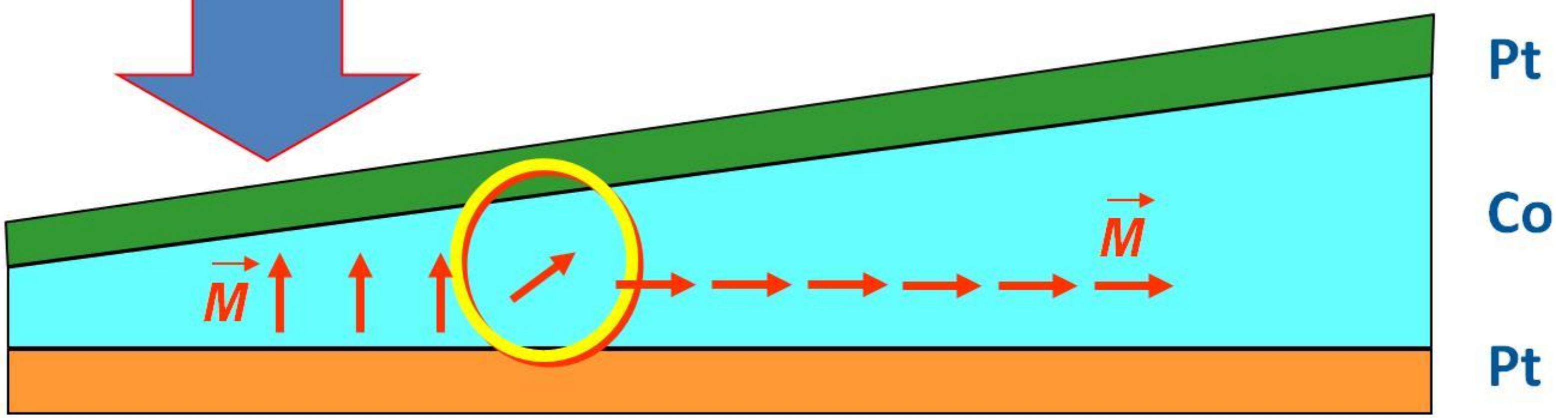
„volume” contribution

„surface” contribution

Irradiation by:

light,

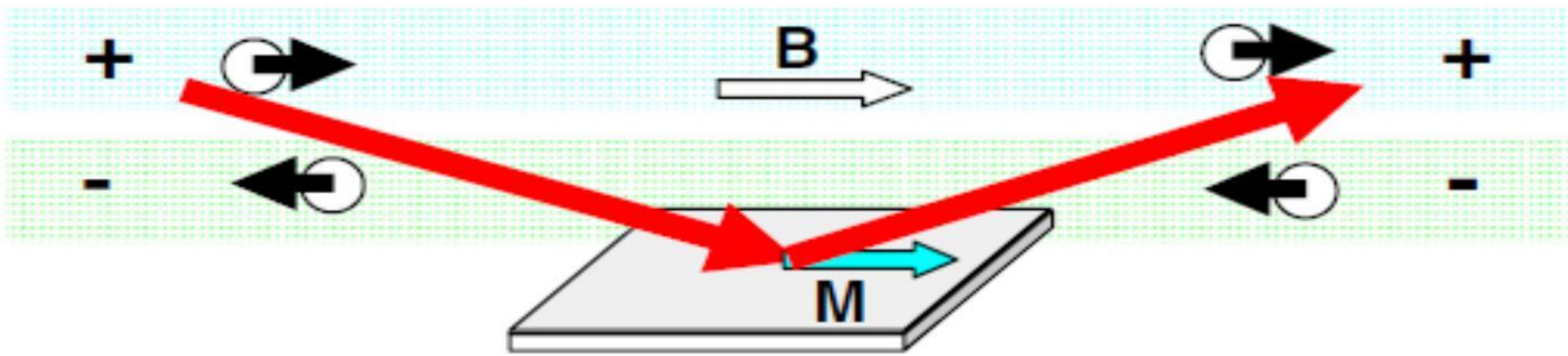
ions



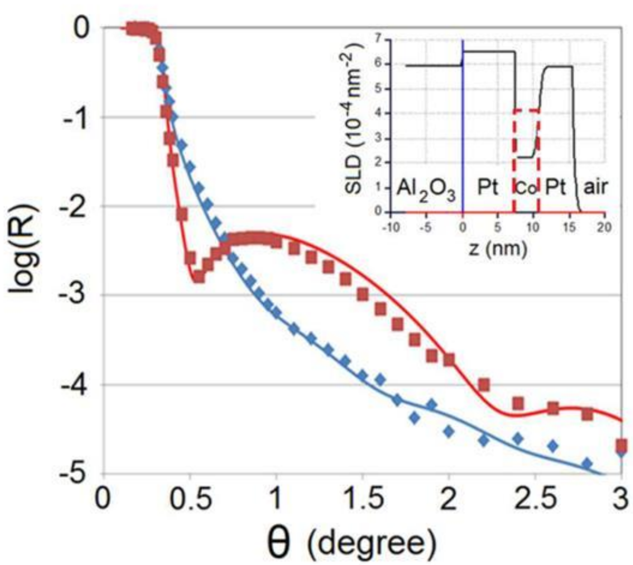
Easy magnetization axis

Easy plane

Idea of polarized neutron reflectivity measurements



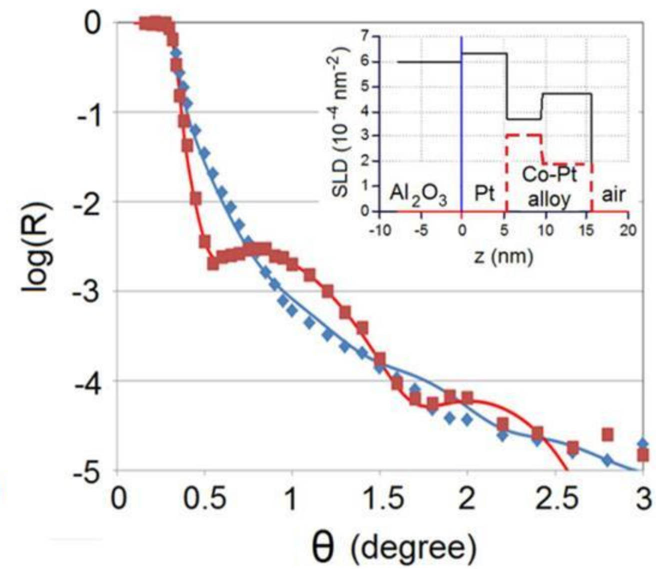
Al_2O_3/Pt(50A)/Co(30A)/Pt(50A)



before irradiation

up-up

down-down



after irradiation

W. Szuszkiewicz, F. Ott, J. Kisielewski et al., *Phase Transitions* **89**, 328 (2016)

Europe's neutron facility landscape

Reactor	Closing year
Risø (Danmark)	2000
Jülich (Germany)	2006
Geestacht (Germany)	2010
– –	
Saclay (France)	2019
Berlin (Germany)	2019
Grenoble (France)	2023 (?)

Still remain

20 MW reactor FRM II Munich (Germany)

10 MW reactor (Czech Republic) (2023?)

10 MW reactor (Hungary)

30 MW reactor (Poland) (2030?)

....

ISIS 1 MW pulsed spallation (Great Britain)

SINQ 200 kW continuous spallation (Swiss)

5 MW ESS (Sweden) pulsed spallation open for experiments 2023

IFMIF/DONES continuous source (Poland?)

Conclusions

1. Investigation of the properties of solids with the use of neutron beam requires:
   - neutrons thermalization
   - selection of neutron energy
2. Time-of-flight neutron beam monochromatization (velocity selection) can be applied for both continuous and pulsed source
3. Bragg diffraction based monochromatization (wavelenght selection) can be applied for a continuous source only – triple axis spectrometer
4. Magnetic or crystal structure determination (elastic scattering, polarized neutron reflectivity, small angle neutron scattering) or imaging does not need a continuous source and can be performed with the use of accelerator-driven pulsed sources
5. For studies of various collective excitations (magnons, spin waves, phonons etc.):
   - time-of-flight method is more convenient if one needs a general picture
   - Bragg diffrection (continuous source, triple axis spectrometer) is recommended for analysis of fine details

Continuous mode of operation at IFMIF gives a chance to complete the ESS experimental possibilities and to study the excitations in solids in details