Совещание по использованию рассеяния нейтронов
и синхротронного излучения в конденсированных средах

Эффект нейтронного гетеродинирования и быстрая кинетика нано-систем

Б.П. Топерверг

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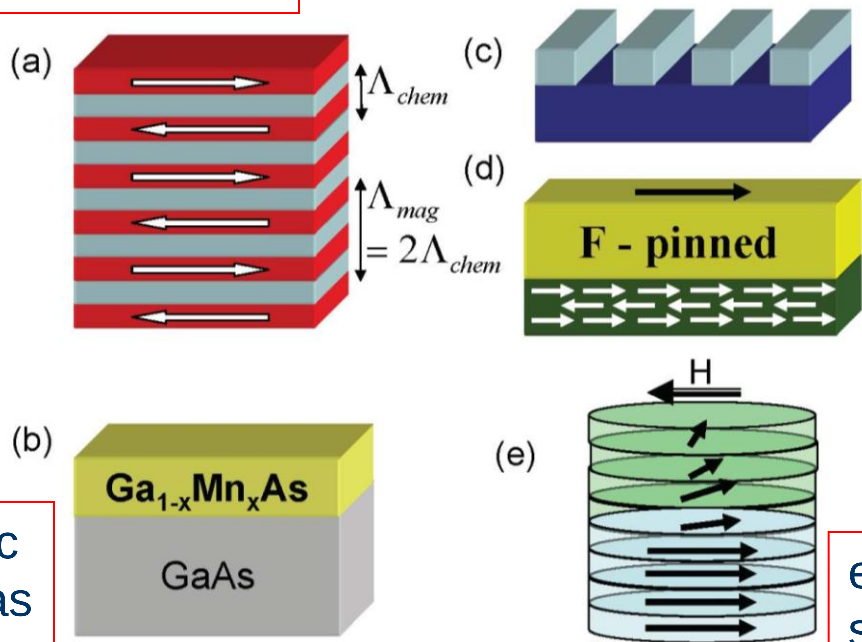
Collaborators

- Kirill Zhernenkov (CEA-Grenoble)
- Dima Gorkov (Ruhr Uni-Bochum)
- Sergey Klimko (LLB Saclay)
- Nicolas Martin (TU München & LLB)
- Louis-Pierre Regnault (CEA-Grenoble)
- Roland Gähler (ILL-Grenoble)
- Hartmut Zabel (Ruhr Uni-Bochum)

Where the spins are and what they are doing in nano-materials. Current subjects for reflectometry:

a) Exchange coupled bi-layers and superlattice with antiferromagnetic ordering (GMR and TMR systems)

c) Laterally patterned magnetic films, nano-wires,etc.



d) Ferromagnetic films on antiferromagnetic substrates with Exchange bias through common interfaces

b) Dilute magnetic semiconductors as spin-injectors in semiconductor heterostructures

e) Spring magnets: soft magnetic layer exchange coupled to a magnetically hard layer (spin valves)

Also: Superconducting films, polymer films, membranes, etc

Recent Review Articles

H. Zabel, K. Theis-Bröhl, B.P. Toperverg,

"Polarized neutron reflectivity and scattering of magnetic nanostructures and spintronic materials"

Handbook of Magnetism and Advanced Magnetic Materials,
H. Kronmüller & S. Parkin (Eds.), NY, Wiley 2007, pp. 1237-1288

A. Remhof, A. Westphalen, K. Theis-Bröhl, J. Grabis, A. Nefedov, B. Toperverg, H. Zabel

"Magnetization Reversal Studies of Periodic Magnetic Arrays via Scattering Methods"

Springer Series in materials science 94, Springer-Verlag Berlin Heidelberg 2007 ***pp.65 - 97***

H.-J.C. Lauter, V. Lauter, B.P. Toperverg

"Reflectivity, Off-Specular Scattering, and GI-SAS: Neutrons"

Polymer Science: A Comprehensive Reference, Vol 2, pp. 411–432 (2012)
Matyjaszewski K & Möller M (eds.) Amsterdam: Elsevier BV

M.R. Fizsimmons & I.K. Schuller

"Neutron scattering – The key characterization tool for nanostructured magneic materials "

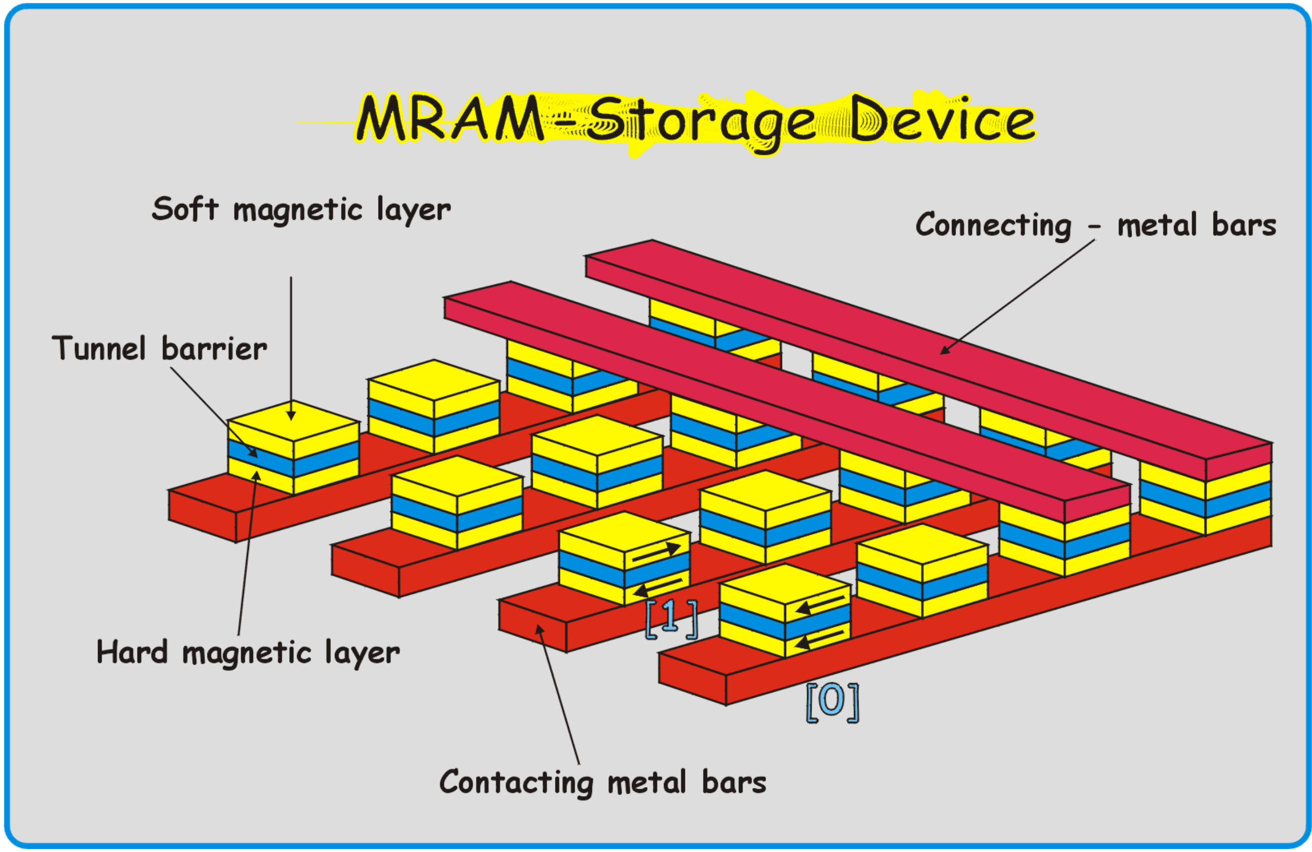
JMMM, 350 (2014) 199-208

To-day spintronic material application:
Magnetic Random Access Memory (MRAM)

- → "read-write" 2D arrays of spin valves
  - Writing with weak magnetic field
  - Reading with electric current

Neutrons:

Intrinsic mechanisms and rates of spin re-arrangement in nano-elements and their ensembles

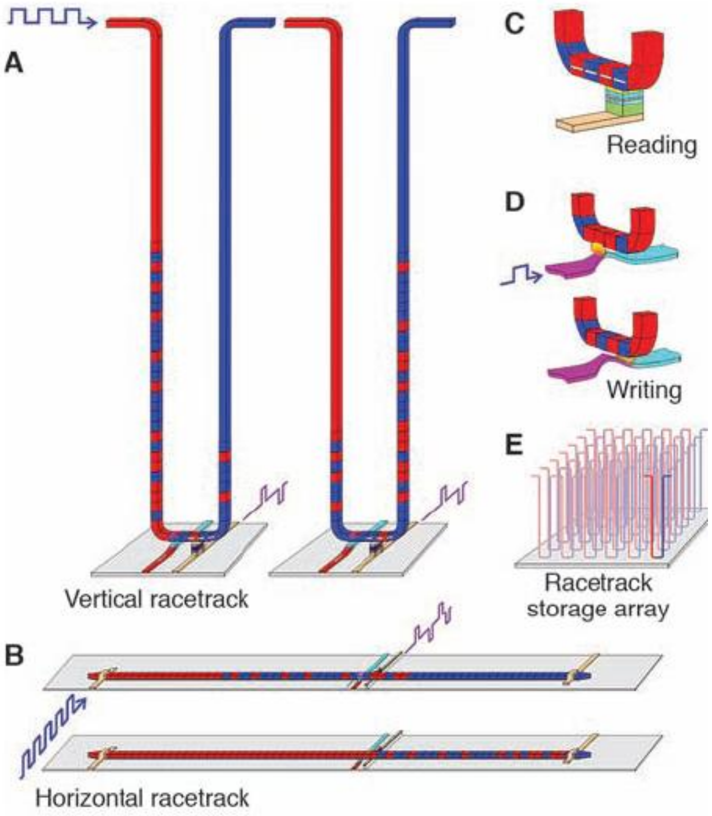


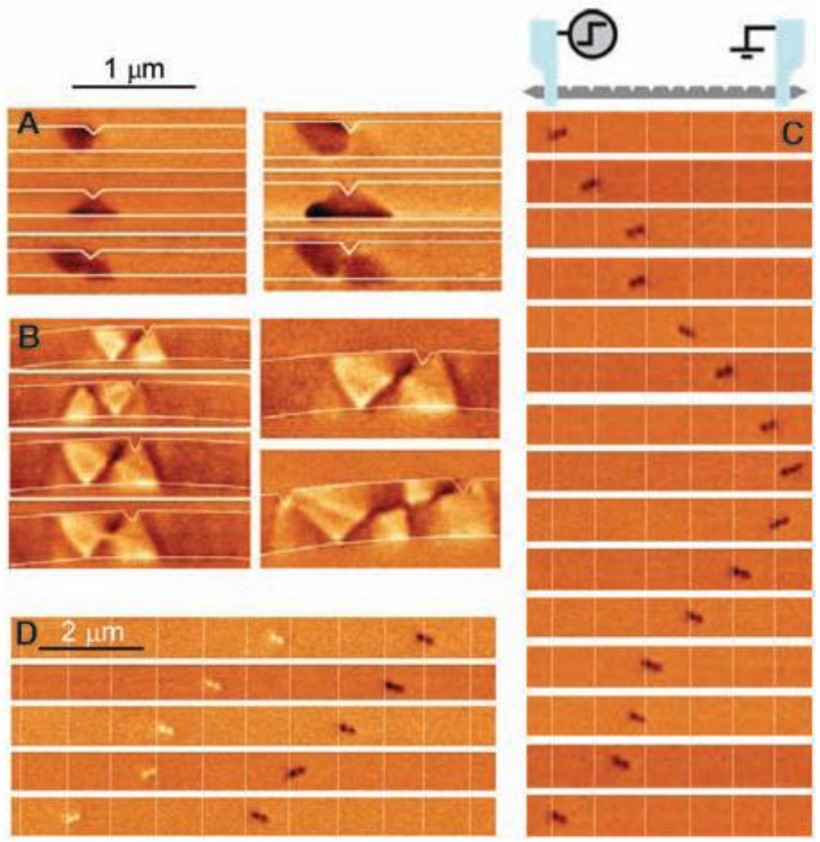
Emerging Challenges: non-linear spin dynamics & kinetics

Magnetic Domain-Wall Racetrack Memory

Stuart S. P. Parkin,* Masamitsu Hayashi, Luc Thomas

11 APRIL 2008 VOL 320 **SCIENCE**

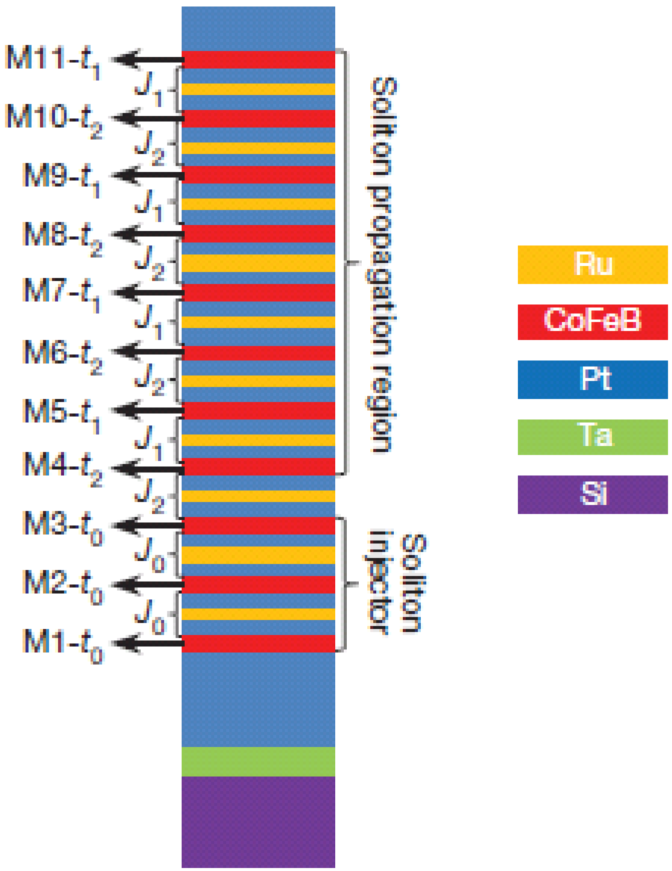


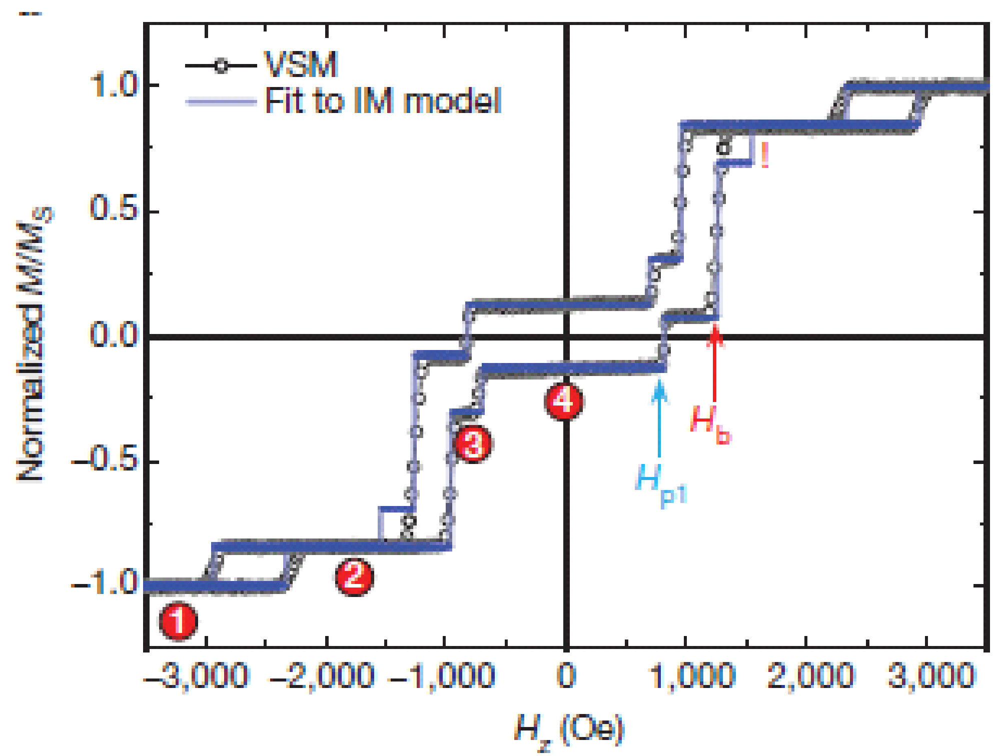


Magnetic ratchet for three-dimensional spintronic memory and logic

Reinoud Lavrijsen[1], Ji-Hyun Lee[1], Amalio Fernández-Pacheco[1], Dorothée C. M. C. Petit[1], Rhodri Mansell[1] & Russell P. Cowburn[1]

31 JANUARY 2013 | VOL 493 | NATURE | 649





Layer-by-layer *time* resolved magnetometry with PNR?

RAPID COMMUNICATIONS

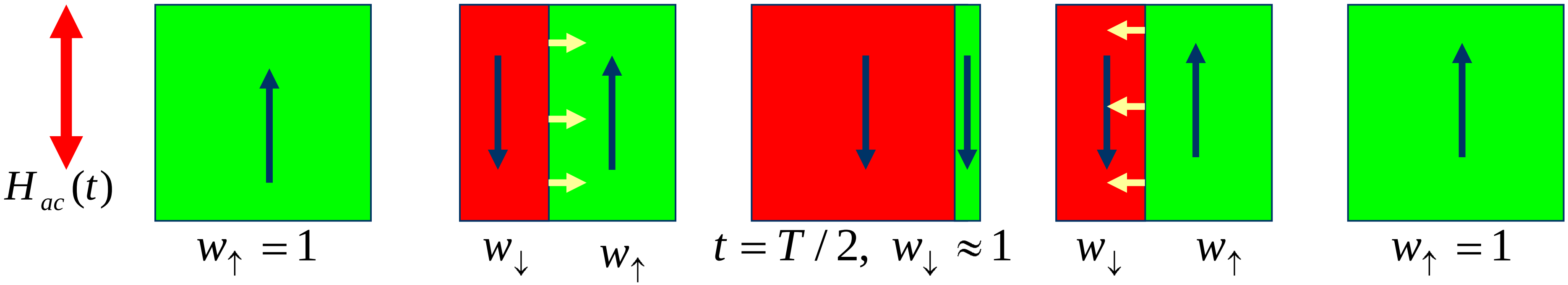
PHYSICAL REVIEW B **88**, 020401(R) (2013)

Frequency dependence of magnetization reversal in thin Fe(100) films

K. Zhernenkov,[1,*] D. Gorkov,[1] B. P. Toperverg,[1,2] and H. Zabel[1]

[1]*Lehrstuhl für Festkörperphysik/Experimentalphysik, Ruhr-Universität Bochum, 44780 Bochum, Germany*

[2]*Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia*



Reduced magnetization $m(t) = M(t)/M_{\text{sat}} = w_\uparrow - w_\downarrow = 1 - 2w_\downarrow(t)$,

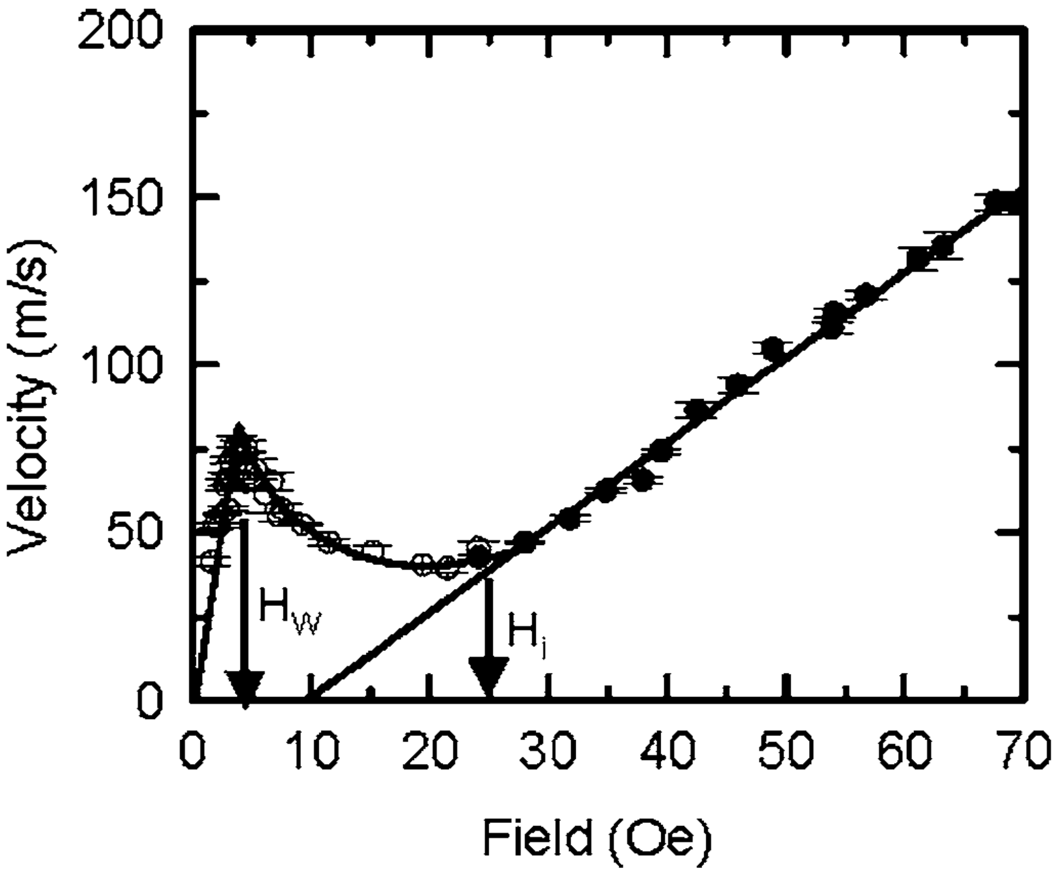
Surface fraction $w_\downarrow(t) = \frac{1}{l}\int_0^t dt'\, v(t')$ with negative magntization , l is domain size

$v(t) = \mu_{\text{DW}} H(t)$ is DW velocity (Landau & Lifshits,1935), μ_{DW} is DW mobility

If $H(t) = H_0 \sin(\omega \cdot t)$ then $w_\downarrow(t) = \mu_{\text{DW}} H_0 \frac{1-\cos(\omega \cdot t)}{\omega \cdot l}$,

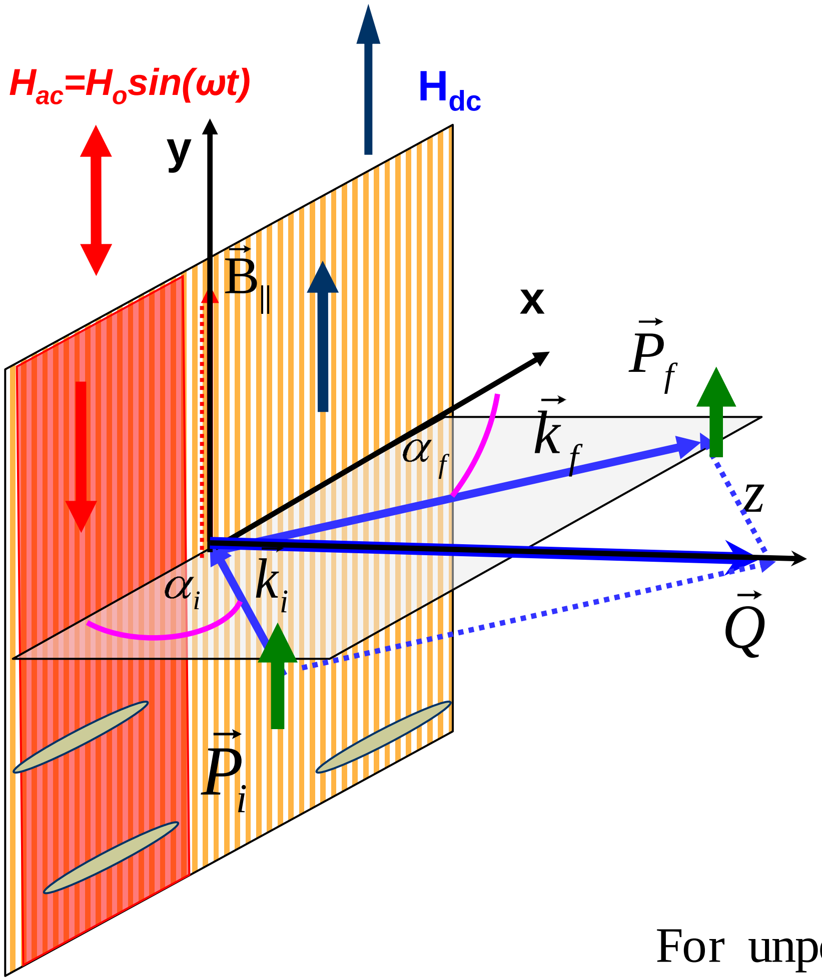
$m(t) = \overline{m} + \Delta m(t)$, where $\overline{m} = 1 - 2\mu_{\text{DW}} H_0 \frac{1}{\omega \cdot l}$, $\Delta m(t) = 2\mu_{\text{DW}} H_0 \frac{\cos(\omega \cdot t)}{\omega \cdot l}$

Landau-Lifshits regime vs Walker break down



Schyer & Walker, 1974

Reflection for polarization collinear with magnetization



Reflection coefficients (ideal polarization, no analysis)

$$R(\vec{b}) = \frac{1}{2} = \left\{ |R_+|^2 \cdot \left[1 + (\vec{P}\cdot\vec{b})\right] + |R_-|^2 \cdot \left[1 - (\vec{P}\cdot\vec{b})\right] \right\}$$

$R_\pm$ are reflection amplitudes for $\pm$ spin states

Surface average for time moment t:

$$R = w_\uparrow R(\vec{b}) + w_\downarrow R(-\vec{b}), \qquad \vec{b} = \vec{B}_\parallel / |\vec{B}_\parallel|$$

$$R^+(t) = \frac{1}{2} \left\{ |R_+|^2 \cdot \left[1 + m(t)\right] + |R_-|^2 \cdot \left[1 - m(t)\right] \right\}$$

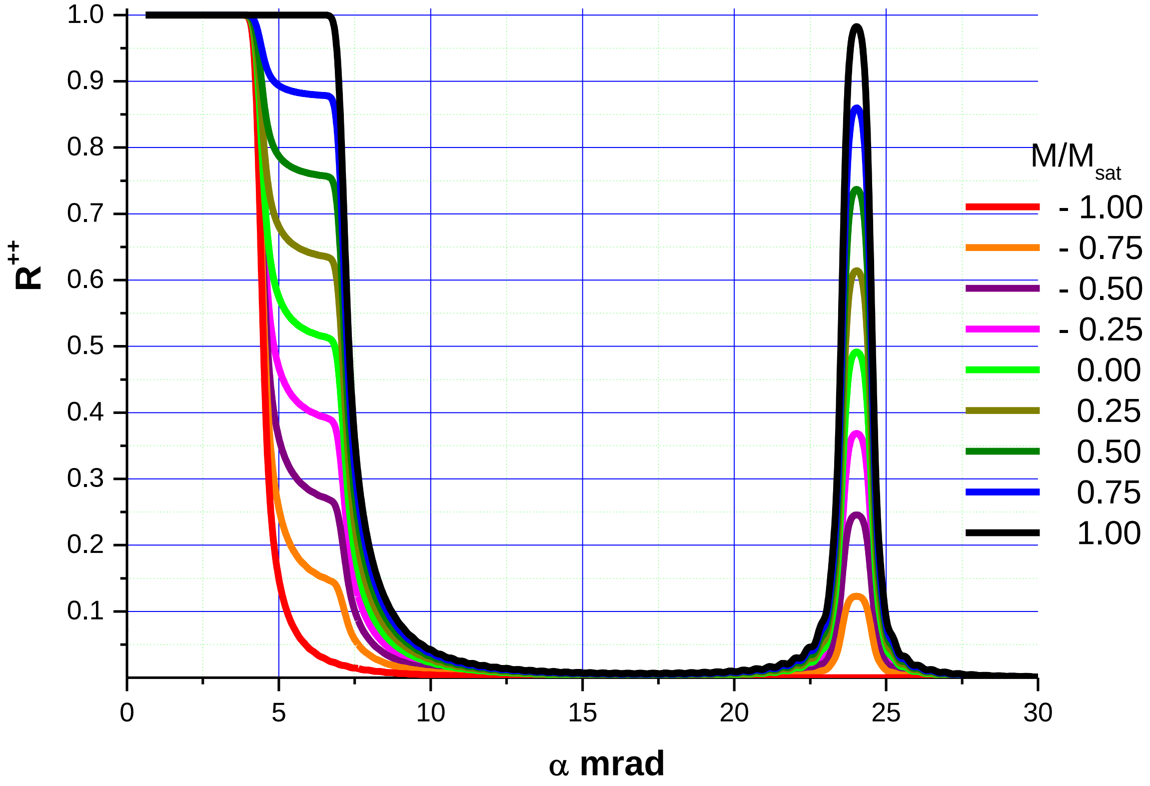
$$R^-(t) = \frac{1}{2} \left\{ |R_+|^2 \cdot \left[1 - m(t)\right] + |R_-|^2 \cdot \left[1 + m(t)\right] \right\}$$

For unpolarized beam $\quad R = \frac{1}{2} \left\{ |R_+|^2 + |R_-|^2 \right\}$ no effect

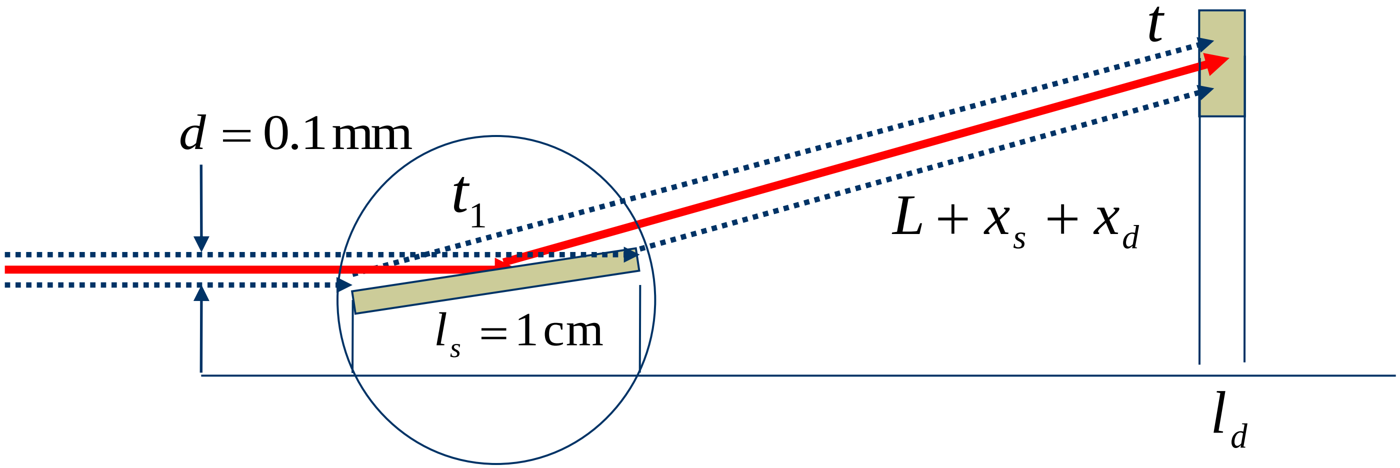
For ideal mirror, $\quad |R_+| = 1, \ |R_-| = 0, \quad$ and $H(t) = H_0 \sin(\omega \cdot t)$

the reflected intensity is modulated as: $\quad R = \frac{\mu_{DW} H_0}{\omega \cdot l} \left[1 - \cos(\omega \cdot t)\right]$

Simulated R^+ reflectivities for [Fe/Si]x50 polarizing Bragg mirror along hysteresis loop



Time modulation and smearing of PNR response



$$I(t) = R_0 + \frac{1}{l_s}\int_{-l_s/2}^{l_s/2} dx_s \frac{1}{l_d}\int_{-l_d/2}^{l_d/2} dx_d \int d\lambda \, R_p \cos\{\omega \cdot [t - (L + x_s + x_d)/v_n]\} \cdot W(\lambda)$$

$$v_n = 1/c\lambda, \quad c = (m_n/2\pi\hbar) = 0.2528 \cdot 10^{-5} \sec/(\mathrm{cm} \cdot \mathring{A}), \; t = \bar{t} + \Delta t, \; \bar{t} = c\lambda L,$$

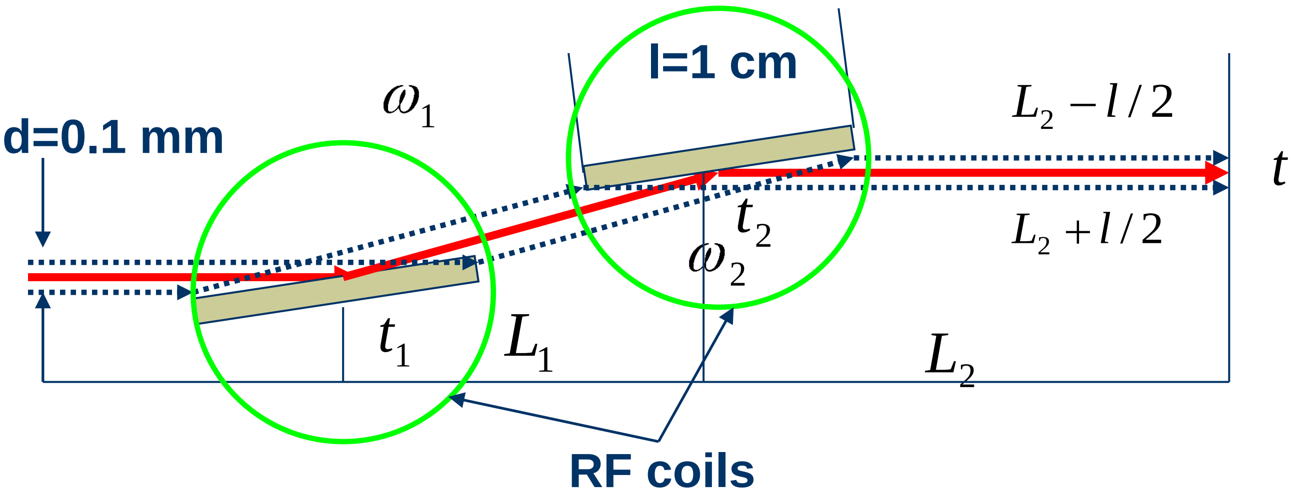
where v_n is neutron velocity, and $W(\lambda)$ is spectral function

$(\Delta t/\bar{t}) = \pm(l/L) \pm (\Delta\lambda/\lambda)$ uncertainty in time,

If $\lambda = 4\mathring{A}$, $L = 100\,\mathrm{cm}$, $l = 1\,\mathrm{cm}$, $\Delta\lambda/\lambda = 1\%$, then $\bar{t} \cong 1\,\mathrm{msec}$,

$\Delta t_l = c\lambda l \cong 10\mu\sec$, $\Delta t_\lambda \cong 10\mu\sec$, $\Delta t \cong 20\mu\sec$, $f = 50\,\mathrm{kHz}$

Time modulation with double reflection



$$I(t) \propto \frac{1}{l}\int_{l/2}^{l/2} dx \int d\lambda\, \mathrm{R}_2[t-(L_2+x)/v_n]\cdot \mathrm{R}_1[t-(L_1+L_2+x)/v_n]\cdot W_0(\lambda)$$

$$\mathrm{R}_1 = \mathrm{R}_0 + \mathrm{R}_\mathrm{P}\cos\{\omega_1[t-(\tau_x+\tau_2)]\}, \qquad \tau_x = x/v_n, \quad \tau_2 = L_2/v_n$$

$$\mathrm{R}_2 = \mathrm{R}_0 + \mathrm{R}_\mathrm{P}\cos\{\omega_2[t-(\tau_x+\tau_2+\tau_1)]\}, \qquad \tau_1 = L_1/v_n$$

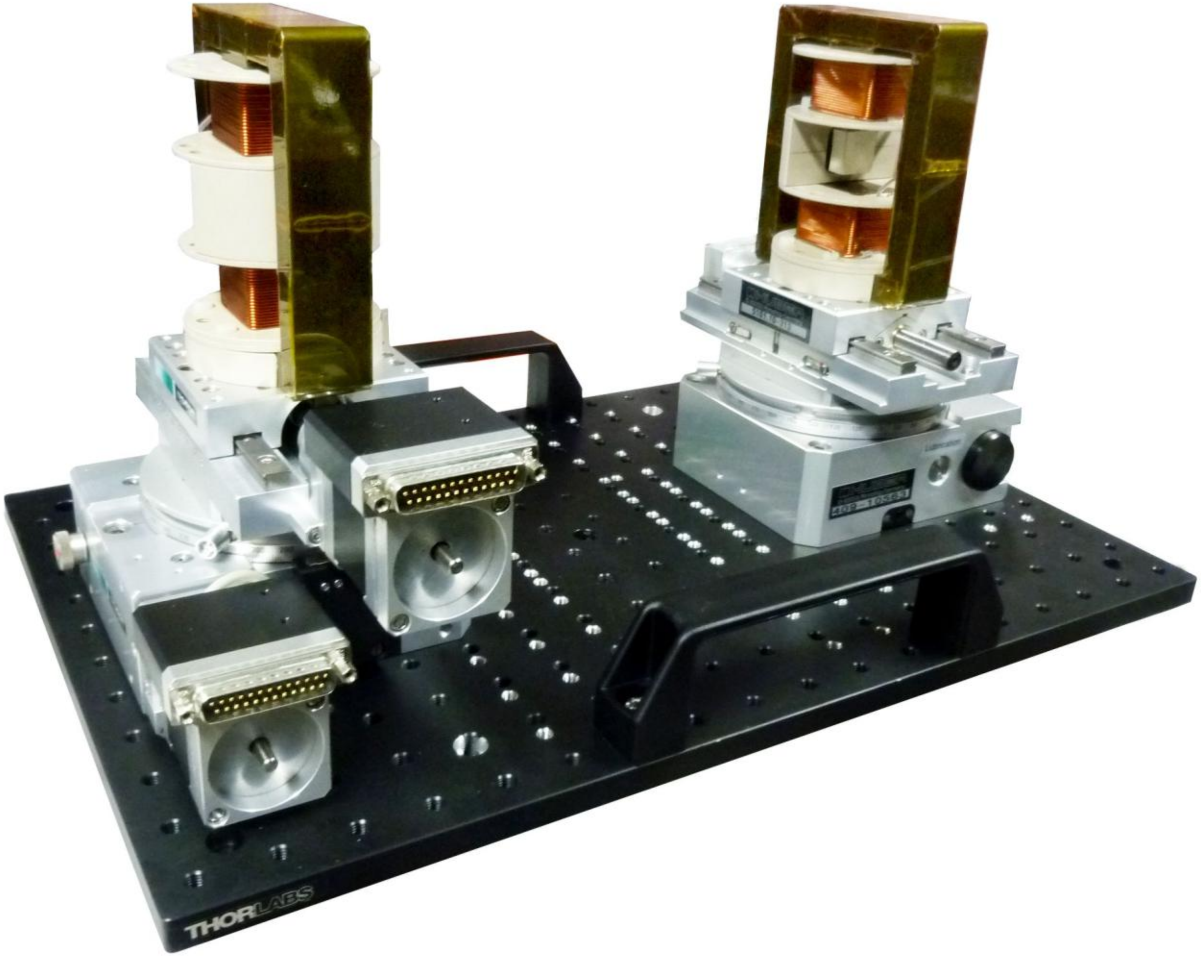
$$<\cos\varphi_1\cdot\cos\varphi_2> = \frac{1}{2}<\cos(\varphi_1-\varphi_2)+\cos(\varphi_1+\varphi_2)> \approx \frac{1}{2}<\cos(\varphi_1-\varphi_2)>$$

$$\varphi_1-\varphi_2 = \omega_\mathrm{H}\cdot(t-\tau_x) - [\omega_\mathrm{H}\cdot\tau_2 - \omega_1\tau_1] \approx \omega_\mathrm{H}\cdot t - \bar{\phi}$$

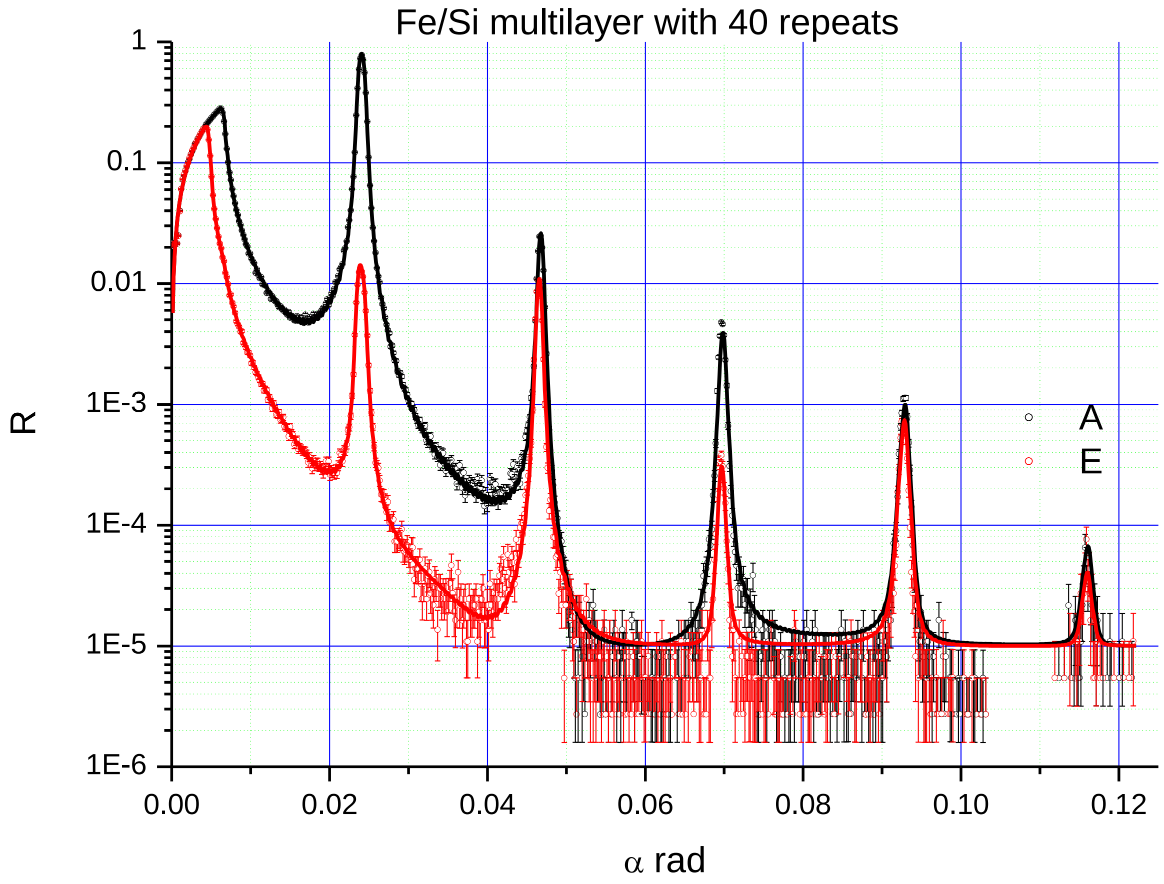
if heterodyne frequency $\omega_\mathrm{H} = \omega_1 - \omega_2$ is small $\omega_\mathrm{H}\tau_x << 1$,

$\bar{\phi} = (\omega_\mathrm{H} L_2 - \omega_1 L_1)/\bar{v}_n$ and at MIEZE conditions $|\,\omega_\mathrm{H}\tau_2 - \omega_1\tau_1\,| << \Delta\lambda/\bar{\lambda}$

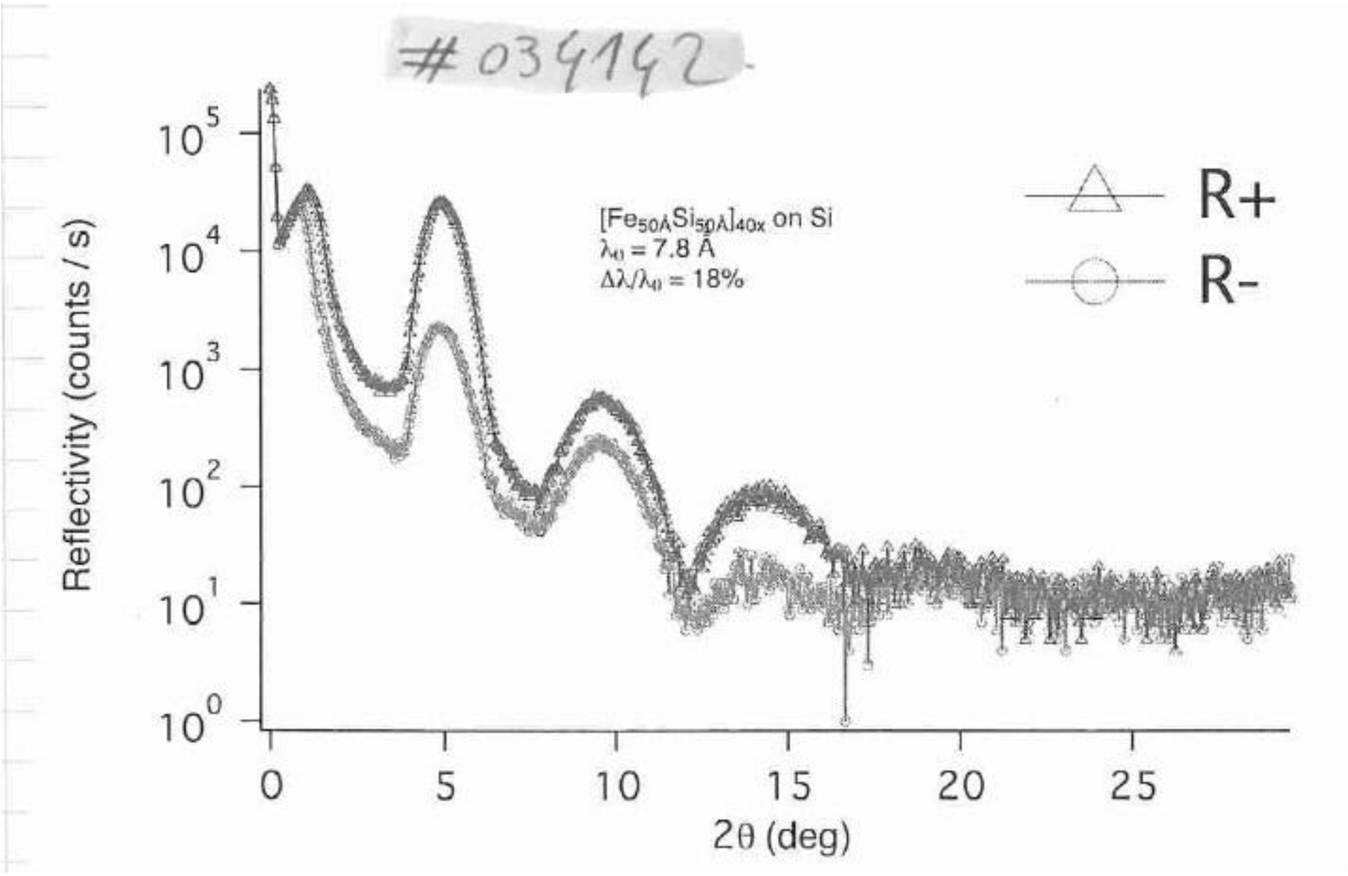
Heterodyne setup



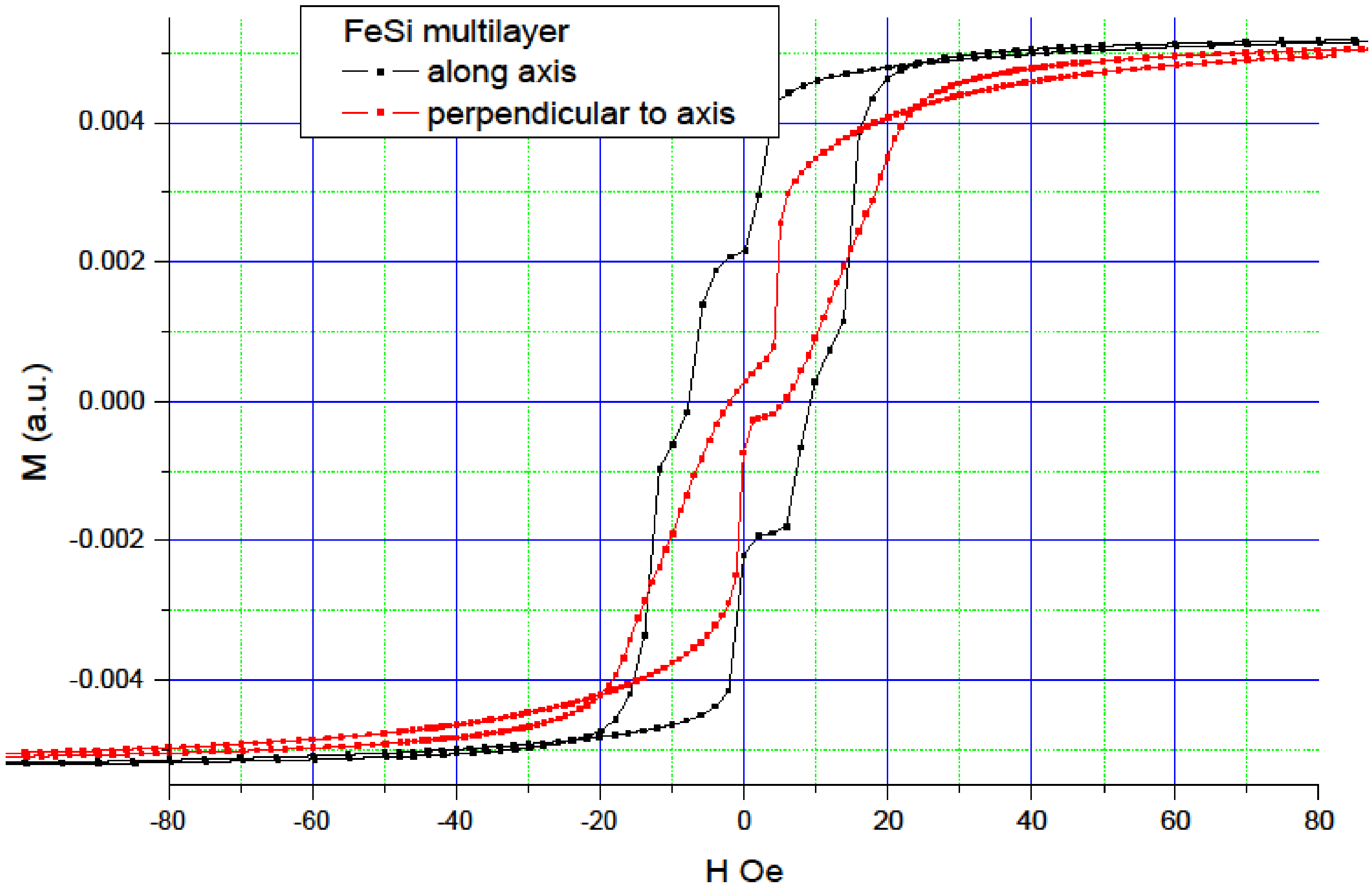
PNR data (SuperADAM) + fit



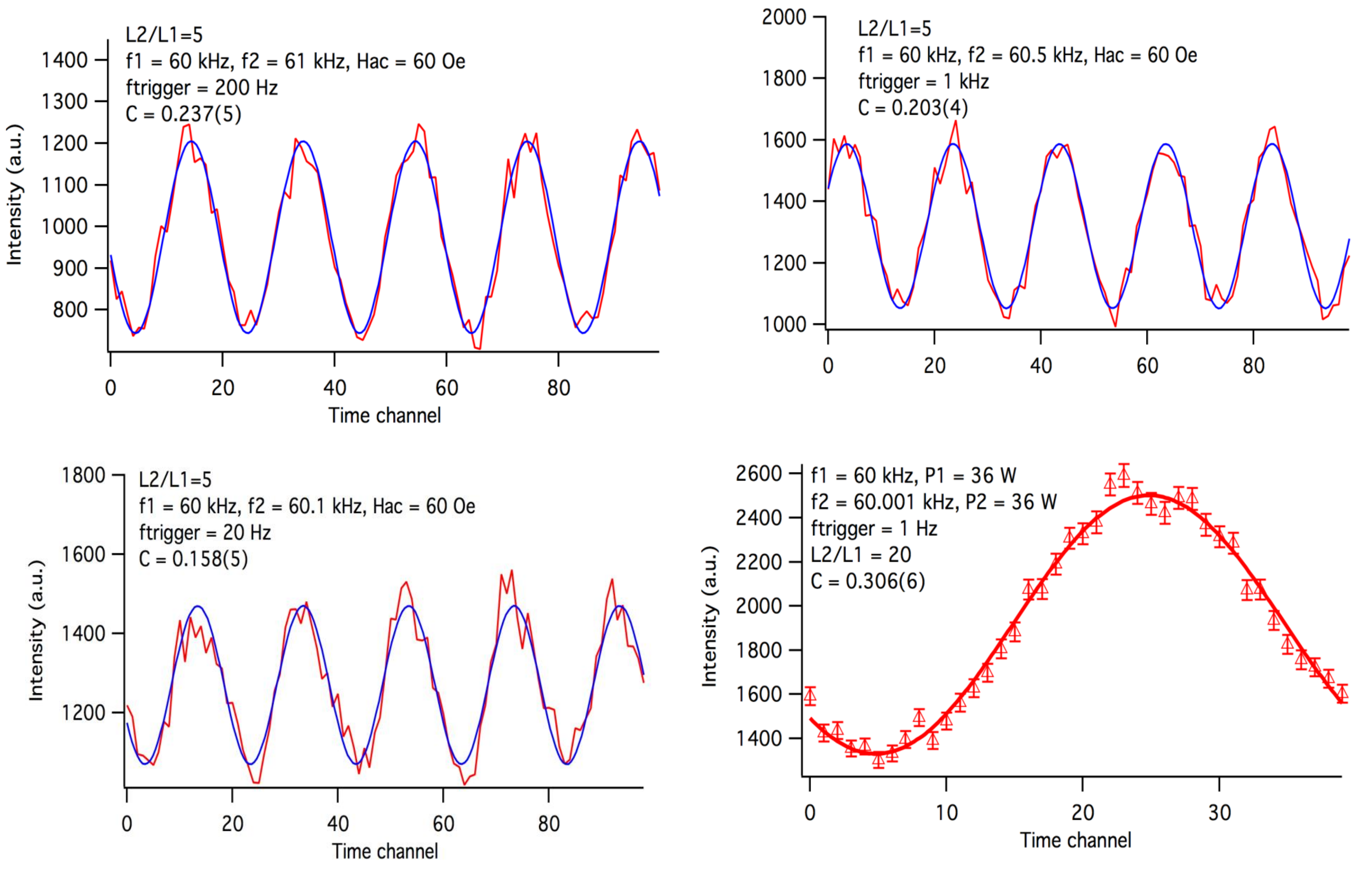
PNR at RESEDA



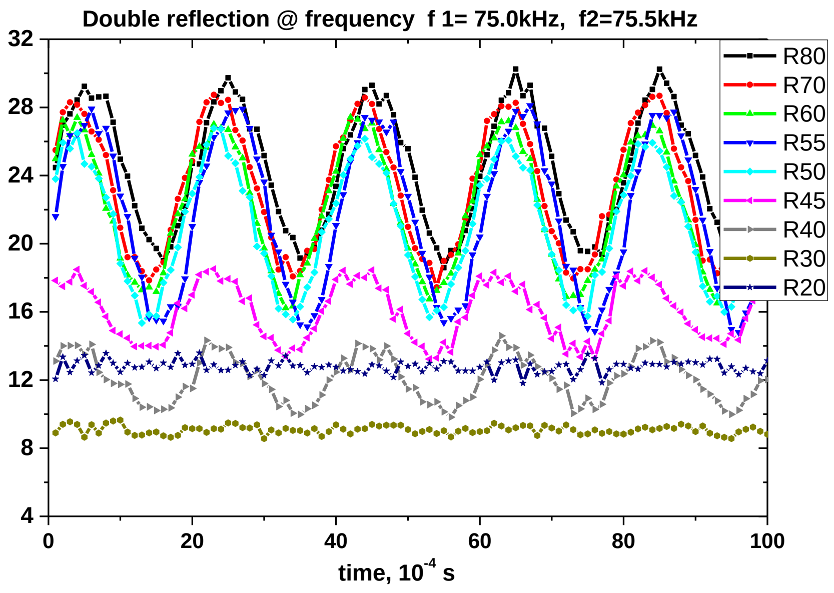
Hysteresis loop from periodic [FeSi]x40 multilayer

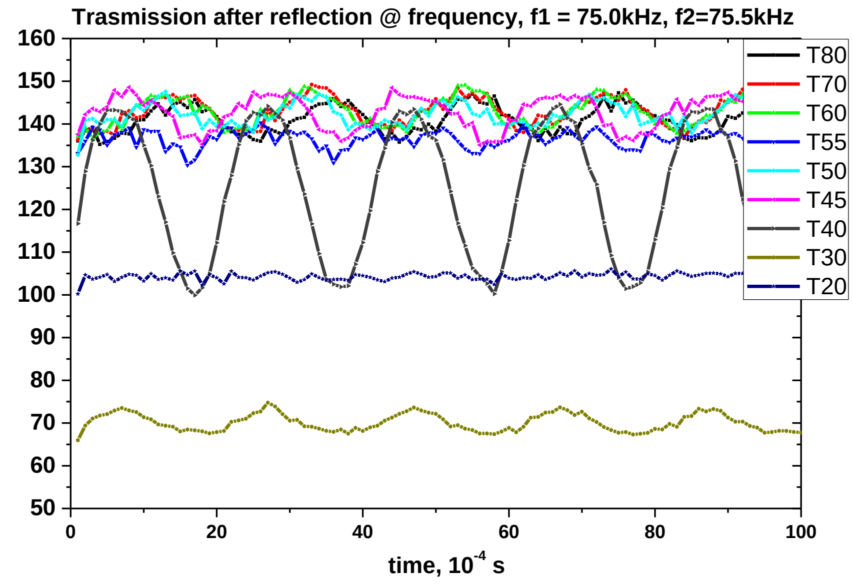


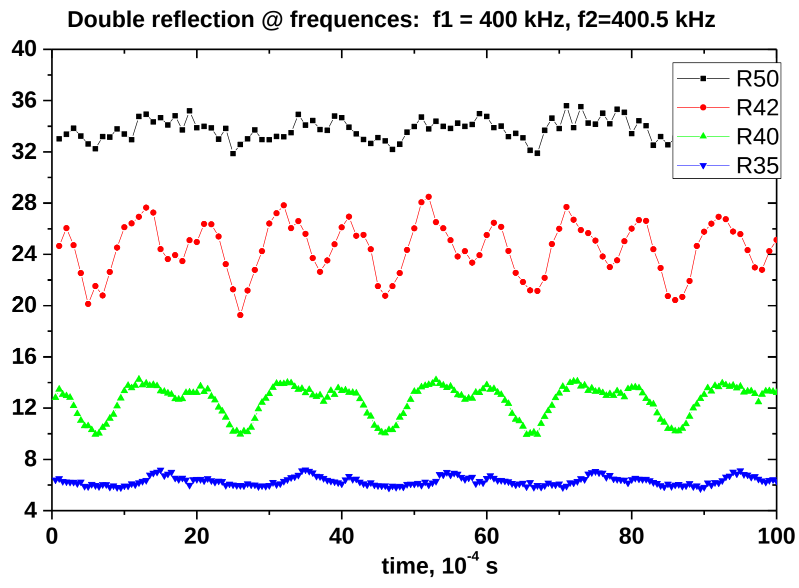
Heterodyne effect measured @ RESEDA (FRM2-Muenchen, 2014)

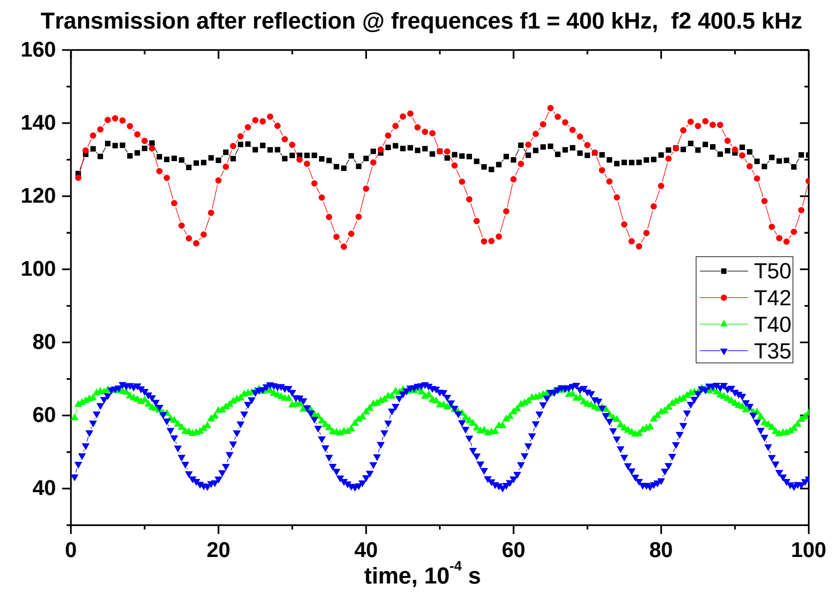


Heterodyne @ fH=500 Hz for frequences f=75 kHz & 0.4 MHz









Phase variation

$$\bar{\phi} = [(L_2 / L_1\} - (\omega_1 / \omega_{\mathrm{H}})](\omega_{\mathrm{H}} L_1 / \bar{v}_n),$$

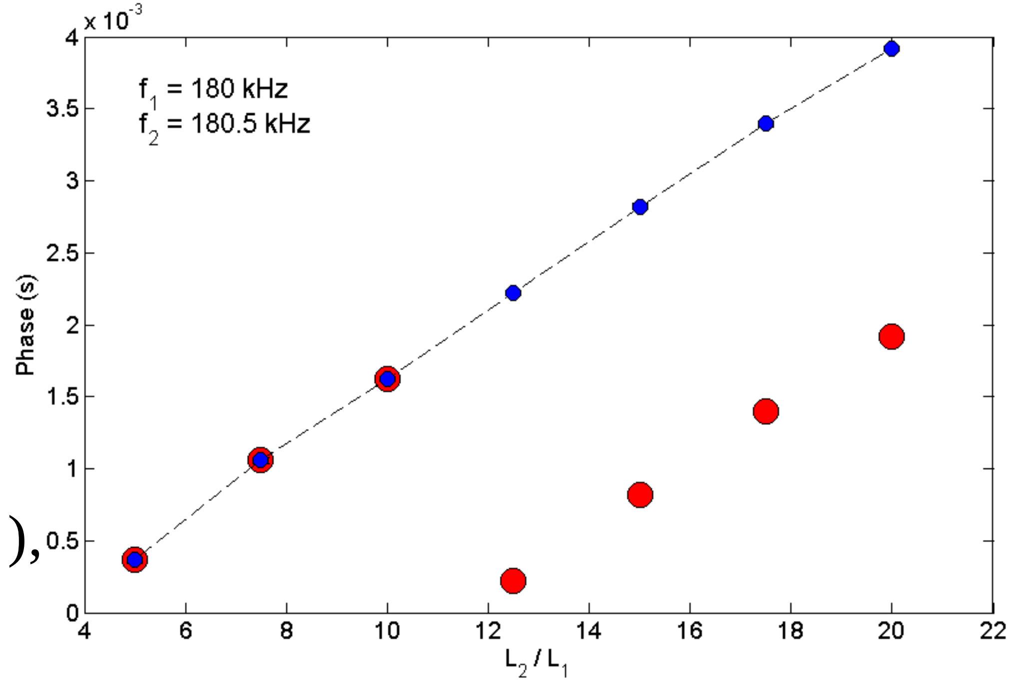
$$L_1 = 19\,\mathrm{cm},\ \lambda = 5.5\,\mathrm{A}$$

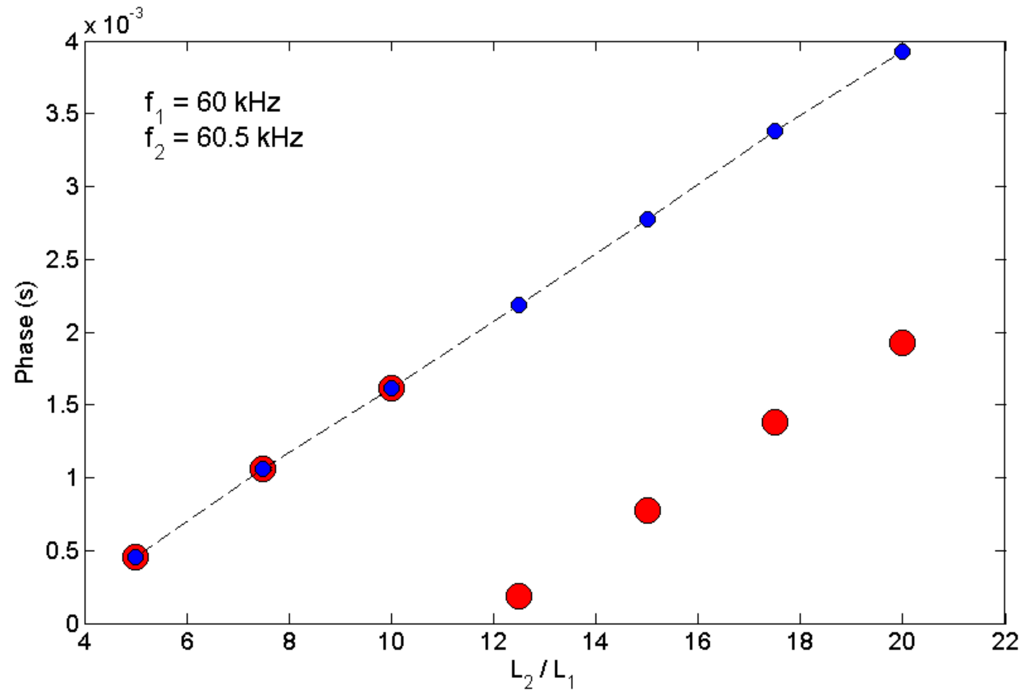
$$f_{\mathrm{H}} = 0.5\,\mathrm{kHz},\ f_1 = 60\,\mathrm{kHz},$$

$$(\omega_{\mathrm{H}} / \omega_1) = 120$$

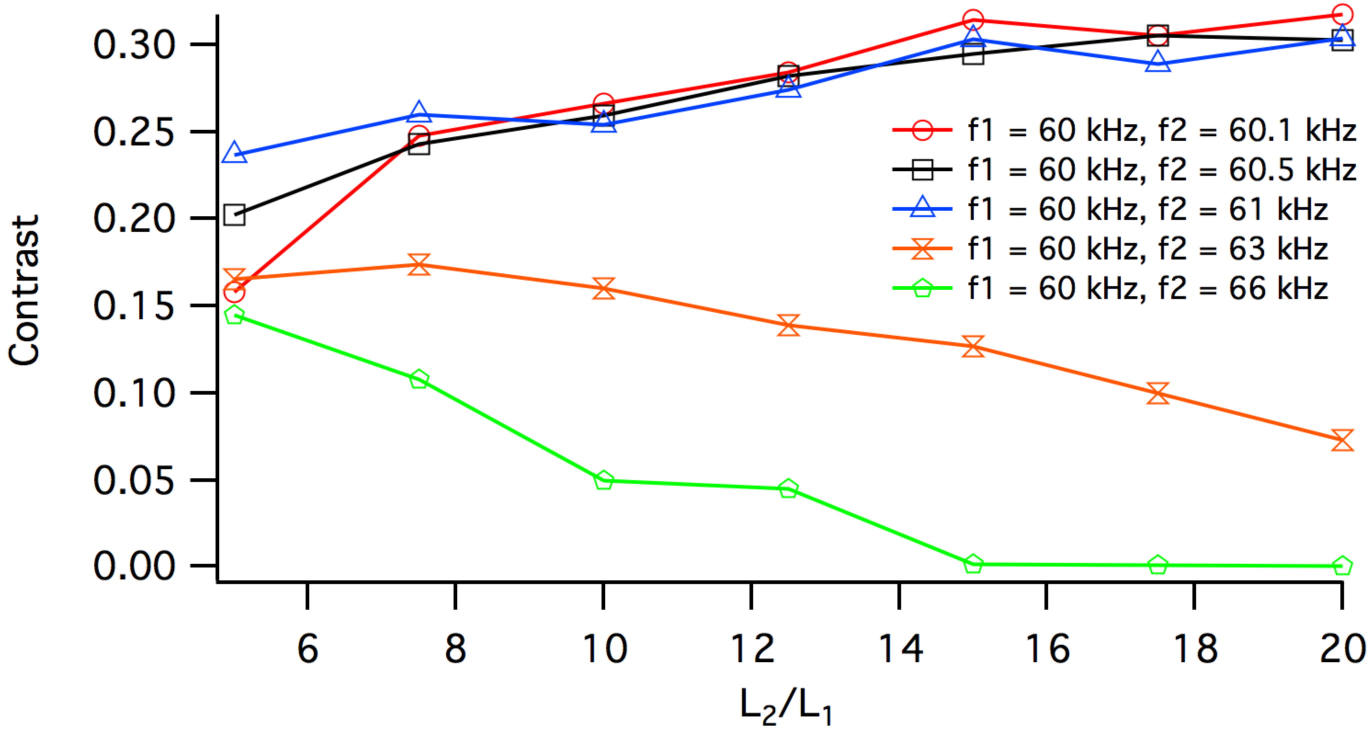
$$\bar{\phi} = 0.13 \cdot (L_2 / L_1\} - 5 \cdot \pi$$

$$(\Delta\lambda / \lambda) = 0.1$$

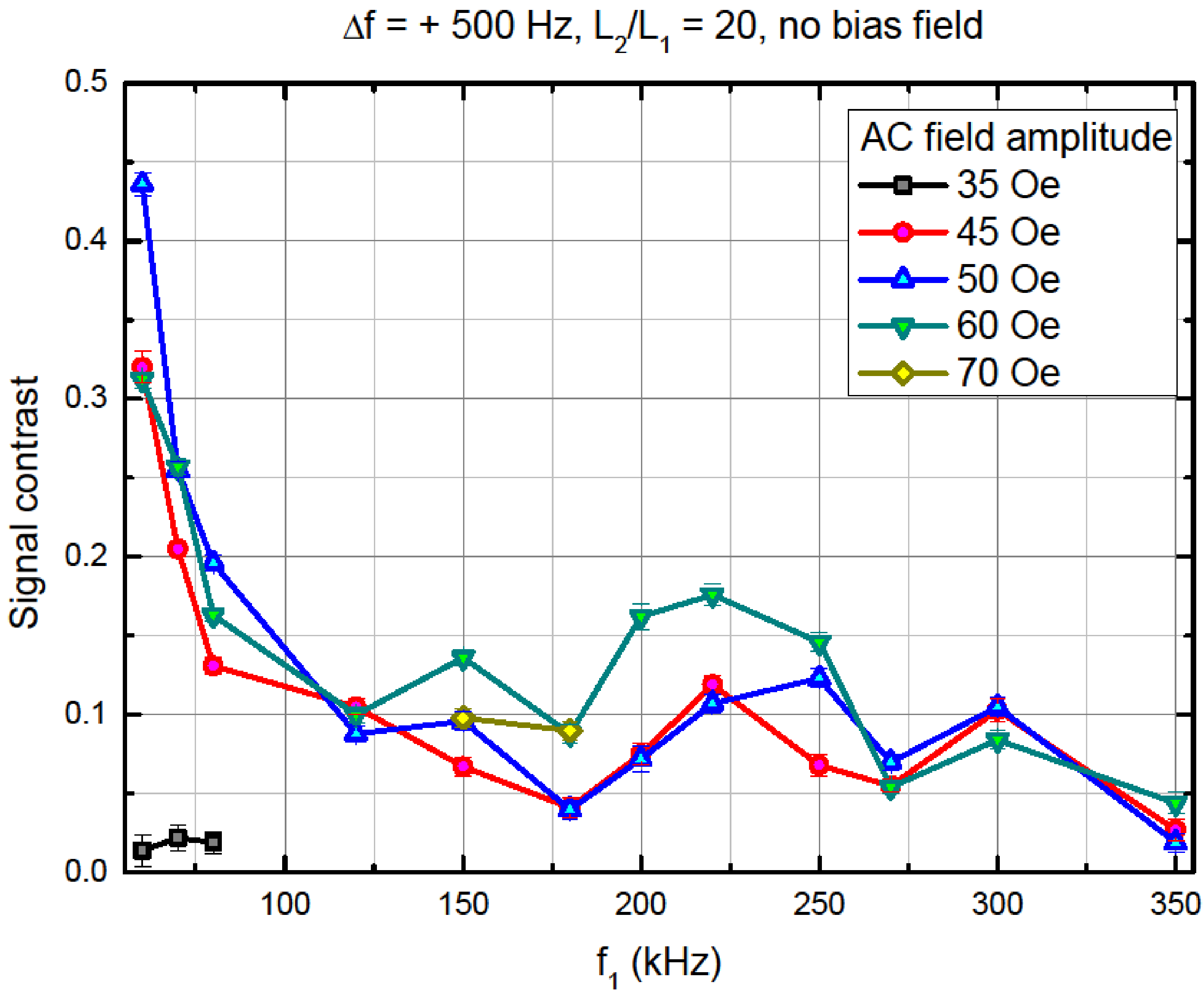




Heterodyne modulation contrast



Frequency scans at different ac amplitudes



Conclusions

Heterodyne effect is experimentally proven to work
with broad wavelength spread

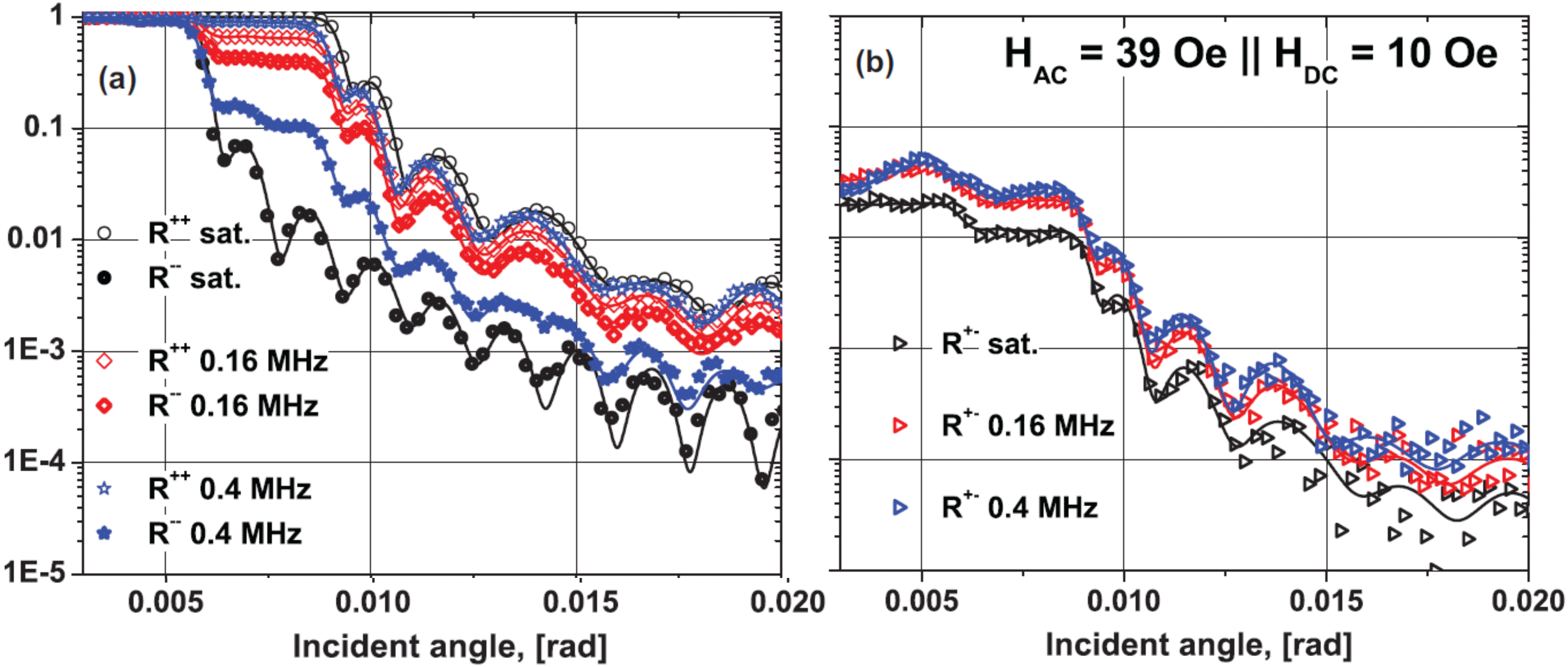
Prototype of the spectrometer fro TRAC PNR is built

Perspectives for development of e.g. spin-echo spectrometer
for inelastic PNR are suggested

PHYSICAL REVIEW B 88, 020401(R) (2013)

Frequency dependence of magnetization reversal in thin Fe(100) films

K. Zhernenkov,[1,*] D. Gorkov,[1] B. P. Toperverg,[1,2] and H. Zabel[1]



Integrated over time PNR from 100 nm Fe film in AC field parallel to DC field and one of easy axes

Frequency dependence of fitting parameters

$$\langle R^{++}\rangle_t = \frac{1}{4}\left|R_+(1+\bar{c}_\gamma) + R_-(1-\bar{c}_\gamma)\right|^2$$

$$\langle R^{--}\rangle = \frac{1}{4}\left|R_+(1-\bar{c}_\gamma) + R_-(1+\bar{c}_\gamma)\right|^2$$

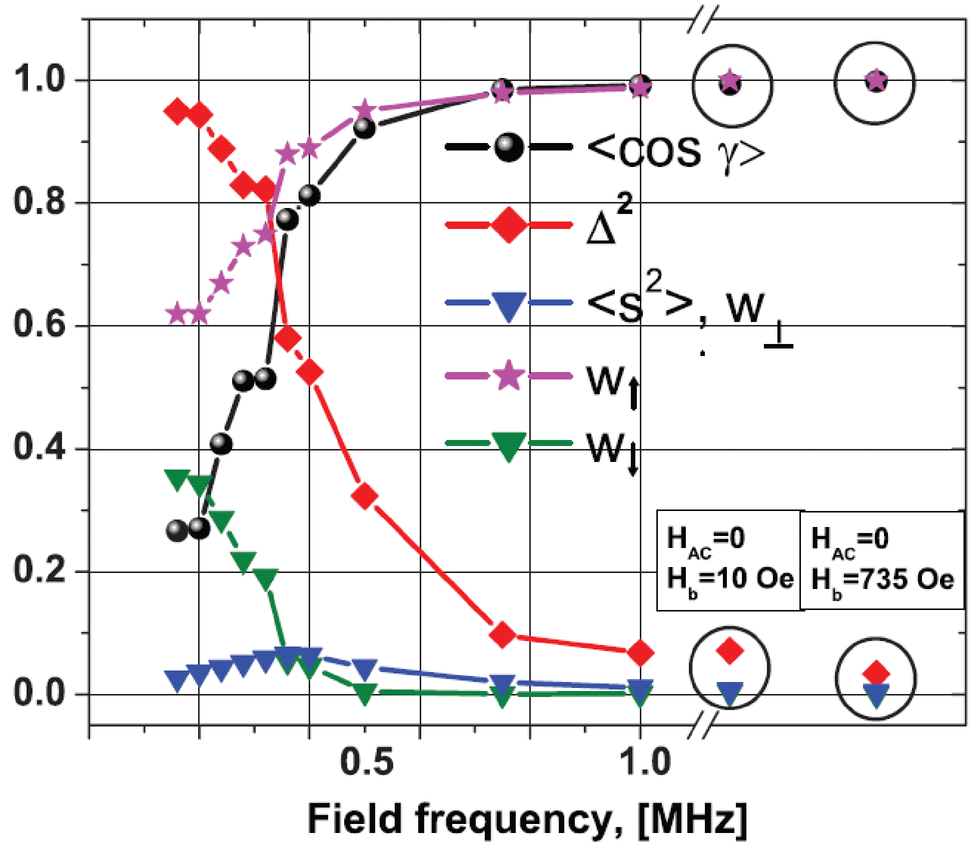
$$\langle R^{+-}\rangle = \langle R^{-+}\rangle = \frac{1}{4}\left|R_+ - R_-\right|^2 \overline{s_\gamma^2}$$

$$\bar{c}_\gamma = \frac{1}{T}\int_0^T dt \cos\gamma(t) = w_\uparrow - w_\downarrow$$

$$\overline{s_\gamma^2} = \frac{1}{T}\int_0^T dt \sin^2\gamma(t) = w_\perp$$

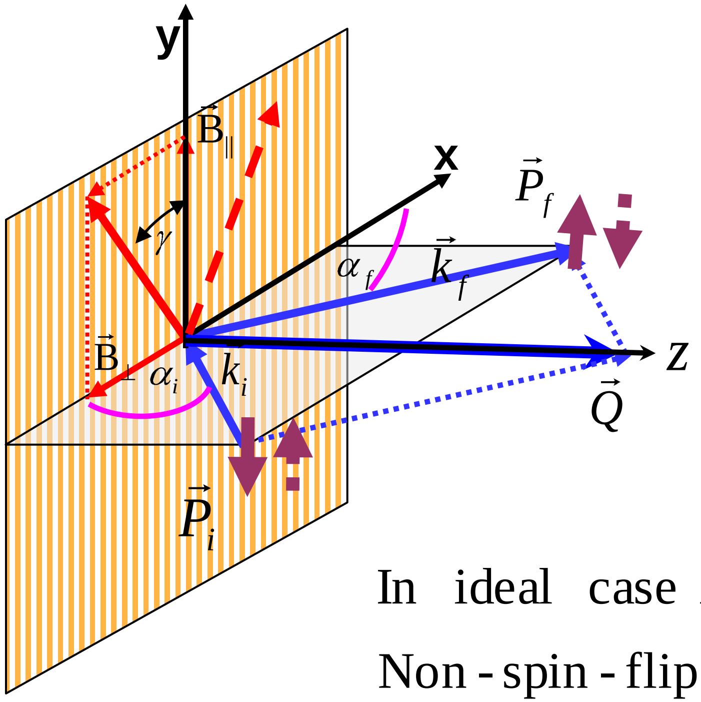
$$w_\uparrow - w_\downarrow + w_\perp = 1$$

$$\Delta = \langle \cos^2\gamma\rangle - \langle\cos\gamma\rangle^2 \text{ is dispersion}$$



@ 400 kHz crossover from 180º+ 90º DW to 180ºDW

General Equation for PNR with 1D polarization analysis



If $\vec{P}_{i,f} = \{0, \pm P_{i,f}, 0\}$, then $(\vec{P}_{i,f} \cdot \vec{b}) = \pm P_{i,f} \cos\gamma$,

$$R = \frac{1}{4}\left[\left(|R_+|^2 + |R_-|^2\right)\cdot\left(1 + P_i \cdot P_f \cdot \langle \cos^2\gamma \rangle\right)\right] + \frac{1}{4}\left(|R_+|^2 - |R_-|^2\right)\cdot\left(P_i + P_f\right)\cdot\langle \cos\gamma \rangle + \frac{1}{2}\mathrm{Re}\left(R_+^* R_-\right)\cdot P_i \cdot P_f \cdot \langle \sin^2\gamma \rangle$$

In ideal case $P_{i,f} = \pm 1$

Non-spin-flip reflectivities:

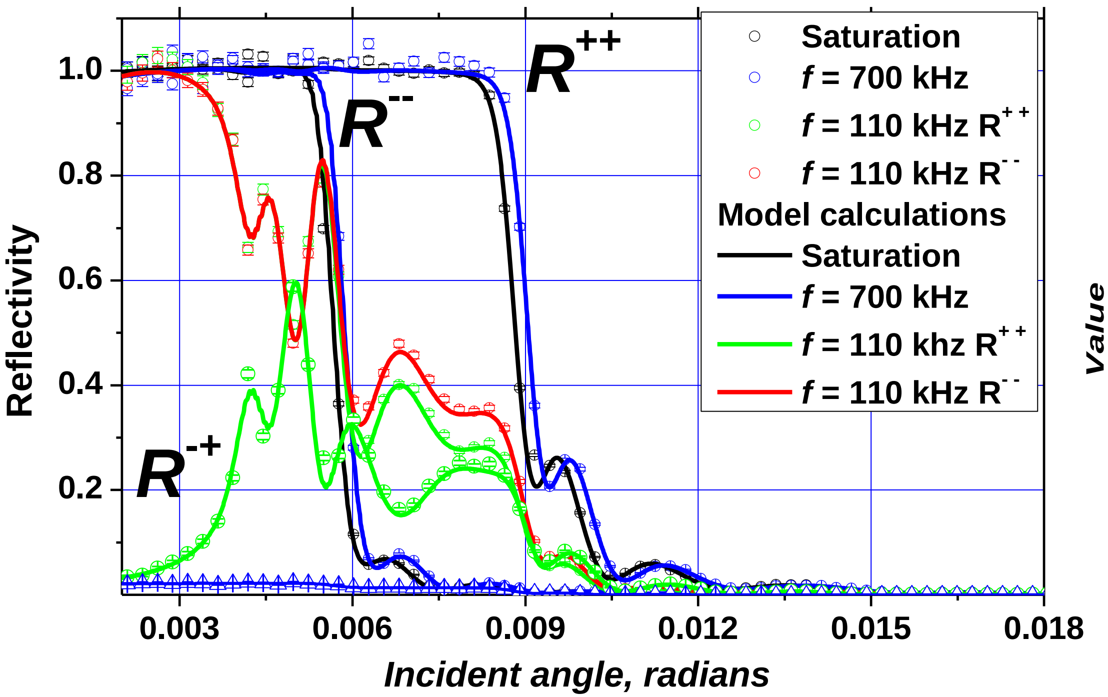
$$R^{\pm\pm} = \frac{1}{4} < \left| (1 \pm \cos\gamma)\cdot R^+ + (1 \mp \cos\gamma)\cdot R^- \right|^2 >$$

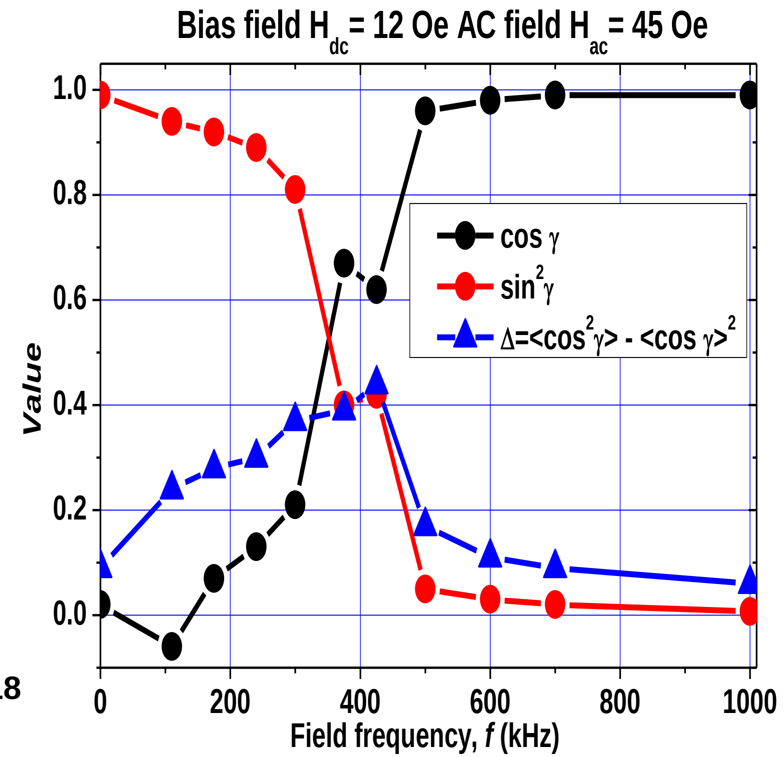
Spin-flip-reflectivities:

$$R^{\pm\mp} = \frac{1}{4} < \left| R^+ - R^- \right|^2 \cdot \sin^2\gamma >$$

where averaging runs over reflecting surface and time

Time averaged PNR for crossed DC and AC fields (with polarization parallel DC field)





K. Zhernenkov, D. Gorkov, B.P.Toperverg, H.Zabel, to be published