Neutron Multilayers

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The Institut Laue Langevin in Grenoble

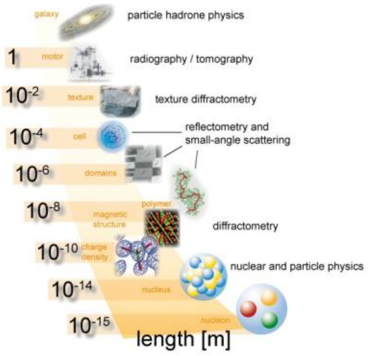
The world's leading facility in neutron science and technology, operating the most intense neutron source on earth.

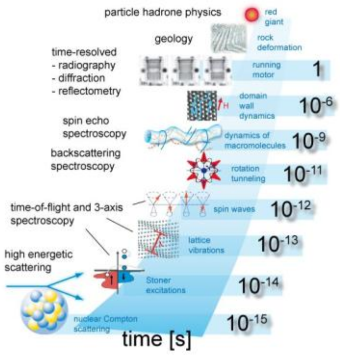
In one year:

~ 800 experiments

~ 1500 researchers

~ 40 world-class instruments

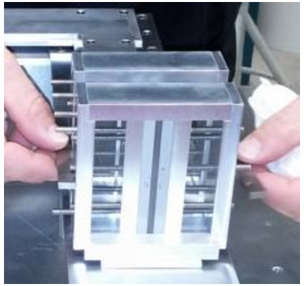




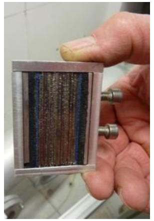
Applications of multilayers in neutron optics

From “small” to “big” projects

Polariser (prototype)



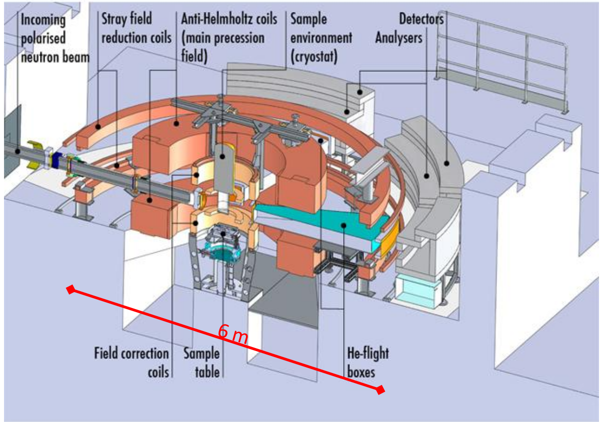
Wavelength filter
(LADI, protein crystallography)



“mass production”: analysers for WASP* instrument

(*Wide-Angle SPin-echo)

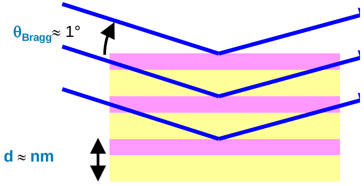
90 cassettes x 37 mirrors x 2 coated sides
➔ 238 m² covered with m=3 supermirrors, 541 layers

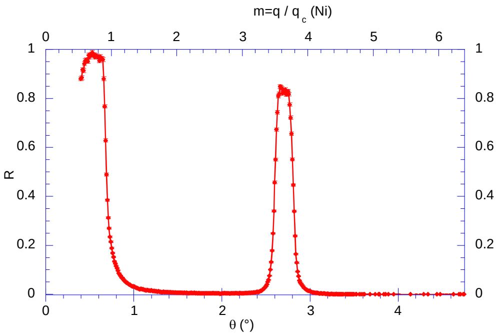


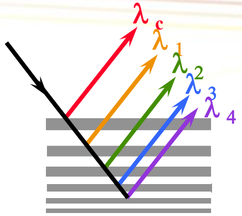
T. Bigault et al., Journ. Phys. Conf. Series, 528, 012017 (2013).
P. Courtois et al., in ILL Annual Report, Grenoble, 2013, p. 82-3.

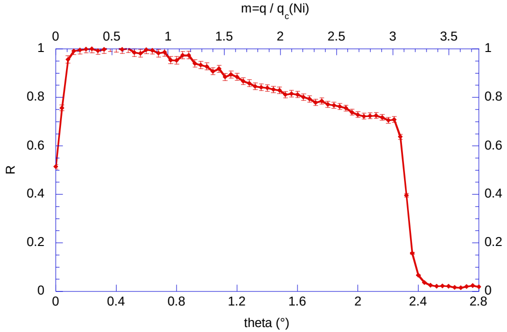
From Bragg mirrors to supermirrors

Extending the operating range





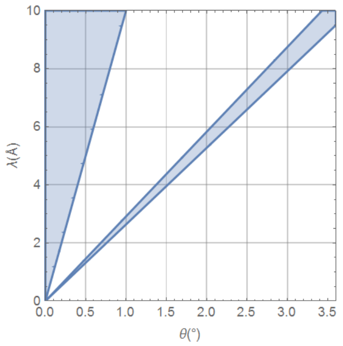


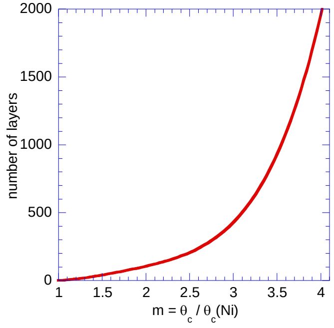


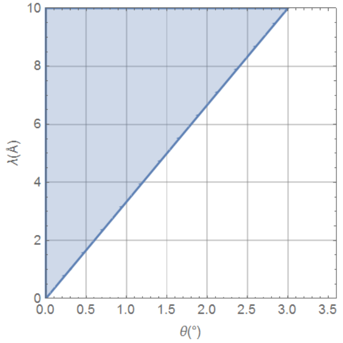
$$q = 4\pi \frac{\sin\theta}{\lambda} = \frac{1}{d}$$

$$q_c = m \times q_c(Ni)$$

Phase space:







Kinematic theory: p: number of bi-layers

N_i b_i : (nuclear) scattering length density of material i

$$R \propto p^2 \left(N_A b_A - N_B b_B\right)^2$$

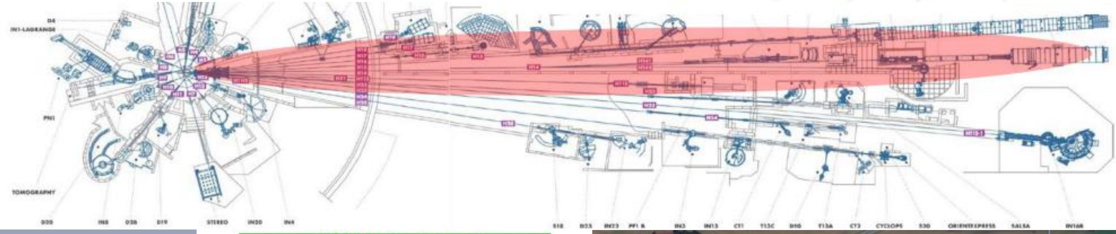
➔ **Ni / Ti**

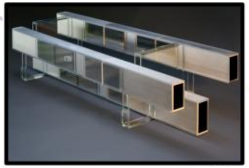
Number of layers for optimum reflectivity vs. “m”:

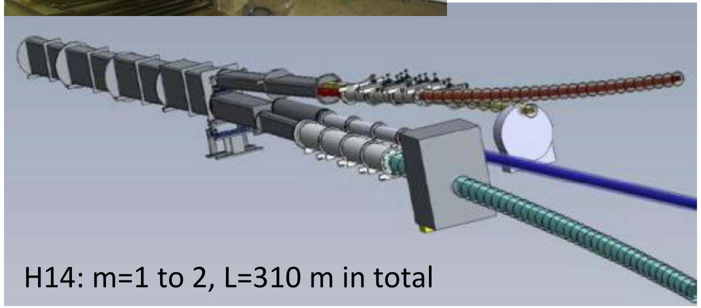
Applications of “standard” Ni/Ti supermirrors

Long guides to collect and transport neutrons to instruments

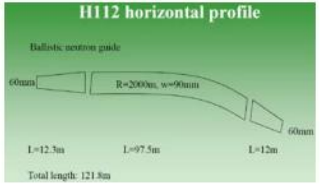
- Neutron sources are poorly directional ➔ large increase of collected solid angle
  ➔ more neutron flux







H14: m=1 to 2, L=310 m in total



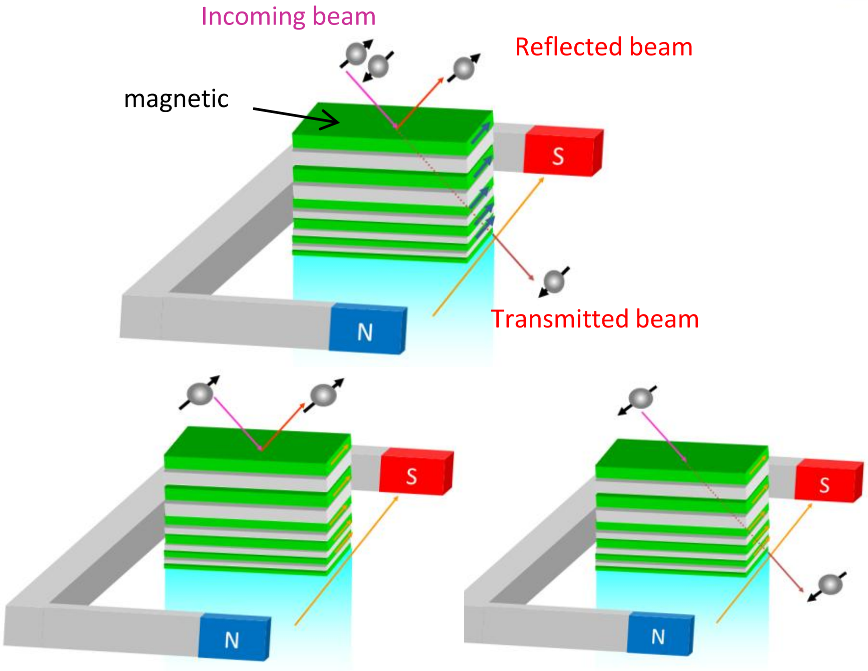
m=2 ballistic guide,
L=148 m in total

…even longer ?

… other applications: monochromators, focusing optics etc

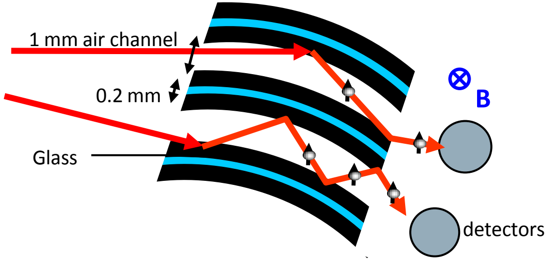
Magnetic multilayers as neutron spin filters

Polarisers / analysers: reflection / transmission mode

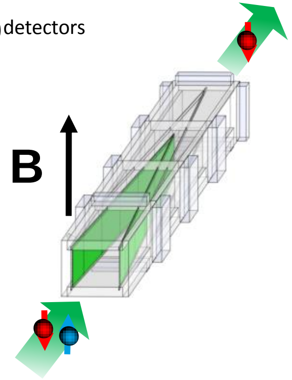


Before the sample: “polariser”
After the sample: “analyzer”

“reflection mode” analyser:



“transmission mode” polariser:



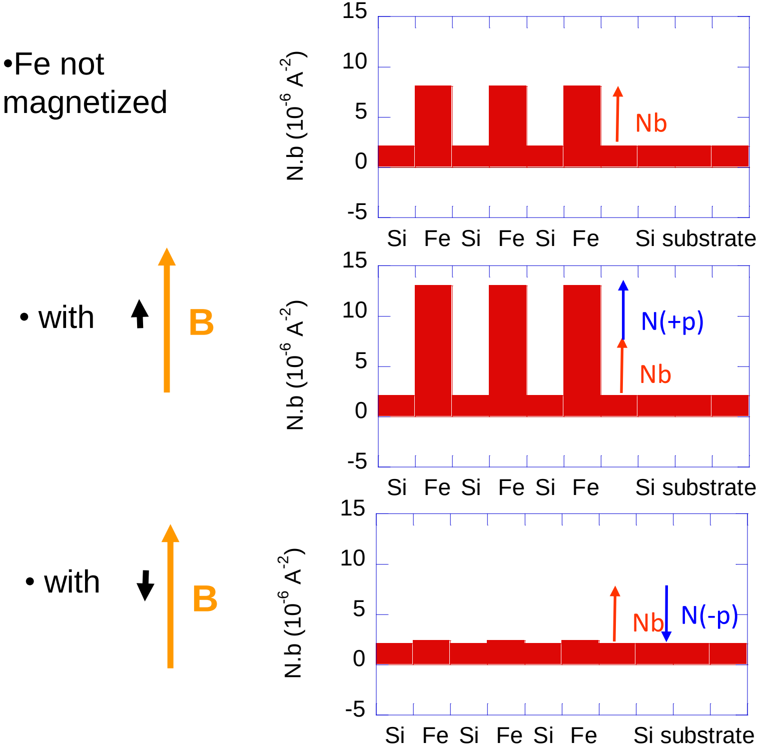
Polarising multilayers & supermirrors: principle

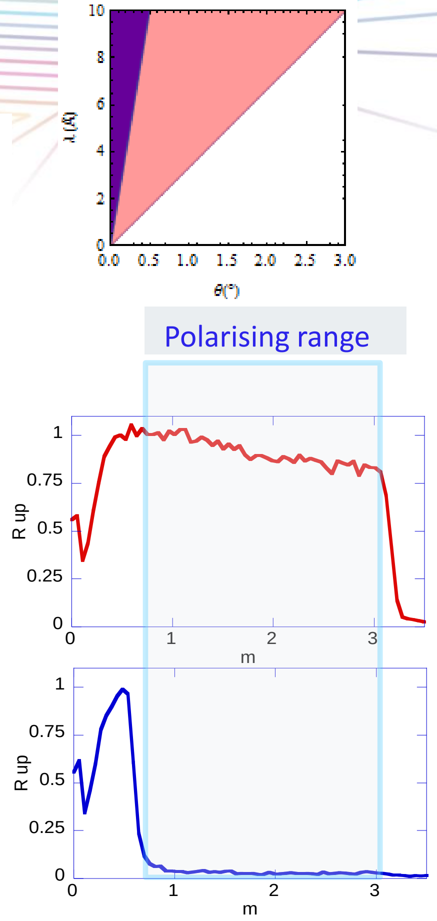
Neutron index of refraction for magnetic materials:
(with nuclear term ***b***
and magnetic term ***p***):

$$n \approx 1 - \frac{\lambda^2}{2\pi} N(b \pm p)$$

$$N.p = \frac{m \cdot \mu}{2\pi \cdot h} B$$

N: atomic density
m: neutron mass
μ : neutron magnetic moment





Example : polariser for PF1B (fundamental physics)

- Aim: measurement of neutron decay with a polarised neutron beam, with an overall precision of 10^{-4}
- Requirements:
  - Few events expected ➔ High neutron flux ➔ use the full cold white divergent beam from the guide :
    - 8x8cm²
    - Wavelengths ~0.2-2 nm, maximum at 0.5 nm, with divergence ~1° at this wavelength
    - The average beam polarisation has to be of the order of 0.9999,

    if possible without strong wavelength dependence… !

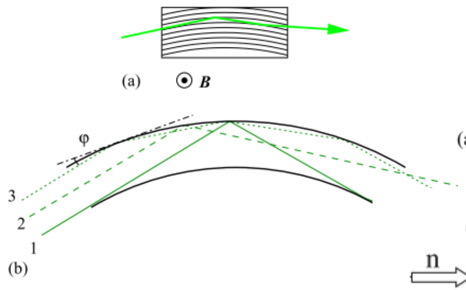
- Existing best solution*:
  - Bender with Co/Ti (m=2.8) supermirrors on glass
  - P = 0.997+/-0.001 ("crossed polariser" geometry)

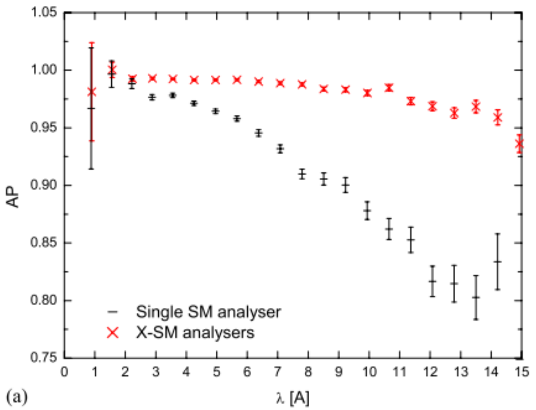
- But :
  - Co activation

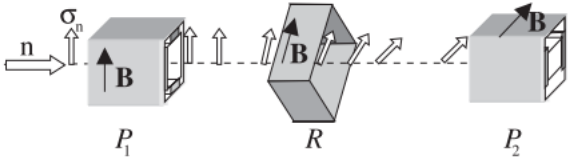
  ➔ the polariser becomes a nuclear waste
  - Glass substrate degradation under irradiation

  ➔ intensity loss with time
  - Large size bender

  ➔ difficult to increase the magnetic field further (gain in P expected)



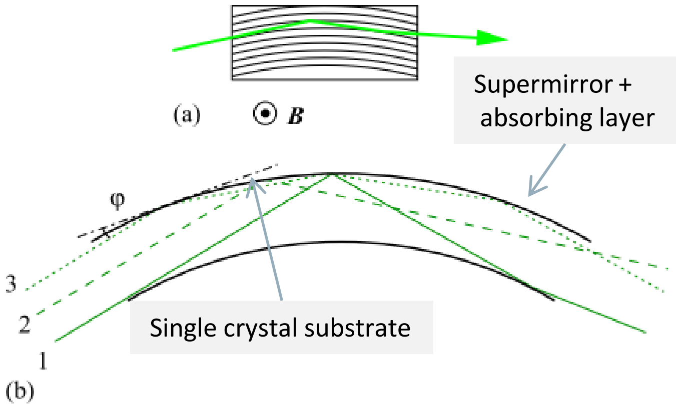




*M. Kreuz, et al., Nucl. Instrum. Meth. Phys. A 547, 583-91 (2005).

New solution

- solid-state bender with Fe/Si supermirrors
  - Co-free ➔ activation is not critical
  - More compact ➔ higher H possible
  - No glass ➔ no irradiation damage expected

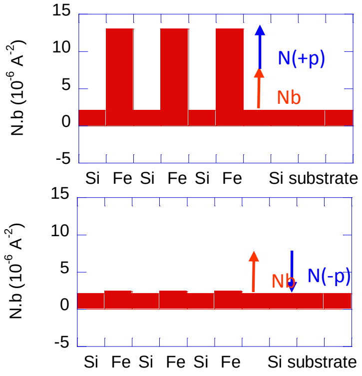


- Points to address:
  1. Optimize polarisation for one supermirror reflection
  2. Improve polarisation at long wavelengths
  3. Push the limit above 0.997: fight against depolarisation effects

1. Optimize polarisation for one supermirror reflection:

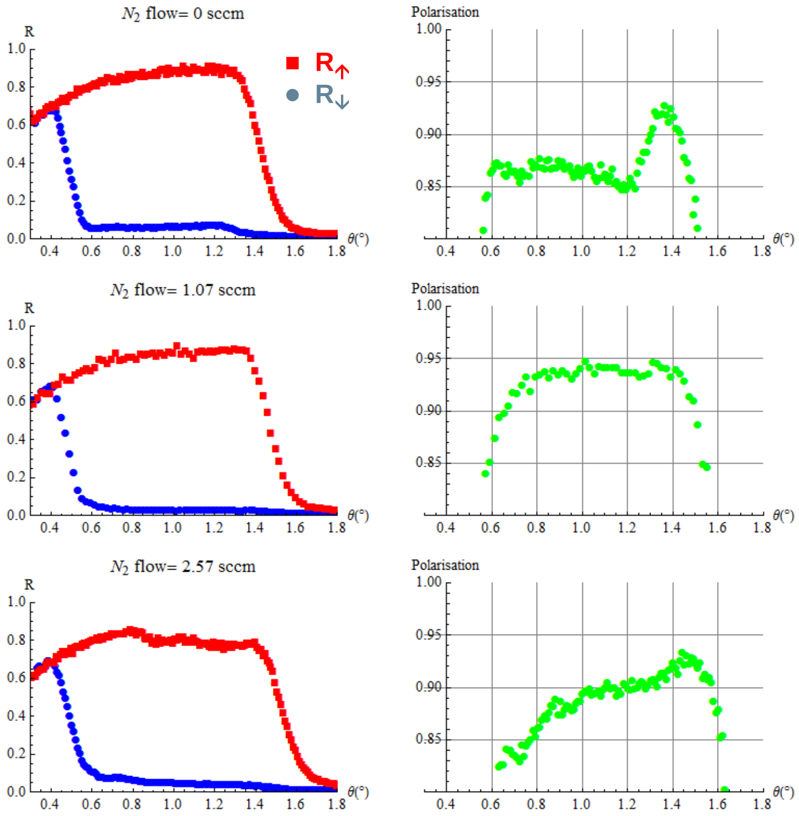
“N.b” tuning by reactive sputtering

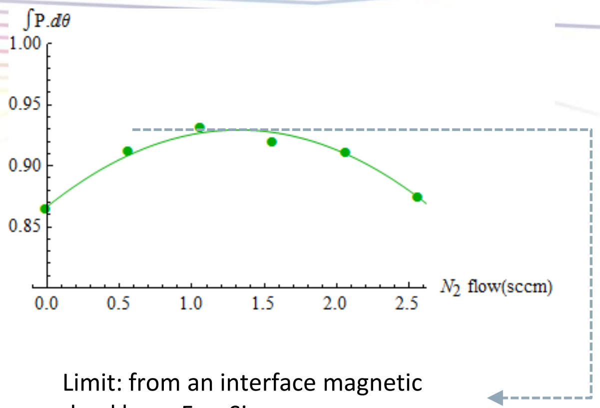
“N.b” matching:



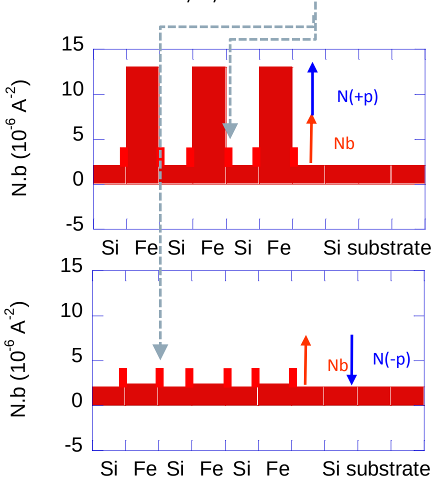
(N.b) for Si layer altered by Nitrogen incorporation:

$$\overline{(N.b)}_{Si_{1-x}N_x} = (1-x)N_{Si}b_{Si} + xN_N b_N$$



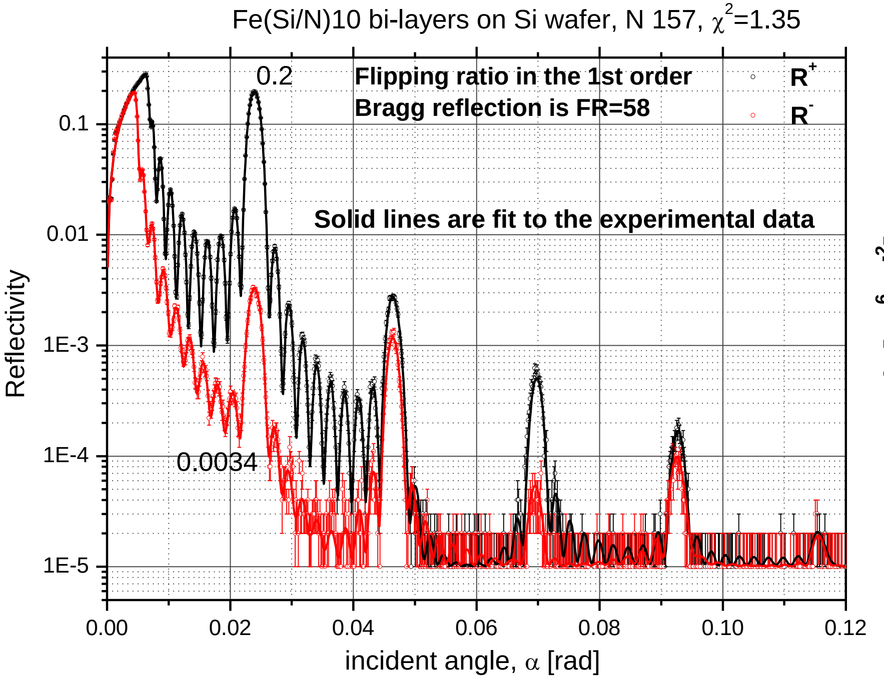


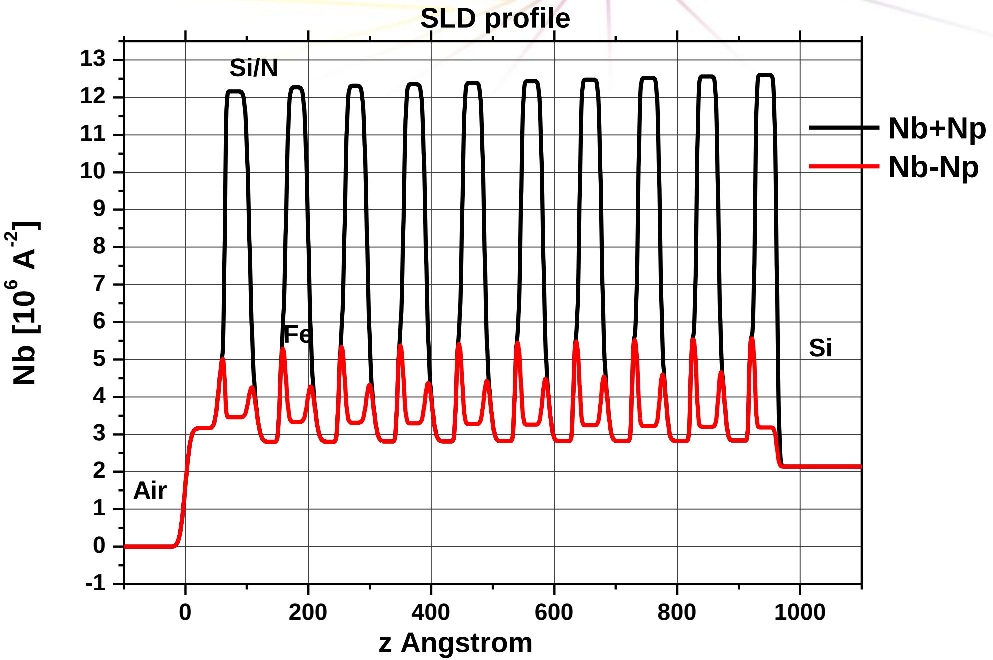
Limit: from an interface magnetic dead layer $Fe_{1-y}Si_y$



1. Optimize polarisation for one supermirror reflection:

Polarised neutron reflectivity (SuperADAM relectometer*)



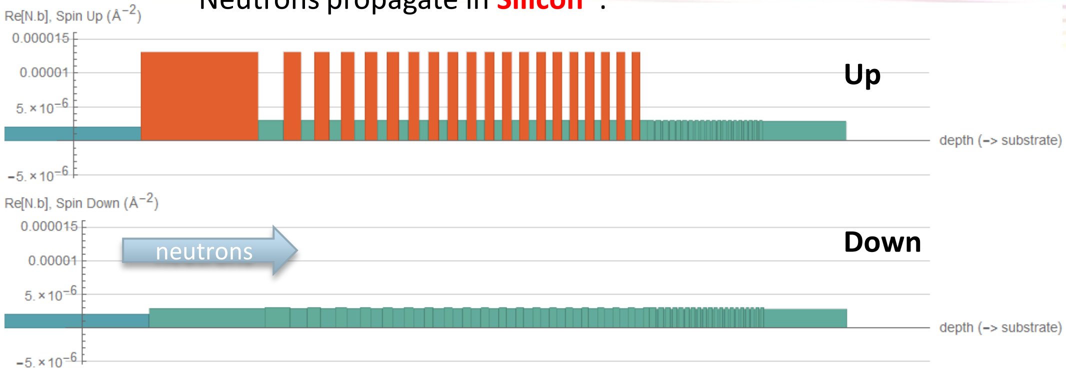


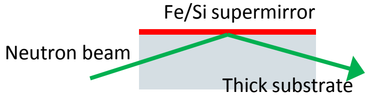
(*Measurements & fits: K. Zhernenkov, D. Gorkov, B. P. Toperverg, unpublished)

2. Improve polarisation at long wavelengths

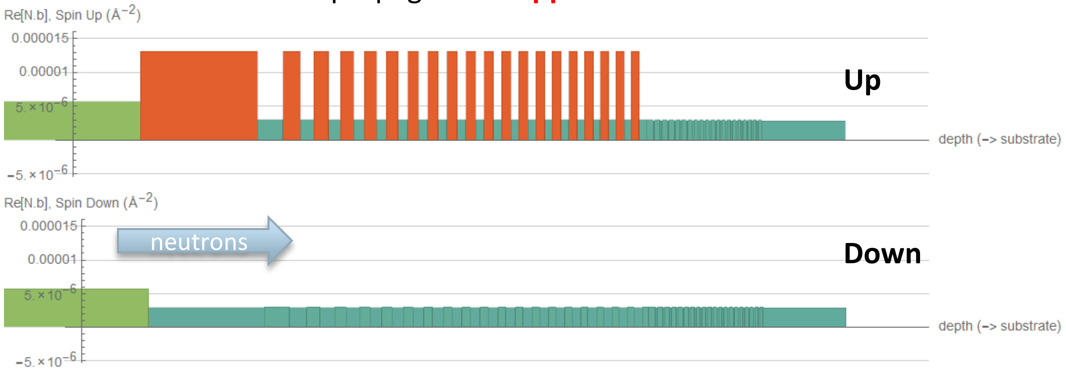
Effect of substrate in a solid-state device

Neutrons propagate in **Silicon** :

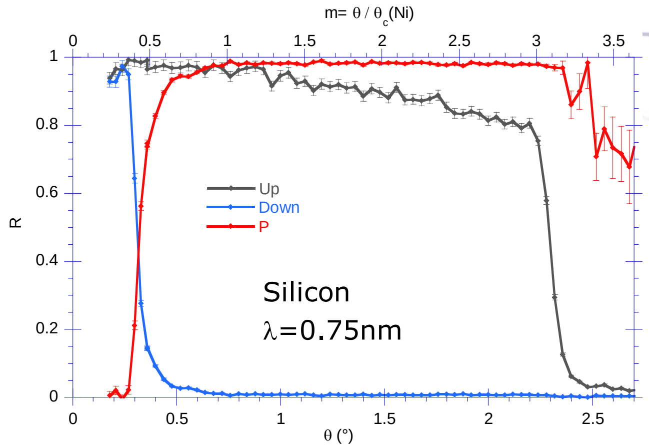


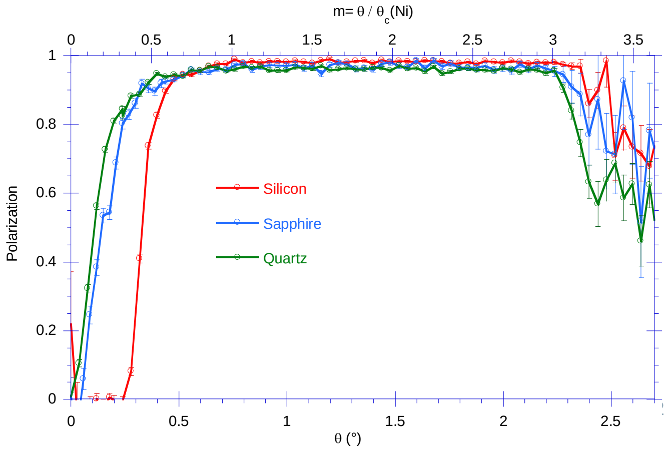


Neutrons propagate in **Sapphire** :



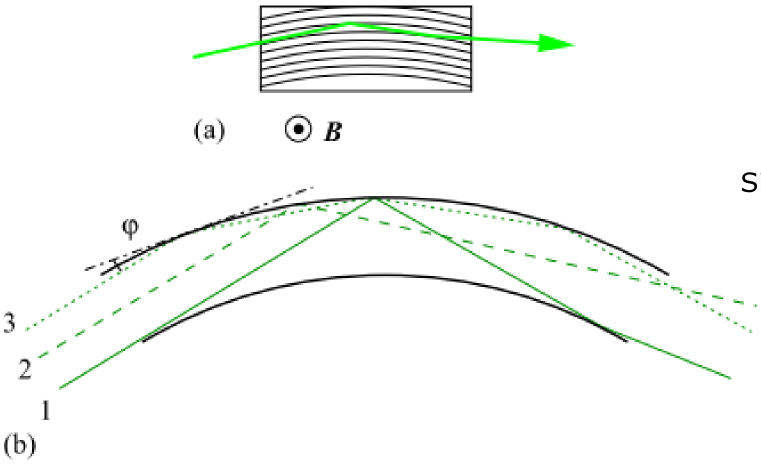
Measured polarised neutron reflectivity:



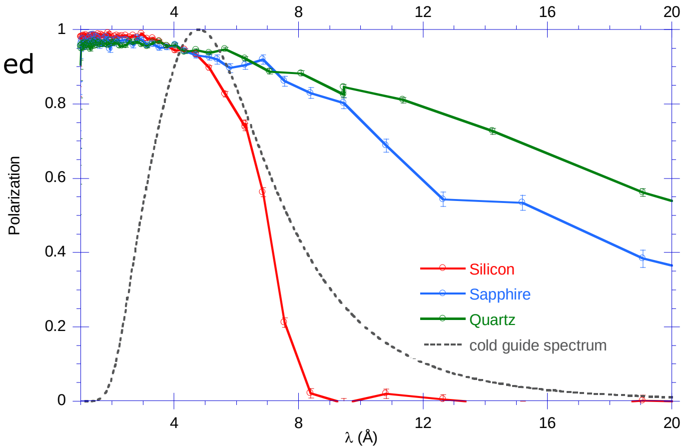


2. Improve polarisation at long wavelengths

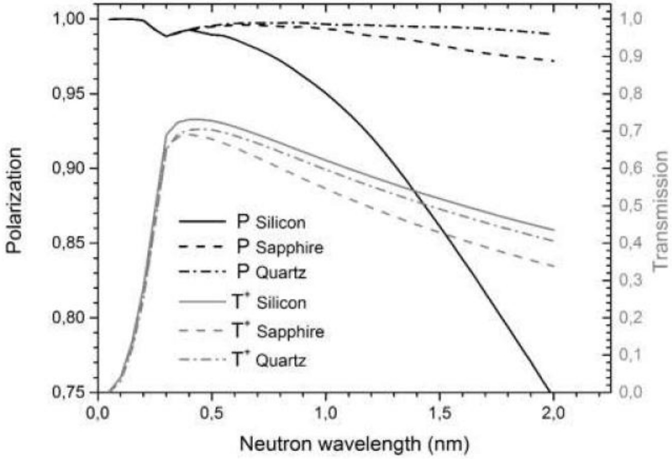
More polarised Garland reflections



Reflectivity measurements rescaled for θ=0.3°:



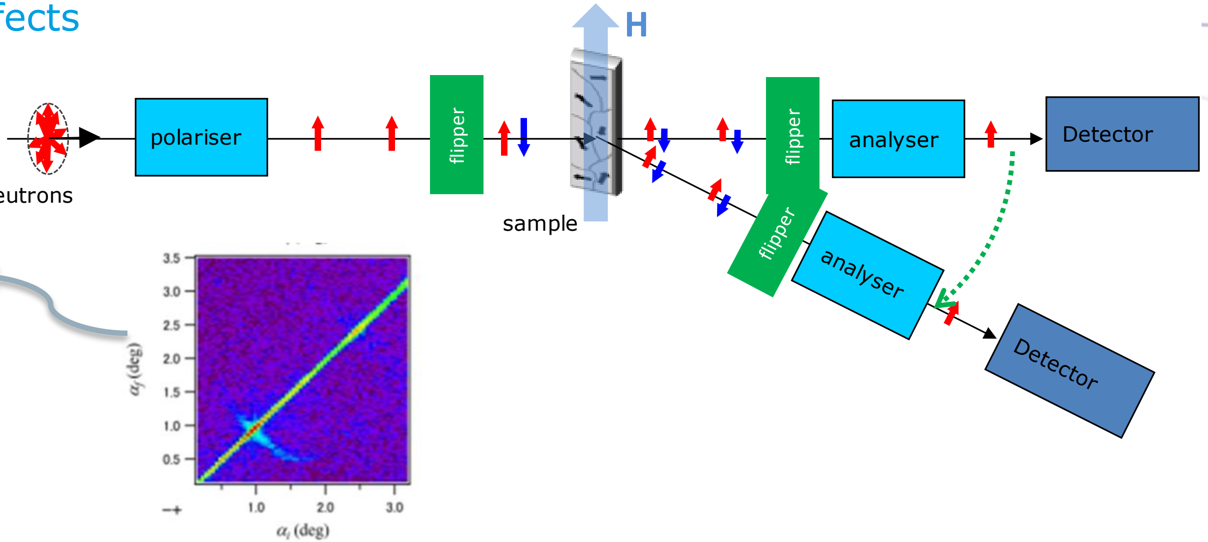
Simulation of full bender*:

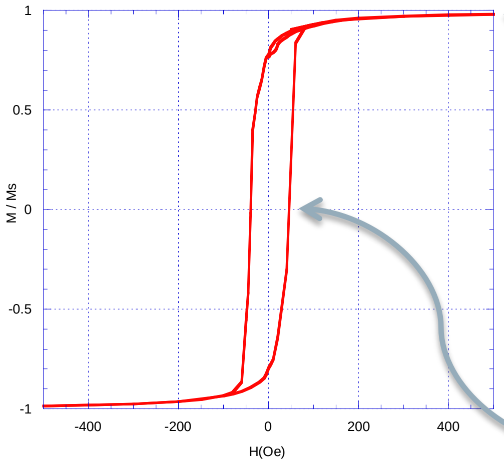


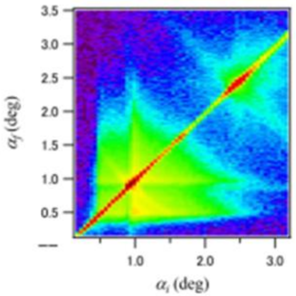
*A. Petukhov et al., Nucl. Instrum. Meth. A 838, 33-8 (2016)

3. Push the polarisation limit above 0.997:

Fight against depolarisation effects





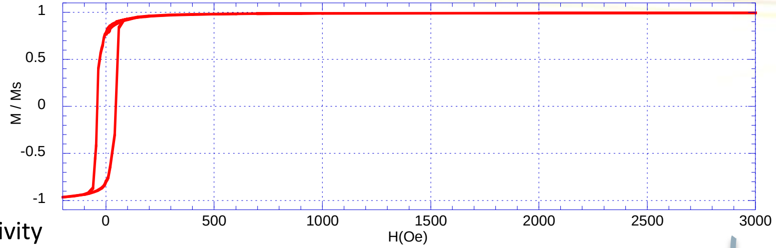


Mis-oriented magnetic regions in the multilayer
➔Spin-flip scattering (specular and off-specular)
➔ depolarisation

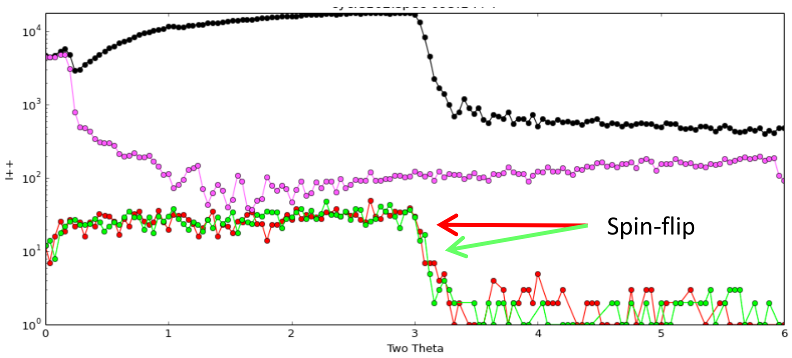
R. Maruyama et al., *Nucl. Instrum. Meth. A* ***819, 37-53 (2016).***

3. Push the polarisation limit above 0.997

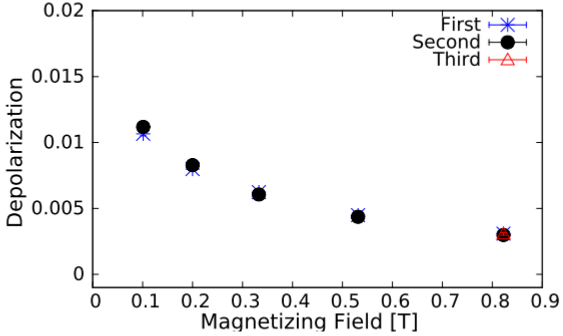
Depolarisation at higher applied fields



Specular polarised neutron reflectivity
with polarisation analysis*
H = 3000 Oe = 0.3T
Fe/Si supermirror m=3 on sapphire (raw data,
work in progress…)



Opaque test bench measurement (PF1B)
Fe/Si supermirror m=3 .6



C. Klauser et al., *Nucl. Instrum. Meth. Phys. A (2016).*

(*SuperADAM, A. Devishvili, A. Pethukov).

Conclusion

Challenges of neutron multilayer fabrication

- Non-polarising case

  Controlling :
  - layer thickness (large range),
  - density,
  - roughness,
  - interface structures,
  - stress

- Polarising case
  - Same as non-polarising,
  - SLD matching for spin down
  - Controlling magnetic structure (perpendicular and in-plane, including spin misalignements)

Thanks to …

- *Collaborators at ILL:*

A. Pethukov, V. Nesvizhevsky, T. Soldner, C. Klauser, D. Jullien, K. Zhernenkov, D. Gorkov, B. P. Toperverg, A. Devishvili, D. Honecker, C. Dewhurst, T. Saerbeck, A. Wildes, P. Falus, P. Fouquet, B. Farago, D. Bazzoli ….

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- *People who provided neutron measurements during ILL shutdowns :*

T. Krist, F. Ott, J. Stahn

- *People who contributed to develop multilayers at the ILL:*

O. Schärpf, I. Anderson, P. Hoghoj, K. Andersen

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