Laboratory for Neutronen Scattering
ETH Zürich & Paul Scherrer Institute

Jochen Stahn

Antiphase magnetic proximity effect in perovskite superconductor / ferromagnet multilayers

SFB 491 Seminar 23. 02. 2006
Ruhr-Universität Bochum

essence

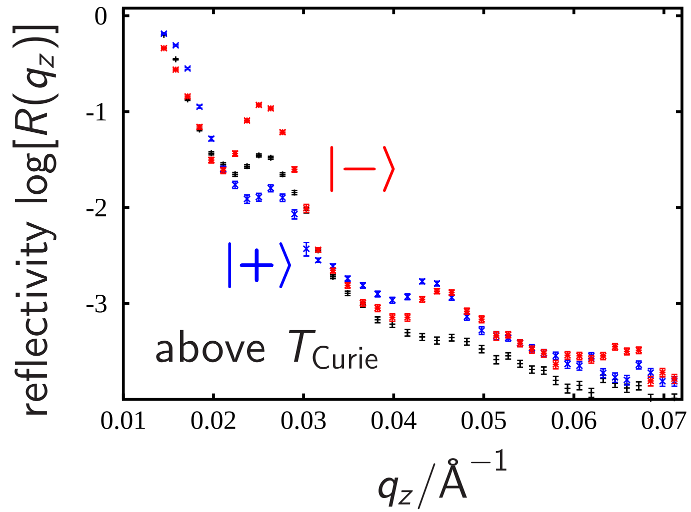
question: What is the magnetic induction (profile) in HTSC / FM multilayers?

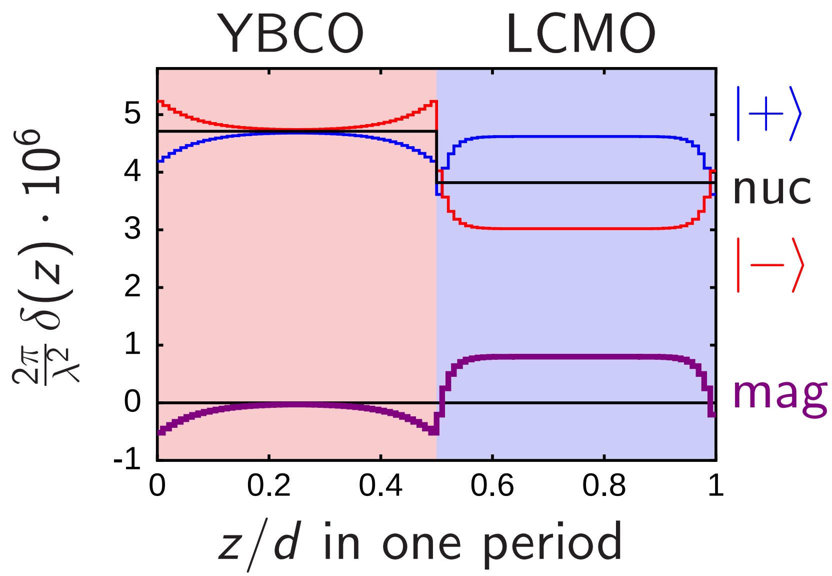
method: polarised neutron reflectometry allows for the determination of $\rho(z)$ and $\mathbf{B}_{\parallel}(z)$

answers: FM layers magnetised parallel

net magnetic moment in SC at the interfaces, antiparallel to FM magnetisation

SC creates and aligns domain walls in FM





cooperators:

[1] LNS, ETHZ & PSI
[2] MPI-FKF, Stuttgart
[3] Universität Fribourg
[4] RUB / ILL
[5] FZ Jülich

samples
G. Cristiani [2]
HU. Habermeier [2]

analysis
J. Hoppler [1]
S. Pekarek [1]

measurements
C. Niedermayer [1]
E. Kenzinger [5]
J. Chakhalian [2]
T. Gutberlet [1]
U. Rücker [5]
M. Wolff [4]

interpretation
C. Bernhard [3]
B. Keimer [2]

interfaces and layered systems "new physics" and "spintronics"?

general idea: the close contact of materials with different (alternative) properties might lead to new phenomena

e.g. – interface of $SrTiO_3/LaTiO_3$ (insulators) is metallic

a multilayer reduces the dimension and forces the interaction coupling phenomena might show up

e.g. – RKKY-interaction
– collosal magnetoresistance
– changed characteristic temperatures

present case: multilayers of a FM with a HTSC (both metals) seem to show an metal/insulator transition in ellipsometry transition for small periods — but stay superconducting / magnetic

so: what happens with the magnetisation and the superconduction order parameter?

overview

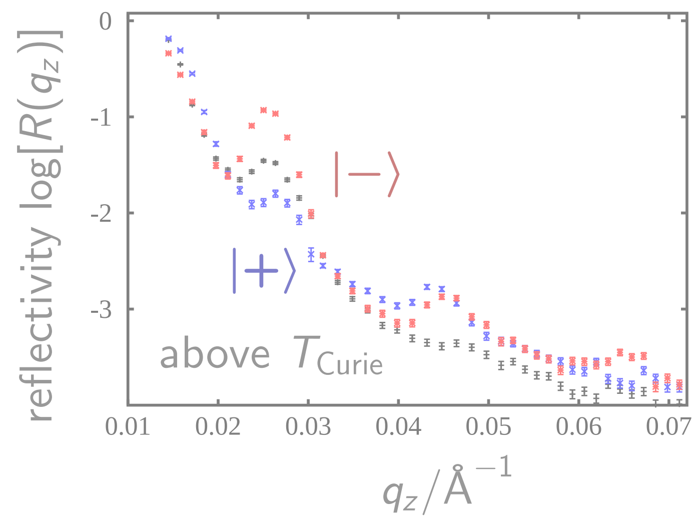
question: What is the magnetic induction (profile) in HTSC / FM multilayers?

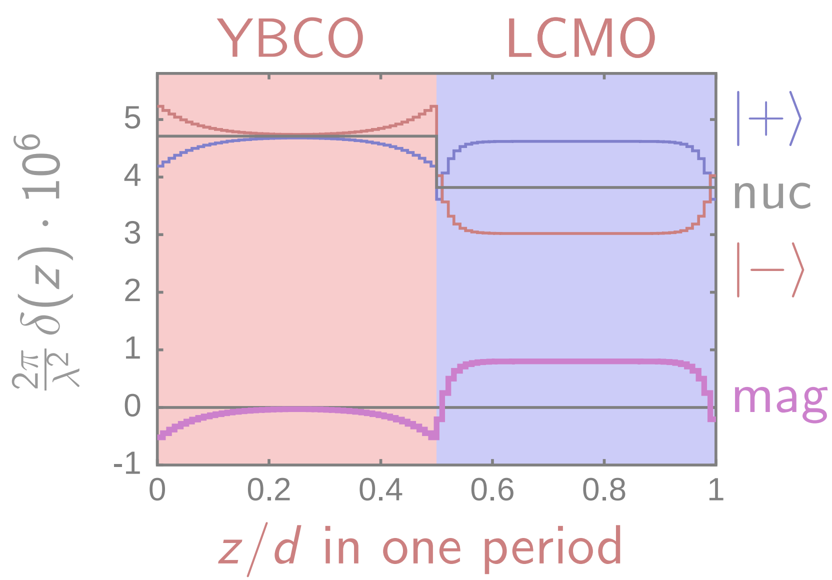
method: polarised neutron reflectometry allows for the determination of $\rho(z)$ and $\mathbf{B}_{\|}(z)$

answers: FM layers magnetised parallel

net magnetic moment in SC at the interfaces, antiparallel to FM magnetisation

SC creates and aligns domain walls in FM

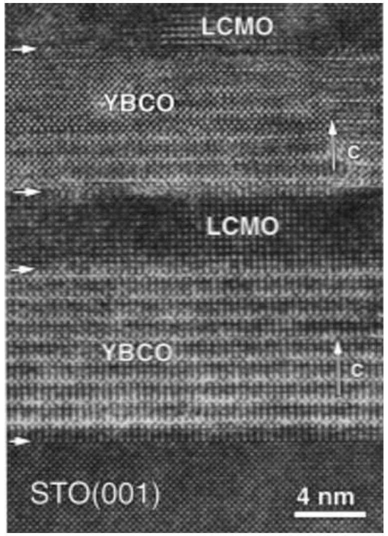




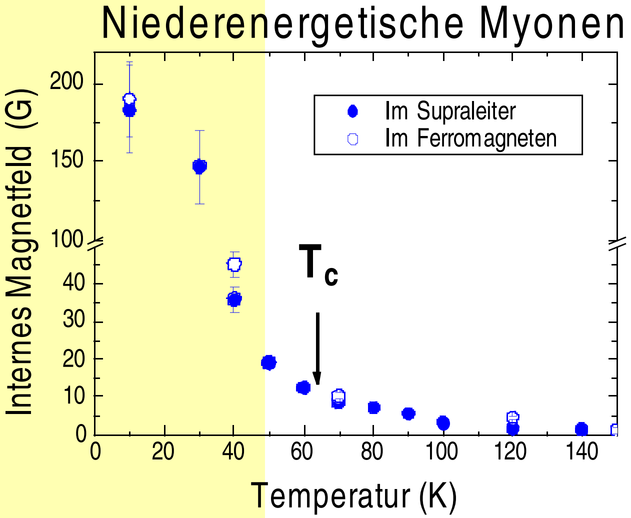
motivation / history:

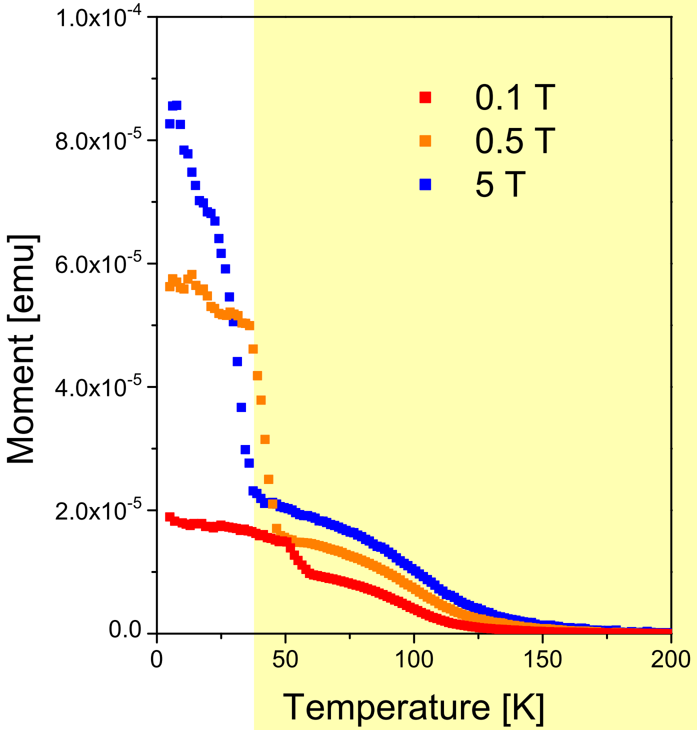
spring 2003:

C. Niedermayer presents nice μSR and magnetisation measurements at PSI



enhanced magnetism below T_c





coexistence of FM and SC in RuSrCuGdO

$\longrightarrow$ competitive order parameters

artificial multilayers to investigate

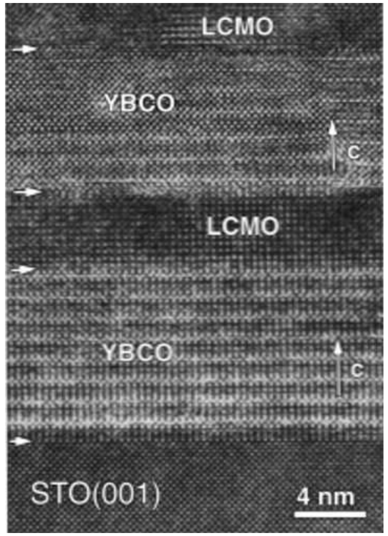
– interaction of FM and SC at the interfaces and

– coupling through the layer

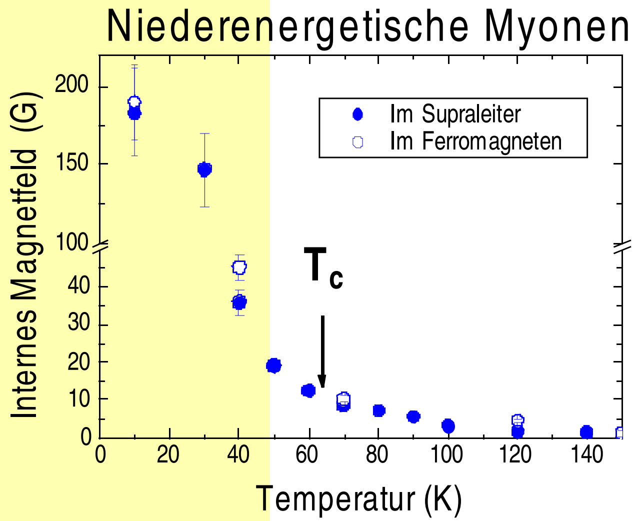
motivation / history:

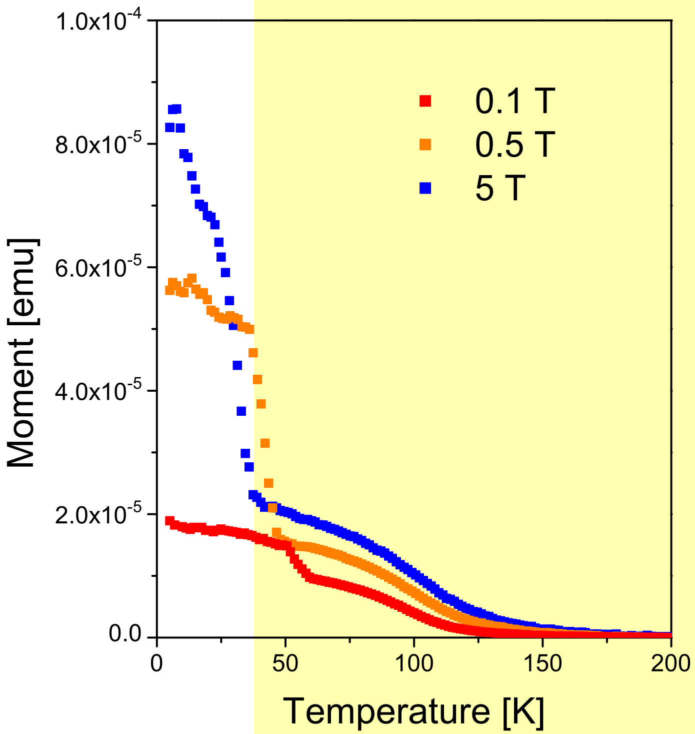
spring 2003:

C. Niedermayer presents nice μSR and magnetisation measurements at PSI



enhanced magnetism below T_c





method of choice
(for a neutron scatterer):

neutrons!

in particular *polarised n-reflectometry*

overview

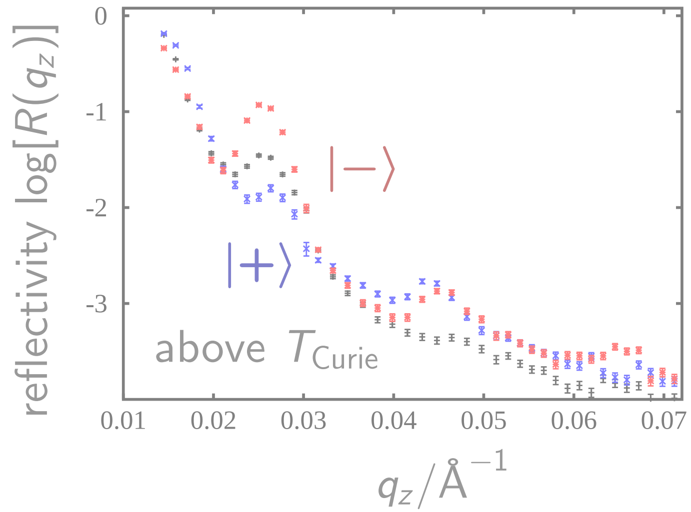
question: What is the magnetic induction (profile) in HTSC / FM multilayers?

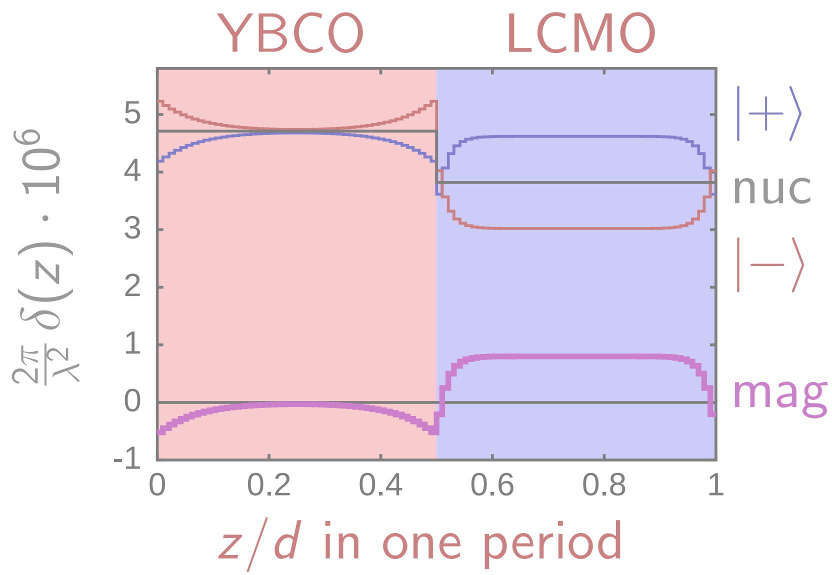
method: polarised neutron reflectometry allows for the determination of $\rho(z)$ and $\mathbf{B}_{\parallel}(z)$

answers: FM layers magnetised parallel

net magnetic moment in SC at the interfaces, antiparallel to FM magnetisation

SC creates and aligns domain walls in FM





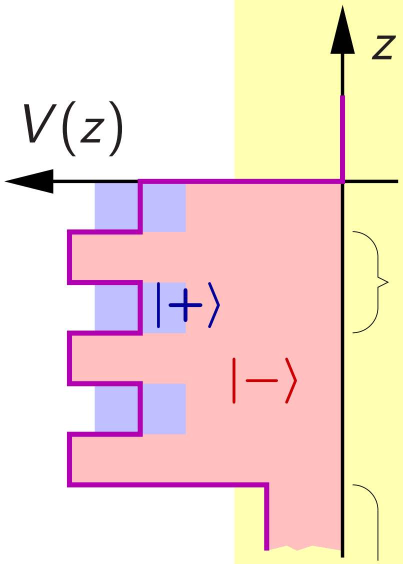
reflectometry

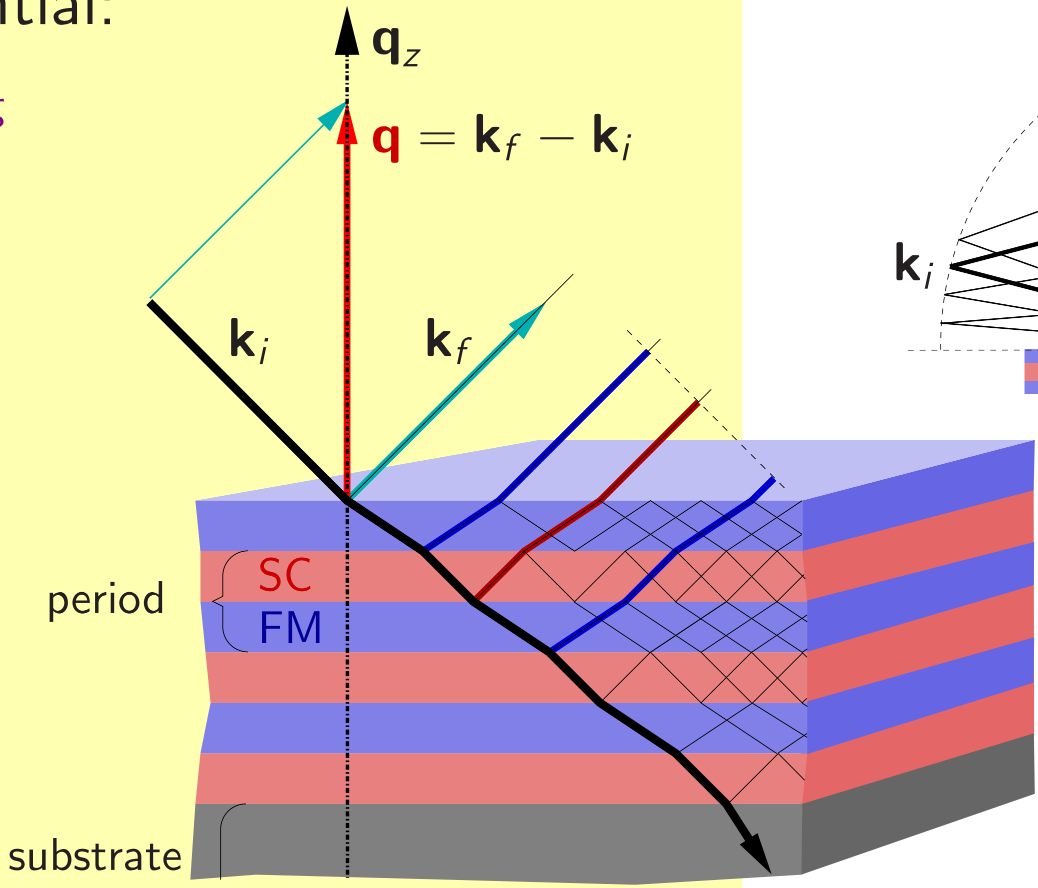
interference of beams reflected from parallel interfaces

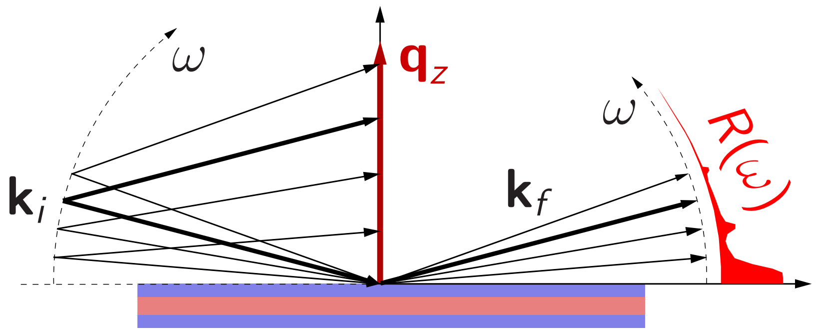
periodic structure $\Rightarrow$ Bragg-condition for constructive interference

scattering potential:

$$V = V_{\text{nuc}} \pm V_{\text{mag}} = V_{\text{nuc}} + \mu \mathbf{B}_{\parallel}$$







layer thickness ratio 1:1 $\Rightarrow$ extinction of even Bragg-peaks

reflectometry **tailored samples**

materials:	HTSC	YBCO	$YBa_2Cu_3O_7$
	FM	LCMO	$La_{2/3}Ca_{1/3}MnO_3$
	substr.	STO	$SrTiO_3$

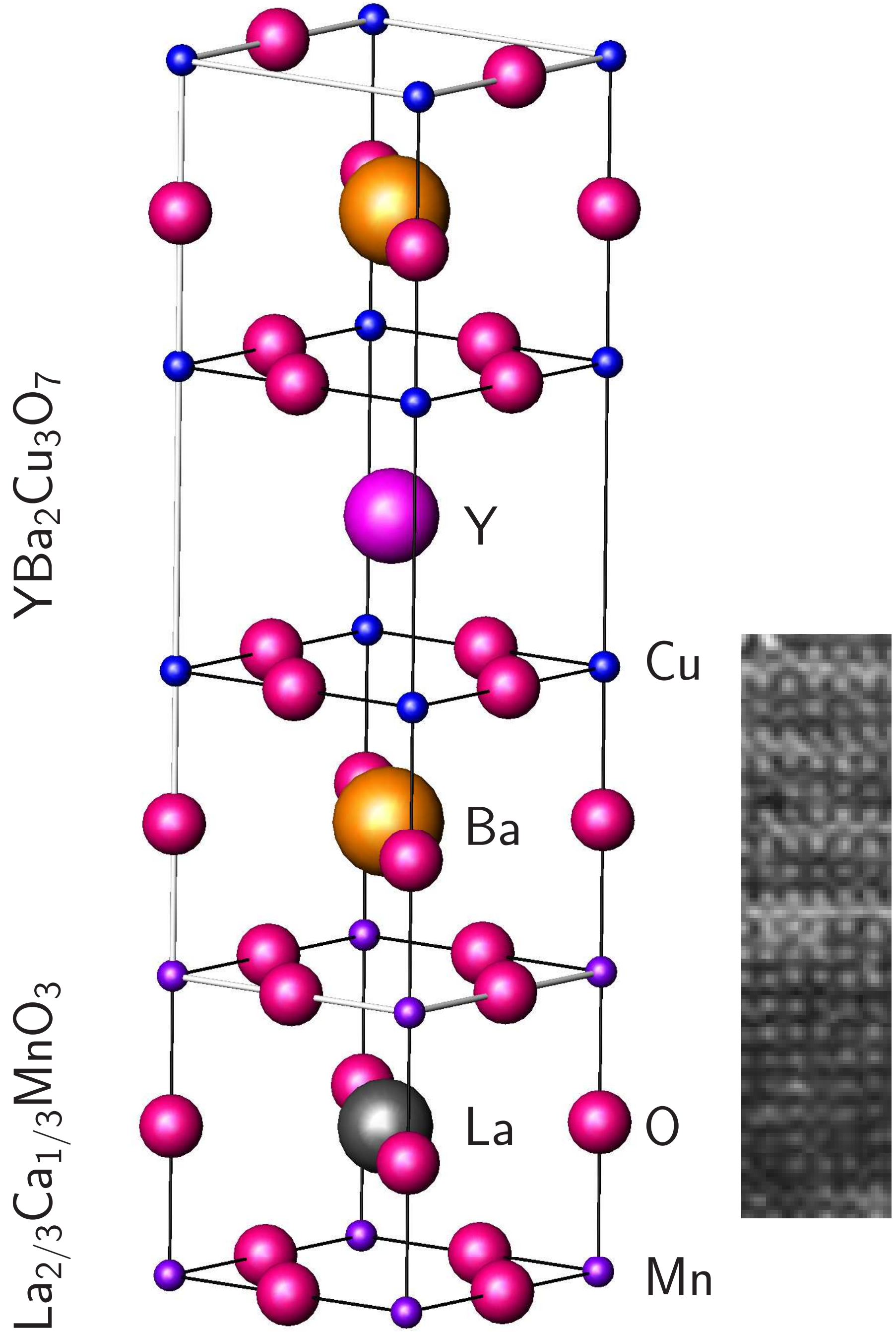
size: $10 \times 10\,mm^2$
(instead of $5 \times 5\,mm^2$)

produced: by *P*ulsed *L*aser *D*eposition

period: 200 Å to 500 Å
5 to 16 periods

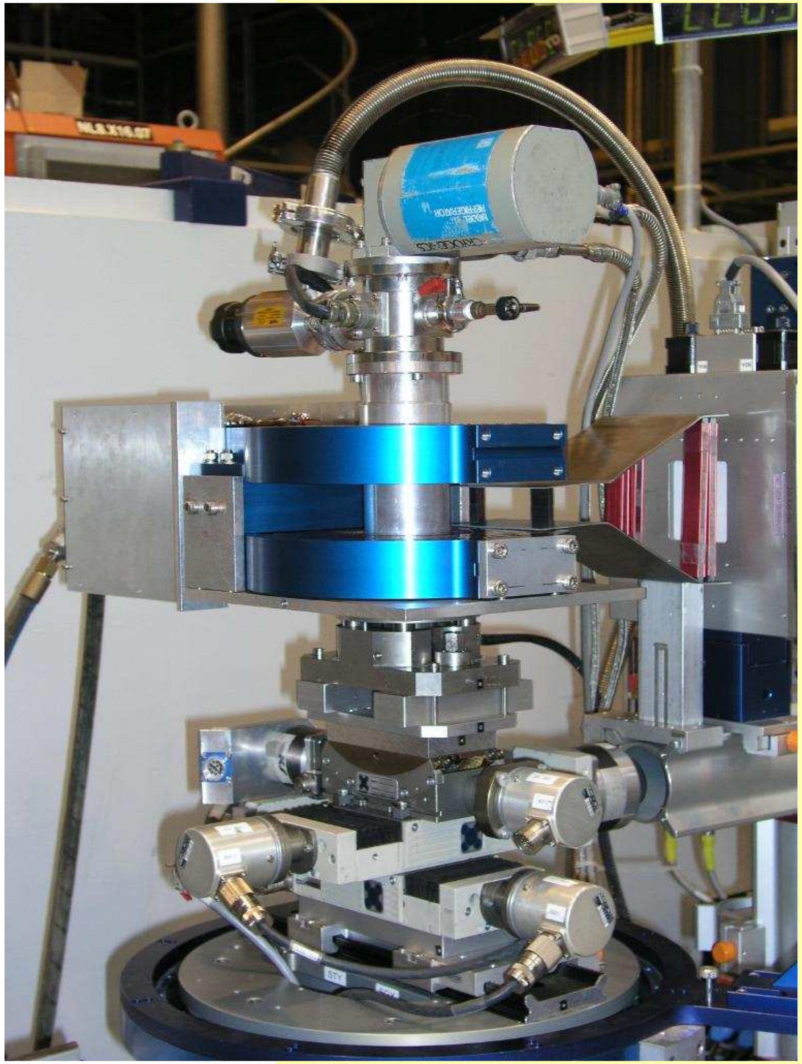
ratios: 1 : 1 and 1 : 2
to cause extinction

non-rough interfaces
(otherwise used to tune T_c)



reflectometry sample environment (at SINQ):

sample holder
with absorber



closed cycle refrigerator
$8\,\mathrm{K} < T < 300\,\mathrm{K}$

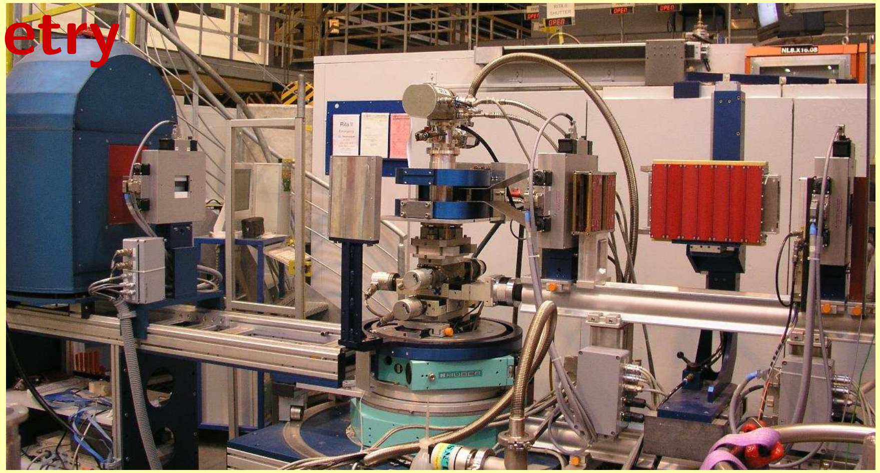
Helmholtz coils
$H \leq 1000\,\mathrm{Oe}$
vol: $40 \times 40 \times 40\,\mathrm{mm}^3$

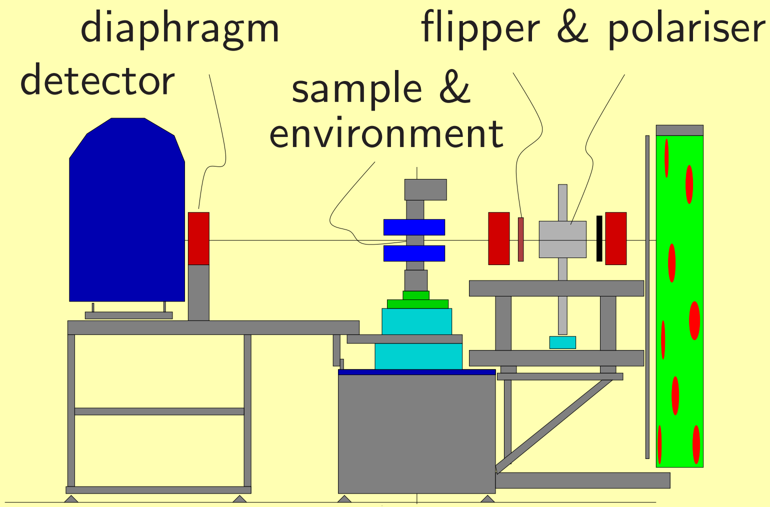
translation stages for alignment

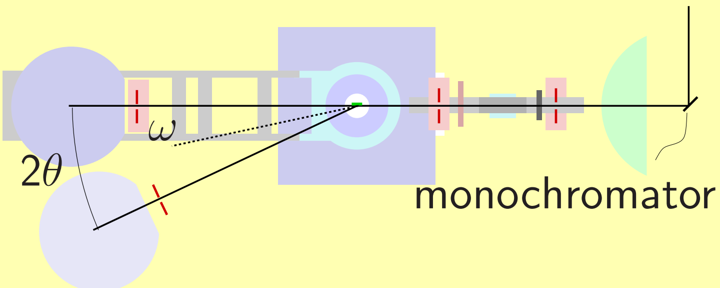
ω-rotation stage

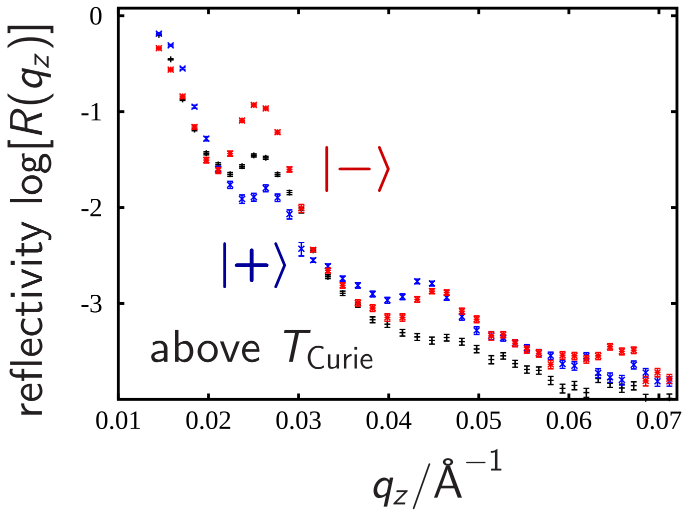
reflectometry

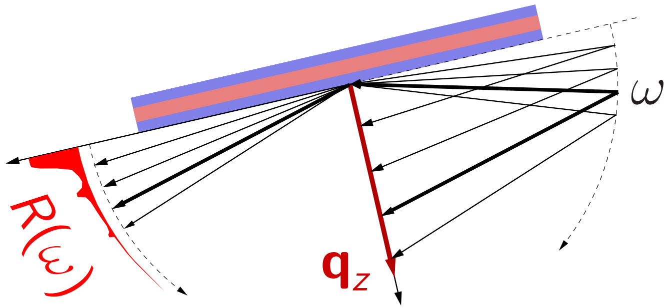
example:
Morpheus @ SINQ











overview

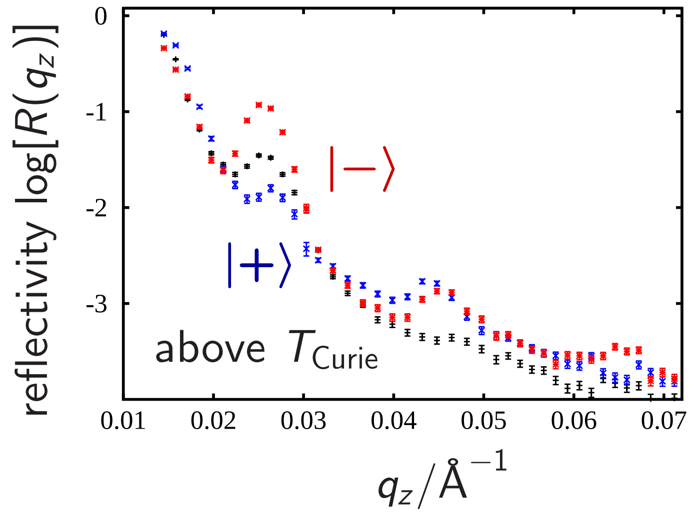
question: What is the magnetic induction (profile) in HTSC / FM multilayers?

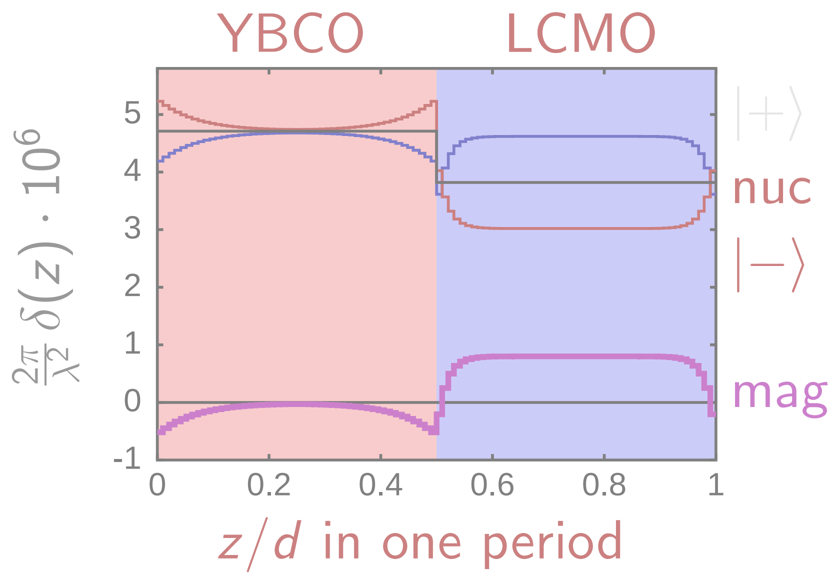
method: polarised neutron reflectometry allows for the determination of $\rho(z)$ and $\mathbf{B}_{\|}(z)$

answers: FM layers magnetised parallel

net magnetic moment in SC at the interfaces, antiparallel to FM magnetisation

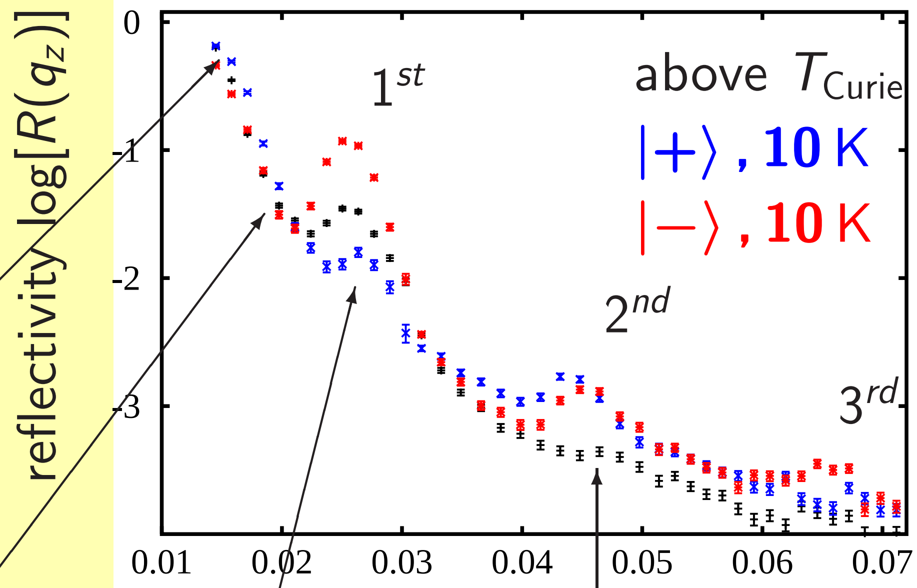
SC creates and aligns domain walls in FM





reflectometry direct interpretation

$\mathbf{H} = 100\,\mathrm{Oe}$
field cooled
$T = 10, 300\,\mathrm{K}$



splitting of the edge of total reflection
$\Rightarrow$ changed potential of the surface

no half-order Bragg-peak
$\Rightarrow$ parallel alignment of **B** in the FM layers

intensity variation of the 1^{st} Bragg-peak
$\Rightarrow$ changed potential in the FM layers
$B_{\parallel}$ can be determined

appearance of a 2^{nd} order Bragg-peak
$\Rightarrow$ $B_{\parallel}(z)$ and $V_{\mathrm{nuc}}(z)$ have different symmetry

reflectometry simulations

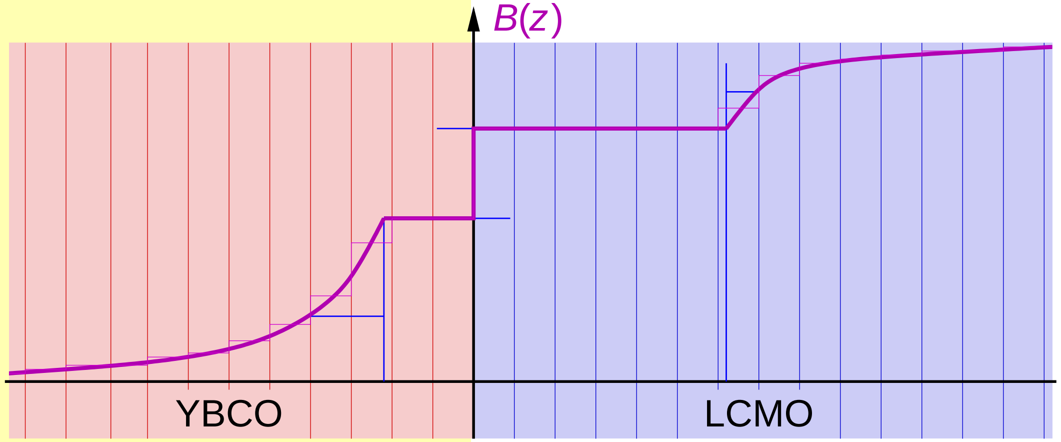
simulations performed with EDXR by Petr Mikulík (no fitting)

bilayer structure has been broken down to some 100 sublayers to pay respect to $\mathbf{B}(z)$.

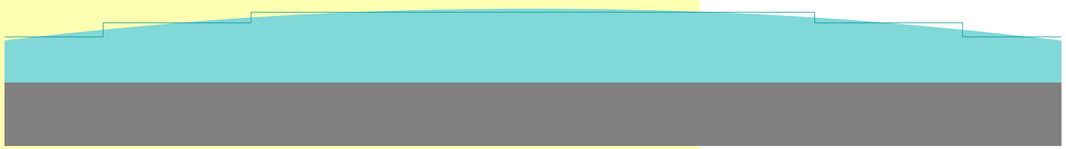
analytic expressions for $B(z)$:

cosh-functions

off-sets with constant B



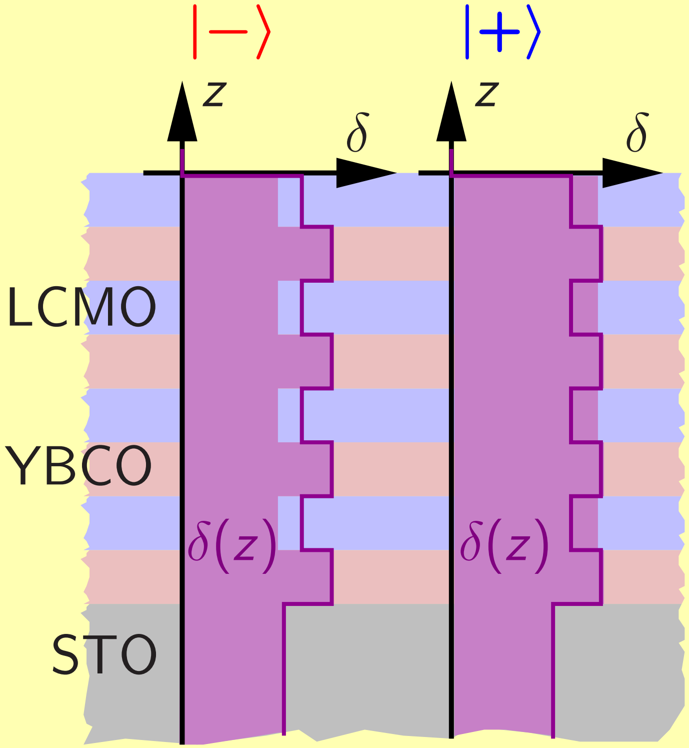
decrease of layer thickness towards the borders taken into account

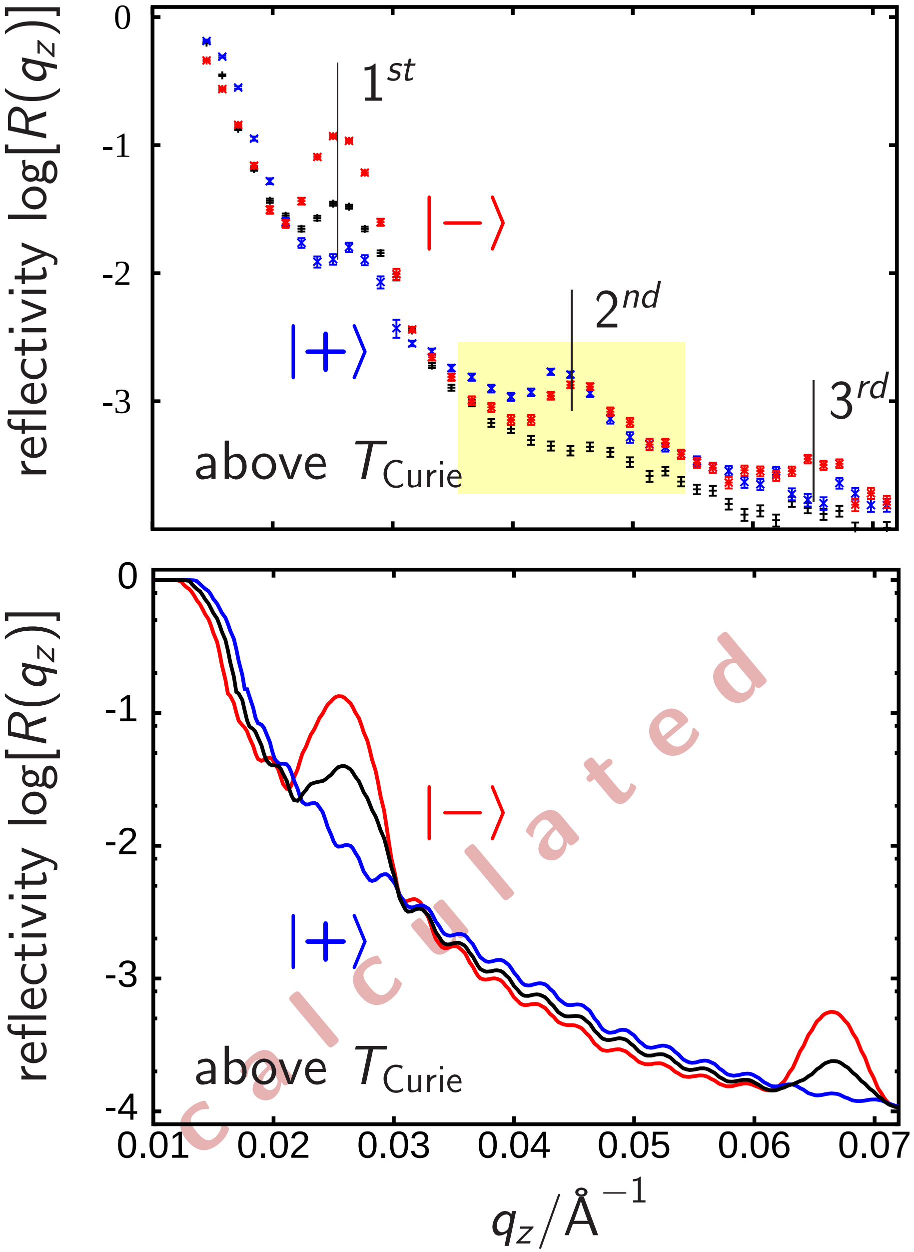


reflectometry **simulation** specular, polarised

sample:

[YBCO(150 Å)/LCMO(140 Å)]$_5$

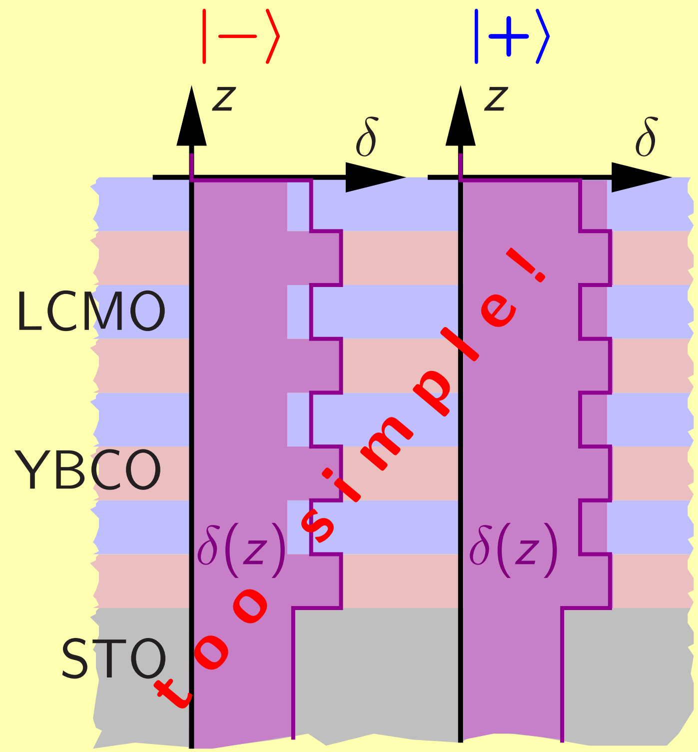


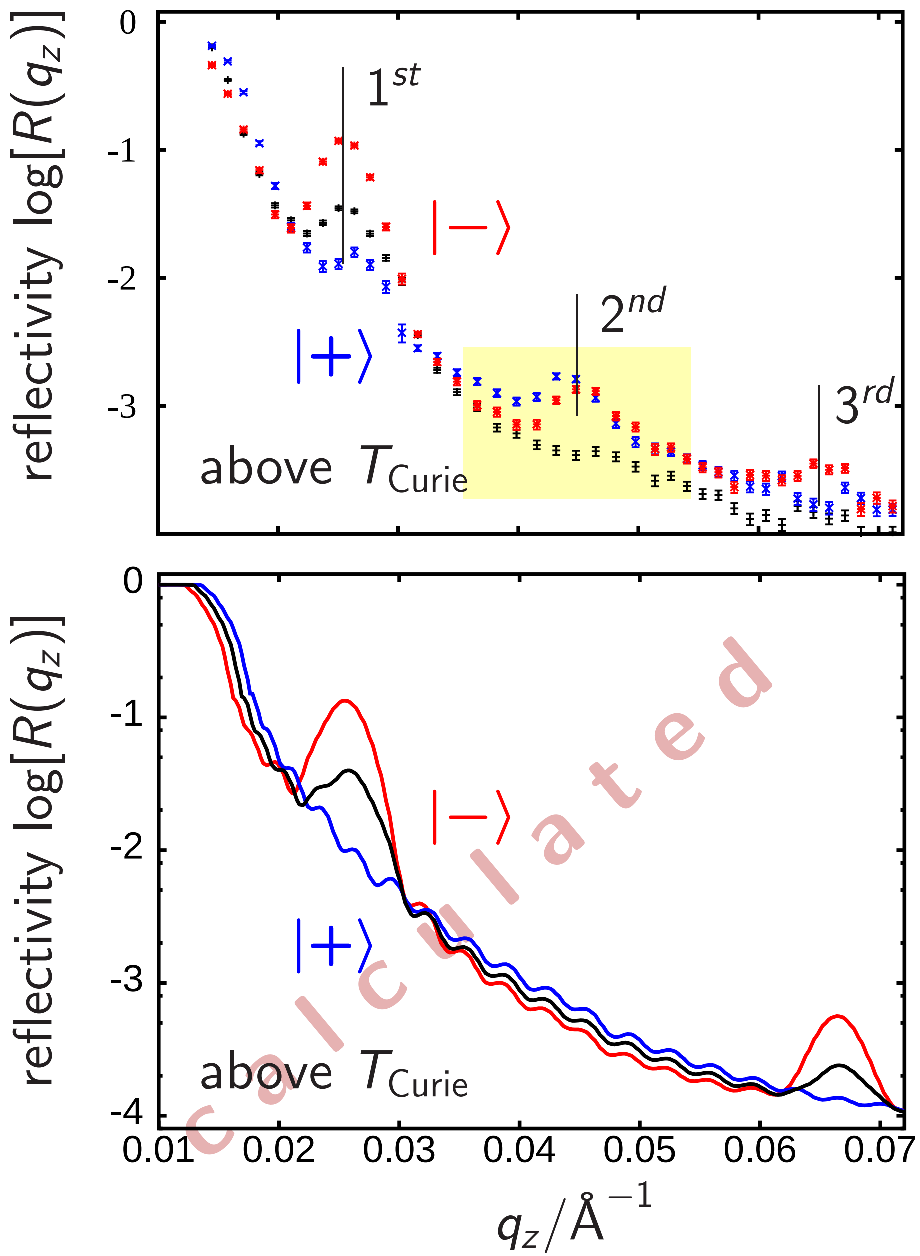


reflectometry specular, polarised

sample:

$[\mathrm{YBCO}(150\,\text{Å})/\mathrm{LCMO}(140\,\text{Å})]_5$





$$\delta_{\mathrm{mag}}(z) \neq \delta_{\mathrm{nuc}}(z) \times \begin{cases} 0 & \text{for YBCO} \\ const & \text{for LCMO} \end{cases}$$

modelling magnetic profile at the interfaces

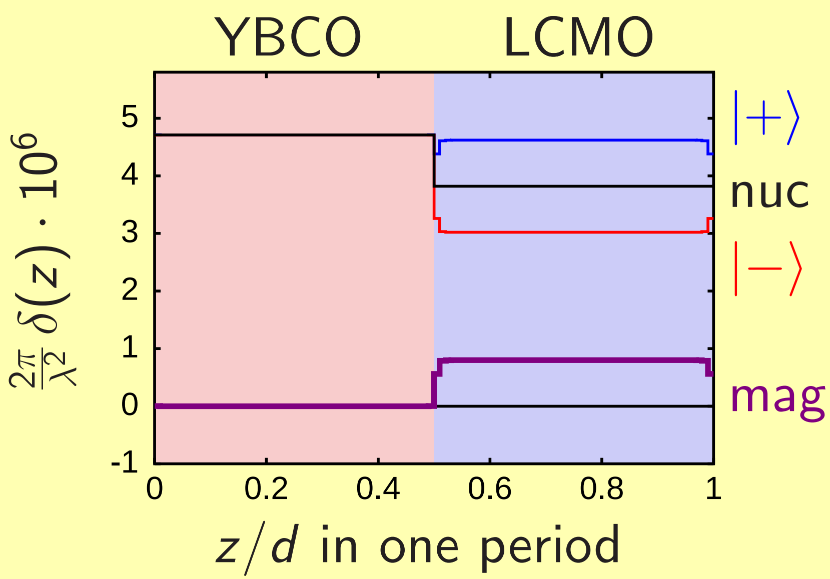
sharp contrast at the interface

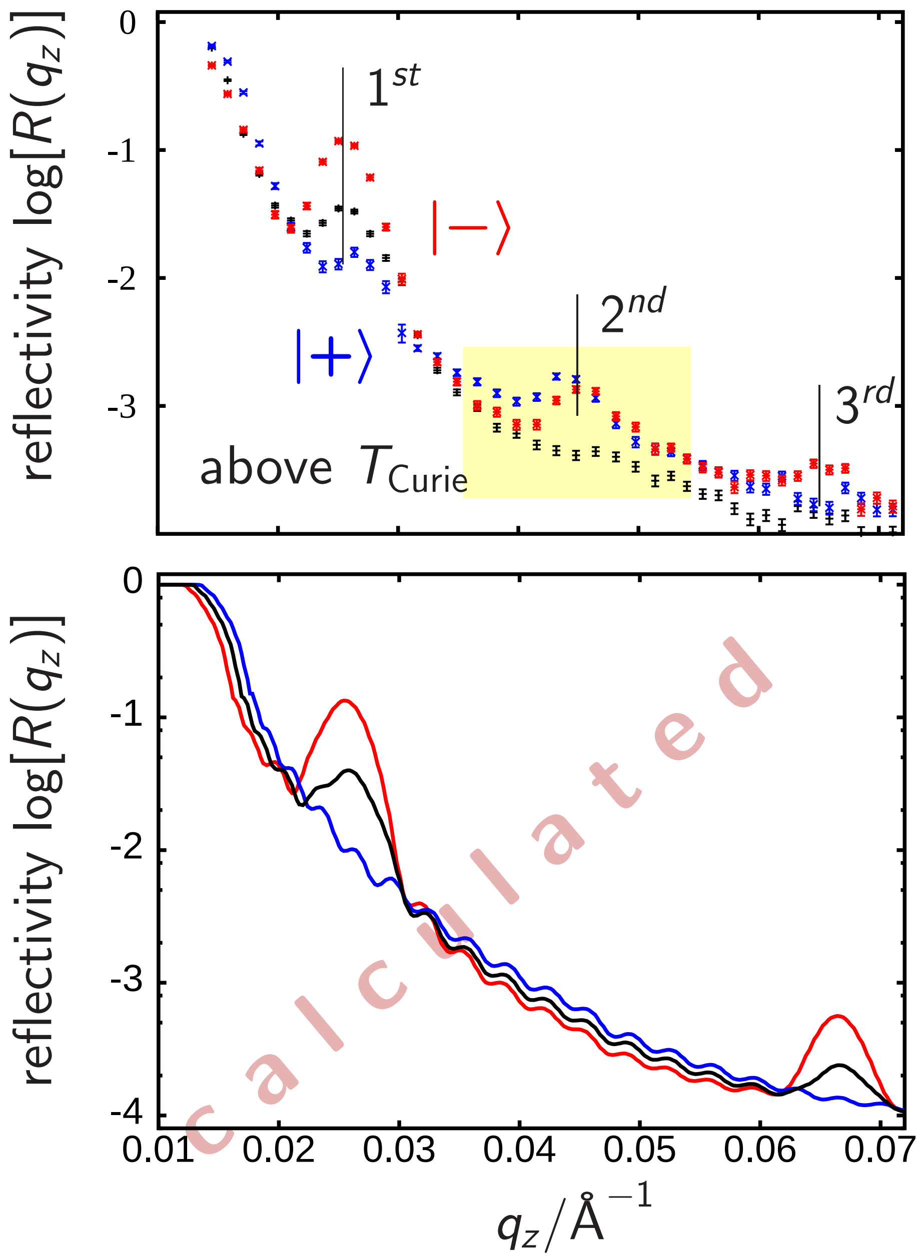
exponential decay into YBCO

AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO





modelling magnetic profile at the interfaces

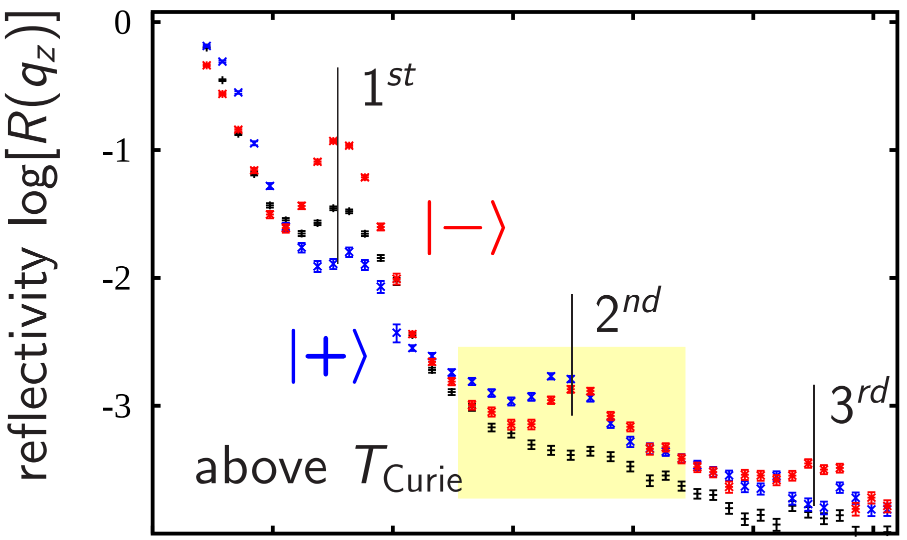
sharp contrast at the interface

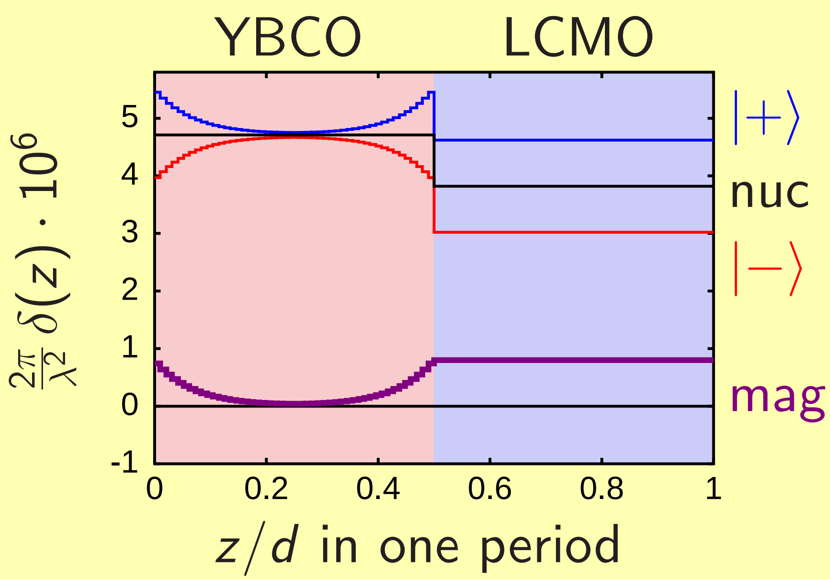
exponential decay into YBCO

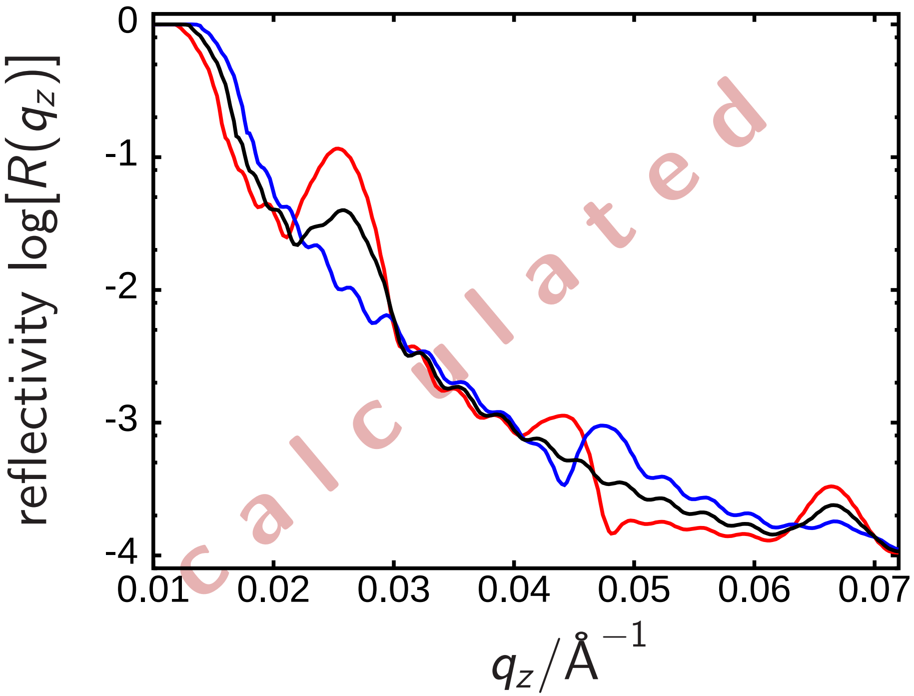
AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO







modelling magnetic profile at the interfaces

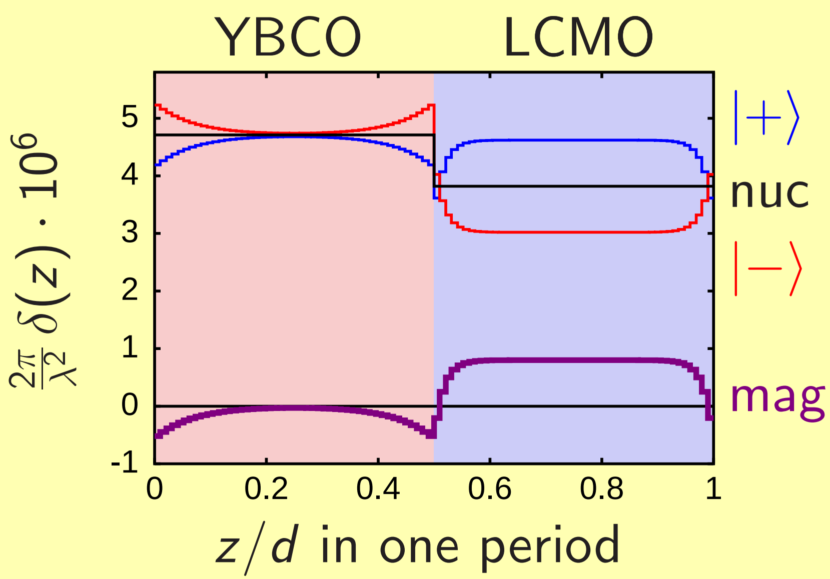
sharp contrast at the interface

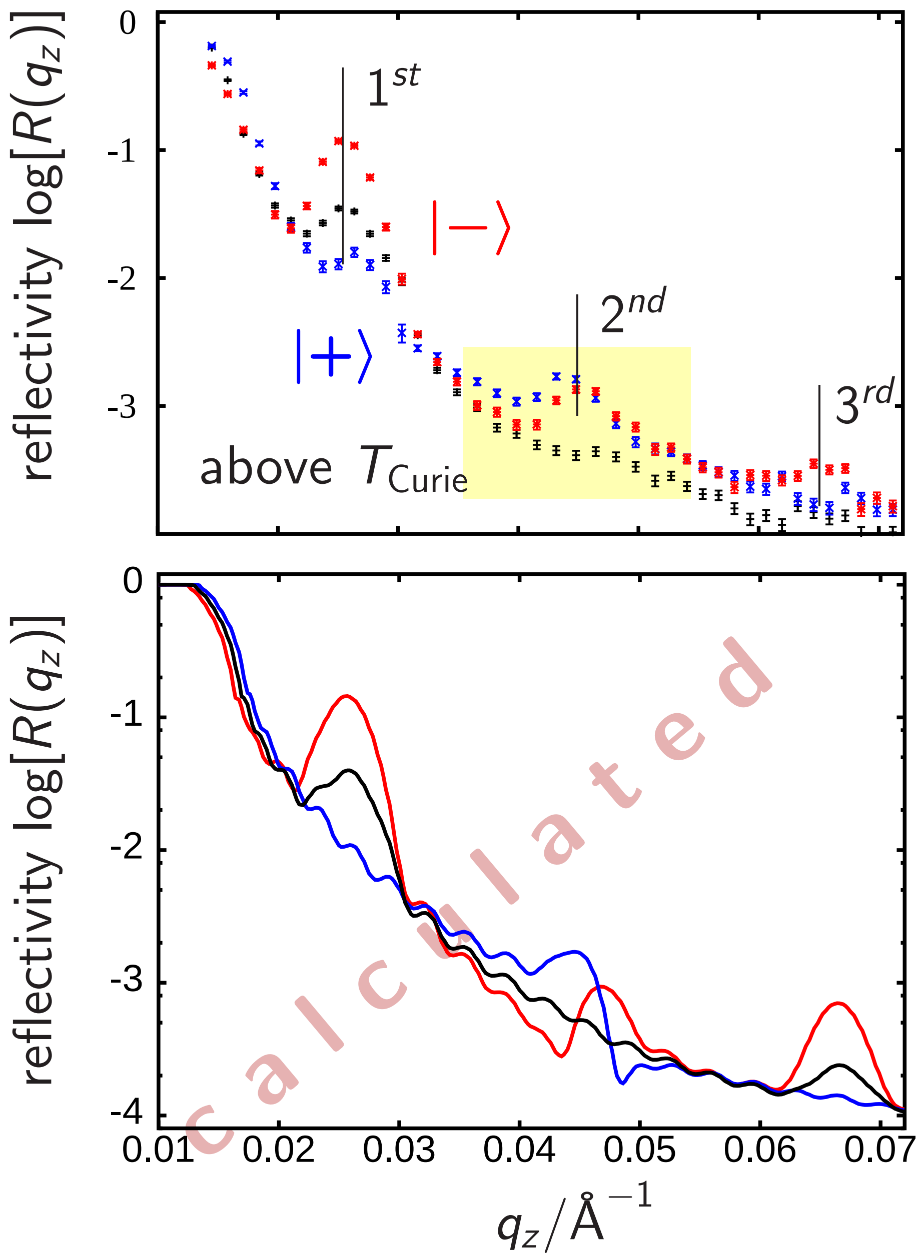
exponential decay into YBCO

AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO





modelling magnetic profile at the interfaces

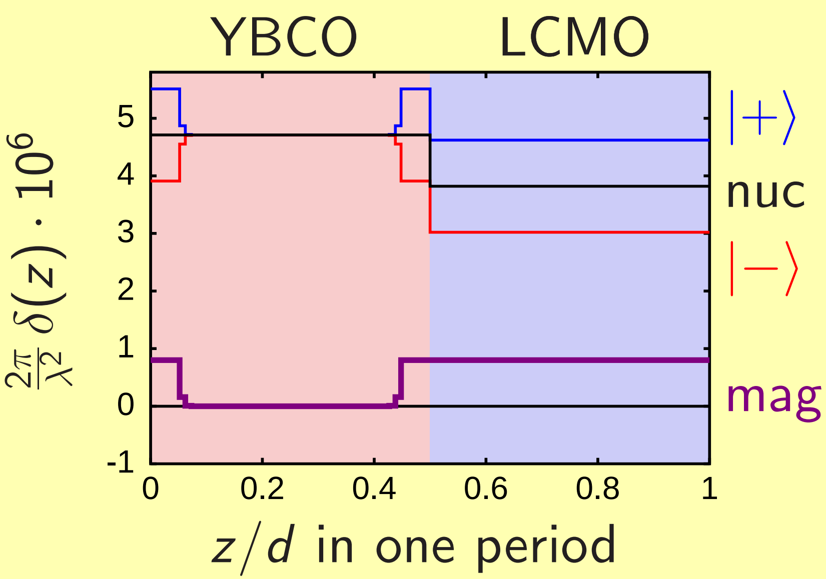
sharp contrast at the interface

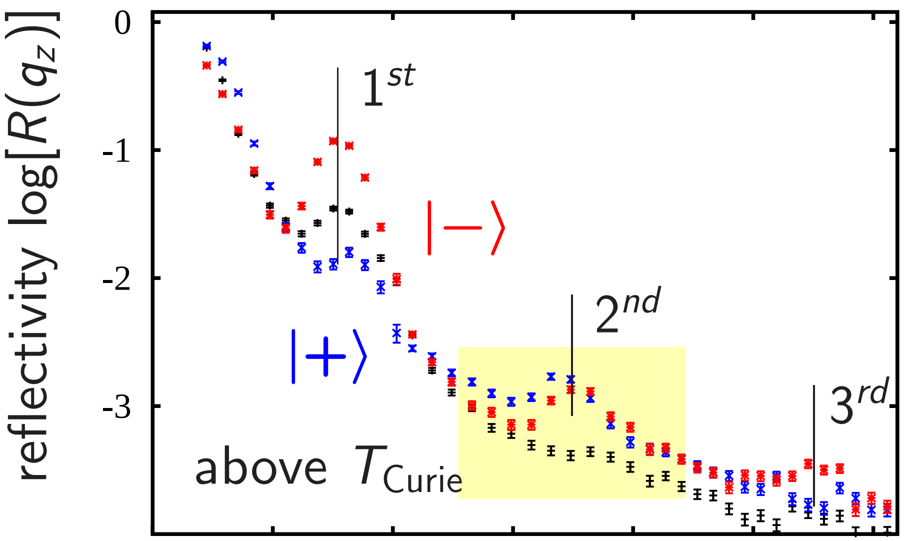
exponential decay into YBCO

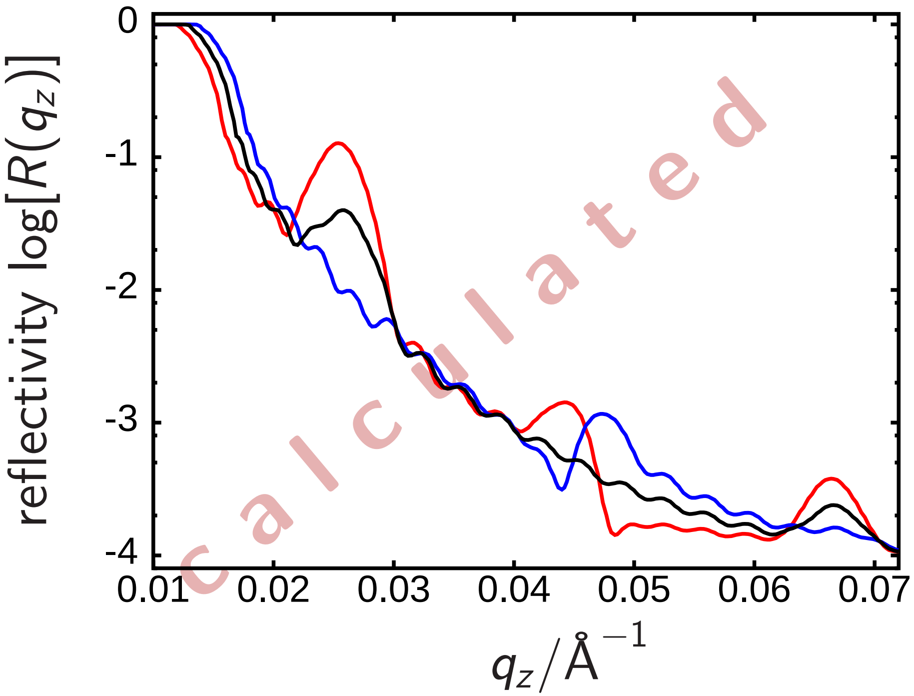
AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO







modelling magnetic profile at the interfaces

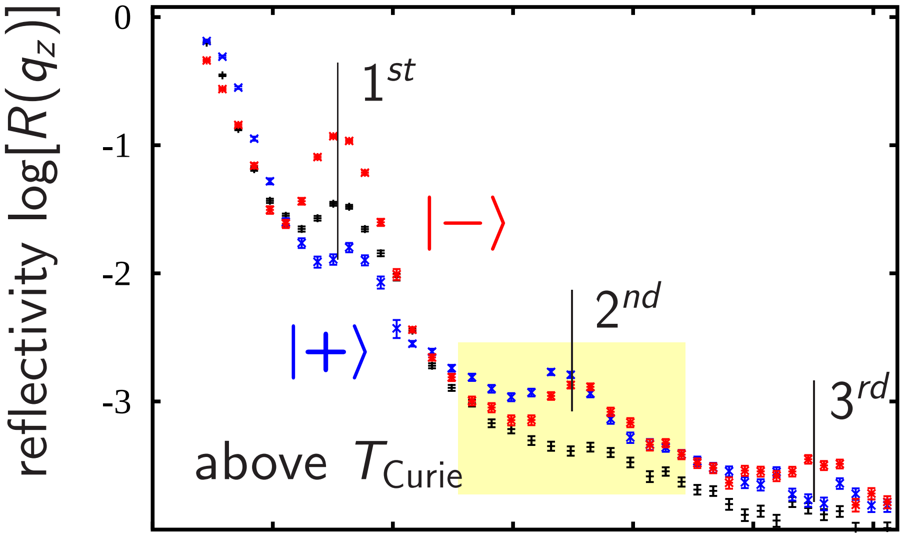
sharp contrast at the interface

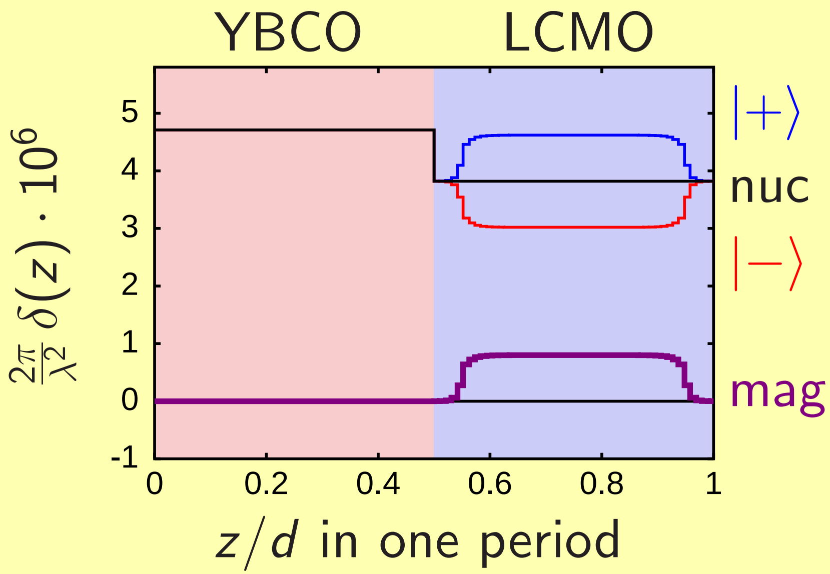
exponential decay into YBCO

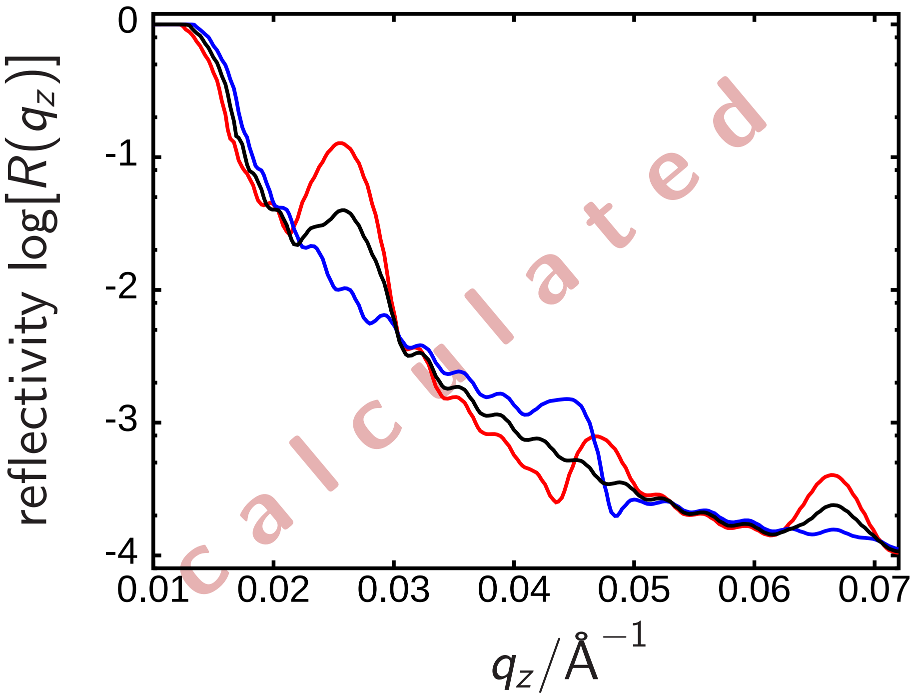
AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO





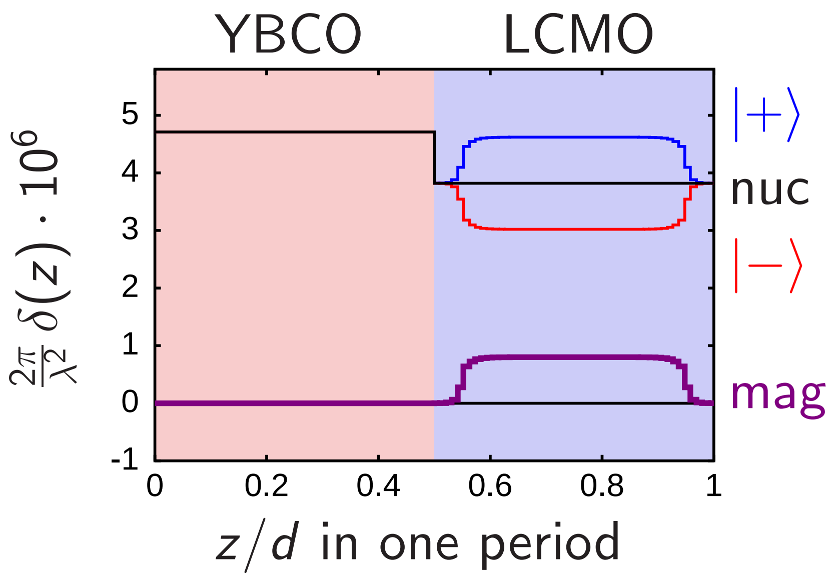


résumé

PNR at RT and below T_{Curie} and T_{c} exclude *all* models besides

AFM-region within LCMO

charge-injection from YBCO leads to a doping of LCMO and thus to an AFM ground state



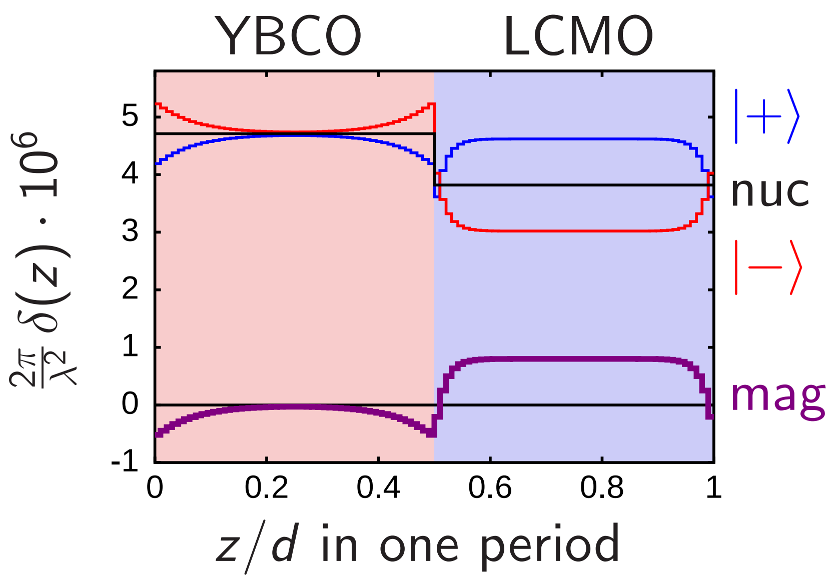
antiphase magnetic proximity effect

AF coupling of Mn and Cu moments through oxygen

or

Cooper pairs penetrate into LCMO and are *polarised*

⇒ antiparallel magnetisation in YBCO



résumé

PNR at RT and below T_{Curie} and T_c
exclude *all* models besides

AFM-region within LCMO

charge-injection from YBCO leads to a doping of LCMO and thus to an AFM ground state

PRB **69**, 174504 (2004):

F. S. BERGERET, A. F. VOLKOV AND K. B. EFETOV

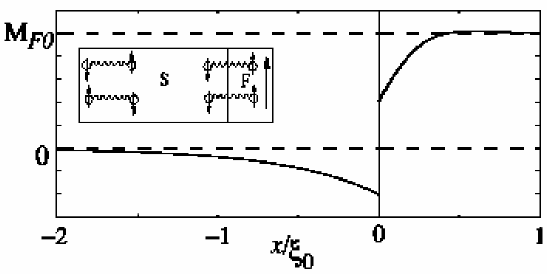
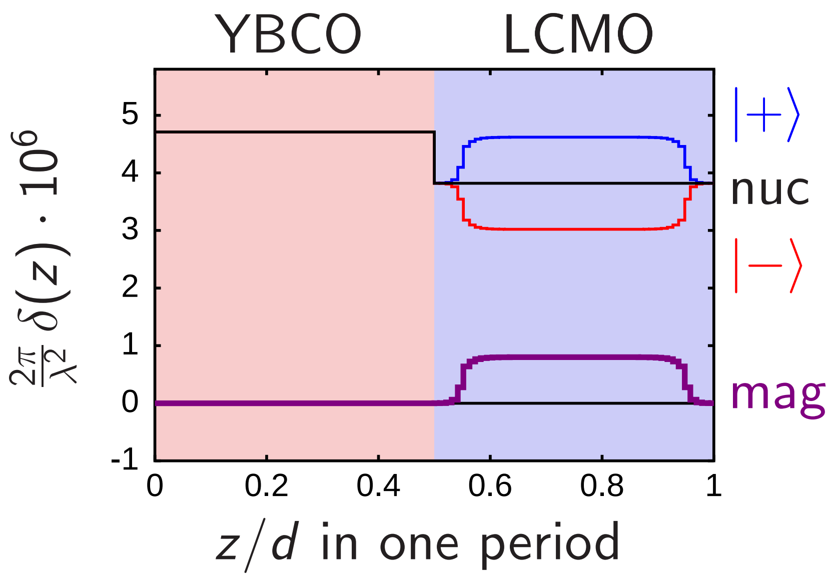
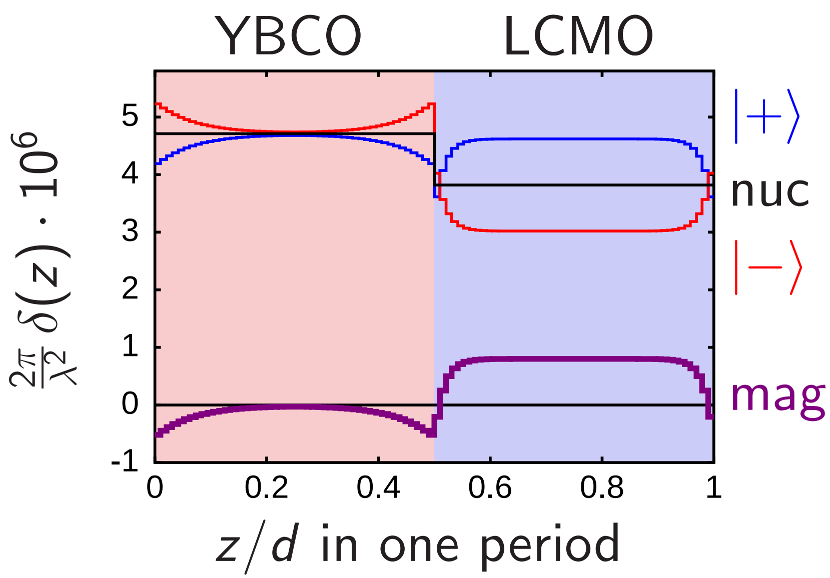


FIG. 1. Spatial dependence of the magnetization in the whole system. Here $\gamma_F/\gamma_S=0.5$, $\bar{\gamma}_F=\gamma_F/\xi_0=0.1$ ($\xi_0=\sqrt{D_S/2T_c}$), $J/T_c=15$, and $d_F/\xi_0=1$. Inset: Schematic view of the inverse proximity effect in a S/F system (for discussion see text).





magnetometry

SQUID measurements by F. Treubel, Konstanz

$T = 5\,\mathrm{K}$

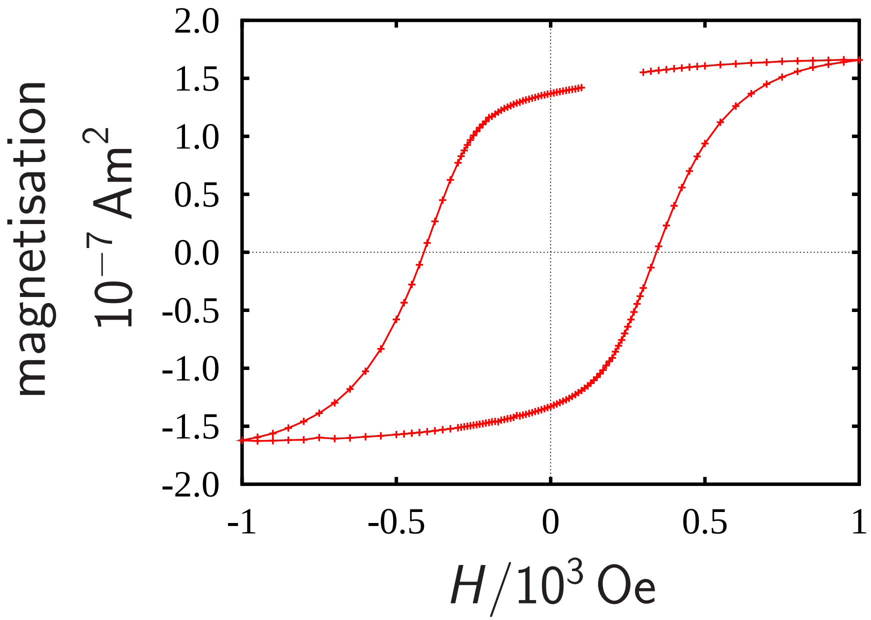
cooled in $H = 100\,\mathrm{Oe}$

coercive field $H_{co} \approx \pm 400\,\mathrm{Oe}$

exchange bias $H_{eb} \approx -60\,\mathrm{Oe}$

$\Downarrow$

presence of an AFM coupling
at the FM-interface



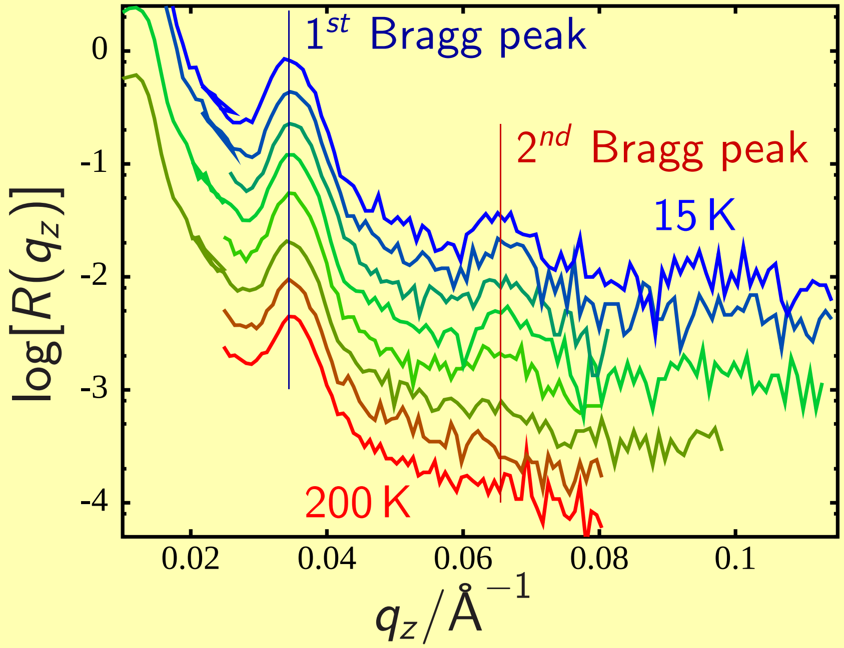
but:

– *magnetically dead layer* might be an AFM

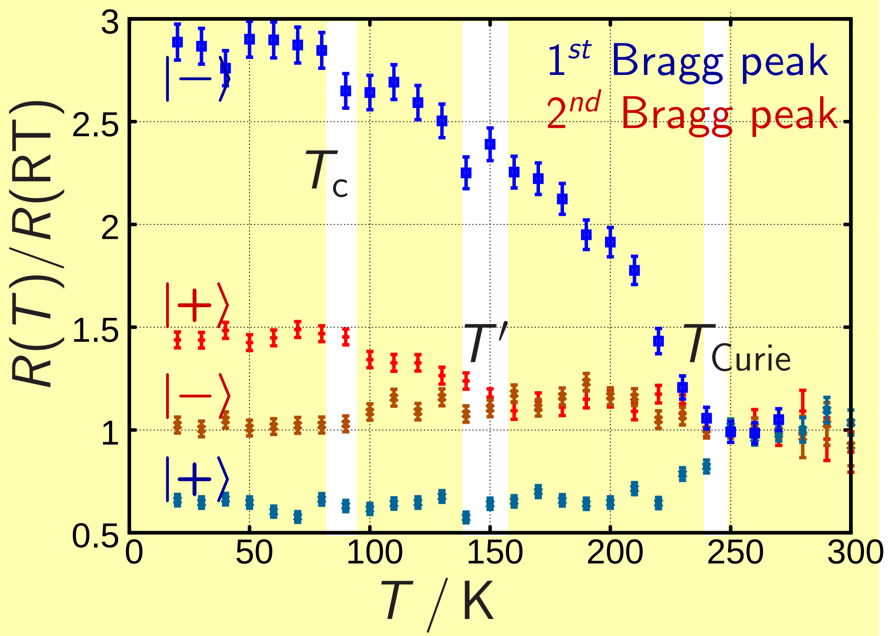
– **B** in YBCO might be an AFM with net magnetic moment

T dependence of $R(q_z)$

$[\text{YBCO}(100\,\text{Å})/\text{LCMO}(100\,\text{Å})]_7$



$[\text{YBCO}(200\,\text{Å})/\text{LCMO}(200\,\text{Å})]_8$

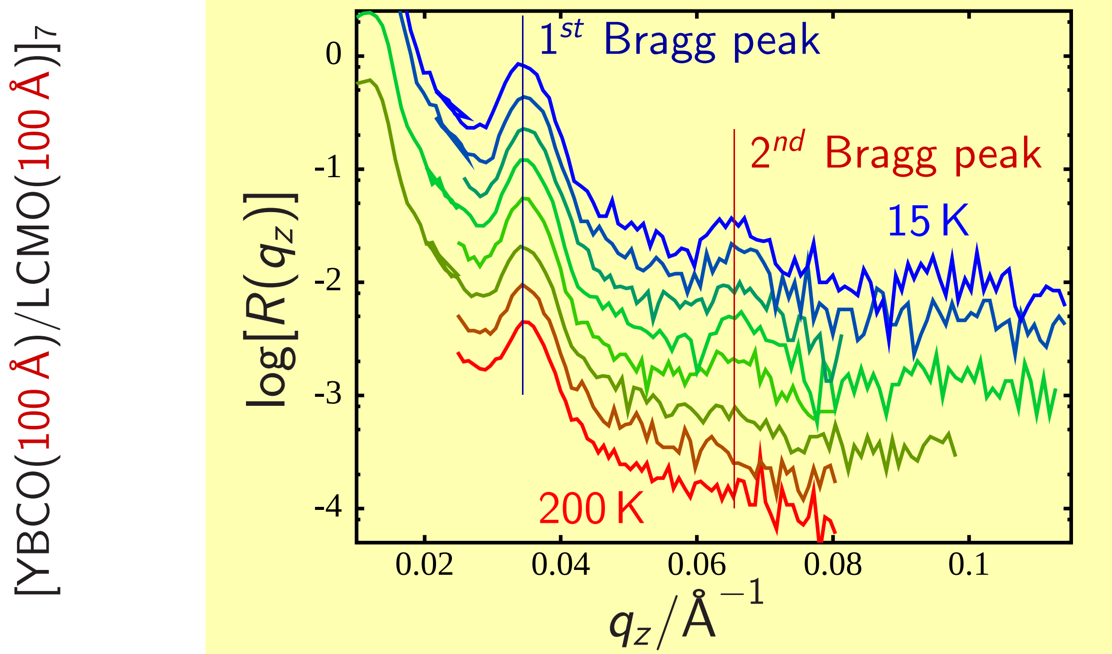


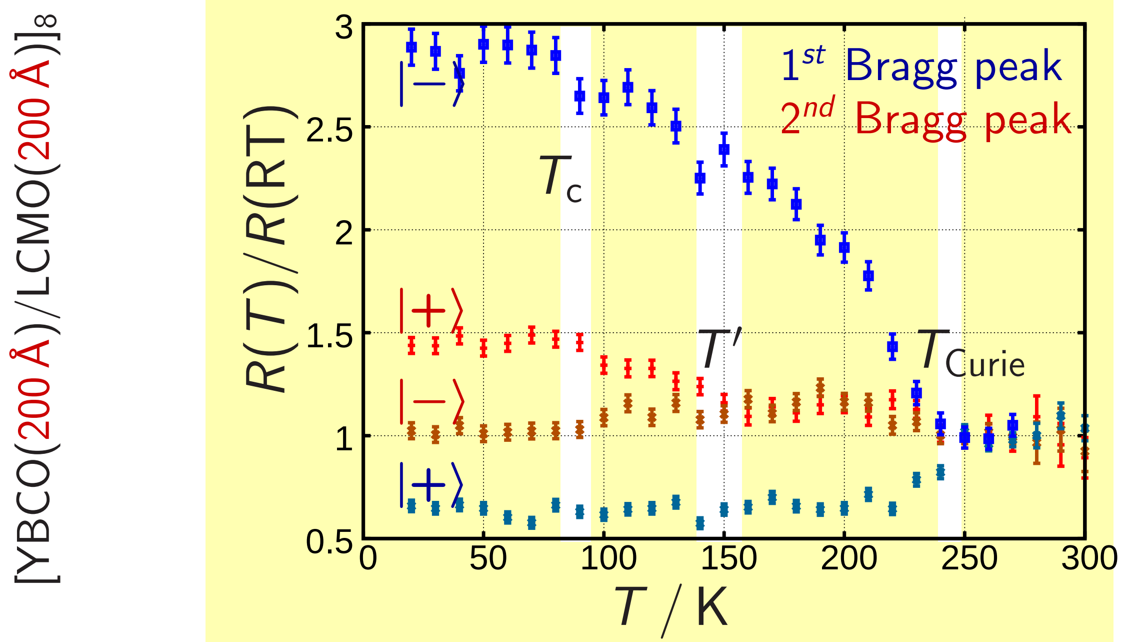
T_{Curie} $(160 \longrightarrow 270\,\text{K})$
onset of FM: changed contrast

T' $(\approx 140\,\text{K})$
formation of 2nd peaks
$B(z)$ and $V_{\text{nuc}}(z)$ differ

T_c $(60 \longrightarrow 90\,\text{K})$
onset of SC

T dependence of $R(q_z)$





T_{Curie} (160 → 270 K)

onset of FM: changed contrast

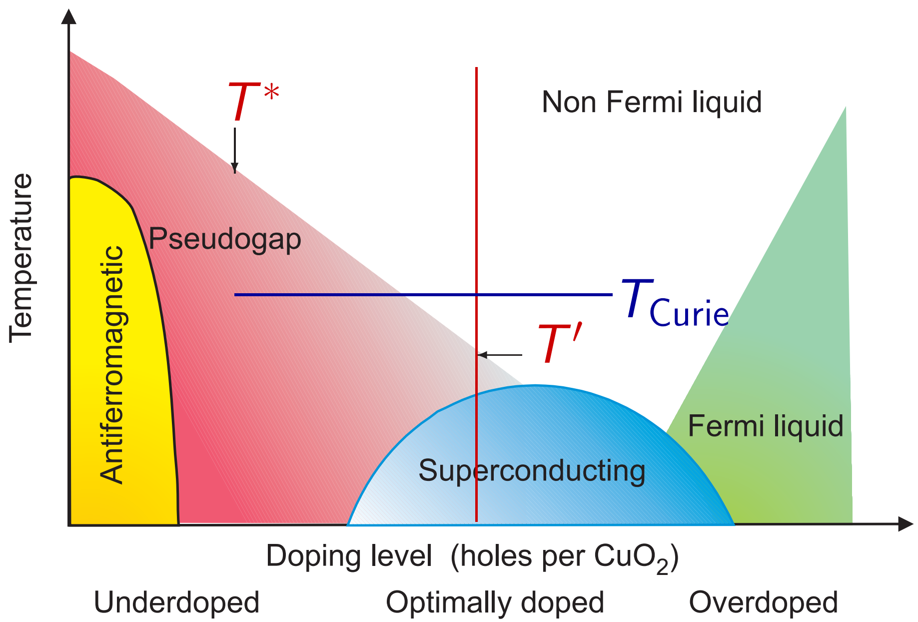
$T' \approx T^*$ ($\approx$ 140 K)

formation of 2nd peaks

$B(z)$ and $V_{nuc}(z)$ differ

T_c (60 → 90 K)

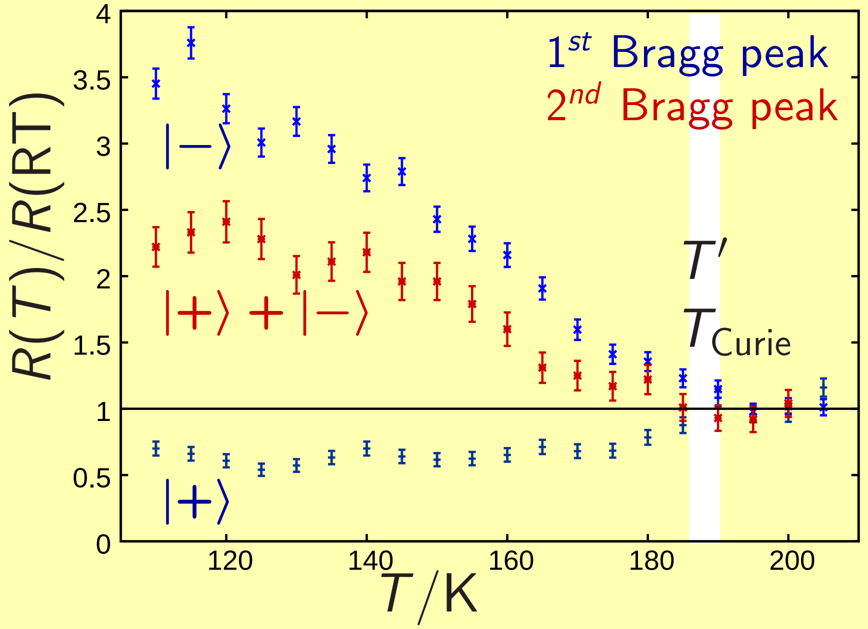
onset of SC



T dependence of $R(q_z)$

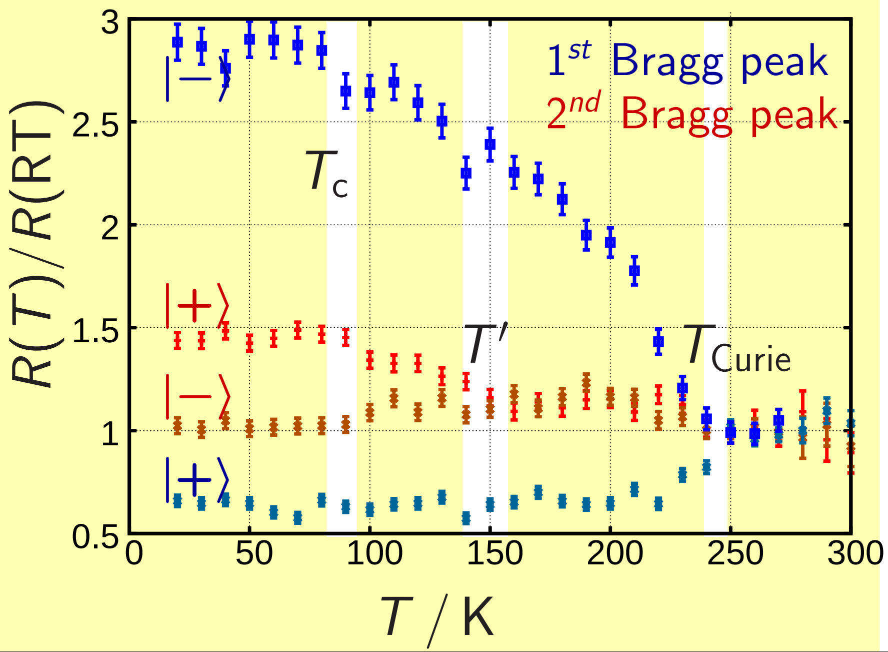
$[YPBCO(200\,Å)/LCMO(200\,Å)]_8$

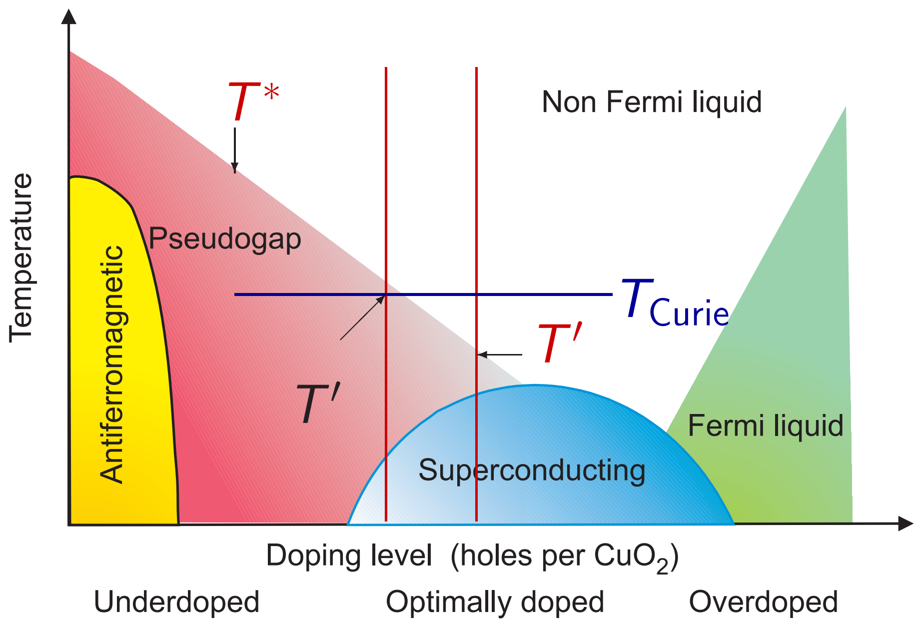
$Y_{0.6}Pr_{0.4}Ba_2Cu_3O_7$



$T' \approx T^*$ varies with doping!

$[YBCO(200\,Å)/LCMO(200\,Å)]_8$





overview

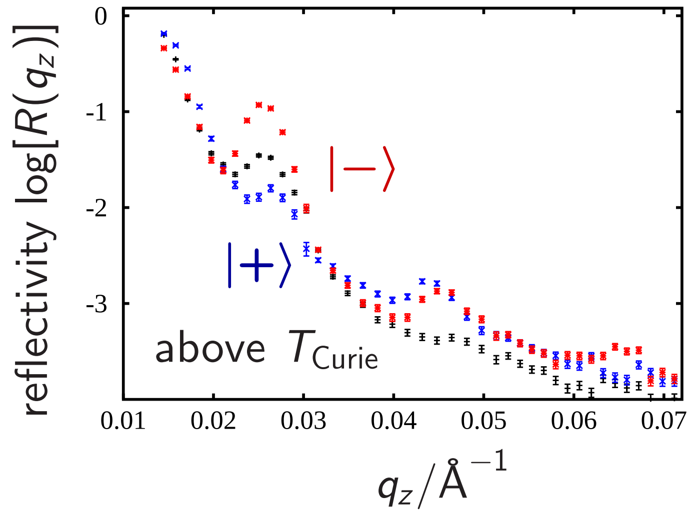
question: What is the magnetic induction (profile) in HTSC / FM multilayers?

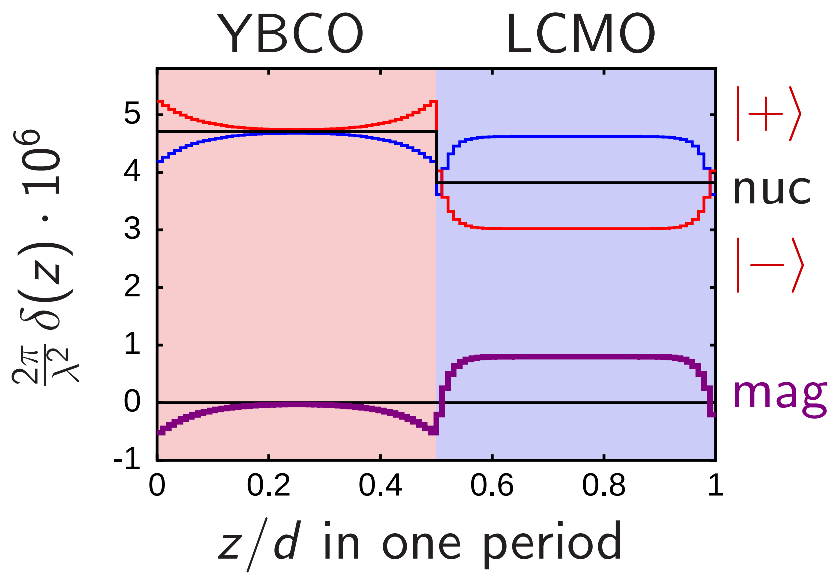
method: polarised neutron reflectometry allows for the determination of $\rho(z)$ and $\mathbf{B}_{\parallel}(z)$

answers: FM layers magnetised parallel

net magnetic moment in SC at the interfaces, antiparallel to FM magnetisation

SC creates and aligns domain walls in FM





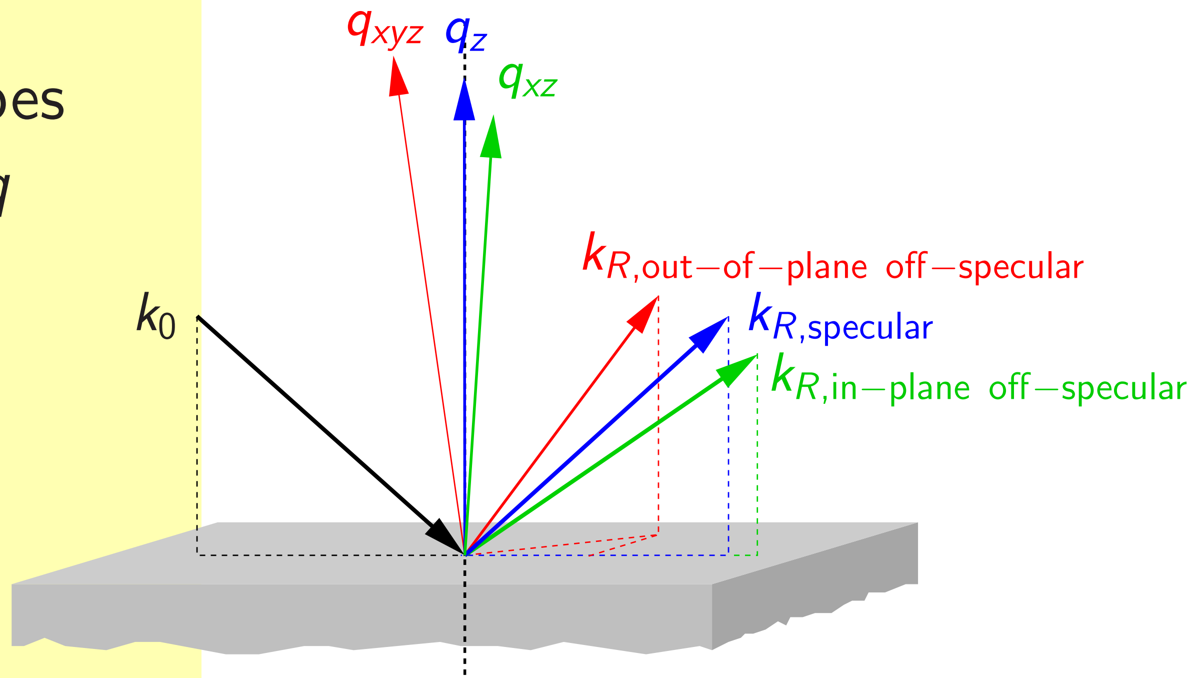
off-specular scattering principle

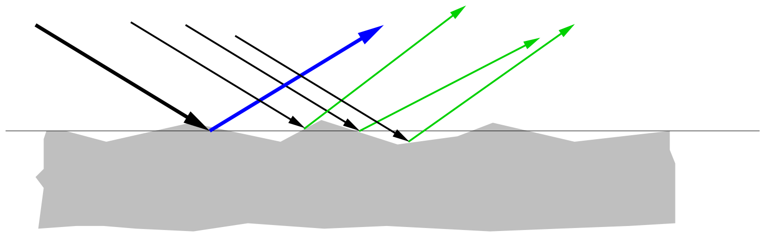
neutron scattering probes a potential parallel to q

if $q \neq q(z)$ also lateral structure is accessible

here:
lateral and vertical correlation length of (magnetic) inhomogeneities

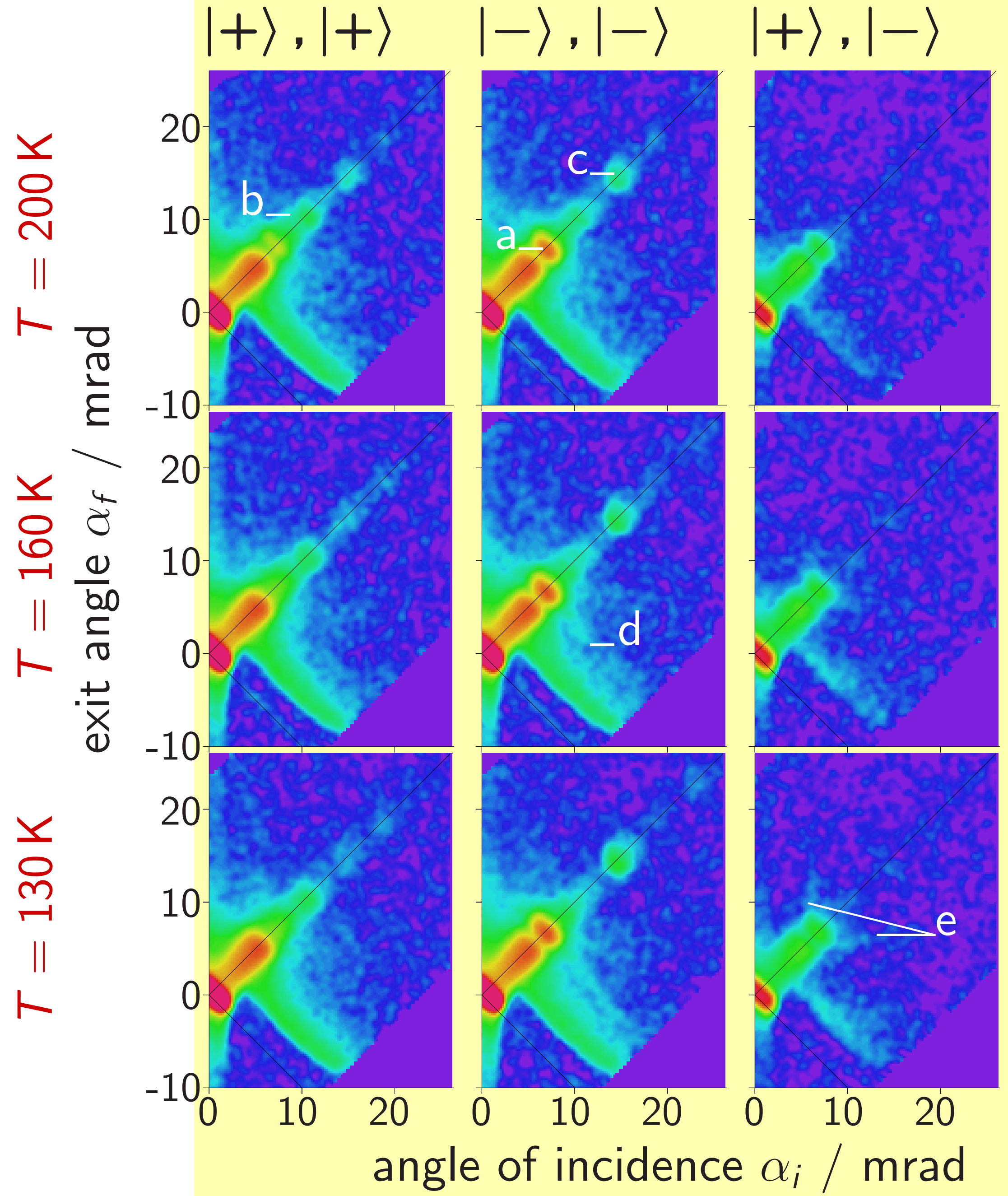
in our cases:
resolution in x: $\approx 0.01^\circ$
resolution in y: $> 1^\circ$
$\Rightarrow$ integrated over y





inclined surface facetts $\Rightarrow \Delta\omega$
height-variation $\Rightarrow$ phase-shifts in k_R
$\Rightarrow$ damping of $R(q_z > q^c)$

off-specular scattering measured on HADAS@Jülich



No off-specular sheets at RT or 200 K
⇒ no structural roughness detectable

Increase of the Bragg sheet at 1st Bragg peak (d) below 160 K
⇒ magnetic roughness, correlated vertically

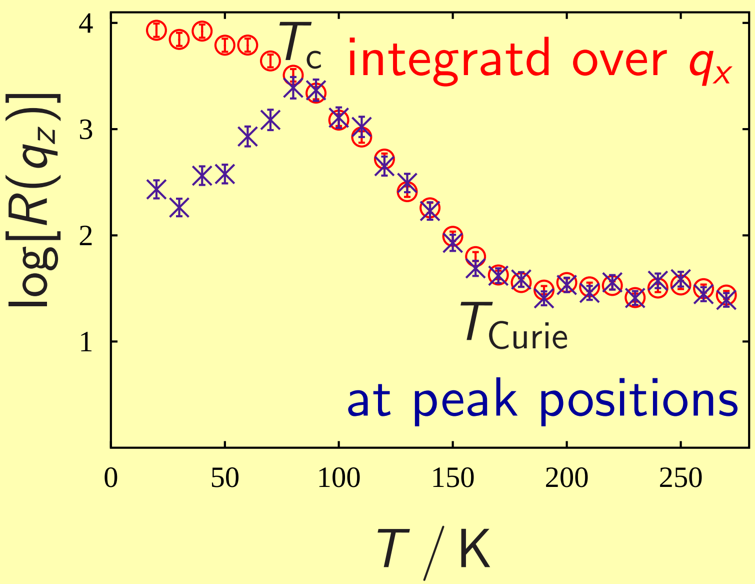
Appearance of sheets in the spin-flip channel (e)
⇒ magnetic moments not parallel to the neutron spins

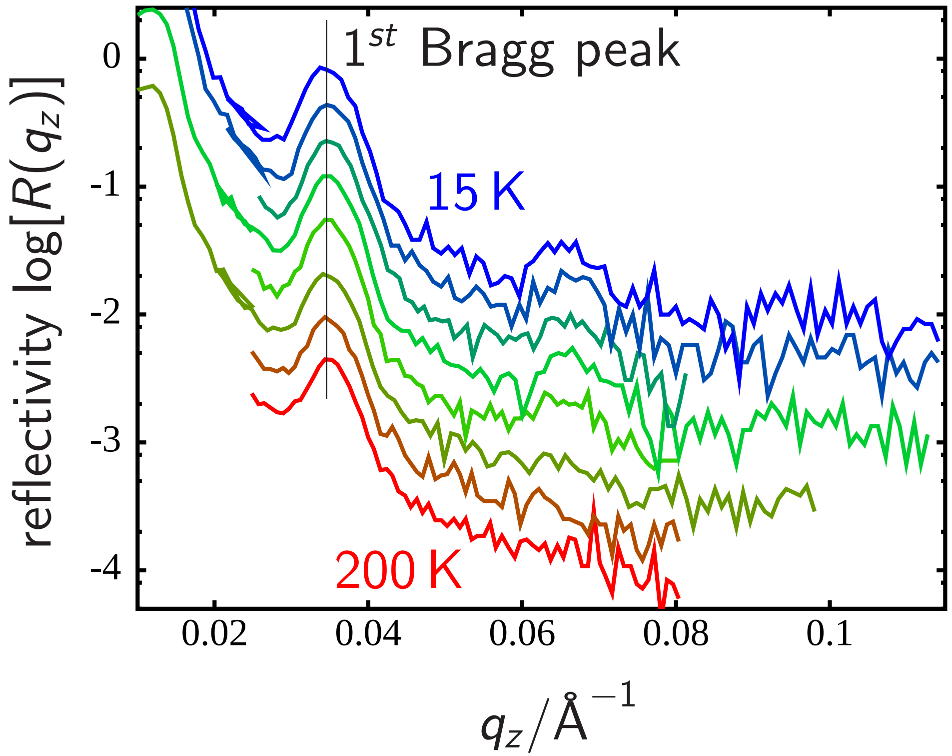
Interpretation (of all measurements):
Magnetic domains of similar size (≈ 5 to 10μm) are formed in the LCMO layers. These are correlated through YBCO over the whole stack.

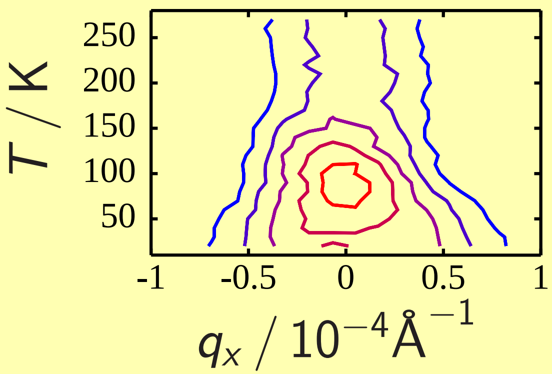
off-specular scattering ω**-scans**

non-polarised, various T

sample: $[YBCO(100\,Å)/LCMO(100\,Å)]_7$

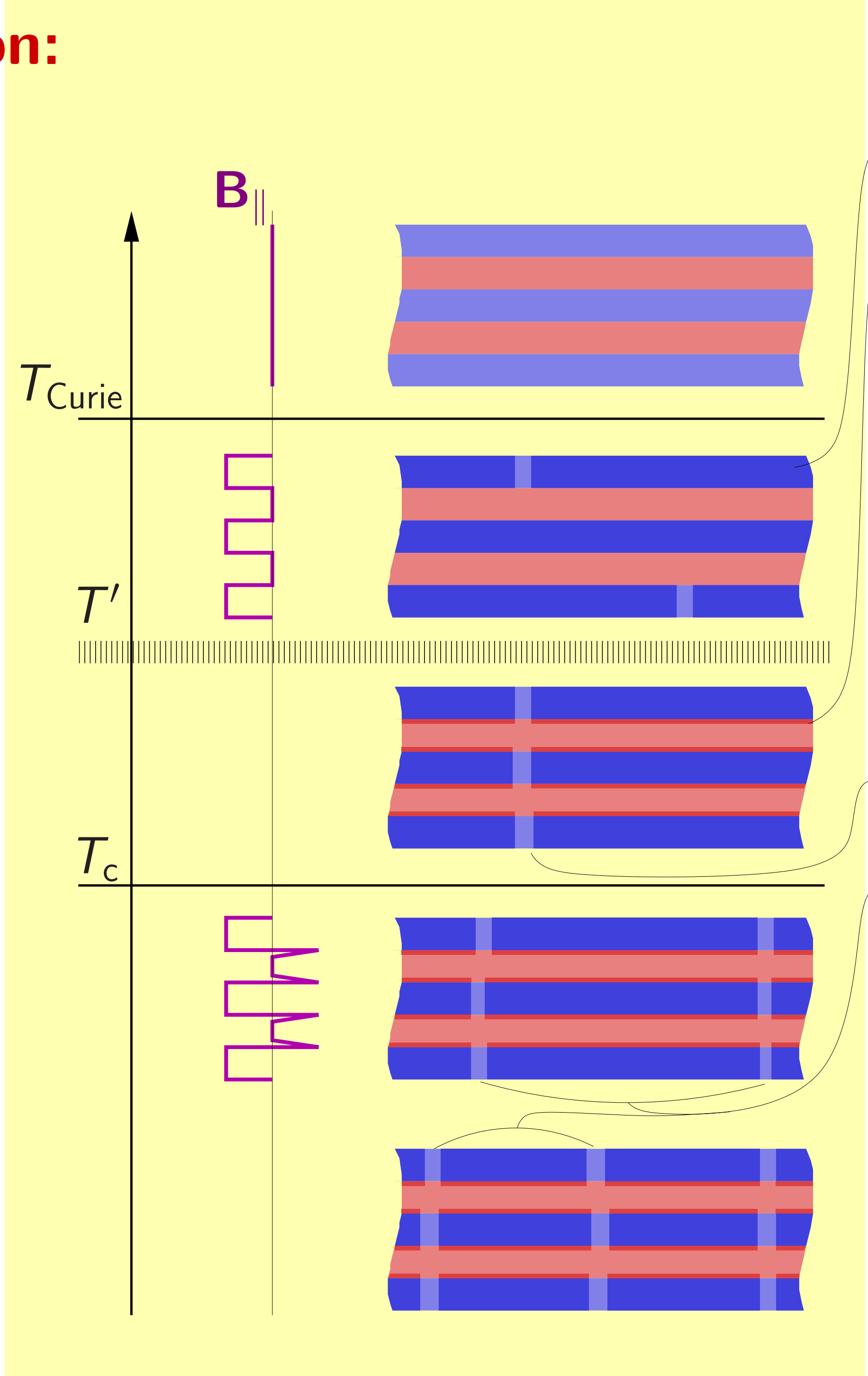






magnetic domains shrink below T_c
from 10 μm to 5 μm when cooling

conclusion:



- all LCMO layers are magnetised parallel
- interface effect of $\mathbf{B}(z)$ of the order of 10 Å is measured at $T_c < T' \approx 140\,\mathrm{K} < T_{Curie}$

– *magnetic dead layer* or *antiphase proximity effect*

- simultaneous appearance of Bragg-sheets

– vertical correlation of magnetic domains

- increase of off-specular scattering below T_c

– shrinking of magnetic domains / characteristic lengthscale

- correlation of domain size with $T < T_c$ and XMCD measurements support the *antiphase proximity effect*

essence

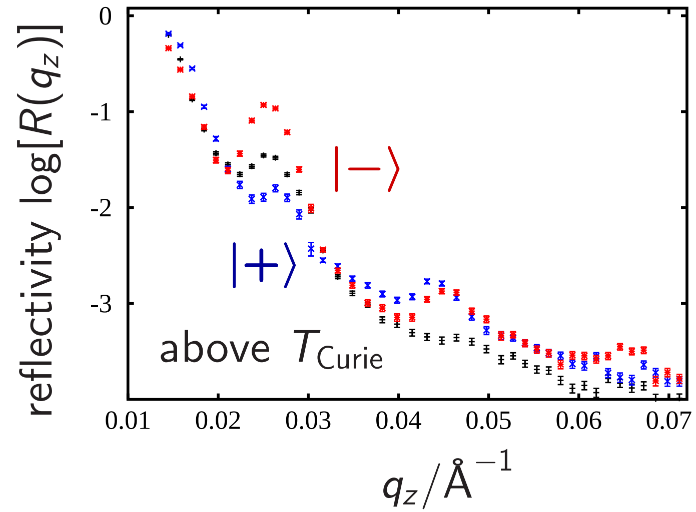
question: What is the magnetic induction (profile) in HTSC / FM multilayers?

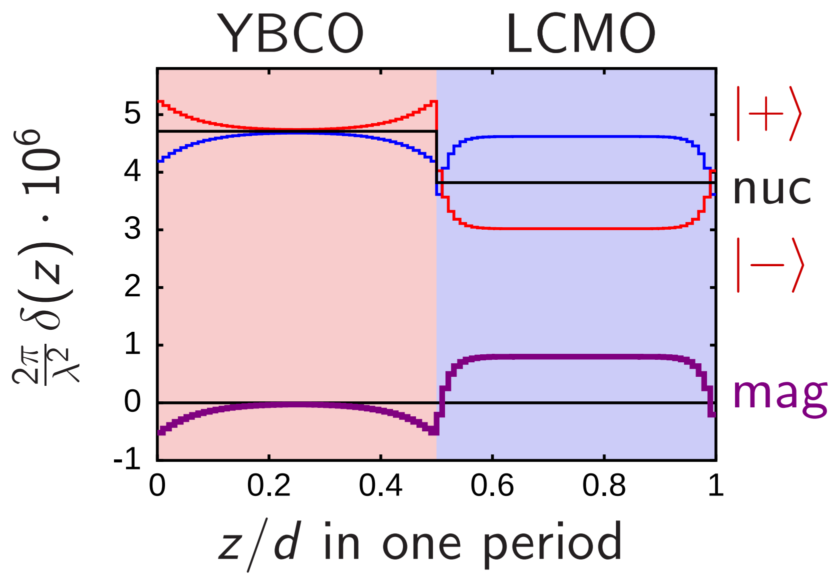
method: polarised neutron reflectometry allows for the determination of $\rho(z)$ and $\mathbf{B}_{\|}(z)$

answers: FM layers magnetised parallel

net magnetic moment in SC at the interfaces, antiparallel to FM magnetisation

SC creates and aligns domain walls in FM





THE END