

Jochen Stahn

Laboratory for Neutron Scattering



Paul Scherrer Institut

Polarised Neutron Reflectometry

a complementary method to RIXS and ARPES

spectroscopy workshop on novel materials

PSI - SYN

Beatenberg, 3. – 7. May 2011

. . . did so far:

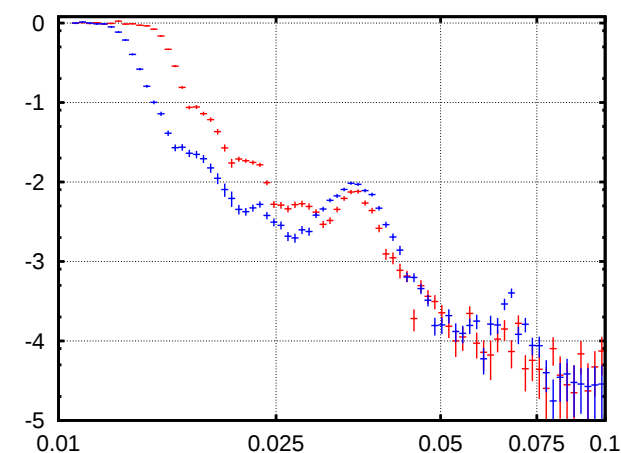
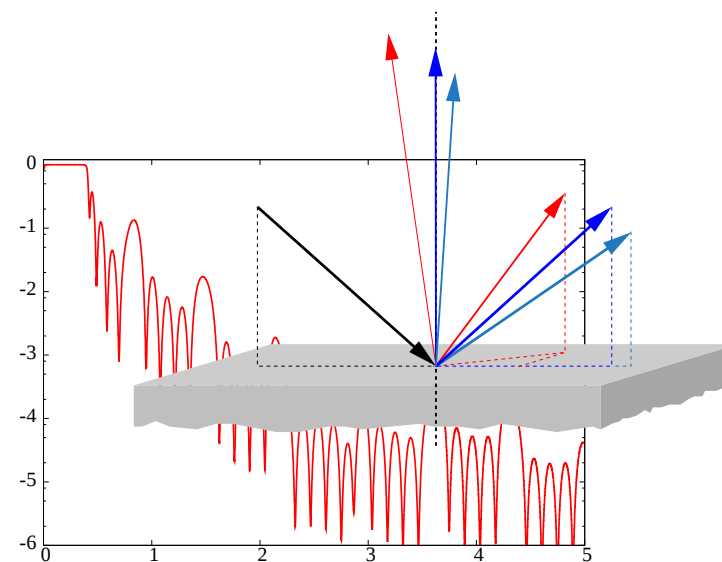
- chemistry studies
- γ -Compton spectroscopy on GaAs
- x-ray diffraction (resonant! HASYLAB, ESRF)
on GaAs and ZnSe in electric fields
- neutron optics development
- instrument scientist, reflectometry
- PNR on layered magnetic films
 - YBCO/LCMO (C. Bernhard, B. Keimer)
 - div. (F. Miletto)
 - LSMO/YBCO (M. Radovic)

Konstanz

Potsdam

PSI

- CV
 - done.
- intro to PNR
 - reflectometry in general
 - ... with neutrons
 - ... on magnetic samples
 - experimental set-up
- experiments: LSMO / YBCO interfaces
 - bi-layers (Y. Sassa, M. Radovic)
 - multilayers (M. Radovic)





flat surfaces partly reflect light

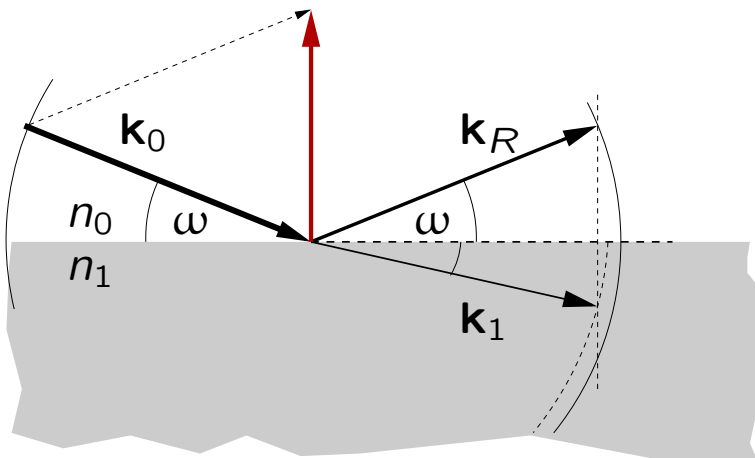
→ picture of the boot

some media also transmit light

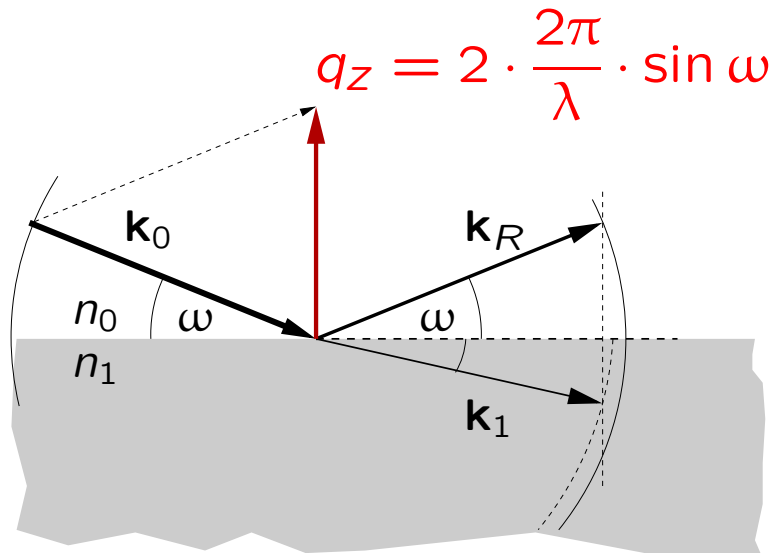
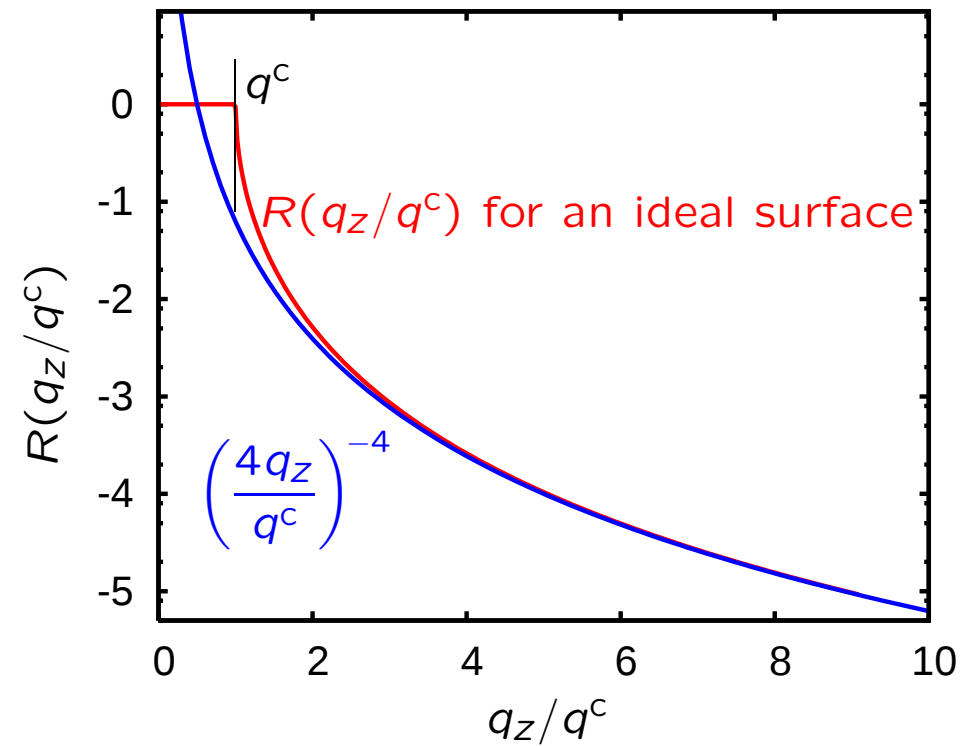
→ ground below the water

parallel interfaces

→ colorful soap bubbles



- reflectivity of a sharp flat surface
- total external reflection for $q_z < q^c$
- exponential decay of $R(q_z)$ for $q_z > q^c$



neutrons / x-rays:

$$\lambda \in \{1 \dots 20 \text{ \AA}\}$$

$$\omega^c < 1^\circ$$

refraction of transmitted beam

$\Rightarrow$ dynamical scattering theory

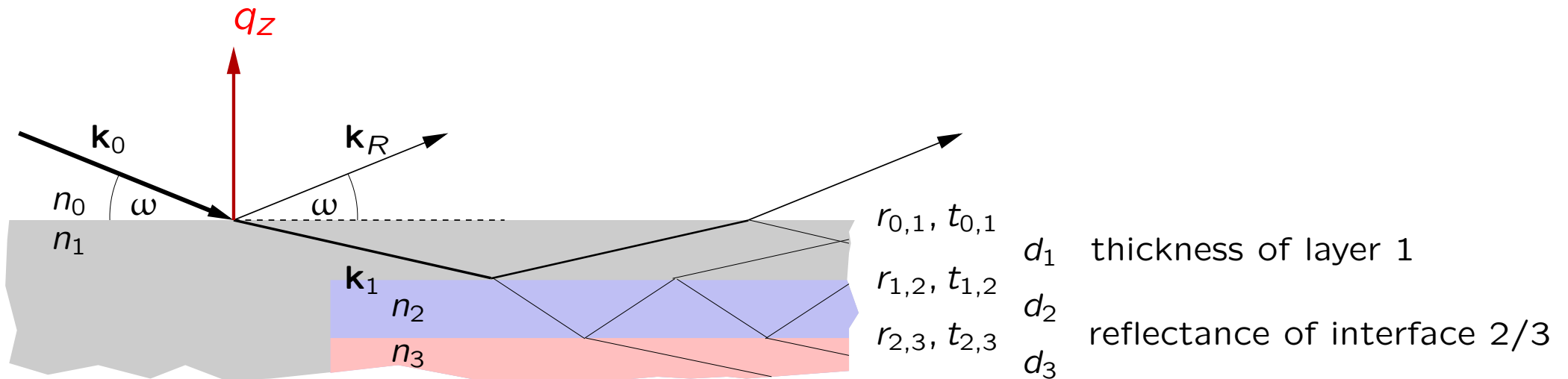
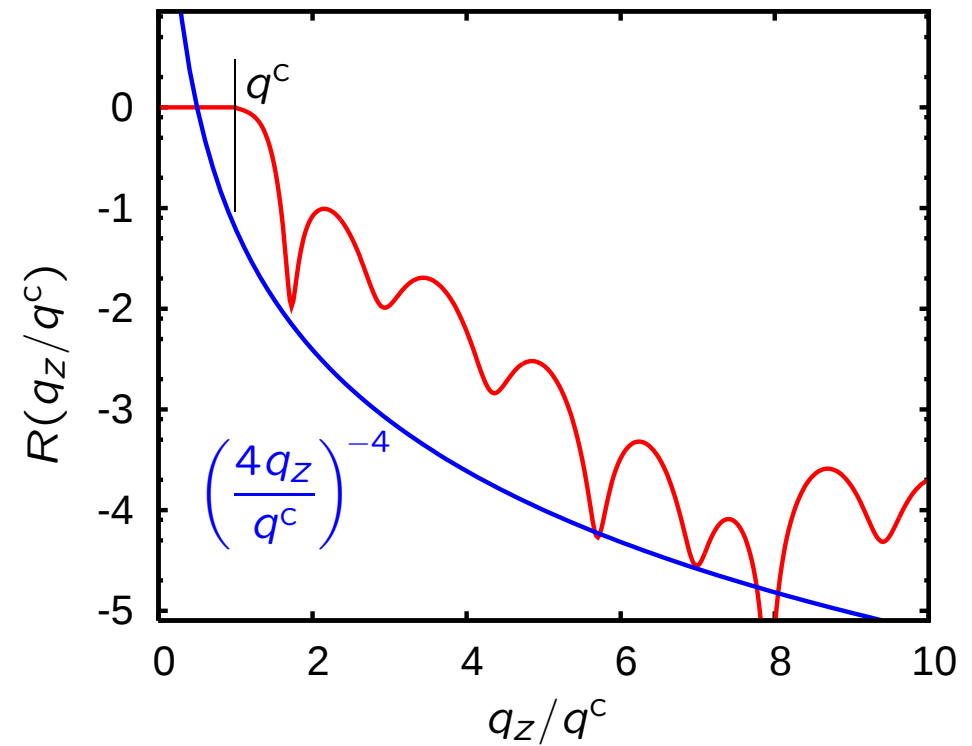
several parallel interfaces:

interference of all waves

⇒ complex reflectance

$$r = r(q_z, n_0, n_1, n_2, \dots, d_1, d_2, \dots)$$

$$R(q_z) = |r(q_z)|^2$$

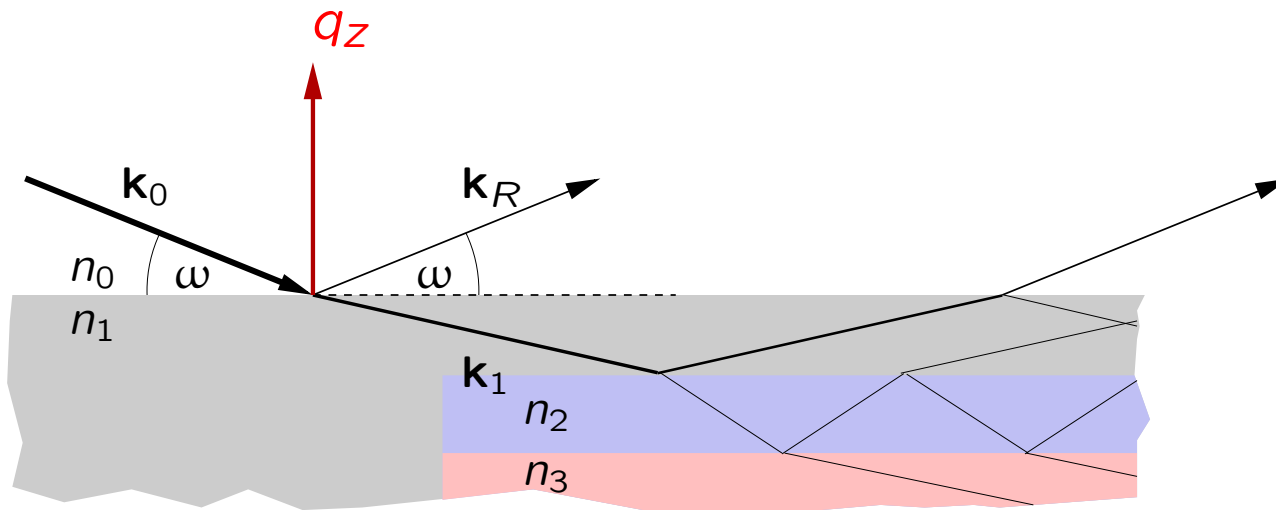


$$R(q_z) = |r(q_z)|^2$$

⇒ all phase information is lost

⇒ one way road:

⇒ calculation of $R(q_z)$ using a model
and
comparison to measured curve(s)



real effects

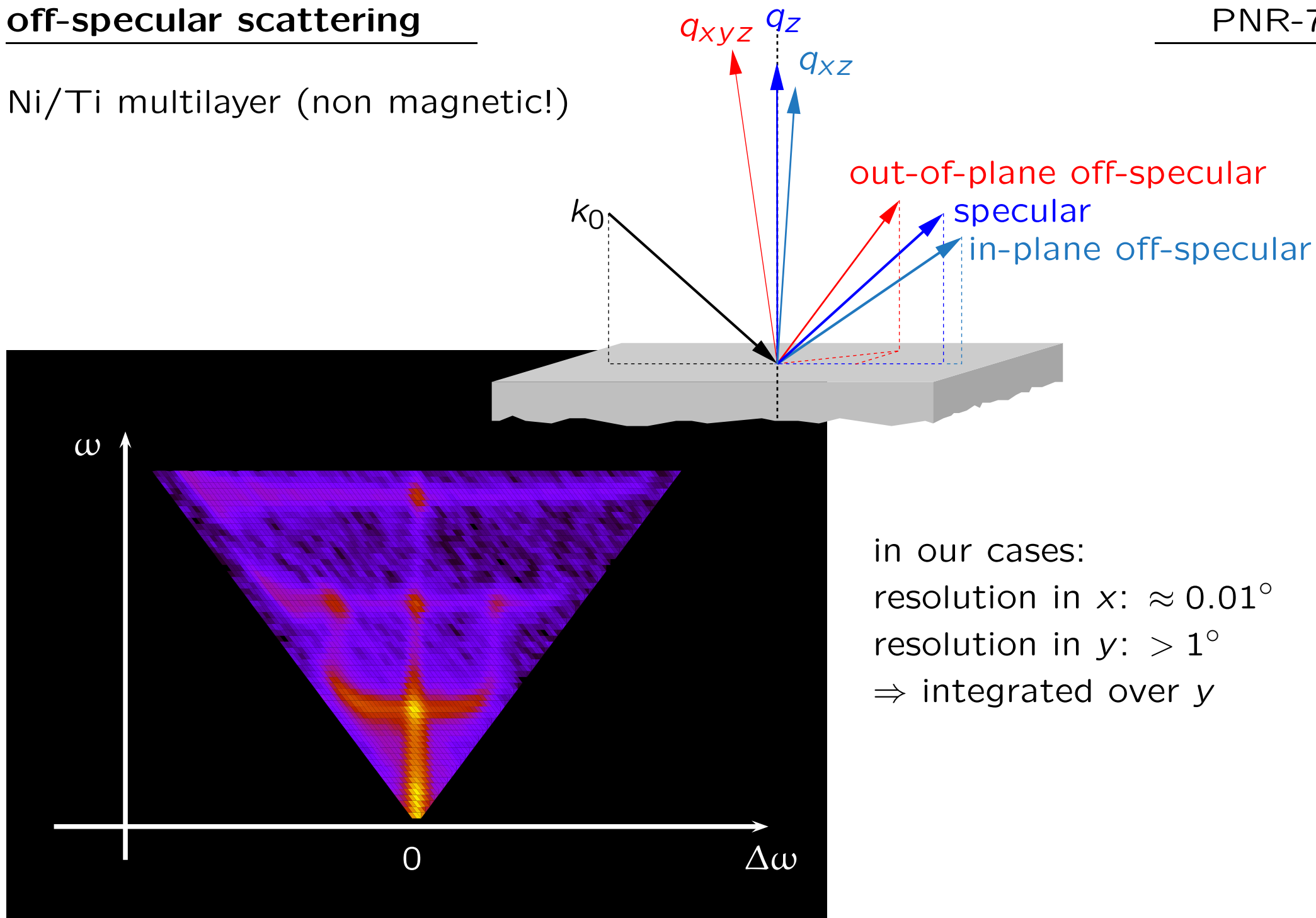
to be taken into account:

- illumination of the sample
- resolution of the set-up
 $\Delta\omega, \Delta\lambda$
- non-sharp interfaces
- inhomogeneous layers

off-specular scattering

PNR-7

Ni/Ti multilayer (non magnetic!)



reflectometry, in general :

J. Daillant, A. Gibaud:

X-ray and Neutron Reflectivity

Lect. Notes Phys. 770 (Springer 2009)

U. Pietsch, V. Holý, T. Baumbach:

High-Resolution X-Ray Scattering

(Springer 2004)

J. Stahn:

Introduction to polarised neutron and resonant x-ray reflectometry

<http://people.web.psi.ch/stahn/publications>

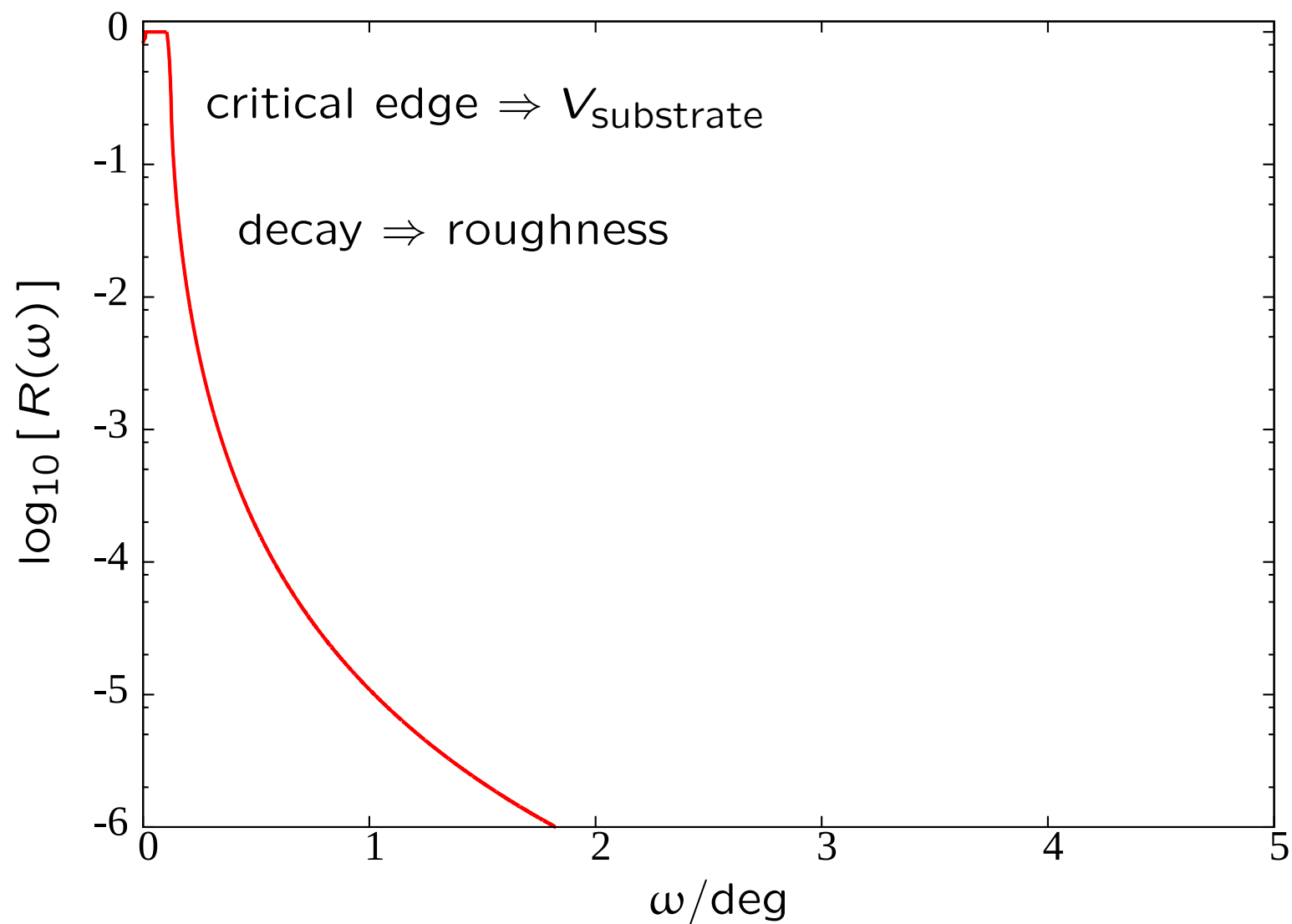
... on magnetic systems

F. Ott:

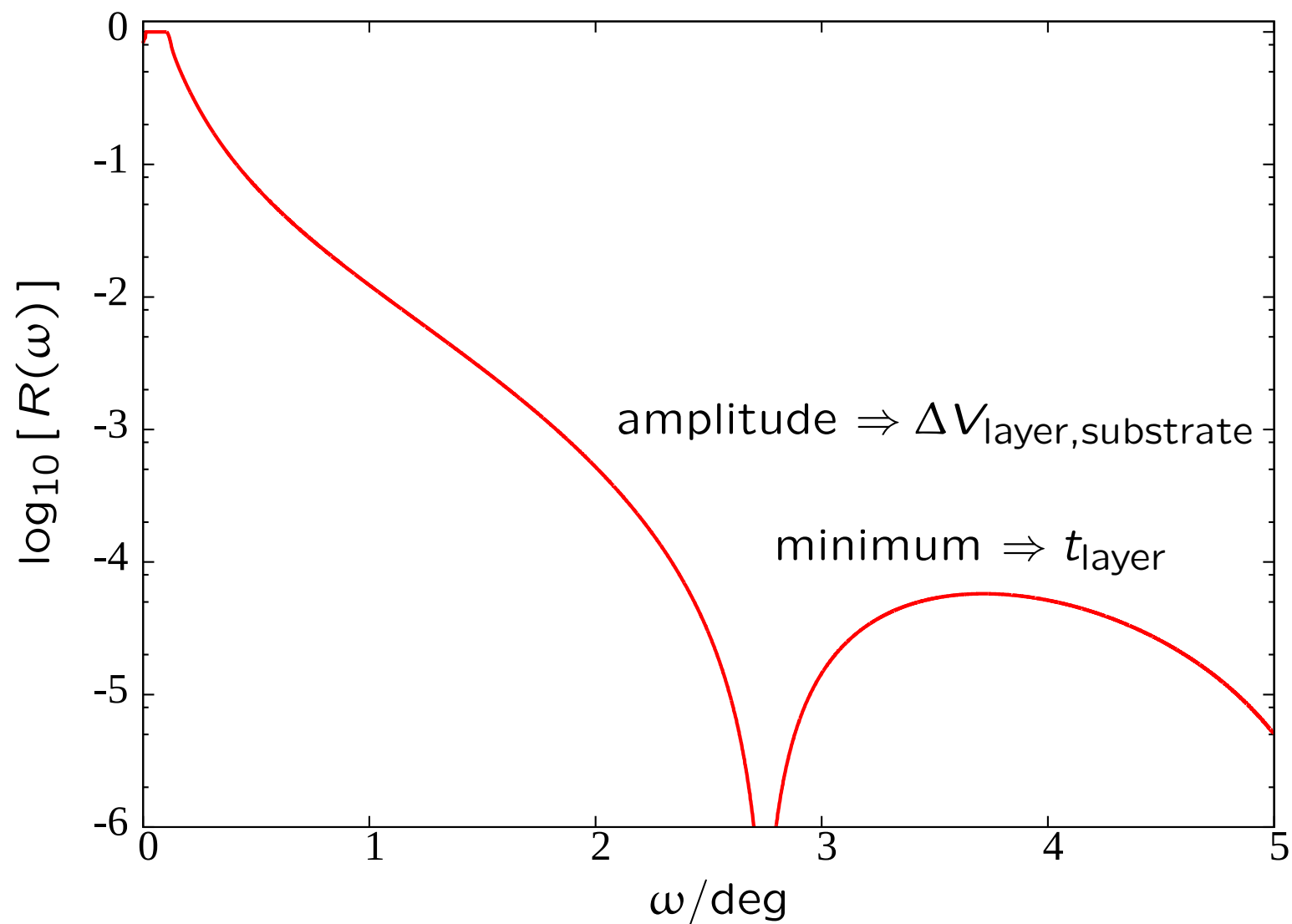
Neutron scattering on magnetic surfaces

C. R. Physique **8**, 763-776 (2007)

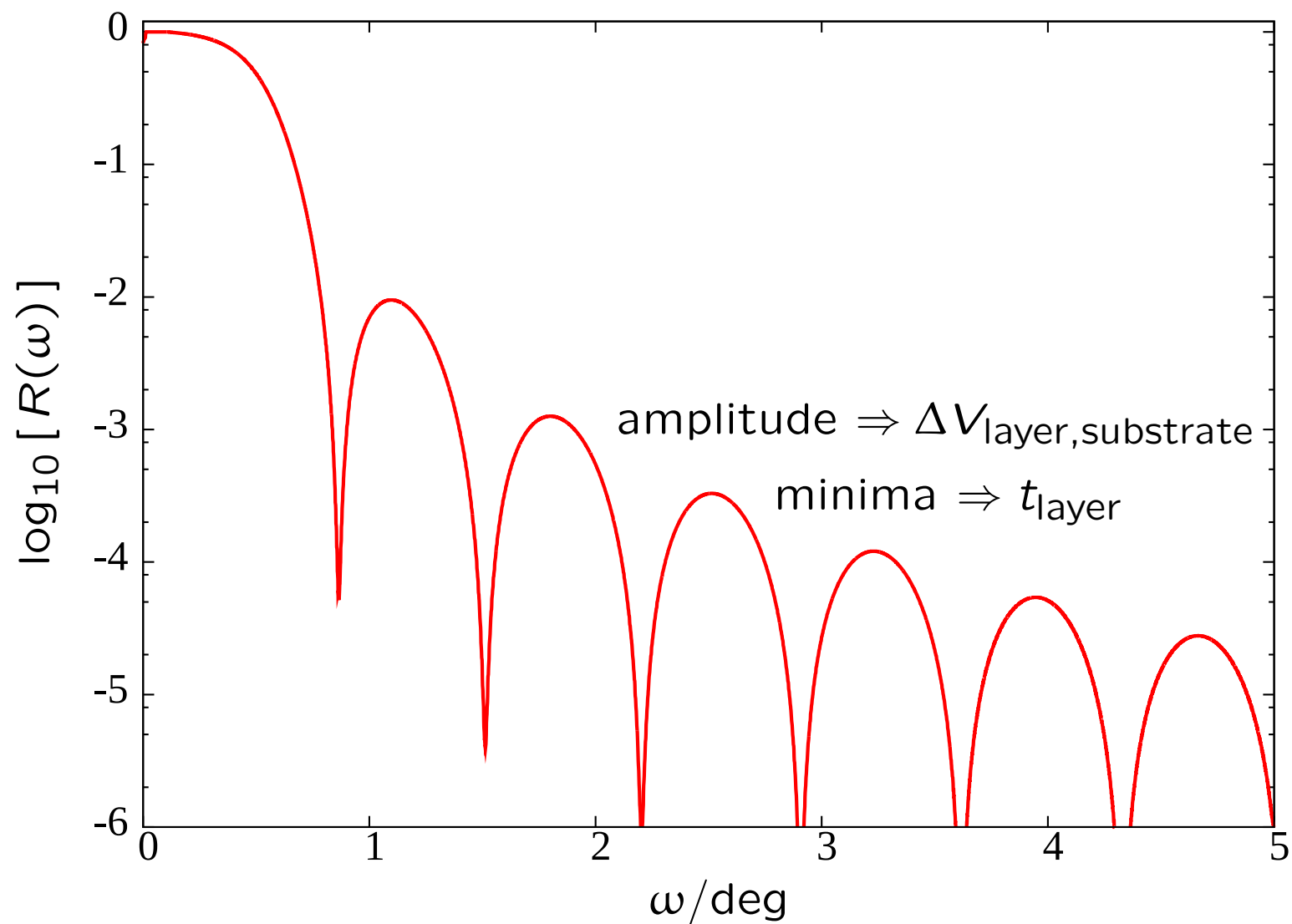
... of a surface



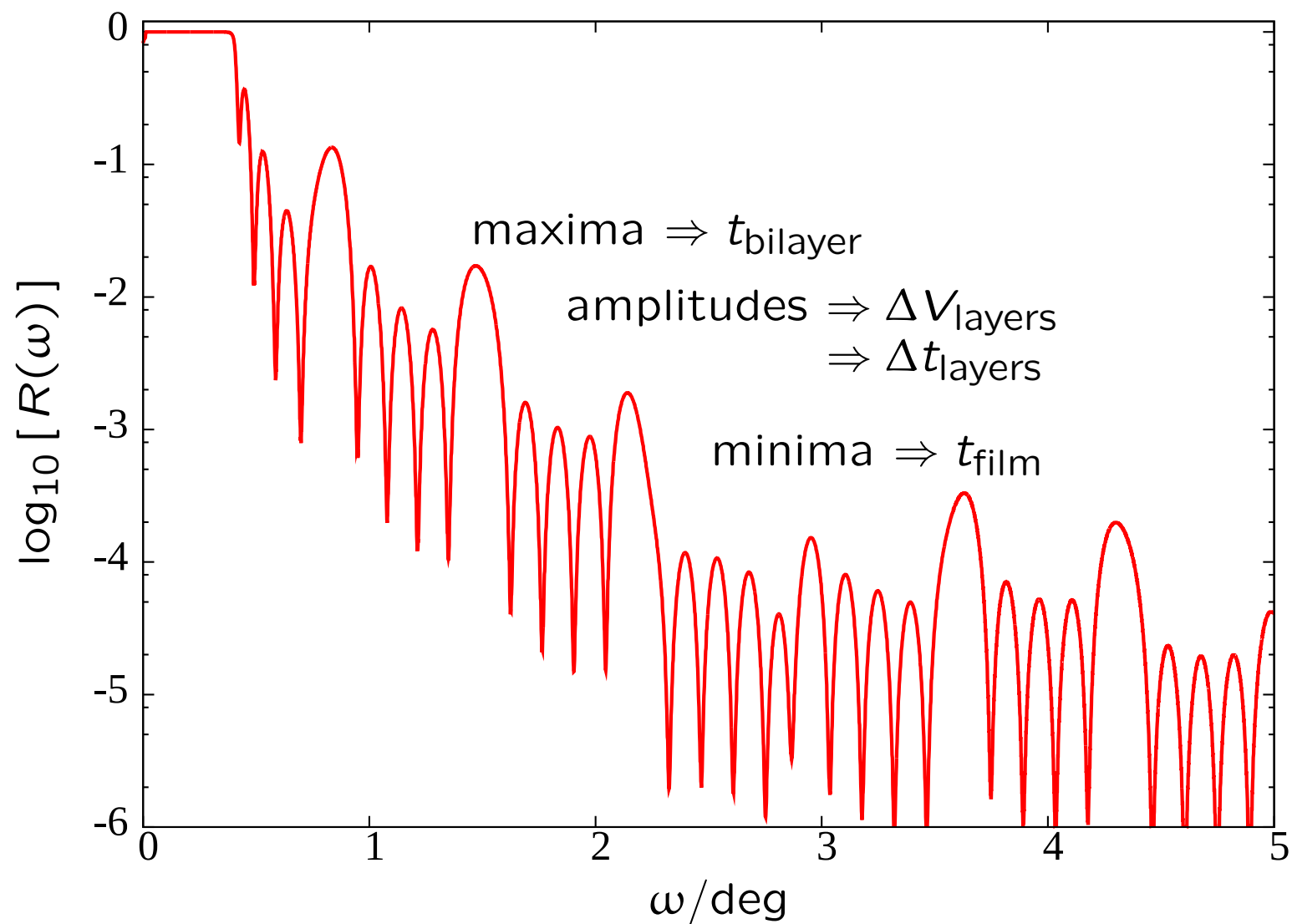
... of a thin layer



... of a thick layer



... of a periodic multilayer



interaction neutron / nucleus j with $\lambda \gg r_{\text{nucleus } j}$

$$V_j^{\text{Fermi}} = b_j \frac{2\pi \hbar^2}{m} \delta(\mathbf{r})$$

$$V_i^n = \frac{1}{Vol} \int_j V_j^{\text{Fermi}} d\mathbf{r}$$

$$= \frac{2\pi \hbar^2}{m} \frac{1}{Vol} \sum_j b_j$$

$$:= \frac{2\pi \hbar^2}{m} \rho^b$$

b : nuclear scattering length
 $\Rightarrow$ isotope specific
complement to XR

interaction neutron magnetic moment μ / magnetic induction $\mathbf{B}$

$$V^m = \mu \mathbf{B}$$

$$:= \frac{2\pi \hbar^2}{m} \rho^m$$

$$\mu \uparrow \uparrow \mathbf{B} \Rightarrow V^m = +\mu B$$

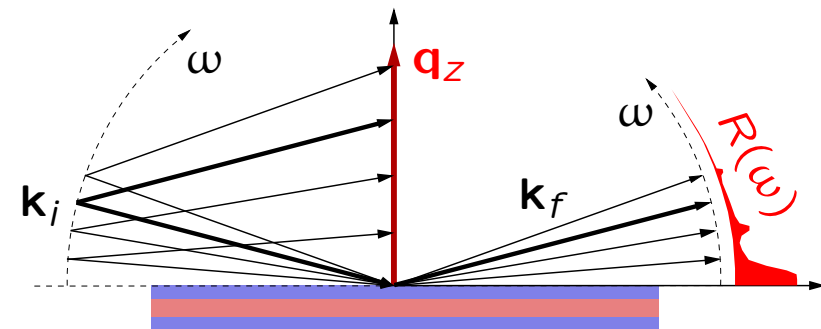
$$\mu \uparrow \downarrow \mathbf{B} \Rightarrow V^m = -\mu B$$

$$\mu \perp \mathbf{B} \Rightarrow V^m = 0$$

$$R = R(q_z) = R(\lambda, \omega) \quad q_z = 4\pi \frac{\sin \omega}{\lambda}$$

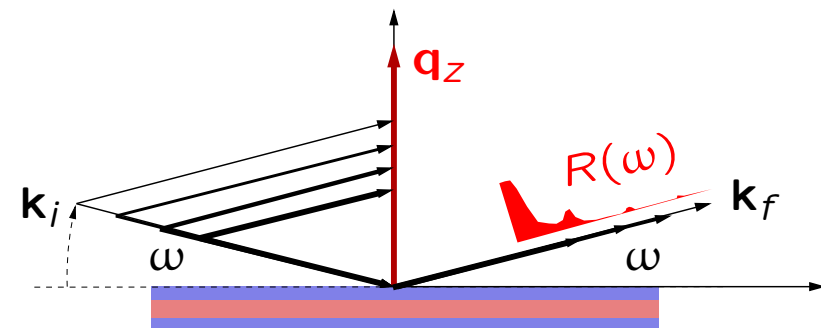
angle-dispersive set-up

variation of ω with fixed λ
detection under 2ω



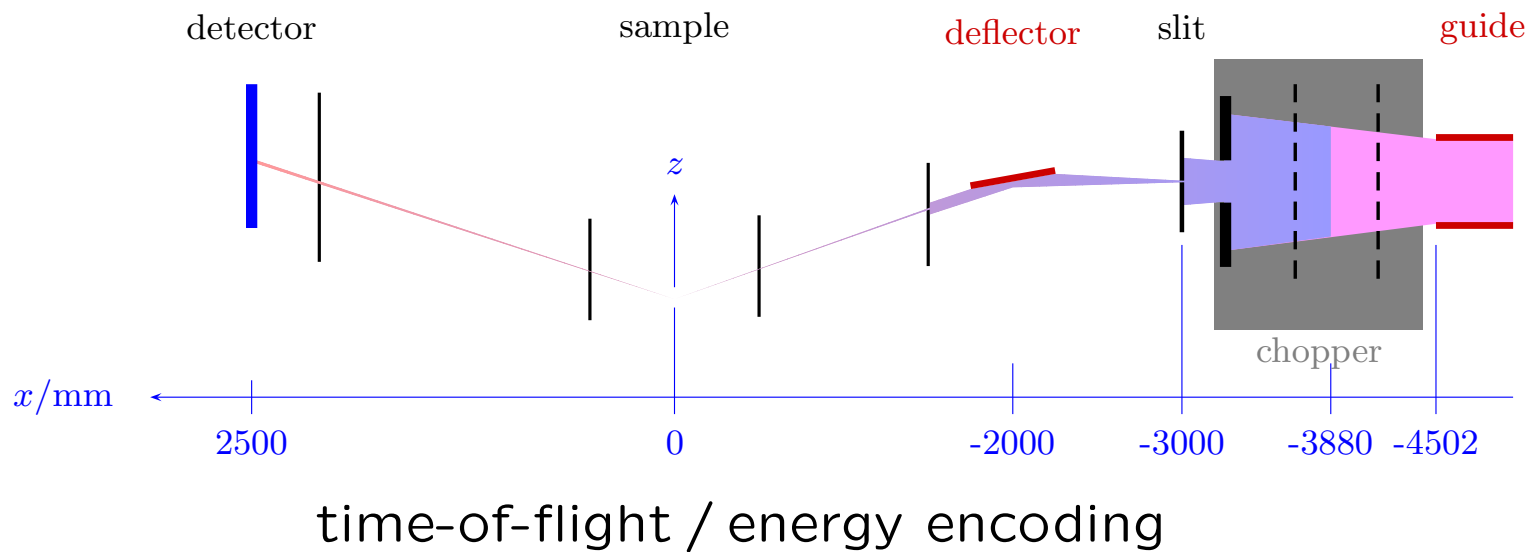
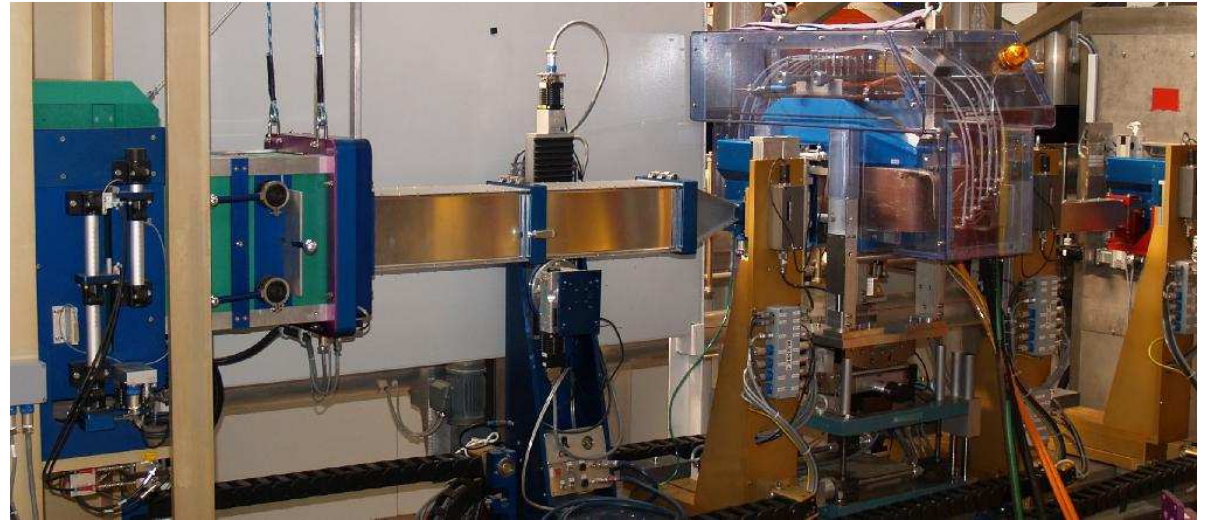
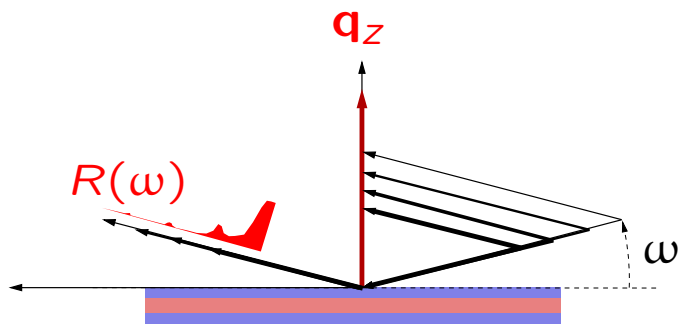
energy-dispersive set-up

variation of λ with fixed ω
detection via time-of-flight



neutron reflectometer

Amor at SINQ



cooling with a
closed cycle refrigerator

$$8\text{ K} < T < 450\text{ K}$$

application of an external magnetic field with
Helmholtz coils

$$-1000\text{ Oe} < H < 1000\text{ Oe}$$

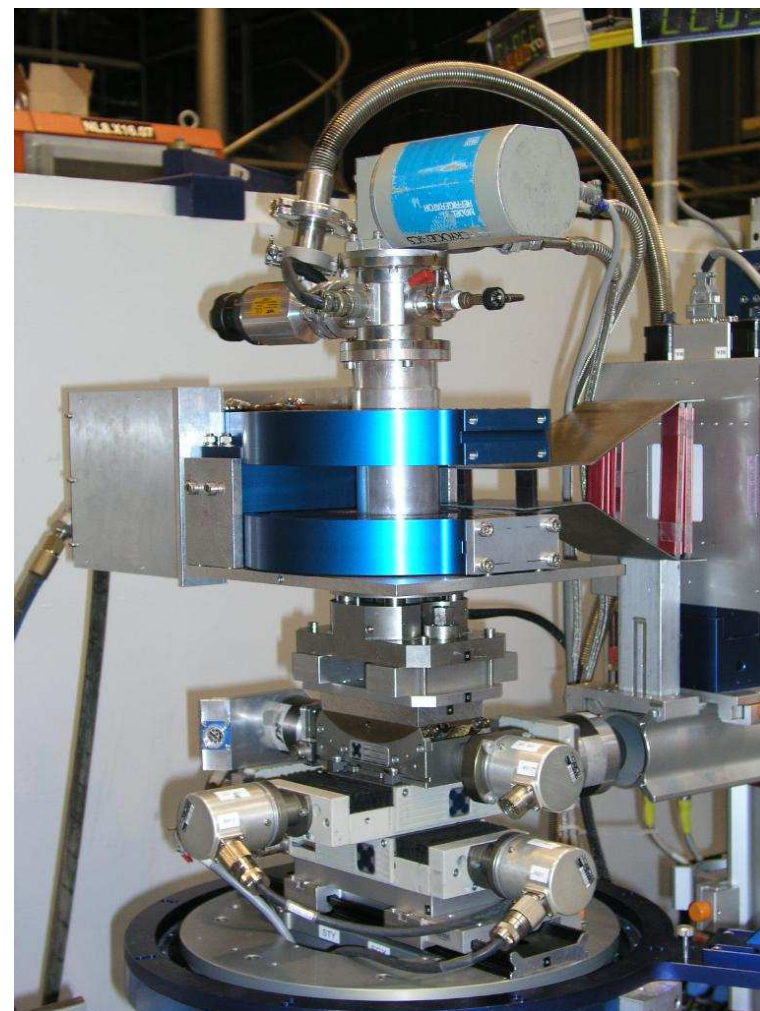
or

usage of a cryo-magnet

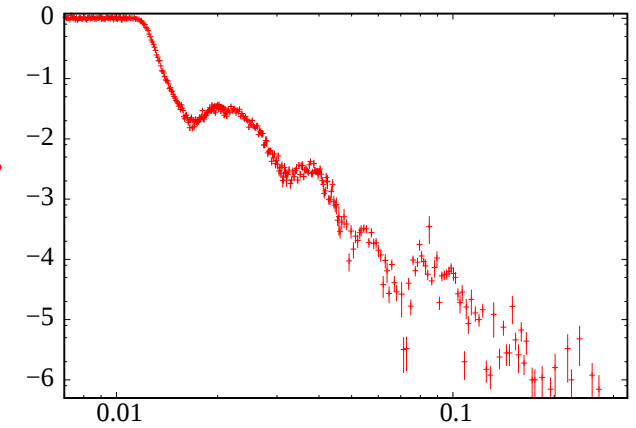
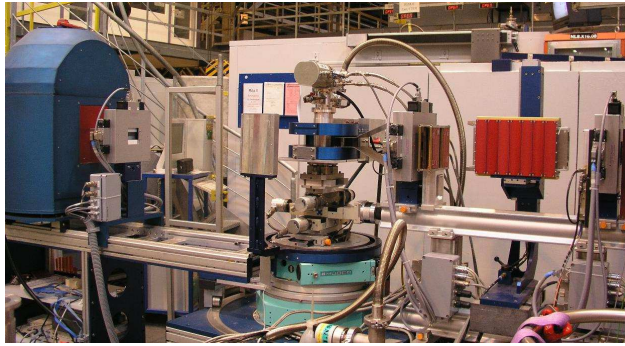
$$1.4\text{ K} < T < 300\text{ K}$$

$$-50\,000\text{ Oe} < H < 50\,000\text{ Oe}$$

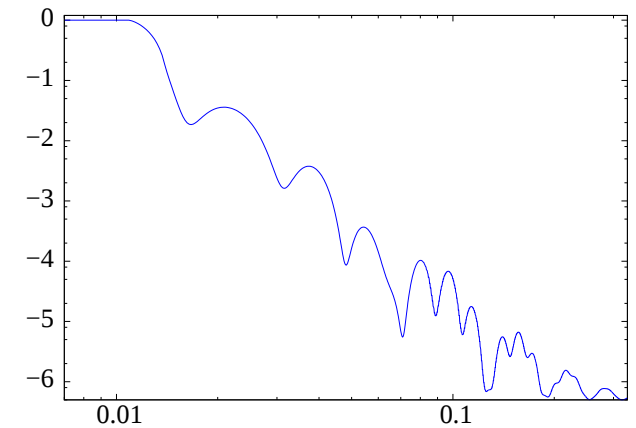
and sample



tilt- and
translation stages
for alignment



?



magnetic signal almost as strong as nuclear one

only $B_{\perp}$ is probed
no element sensitivity

high **depth resolution** (down to 0.1 nm)

strongly **model-based**

penetration depth 1 000 nm

resolution limit 500 nm

limited q_z -range accessible

extreme sample environments are *no* problem

time-consuming data analysis

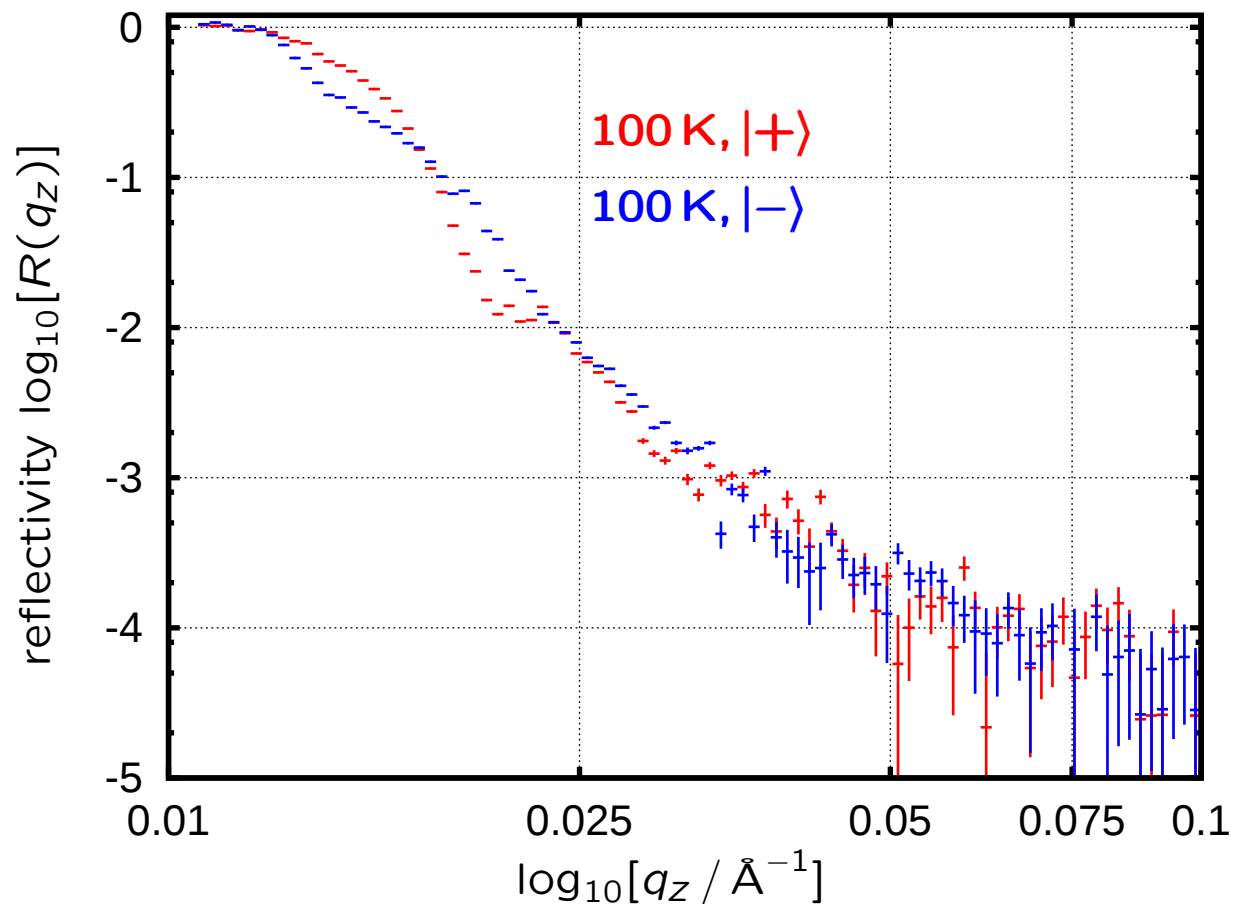
supporting methods needed

bi-layer: STO / LSMO / YBCO

Y. Sassa, M. Radovic, Oct. 2009

sample size: $10 \times 5 \text{ mm}^2$

measurement time: 6 h



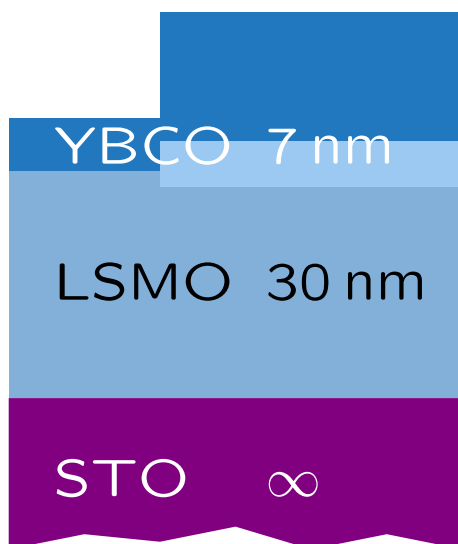
bi-layer: STO / LSMO / YBCO

Y. Sassa, M. Radovic, Oct. 2009

sample size: $10 \times 5 \text{ mm}^2$

measurement time: 6 h

fit-time: 8 h

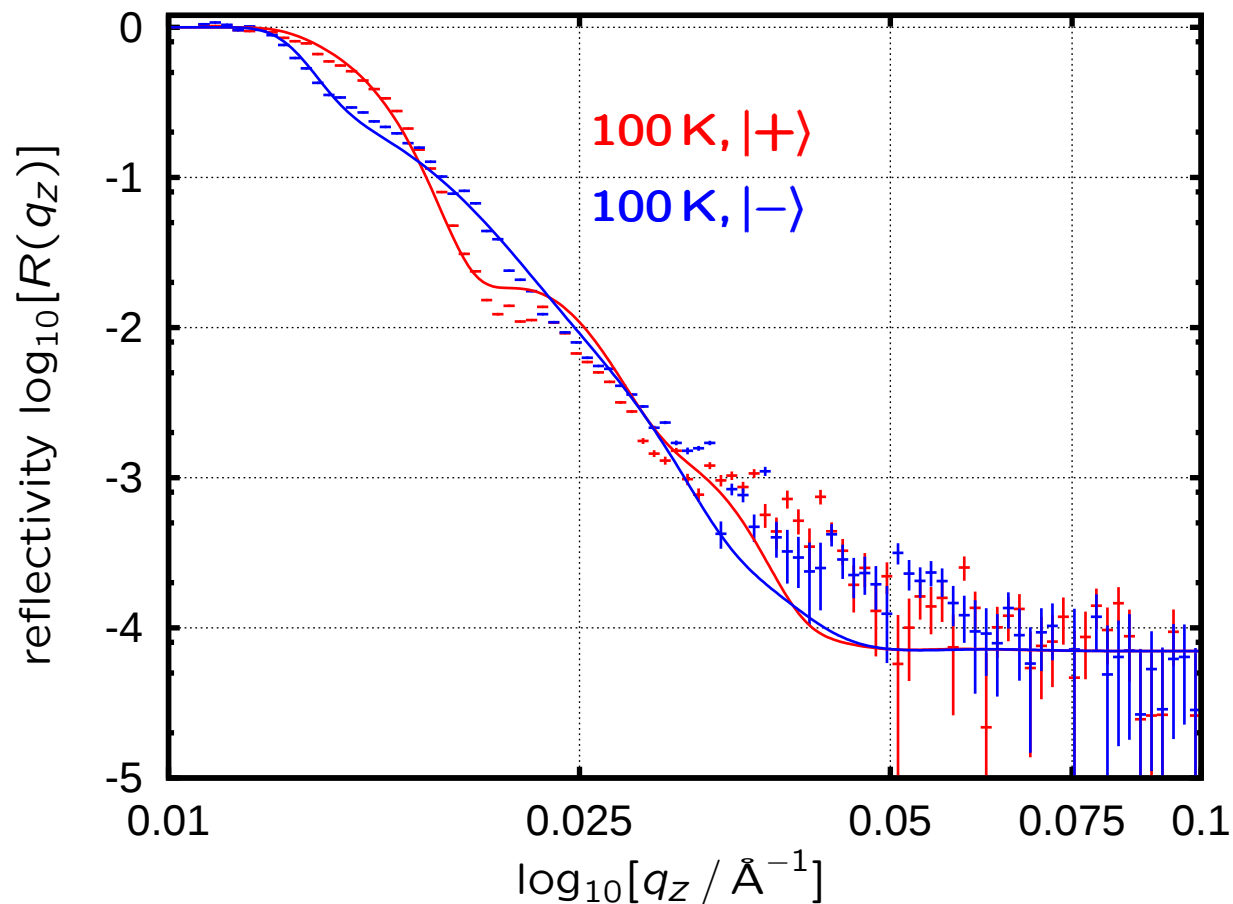


simulation

free parameters:

thicknesses

magnetisation



fit is not satisfactory!

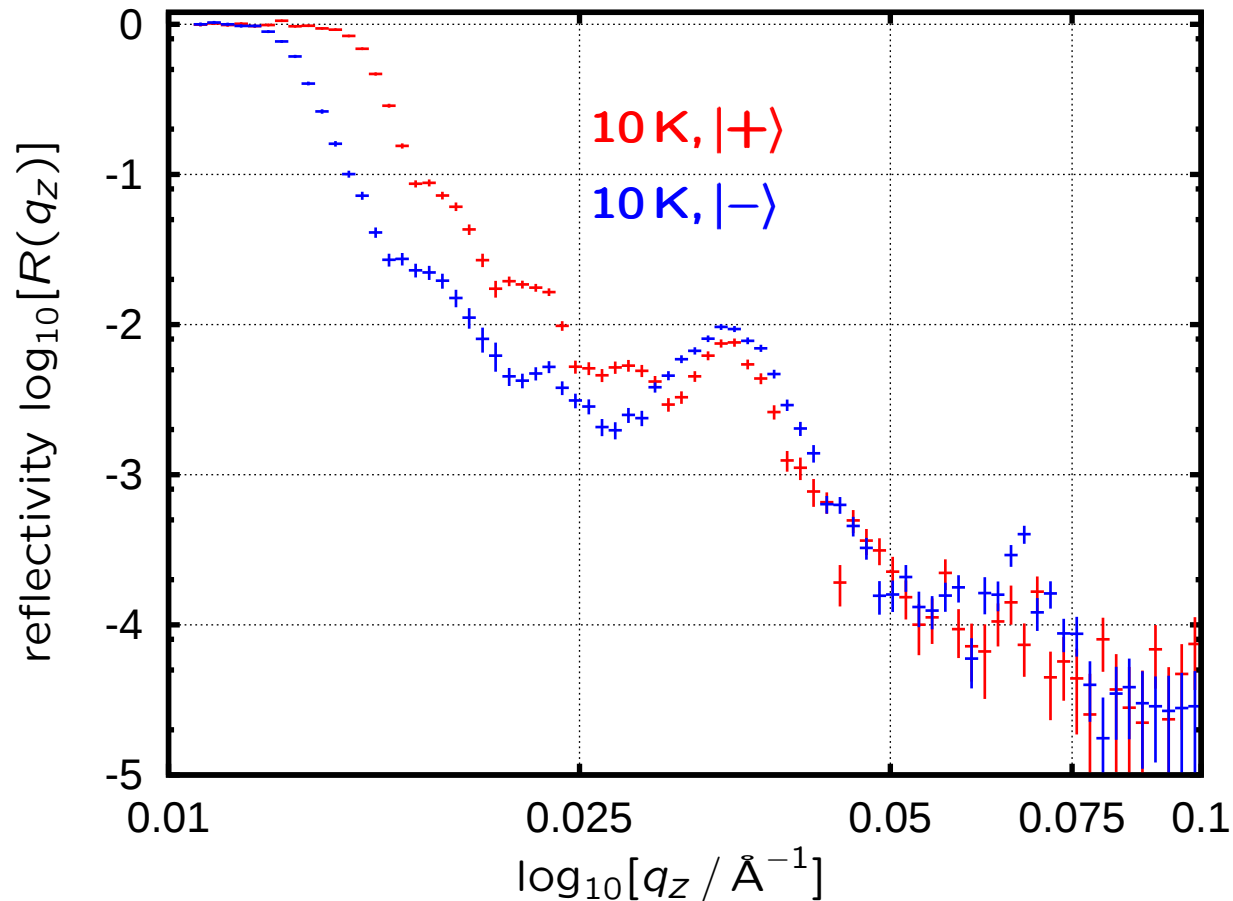
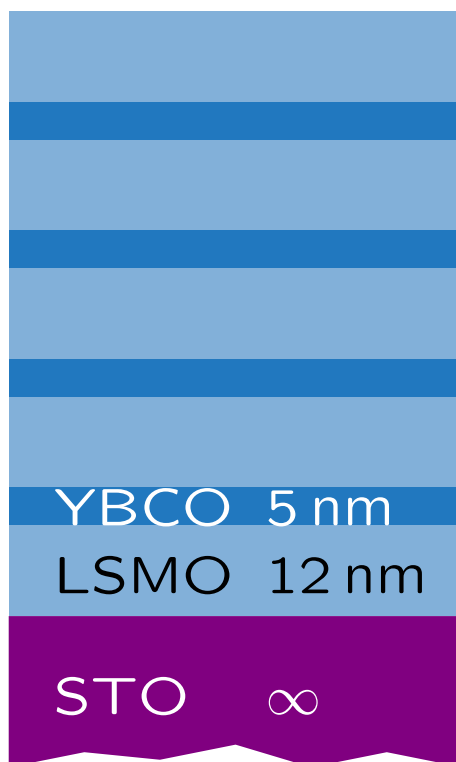
multi-layer: $\text{STO} / [\text{LSMO} / \text{YBCO}]_4 / \text{LSMO}$

ELLA 10-018

M. Radovic, May 2010

sample size: $5 \times 5 \text{ mm}^2$

measurement time: 18 h



multi-layer: $\text{STO} / [\text{LSMO} / \text{YBCO}]_4 / \text{LSMO}$

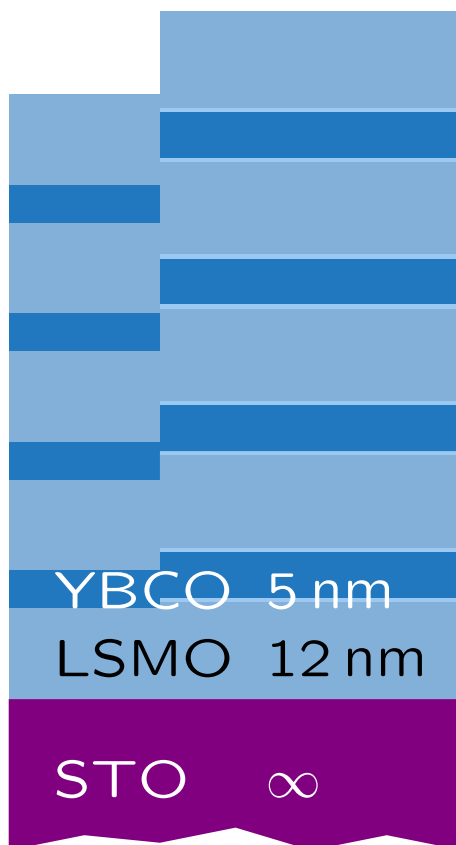
ELLA 10-018

M. Radovic, May 2010

sample size: $5 \times 5 \text{ mm}^2$

measurement time: 18 h

fit-time: 12 h



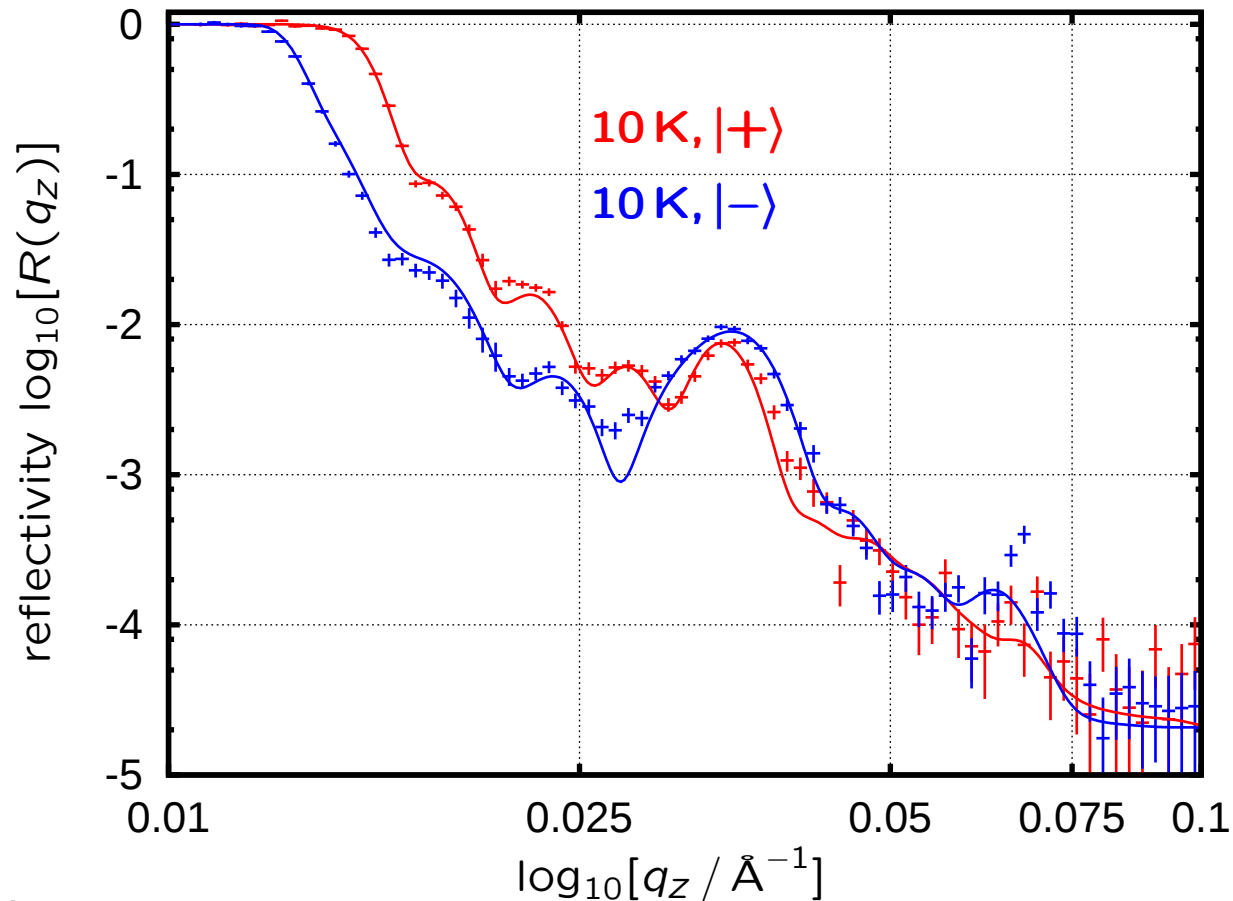
simulation

free parameters:

thicknesses

magnetisation

magnetically dead layers

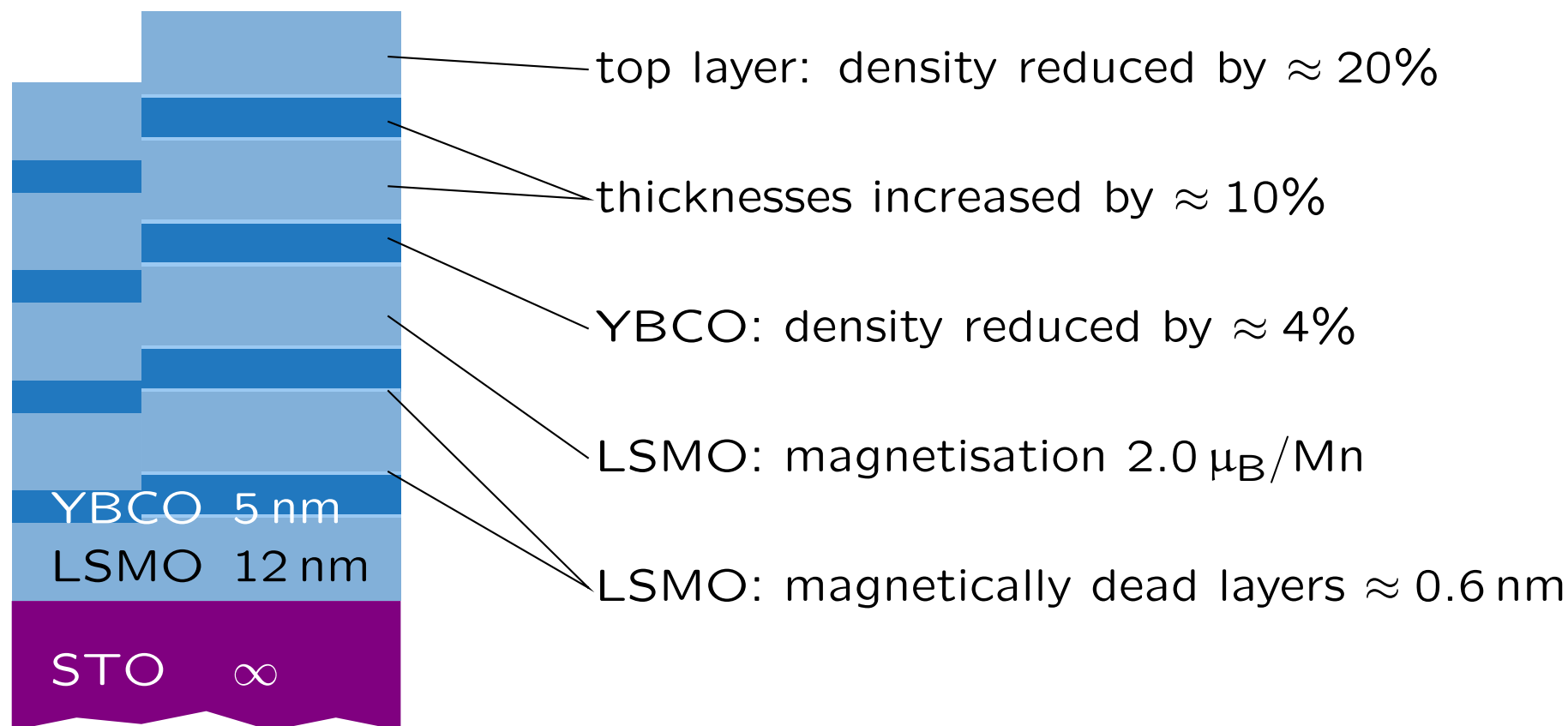


fit is good

multi-layer: $\text{STO} / [\text{LSMO} / \text{YBCO}]_4 / \text{LSMO}$

ELLA 10-018

M. Radovic, May 2010



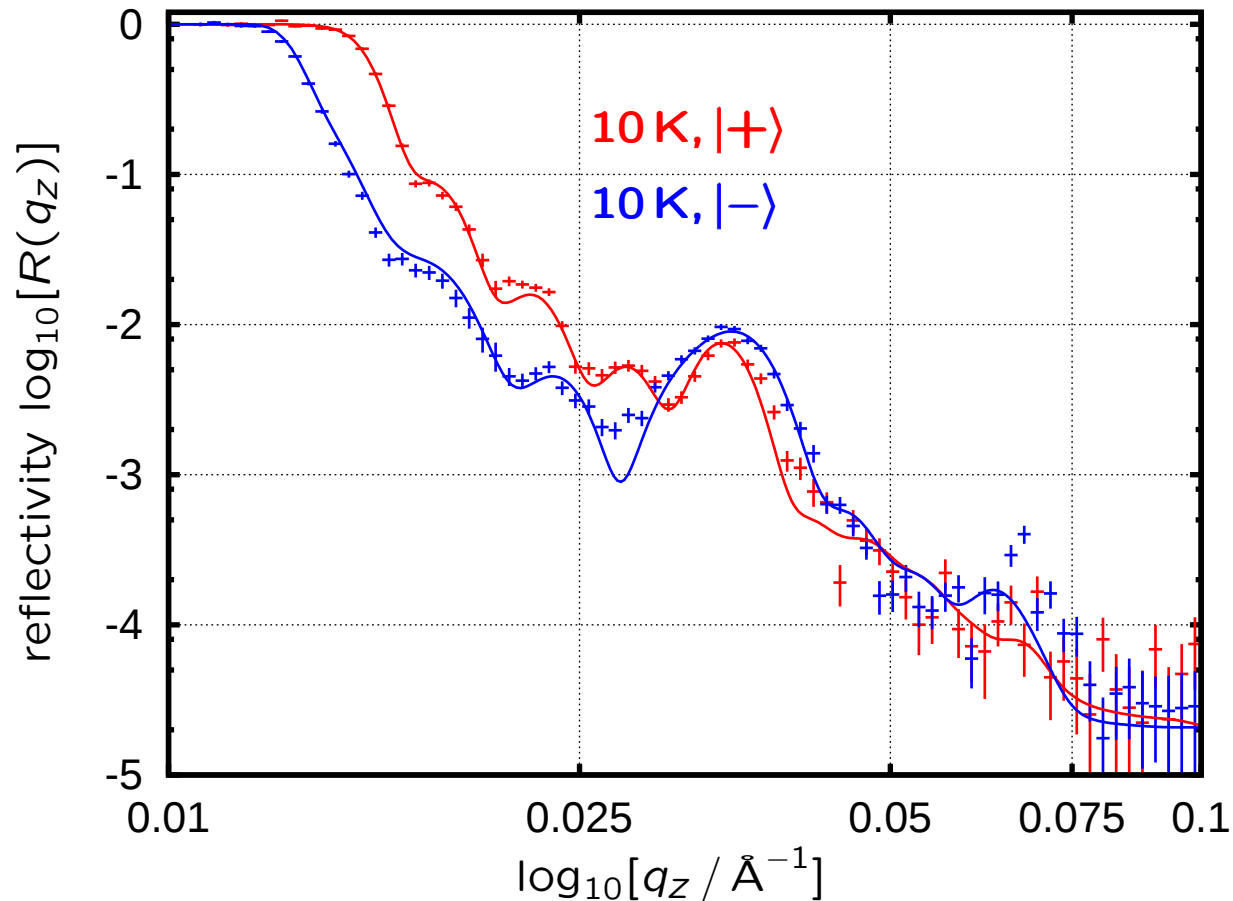
multi-layer: $\text{STO} / [\text{LSMO} / \text{YBCO}]_4 / \text{LSMO}$

ELLA 10-018

M. Radovic, May 2010



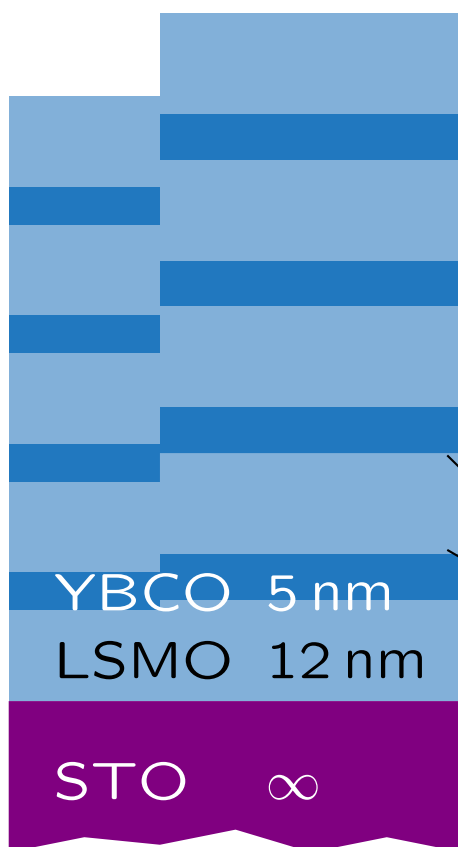
LSMO: magnetically dead layers ≈ 0.6 nm



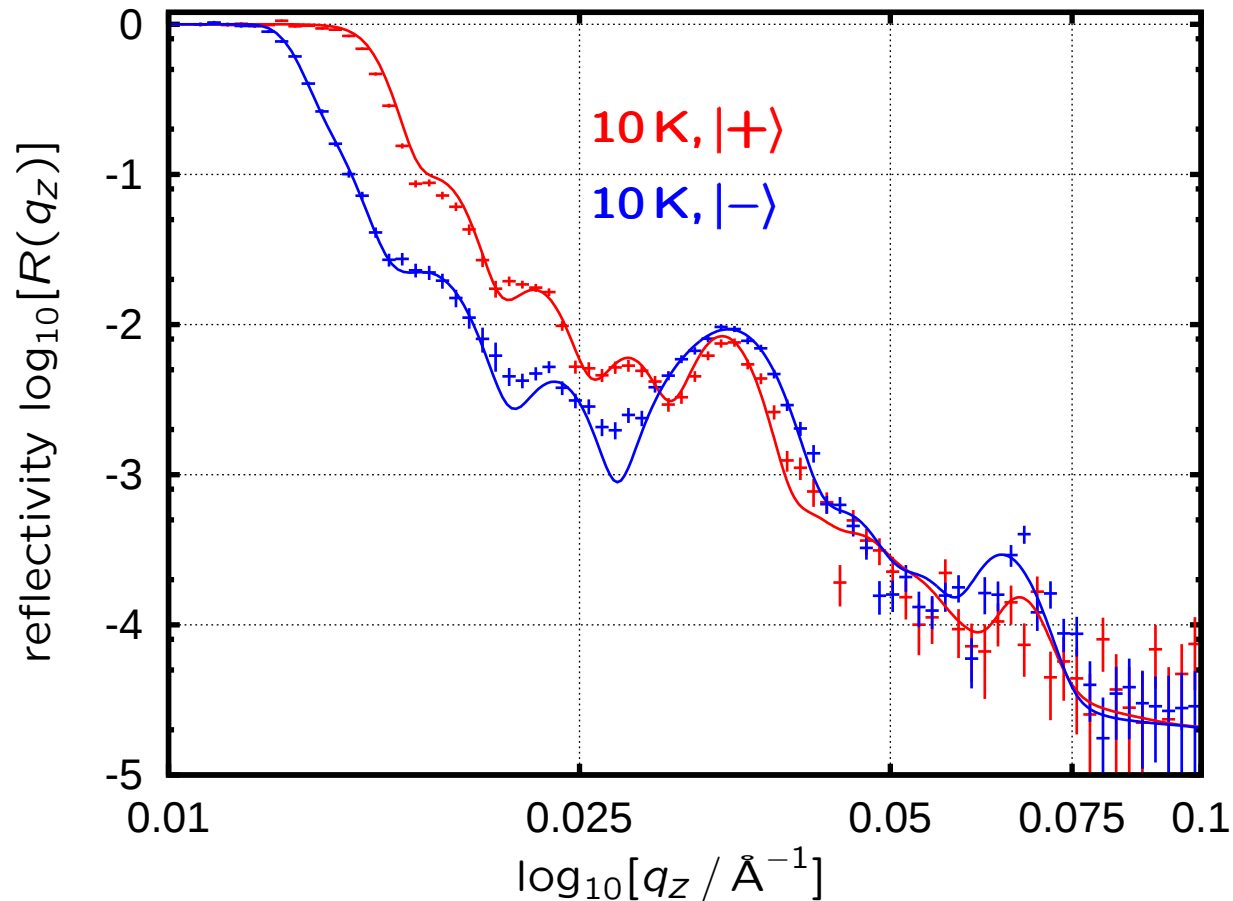
multi-layer: STO / [LSMO / YBCO]₄ / LSMO

ELLA 10-018

M. Radovic, May 2010



LSMO: no magnetically dead layers



⇒ higher q_z & better statistics needed

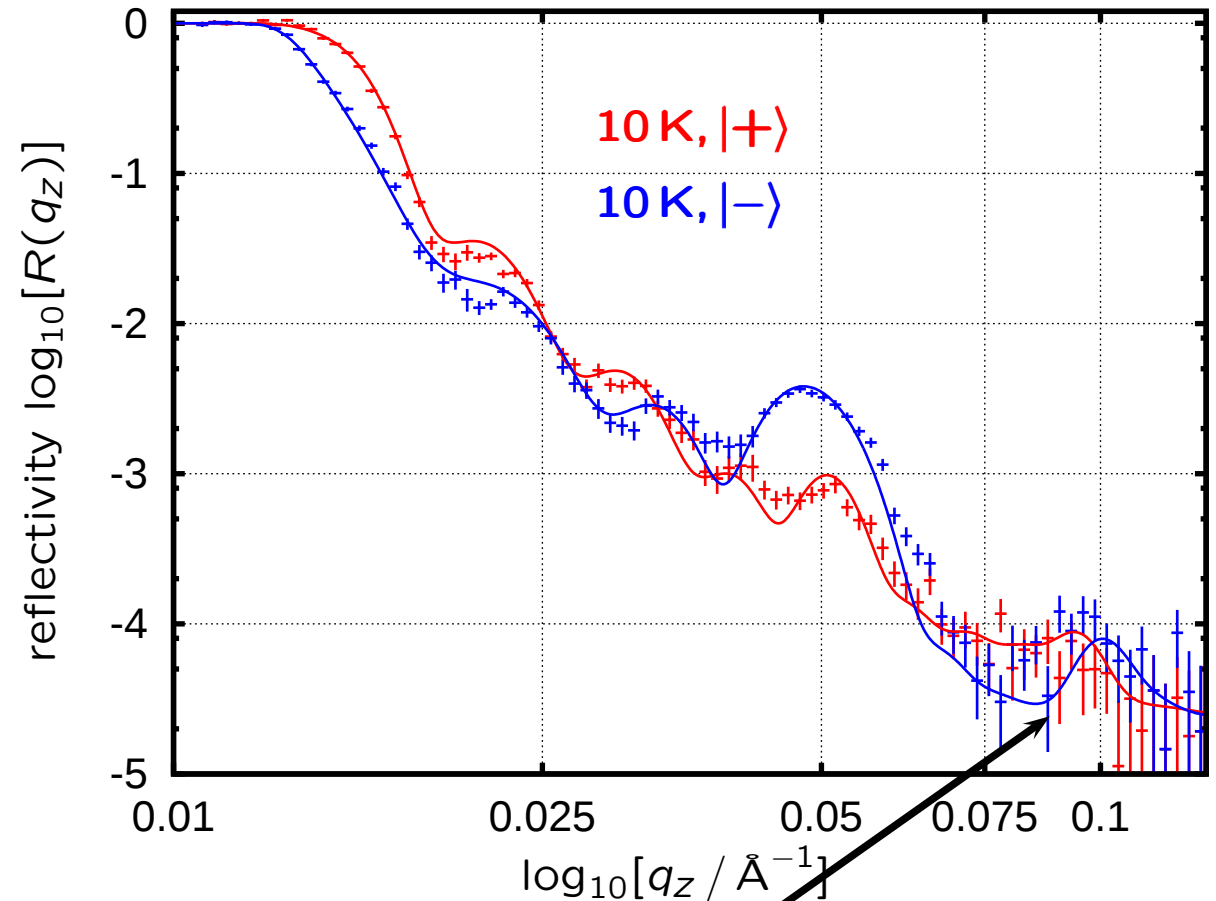
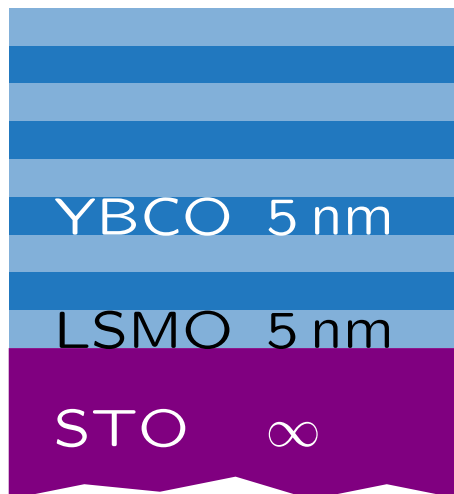
multi-layer: $\text{STO} / [\text{LSMO} / \text{YBCO}]_4 / \text{LSMO}$

ELLA 10-021

M. Radovic, May 2010

sample size: $5 \times 5 \text{ mm}^2$

measurement time: 18 h



structurally forbidden peak

$\Rightarrow$ magnetic profile breaks symmetry

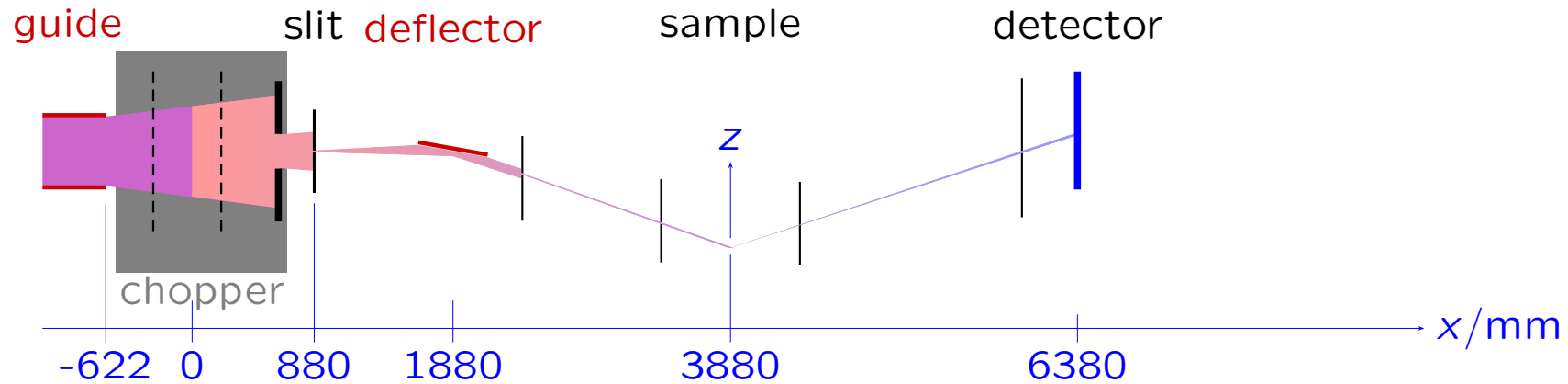
magnetically dead layer of $\approx 0.6 \text{ nm}$

to be fitted with a more complex model

- PNR probes $\rho(z)$ where $\rho = \rho(\text{composition}, B_{\perp})$
 - atomic depth resolution
 - lateral integration over several μm
- data analysis via comparison with model
 - $\Rightarrow$ no unique solution
 - $\Rightarrow$ PNR is a *team-player*

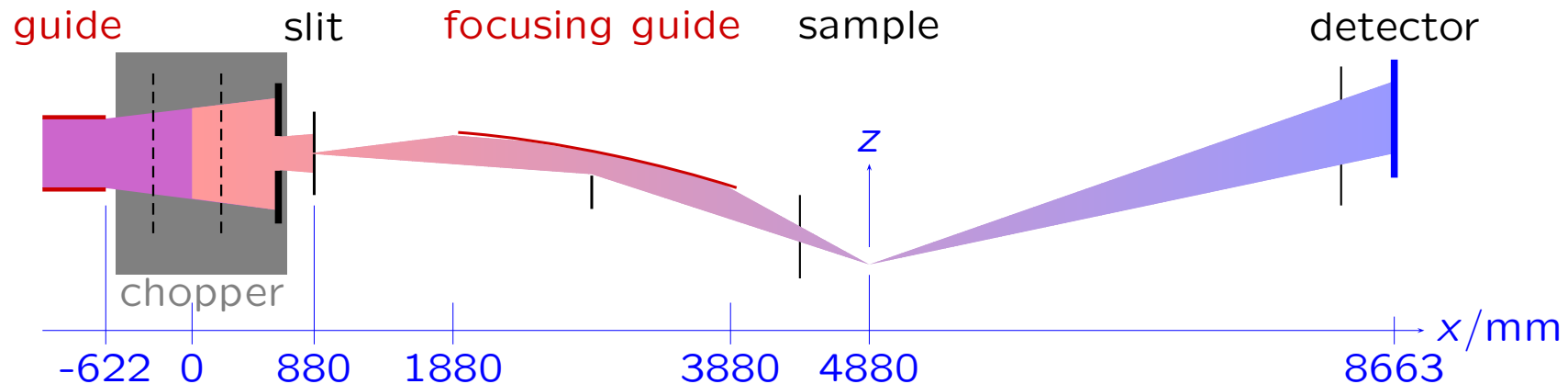
	probes	depth	
ARPES	surface	1 nm	
RIXS	bulk	100 nm	element specific
PNR	interfaces	1 000 nm	$\rho(z), B_{\perp}$
XR	interfaces	100 nm	$\rho(z)$

conventional TOF set-up on Amor:



- Δq defined by flight-path length and slits
- energy-dispersive

selene set-up on Amor:



- Δq defined by flight-path length and position-sensitive detector
- energy- and angle-dispersive