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

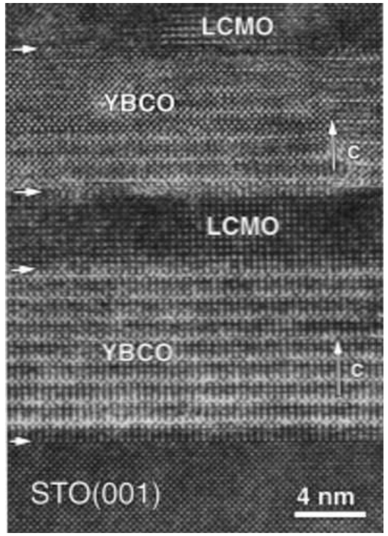
17. 03. 2005

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

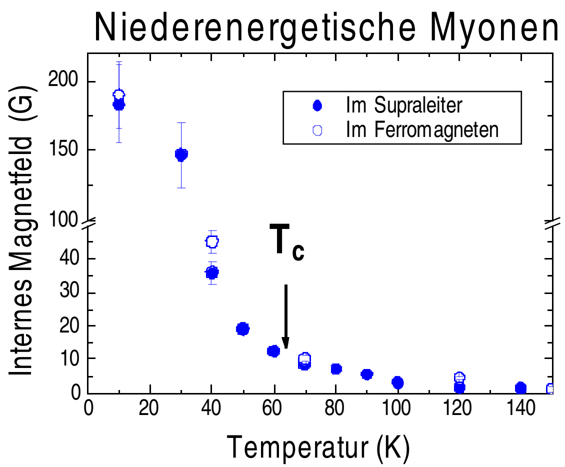
motivation / history:

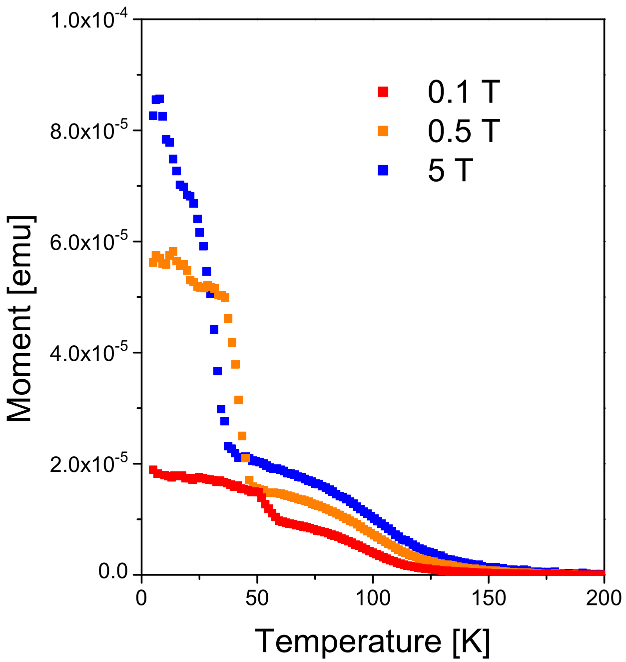
spring 2003:

C. N. presents nice μSR and magnetisation measurements at PSI



no explanation at that time.





method of choice (for a neutron scatterer):

neutrons!

in particular *polarised n-reflectometry*

outline:

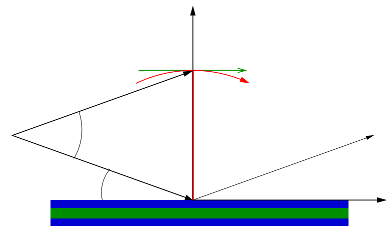
introduction to neutron reflectometry

principles

specular (unpolarised / polarised)

off-specular

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

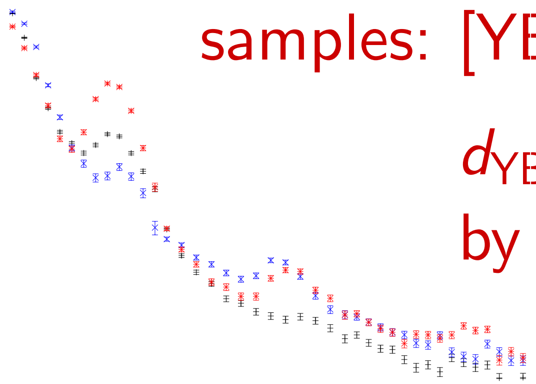


literature: P. Mikulík: thesis
V. Holý *et al.*: Springer Tracts in Modern Physics, Vol. 149
J. Daillant *et al.*: Lecture Notes in Physics, m 58

and in parallel (if possible)

presentation of recent measurements on YBCO / LCMO multilayers

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



samples: $[YBa_2Cu_3O_7\,(d_{YBCO})\,/\,La_{2/3}Ca_{1/3}MnO_3\,(d_{LCMO})]_n$

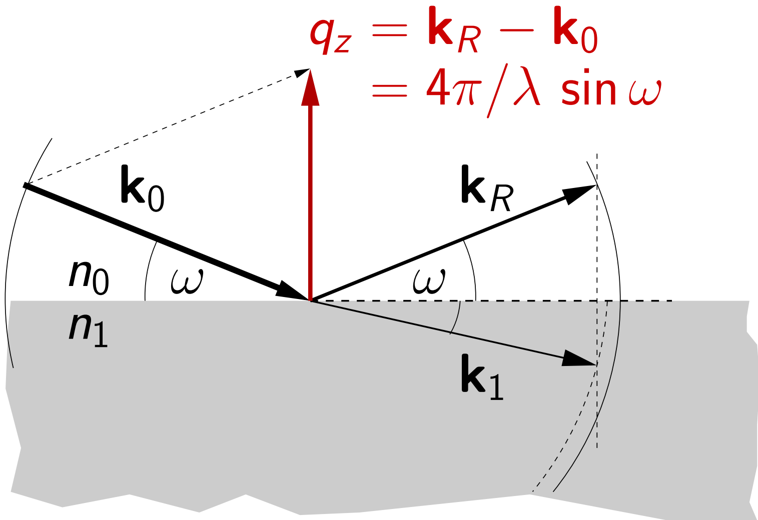
$d_{YBCO} = d_{LCMO} = 100\,Å$ and $150\,Å$

by H.-U. Habermeier & G. Cristiani

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

basis: *index of refraction* varies at the interface

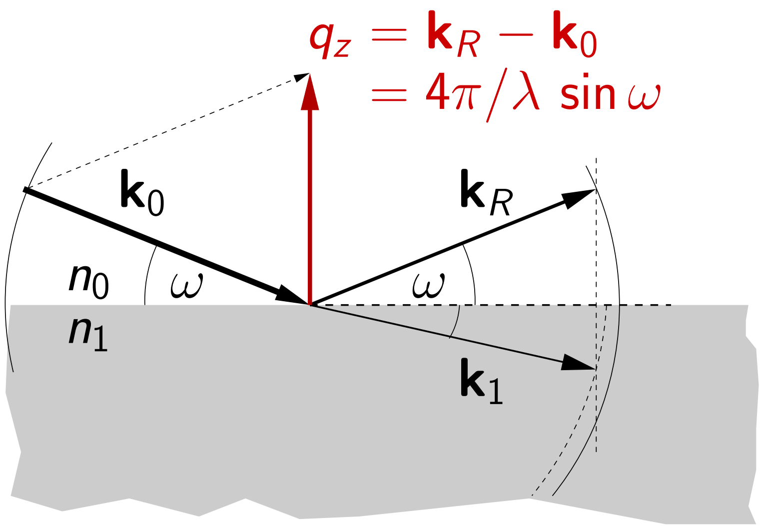
$$\begin{aligned}
\text{index of refraction} \quad n &= \sqrt{1 - V/E} \\
&\approx 1 - V/2E \\
&= 1 - \delta \\
|\delta| &< 10^{-5} \\
\text{kinetic energy} \quad E &\propto k_0 \\
\text{mean nuclear potential} \quad V &\propto \Sigma_i \, \rho_i b_i \\
\text{nuclear scattering length} \quad b_i & \\
k_j &\neq k_0 \\
\text{critical transfer} \quad q^c &\approx 4\pi/\lambda \sqrt{2\delta} \\
\text{Fresnel reflectivity } R^F(q_z) &= |r(q_z)|^2 \\
r(q_z) &= \frac{1 - \sqrt{1 - (q^c/q_z)^2}}{1 + \sqrt{1 - (q^c/q_z)^2}}
\end{aligned}$$

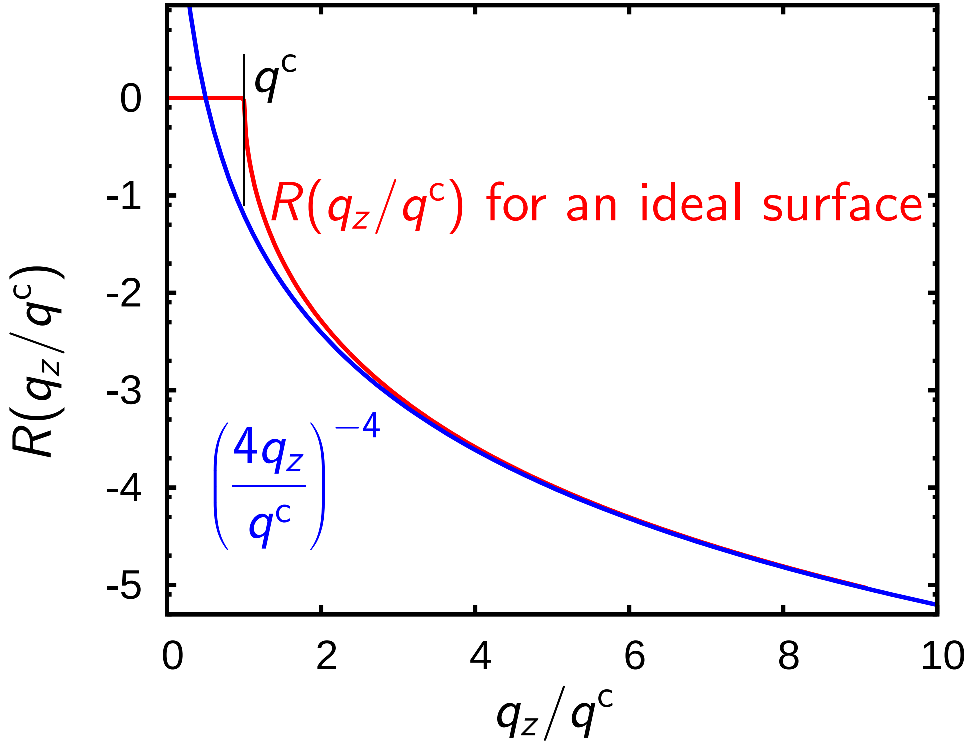


principle of (n) reflectometry: specular, single surface, unpolarised

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

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





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

stack of plane-parallel interfaces:

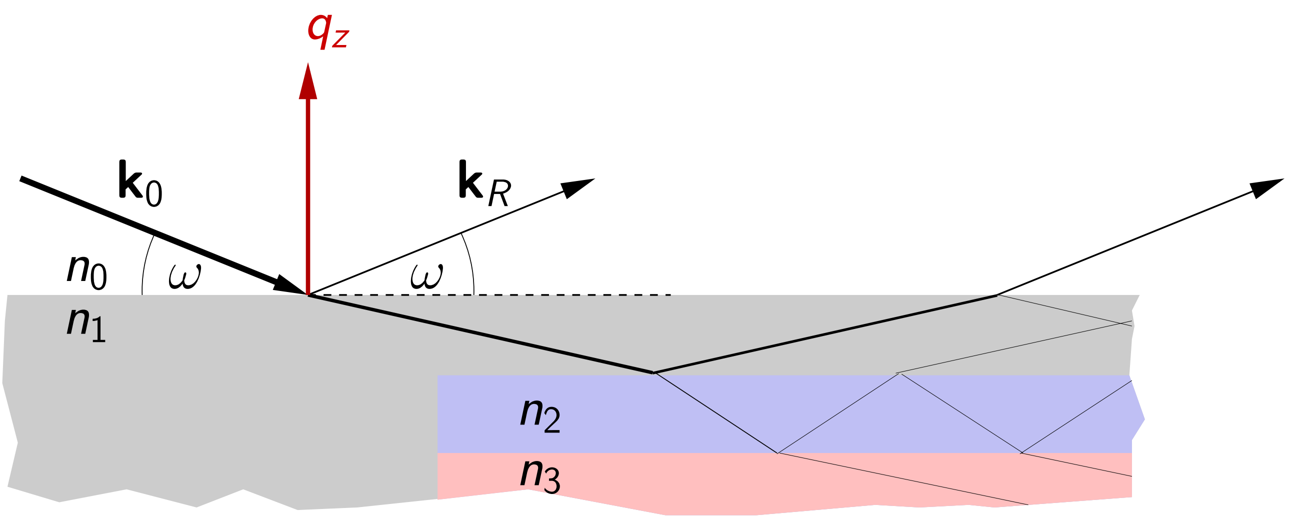
$$\mathbf{u}_i = \begin{pmatrix} u_{i,+} \\ u_{i,-} \end{pmatrix} \text{ with } \left\{ \begin{array}{ll} u_{i,+} & \text{up-traveling waves} \\ u_{i,-} & \text{down-traveling waves} \end{array} \right\} \text{ in layer } i$$

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

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

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

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



$$\Rightarrow r = \frac{u_{0,+}}{u_{0,-}} = \frac{M_{12}}{M_{22}}$$

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

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

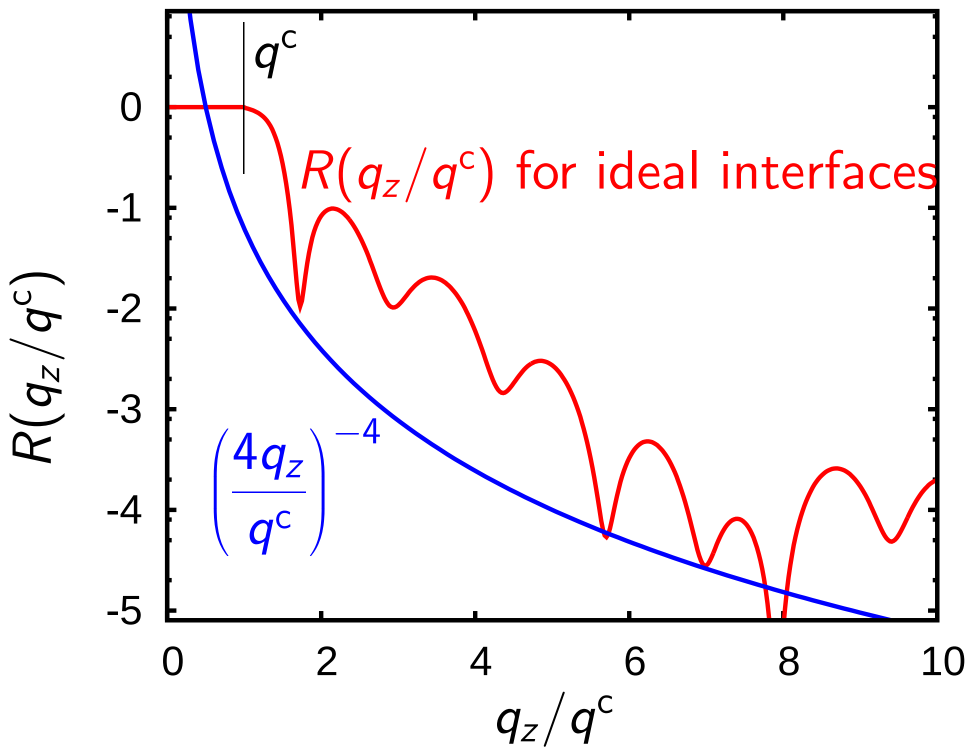
stack of plane-parallel interfaces:

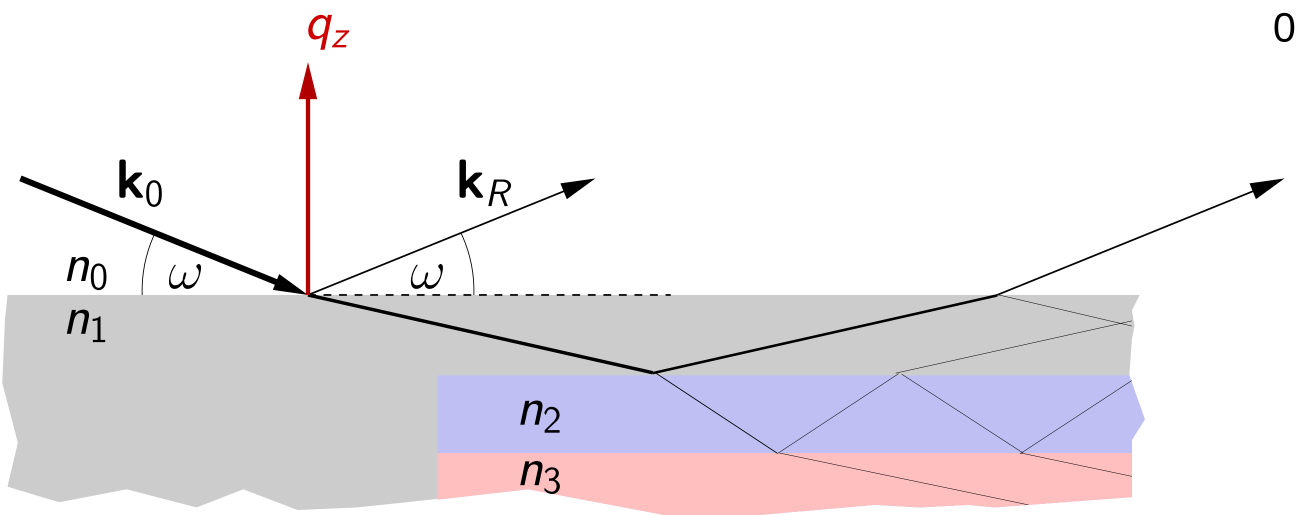
$$R(q_z) = \left| \frac{M_{12}}{M_{22}} \right|^2$$

dynamic theory, exact

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

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





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

angle-dispersive

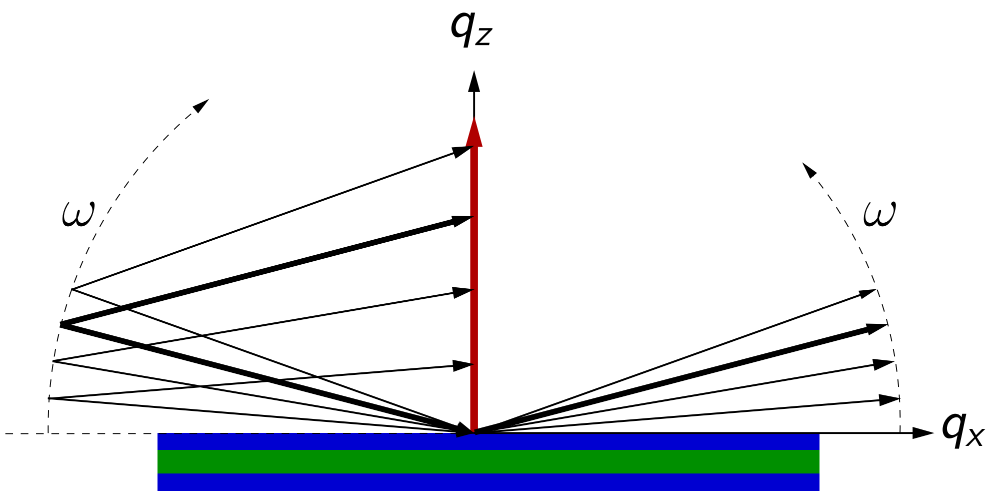
constant k_0

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

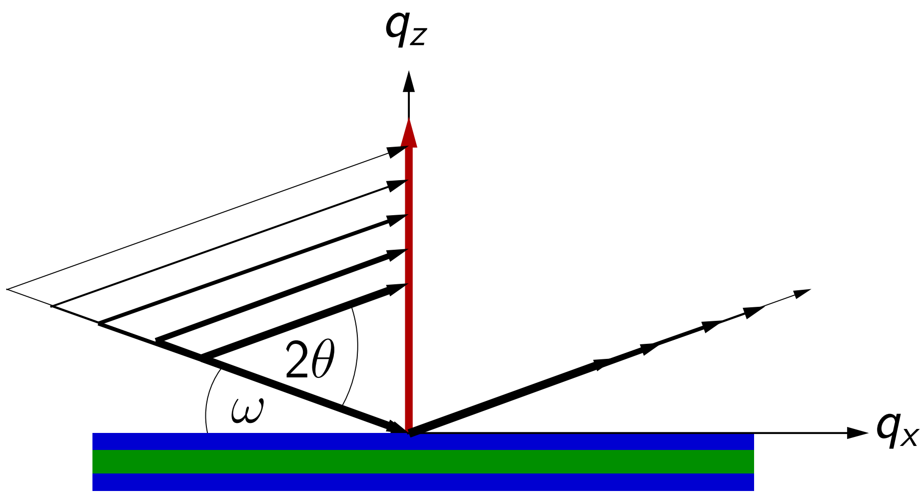
constant $\mathbf{k}_0/k_0$

2θ and ω are fix

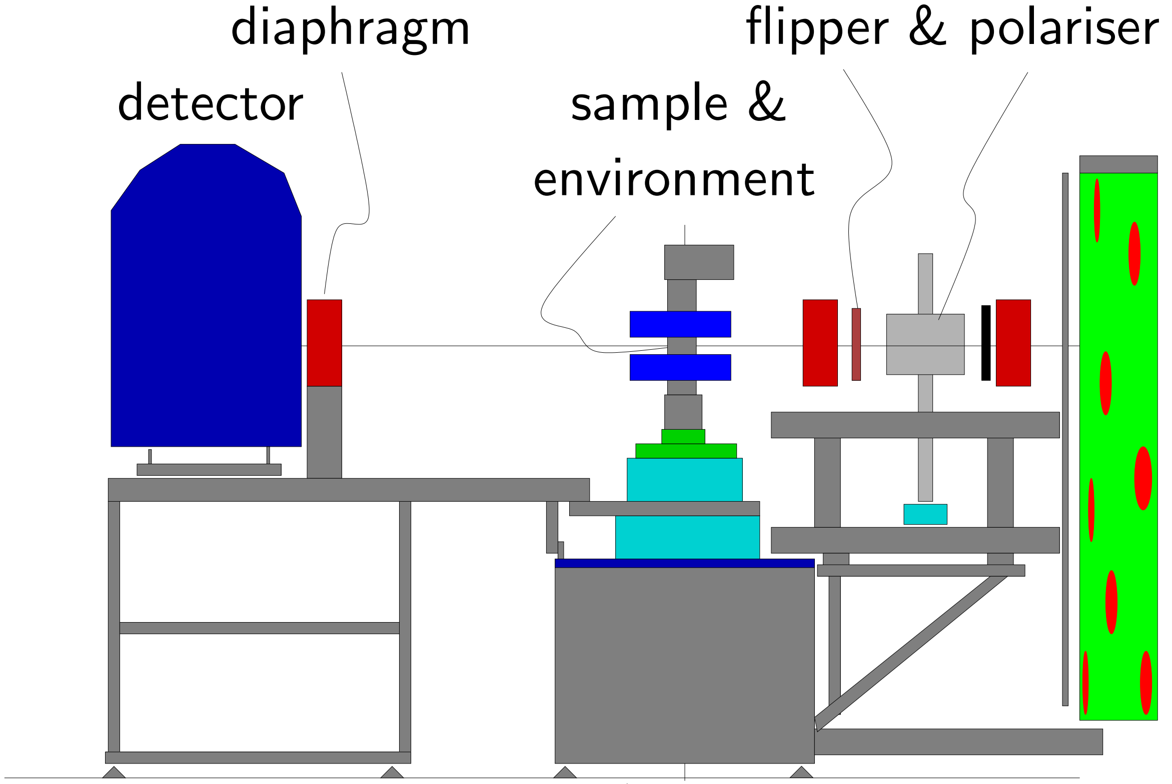
q_z-range couvered by 1 shot

resolution: ΔE of detector

TOF: time-resolution



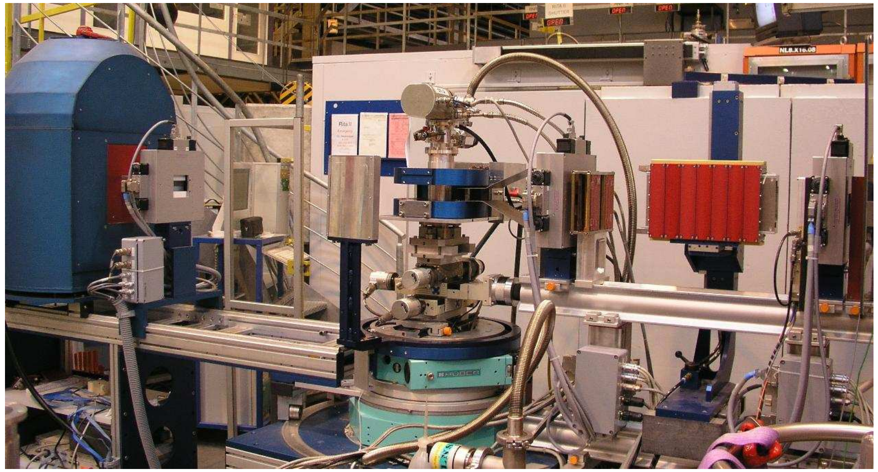
typical instruments: angle dispersive, Morpheus @ SINQ

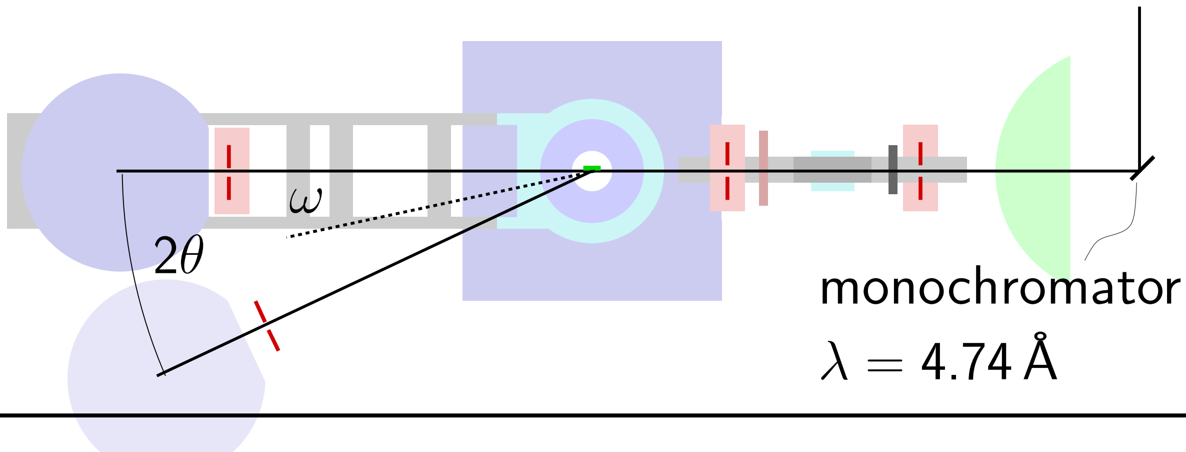


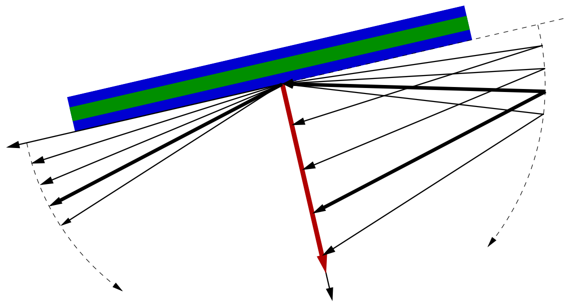
specular scan:

detector angle = 2× angle of incidence

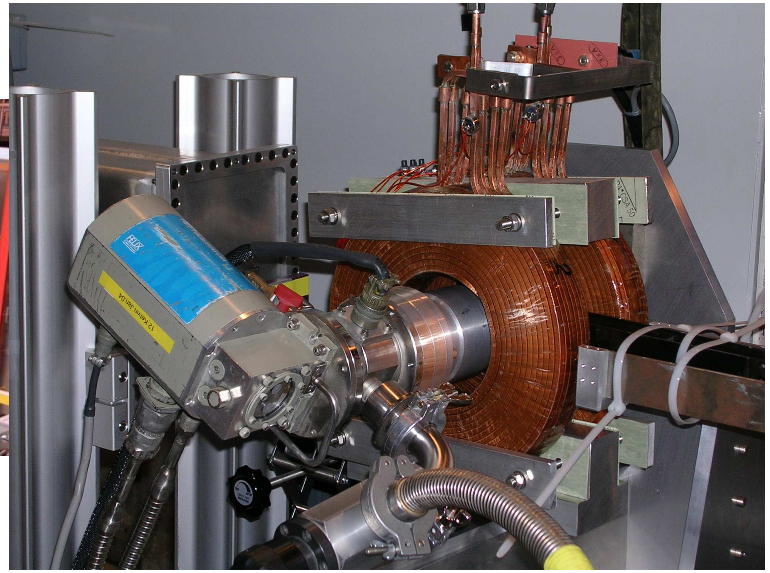
$2\theta = 2 \times \omega$

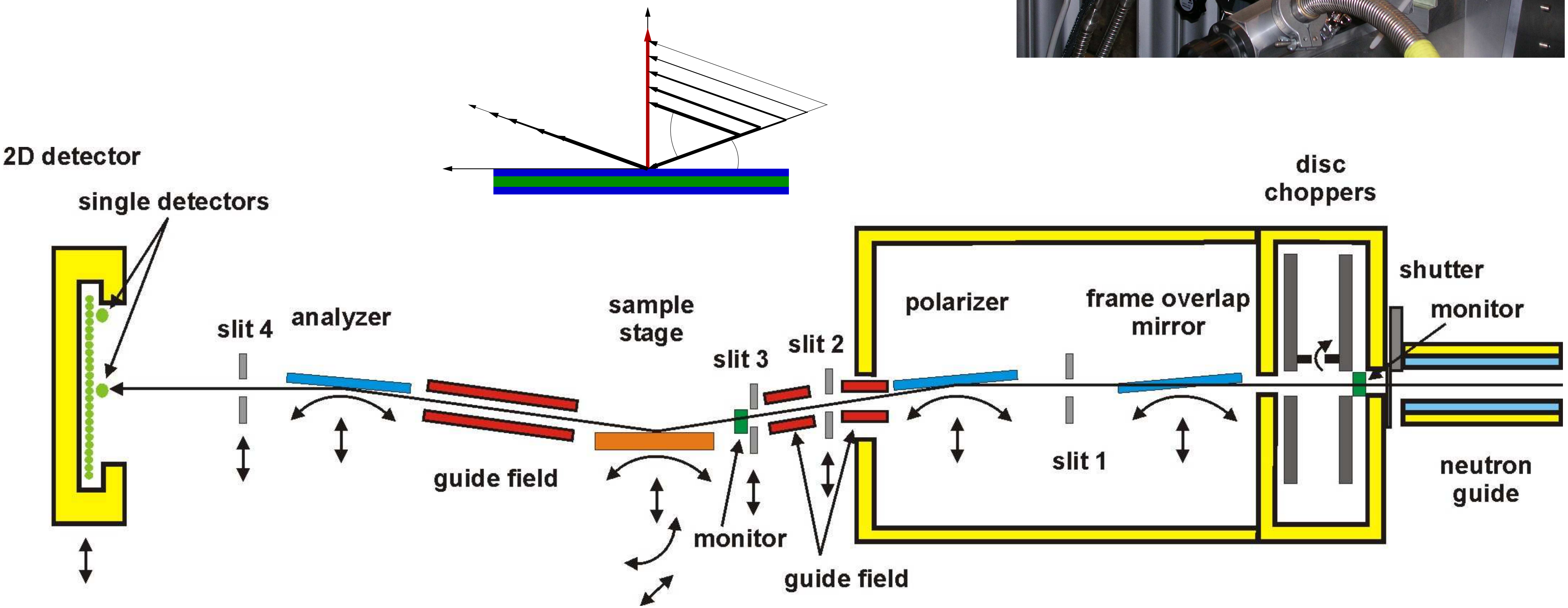






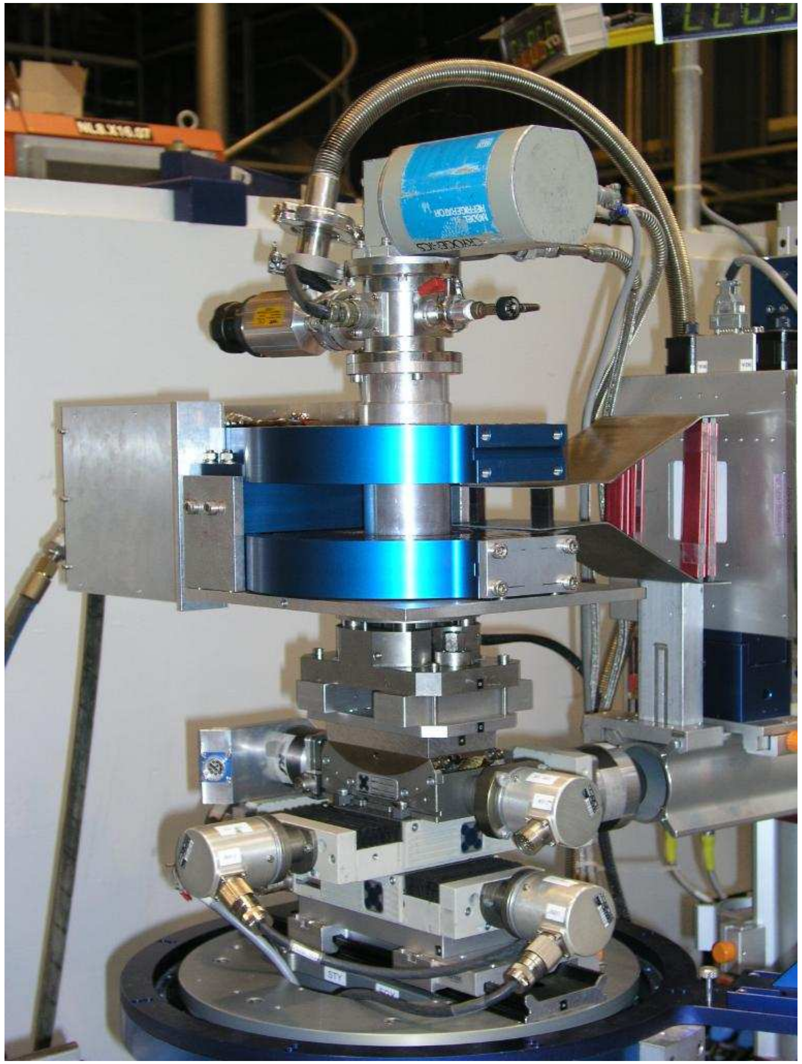
typical instruments: energy dispersive, AMOR @ SINQ





sample environment:

sample holder
with absorber



closed cycle refrigerator

$8\,\mathrm{K} < T < 300\,\mathrm{K}$

Helmholtz coils

$H \leq 1000\,\mathrm{Oe}$

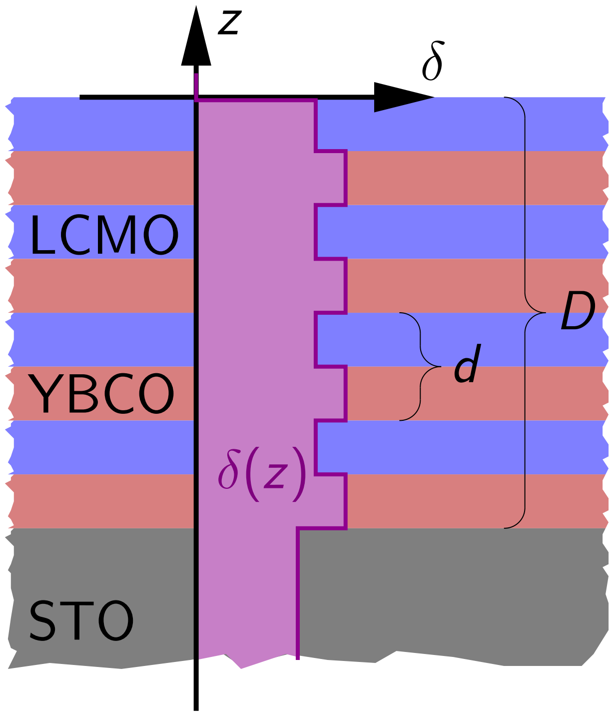
vol: $40 \times 40 \times 40\,\mathrm{mm}^3$

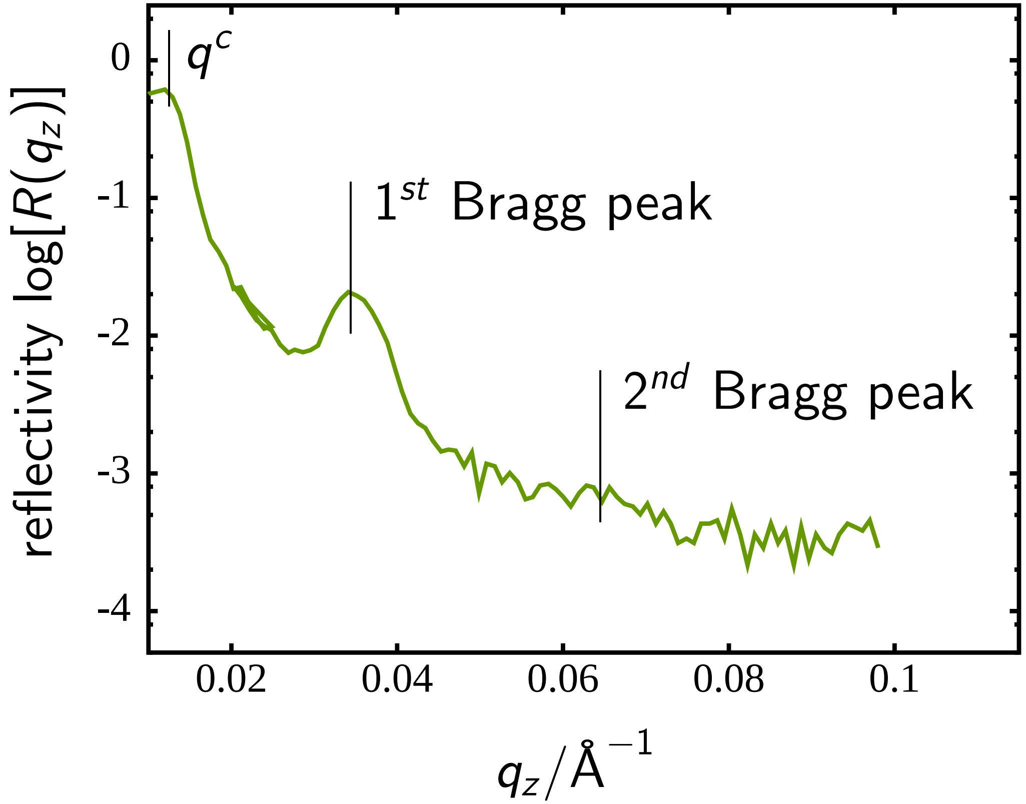
translation stages for alignment

ω-rotation stage

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

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



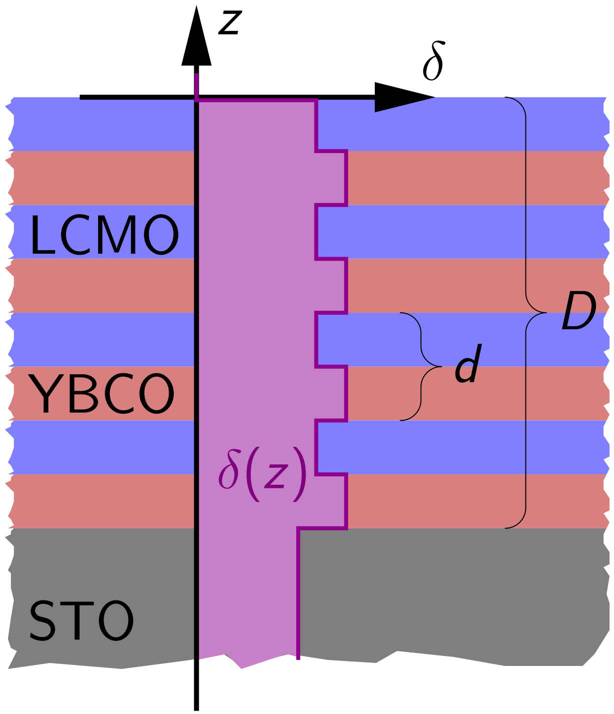


– edge of total external reflection $q_c \propto \sqrt{2\delta}$

– appearance of a Bragg-peak

specular measurements: periodic ml, ideal case

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



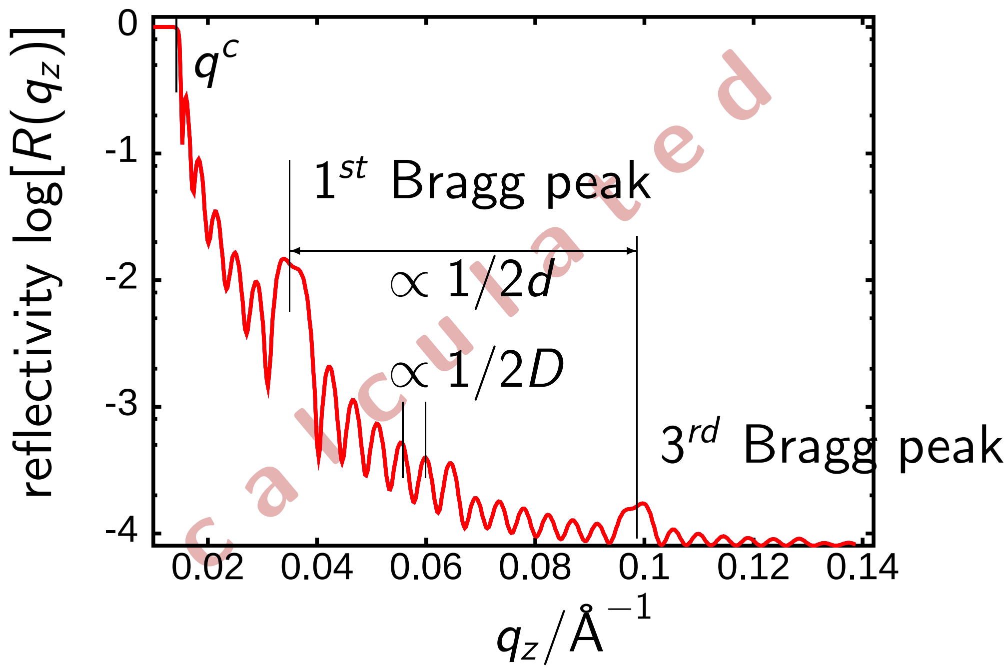
periodicity in z-direction

⇒ 1D crystal

⇒ Bragg-peaks appear

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

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



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

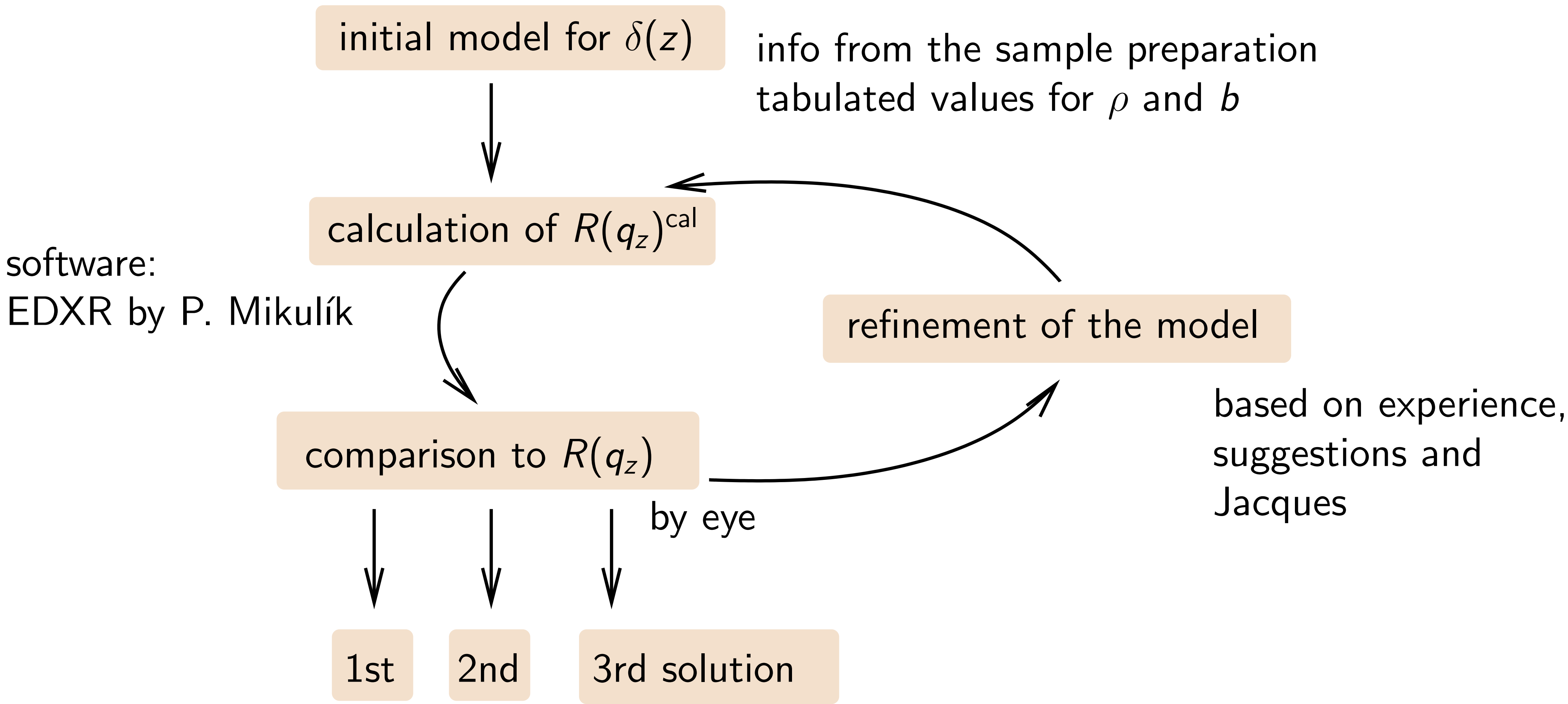
⇒ extinction of all *even* orders

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

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

$\Rightarrow$ lack of phase information

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



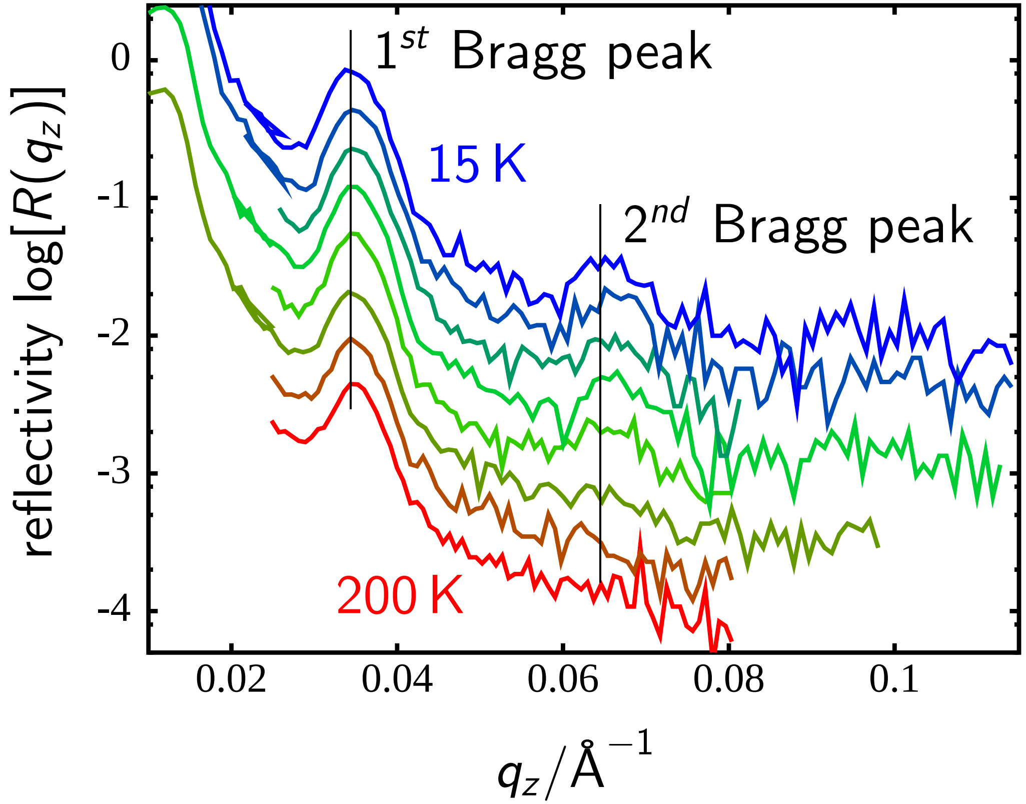
modelling: from $R(q_z)$ to $\delta(z)$

in the case [YBCO(150 Å)/LCMO(140 Å)]$_6$ the *free* parameters are:

	result	initial value
– bilayer thickness d	290 Å	400 Å
– thickness ratio $t_{\mathrm{YBCO}} : t_{\mathrm{LCMO}}$	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: $[\mathrm{YBCO}(100\,\text{Å})/\mathrm{LCMO}(100\,\text{Å})]_7$



observations:

– shift of q^{c} below $T_{\mathrm{m}} \approx 165\,\mathrm{K}$

– increase of 1^{st} Bragg peak for $T_{\mathrm{c}} < T < T_{\mathrm{m}}$

– appearance of a 2^{nd} Bragg peak below T_{m}

$\Rightarrow$ polarised measurements to probe the magnetic profile

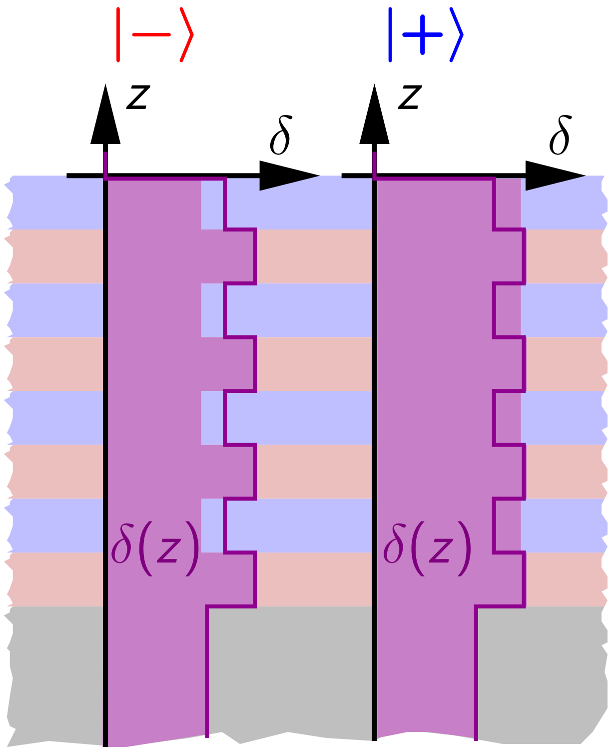
principle of (n) reflectometry: specular, polarised

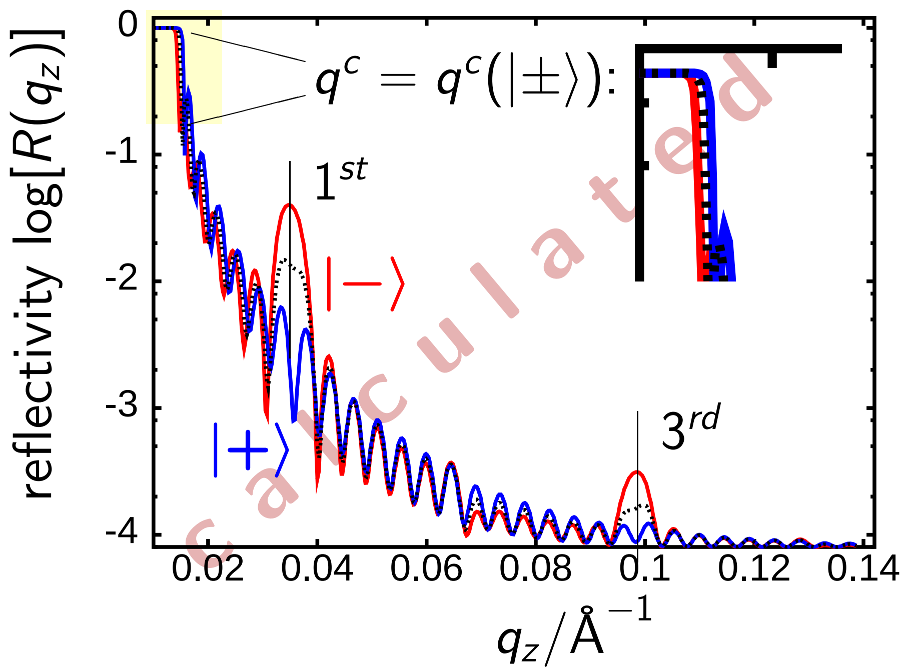
$$\delta = \frac{V}{2E} \quad \text{where} \quad V = V_{\text{nuc}} - \underbrace{V_{\text{mag}}}_{\boldsymbol{\mu}\mathbf{B}_{||}}$$

$\boldsymbol{\mu}$ neutron magnetic moment

$\mathbf{B}_{||}$ in-plane magnetic induction averaged over several μm

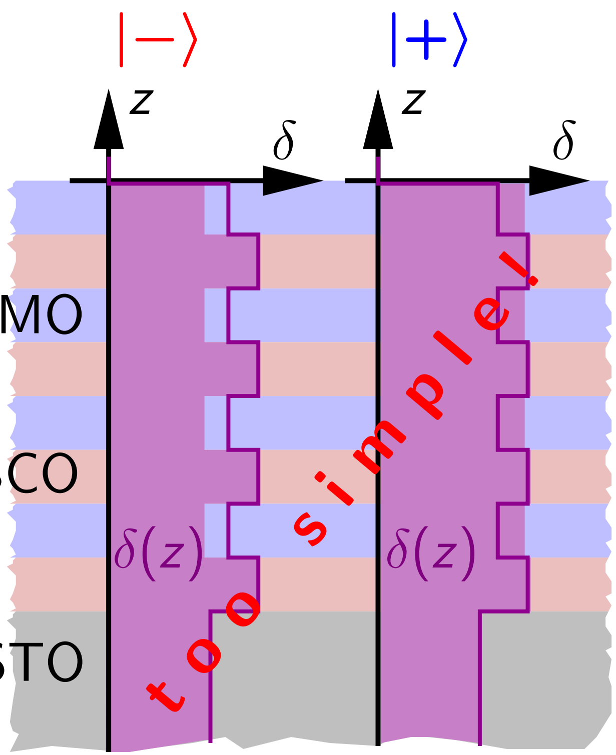
$\Rightarrow R(q_z) \longrightarrow R(q_z, |\pm\rangle)$

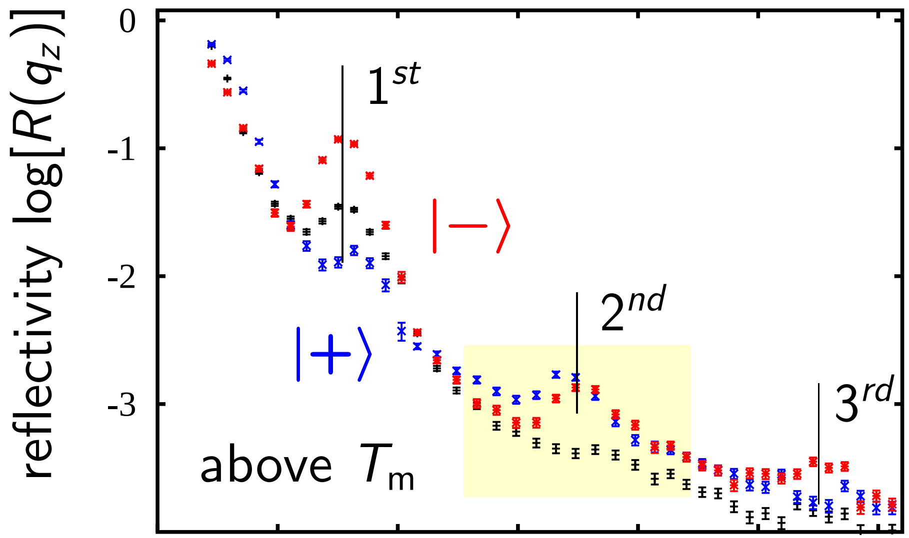


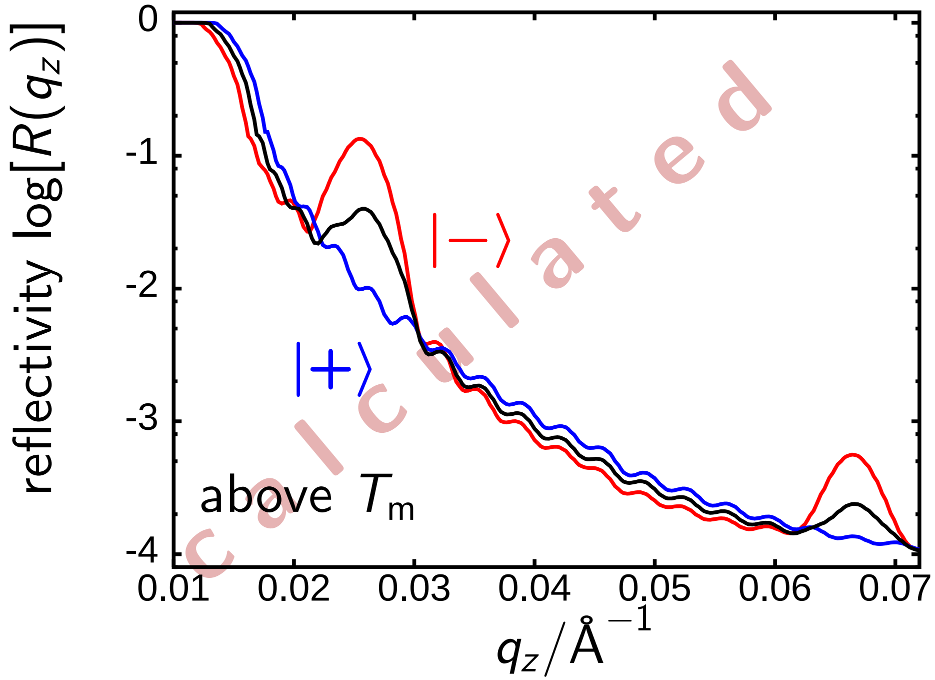


reflectometry: specular, polarised

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

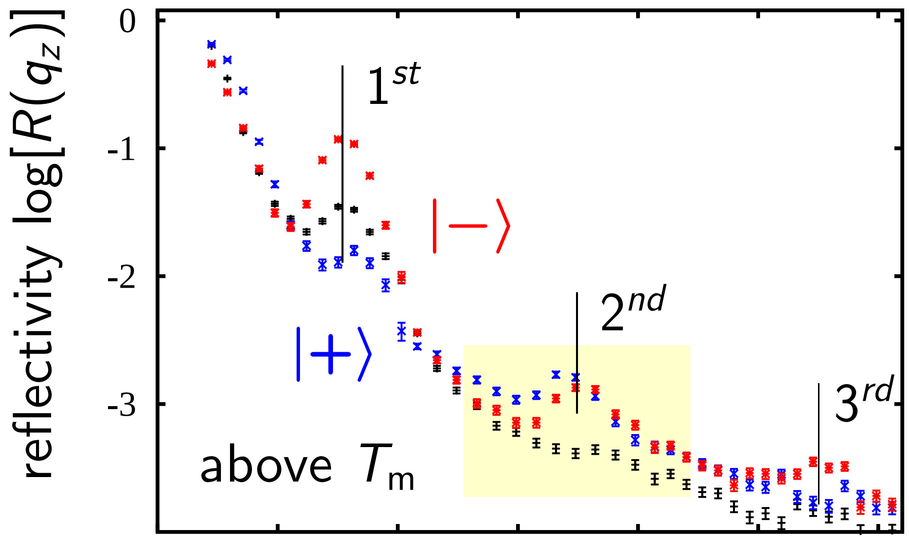
sharp contrast at the interface

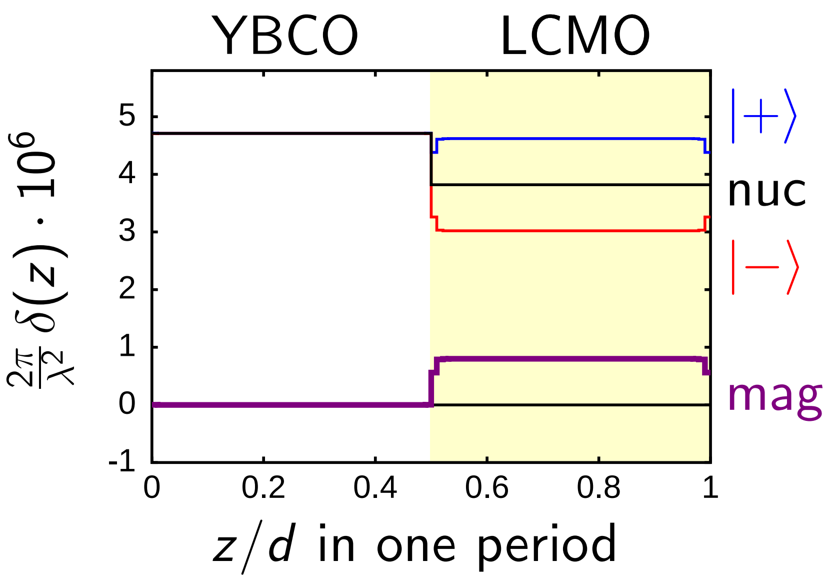
exponential decay into YBCO

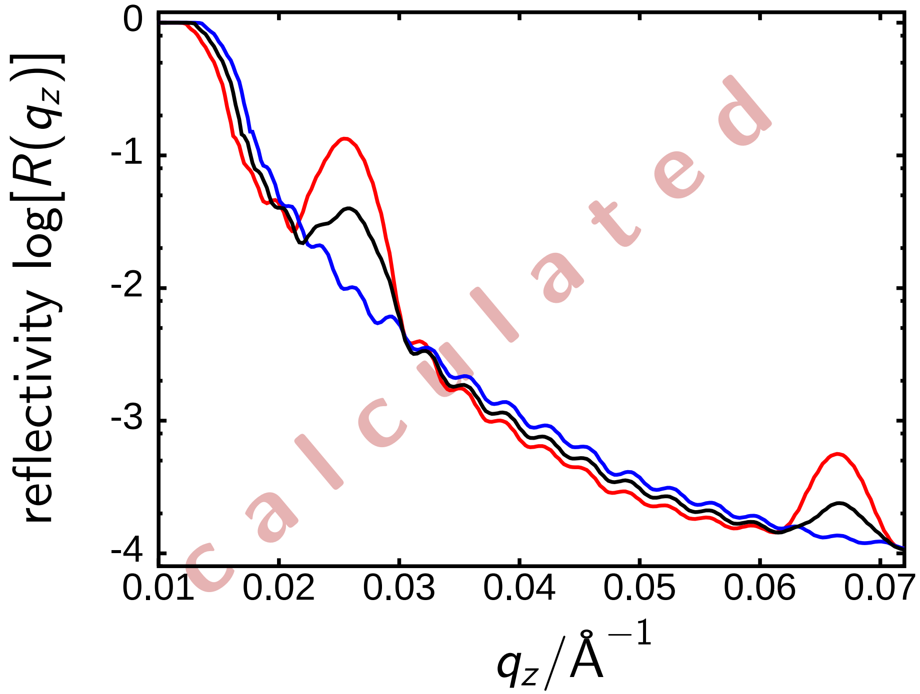
AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO







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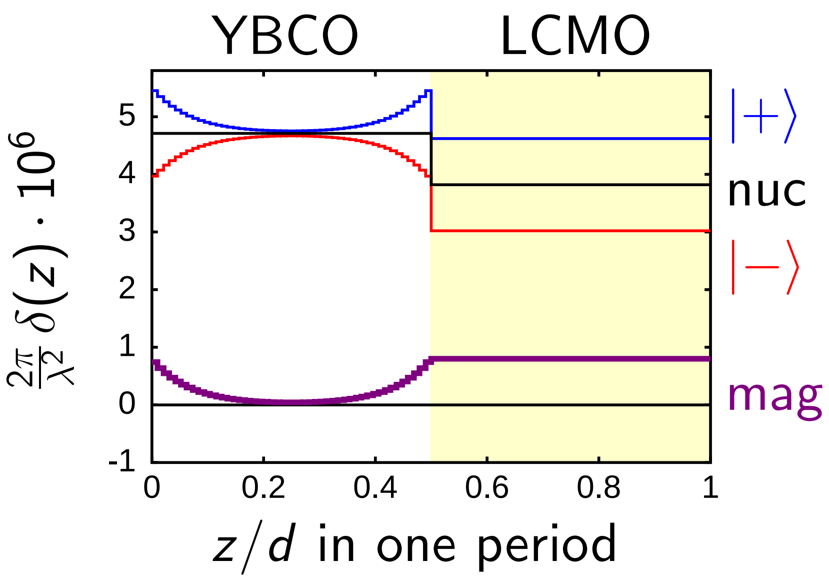
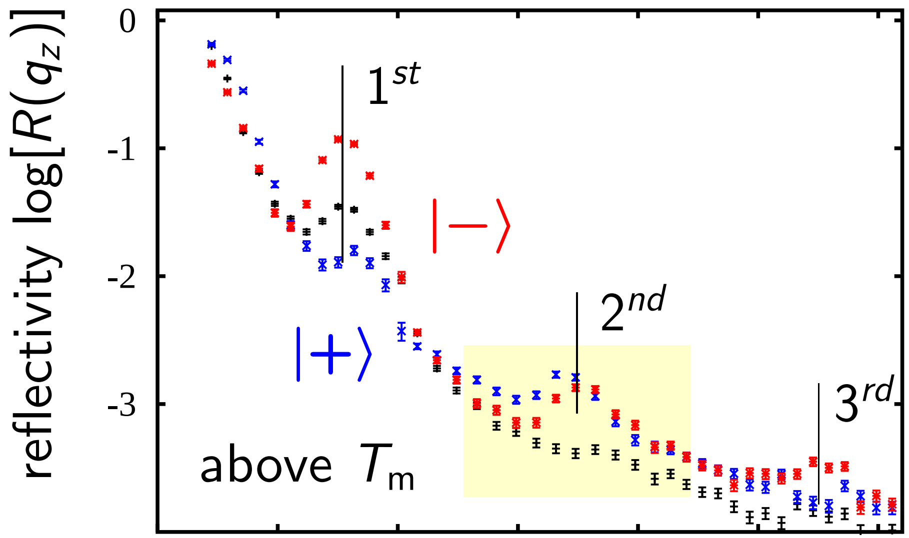
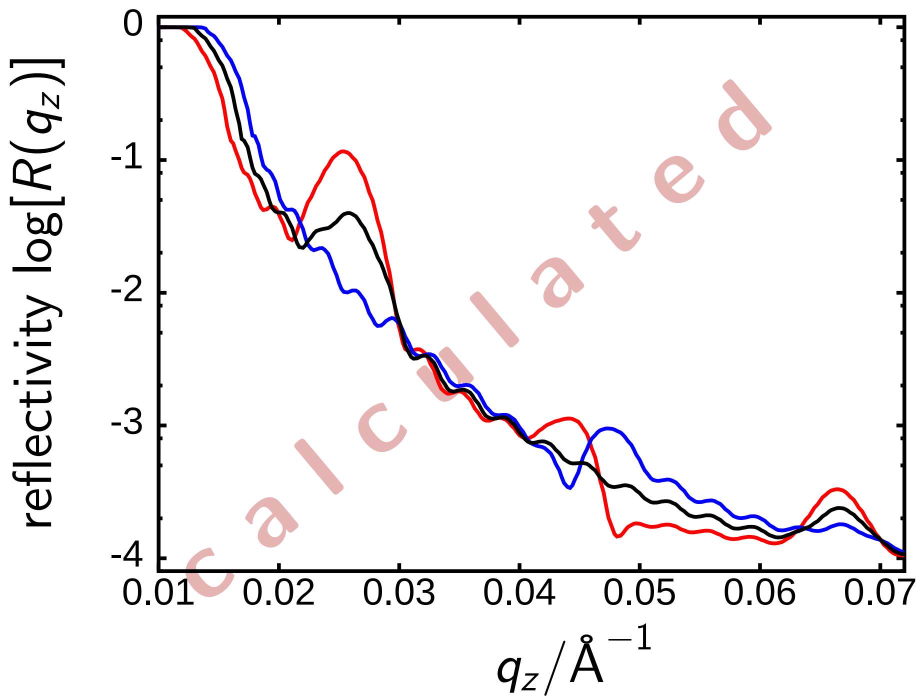
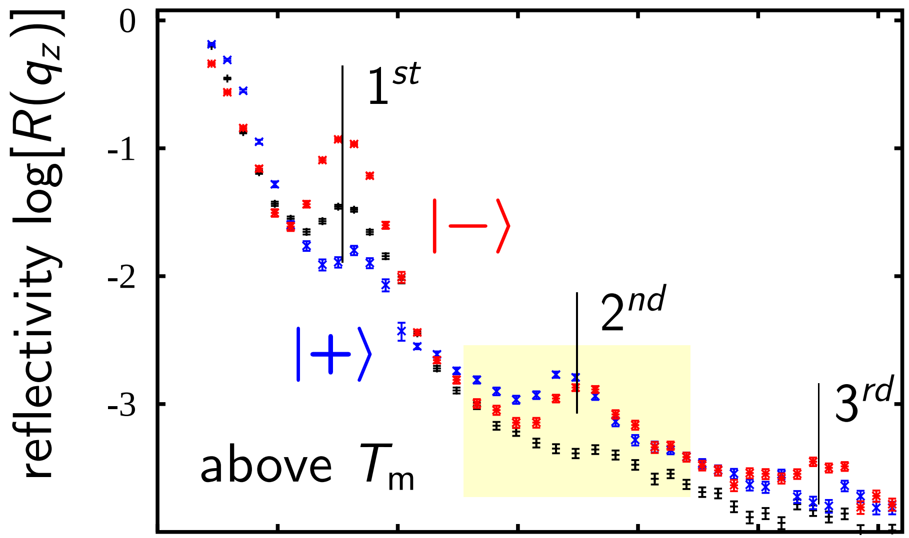


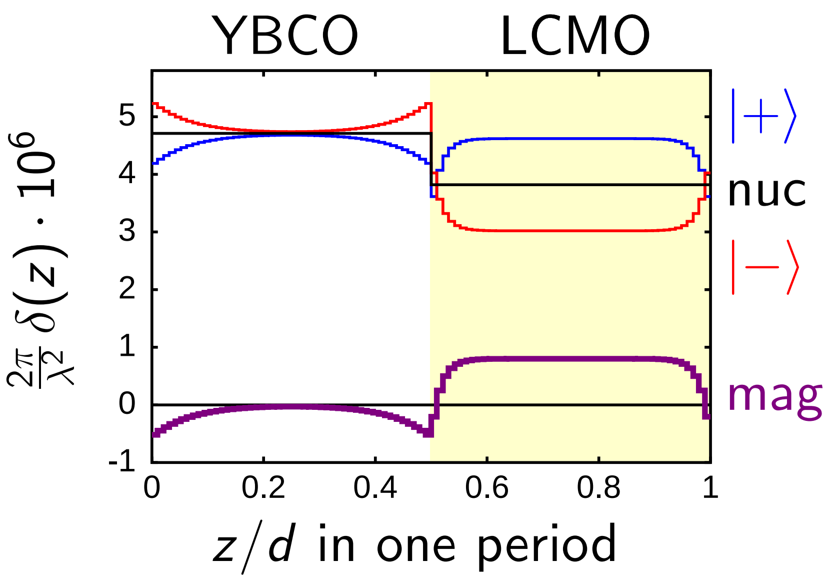


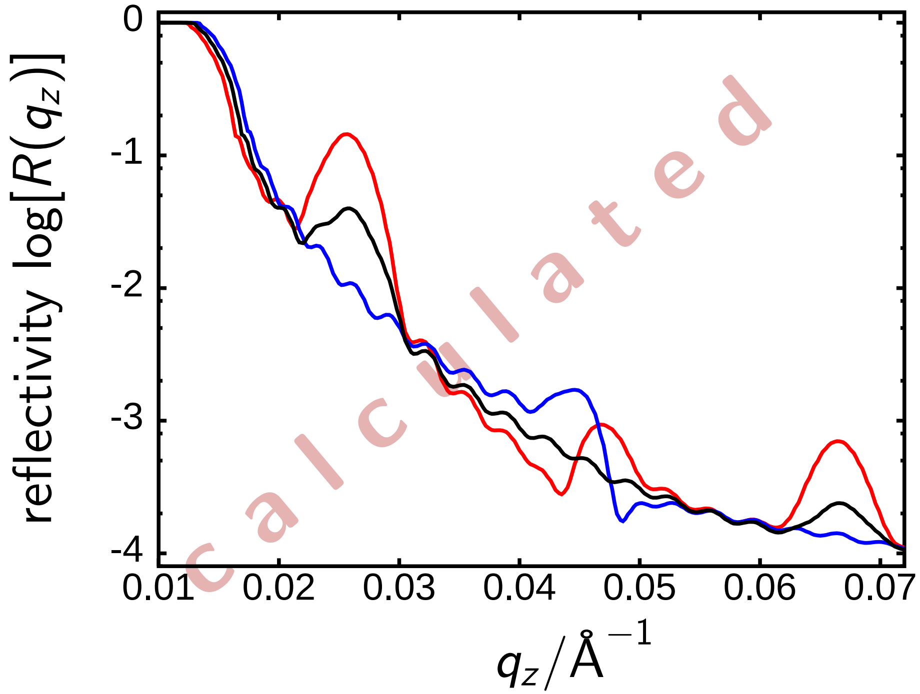


modelling: magnetic profile at the interfaces

- 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

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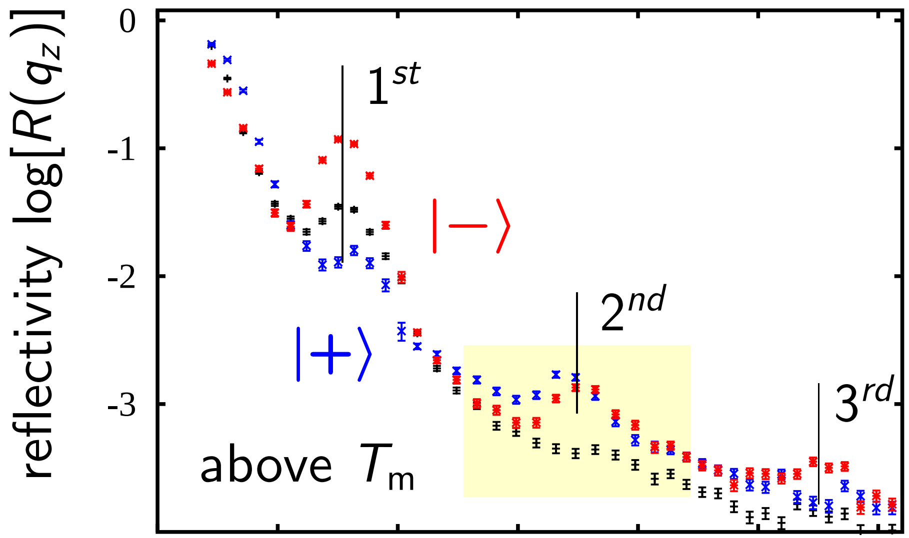

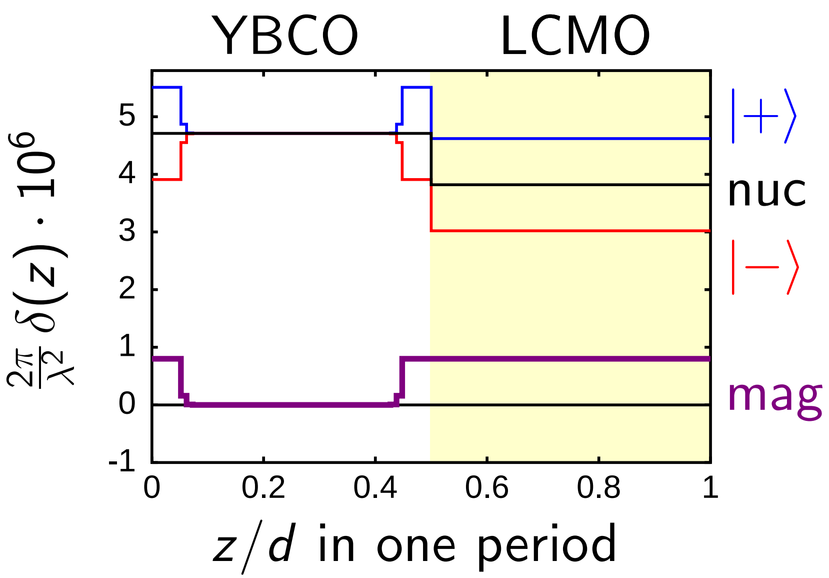

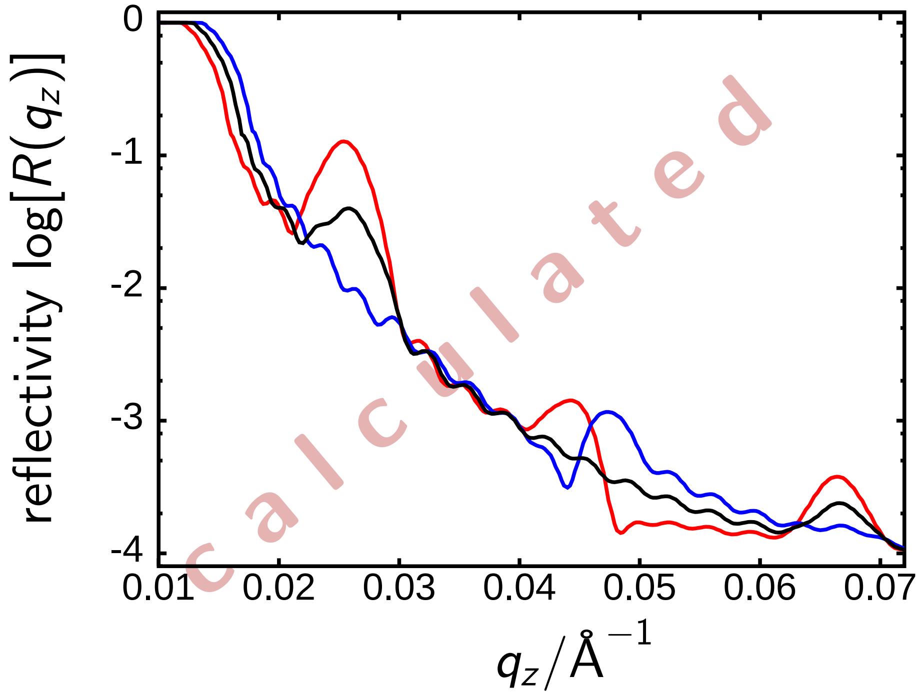

modelling: magnetic profile at the interfaces

sharp contrast at the interface

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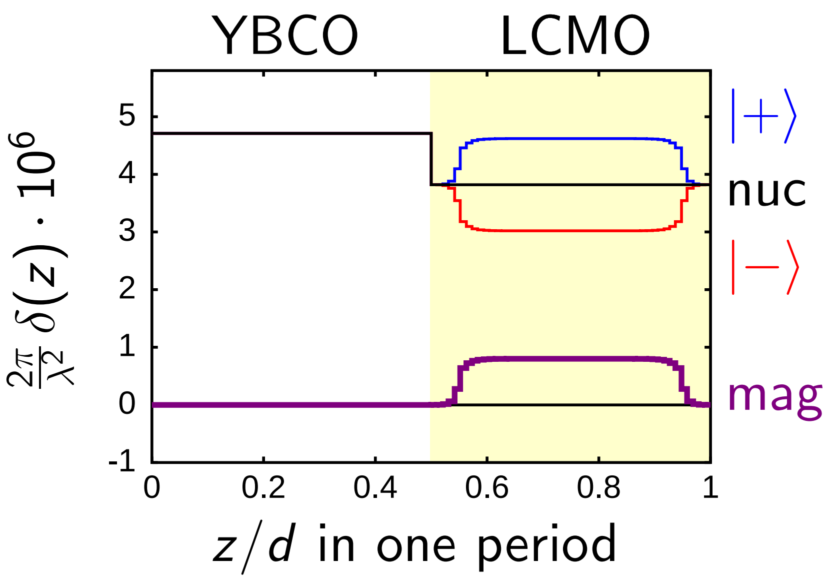
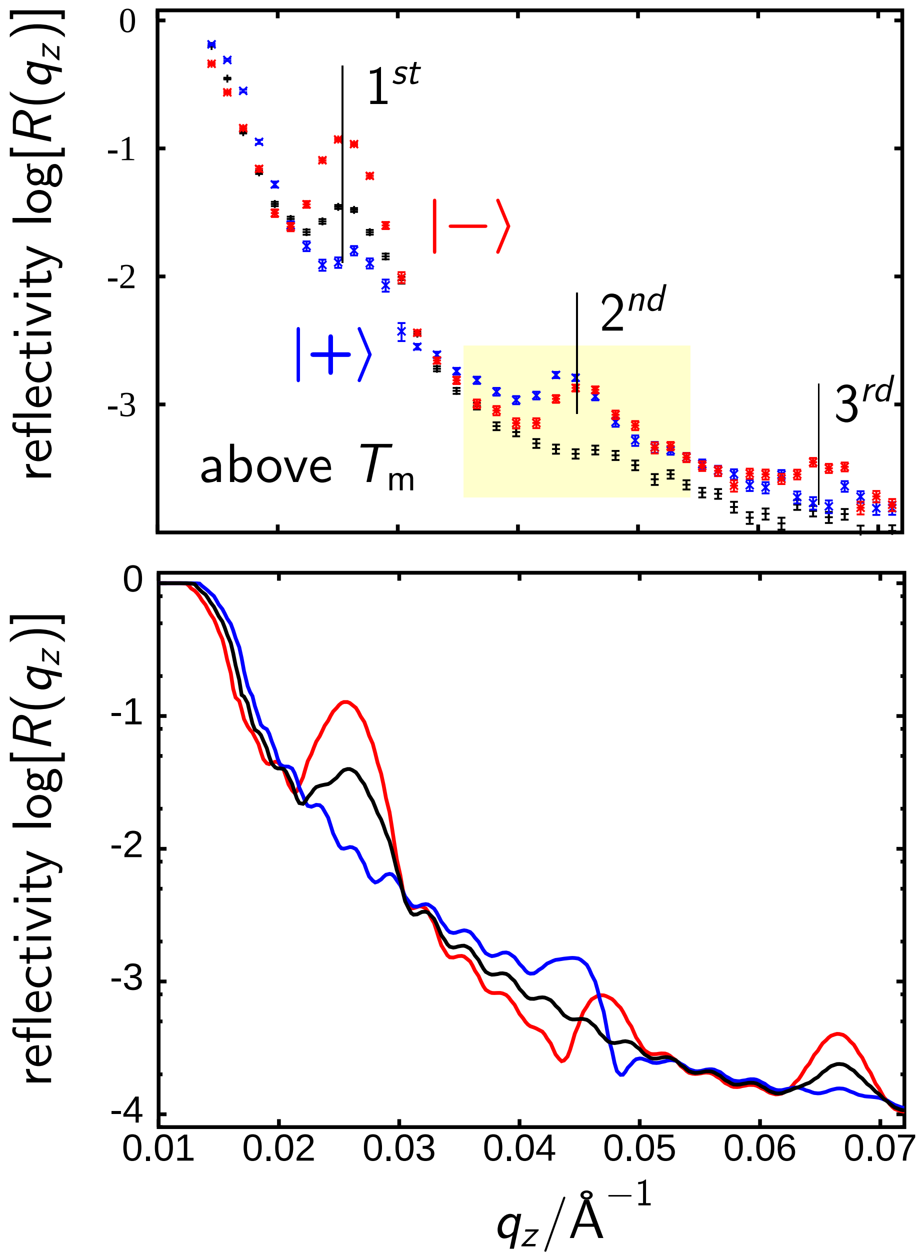
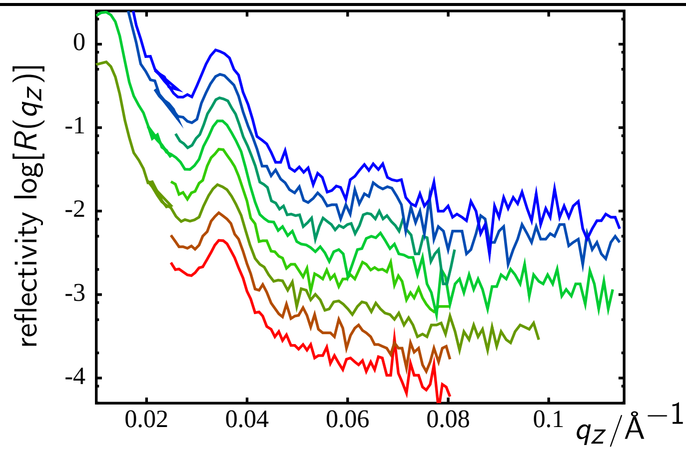
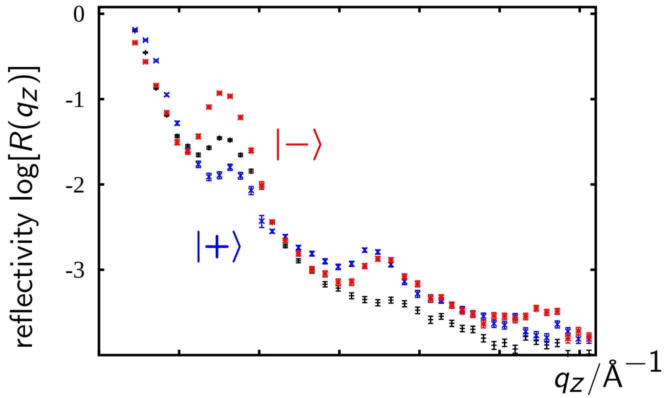
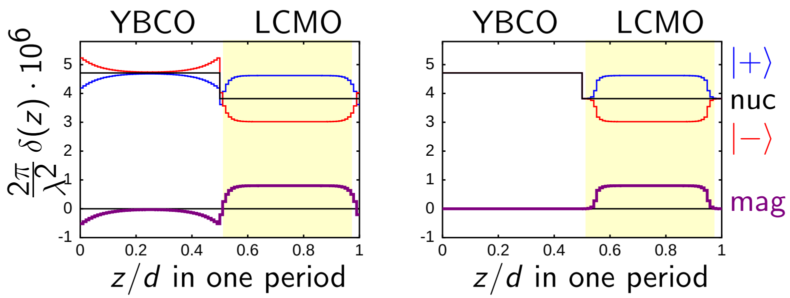




specular polarised neutron reflectometry — first résumé:

reflectometry	$[YBCO/LCMO]_n$
kinematic limit $R(q_z)/R(q^c) \propto \mid \mathcal{F}[\delta(z)]_{q_z} \mid^2$ periodic structure ⇒ Bragg peaks $q^c \Rightarrow \langle\delta\rangle$	
polarised neutrons probe $\mathbf{B}_{\vert\vert}$	
no direct method modelling is required ⇒ no unique solution	

magnetometry:

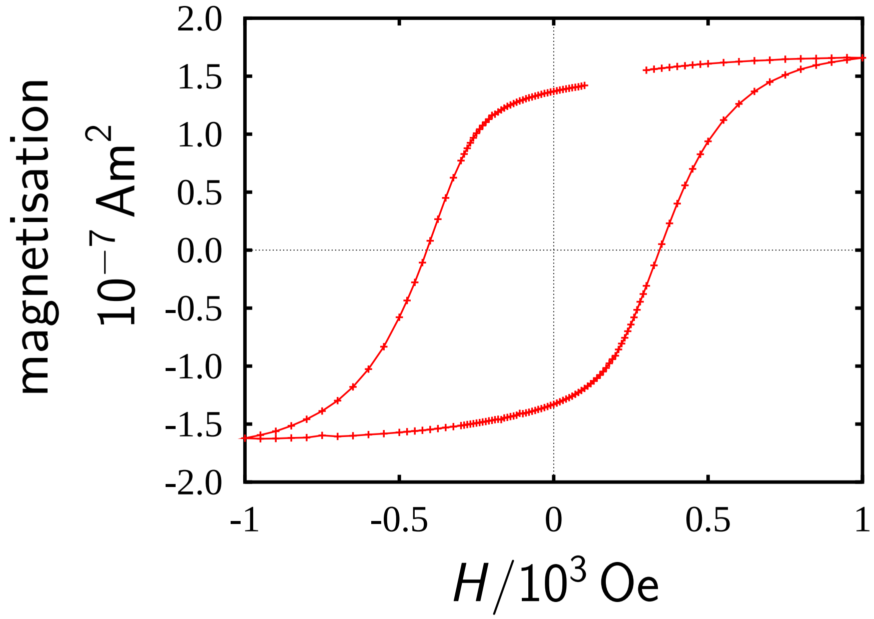
SQUID measurements by F. Treubel, Konstanz

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

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

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

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



$\Downarrow$

presence of an AFM coupling
at the FM-interface

but:

– *magnetically dead layer* might be an AFM

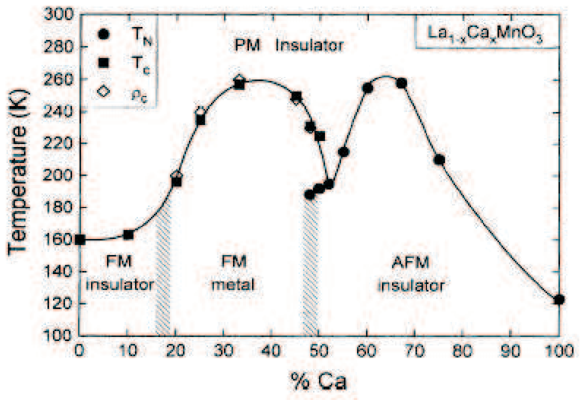
– **B** in YBCO might be an AFM with net magnetic moment

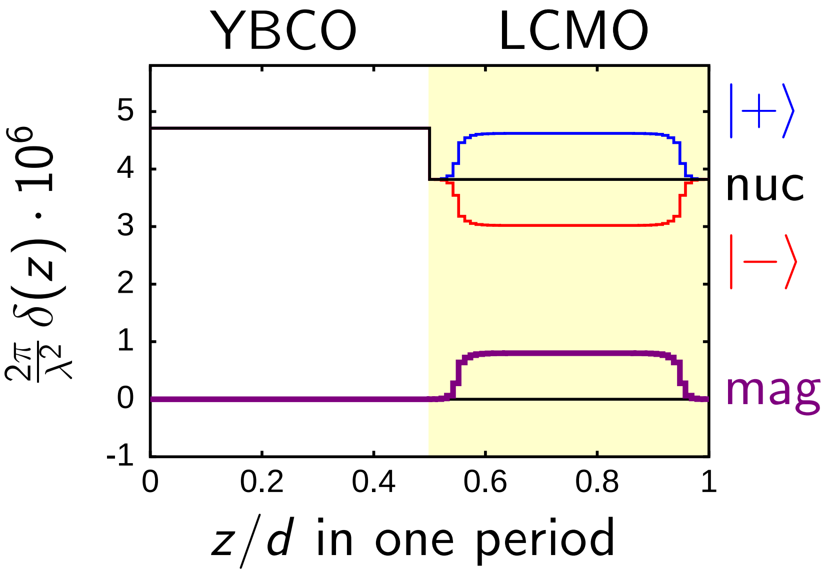
models for the magnetisation profile:

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

AFM-region within LCMO

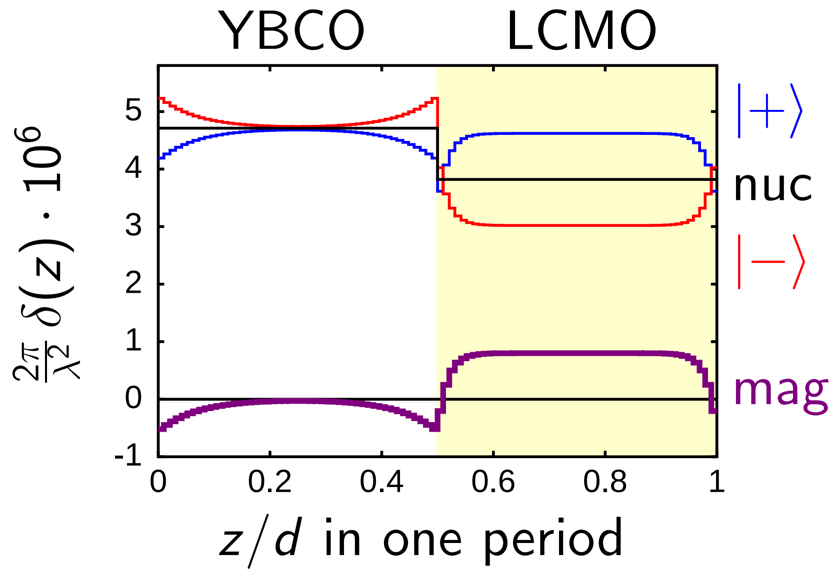
charge-injection from YBCO leads to a doping of LCMO and thus to an AFM ground state



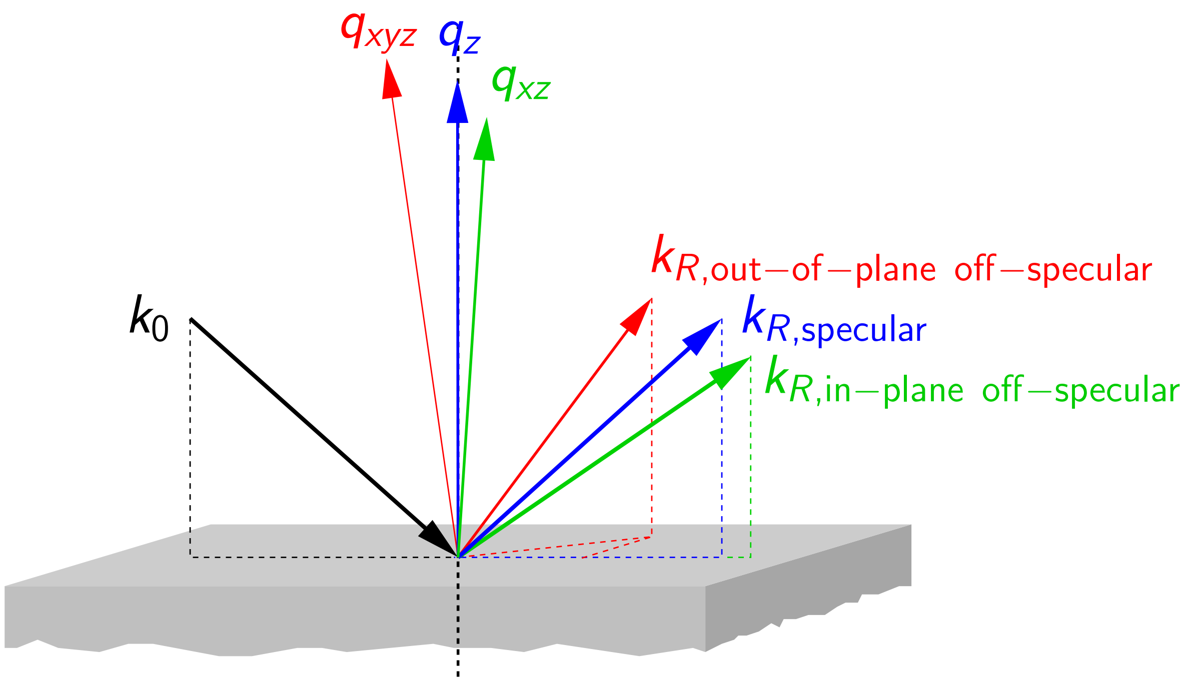


antiphase magnetic proximity effect

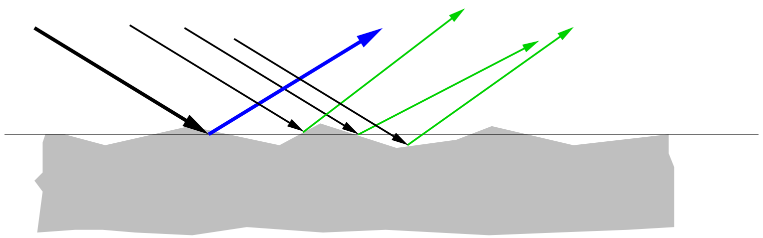
Cooper pairs penetrate into LCMO and are *polarised* $\Rightarrow$ antiparallel magnetisation in YBCO

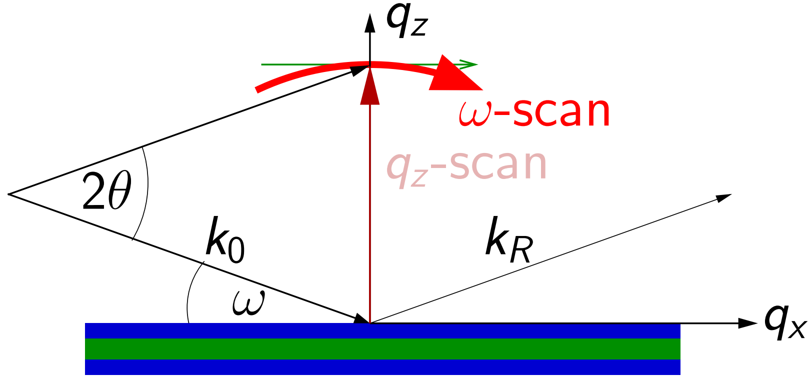


off-specular reflectometry: lateral structure is probed



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





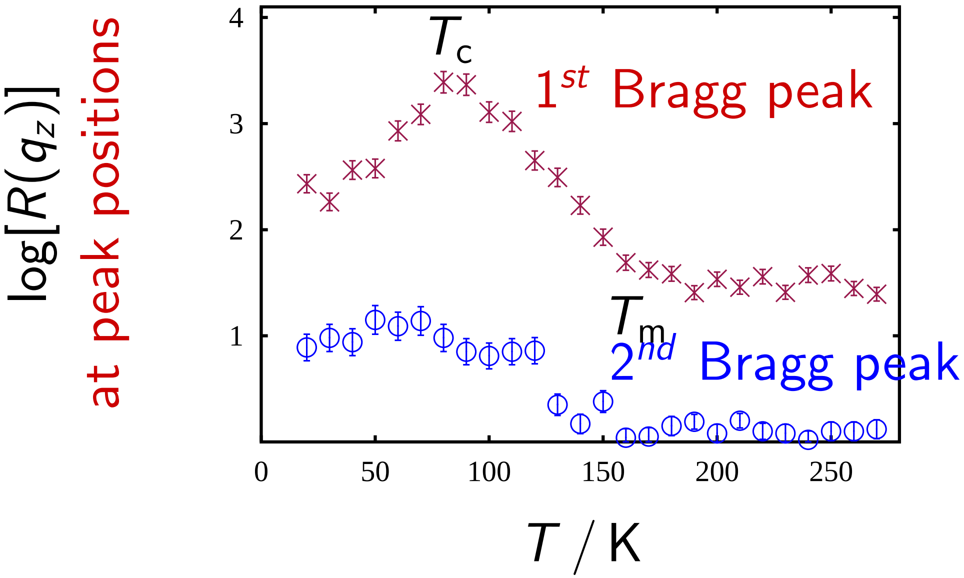
inclined surface facetts $\Rightarrow \Delta\omega$

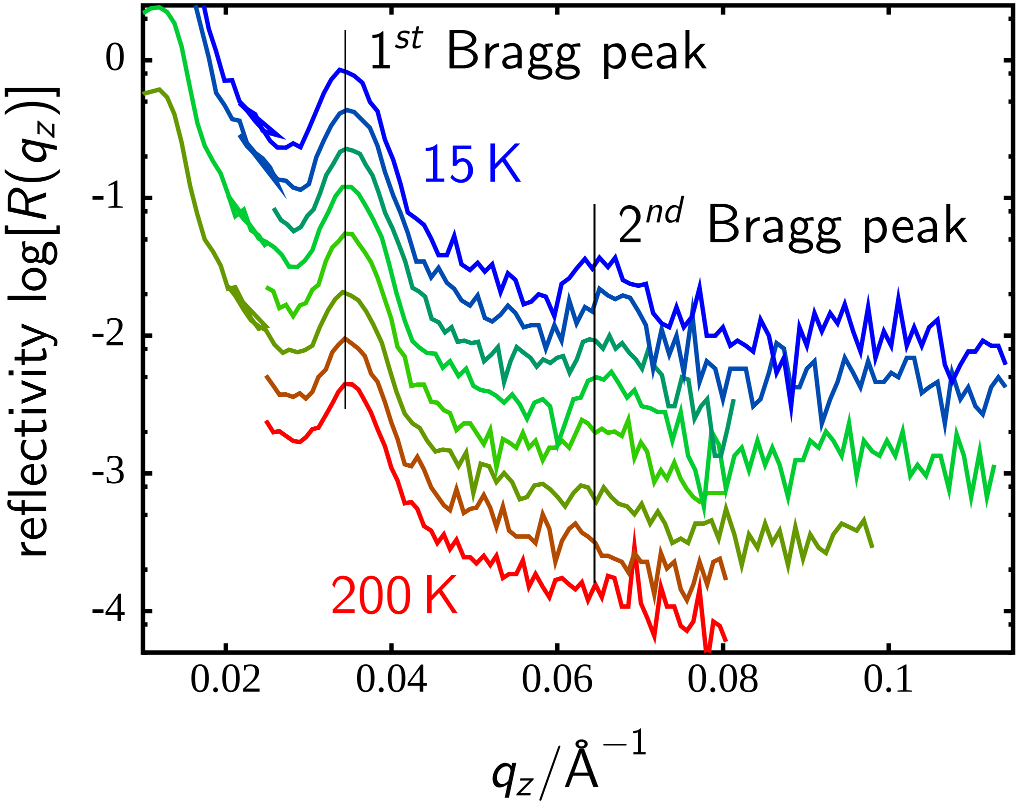
height-variation $\Rightarrow$ phase-shifts in k_R

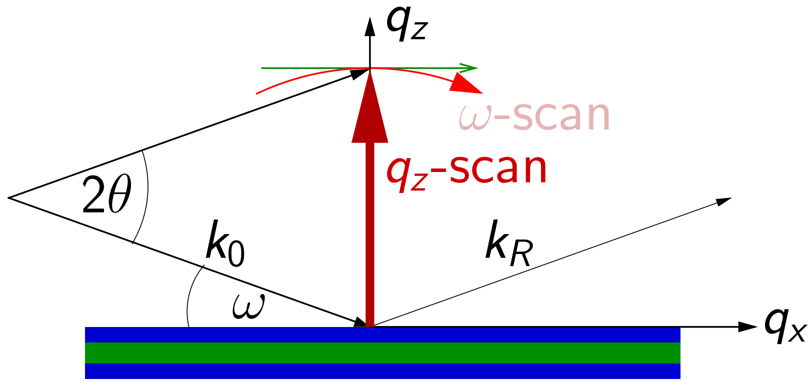
$\Rightarrow$ damping of $R(q_z > q^c)$

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

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

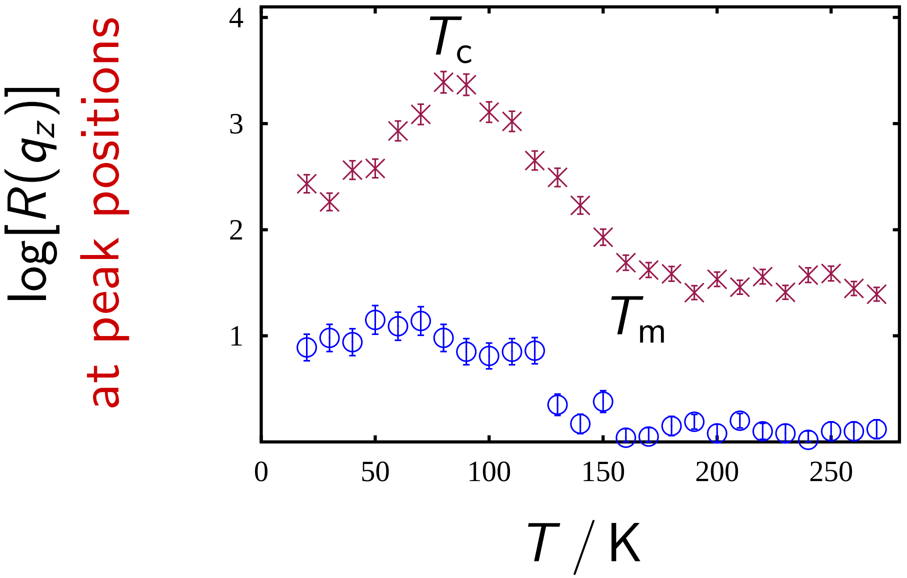


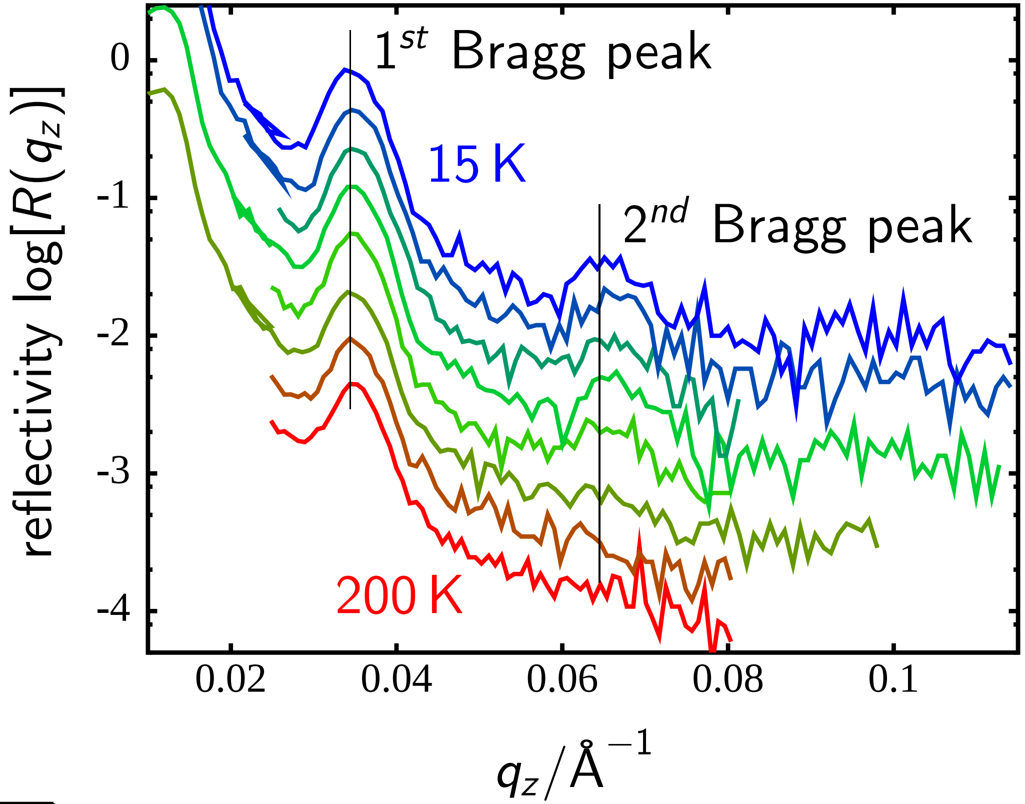


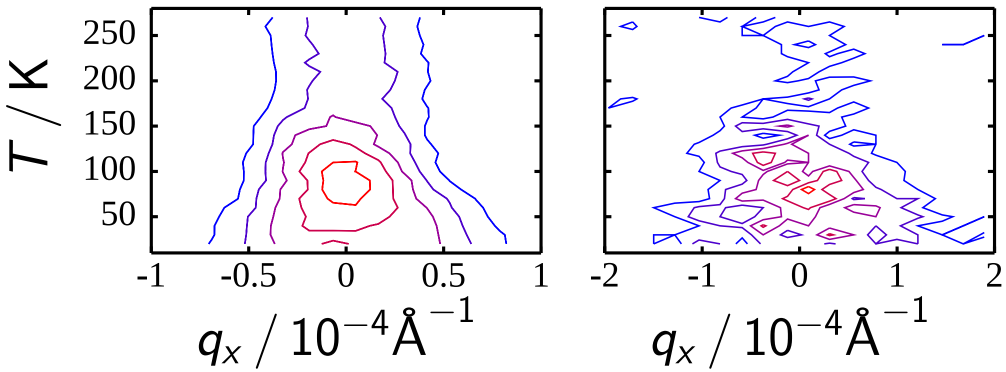


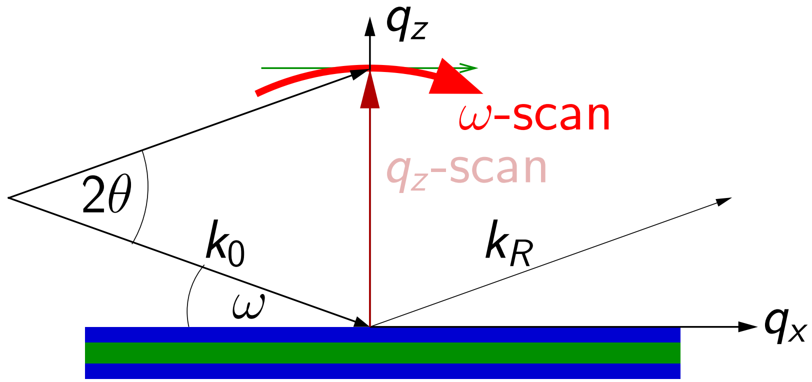
off-specular measurements: periodic ml, non-polarised, various T

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



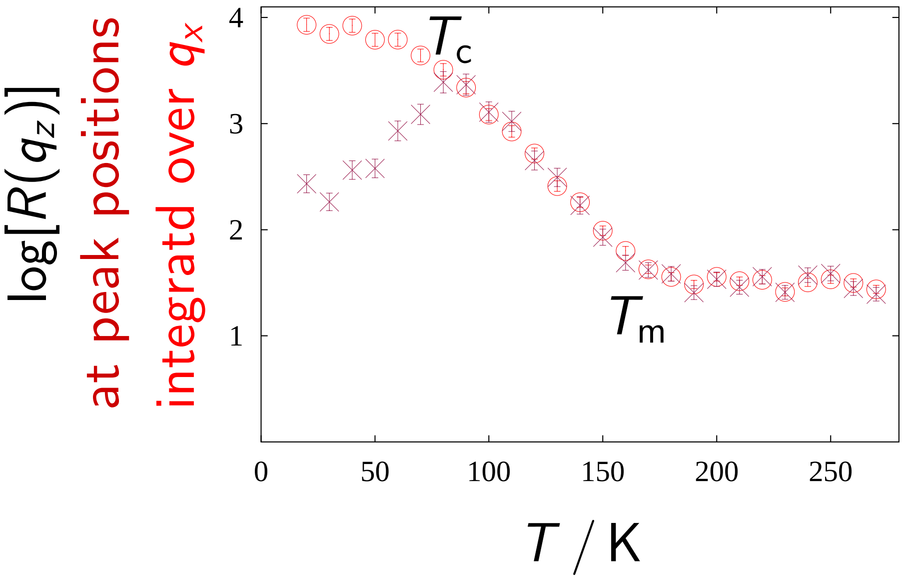


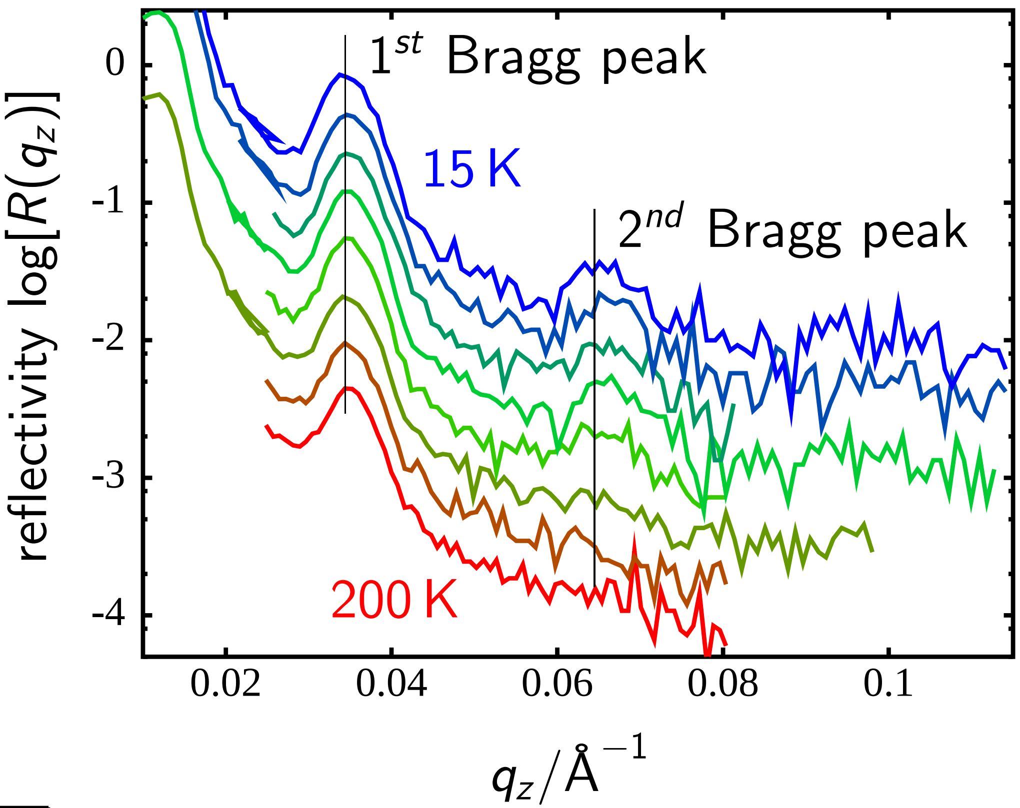


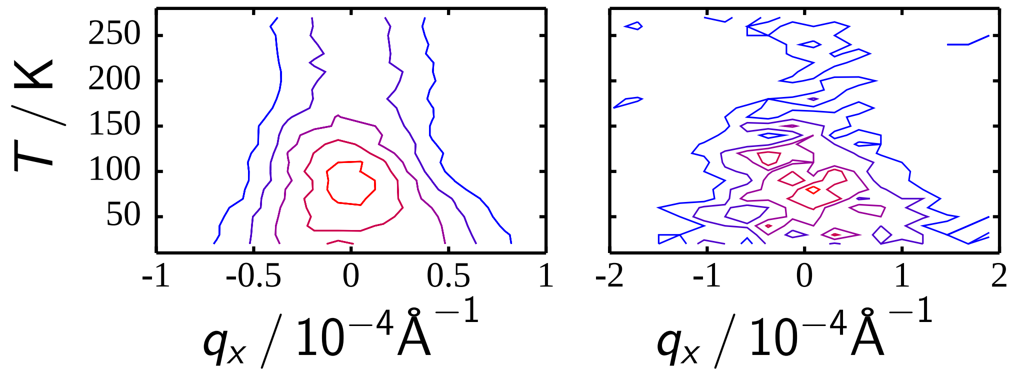


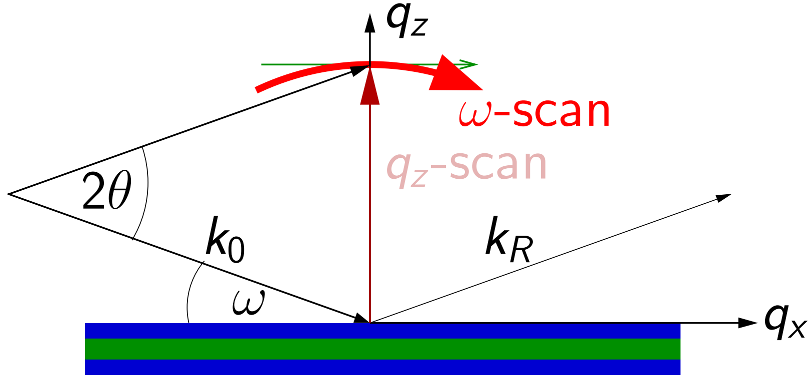
off-specular measurements: periodic ml, non-polarised, various T

sample: [YBCO(100 Å)/LCMO(100 Å)]$_7$









interpretation of off-specular scans:

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

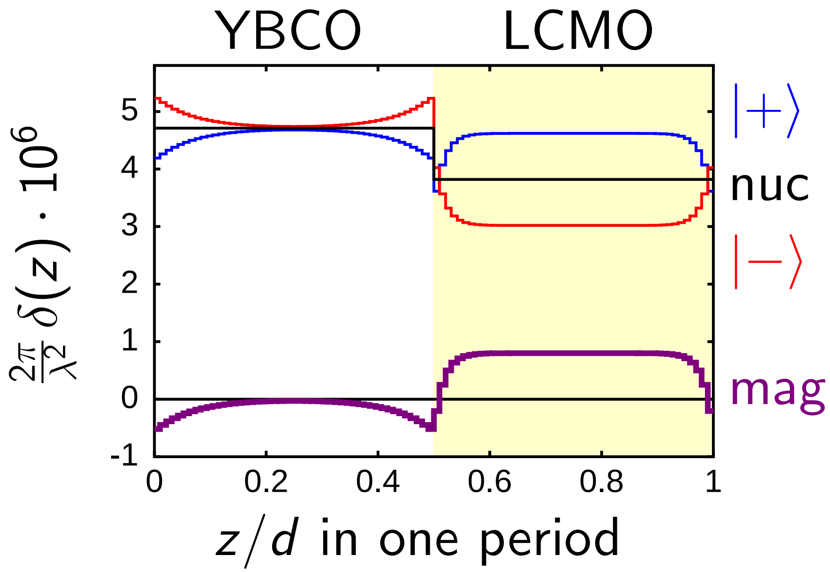
$$T > T_c \quad : \quad \Lambda_{||} \approx 16\,\mu\text{m}$$

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

$\Rightarrow$ SC directely 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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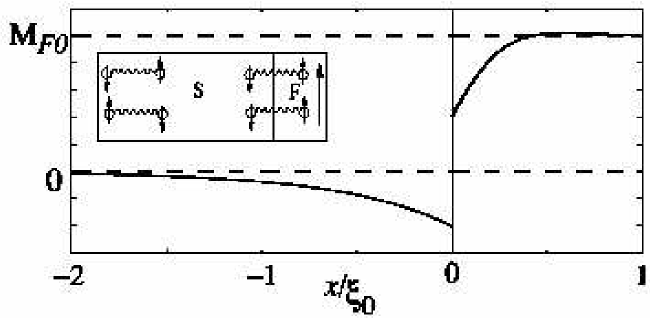


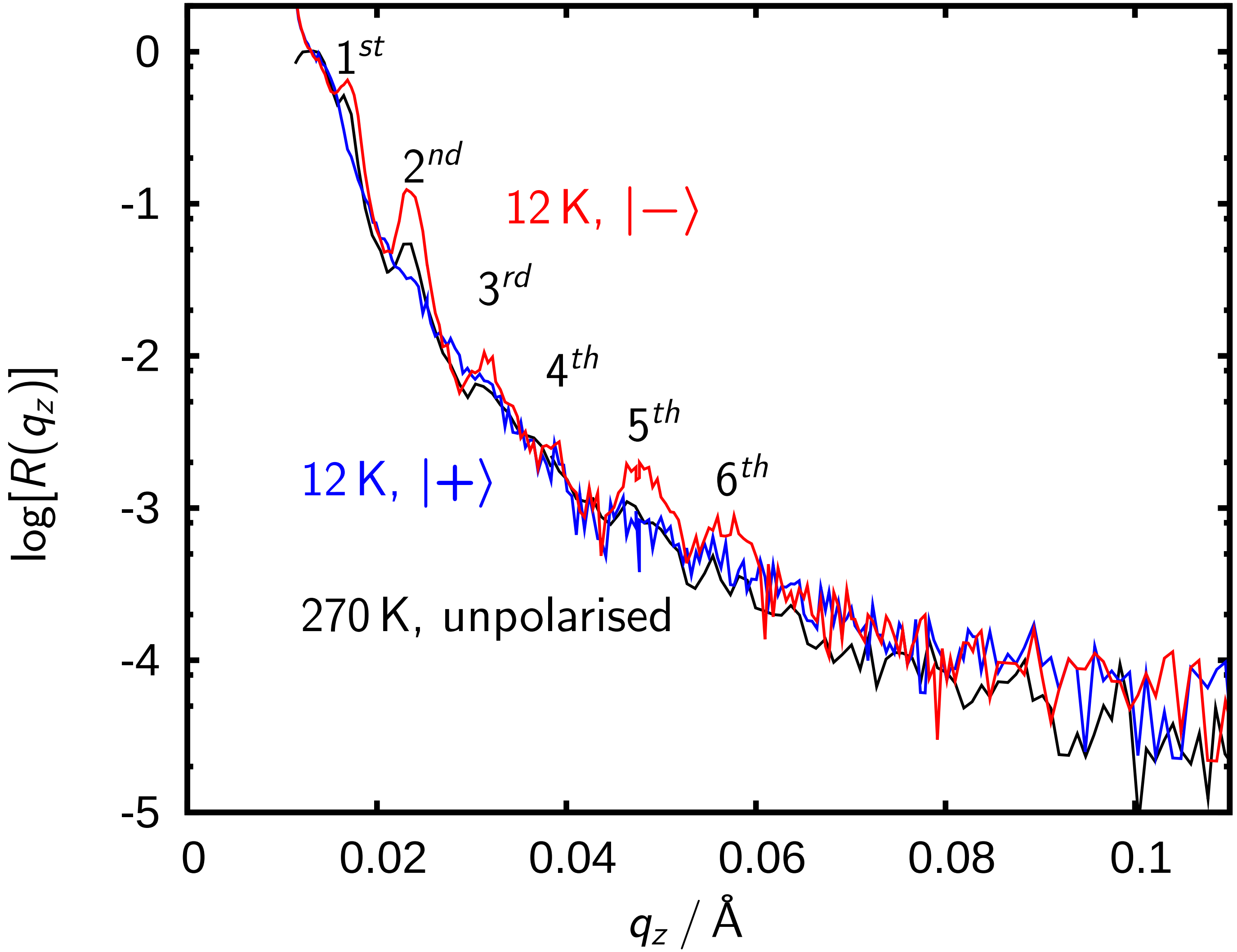
FIG. 1. Spatial dependence of the magnetization in the whole system. Here $\gamma_F/\gamma_S=0.5$, $\bar{\gamma}_F=\gamma_F/\xi_0=0.1$ ($\xi_0=\sqrt{D_S/2T_c}$), $J/T_c=15$, and $d_F/\xi_0=1$. Inset: Schematic view of the inverse proximity effect in a S/F system (for discussion see text).

PRB **69**, 174504 (2004)

recent measurements:

19. 10. 2004

sample Y-LCM68: [YBCO(500 Å)/LCMO(250 Å)]$_5$



fitted values (RT, unpolarised):

roughness $\approx$ 5 Å

$t_{\mathrm{YBCO}} \approx$ 520 Å

$t_{\mathrm{LCMO}} \approx$ 180 Å

decreasing resolution with q_z

$\Rightarrow$ decreased d at the edges?

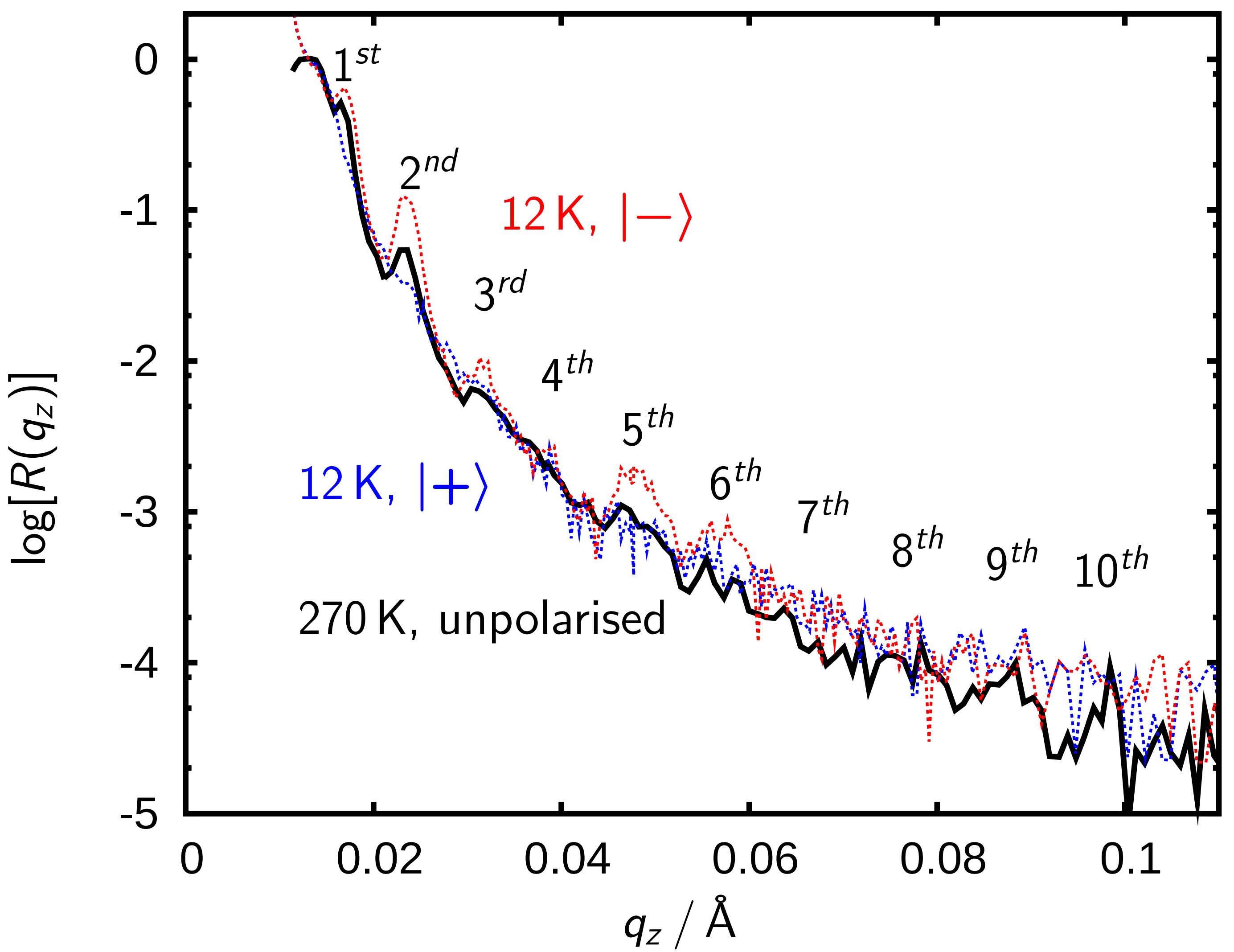
no plateau below q^c

$\Rightarrow$ bent sample?

recent measurements:

19. 10. 2004

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



samples:

G. Cristiani

HU. Habermeier

measurements:

J. Chakhalian

T. Gutberlet

J. Hoppler

C. Niedermayer

S. Pekarek

analysis:

J. Hoppler

S. Pekarek

interpretation:

C. Bernhard

J. Chakhalian

B. Keimer

C. Niedermayer