ПЕТЕРБУРГСКИЙ ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ НИЦ КИ (ГАТЧИНА, РОССИЯ)

Н.К. Плешанов

Зеркальный флиппер для монохроматических нейтронов: измерение эффективности, перспективы

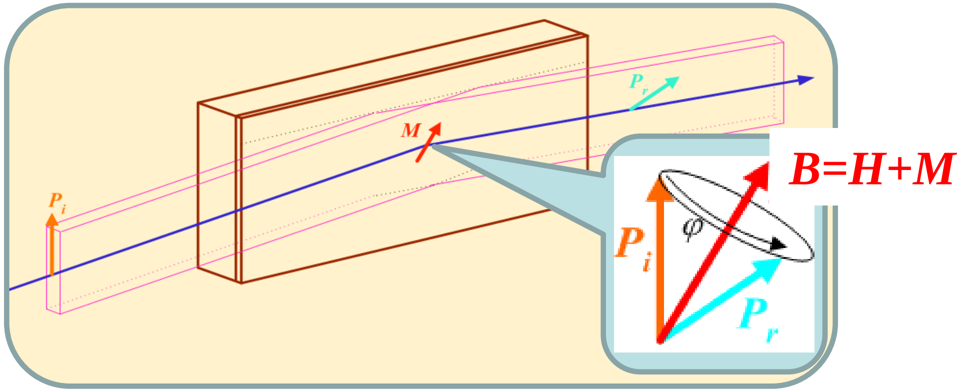
Mirror flipper for monochromatic neutrons: measuring the efficiency, prospects

Школа по физике поляризованных нейтронов
15-16 декабря 2016, НИЦ КИ ПИЯФ, Гатчина, Россия

Neutron spin-turning reflectors

To be of practical interest,

- **the reflectivities $R_\pm$ should be close to 1,**
- **the spins should rotate about one axis (fields in layers are collinear), be inclined to the axis and the rotation angles weakly depend on q (on wavelength and glancing angle),**
- **precession condition $R_- = R_+$.**



Neutron spin manipulation optics

Neutron spin manipulation optics based on quantum aspects of the neutron interaction with magnetically anisotropic layers signifies transition from 1D (spin selection) to 3D (spin manipulation) in polarized neutron optics.

Solutions that provide a high reflectivity (R ~ 1) and a weak dependence of the spin rotation angles on the neutron wavelength and on the glancing angle were suggested. They open new possibilities for spin manipulations. Neutron spin-turning reflectors (particularly, $\pi/2$-turners and π-turners) may be either directly used or combined to build compact devices: 3D-polarizers, 3D-analyzers, 3D-rotators (spin manipulators), hyperpolarizers, (Larmor and quantum) spin precessors and antiprecessors.

N.K. Pleshanov, J. Phys.: Conf. Ser. 528 (2014) 012023. – Neutron spin manipulation optics: basic principles and possible applications.

N.K. Pleshanov, J. Surf. Investig.: X-ray Synchrotron Neutron Tech. 9, 24 (2015). – Neutron spin-turning reflectors.

Neutron spin optics (NSO)

NSO will essentially broaden the functionality of polarized neutron optics and contribute to development of neutron instrumentation for obtaining information about the objects under study. Compactness, zero-field option and multi-functionality of the NSO devices are among the advantages, as compared to the existing spin manipulation techniques, and may play an important role in developing alternative schemes of measurements, esp. with small samples.

It is difficult to foresee all consequences of development of NSO, e.g., hyperpolarization of neutron beams. (A hyperpolarizer not only separates neutrons with the opposite spins, but also flips the 'wrong' spins, thus polarizing up to 100 % of neutrons, with the increase either in the angular divergence or in the width of the beam, in accordance with the Liouville theorem).

N.K. Pleshanov, J. Phys.: Conf. Ser. 528 (2014) 012023. – Neutron spin manipulation optics: basic principles and possible applications.

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Neutron spin optics (NSO)

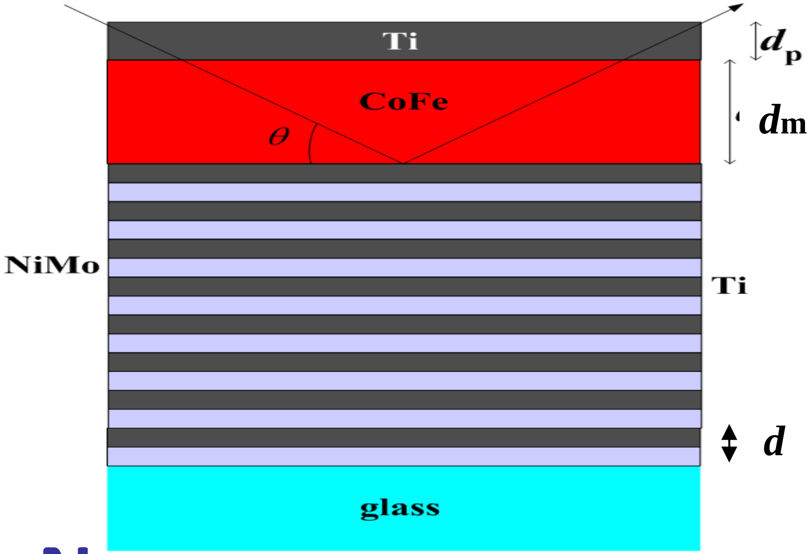
To reveal the potential of NSO, the development of the basic elements including

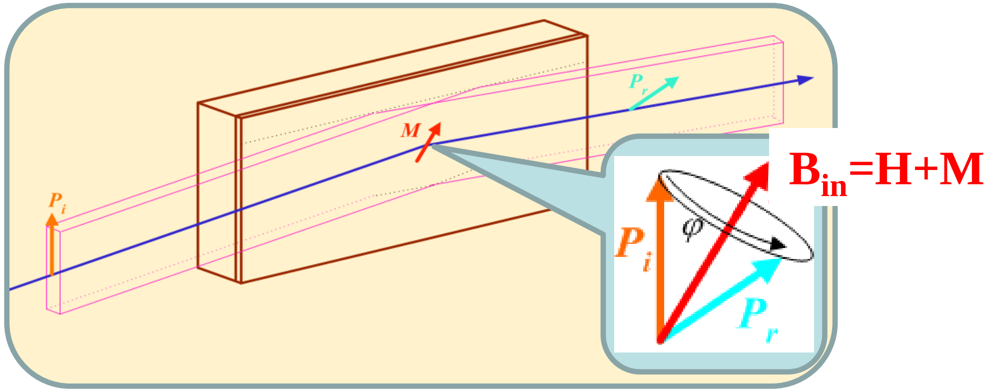
- spin turning reflectors, incl. $\pi/2$- and π-turners (flippers)
- spin precessors (compact counterparts of precession coils)

are required, as well as the study of polarization phenomena under reflection of neutrons from real layered structures.

First neutron mirror spin flipper

The multilayer-backed mirror flipper for monochromatic beams





Neutrons traverse a weakly-reflecting magnetic layer twice, before and after reflection from a non-magnetic multilayer. The Larmor precession angle in the magnetic layer is

$$\varphi = 2\omega_L \Delta t = \frac{2|\mu_n|B_{in}}{\hbar}\frac{2d_m}{\sin\theta}\frac{m_n}{h}\lambda = CB_{in}\lambda\frac{2d_m}{\sin\theta}$$

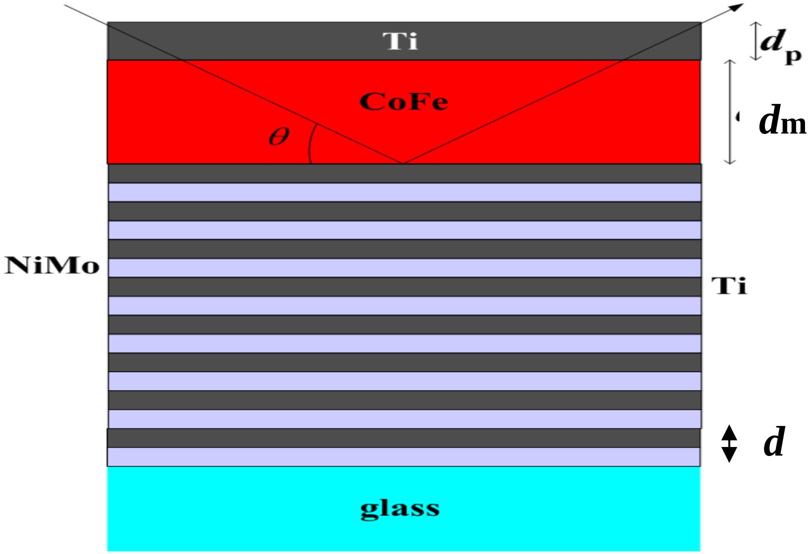
$$C = 4\pi m_n|\mu_n|/h^2 \cong 4.63\cdot 10^{-4}\ \mathrm{T}^{-1}\mathrm{nm}^{-2}$$

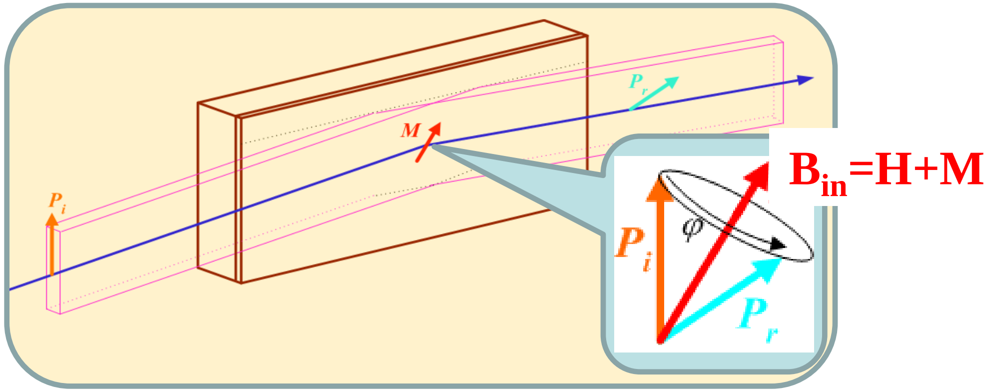
The Bragg condition $2d\sin\theta = \lambda$ $\Rightarrow$ $\varphi = 4CB_{in}dd_m$

To take into account the refraction in the multilayer, $d \rightarrow 2\pi/q_B$ $\Rightarrow$ $\varphi = 8\pi CB_{in}d_m/q_B$

First neutron mirror spin flipper

The multilayer-backed mirror flipper for monochromatic beams





$\varphi = 8\pi C B_{in} d_m / q_B$ ⇒ $d_m(\pi) = q_B/(8CB_{in})$

$q_B = 0.5\ \mathrm{nm}^{-1}$ $B_s \cong 2.0\ \mathrm{T}$ (experiment at H=50 mT) $B_{in} = 0.95B_s \Rightarrow d_m(\pi) = 71.1$ nm

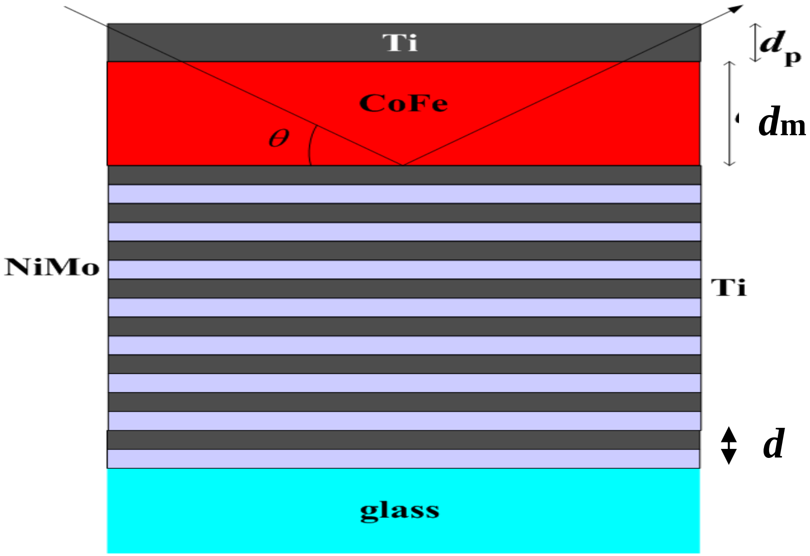
$$d_{a,b} = \frac{2}{\sqrt{q_B^2 - q_{a,b}^2}}$$

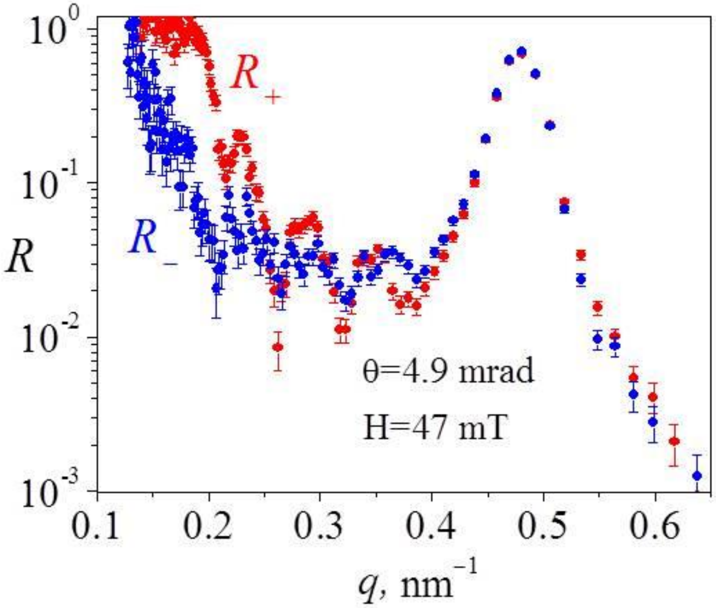
d_a(NiMo)= 6.92 nm
d_b(Ti) = 6.14 nm **(quarter-wavelength layers)**

d_p(Ti) = 30 nm **(protective layer)**

[V.A. Matveev, N.K. Pleshanov, O.V. Gerashchenko, V.Yu. Bairamukov, J. Surf. Investig.: X-ray Synchrotron Neutron Tech. 8, 991 (2015)]

First neutron mirror spin flipper





glass substrate + {NiMo(6.92 nm)/Ti(6.14 nm)}x20 + CoFe(71.1nm) + Ti(30 nm)

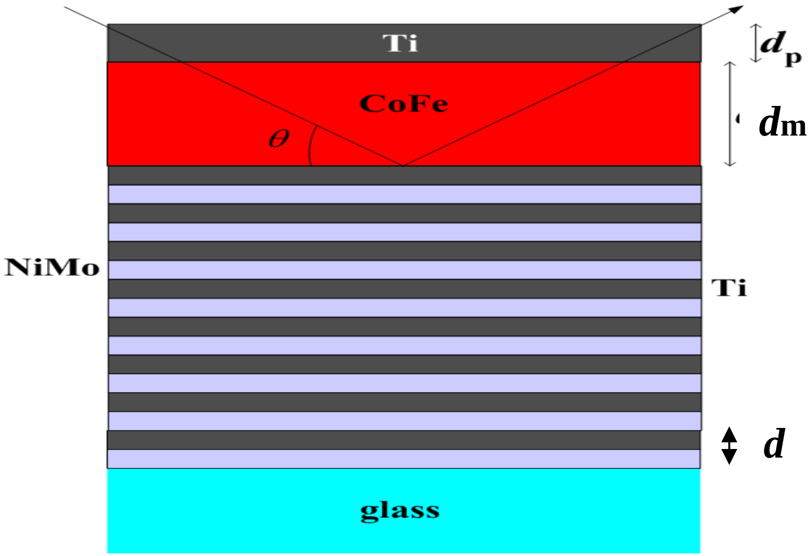
The spin-up (+) and spin-down (–) neutron reflectivities $R_{\pm}(q)$ for the structure (left) in the external field 47 mT, measured at the reflectometer NR-4M (PNPI, Gatchina).

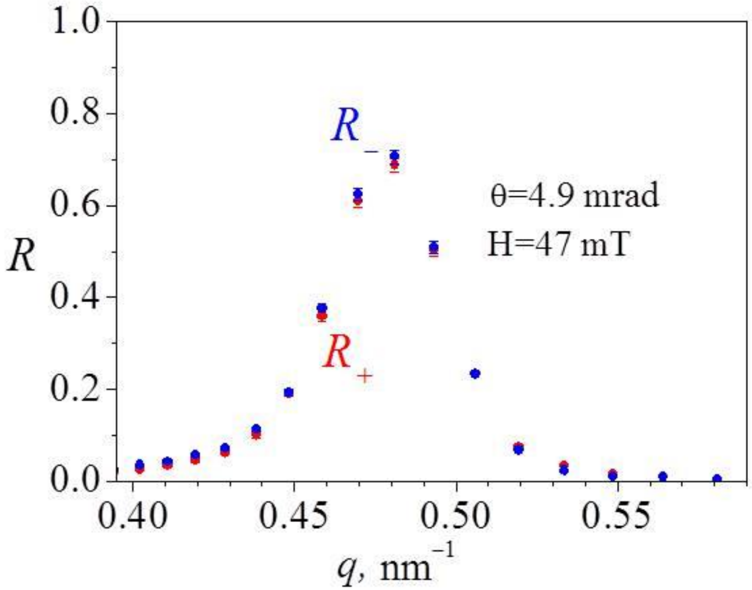
[N.K. Pleshanov, V.G. Syromyatnikov, NIM A 837 (2016) 40-43. – Testing the first neutron mirror flipper.]

$R_+ \cong R_-$ for the Bragg peak

$\Delta q_B / q_B = 11\%$ (FWHM)

First neutron mirror spin flipper





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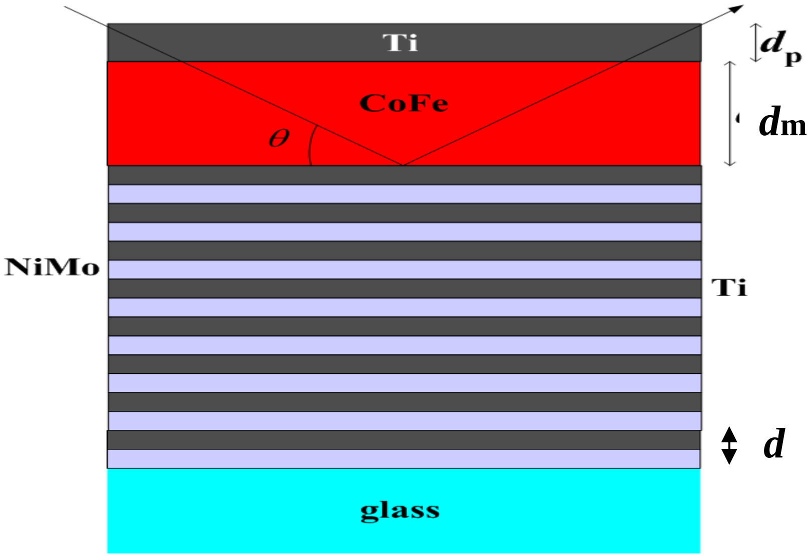
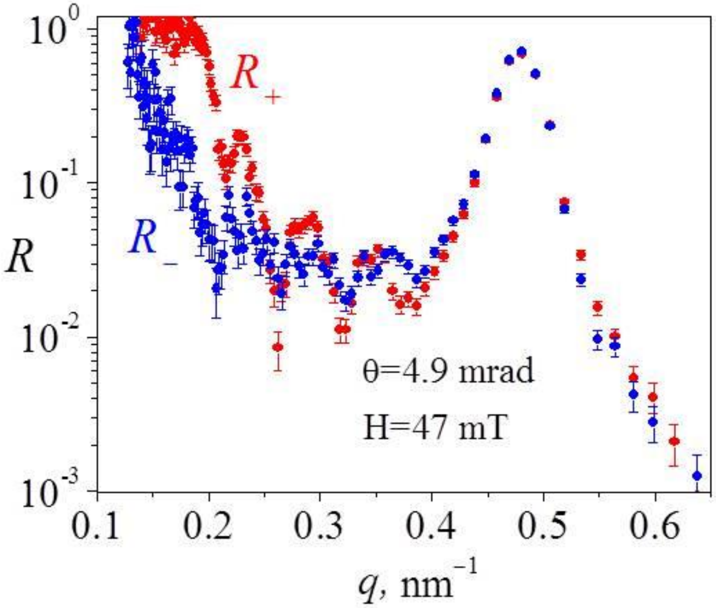
$R_+ \cong R_-$ for the Bragg peak

$\Delta q_B / q_B = 11\%$

$q_B = 0.48$ nm^{-1}

First neutron mirror spin flipper





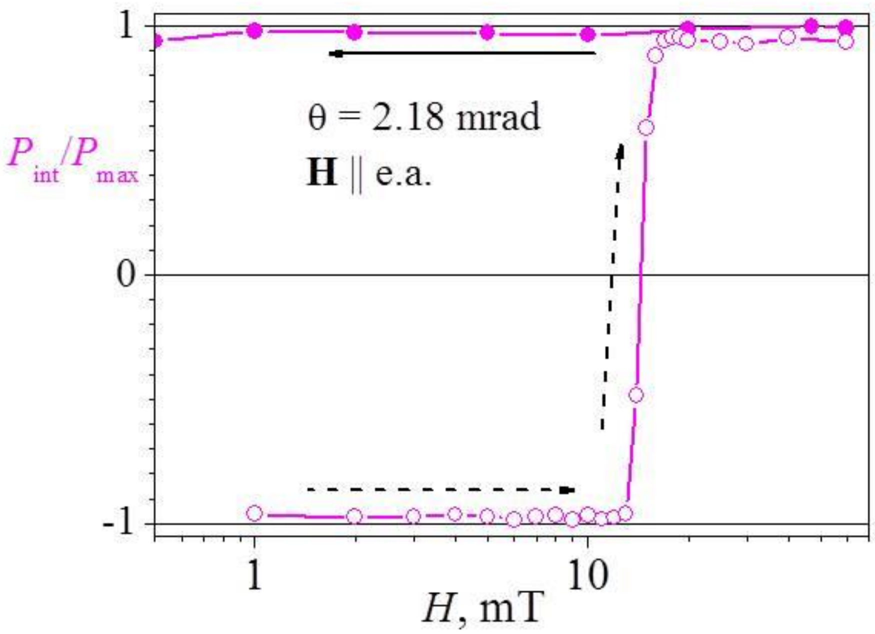
glass substrate +
{NiMo(6.92 nm)/Ti(6.14 nm)}x20 +
CoFe(71.1nm) + Ti(30 nm)

The spin-up (+) and spin-down (–) neutron reflectivities $R_\pm(q)$ for the structure (left) in the external field 47 mT, measured at the reflectometer NR-4M (PNPI, Gatchina).

In the low *q* region: $R_+ \neq R_-$

It can be used to study the reversal of the CoFe layer magnetization by measuring integral reflectivities at a small glancing angle.

First neutron mirror spin flipper



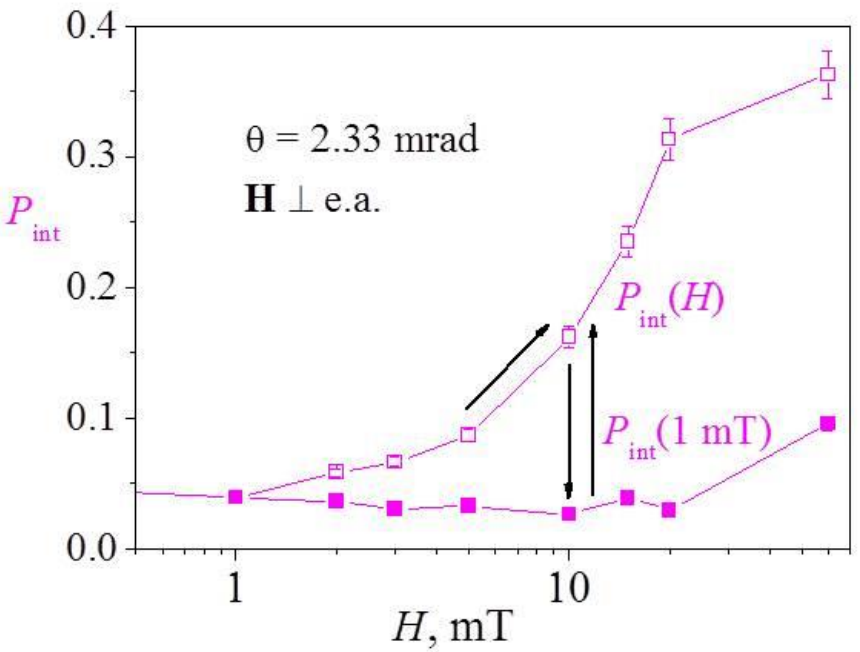
The integral polarization $P_{int} = (I_+ - I_-)/(I_+ + I_-)$, normalized to max($P_{int}$), measured with a white beam of thermal neutrons at the glancing angle θ = 2.18 mrad as a function of the external field *H* || easy axis.

(+60 mT → 0 → –60 mT → 0 →+60 mT)

The integral polarization represents the hysteresis loop (here *H* || e.a.) :

! **The magnetization reversal starts about 12 mT**

First neutron mirror spin flipper



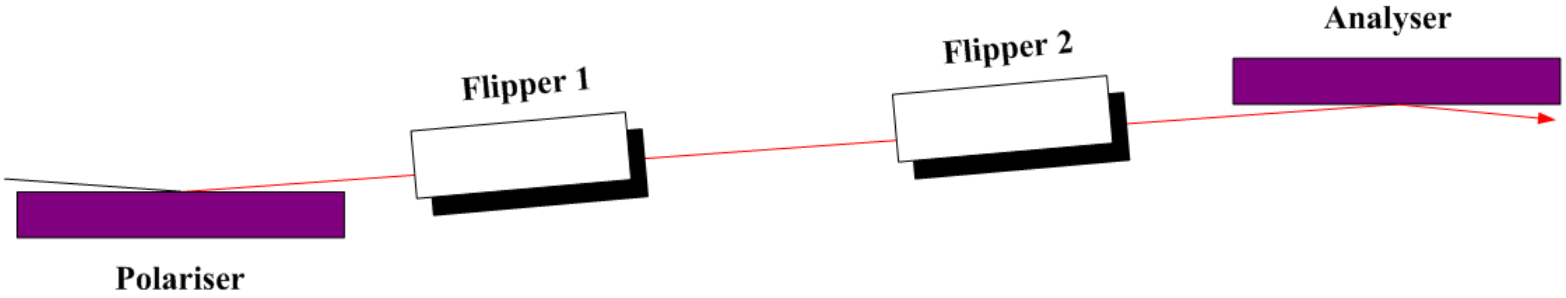
The integral polarization $P_{int} = (I_+ - I_-)/(I_+ + I_-)$ measured with a white beam of thermal neutrons at θ=2.33 mrad as a function of $H \perp$ easy axis. The sample magnetized in H=60 mT was turned in H=0 about its surface normal by 90°. Then the field H changed as follows

(0 → 1 mT → 2 mT → 1 mT → 3 mT → 1 mT → …)

No oppositely magnetized domains form in the fields ≤20 mT (single-domain magnetic spring)

! **The mirror spin flipper, in principle, can work in guide fields up to 20 mT ;**

Standard method of measuring the flipper efficiencies



$$f_1 = \frac{1}{2}\left(1 + \frac{I_{\text{on,on}} - I_{\text{on,off}}}{I_{\text{off,off}} - I_{\text{off,on}}}\right)$$

$$f_2 = \frac{1}{2}\left(1 + \frac{I_{\text{on,on}} - I_{\text{off,on}}}{I_{\text{off,off}} - I_{\text{on,off}}}\right)$$

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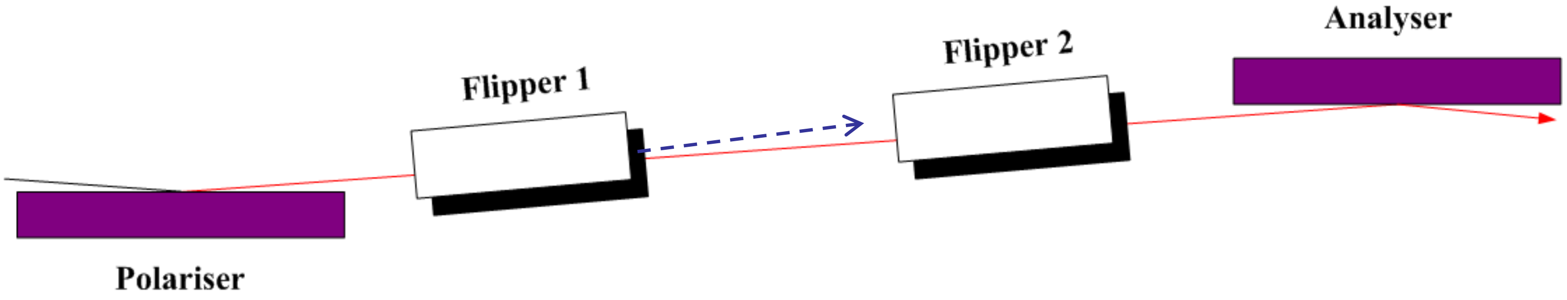

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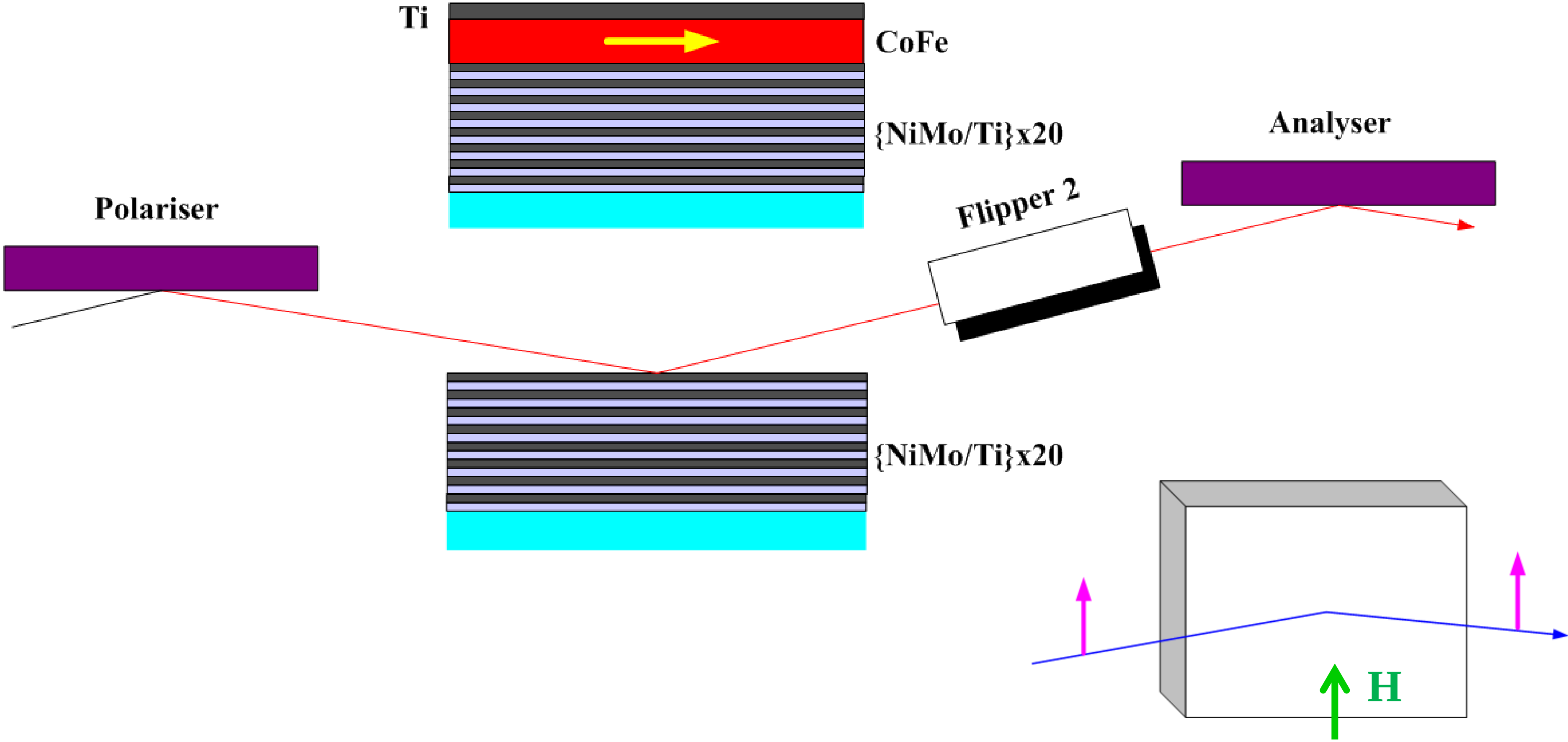
$$f_2 = \frac{1}{2}\left(1 + \frac{I_{\text{on,on}} - I_{\text{off,on}}}{I_{\text{off,off}} - I_{\text{on,off}}}\right)$$

A mirror spin flipper (1) would change both intensity and direction of the beam, violating the requirement of the method that source, flipper 2 and analyzer in the measurements be the same.

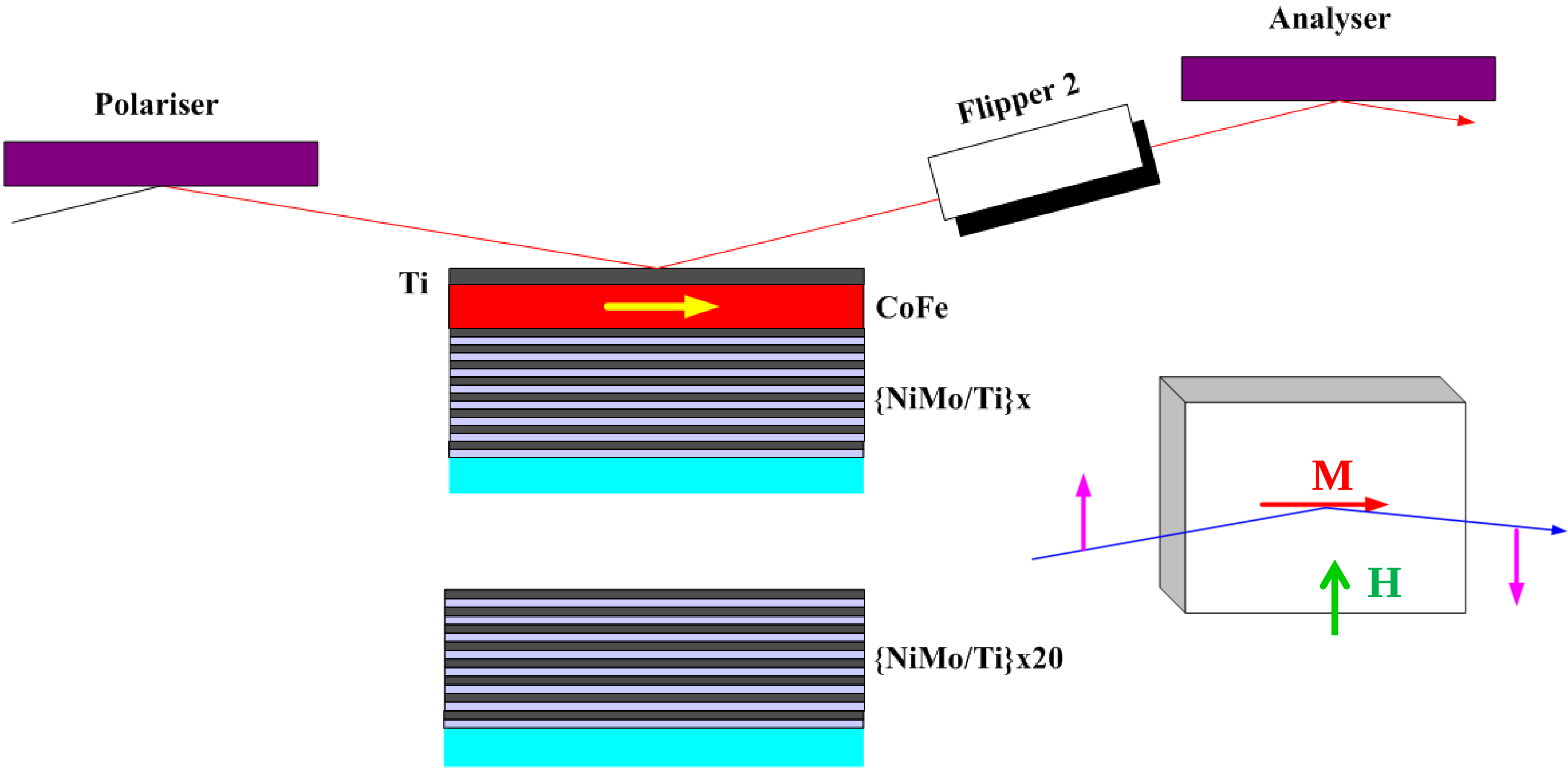
Modified method of measuring the flipper efficiencies



Two multilayer samples were prepared in the same sputtering process; only one was later coated with the magnetic film.

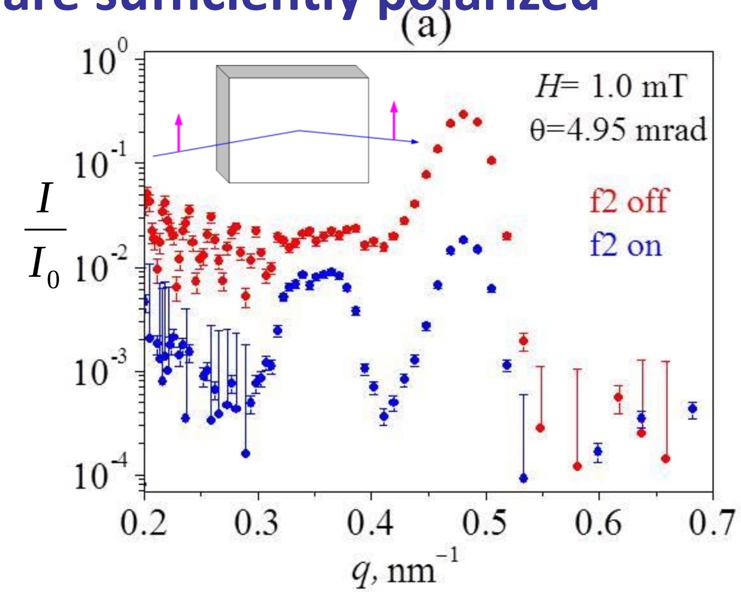
Modified method of measuring the flipper efficiencies

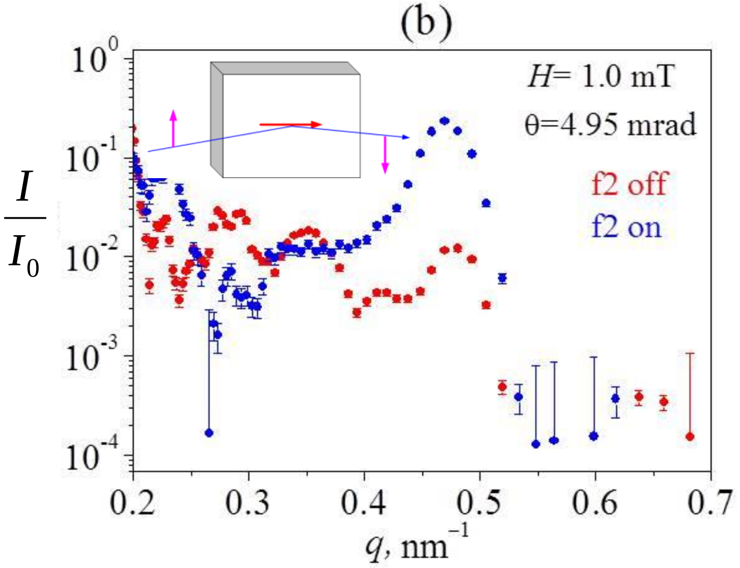
The same glancing angles mean the same neutron paths, therefore, the efficiencies of flipper 2 and the analyzer will be identical in each set of 4 TOF measurements.



First neutron mirror spin flipper

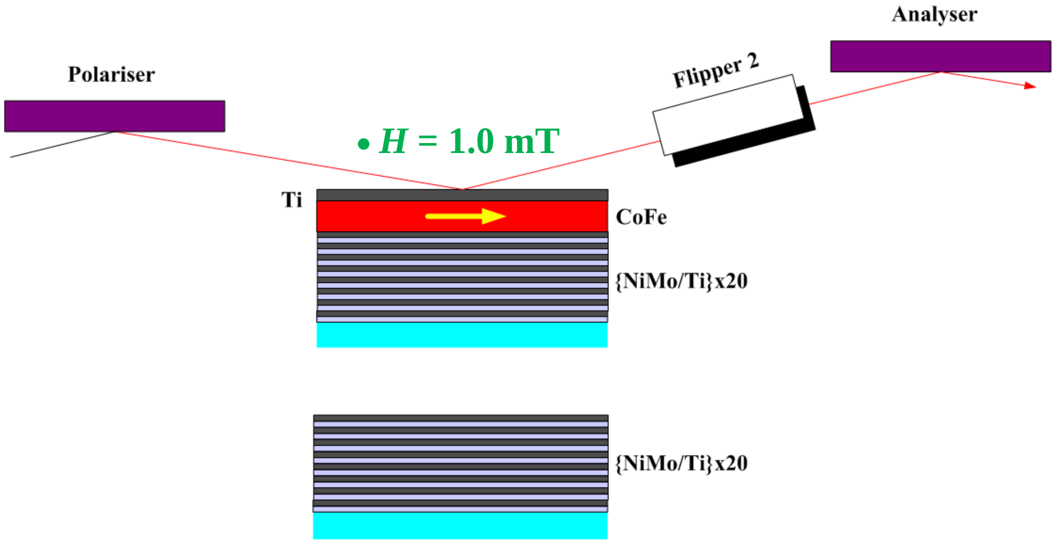
(a) The Bragg-reflected neutrons are sufficiently polarized





(a) Normalized TOF intensities, measured with the non-magnetic sample (NiMo/Ti multilayer) at θ = 4.95 mrad in a field 1 mT with flipper 2 switched off and on, are represented as functions of *q* .

(b) Normalized TOF intensities, measured with the mirror flipper at θ = 4.95 mrad in a field 1 mT with flipper 2 switched off and on, are represented as functions of *q* .

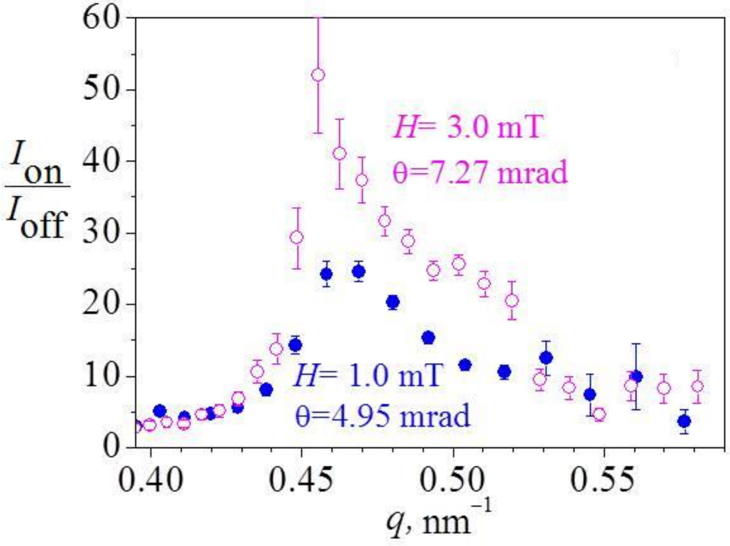


(b) The polarization of the Bragg-reflected neutrons is reversed

First neutron mirror spin flipper

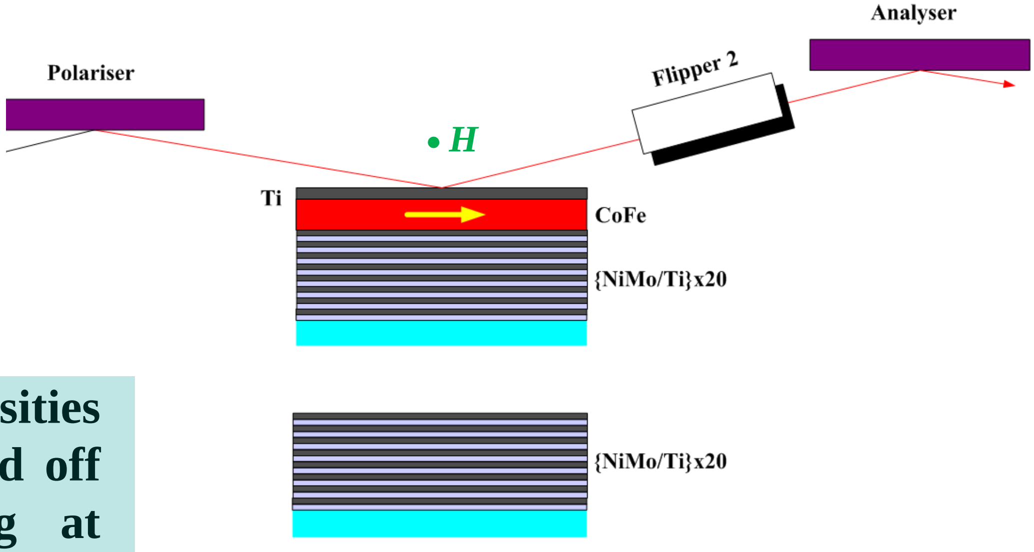
The Bragg peak for θ = 4.95 mrad is at λ = 0.13 nm.

The Bragg peak for θ = 7.27 mrad is at λ = 0.19 nm.



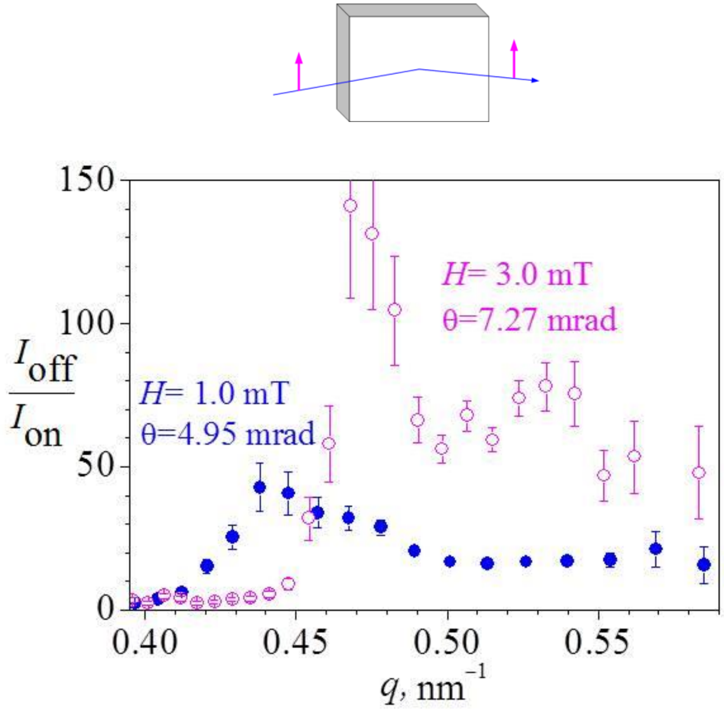
The ratios of the Bragg peak intensities measured with flipper 2 switched on and off for the mirror spin flipper working at wavelengths 0.13 nm (θ =4.95 mrad, H =1 mT) and 0.19 nm (θ =7.27 mrad, H =3 mT) are represented as functions of *q*.

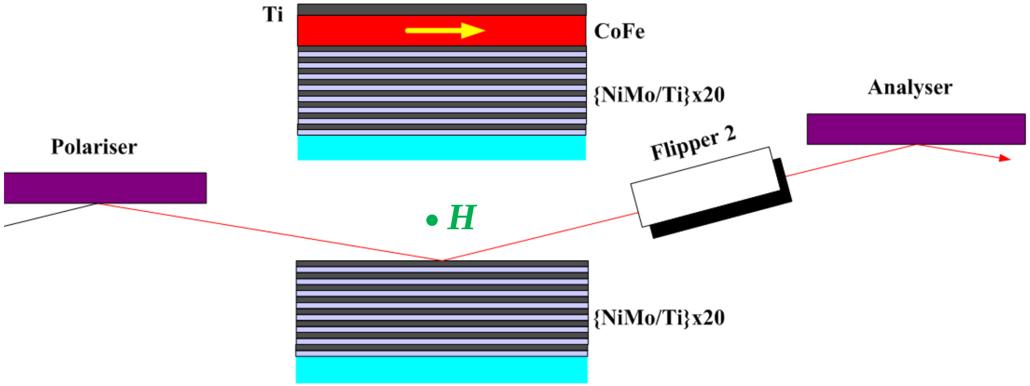
The ratios of the intensities obtained with the mirror flipper for wave-lengths 0.13 nm and 0.19 nm



First neutron mirror spin flipper

The (inverse) ratios of the intensities obtained with the non-magnetic ML for wavelengths 0.13 nm in 1 mT and 0.19 nm in 3 mT (better polarized!).





The ratios of the Bragg peak intensities measured with flipper 2 switched off and on for the non-magnetic multilayer working at wavelengths 0.13 nm (θ =4.95 mrad, H =1 mT) and 0.19 nm (θ =7.27 mrad, H =3 mT) are represented as functions of *q*.

Modified method of measuring the flipper efficiencies

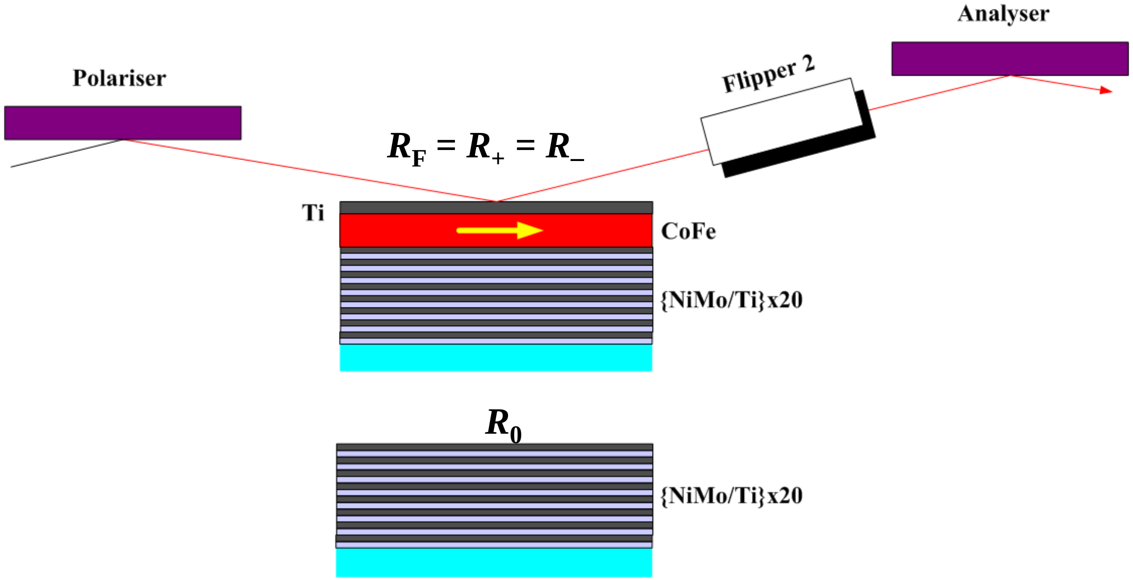
To evaluate the flipping efficiencies

$$f_1 = \frac{1}{2}\left(1 + \frac{I_{\text{on,on}} - I_{\text{on,off}}}{I_{\text{off,off}} - I_{\text{off,on}}}\right)$$

$$f_2 = \frac{1}{2}\left(1 + \frac{I_{\text{on,on}} - I_{\text{off,on}}}{I_{\text{off,off}} - I_{\text{on,off}}}\right)$$

$$R_{\text{F}} = R_0$$

the integral Bragg peak intensities obtained with the non-magnetic ML ($I_{\text{off,off}}$, $I_{\text{off,on}}$) and the mirror flipper ($I_{\text{on,off}}$, $I_{\text{on,on}}$) are further used.



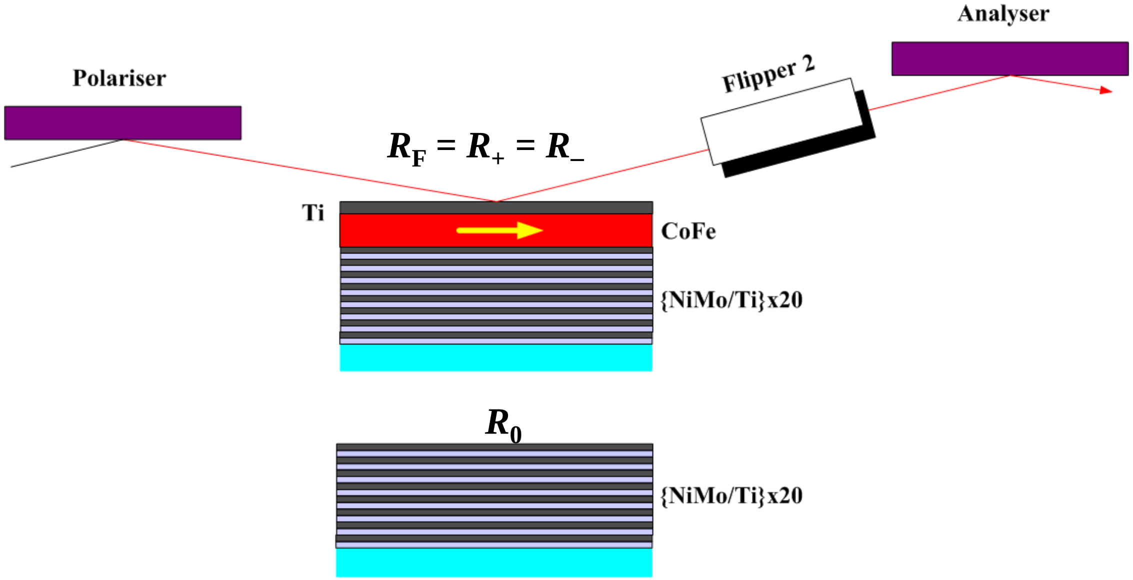
Modified method of measuring the flipper efficiencies

The expressions modified for $R_0 \neq R_F$

$$f_1 = \frac{1}{2}\left(1 + \rho \frac{I_{\text{on,on}} - I_{\text{on,off}}}{I_{\text{off,off}} - I_{\text{off,on}}}\right)$$

$$f_2 = \frac{1}{2}\left(1 + \frac{\rho I_{\text{on,on}} - I_{\text{off,on}}}{I_{\text{off,off}} - \rho I_{\text{on,off}}}\right)$$

$$\rho = \frac{R_0}{R_F}$$



Modified method of measuring the flipper efficiencies

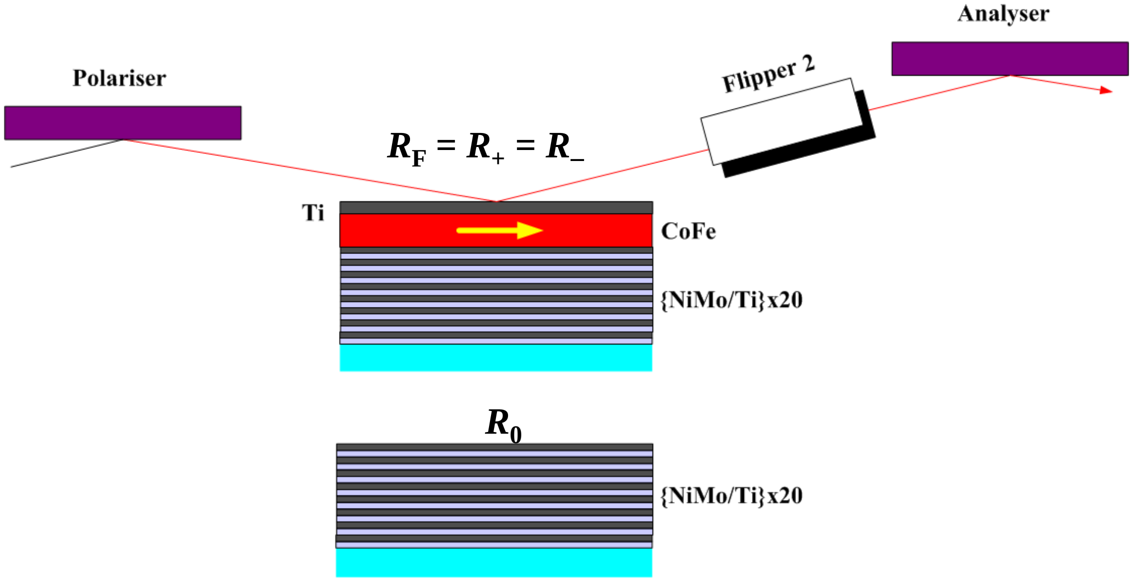
$$\sigma_0 = \frac{I_{\mathrm{off,off}} - I_{\mathrm{off,on}}}{I_{\mathrm{off,off}} + I_{\mathrm{off,on}}}$$

$$\sigma_F = \frac{I_{\mathrm{on,on}} - I_{\mathrm{on,off}}}{I_{\mathrm{on,on}} + I_{\mathrm{on,off}}}$$

$$f_1 = \frac{1}{2}\left[1 + \frac{|\sigma_{\mathrm{F}}|/\sigma_0}{1 + (P_0 P_A/\sigma_0 - 1)(|\sigma_{\mathrm{F}}| + \sigma_0)/(1+\sigma_0)}\right]$$

$$f_2 = \frac{1 + (P_0 P_A)^{-1}}{1 + \sigma_0^{-1}}$$

(P_0 = polarizer efficiency,
P_A = analyzer efficiency)



First neutron mirror spin flipper

$$\sigma_0 = \frac{I_{\mathrm{off,off}} - I_{\mathrm{off,on}}}{I_{\mathrm{off,off}} + I_{\mathrm{off,on}}}$$

$$\sigma_F = \frac{I_{\mathrm{on,on}} - I_{\mathrm{on,off}}}{I_{\mathrm{on,on}} + I_{\mathrm{on,off}}}$$

$$f_1 = \frac{1}{2}\left[1 + \frac{|\sigma_{\mathrm{F}}|/\sigma_0}{1 + (P_0 P_A/\sigma_0 - 1)(|\sigma_{\mathrm{F}}| + \sigma_0)/(1+\sigma_0)}\right]$$

$$f_2 = \frac{1 + (P_0 P_A)^{-1}}{1 + \sigma_0^{-1}}$$

$$\sigma = \frac{J_{\mathrm{off}} - J_{\mathrm{on}}}{J_{\mathrm{off}} + J_{\mathrm{on}}}$$

$$P_0 P_A = [(1 + \sigma^{-1}) f_2 - 1]^{-1}$$

from the experimental data **P_0P_A = 0.98 (H= 3 mT)**

H (mT)	Θ (mrad)	λ (nm)	f_1	f_2
3	7.27	0.189	0.975 ± 0.005	0.995 ± 0.005

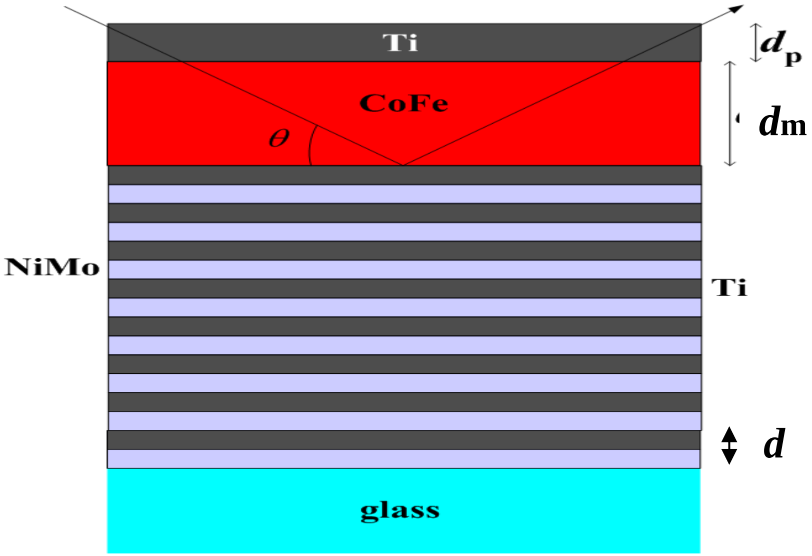
the efficiency of the mirror spin flipper **f_1 = 0.975 ± 0.005**

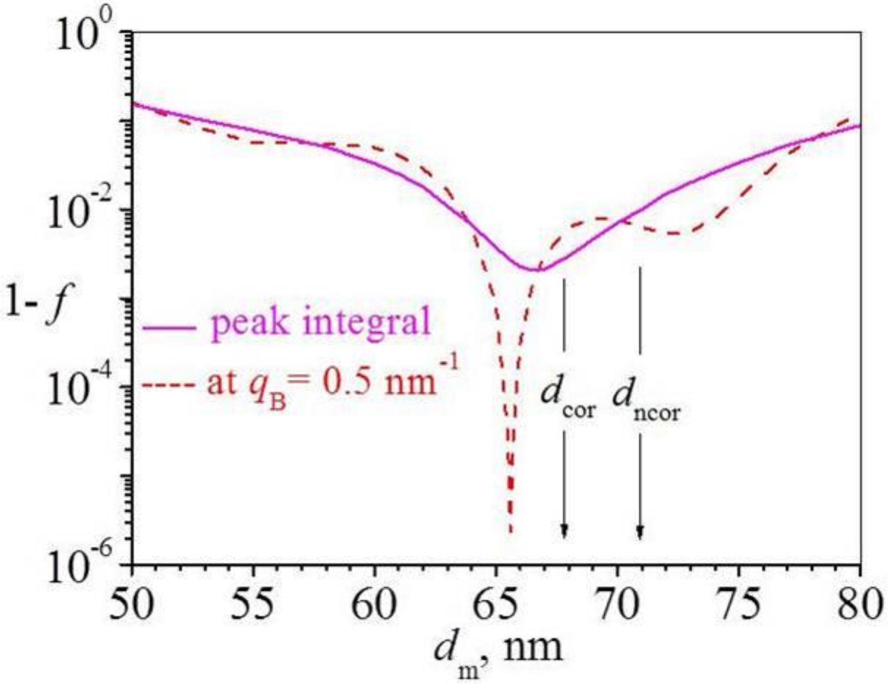
NSF portion in the Bragg peak integral **0.025**

Neutron mirror spin flippers: prospects

Can the efficiency be improved?

Neutron mirror spin flippers: prospects





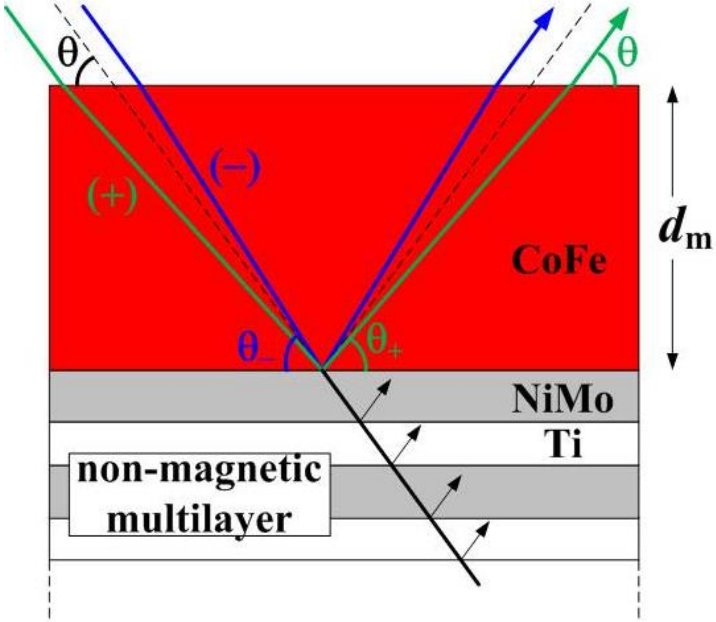
glass substrate + {NiMo(6.92 nm)/Ti(6.14 nm)}x20 + CoFe(d_m) + Ti(30 nm)

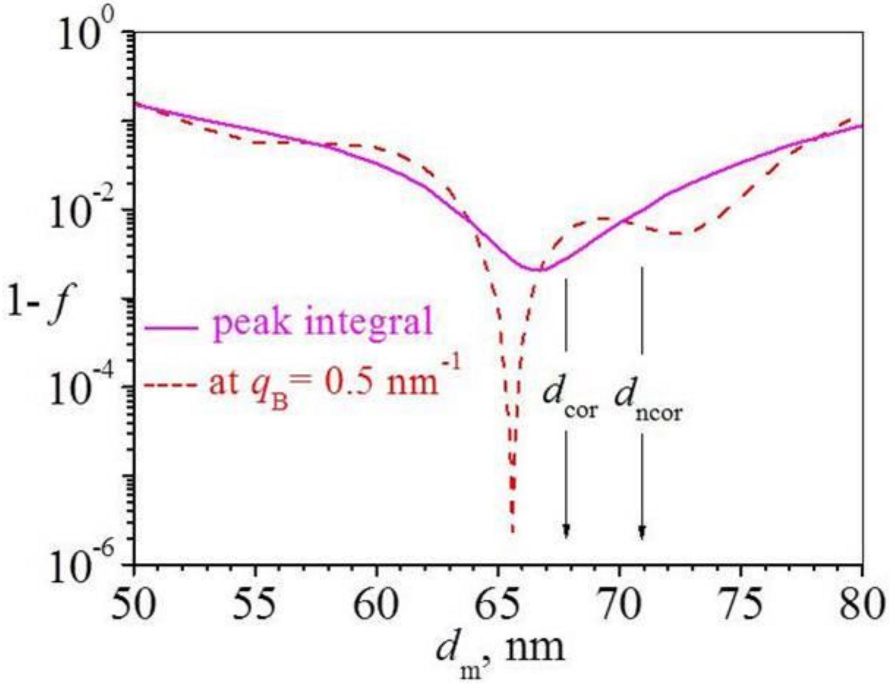
Calculated NSF portions in the neutron reflectivity at $q=q_B=0.5\ \mathrm{nm}^{-1}$ (dashed curve) and in the Bragg peak integral (solid curve) for the mirror flipper (left) as functions of the magnetic layer thickness d_m.

$d_{ncor} = q_B/(8CB_{in})$ $\Rightarrow$ $d_{ncor} = 71.1$ nm

NSF integral is minimum (0.25%) with d_m = 66.5 nm

Neutron mirror spin flippers: prospects





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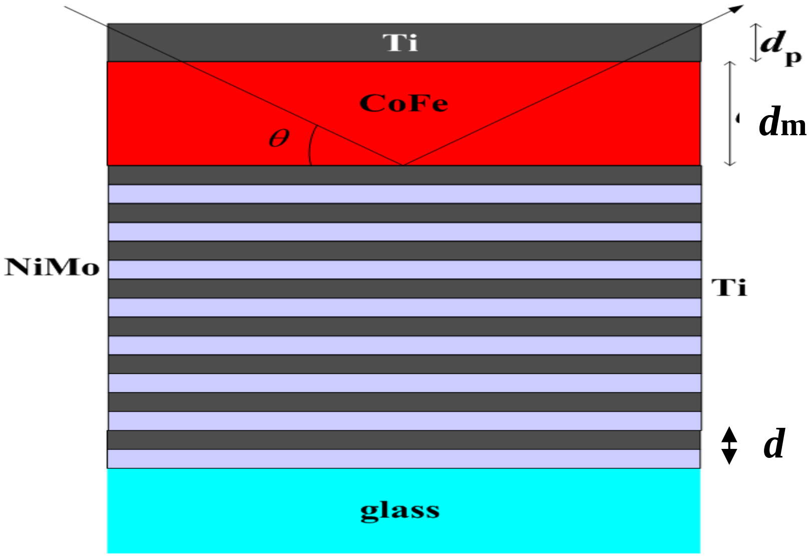
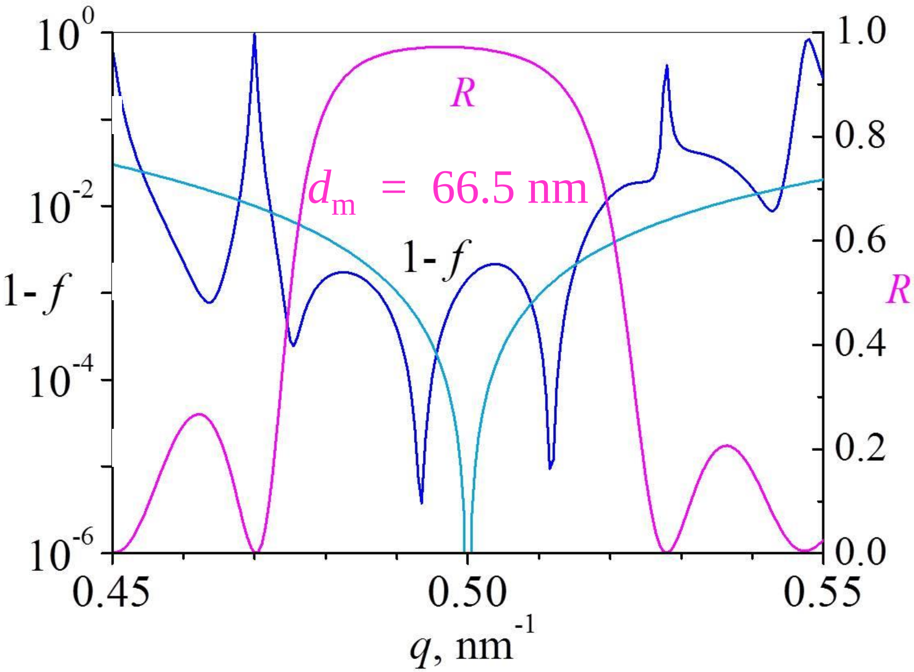
$d_{ncor} = q_B/(8CB_{in})$ $\Rightarrow$ $d_{ncor} = 71.1$ nm

NSF integral is minimum (0.25%) with $d_m = 66.5$ nm

spin-dependent refraction in CoFe layer $d_{cor} = \pi\left(\sqrt{q_B^2 - q_-^2} - \sqrt{q_B^2 - q_+^2}\right)^{-1}$ $\Rightarrow$ $d_{cor} = 67.8$ nm

Neutron mirror spin flippers: prospects

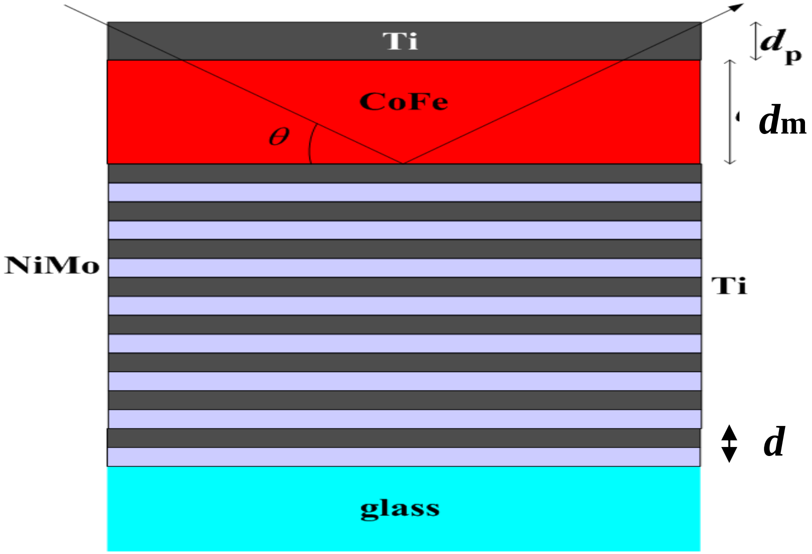




glass substrate + {NiMo(6.92 nm)/Ti(6.14 nm)}x20 + CoFe(66.5 nm) + Ti(30 nm)

The neutron reflectivity *R* and the NSF portion 1-*f* calculated as functions of *q* for a purely Larmor precession in the CoFe (66.5 nm) layer and for an exact spin behavior in the mirror flipper structure (left).

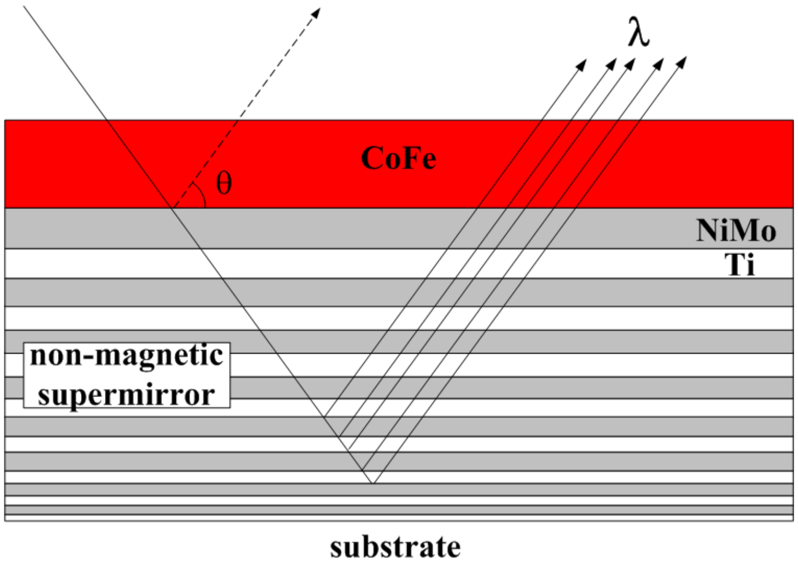
Multilayer-backed flippers for monochromatic beams

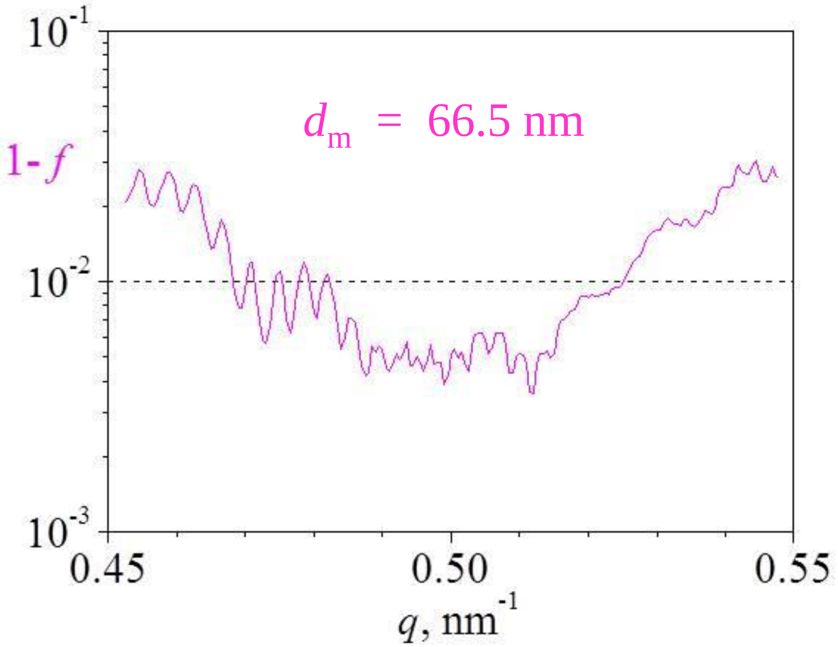


Multilayer-backed flippers can combine monochromatization of a polarized beam with flipping spins

Neutron mirror spin flippers: prospects

Supermirror-backed flippers for monochromatic beams



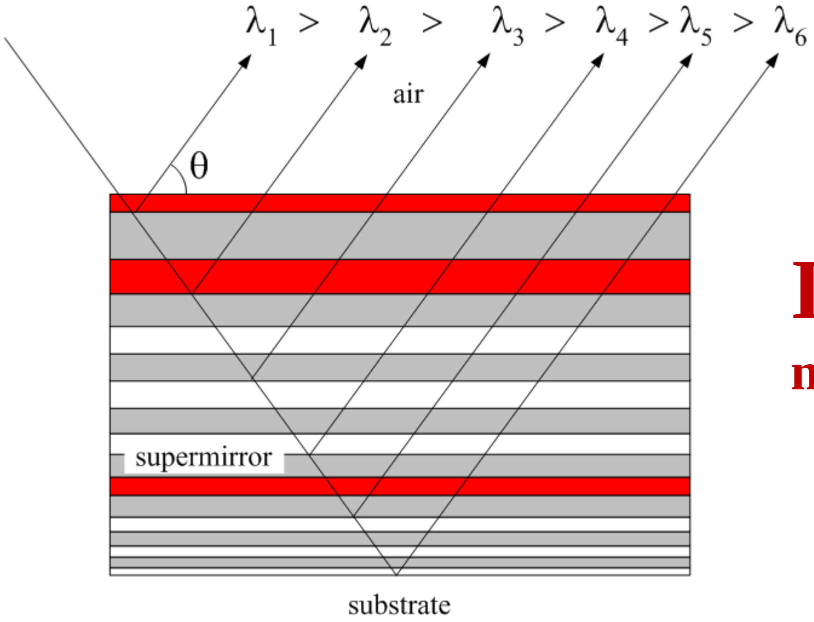


The NSF portion in the reflectivity calculated as a function of *q* for a supermirror-backed spin flipper structure (left).

To avoid undesirable loss in intensity, supermirror-backed flippers (R ≈ 1) can be used to flip spins of monochromatized neutrons

Neutron mirror spin flippers: prospects

Supermirror-based flippers for white beams



①

Inclusion of magnetic layers into a non-magnetic supermirror.

To flip spins of neutrons in the white beam, broadband supermirror-based flippers have been suggested

[N.K. Pleshanov, J. Phys.: Conf. Ser. 528 (2014) 012023. – Neutron spin manipulation optics: basic principles and possible applications.]

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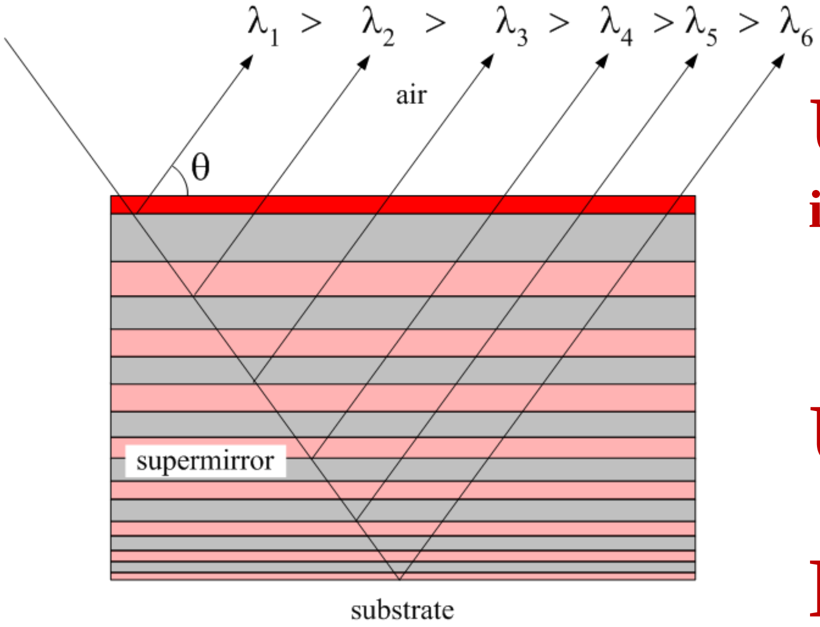
Supermirror-based flippers for white beams



2

Use of magnetic interlayers at each interface of a non-magnetic supermirror.

3

Use of layers with low magnetization.

Neutrons reflected at different depths, depending on q, spend the same total time in magnetic layers so that their spins rotate by the same angle (by π for the flippers).

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Neutron mirror spin flippers: prospects

Advantages of mirror flippers

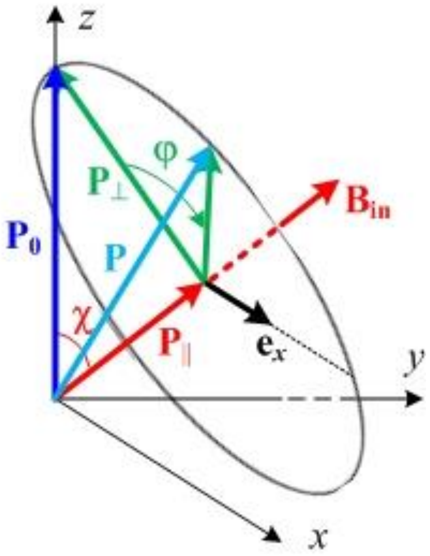
- ✓ **compactness** (miniaturization unlimited),
- ✓ **zero-field option** (no external fields are required, guide fields are optional),
- ✓ **multi-functionality** (handling beam spectrum, beam divergence and spin manipulations at the same time).

Neutron mirror spin turners: prospects

The mirror spin flipper is a particular case of mirror spin turners.

$$\mathbf{P}_0 = \mathbf{P}_{\|} + \mathbf{P}_{\perp}$$
$$\mathbf{P}_{\|} = P_0\cos\chi\ (0, \sin\chi, \cos\chi) = P_0\ (0, \sin\chi\cos\chi, \cos^2\chi)$$
$$\mathbf{P}_{\perp} = \mathbf{P}_0 - \mathbf{P}_{\mathbf{B}} = P_0\ (0, -\sin\chi\cos\chi, \sin^2\chi)$$

$$\mathbf{P}=\mathbf{P}_{\|}+P_{\perp}\sin\varphi\cdot\mathbf{e}_x+\mathbf{P}_{\perp}\cos\varphi=P_0[\sin\chi\sin\varphi,\sin\chi\cos\chi(1\text{-}\cos\varphi),\cos^2\chi+\cos\varphi\sin^2\chi]$$



The spin turner efficiency is the portion of neutrons reflected with spins parallel to a given direction (P):

$$\varepsilon(\Delta\varphi) = 1 - \sin^2\chi\ \sin^2(\Delta\varphi/2)$$

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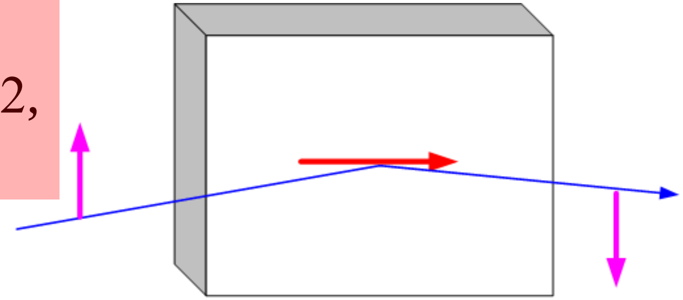
Neutron mirror spin turners: prospects

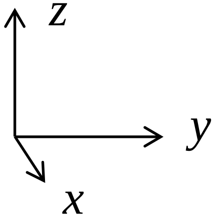
$\mathbf{P}_0 = (0,0,1)$

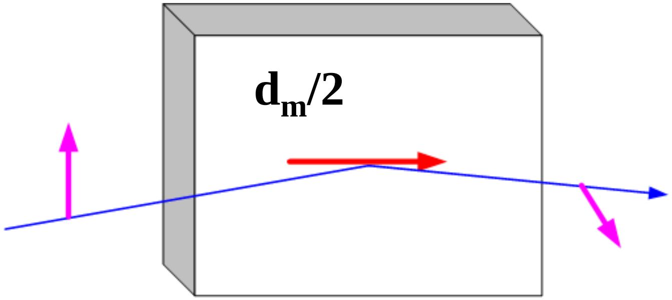
$\mathbf{P} = [\sin\chi\sin\varphi,\ \sin\chi\cos\chi(1-\cos\varphi),\ \cos^2\chi+\cos\varphi\sin^2\chi]$

$P_z = -1$:
$\chi = \pm\,\pi/2$,
$\varphi = \pm\,\pi$



π-turner

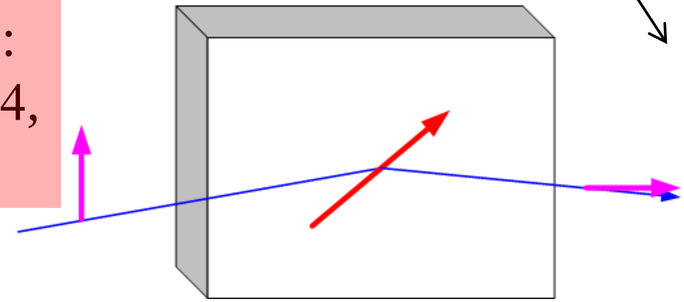




π/2-turner
(out-of-plane)

$P_x = \pm 1$:
$\chi = \pm\,\pi/2$,
$\varphi = \mp\pi/2$

$P_y = \pm 1$:
$\chi = \pm\,\pi/4$,
$\varphi = \pm\,\pi$



π/2-turner
(in-plane)

The mirror spin flipper is a particular case of mirror spin turners.

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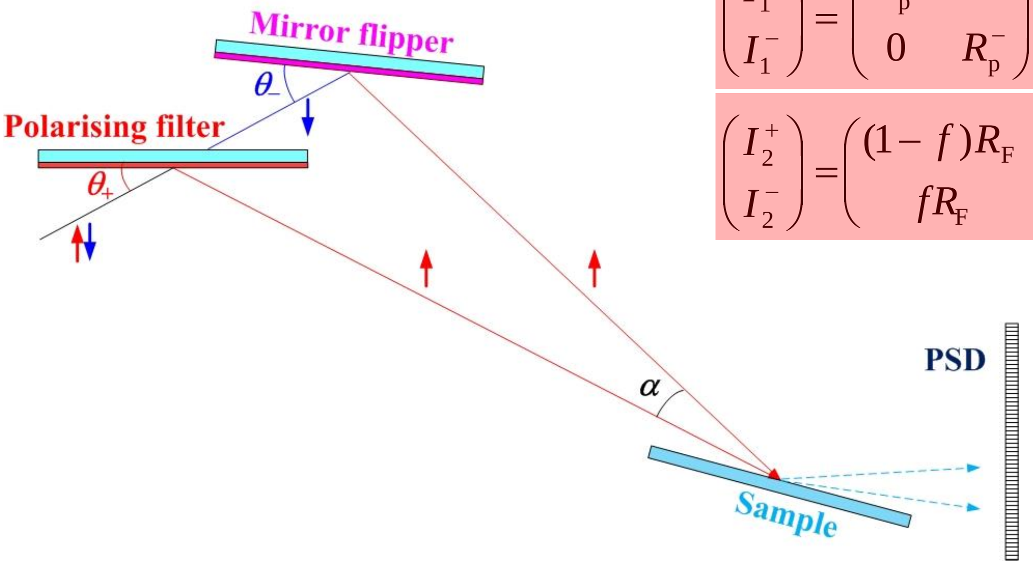
Hyperpolarizer for a reflectometer with a monochromatic beam



$$\begin{pmatrix} I_1^+ \\ I_1^- \end{pmatrix} = \begin{pmatrix} R_\mathrm{p}^+ & 0 \\ 0 & R_\mathrm{p}^- \end{pmatrix} \begin{pmatrix} I_0/2 \\ I_0/2 \end{pmatrix} = \frac{I_0}{2} \begin{pmatrix} R_\mathrm{p}^+ \\ R_\mathrm{p}^- \end{pmatrix}$$

$$\begin{pmatrix} I_2^+ \\ I_2^- \end{pmatrix} = \begin{pmatrix} (1-f)R_\mathrm{F} & fR_\mathrm{F} \\ fR_\mathrm{F} & (1-f)R_\mathrm{F} \end{pmatrix} \begin{pmatrix} (1-R_\mathrm{p}^+)T_s & 0 \\ 0 & (1-R_\mathrm{p}^-)T_s \end{pmatrix} \begin{pmatrix} I_0/2 \\ I_0/2 \end{pmatrix}$$

$$I_1 = I_0(R_\mathrm{p}^+ + R_\mathrm{p}^-)/2 \qquad P_1 = P_p$$

$$I_2 = I_0 R_\mathrm{F} T_s (2 - R_\mathrm{p}^+ - R_\mathrm{p}^-)/2$$

$$P_2 = P_\mathrm{p} \frac{2f-1}{2/(R_\mathrm{p}^+ + R_\mathrm{p}^-) - 1}$$

$$G_h = (I_1 + I_2)/I_1 = 1 + R_\mathrm{F} T_s [2/(R_\mathrm{p}^+ + R_\mathrm{p}^-) - 1]$$

Scheme of a hyperpolarizer for a monochromatic beam reflectometer; α >> Δθ is the angle between the beams formed by the polarizing filter and the mirror flipper .

R^+_p	R^-_p	T_s	R_F	f	P_1	P_2	G_h
0.9	0.01	0.8	0.9	0.975	0.978	0.776	1.862
0.9 {x2}	0.01 {x2}					0.854	
0.99	0.005	0.9	0.95	0.99	0.99	0.96	1.864
0.99 {x2}	0.005 {x2}					0.975	

POTENTIAL of NSO

Combining NSO elements, one can build compact devices, including devices for 3D-polarization and 3D-analysis, as well as spin manipulators and hyperpolarizers. NSO is directly applicable to developing such techniques as reflectometry with 3D-polarimetry, Neutron optical Spin Echo (NoSE), including compact NoSE and TOF NoSE schemes based on reflecting $\pi/2$- and π-turners, and precessors. With a progress in NSO, there may appear the possibility of developing polarimetry with VCN and even UCN, which is an equivalent of ellipsometry, but with extremely high sensitivity to surface magnetism.

SUMMARY

- A neutron mirror spin flipper was tested, its efficiency was found to be 97.5±0.5%.
- A method for measuring the efficiency of neutron mirror flippers was developed.
- Prospects in improving and developing neutron mirror flippers were considered.
- Scheme of a hyperpolarizer for monochromatic beam mode reflectometers was described.

Preparation of the samples

V.P. Kharchenkov, N.G. Kolyvanova, V. Yu. Sukharev

Assistance in neutron measurements

V.G. Syromyatnikov

(PNPI, Gatchina, Russia)

Thanks for your attention!