Neutron waveguide regime to study proximity effects at superconductor/ferromagnet interface

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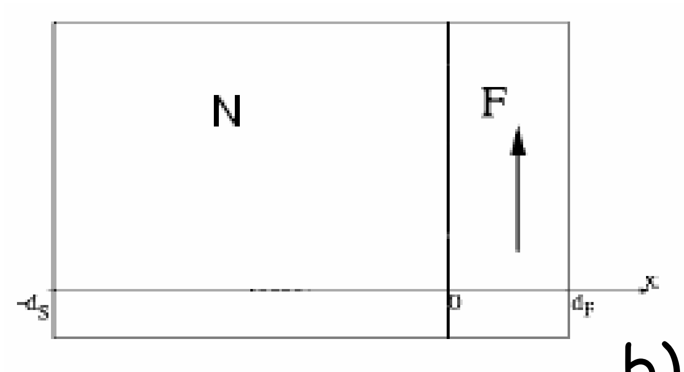
Proximity effects at superconductor/ferromagnet interface. Base models



$T>T_c$

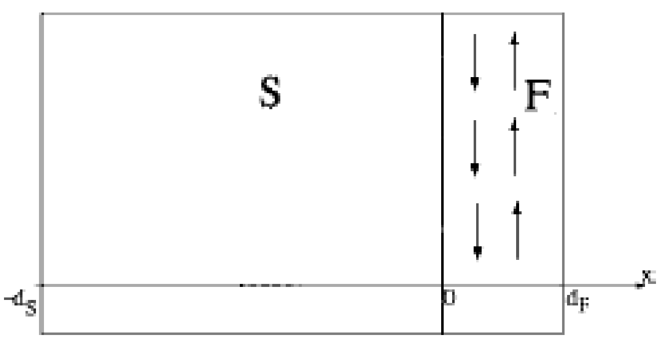
b) Inverse proximity effects

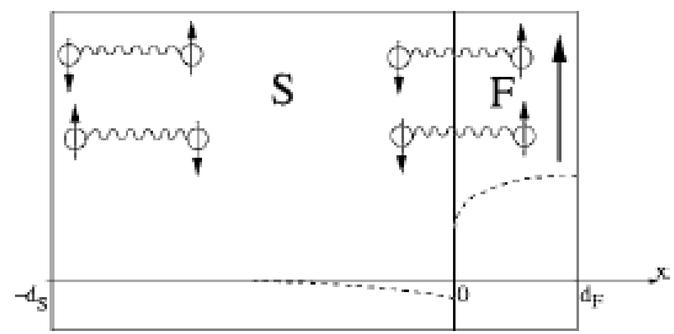
Bergeret, Volkov, Efetov (2004)

a) Domain structure

Buzdin, Bulaevskii (1988),
Bergeret et al (2000)

$T<T_c$



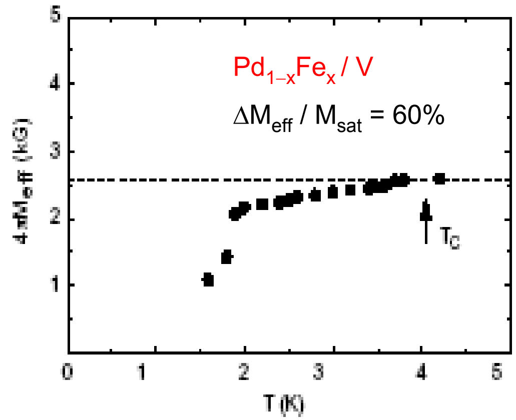


Dashed line – magnetization profile

Proximity effects. Base experiments

Ferromagnetic resonance

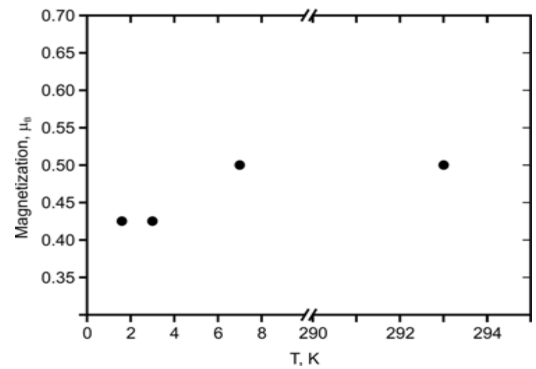
PdFe(~3nm)/V(40nm)
H = 2 kOe



Mühge et al. Physica C **296** (1998) 325
Garifullin et al. Appl. Magn. Res. **22** (2002) 439

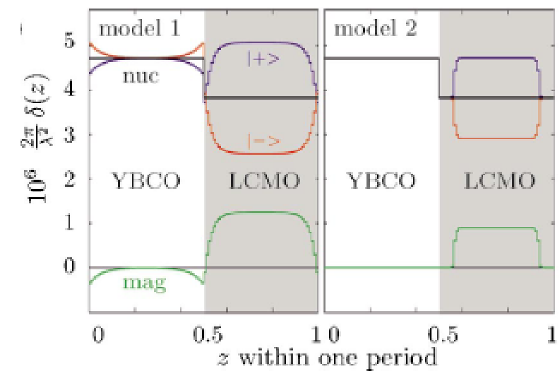
Polarized neutron reflectometry

V(40nm)/[Fe(5nm)/V(5nm)]$_{10}$
H = 0.7 kOe



Aksenov et al. Physica B **356** (2005) 9

[YBCO/LCMO]$_n$
H = 0.1 kOe

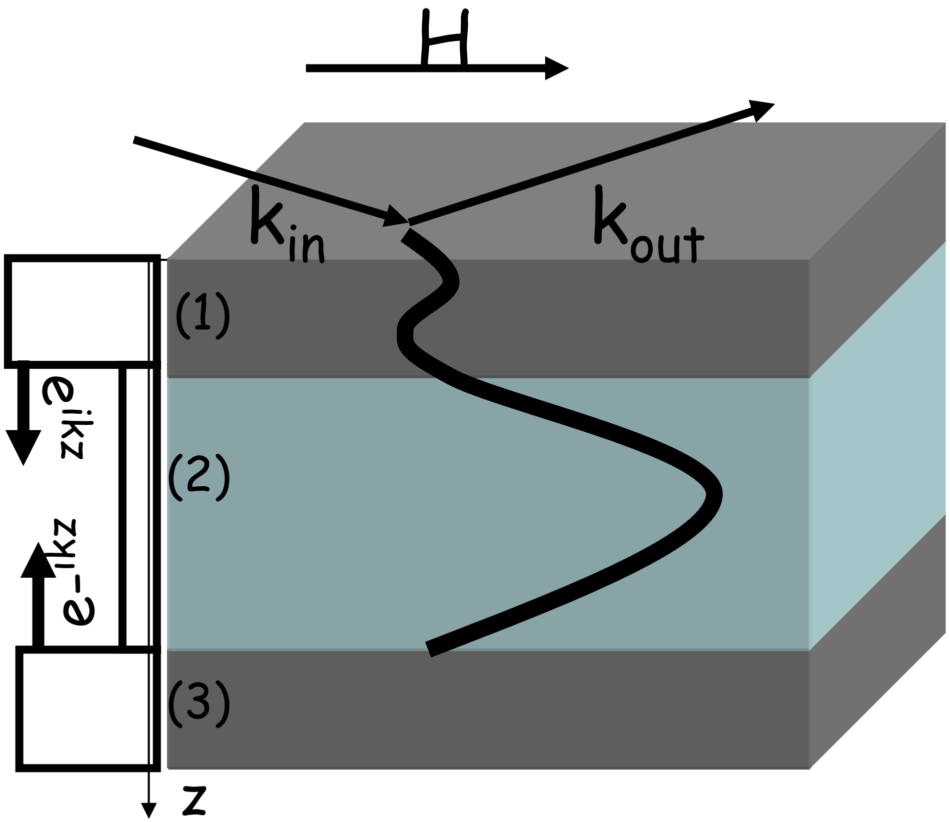


Stahn J. et al. P R B **71** (2005) 140509

PNR possibilities: $d_F \sim 10$ nm, $M_F \sim 1\ \mu_B$
Requierements for study effects: $d_F \sim 1$ nm, $M_F \sim 0.1\ \mu_B$

For single S/F interface enhancement of the PNR signal is required!

Resonant enhancement of neutron standing wave (waveguide mode)



$$\psi_2(z) \sim \frac{\left(e^{ik_2 z} + e^{ik_2(d_2 - z)} r_{23}\right)}{1 - r_{21} r_{23} e^{2ik_2 d_2}}$$

resonance condition
$\arg(r_{21}) + \arg(r_{23}) + 2(kd_2) = 2\pi n$,
$|r_{21}| = |r_{23}| = 1$

$\Psi(k,z) \to \infty$

Diffuse:

$I_d \sim |\Psi(k_{out})|^2 \; |\Psi(k_{in})|^2 \langle M(x,y), M(0,0) \rangle$

Spin-flip:

$I_{sf} \sim |\Psi(k_{out})|^2 \; |\Psi(k_{in})|^2 \; M_{\perp}^2$

Enhancement factor η >>1

Designing of the structure. Choice of the materials

superconductors

material,	Tc, K	Hcm, Oe	type of lattice, cells param a/b/c (A), α/β/γ (grad)	ρ, 10^{-6} A^{-2}
In	3.41	281.5	tetragonal 3.3/3.3/5.0, 90/90/90	1.55 – 0.2i
La	5	800	hcp 3.8/3.8/12.1, 90/90/120	2.20
Nb	9.25	2060	bcc, 3.3/3.3/3.3 90/90/90	3.947
Pb	7.19 6	803	ccp, 4.9/4.9/4.9 90/90/90	3.103
Sn	3.72 2	305	tetragonal, 5.8/5.8/3.2 90/90/90	2.302
Tc	7.8	1410	hcp, 2.7/2.7/4.4 90/90/120	4.8
V	5.4	1408	bcc, 3.0/3.0/3.0 90/90/90	-0.27

Requirements to materials:

- Crystallography "closeness" of materials
- Strong superconductor with low-SLD
- Weak and thin (~ 1nm) ferromagnet
- High-SLD materials on top (Cu) and bottom (MgO)

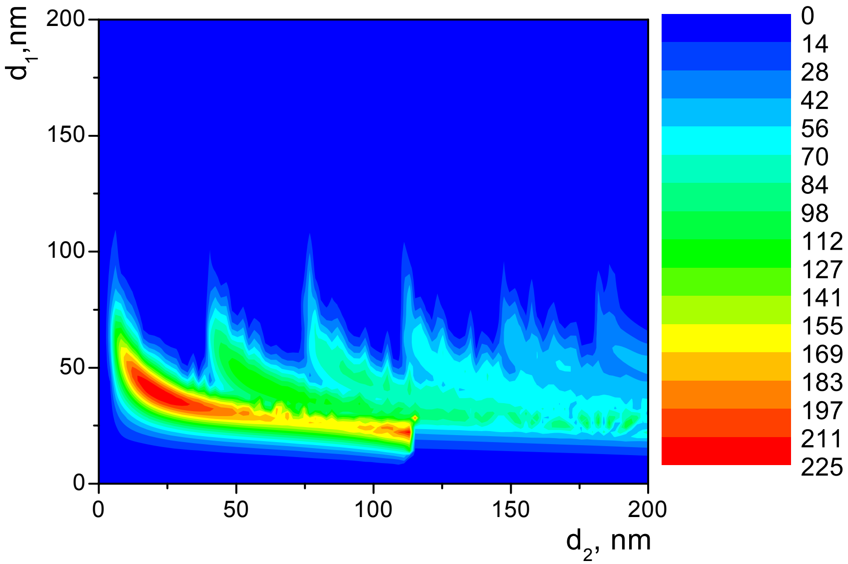
ferromagnets

material	Tк, K	B_{sat}, Oe	type of lattice, cells parameters a/b/c (A), α/β/γ (grad)	ρ, 10^{-6} A^{-2}
Fe	1044	2160 0	bcc, 2.9/2.9/2.9 90/90/90	8.02
Co	1388	1820 0	hcp, 2.5/2.5/4.0 90/90/120	2.26
Ni	627. 4	6200	ccp, 3.5/3.5/3.5 90/90/90	9.41

Designing of the structure. Optimization calculations

Calculation of the enhancement factor

$Cu(d_1)/V(d_2)/Fe(\sim1nm)/MgO$

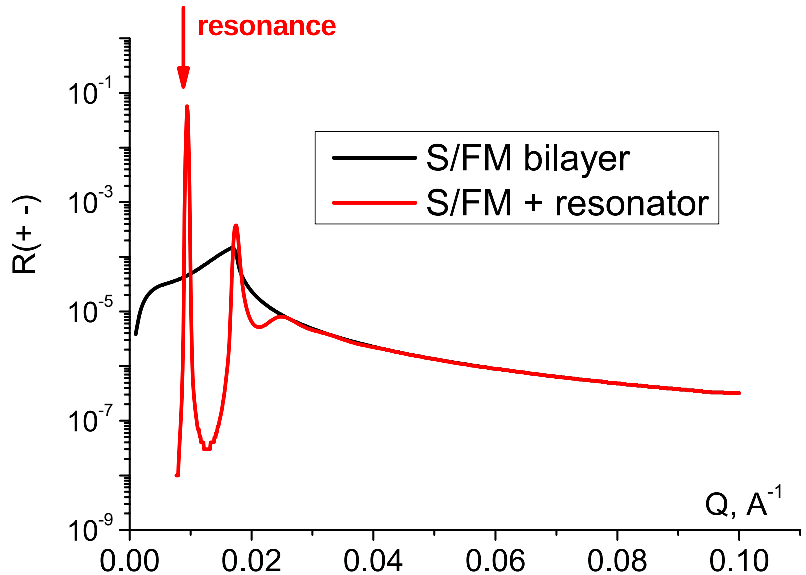


Yu.N. Khaidukov, Yu.V. Nikitenko, V.L. Aksenov, arXiv:0801.3967v1

Results of the optimization:

Cu(33nm)/V(40nm)/Fe(1nm)/MgO

$\eta = 225$

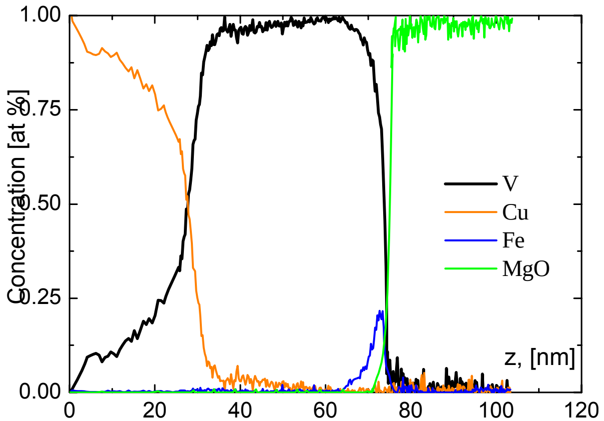


At neutron flux ~10^3 n/sec and resolution of reflectometer dQ/Q=1.5 % such structures allow to observe change of magnetization in FM layer of the order of 1 %

Sample preparation and characterization

Cu(33nm)/V(40nm)/^{57}Fe(1.0nm)/MgO

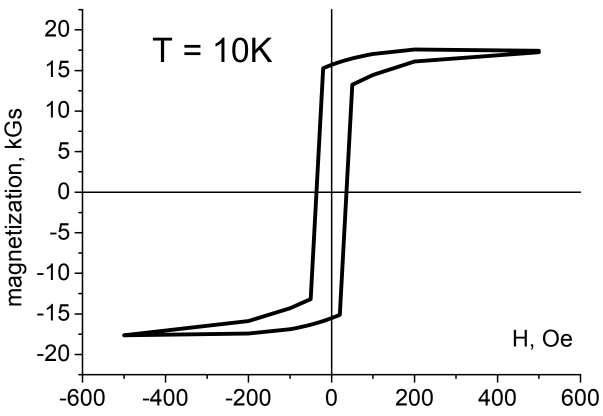
SNMS



$\sigma_{sub} \approx 0.3$ nm

$\sigma_{S/FM} \leq 0.5$ nm

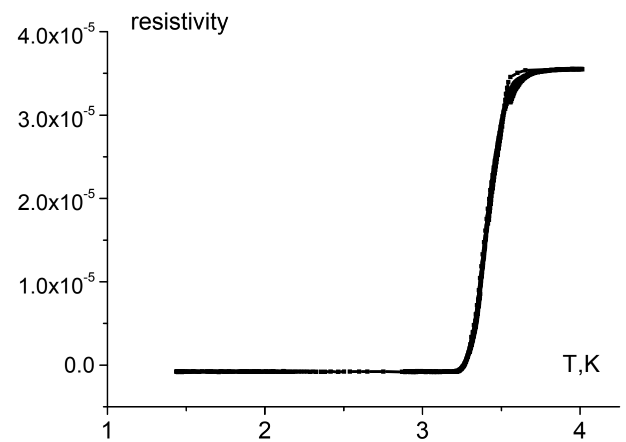
SQUID



$H_{sat} = 500$ Oe

$M_{sat} = 18$ kGs

Transport

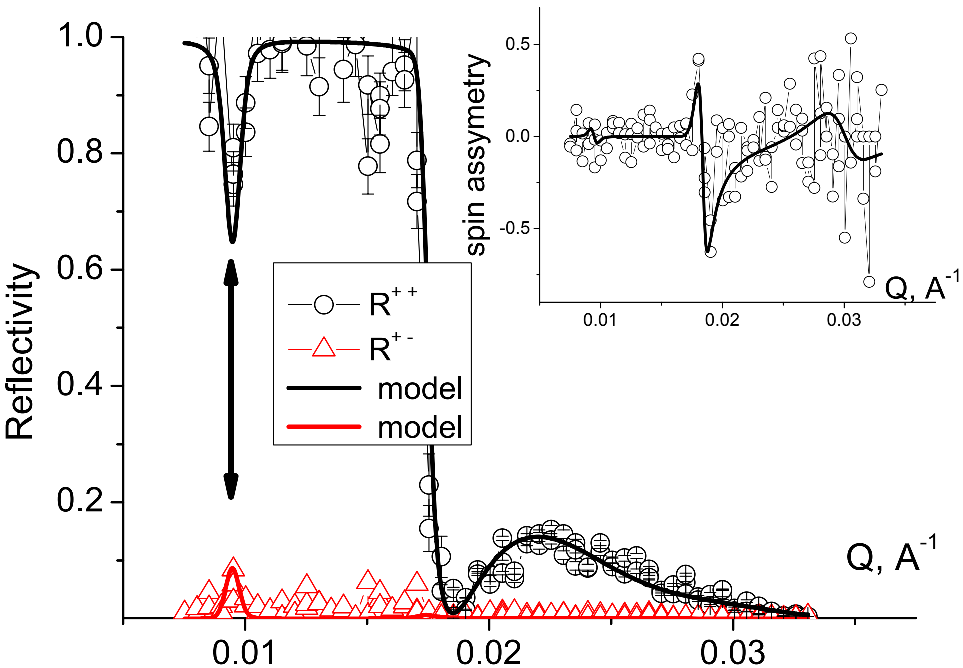


$T_C = 3.5$ K

$H_{C1} = 2.6$ кOe

Test of the waveguide properties. RT-PNR experiments

Cu(33nm)/V(40nm)/Fe(1nm)/MgO



Obtained enhanced factor

η_{exp} = 160 (η_{th} = 225)

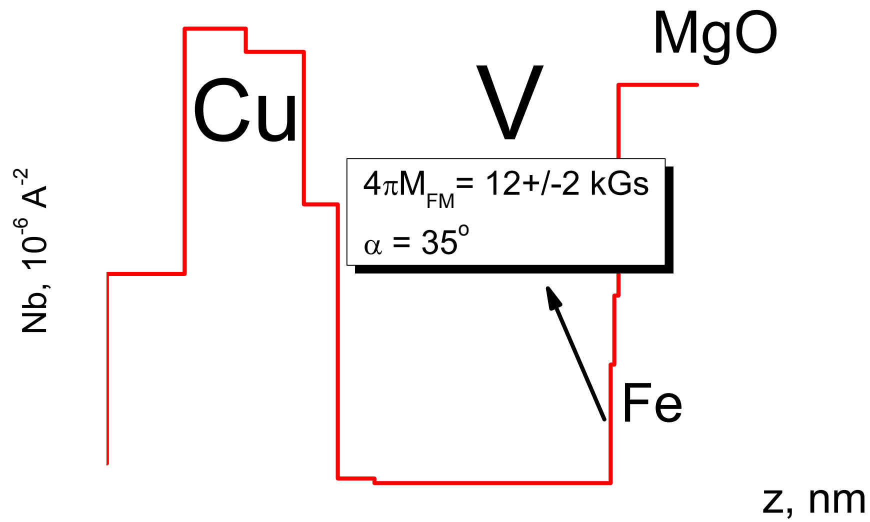
N-REX+ @ FRM2

room temperature

λ = 5.5 Å,

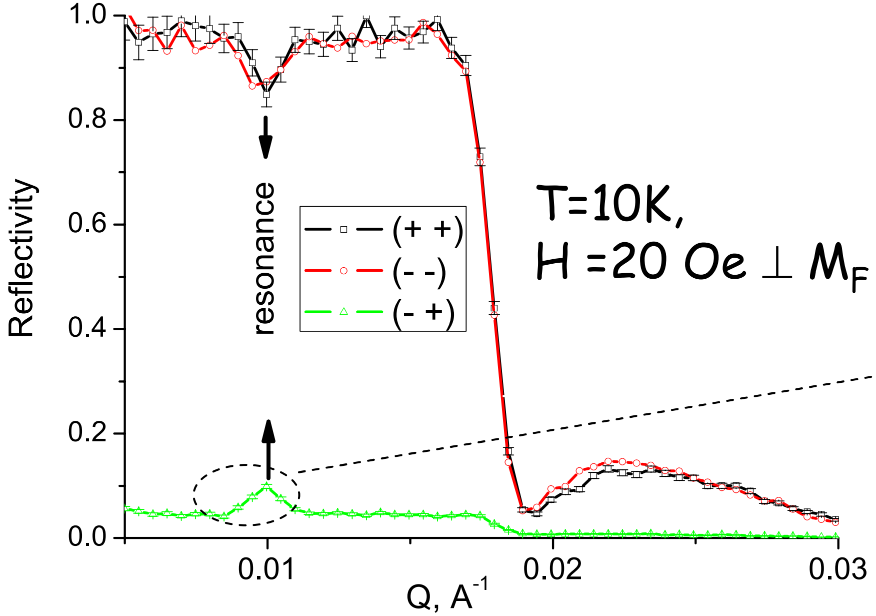
dQ/Q = 4%

Full polarization mode

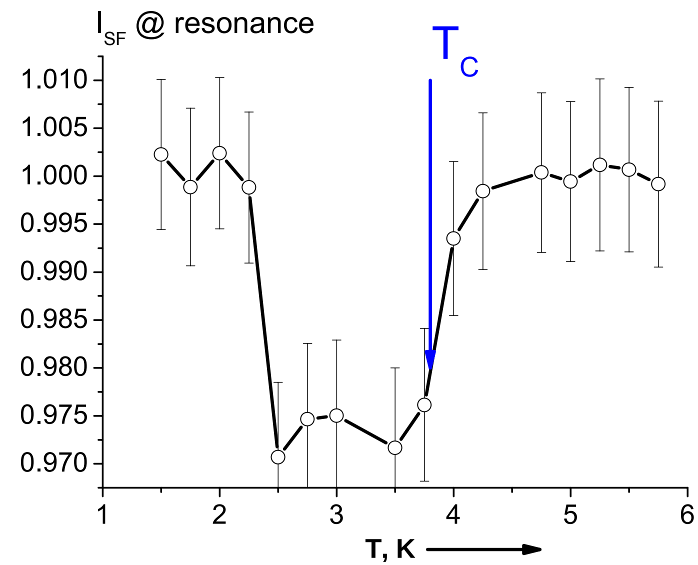


Magnetic state of the system close to T_C

Cu(33nm)/V(40nm)/Fe(~1nm)/MgO



Temperature dependence of (+ -) resonant peak



ADAM @ ILL

λ = 4.4 Å

dQ/Q = 3%

Full polarization mode

Time of meas. – 8 hours

stat. error ~ 1%

Sensitivity is comp. to SQUID

No significant changes of diffuse scattering has been observed!

Magnetization profile

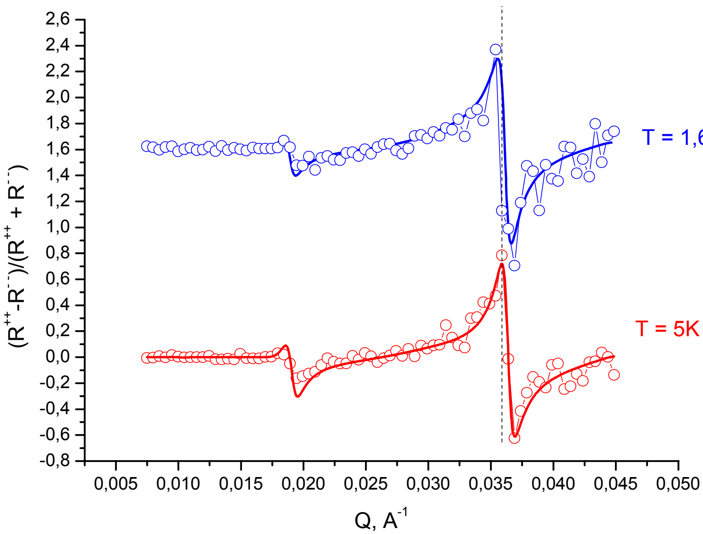
$Cu(33nm)/V(40nm)/^{57}Fe(1.0nm)/MgO$

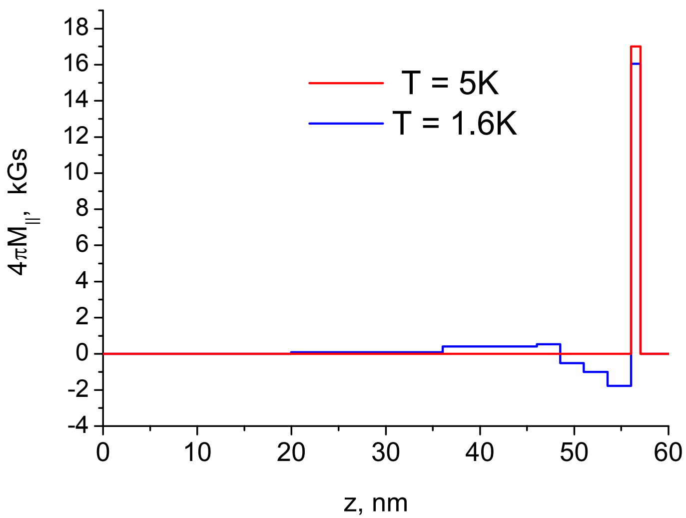
Spin assymetry

$$SA(Q) \equiv [R^{++} - R^{--}]/[R^{++} + R^{--}]$$

$$SA(Q) \sim \int M_{||}(z)\, e^{-iQZ}\, dz$$

$$M_{||} \,||\, H,\ M_{||} = |M| \cos\alpha$$





Shift of the oscillations speak about new magnetic size

Inversed proximity effect

Conclusions

To increase weak magnetic scattering (spin-flip and diffuse) from S/F bilayer it is suggested to use regime of waveguide enhanced standing waves.

• The calculations and experiment have shown that resonant structure Cu(32nm)/V(40nm)/Fe(~1nm)/MgO allows to increase signal more than **150** times.

• This enhancement allowed to detect small changes of spin flip scattering (1-3%) below Tc of the superconductor. No change of diffuse scattering within the error bars have been detected.

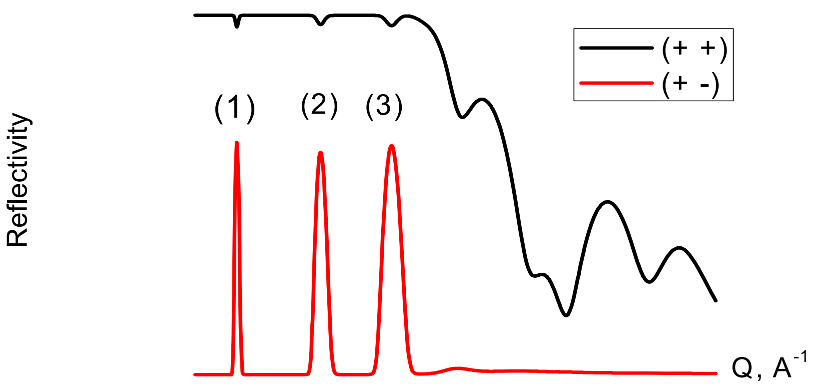
Outlook

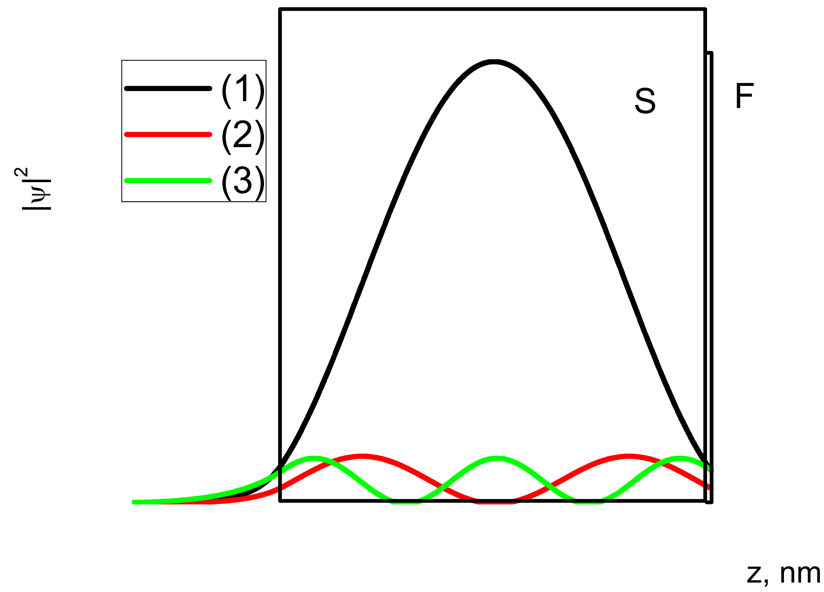
3 mode resonator (n=1,2,3)

resonance condition

$\arg(r_{21}) + \arg(r_{23}) + 2(kd_2) = 2\pi n$,

Cu(32nm)/V(90nm)/Fe(~1nm)/MgO





Allow to study:

- vortex state and its modifications due to proximity effects
- non-elastic scattering from magnetic excitations
- ...

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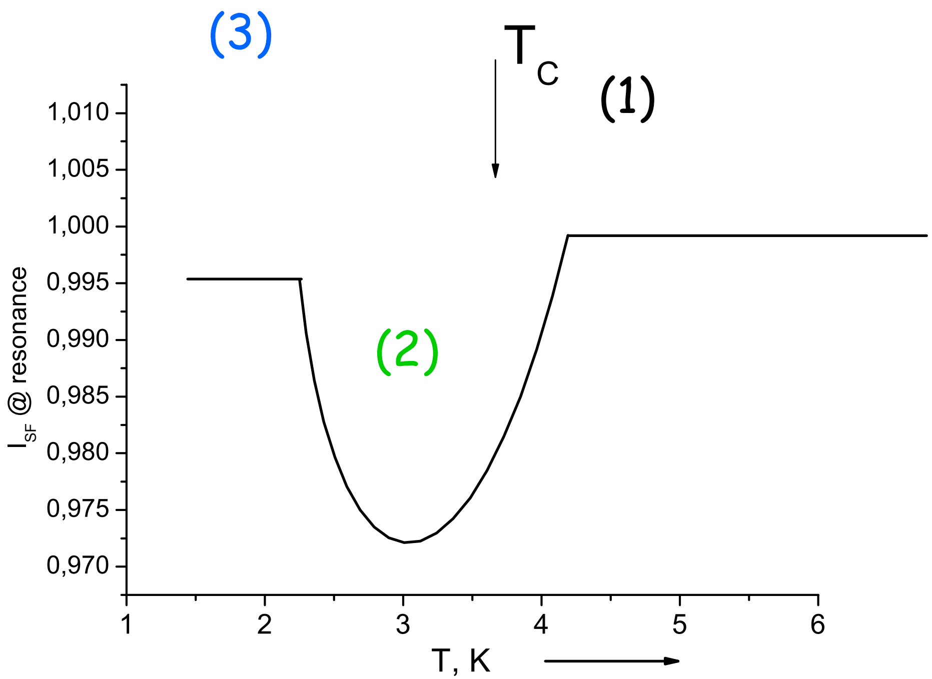
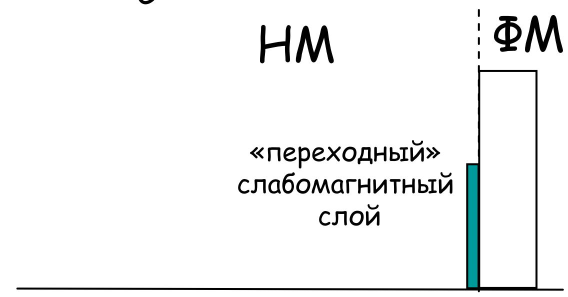
L. Kiss
(SQUID)

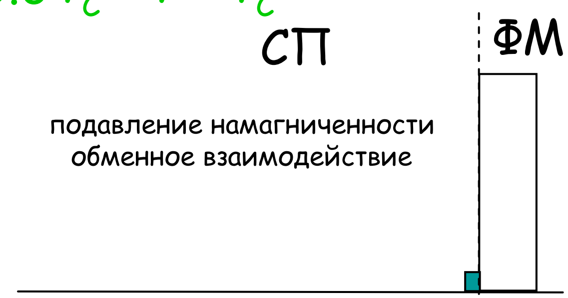
Выводы



(1) $T > T_C$



(2) $0.6T_C < T < T_C$



(3) $T < 0.6T_C$