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Neutron Reflectometry as a Probe of Magnetic Profiles in HTSC/FM Multilayers

17. 03. 2005

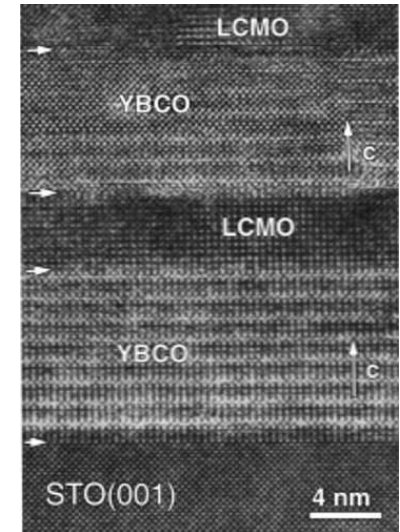
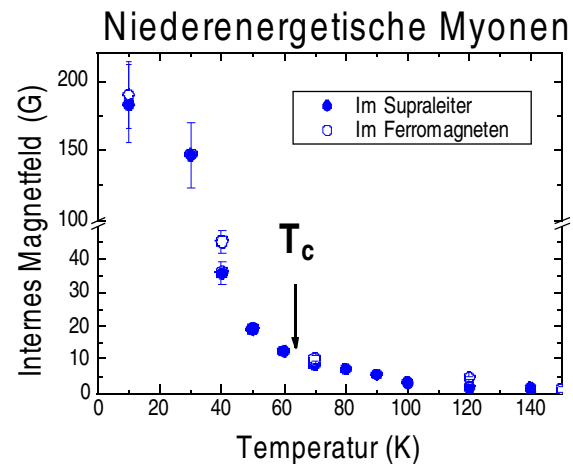
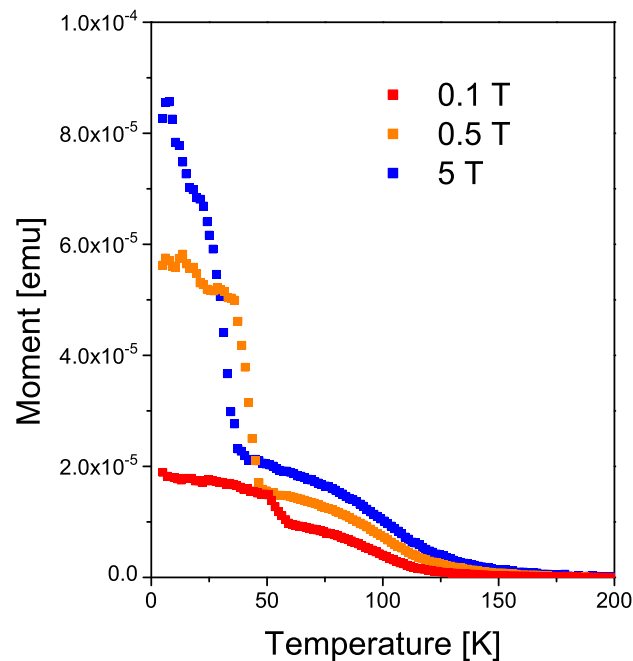
short version of the seminar given at the
MPI-FKF at Stuttgart 22. 10. 2004

motivation / history:

spring 2003:

C. N. presents nice μ SR and magnetisation measurements at PSI

no explanation at that time.



method of choice
(for a neutron scatterer):

neutrons!

in particular *polarised n-reflectometry*

outline:

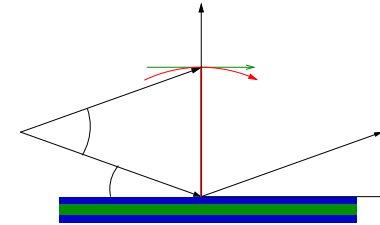
introduction to neutron reflectometry

principles

specular (unpolarised / polarised)

off-specular

$$n = \sqrt{1 - V/E} \approx 1 - V/2E \\ \approx 1 - \delta \quad \text{with } |\delta| < 10^{-5}$$



literature: P. Mikulík: thesis

V. Holý *et al.*: Springer Tracts in Modern Physics, Vol. 149

J. Daillant *et al.*: Lecture Notes in Physics, m 58

and in parallel (if possible)

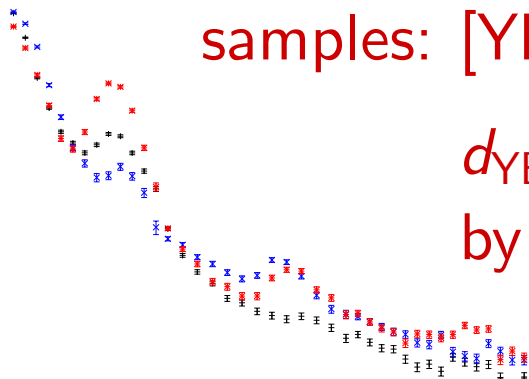
presentation of recent measurements on YBCO / LCMO multilayers

cooperation with J. Chakhalian, C. Bernhard & B. Keimer, MPI-FKF

samples: $[\text{YBa}_2\text{Cu}_3\text{O}_7 (d_{\text{YBCO}}) / \text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3 (d_{\text{LCMO}})]_n$

$d_{\text{YBCO}} = d_{\text{LCMO}} = 100 \text{ \AA}$ and $150 \text{ \AA}$

by H.-U. Habermeier & G. Cristiani



principle of (n) reflectometry: specular, single surface, unpolarised

basis: *index of refraction* varies at the interface

$$\begin{aligned} \text{index of refraction} \quad n &= \sqrt{1 - V/E} \\ &\approx 1 - V/2E \\ &= 1 - \delta \end{aligned}$$

$$|\delta| < 10^{-5}$$

$$\text{kinetic energy} \quad E \propto k_0$$

$$\text{mean nuclear potential} \quad V \propto \sum_i \rho_i b_i$$

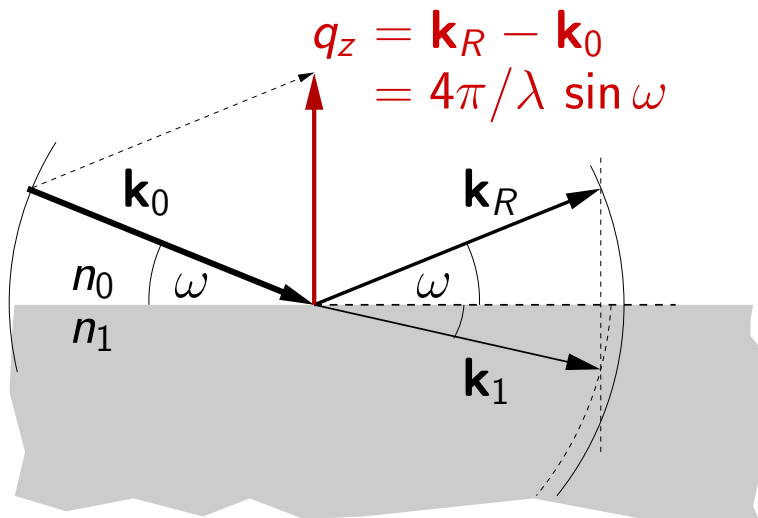
$$\text{nuclear scattering length} \quad b_i$$

$$k_j \neq k_0$$

$$\text{critical transfer} \quad q^c \approx 4\pi/\lambda \sqrt{2\delta}$$

$$\text{Fresnel reflectivity} \quad R^F(q_z) = |r(q_z)|^2$$

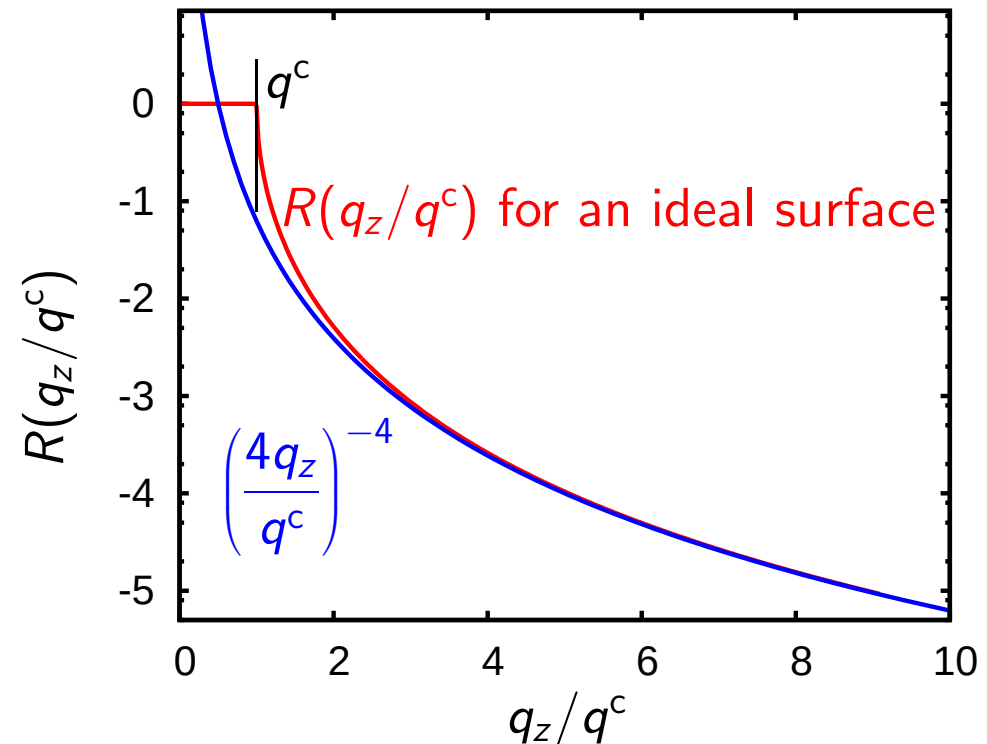
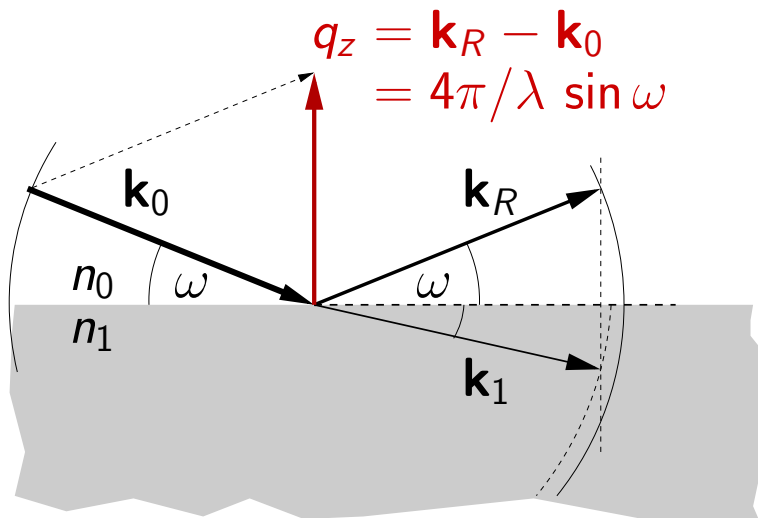
$$r(q_z) = \frac{1 - \sqrt{1 - (q^c/q_z)^2}}{1 + \sqrt{1 - (q^c/q_z)^2}}$$



principle of (n) reflectometry: specular, single surface, unpolarised

$$\text{Fresnel reflectivity } R^F(q_z) = \left| \frac{1 - \sqrt{1 - (q^c/q_z)^2}}{1 + \sqrt{1 - (q^c/q_z)^2}} \right|^2$$

$$\propto q_z^{-4} \text{ for } q_z > 3q^c$$



principle of (n) reflectometry: matrix -method to calculate R

stack of plane-parallel interfaces:

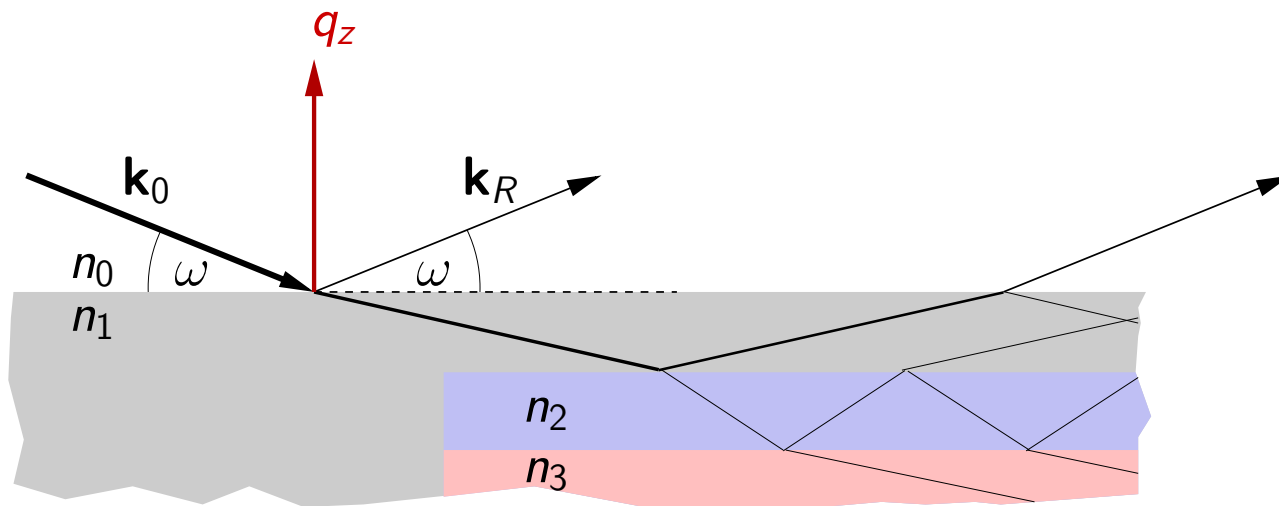
$$\mathbf{u}_i = \begin{pmatrix} u_{i,+} \\ u_{i,-} \end{pmatrix} \text{ with } \begin{cases} u_{i,+} \text{ up-traveling waves} \\ u_{i,-} \text{ down-traveling waves} \end{cases} \text{ in layer } i$$

$\mathbf{u}_i$ and $\mathbf{u}_{i+1}$ are connected by the refraction matrix: $\mathbf{u}_i = \mathbf{l}_{i,i+1} \mathbf{u}_{i+1}$

taking into account the phase shifts by a the transfer matrix $\mathbf{T}_i$ one gets

$$\mathbf{u}_0 = \mathbf{l}_{0,1} \mathbf{T}_1 \mathbf{l}_{1,2} \mathbf{T}_2 \dots \mathbf{T}_n \mathbf{l}_{n,s} \mathbf{u}_s = \mathbf{M} \mathbf{u}_s$$

where s denotes the semi-infinite substrate $\Rightarrow u_{s,+} = 0$.



$$\begin{aligned} \Rightarrow r &= \frac{u_{0,+}}{u_{0,-}} \\ &= \frac{M_{12}}{M_{22}} \\ R &= \left| \frac{M_{12}}{M_{22}} \right|^2 \end{aligned}$$

principle of (n) reflectometry: matrix -method to calculate R

stack of plane-parallel interfaces:

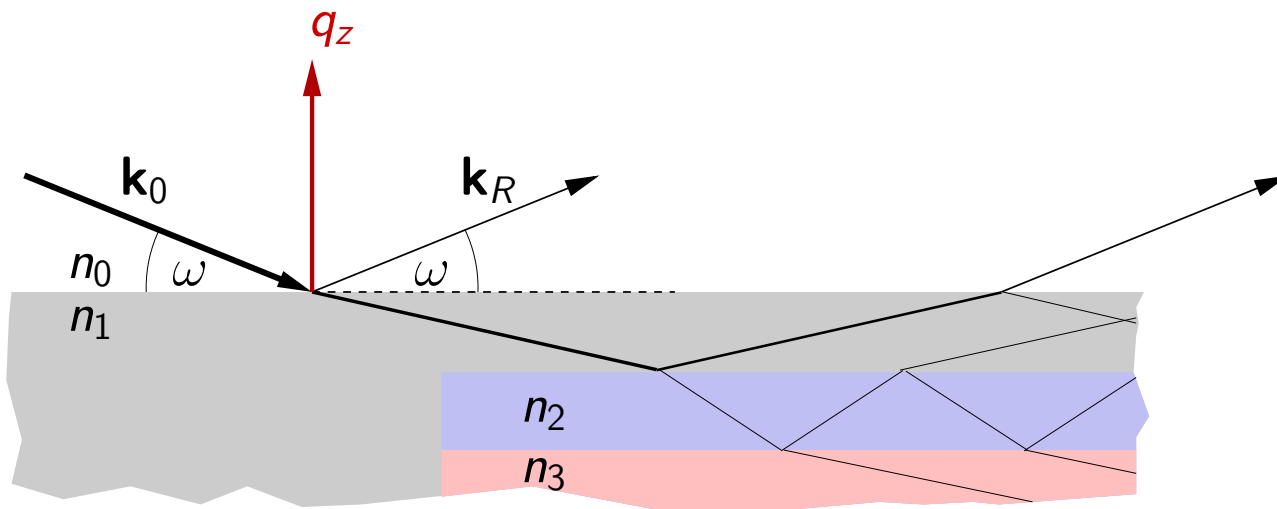
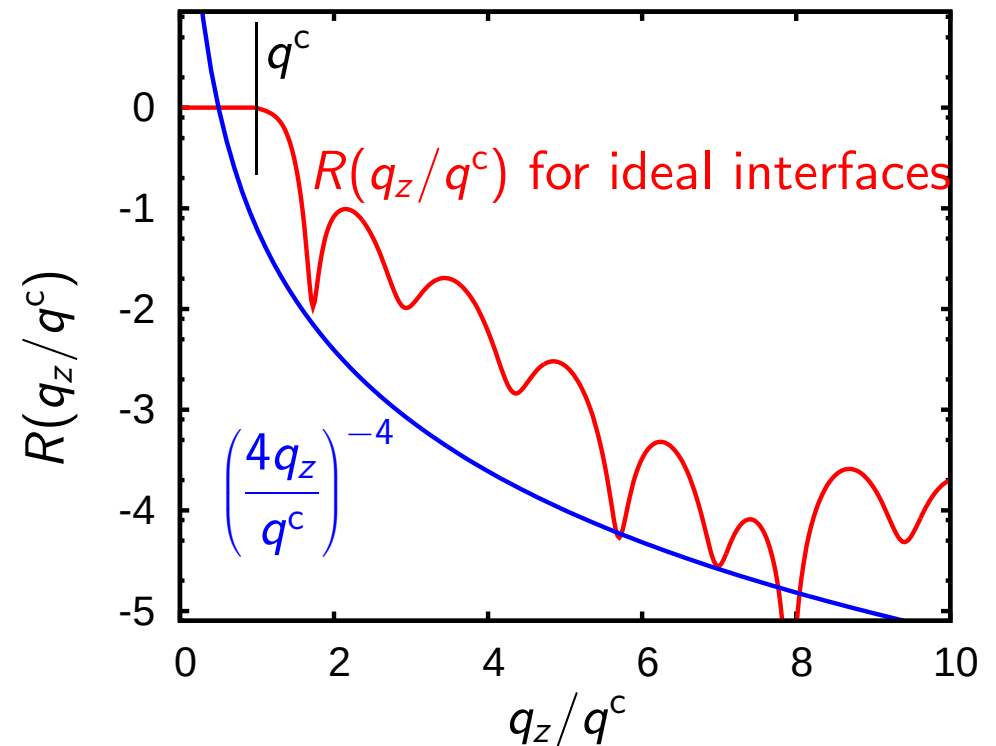
$$R(q_z) = \left| \frac{M_{12}}{M_{22}} \right|^2$$

dynamic theory, exact

kinetic theory

($q_z \gg q^c$, weak interaction):

$$R(q_z)/R^F(q_z) \propto |\mathcal{F}[\delta(z)]_{q_z}|^2$$



principle of (n) reflectometry: angle- vs. energy-dispersive

angle-dispersive

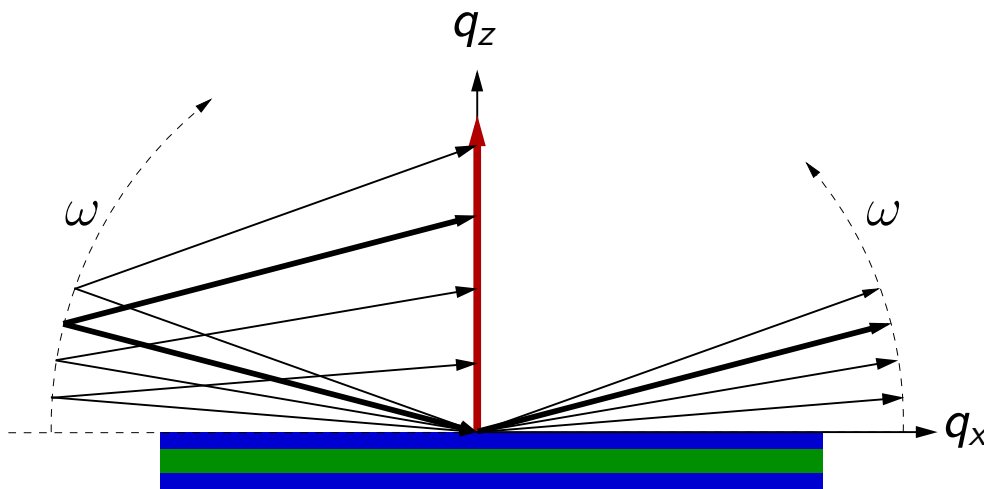
constant k_0

varying $\mathbf{k}_0/k_0$

2θ and ω are scanned

q_z scanned point by point

resolution: $\Delta\omega$



energy-dispersive

varying k_0

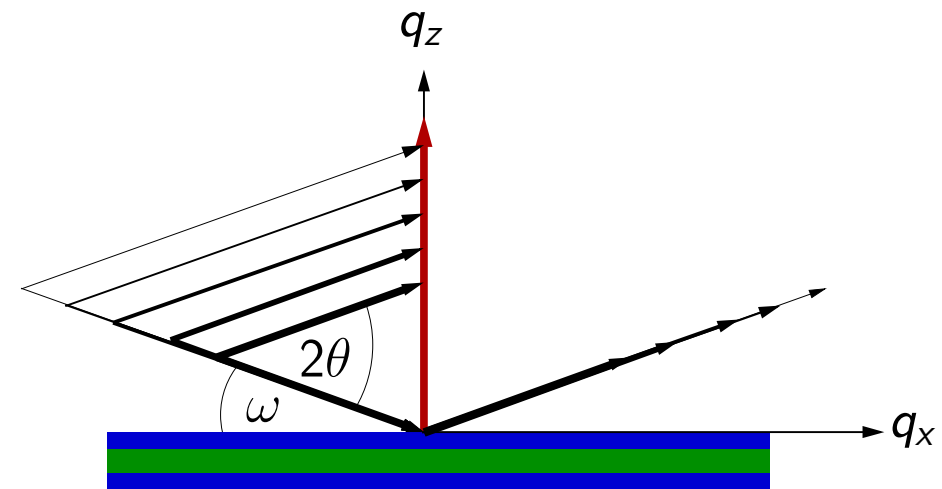
constant $\mathbf{k}_0/k_0$

2θ and ω are fix

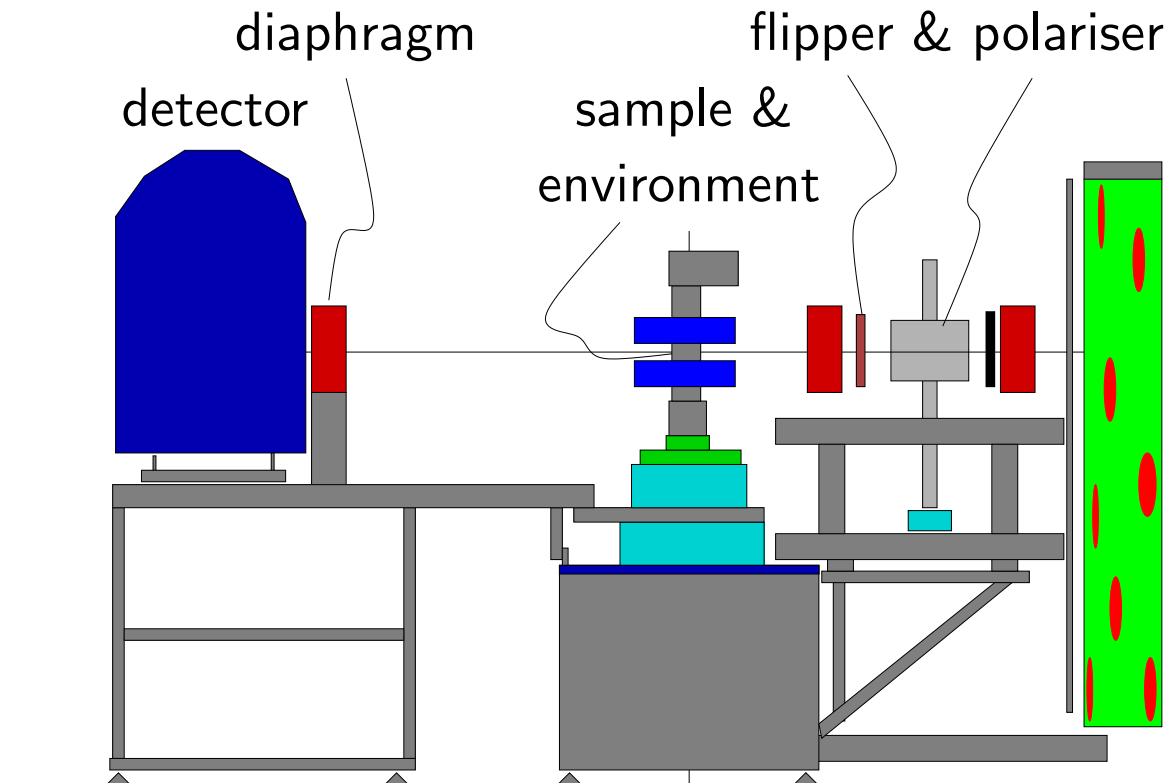
q_z -range covered by 1 shot

resolution: ΔE of detector

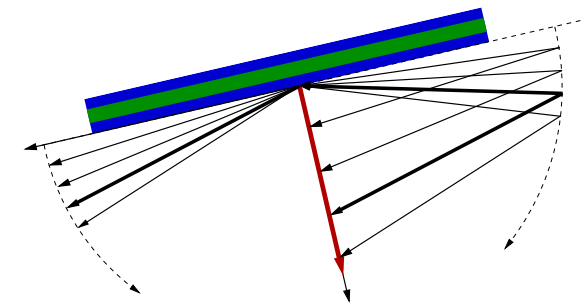
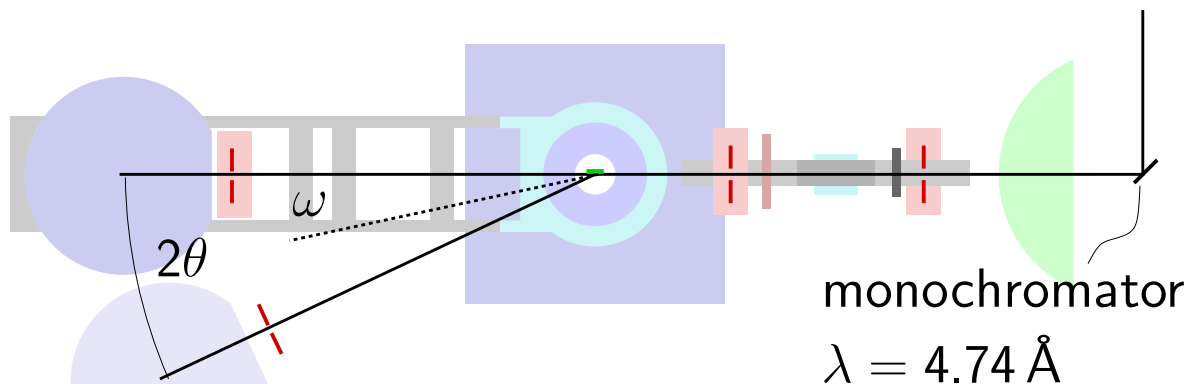
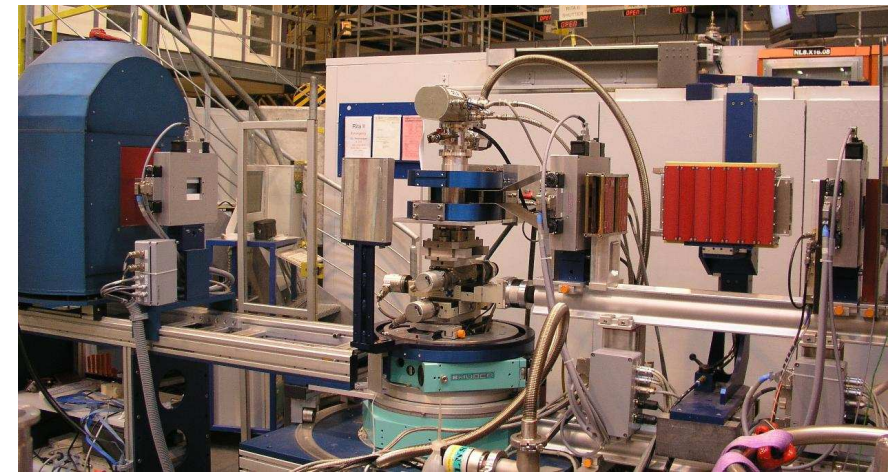
TOF: time-resolution



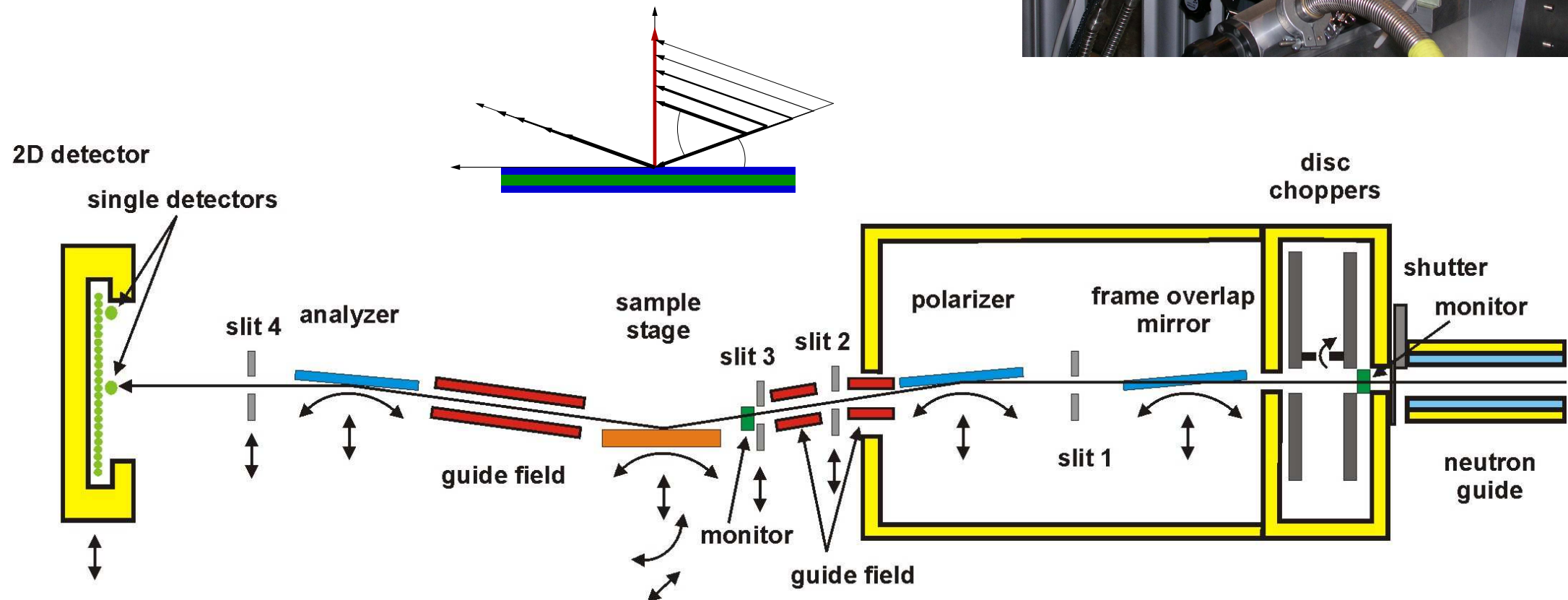
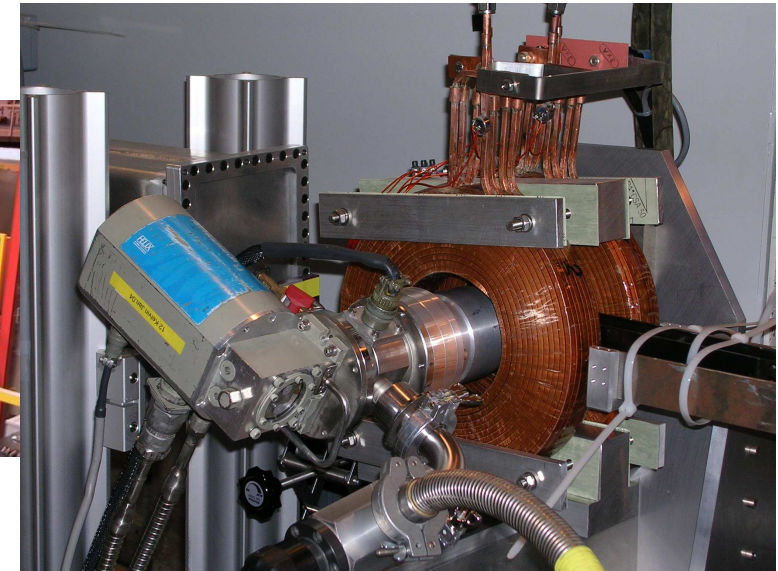
typical instruments: angle dispersive, Morpheus @ SINQ



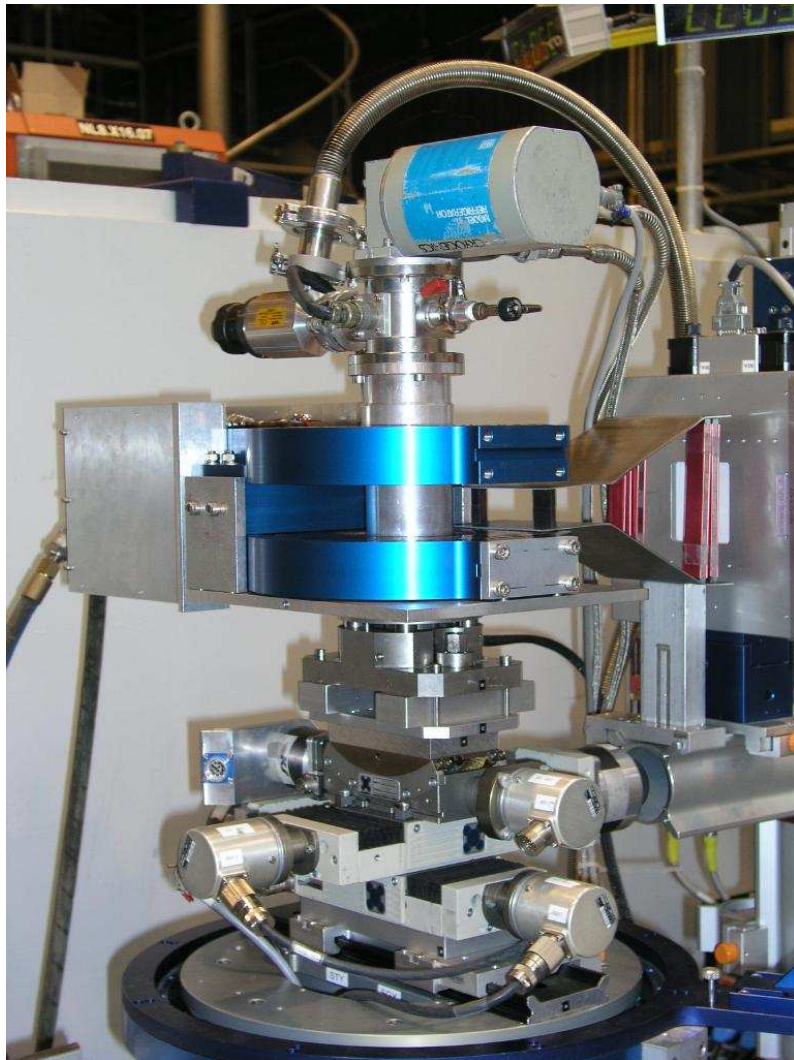
specular scan:
detector angle = $2 \times$ angle of incidence
 $2\theta = 2 \times \omega$



typical instruments: energy dispersive, AMOR @ SINQ



sample environment:



sample holder
with absorber



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

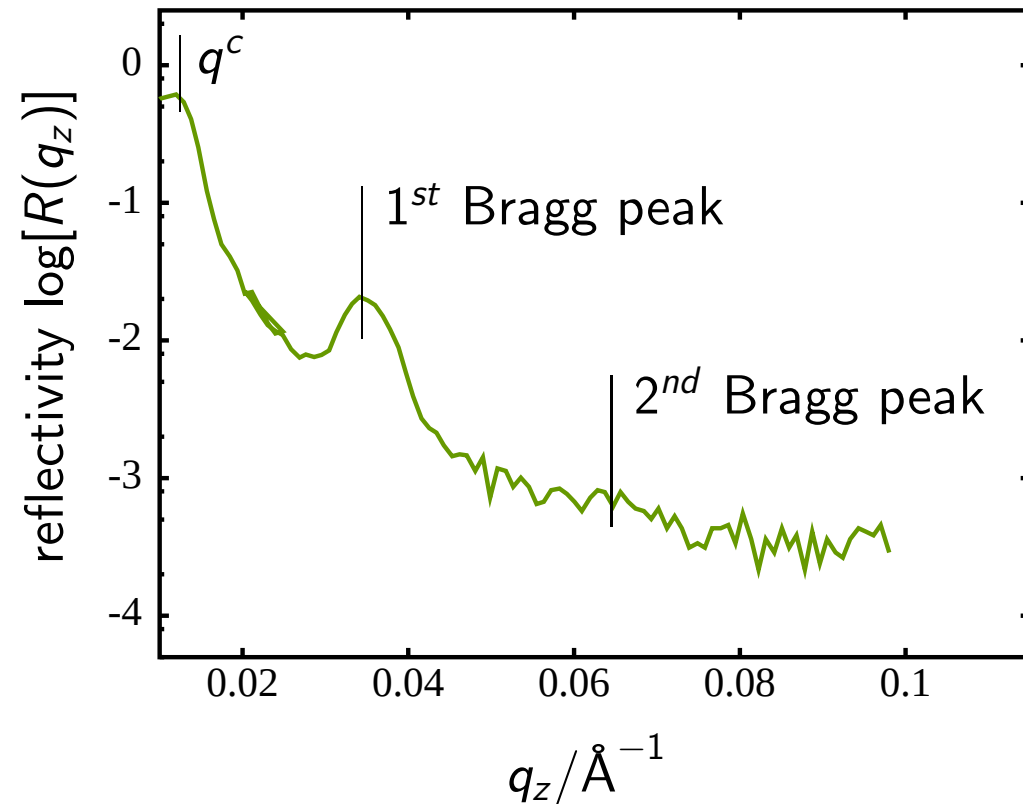
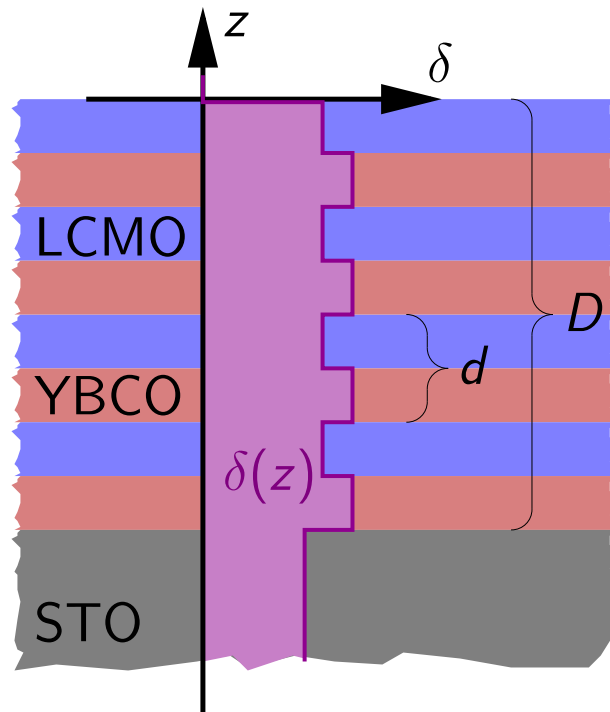
Helmholtz coils
 $H \leq 1000\text{ Oe}$
vol: $40 \times 40 \times 40\text{ mm}^3$

translation stages for alignment

ω -rotation stage

specular measurements: periodic ml, non-polarised, above T_m

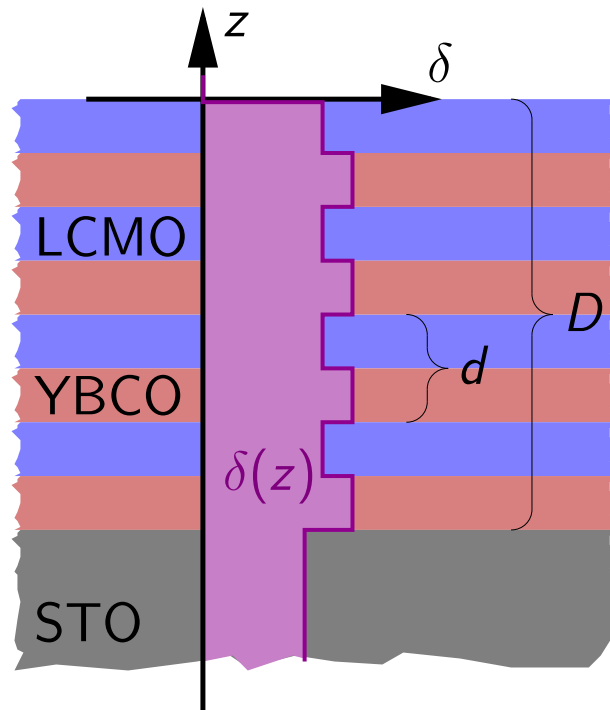
sample: $[\text{YBCO}(100 \text{ \AA})/\text{LCMO}(100 \text{ \AA})]_7$



- edge of total external reflection $q_c \propto \sqrt{2\delta}$
- appearance of a Bragg-peak

specular measurements: periodic ml, ideal case

sample: $[\text{YBCO}(100 \text{ \AA})/\text{LCMO}(100 \text{ \AA})]_7$



periodicity in z -direction

$\Rightarrow$ 1D crystal

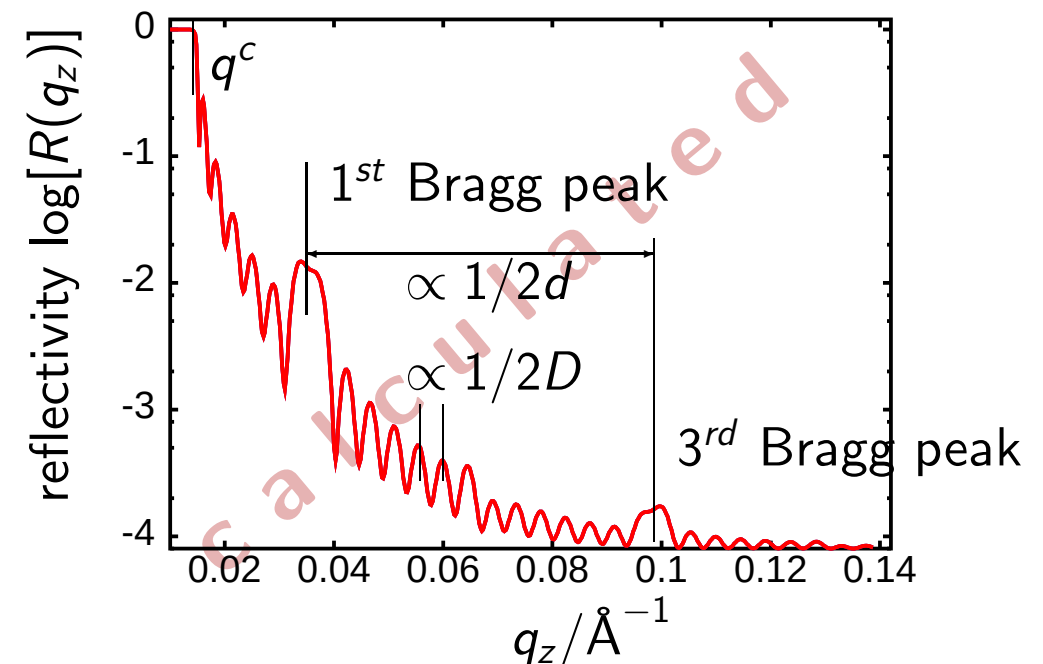
$\Rightarrow$ Bragg-peaks appear

intensity is determined by contrast in $\delta(z)$

intensity ratio is given by *structure factor*
of the *unit cell* = period d

$$t_{\text{YBCO}} = t_{\text{LCMO}}$$

$\Rightarrow$ extinction of all even orders

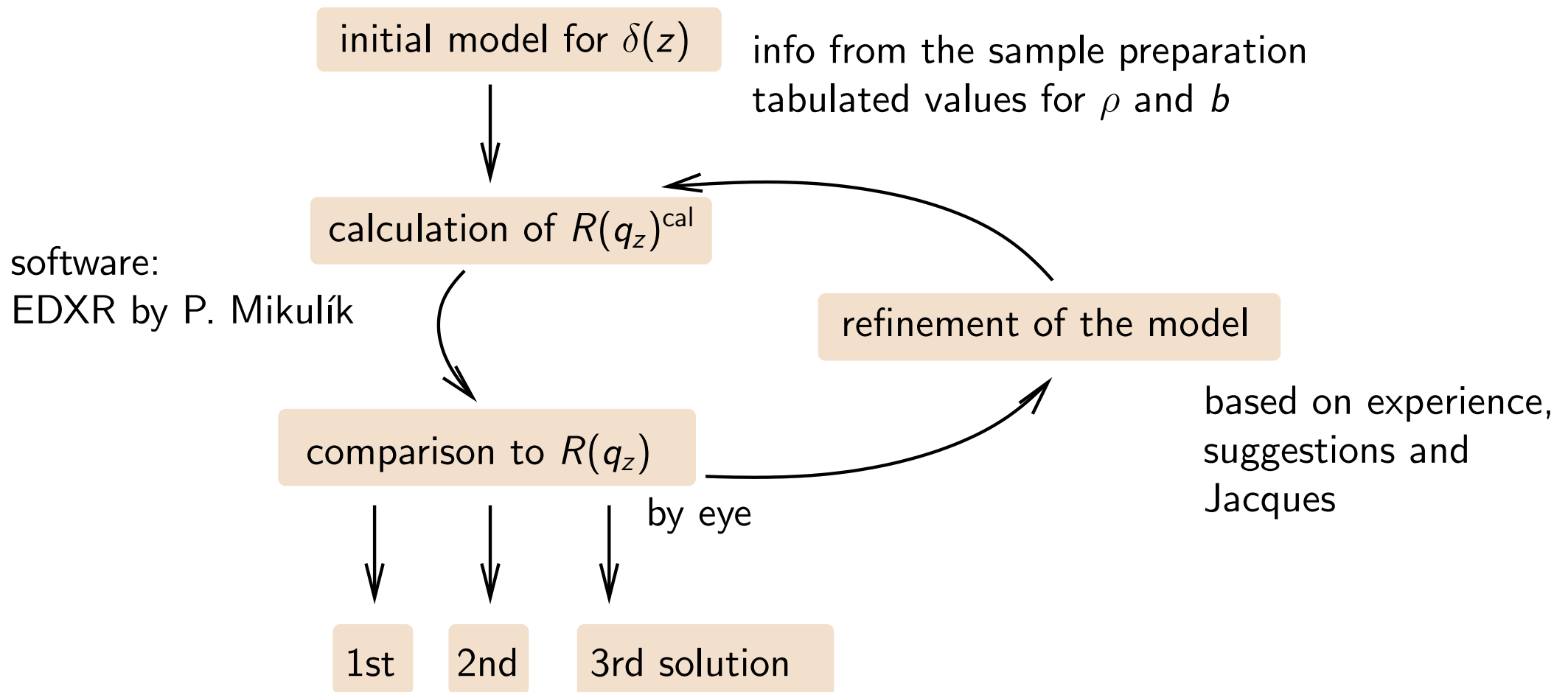


modelling: from $R(q_z)$ to $\delta(z)$

$$R(q_z) \propto |\mathcal{F}[\Delta\delta(z)]_{q_z}|^2$$

$\Rightarrow$ lack of **phase** information

$\Rightarrow$ no direct way from R to $\delta(z)$



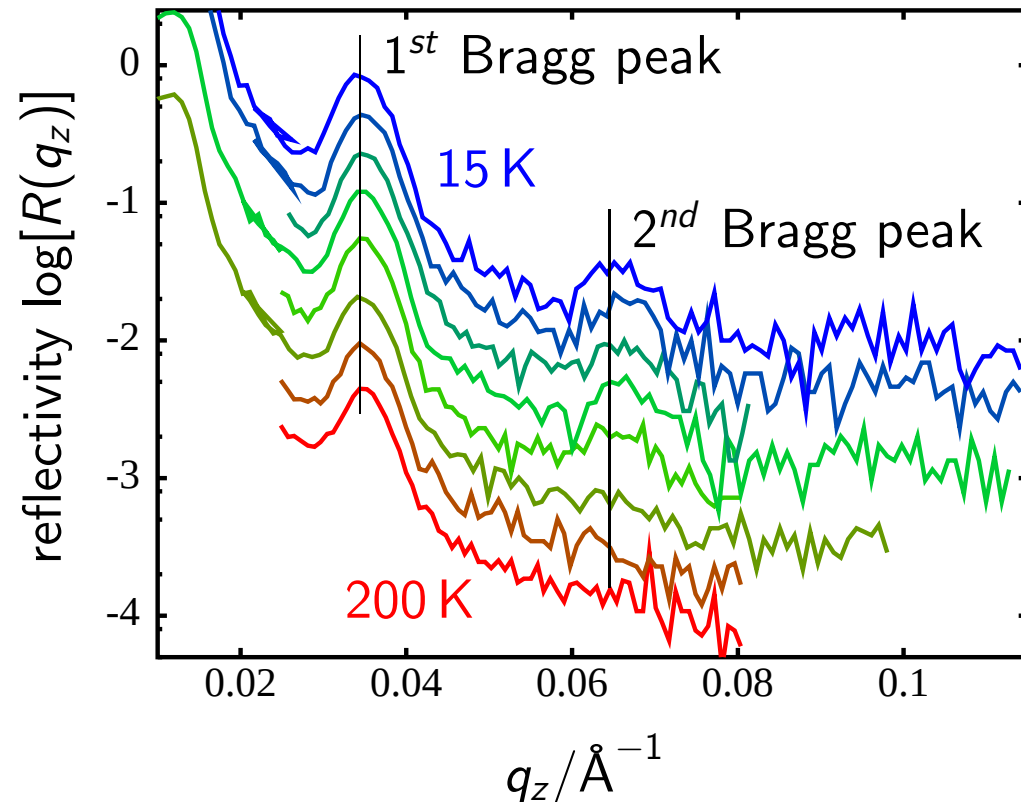
modelling: from $R(q_z)$ to $\delta(z)$

in the case $[\text{YBCO}(150 \text{ \AA})/\text{LCMO}(140 \text{ \AA})]_6$ the *free* parameters are:

	result	initial value
– bilayer thickness d	290 Å	400 Å
– thickness ratio $t_{\text{YBCO}} : t_{\text{LCMO}}$	15 : 14	1 : 1
– densities ρ_{YBCO} and ρ_{LCMO}	100 %, 98 %	100 %, 100 %
– interface roughnesses	12 Å	0 Å
– resolution	0.08°	
– background	10^{-3}	
– scaling		

specular measurements: periodic ml, non-polarised, various T

sample: $[\text{YBCO}(100 \text{ \AA})/\text{LCMO}(100 \text{ \AA})]_7$



observations:

- shift of q^c below $T_m \approx 165 \text{ K}$
- increase of 1st Bragg peak for $T_c < T < T_m$
- appearance of a 2nd Bragg peak below T_m

⇒ polarised measurements to probe the magnetic profile

principle of (n) reflectometry: specular, polarised

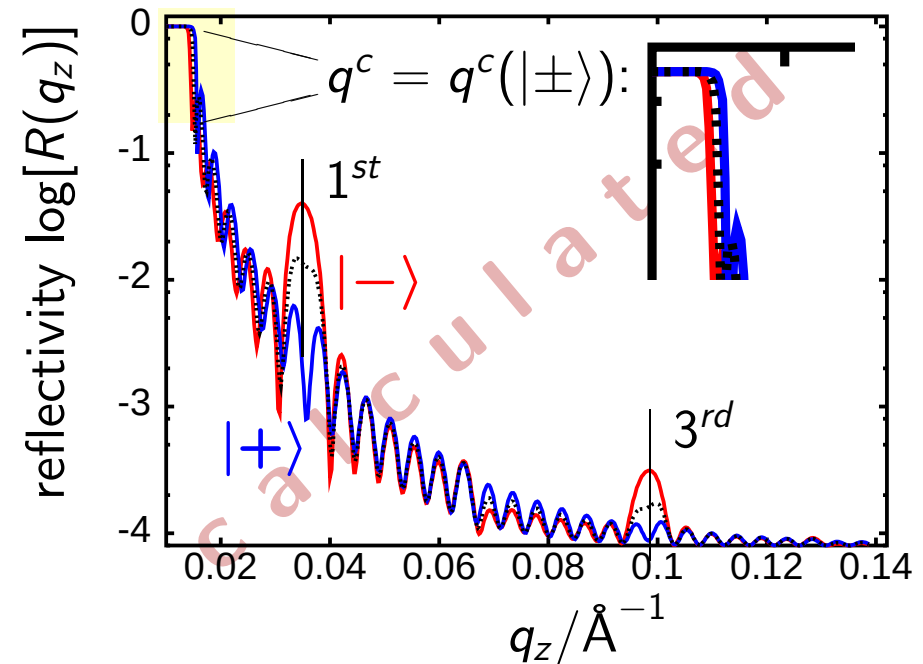
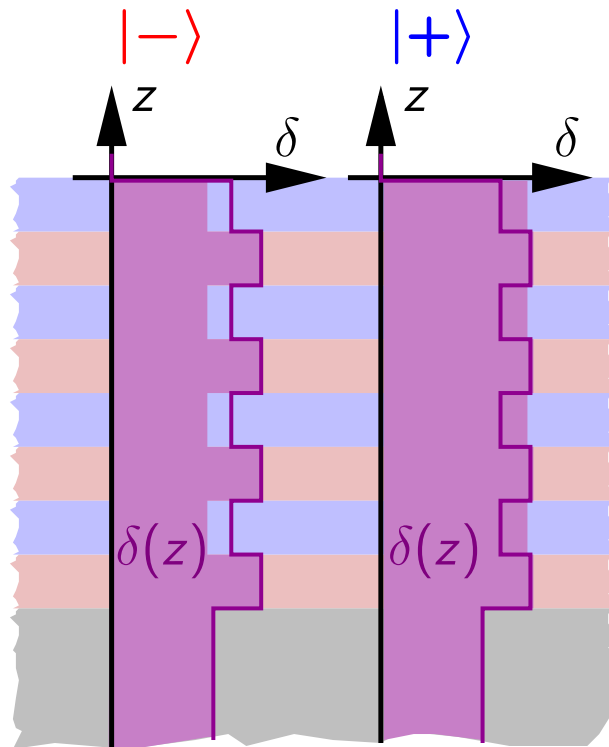
$$\delta = \frac{V}{2E} \quad \text{where} \quad V = V_{\text{nuc}} - \underbrace{V_{\text{mag}}}_{\mu \mathbf{B}_{\parallel}}$$

μ neutron magnetic moment

$\mathbf{B}_{\parallel}$ in-plane magnetic induction

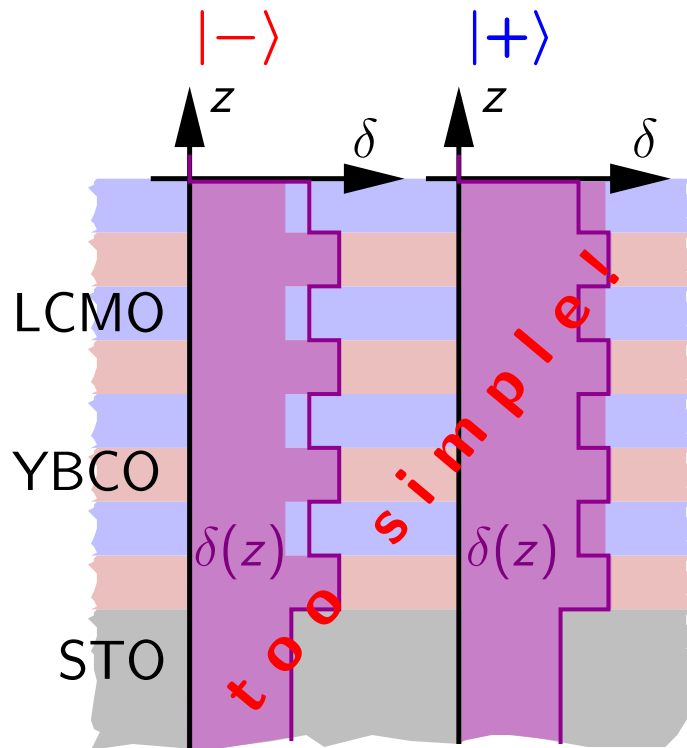
averaged over several μm

$$\Rightarrow R(q_z) \rightarrow R(q_z, |\pm\rangle)$$

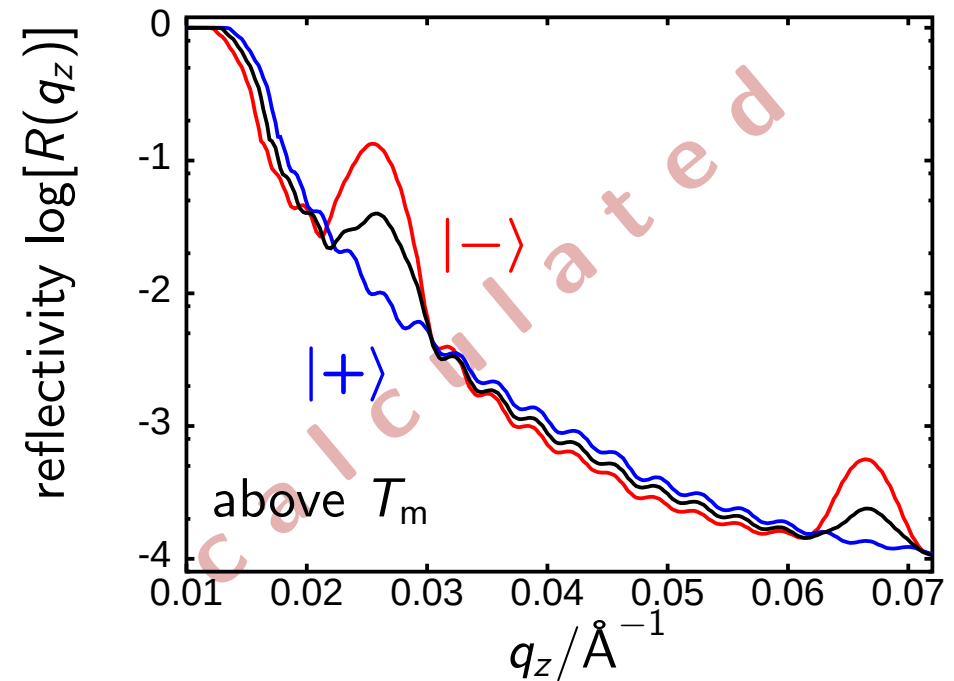
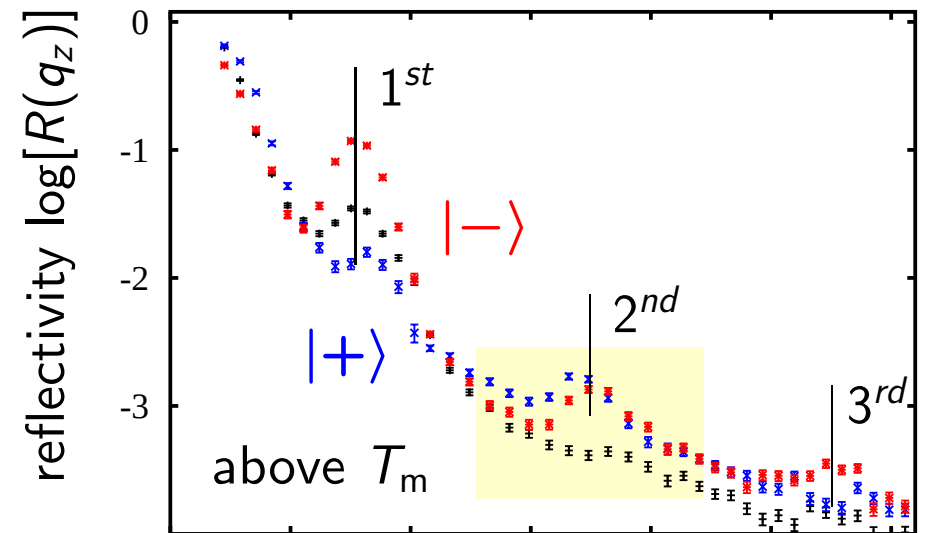


reflectometry: specular, polarised

sample:



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



modelling: magnetic profile at the interfaces

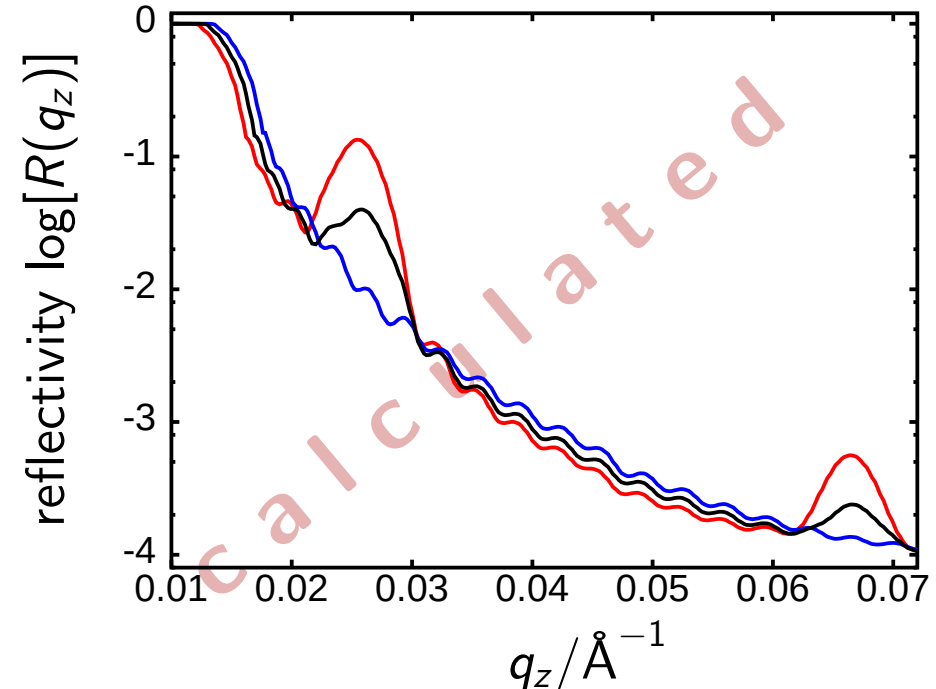
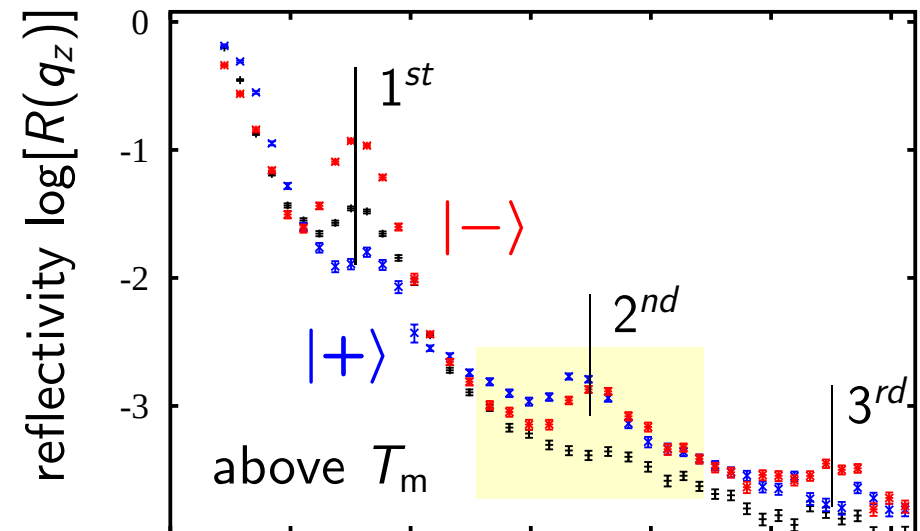
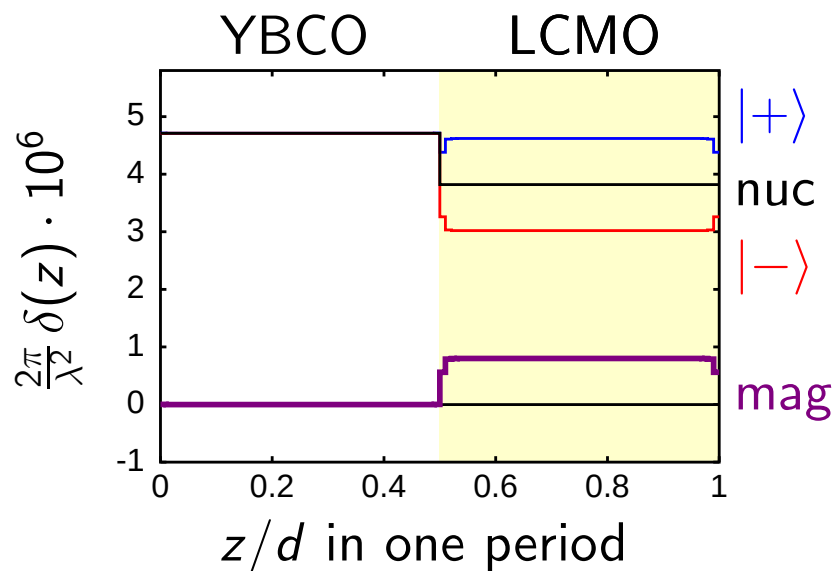
sharp contrast at the interface

exponential decay into YBCO

AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO



modelling: magnetic profile at the interfaces

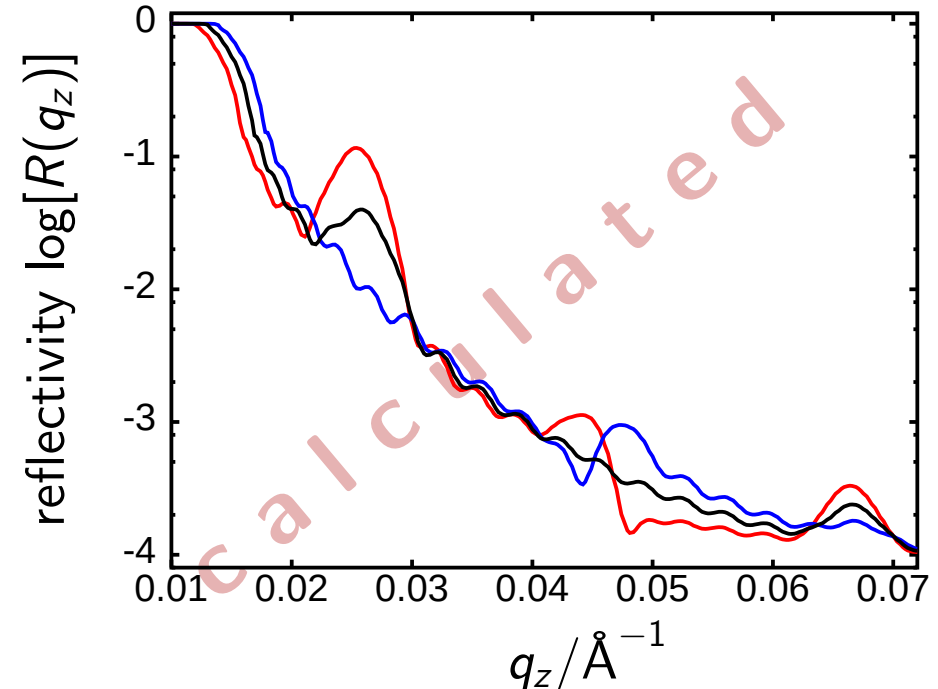
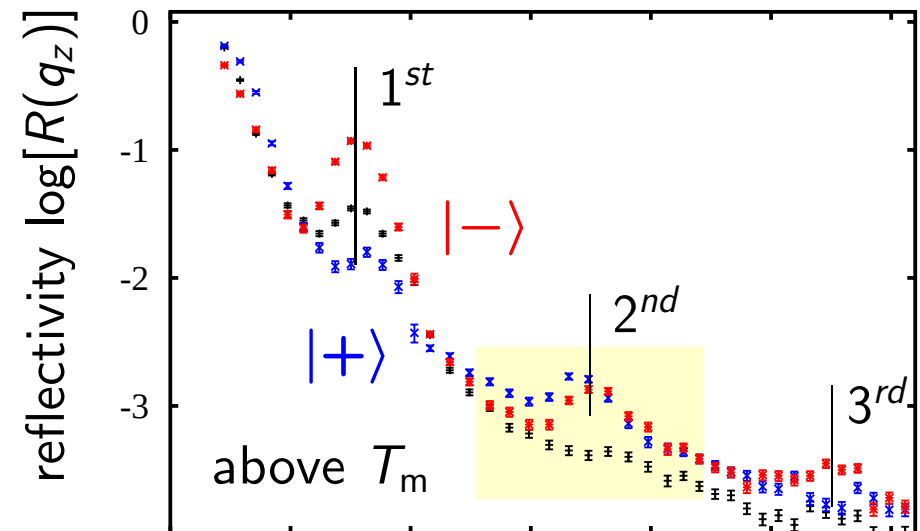
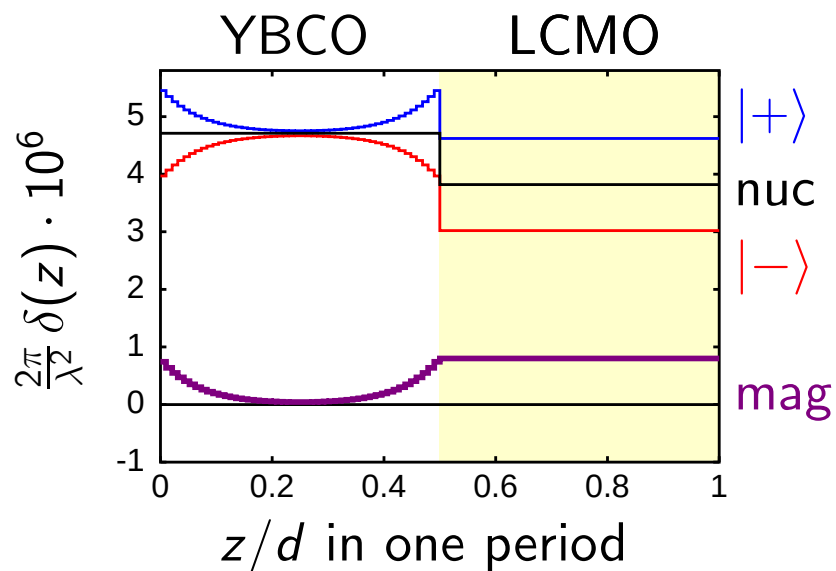
sharp contrast at the interface

exponential decay into YBCO

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magnetically dead layer in LCMO



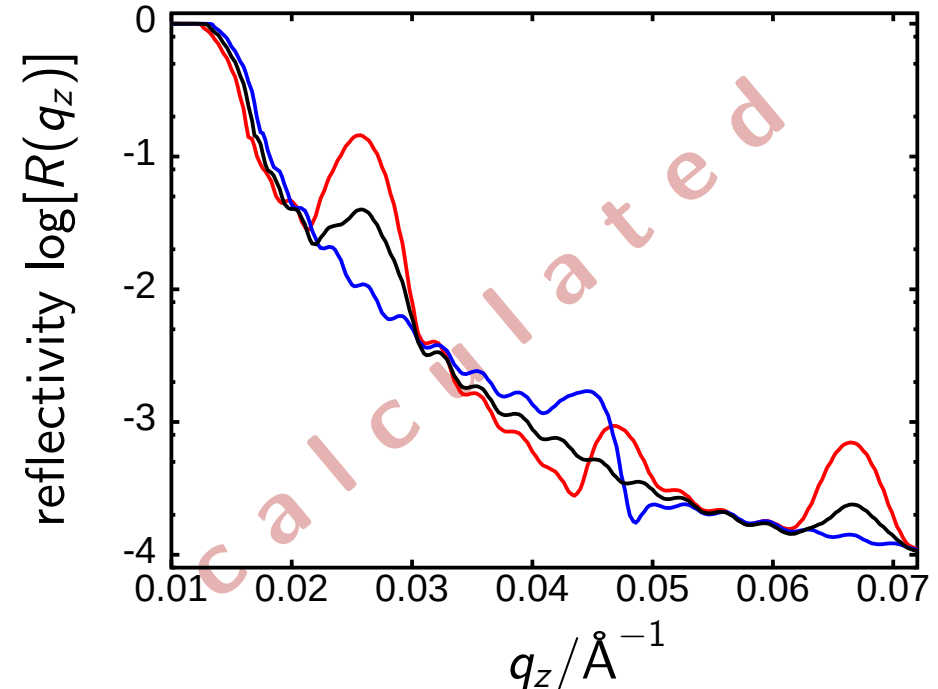
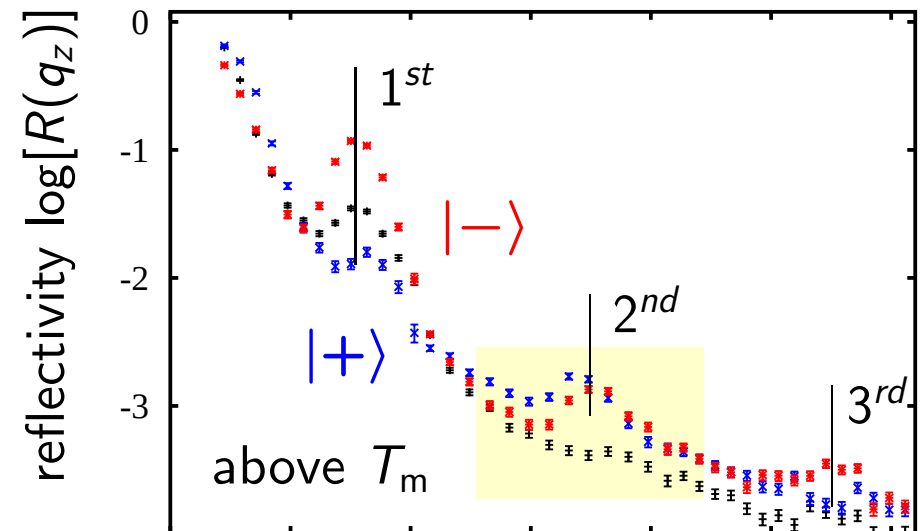
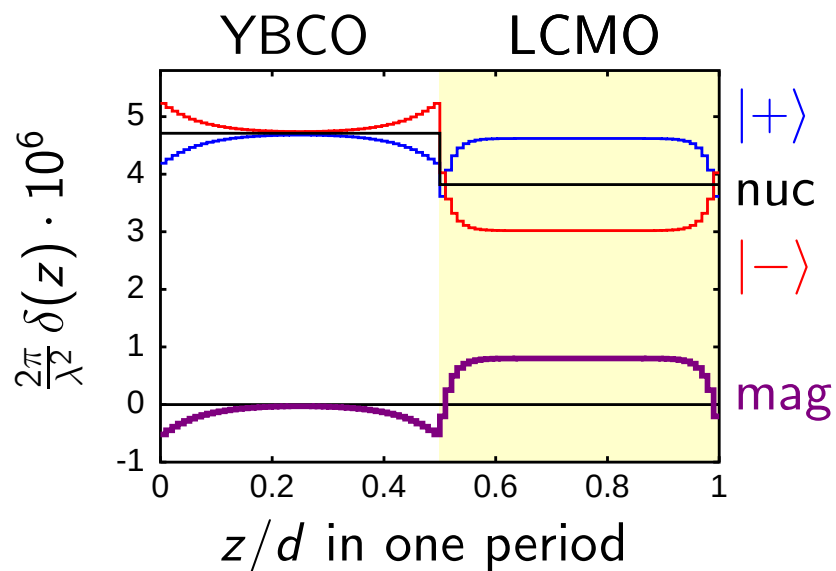
modelling: magnetic profile at the interfaces

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

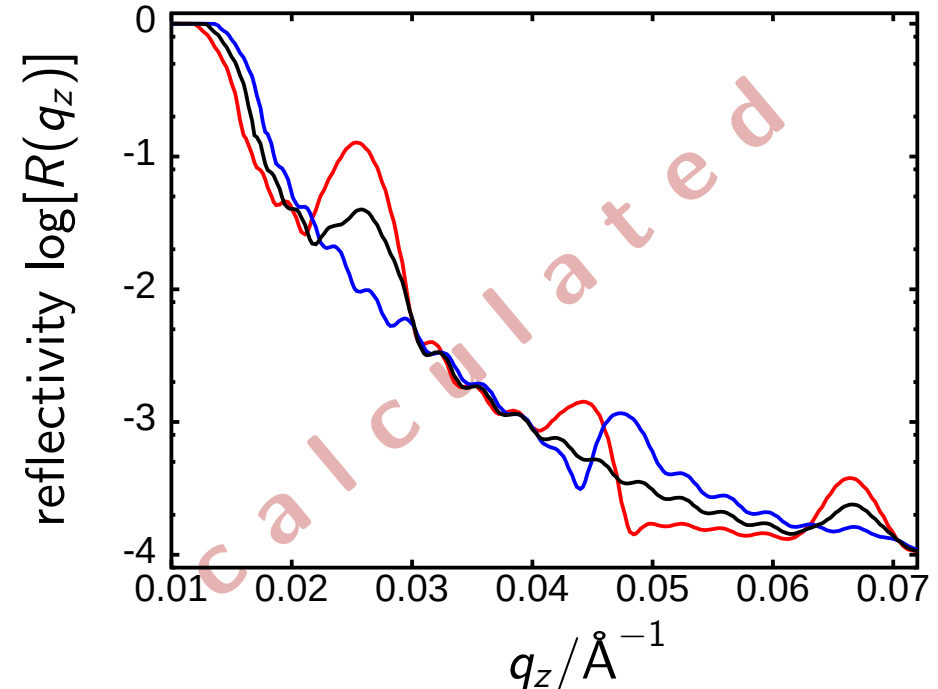
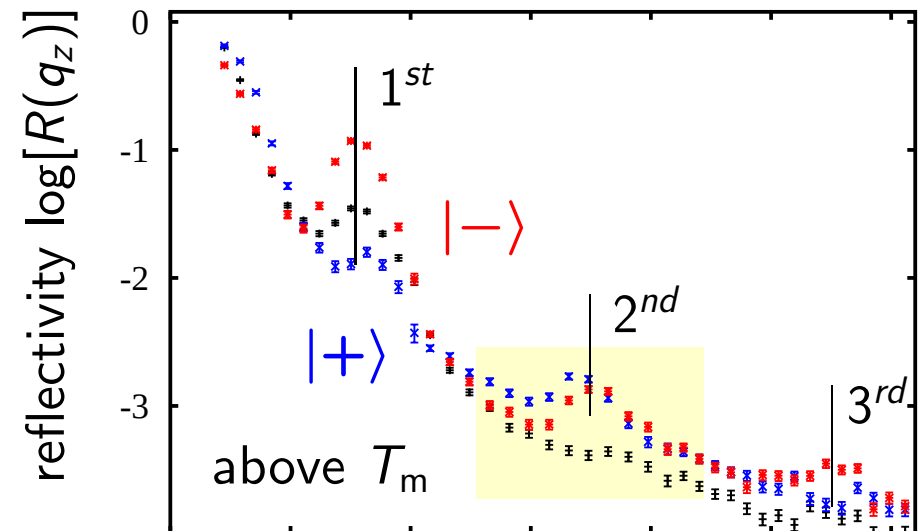
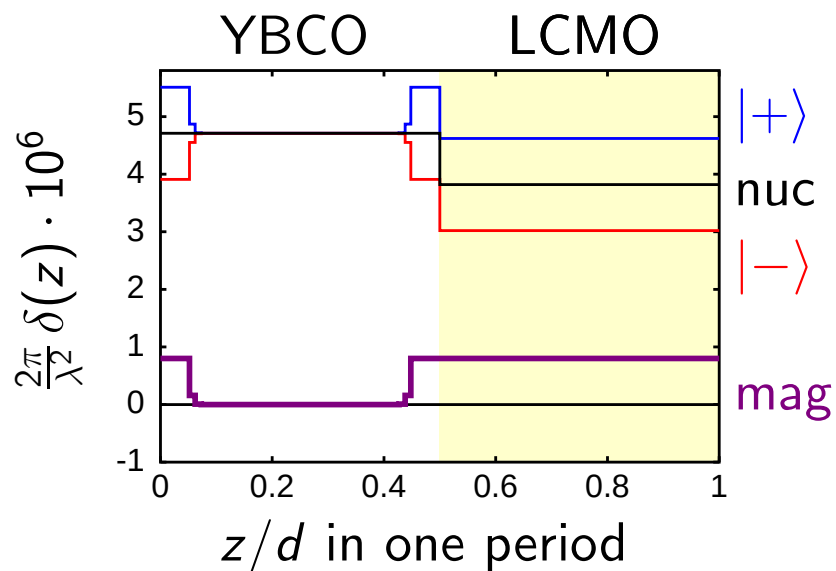
sharp contrast at the interface

exponential decay into YBCO

AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO



modelling: magnetic profile at the interfaces

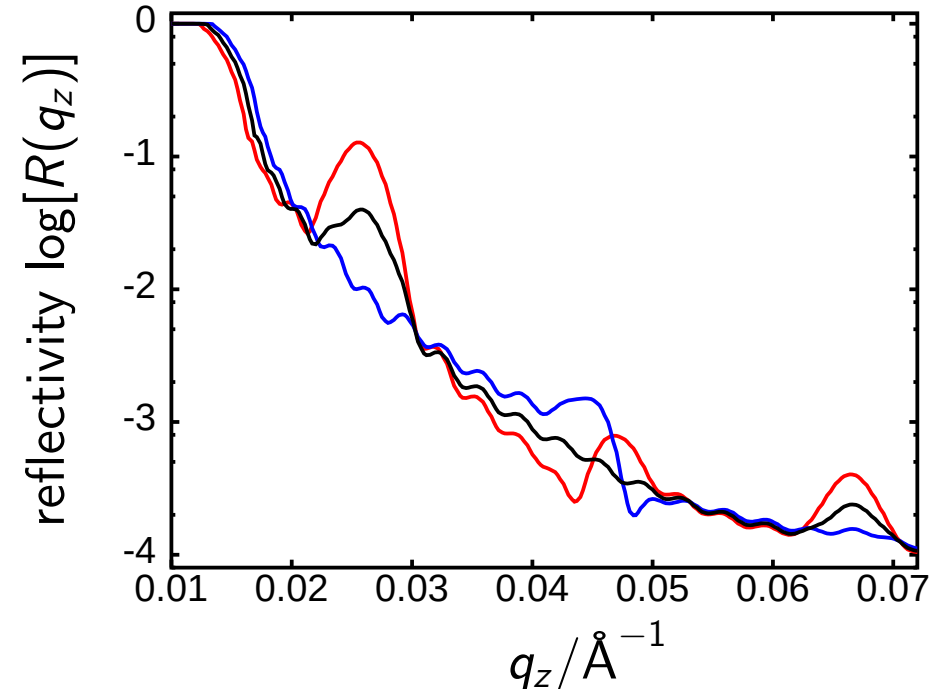
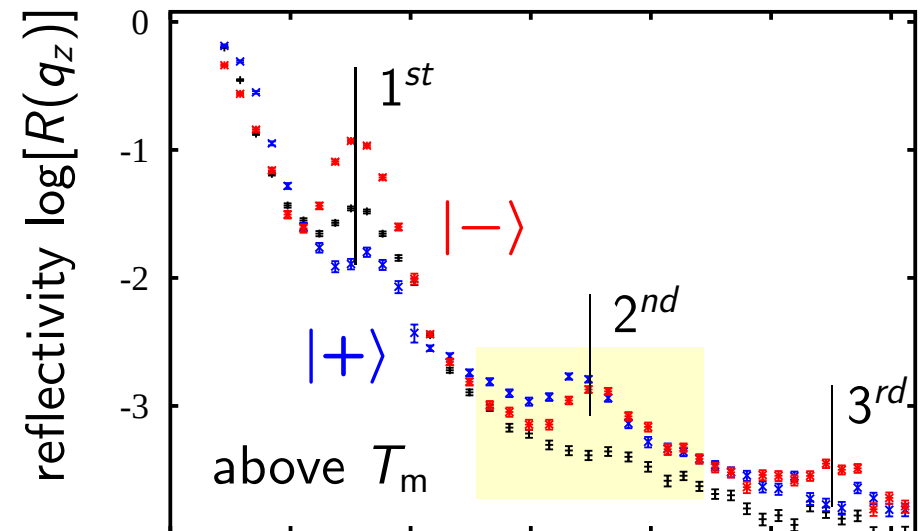
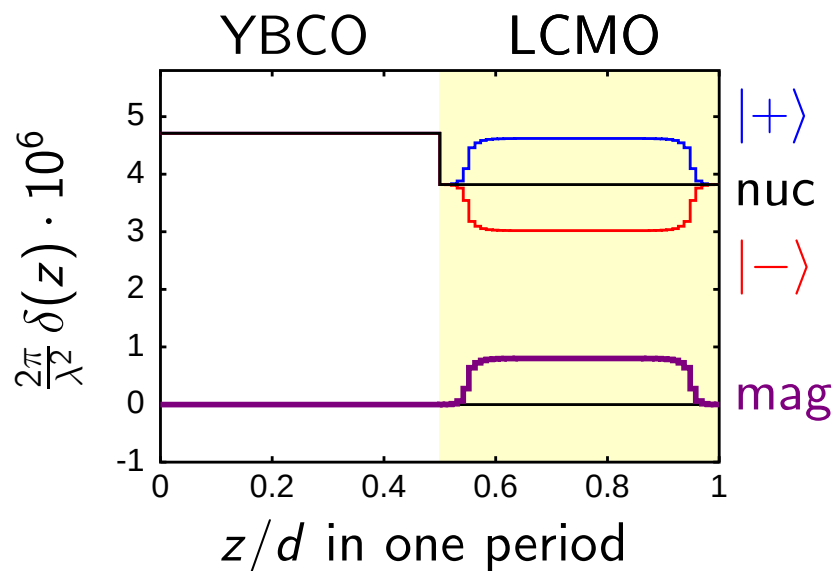
sharp contrast at the interface

exponential decay into YBCO

AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO



specular polarised neutron reflectometry — first résumé:

reflectometry

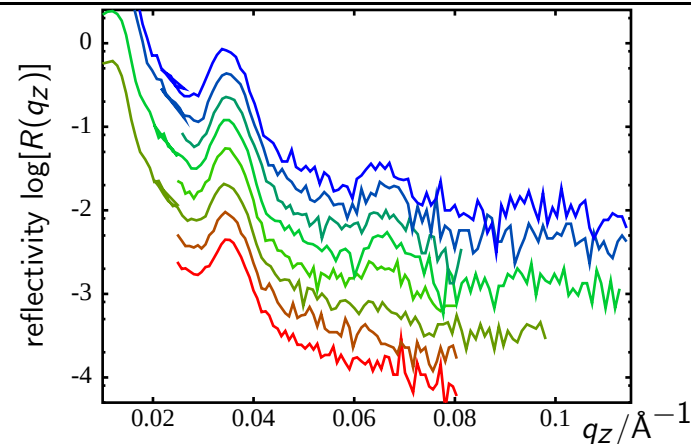
kinematic limit

$$R(q_z)/R(q^c) \propto |\mathcal{F}[\delta(z)]_{q_z}|^2$$

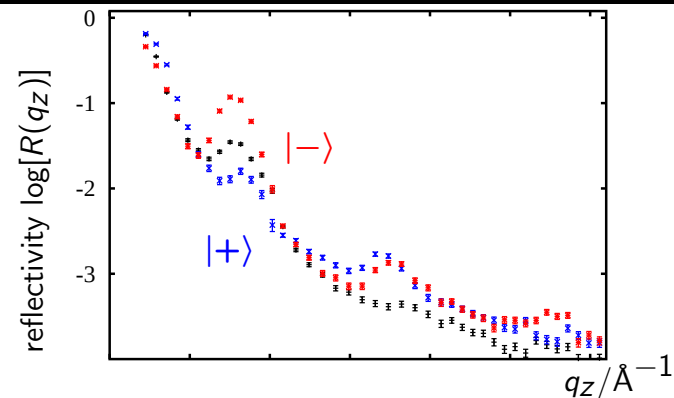
periodic structure $\Rightarrow$ Bragg peaks

$$q^c \Rightarrow \langle \delta \rangle$$

$[\text{YBCO}/\text{LCMO}]_n$



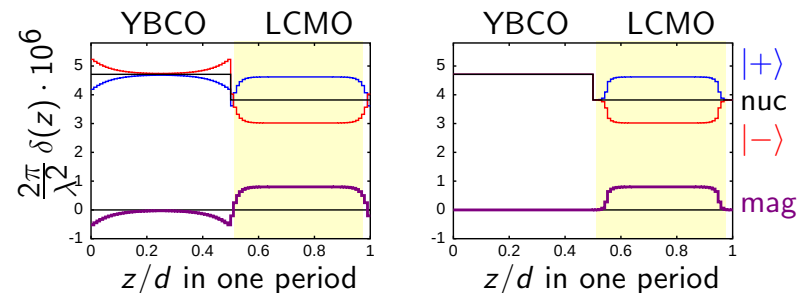
polarised neutrons probe $\mathbf{B}_{||}$



no direct method

modelling is required

$\Rightarrow$ no unique solution



magnetometry:

SQUID measurements by F. Treubel, Konstanz

$$T = 5 \text{ K}$$

cooled in $H = 100 \text{ Oe}$

coercitive field $H_{\text{co}} \approx \pm 400 \text{ Oe}$

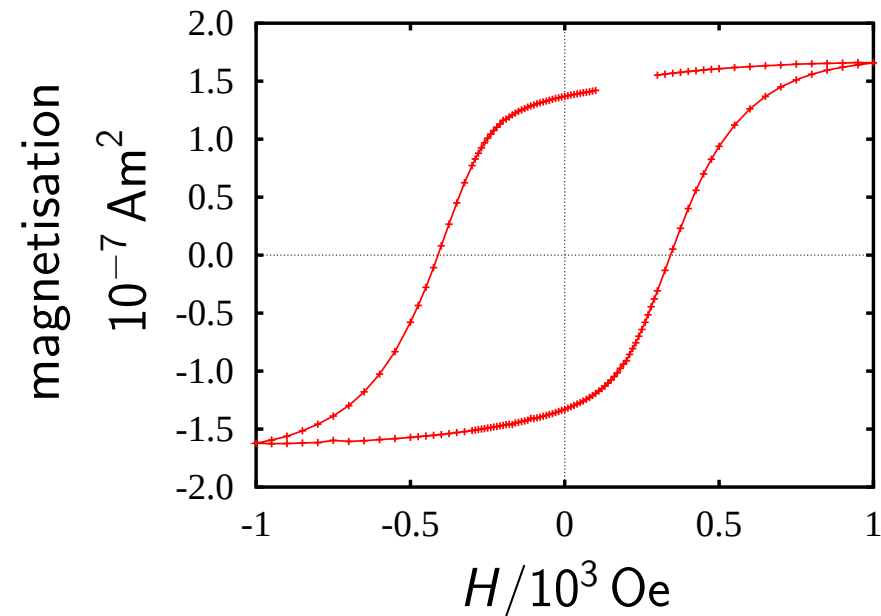
exchange bias field $H_{\text{eb}} \approx -60 \text{ Oe}$



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

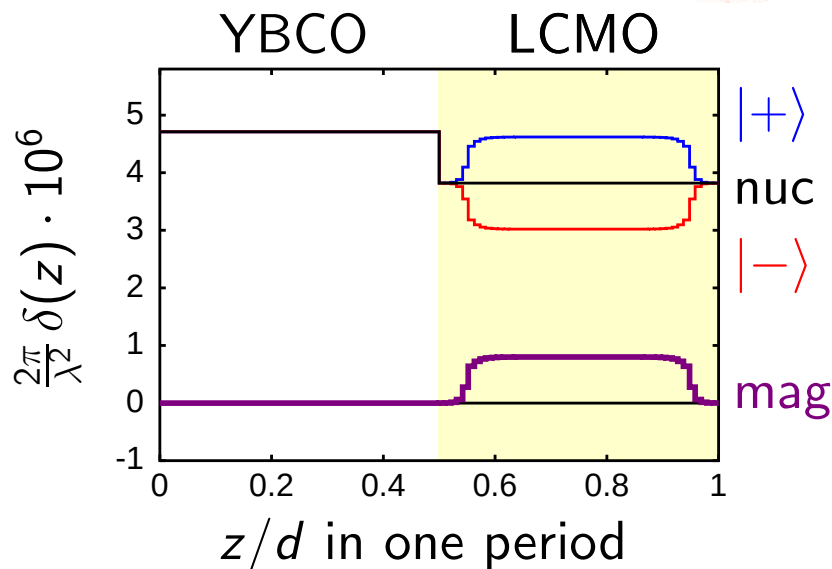
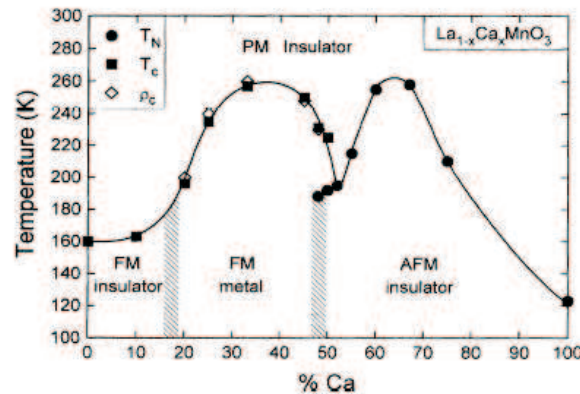


models for the magnetisation profile:

PNR at RT and below T_m and T_c exclude *all* models besides

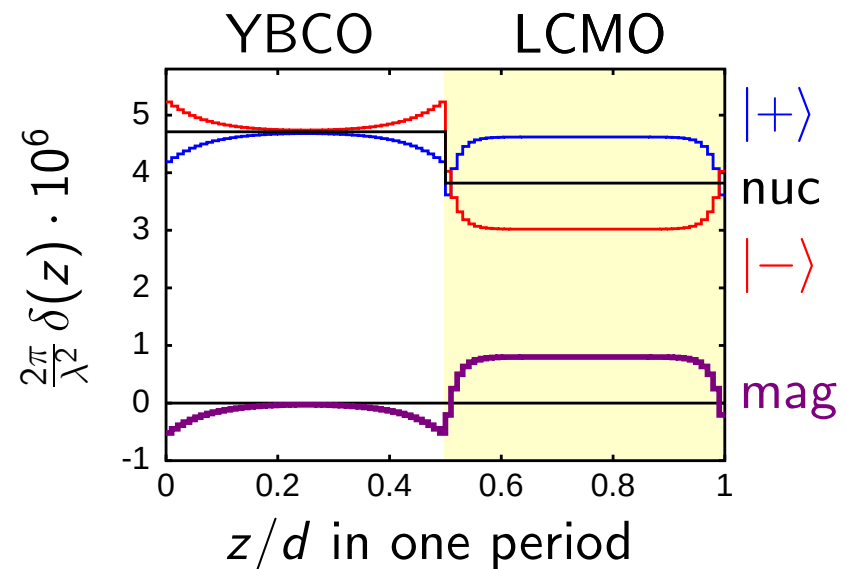
AFM-region within LCMO

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

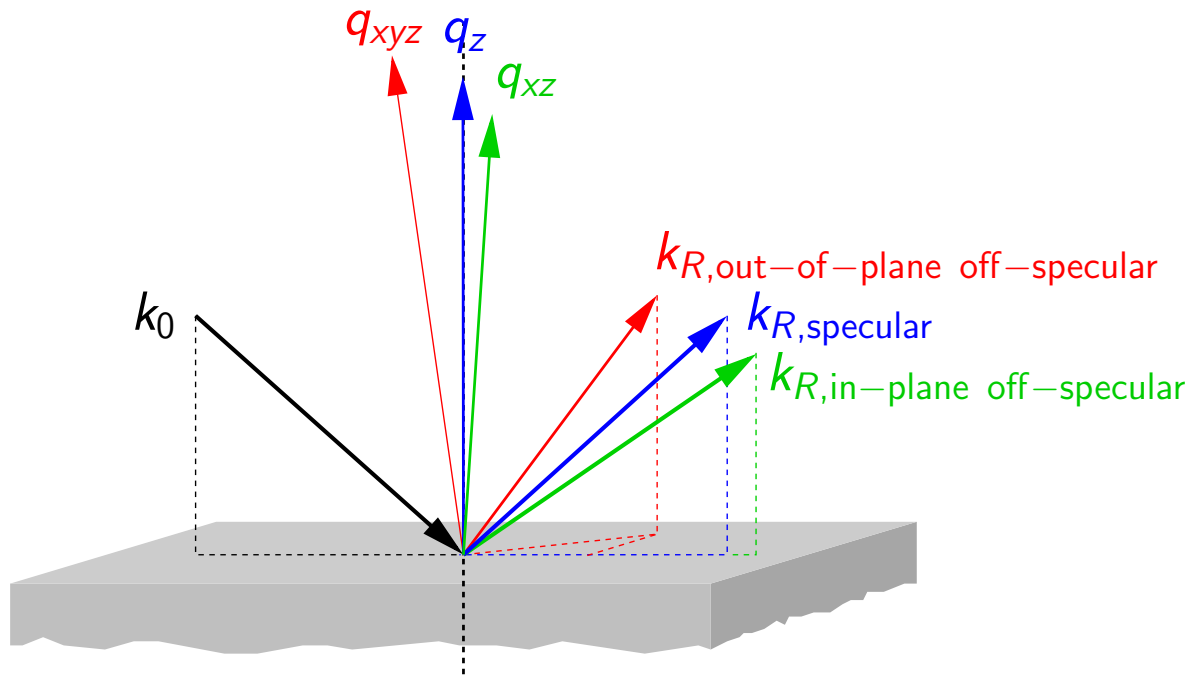


antiphase magnetic proximity effect

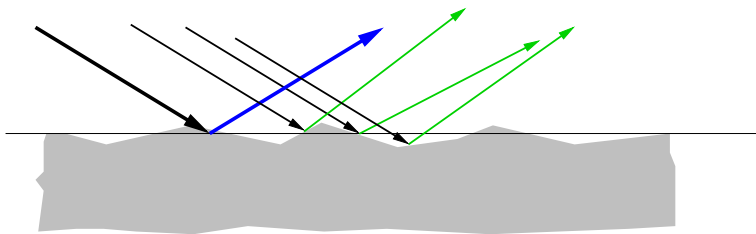
Cooper pairs penetrate into LCMO and are *polarised* $\Rightarrow$ antiparallel magnetisation in YBCO



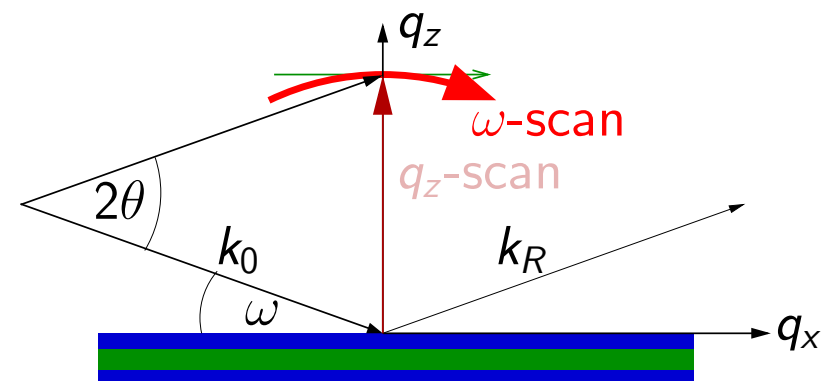
off-specular reflectometry: lateral structure is probed



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

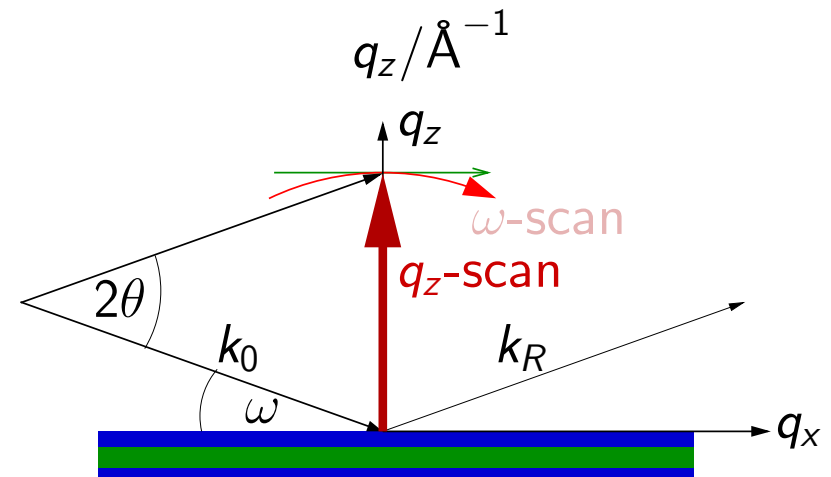
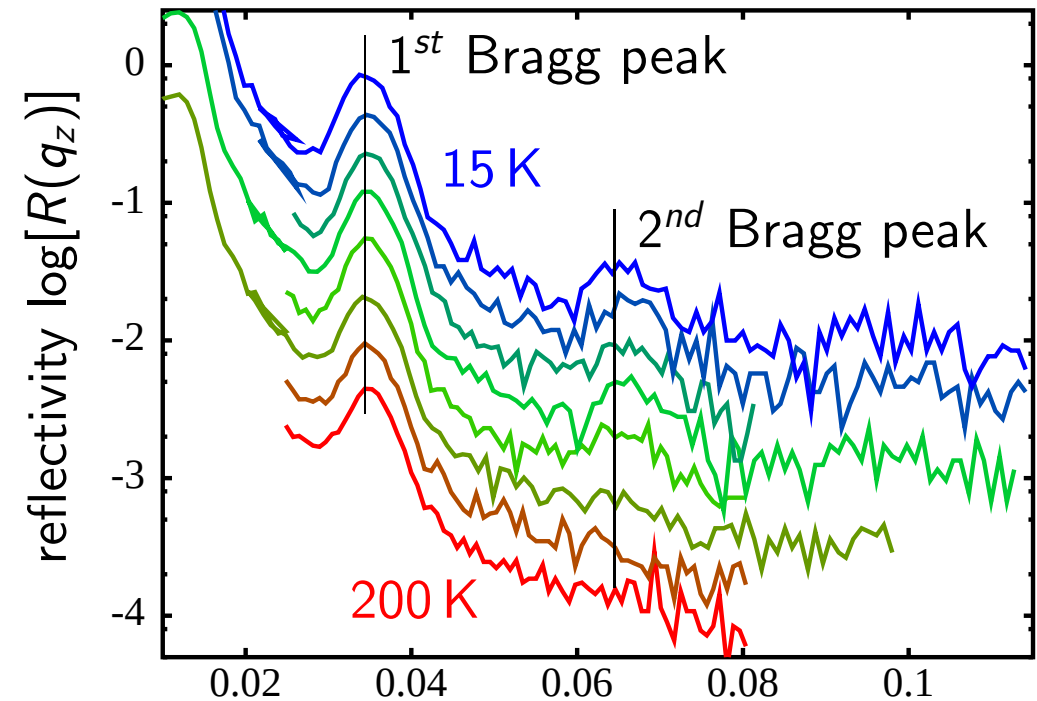
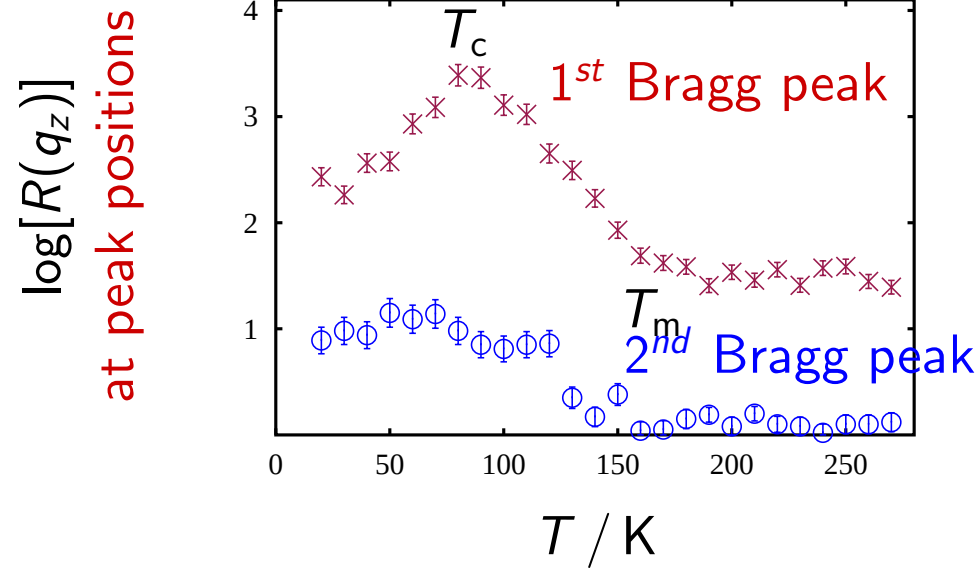


inclined surface facets $\Rightarrow \Delta\omega$
 height-variation $\Rightarrow$ phase-shifts in k_R
 $\Rightarrow$ damping of $R(q_z > q^c)$



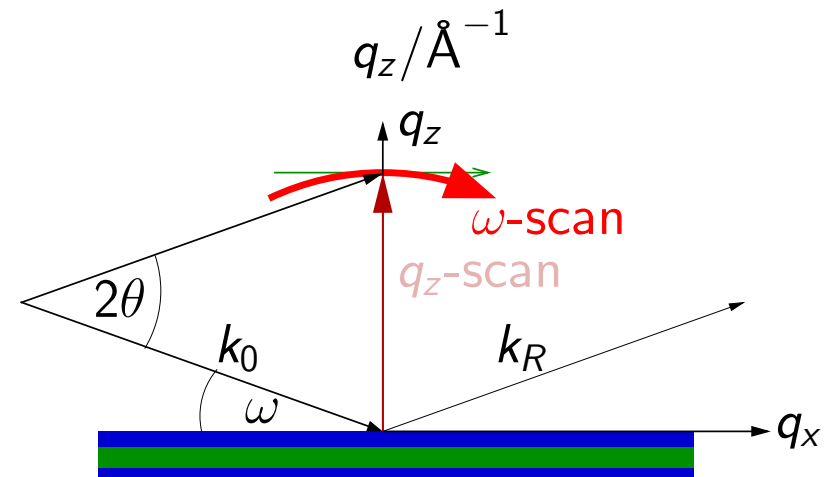
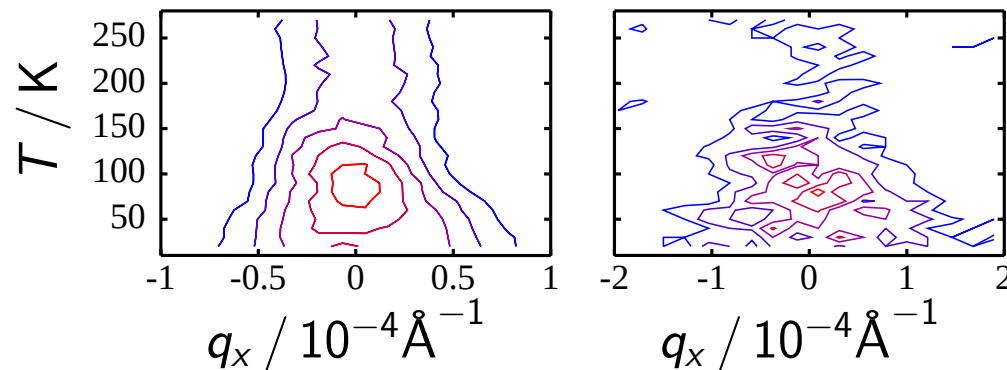
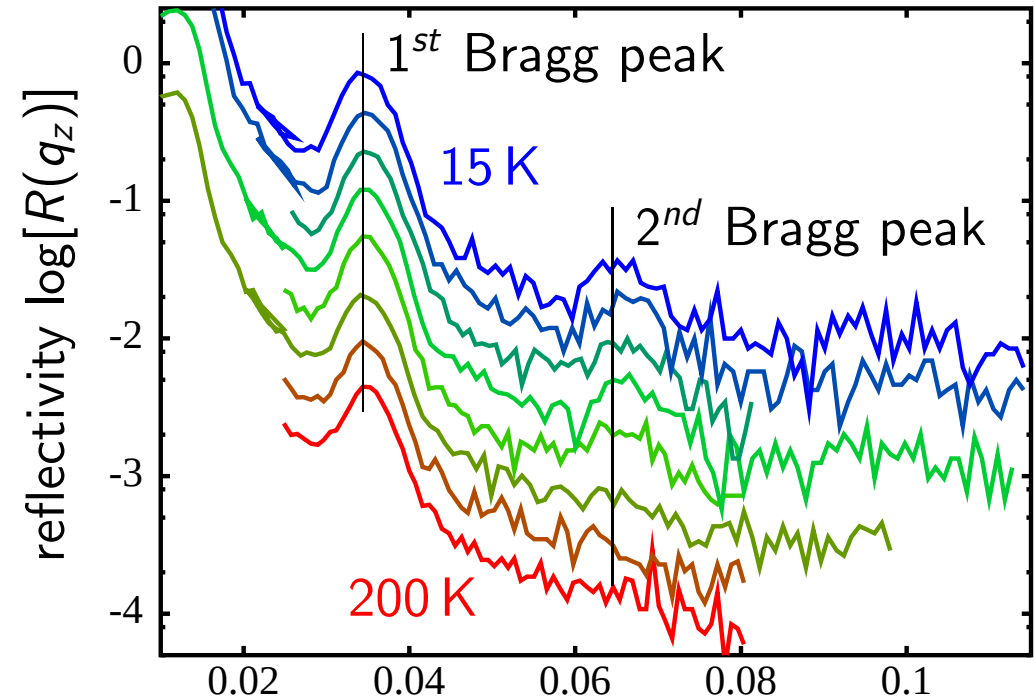
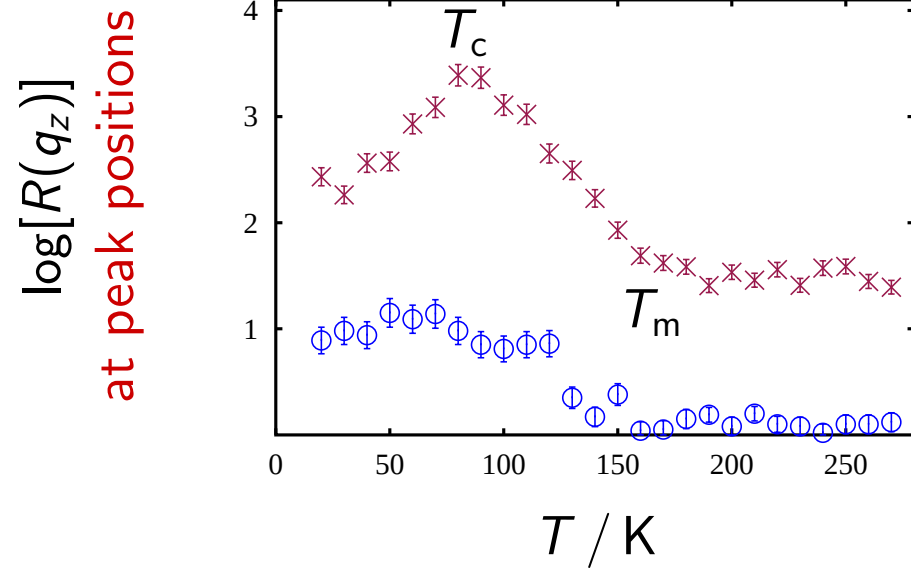
specular measurements: periodic ml, non-polarised, various T

sample: $[\text{YBCO}(100 \text{ \AA})/\text{LCMO}(100 \text{ \AA})]_7$



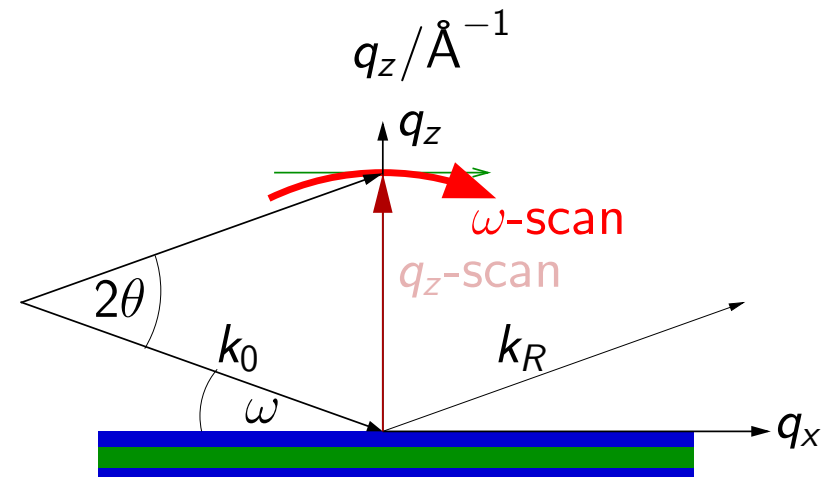
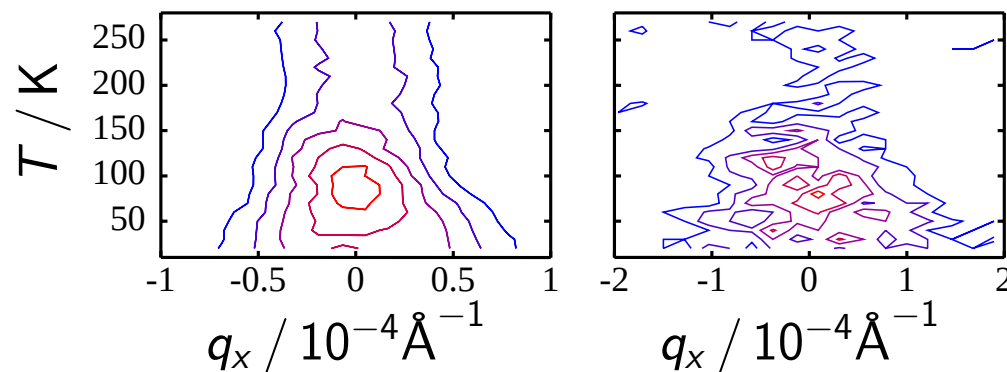
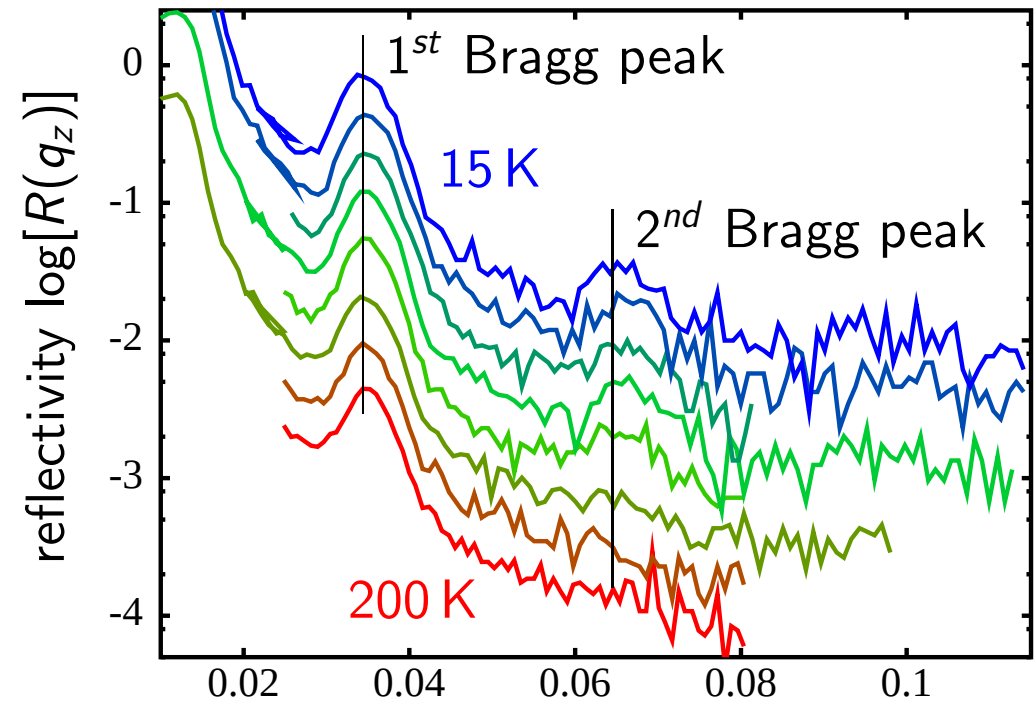
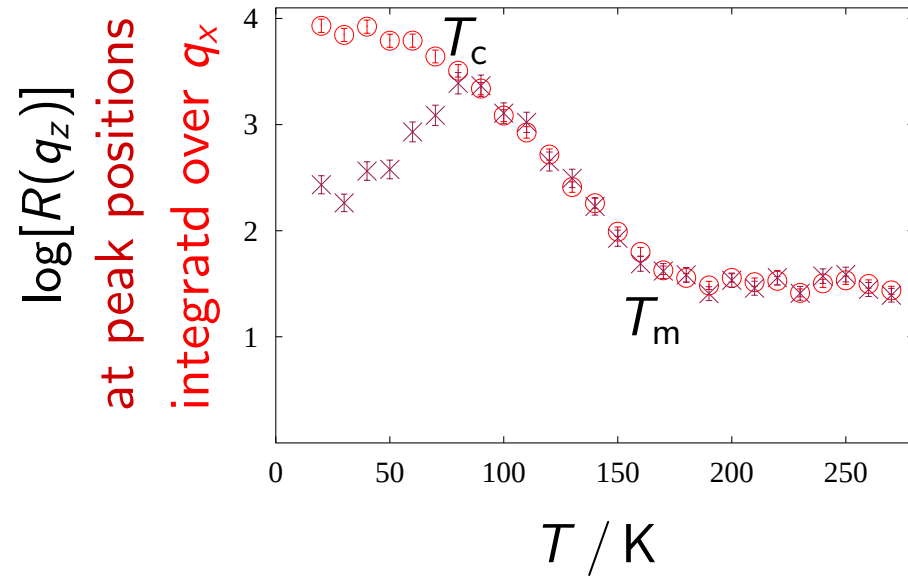
off-specular measurements: periodic ml, non-polarised, various T

sample: $[\text{YBCO}(100 \text{ \AA})/\text{LCMO}(100 \text{ \AA})]_7$



off-specular measurements: periodic ml, non-polarised, various T

sample: $[\text{YBCO}(100 \text{ \AA})/\text{LCMO}(100 \text{ \AA})]_7$



interpretation of off-specular scans:

Δq_x gives the lateral correlation length $\Lambda_{||}$

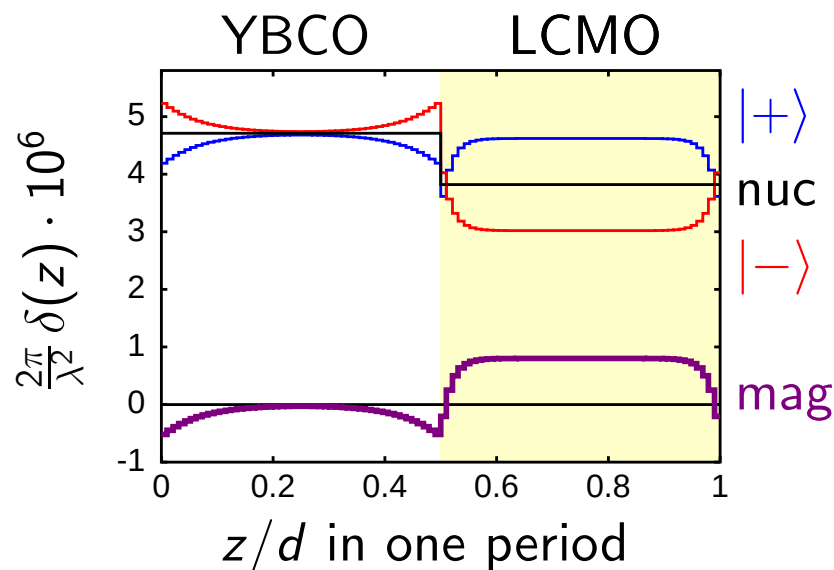
$$T > T_c : \Lambda_{||} \approx 16 \mu\text{m}$$

$$T = 15 \text{ K} : \Lambda_{||} \approx 8 \mu\text{m}$$

$\Rightarrow$ SC directly influences the lateral correlation of $\mathbf{B}_{||}$

$\Rightarrow$ model of direct contact of SC and FM is favored!

$\Rightarrow$ *antiphase magnetic proximity effect*



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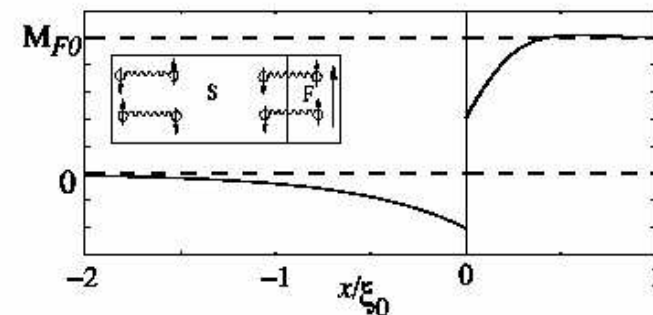
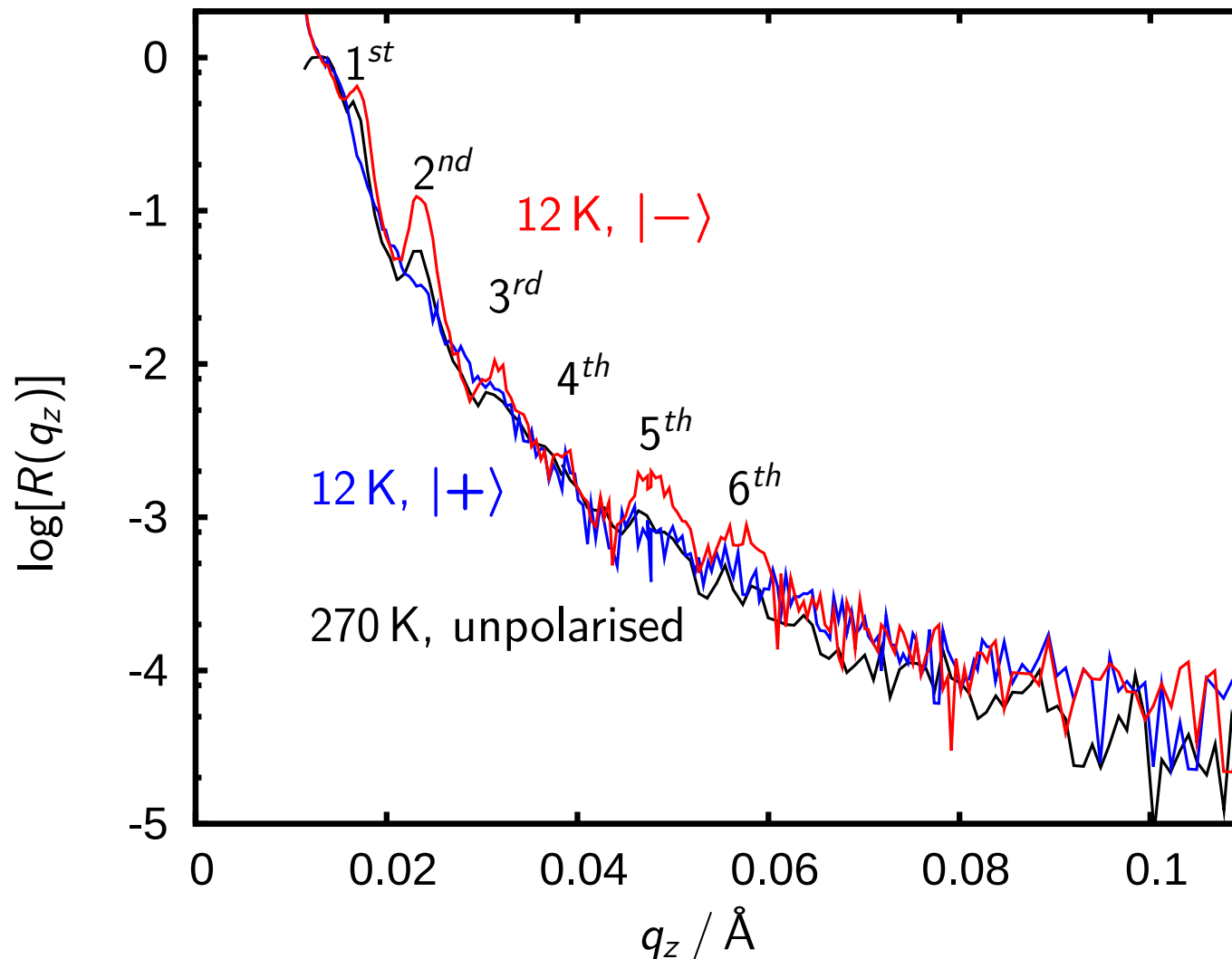


FIG. 1. Spatial dependence of the magnetization in the whole system. Here $\gamma_F/\gamma_S=0.5$, $\bar{\gamma}_F=\gamma_F/\xi_0=0.1$ ($\xi_0=\sqrt{D_S/2T_c}$), $J/T_c=15$, and $d_F/\xi_0=1$. Inset: Schematic view of the inverse proximity effect in a S/F system (for discussion see text).

recent measurements:

19. 10. 2004

sample Y-LCM68: $[\text{YBCO}(500 \text{ \AA})/\text{LCMO}(250 \text{ \AA})]_5$



fitted values
(RT, unpolarised):

roughness $\approx 5 \text{ \AA}$

$t_{\text{YBCO}} \approx 520 \text{ \AA}$

$t_{\text{LCMO}} \approx 180 \text{ \AA}$

decreasing resolution with q_z
 $\Rightarrow$ decreased d at the edges?

no plateau below q^c
 $\Rightarrow$ bent sample?

recent measurements:

19. 10. 2004

sample Y-LCM68: $[\text{YBCO}(514 \text{ \AA})/\text{LCMO}(181 \text{ \AA})]_5$

samples:

G. Cristiani

HU. Habermeier

measurements:

J. Chakhalian

T. Gutberlet

J. Hoppler

C. Niedermayer

S. Pekarek

analysis:

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interpretation:

C. Bernhard

J. Chakhalian

B. Keimer

C. Niedermayer

