PAUL SCHERRER INSTITUT

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Laboratory for Neutron Scattering and Imaging

Erice School *Neutron Science and Instrumentation*, IV course
Neutron Precession Techniques
Erice, Sicily, Italy, 01. – 08. 07. 2017

Solid State Polarisers

and

Focussing Neutron Optics

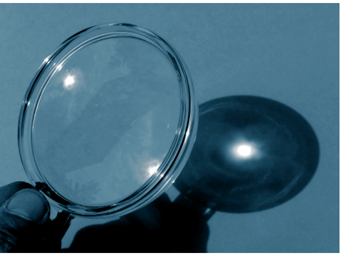
outline

basics

- reflectometry
- supermirrors
- polarising coatings

polarisers

- overview
- reflective coatings
- comparison



focusing optics

- refractive
- reflective

basics

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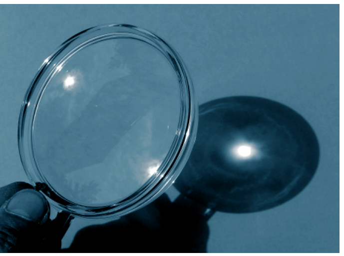


focusing optics

- refractive
- reflective

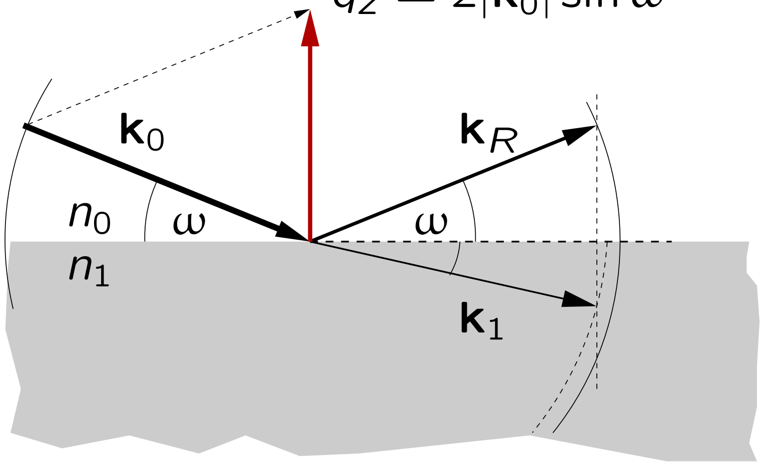
analogy to visible light

flat surfaces partly reflect light

→ image of the boot

some media also transmit light

→ ground below the water



reflectivity of a surface

function of index of refraction n

analogy to visible light

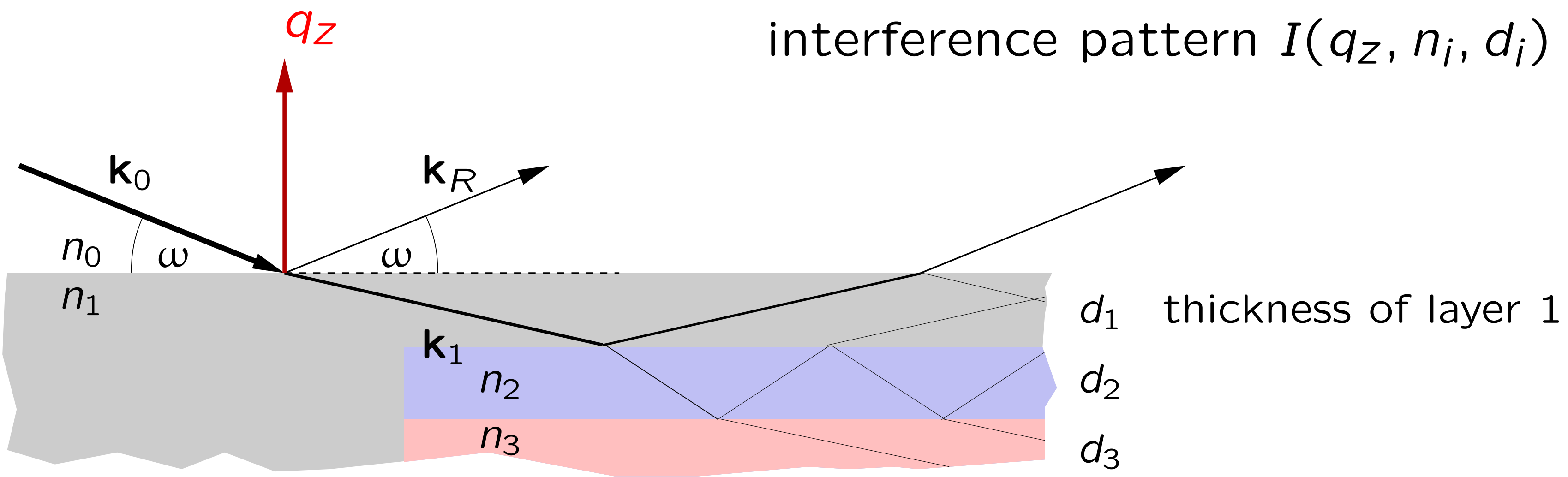
flat surfaces partly reflect light
→ image of the boot

some media also transmit light
→ ground below the water

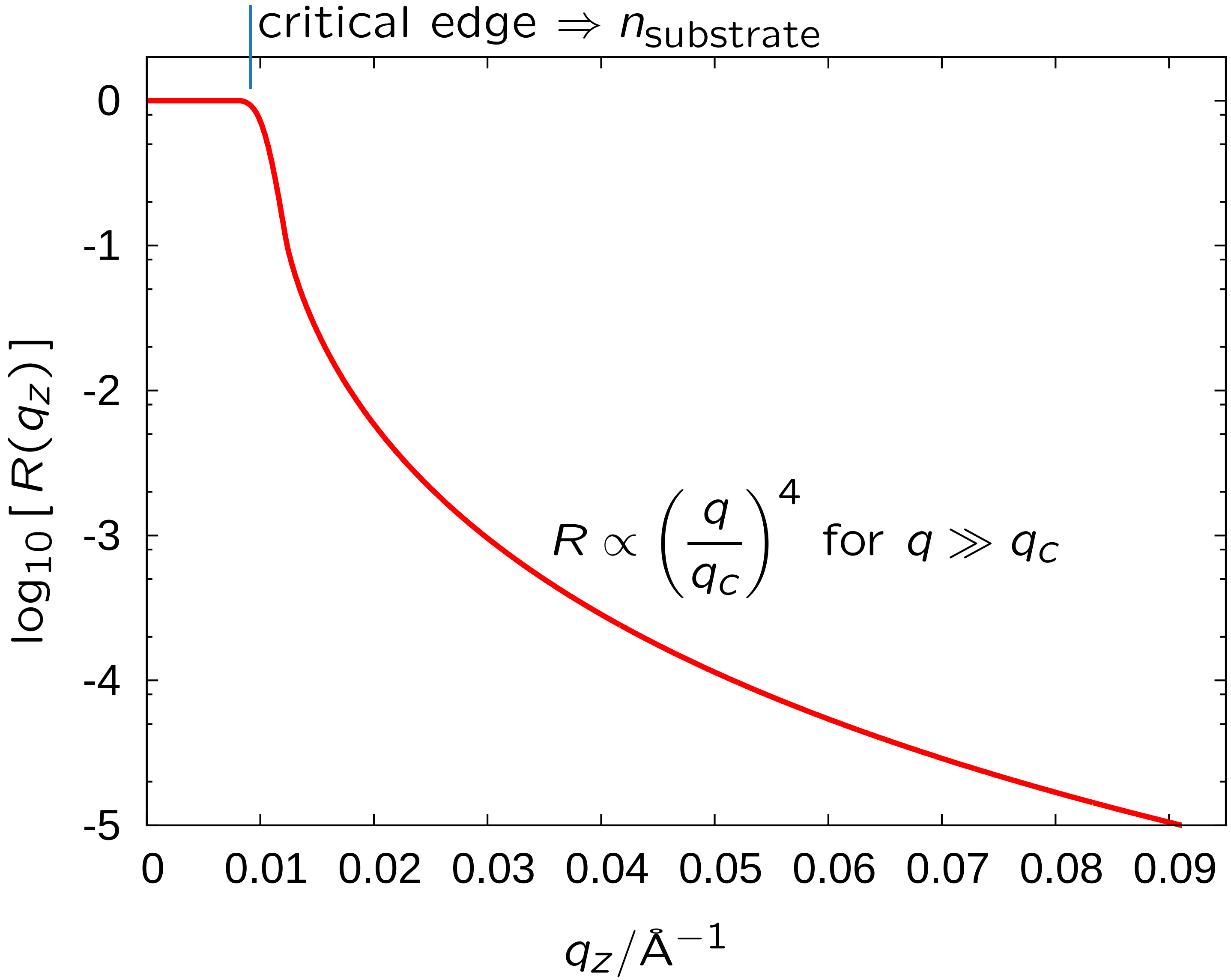
parallel interfaces cause interference
→ colourful soap bubbles

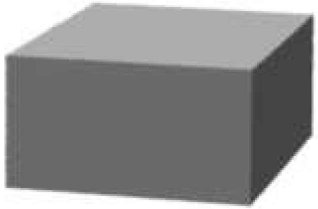
reflectivity of plane parallel interfaces

interference pattern $I(q_z, n_i, d_i)$

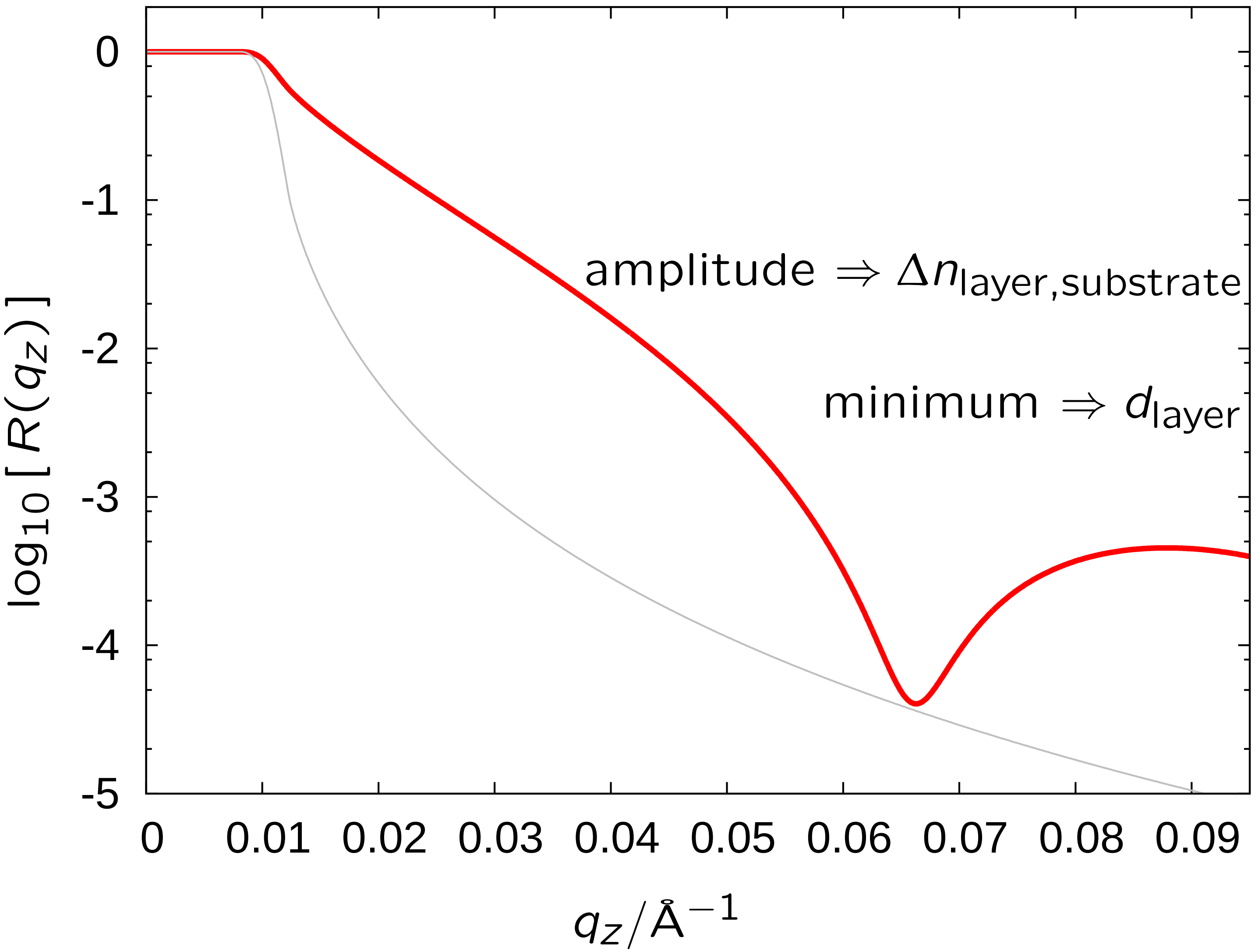


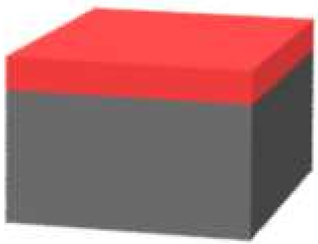
simulated reflectivity of a **surface**



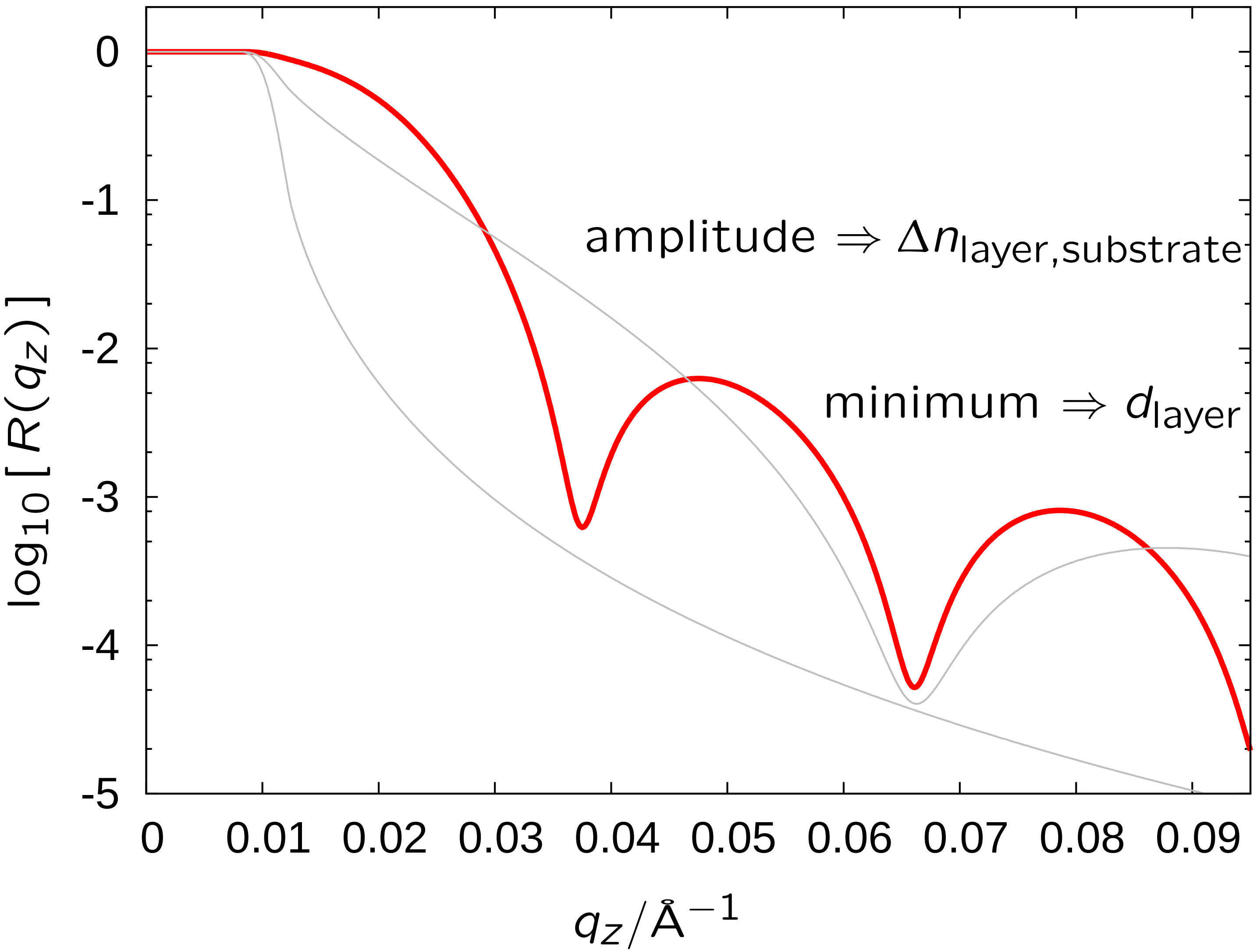


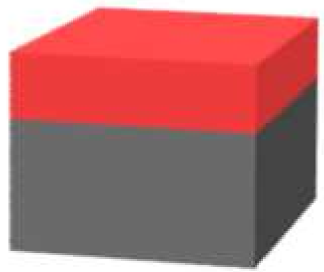
simulated reflectivity of a **thin layer**



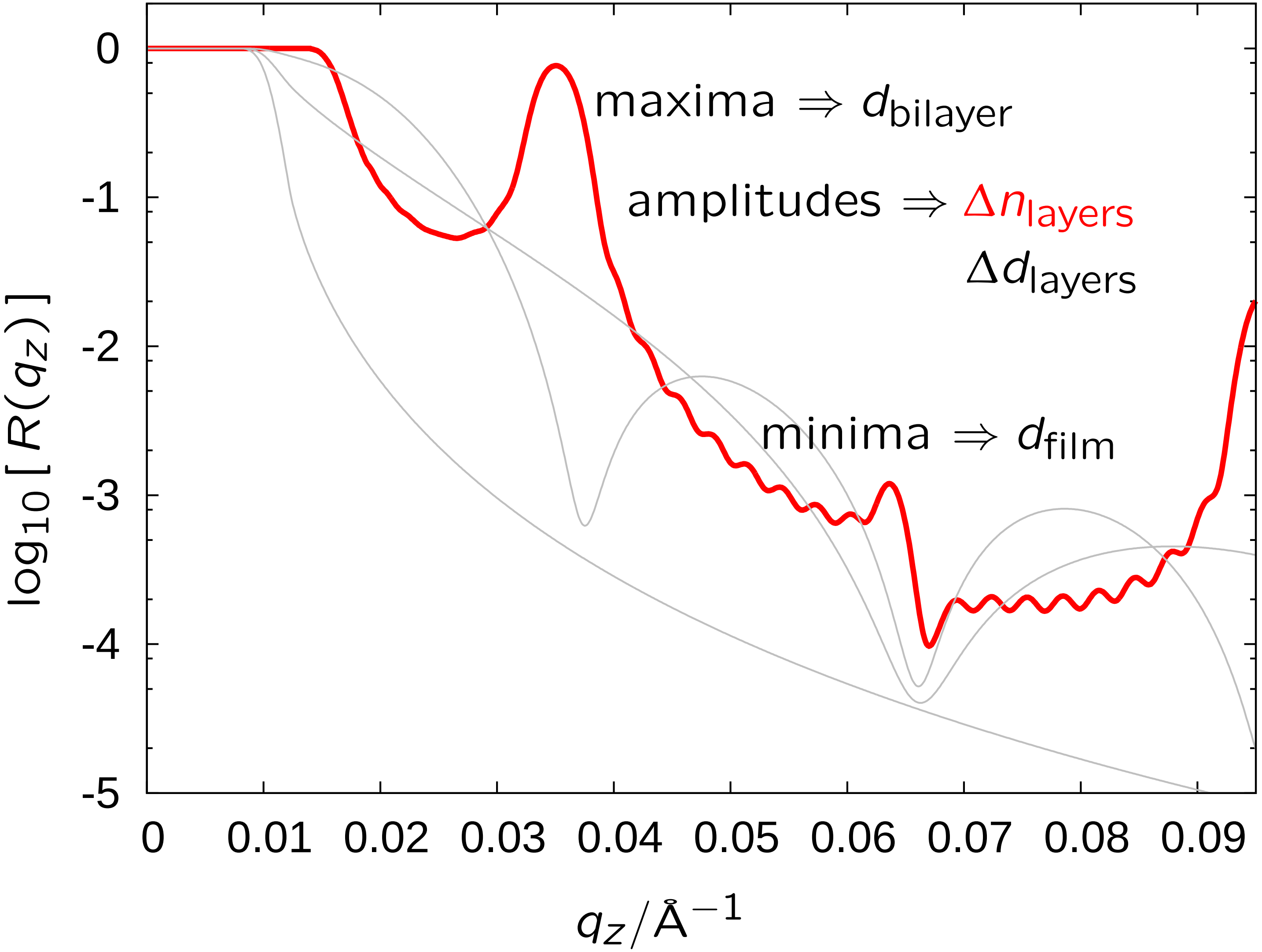


simulated reflectivity of a **thick layer**

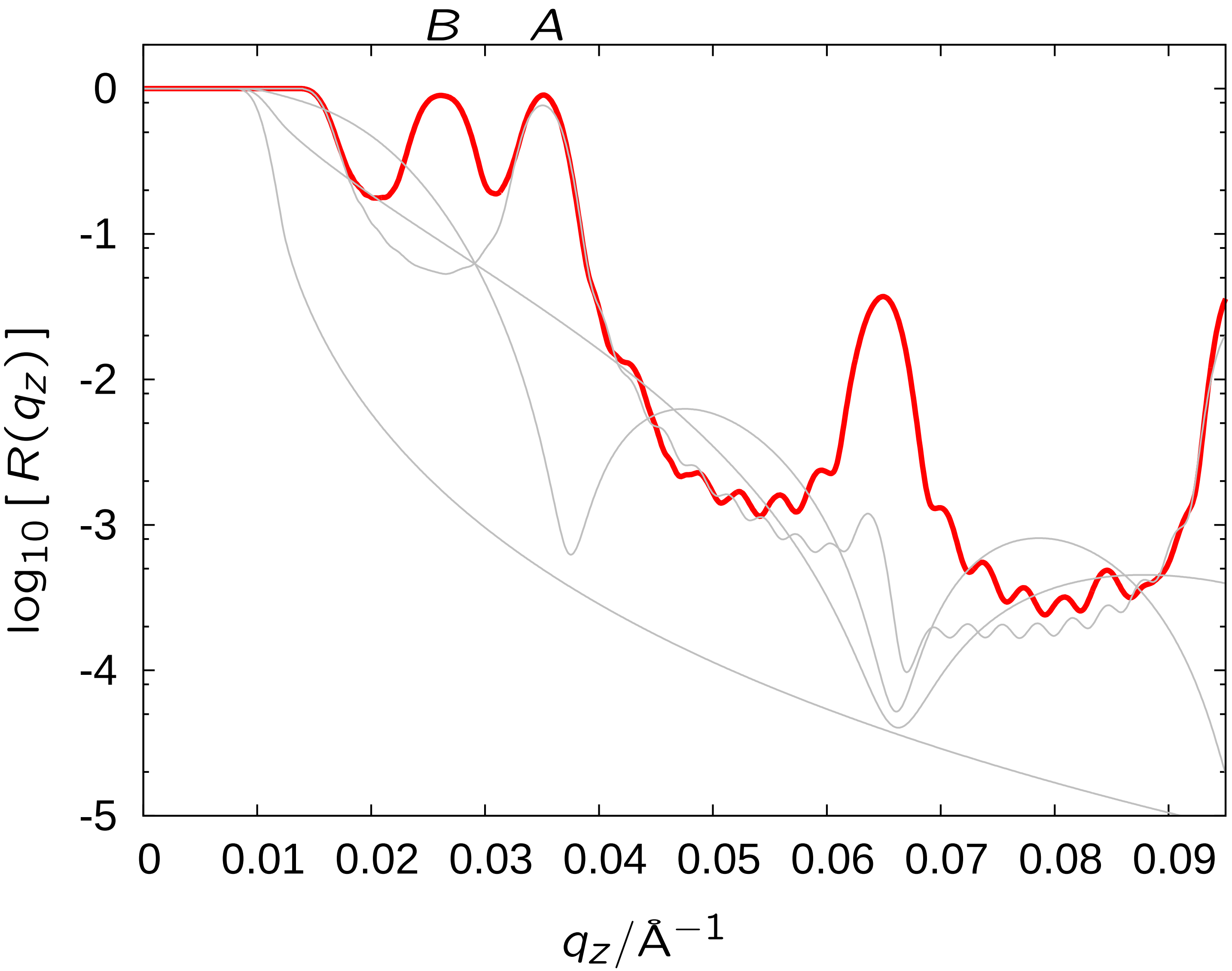


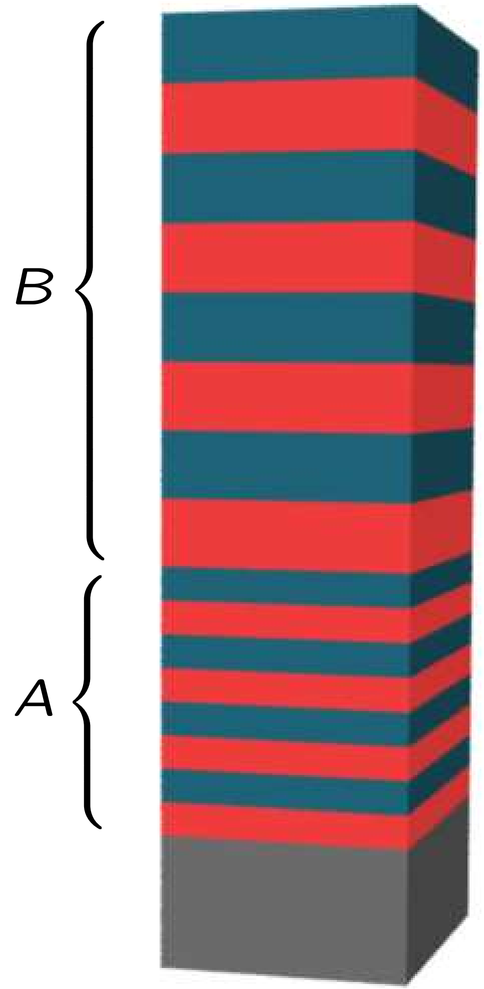


simulated reflectivity of a **periodic stack of layers**
= multilayer, ml

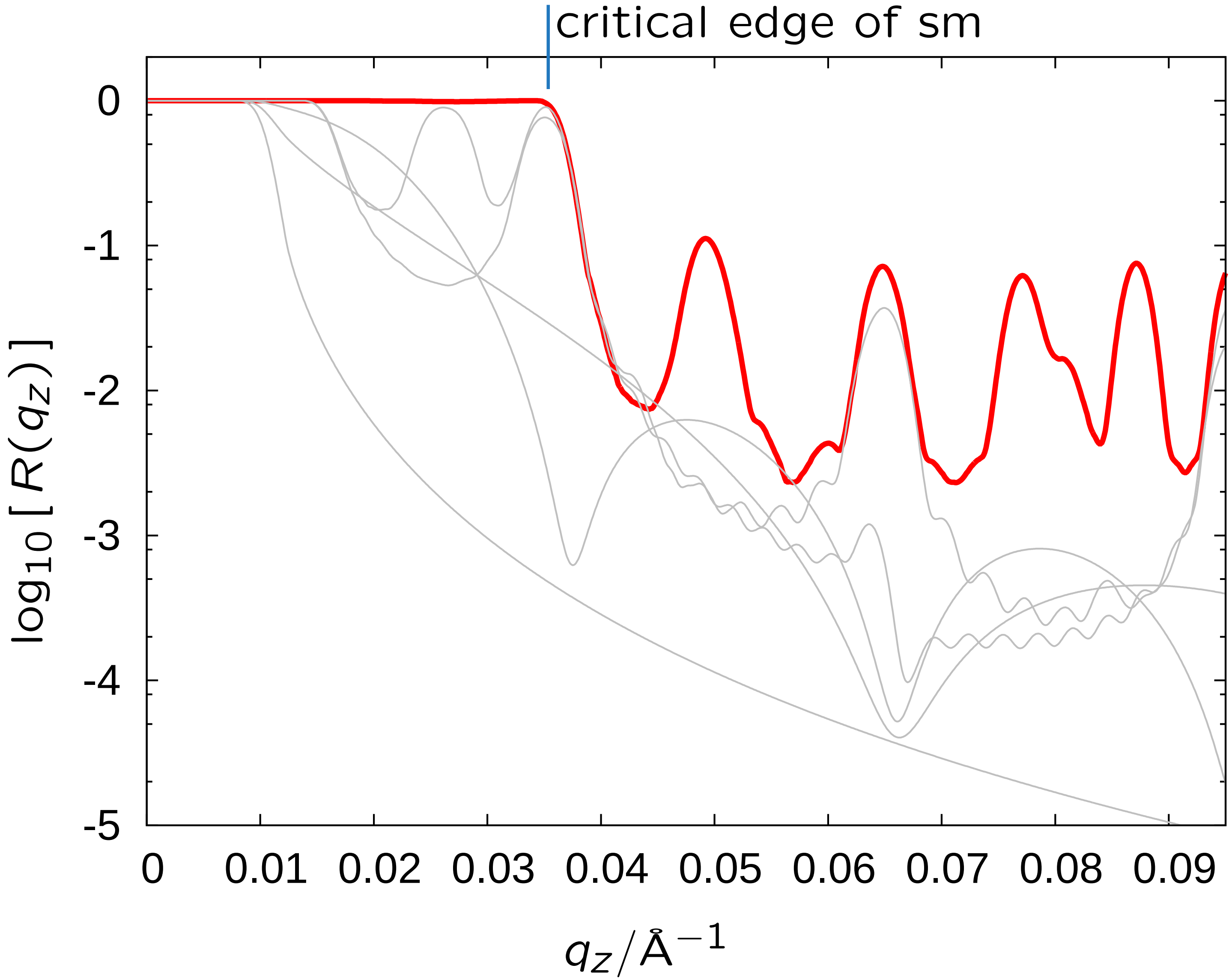


simulated reflectivity of a **stack of mls**

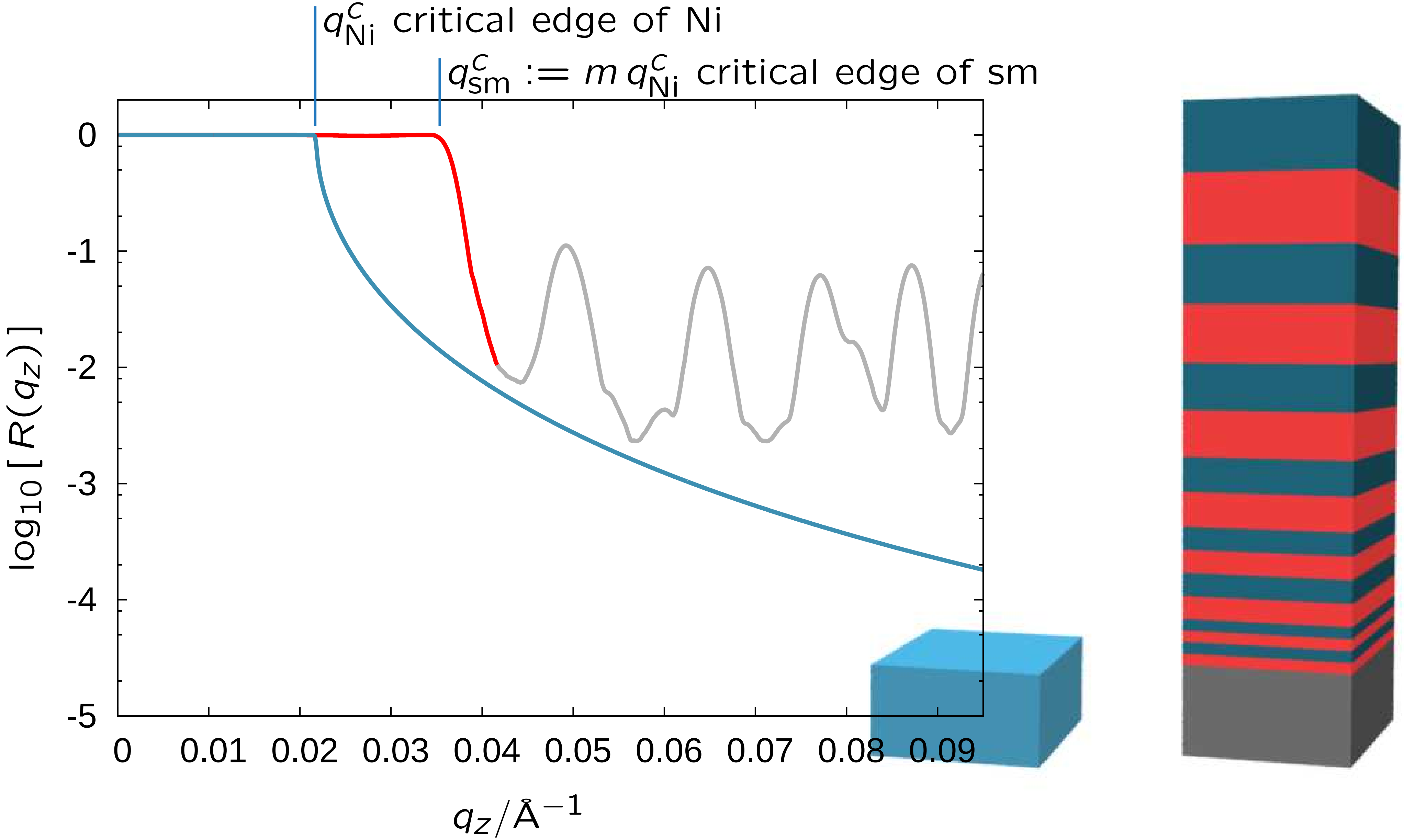




simulated reflectivity of a **stack with thickness gradient**
= supermirror, sm



simulated reflectivity of a **sm**
and of **Ni**



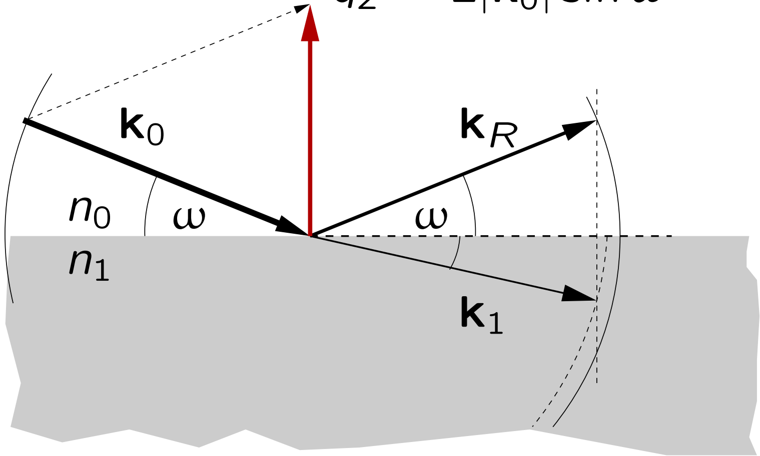
index of refraction

$$n := \frac{|k_i|}{|k_0|}$$

$$\approx 1 - \frac{V}{2E_{\mathrm{kin}}}$$

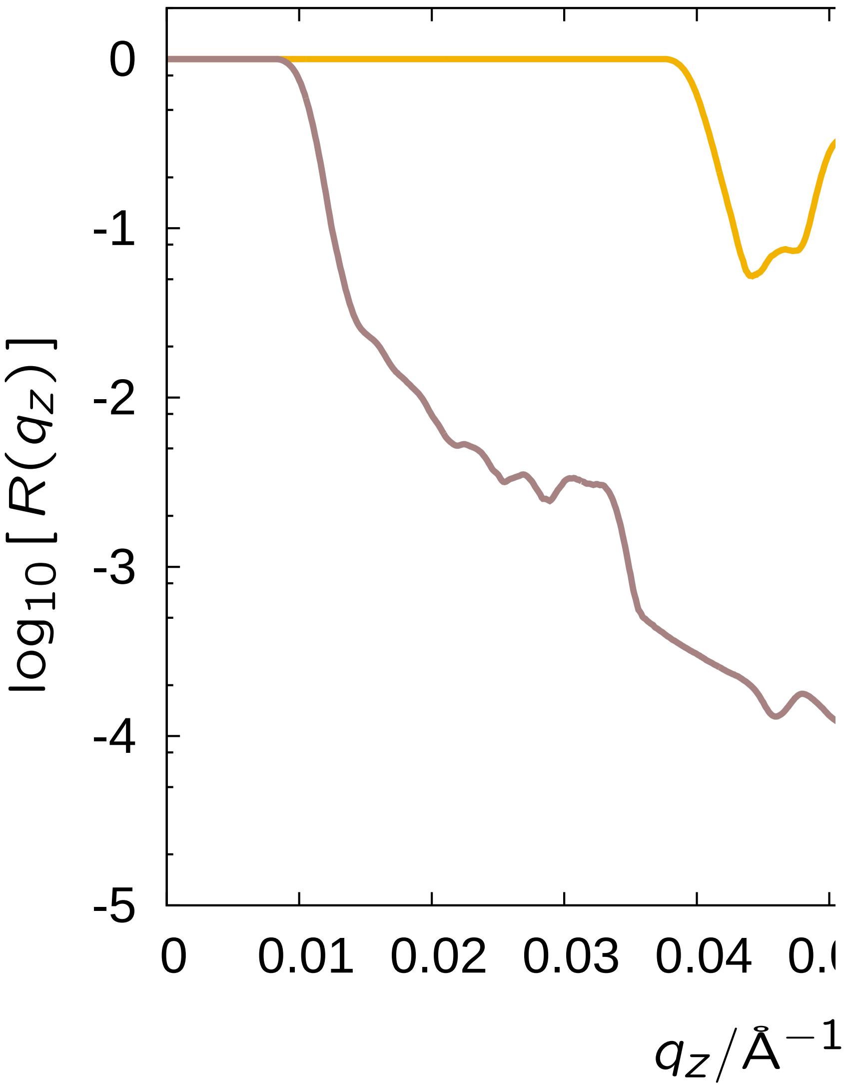
$$V = \frac{2\pi\hbar^2}{m_\mathrm{n}}\rho^b - \underbrace{\boldsymbol{\mu}_\mathrm{n}\mathbf{B}}_{\pm\mu_\mathrm{n}B}$$

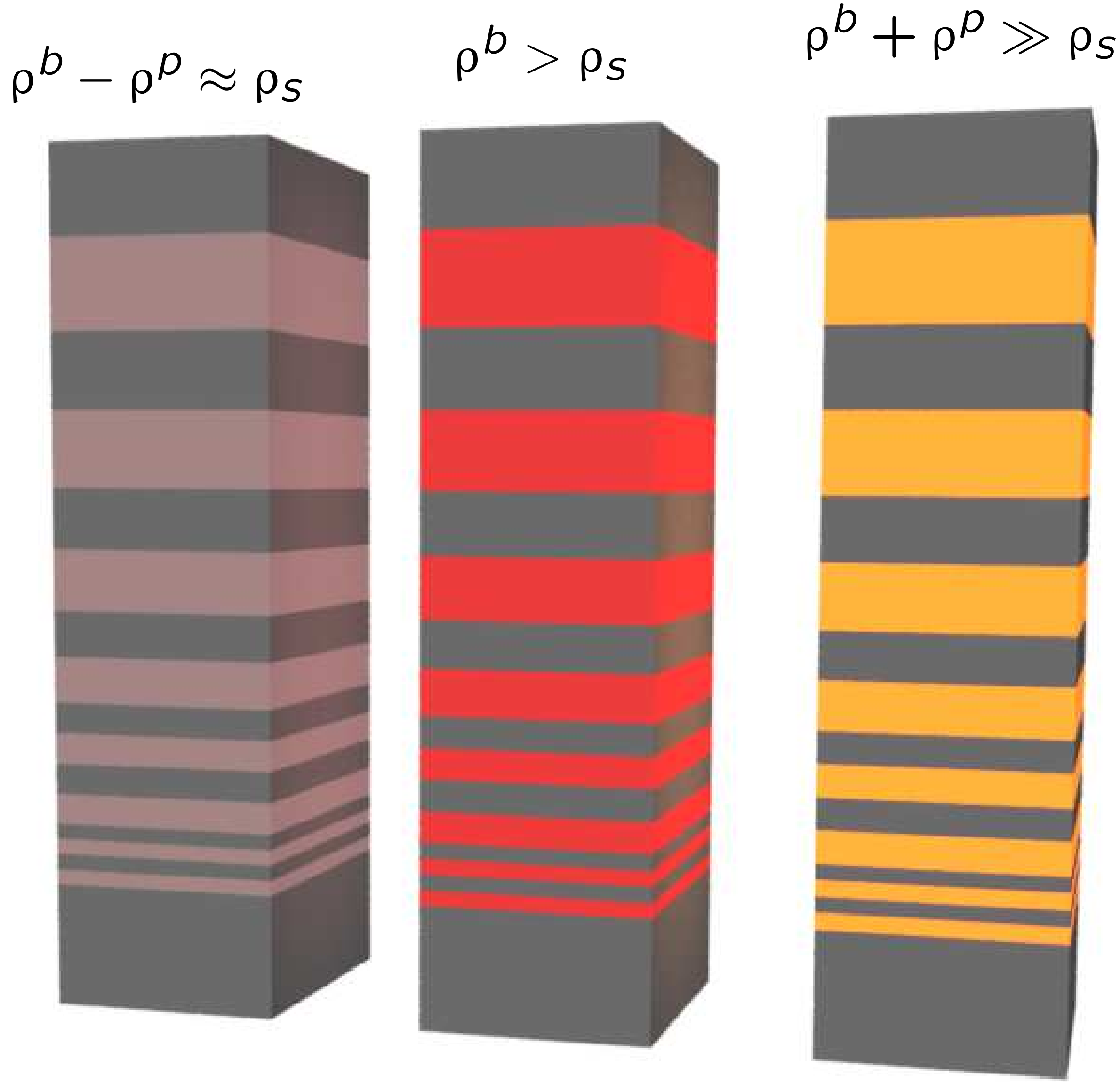
$$:= \frac{2\pi\hbar^2}{m_\mathrm{n}}\left(\rho^b \pm \rho^m\right)$$



$$|\mathbf{k}| = 2\pi/\lambda$$

polarising sm

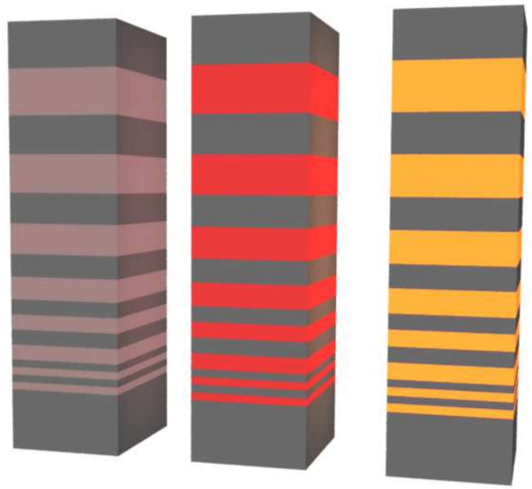




polarising sm coatings

FM	spacer	substrate	pro	con
$Fe_{89}Co_{11}$	Si	Si		Co
Fe	Si : N		high transmission low activation	$q_c^{\mid-\rangle}$
FeCoV	Ti : N	absorber	$q_c^{\mid-\rangle} < 0\,\text{Å}^{-1}$	Co
$Fe_{0.5}Co_{0.5}$				Co

Co gets activated ⇒ avoid whenever possible!

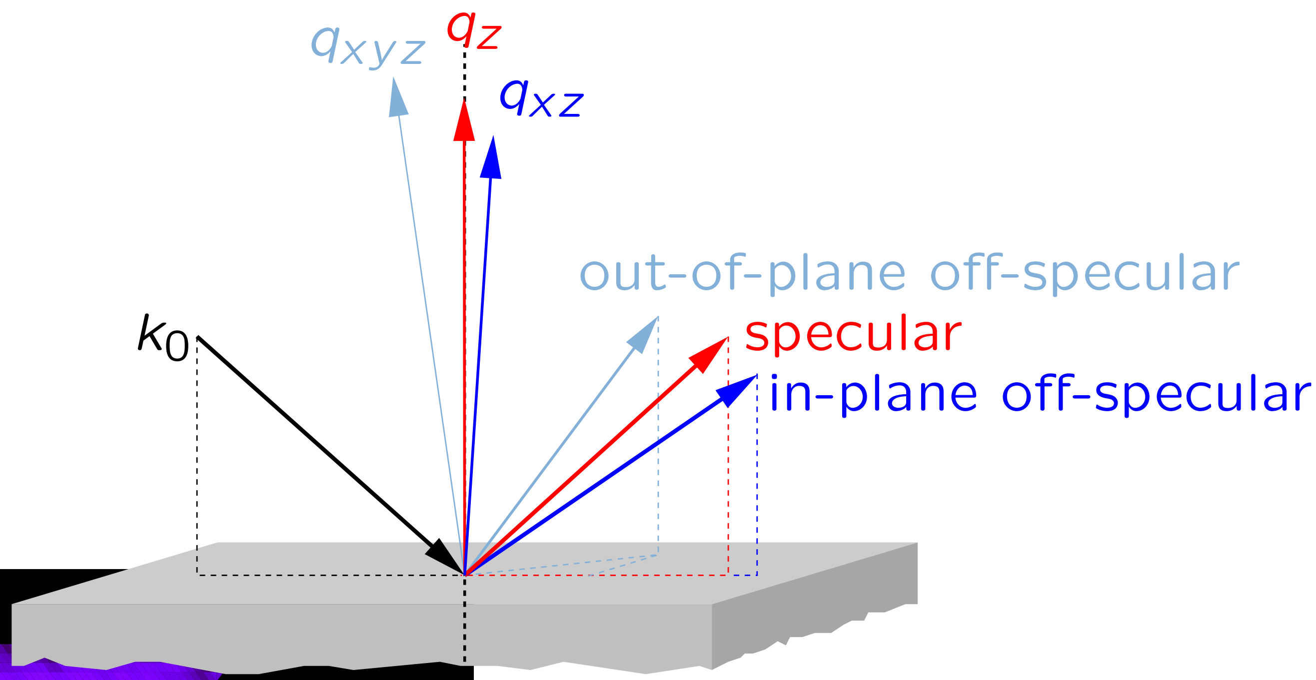


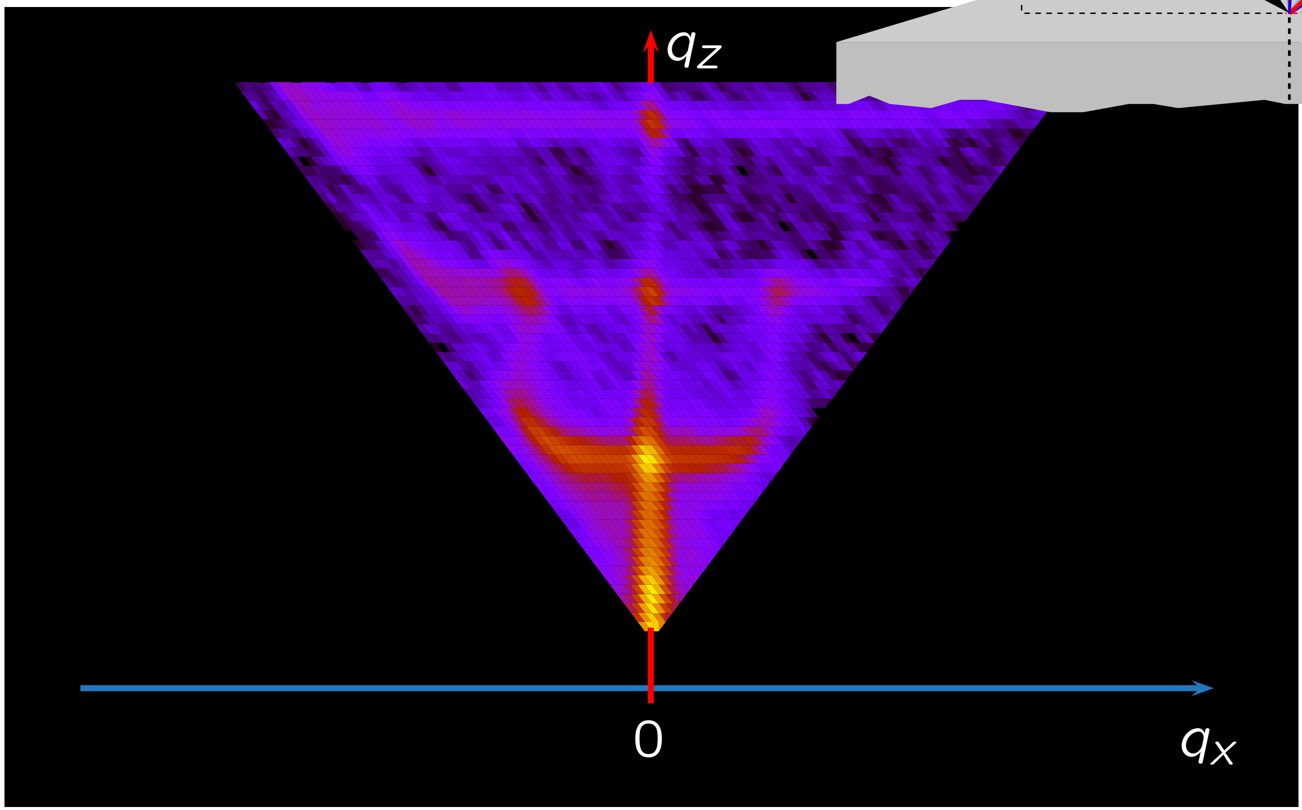
off-specular scattering

$\rho = \rho(x, z)$

$\Rightarrow R(q_x) \neq 0!$

$\Rightarrow$ dilution of phase space
background
losses





$\rho^{\text{magnetic}}(x, y) \neq 0$

$\Rightarrow$ spin flip

Ni/Ti multilayer

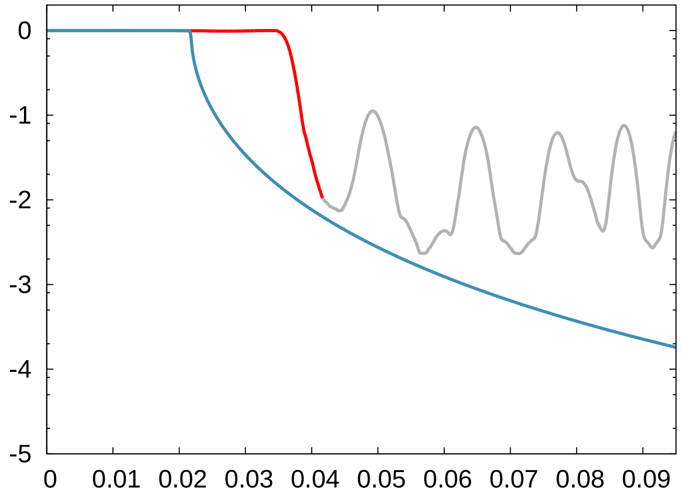
keep in mind:

$$\begin{aligned} R(q_z) &= R(n(z), B(z)) \\ &= 1 & \forall \quad q_z < q_c \\ &= 1 \ldots 0.55 & \text{for} \quad q_z < q_{sm} \\ &\propto q_z^{-4} & \forall \quad q_z \gg q_c \end{aligned}$$

- typical numbers:

	$\rho^b / 10^{-6}\,\text{Å}^{-2}$	$q_c\,/\,\text{Å}^{-1}$	ω_c @4 Å
Si, $Fe^{\vert-\rangle}$	2.1	0.010	0.18°
$Fe^{\vert+\rangle}$	13.9	0.026	0.47°
Ni	9.4	0.022	0.40°
Ti	-3.4		

$\Rightarrow$ small angles $\Rightarrow$ geometrical constraints



- roughness $\Rightarrow$ off-specular scattering $\Rightarrow$ background & depolarisation

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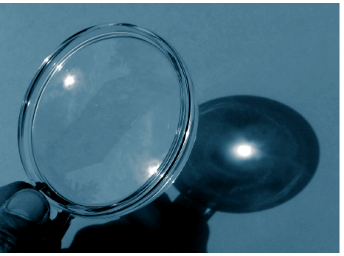
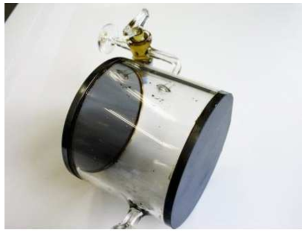


focusing optics
- refractive
- reflective

overview

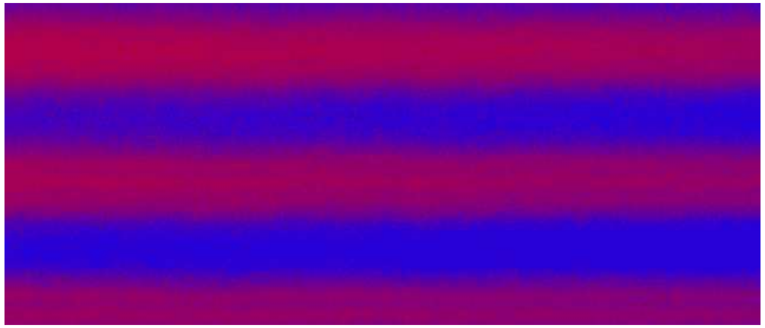
transmission throgh polycristalline Fe
6 mm Fe: $P = 33\%$ at $\lambda = 3.6$ Å

^{3}He
→ talk by E. Babcock



Heusler alloy
crystal monochromator

thin film coatings



Heusler alloy monochromator / analyser

Cu_2MnAl single crystals

with $F_{\text{magnetic}}(111) = \pm F_{\text{nuclear}}(111)$

$\Rightarrow F(111)$ reflex strong for $\boldsymbol{\mu}_n \uparrow\uparrow \mathbf{B}$

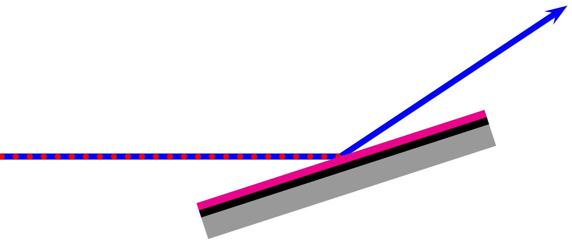
weak for $\boldsymbol{\mu}_n \downarrow\uparrow \mathbf{B}$

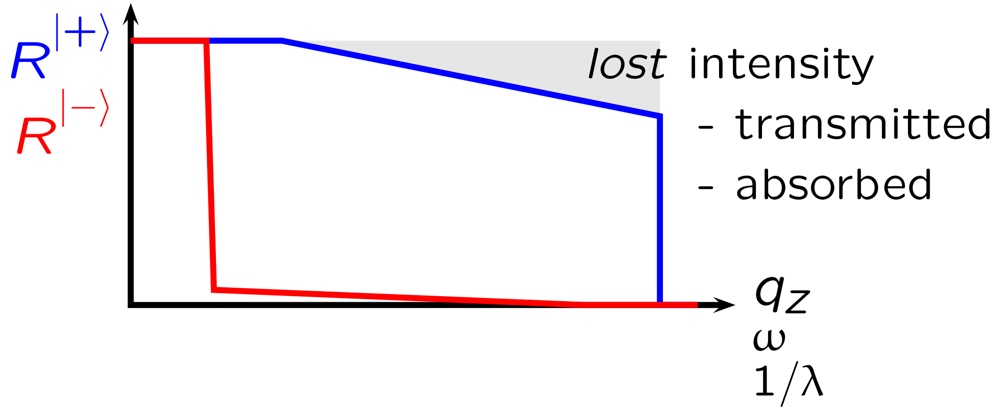
- $\lambda \in [0.8, 6.5]$ Å
- $\Delta\lambda/\lambda \approx 1\%$
- $\boldsymbol{P \approx 95\%}$

- used for triple-axis spectrometers

P. Courtois et al: N.I.M. A **529**, 157 (2004)

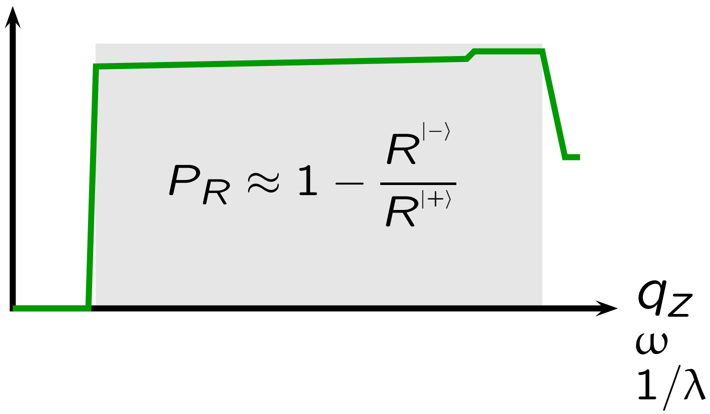
Using Reflected beam

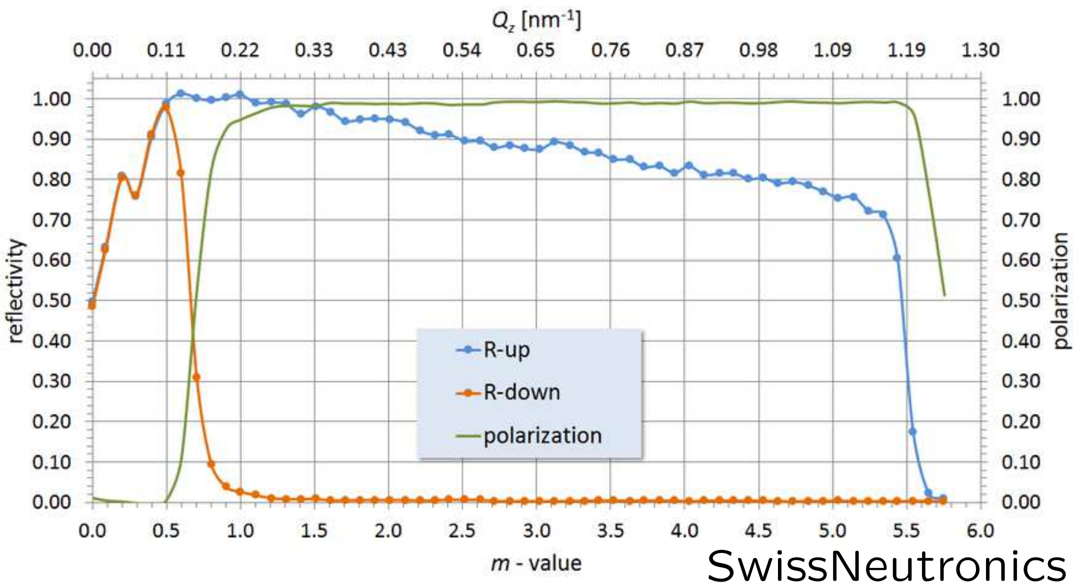




- trajectory is inclined
- high polarisation
  $\boldsymbol{P_R \approx 96\% - 99\%}$

$$P_R = \frac{R^{|+\rangle} - R^{|-\rangle}}{R^{|+\rangle} + R^{|-\rangle}}$$



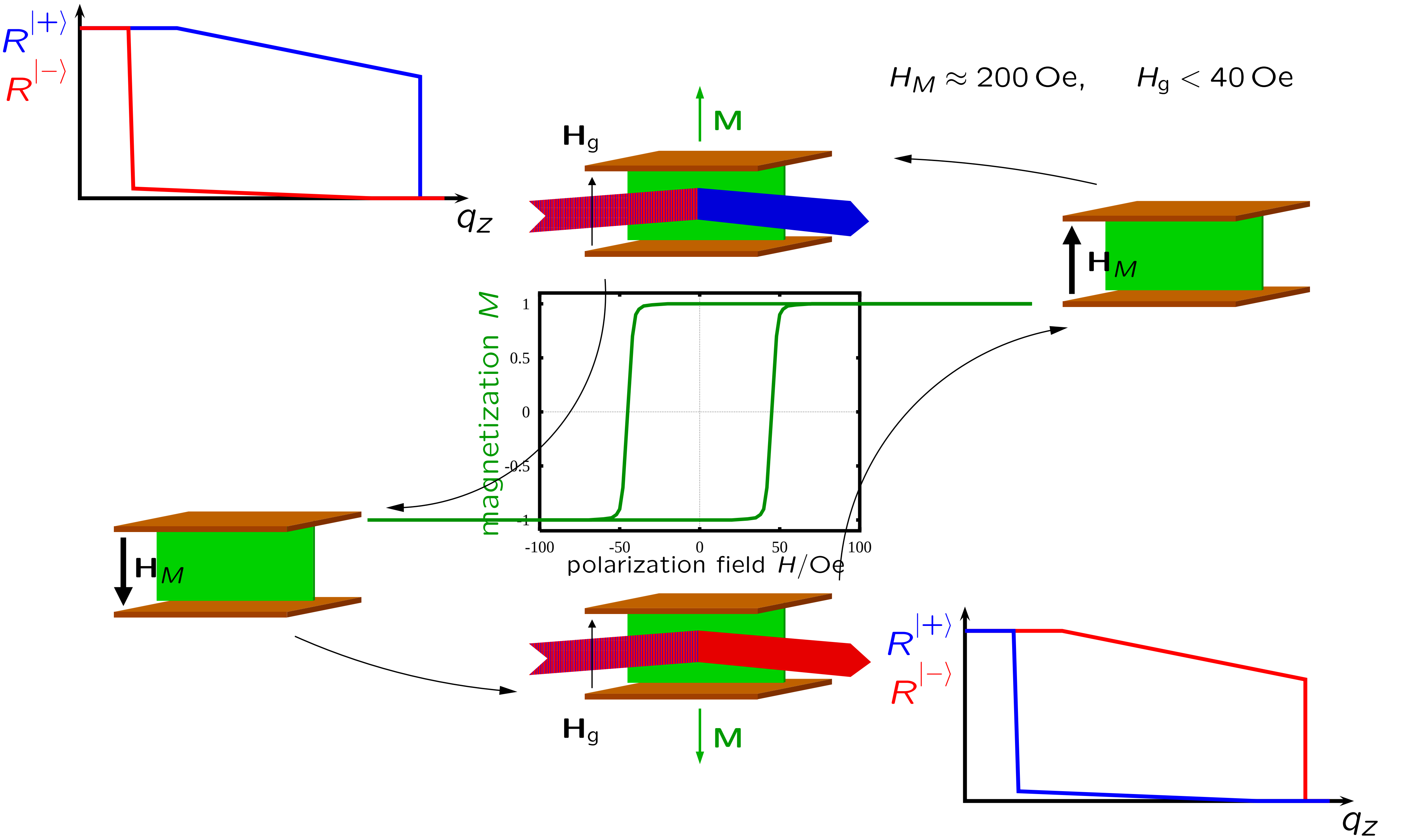


SwissNeutronics

single, falt mirror

switchable remanent polariser

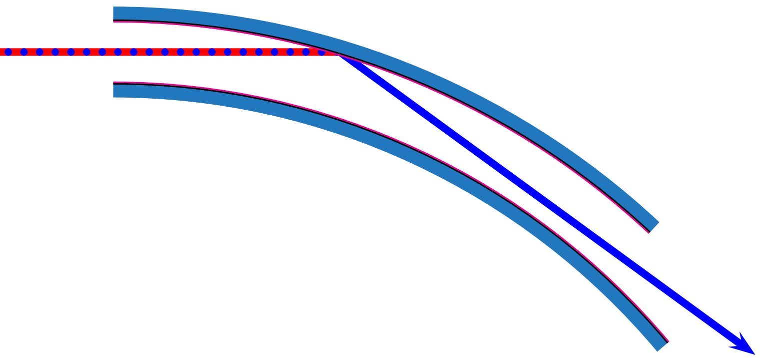
$H_M \approx 200\,\mathrm{Oe}, \qquad H_g < 40\,\mathrm{Oe}$



polarisers - based on SM

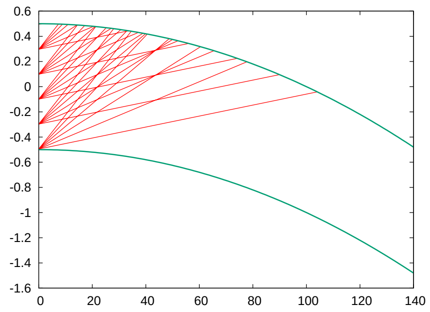
bender

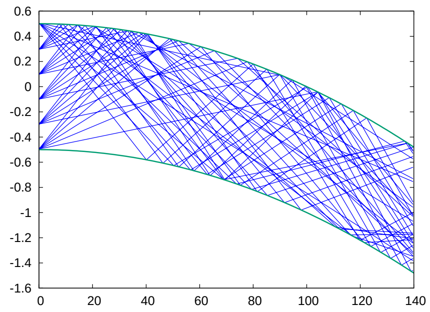
$$\frac{\text{length}}{\text{width}} \approx 150$$

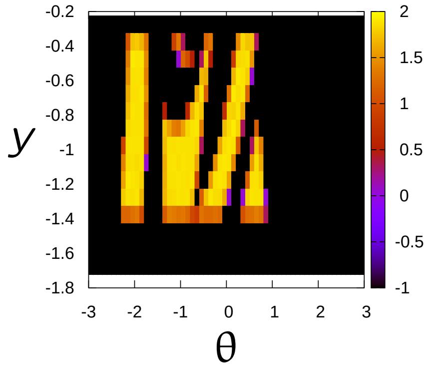


$|-\rangle$ $|+\rangle$ $|+\rangle$

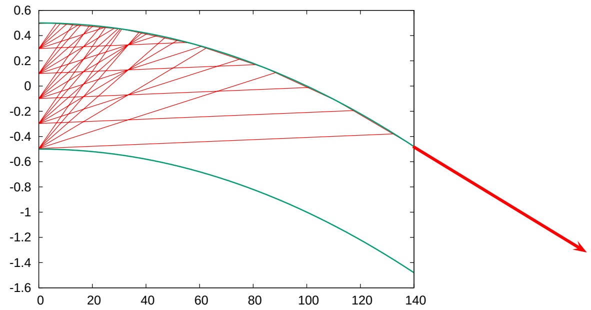
optimum parameters





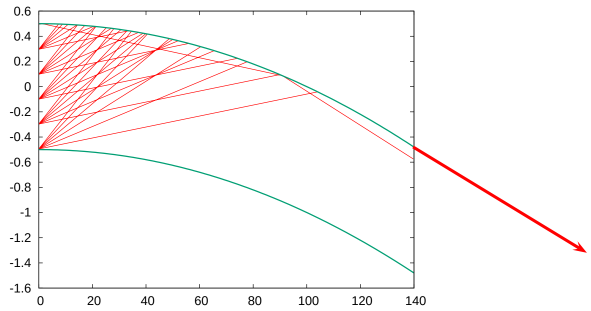


too large $\delta\theta$



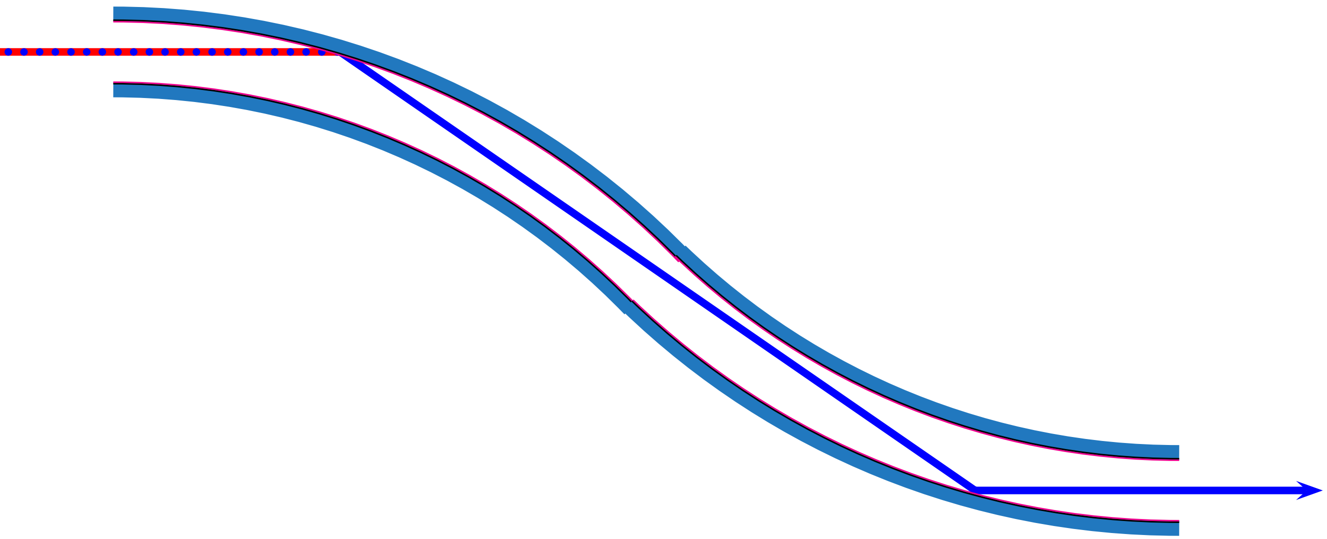
garland reflections of $|-\rangle$

too high λ

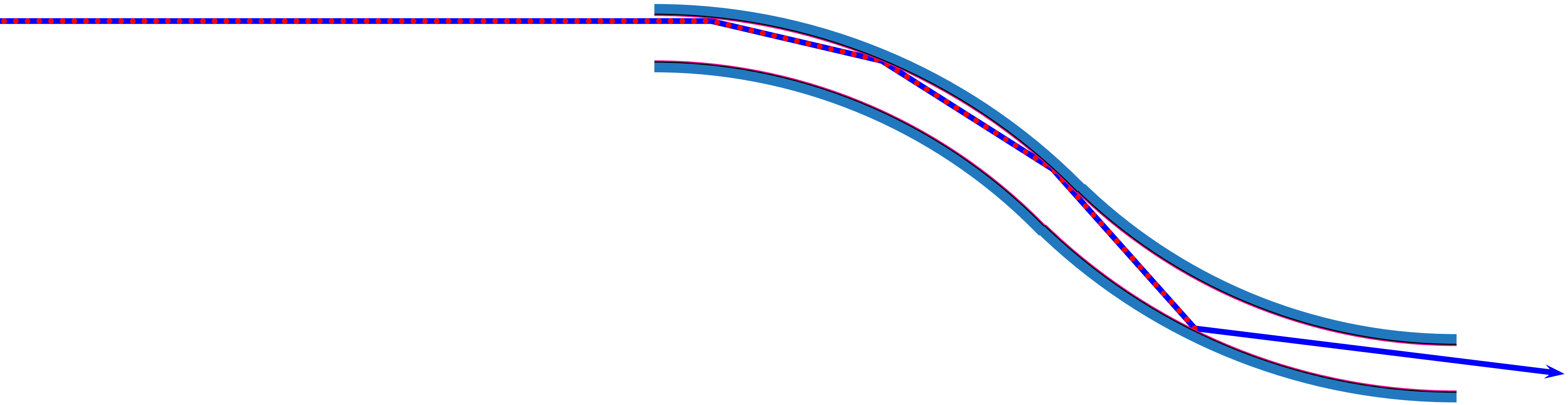


S-bender

$$\frac{\text{length}}{\text{width}} \approx 250$$



- almost straight trajectory
- garland-problem is solved

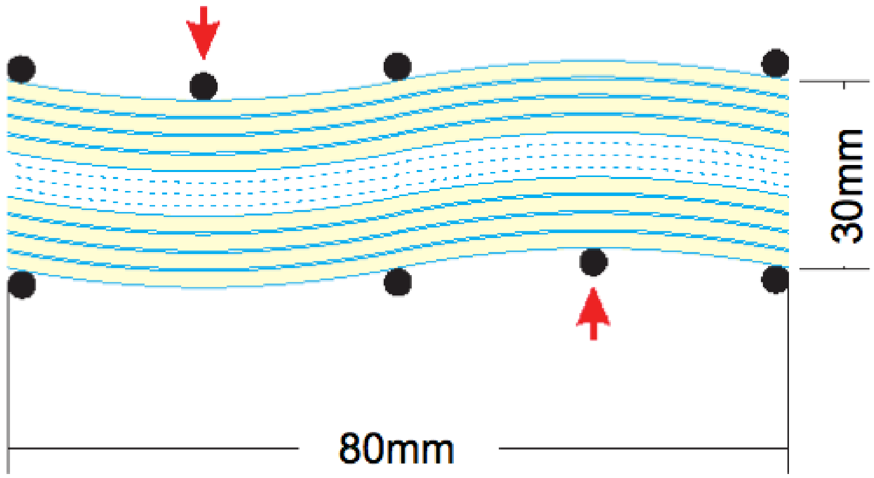


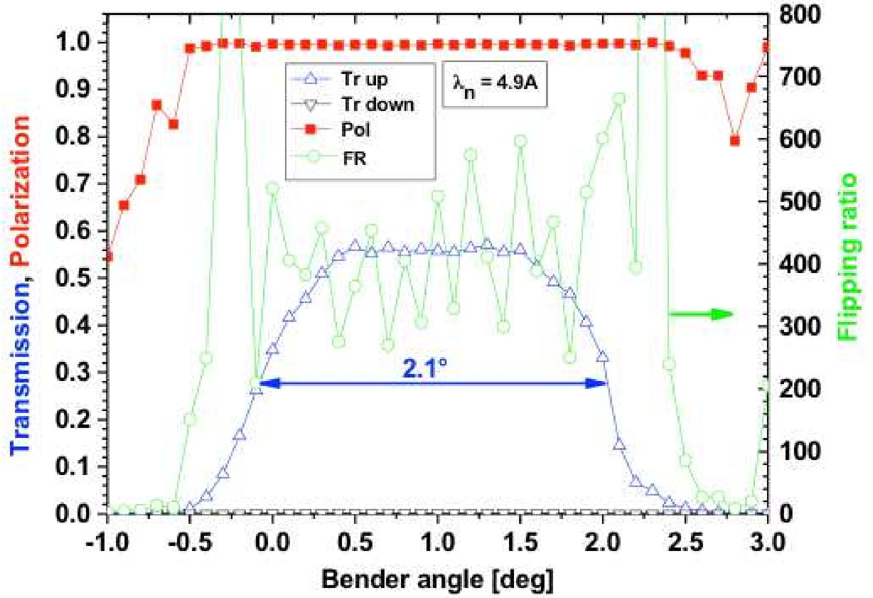
application: solid-state S-bender

Si wafers (150 µm) used as channel

- thin and short channels
- $q_c^{|-\rangle} < 0\,\text{Å}^{-1}$
- no dark regiond due to substrate
- higher absorption

this principle also applies to benders

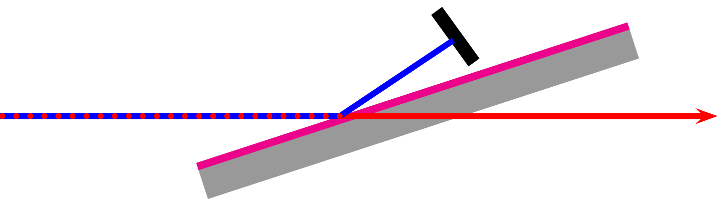


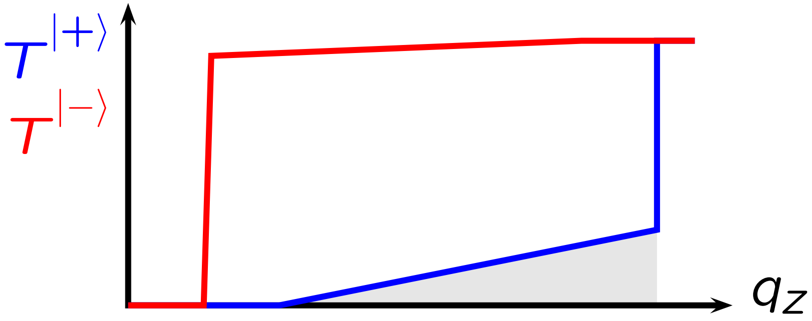


T. Krist et al.: N.I.M. **698**, 94 (2013)

polarisers - based on SM

using Transmitted beam

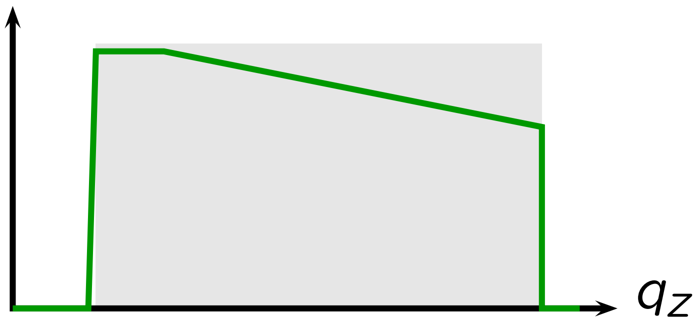


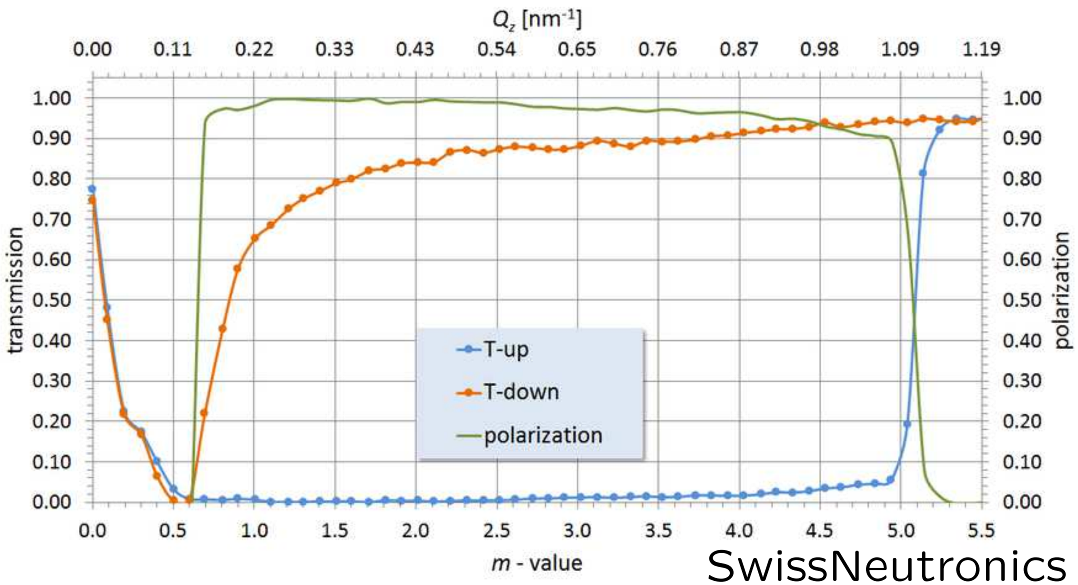


- straight trajectory

- moderate polarisation
  $\boldsymbol{P_T \approx 60\% - 80\%}$

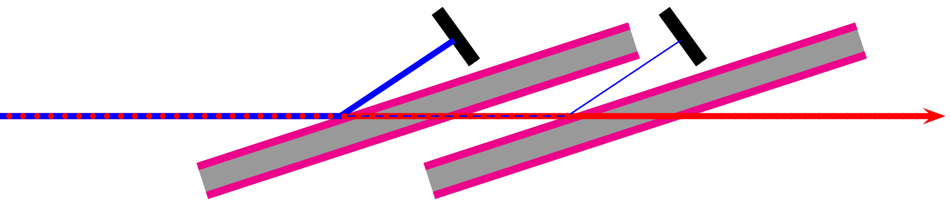
$$P_T = \frac{T^{|-\rangle} - T^{|+\rangle}}{T^{|-\rangle} + T^{|+\rangle}}$$

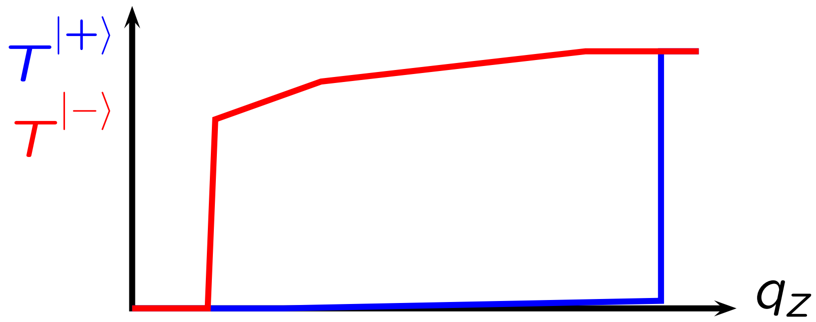




SwissNeutronics

using Transmitted beam

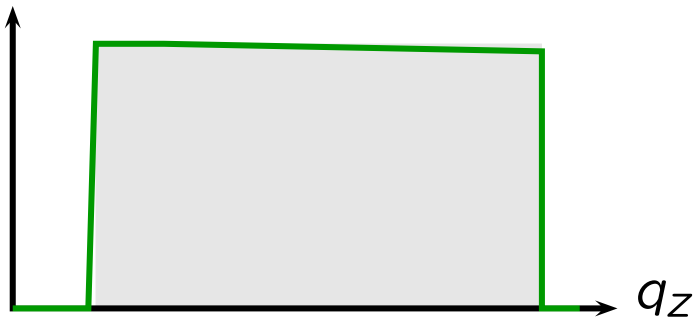


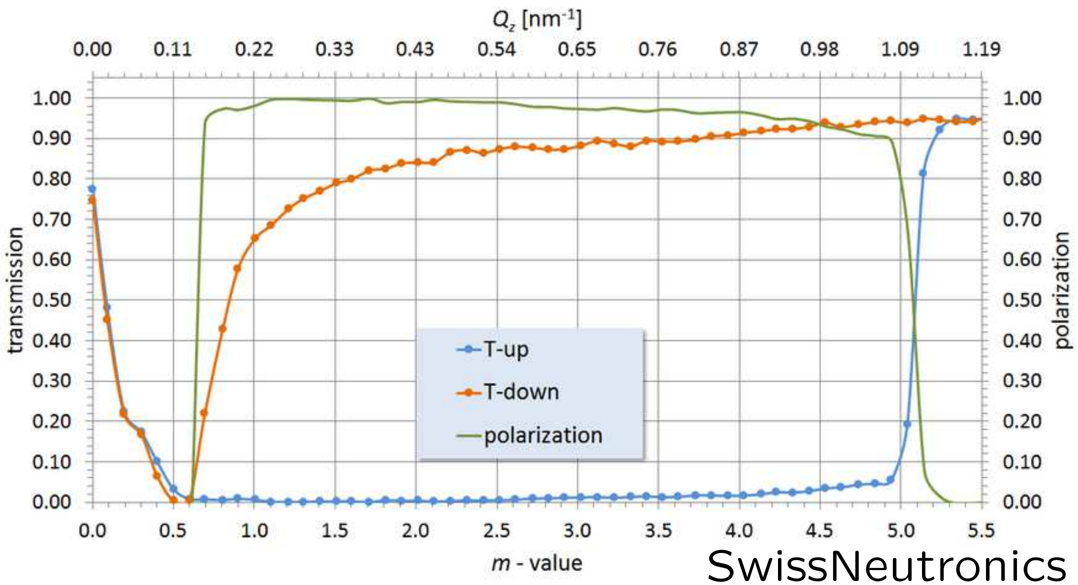


- straight trajectory

- high polarisation
  $P_T \approx 96\% - 99\%$

$$P_T = \frac{T^{|-\rangle} - T^{|+\rangle}}{T^{|-\rangle} + T^{|+\rangle}}$$





SwissNeutronics

increase of efficiency by multiple transmission:

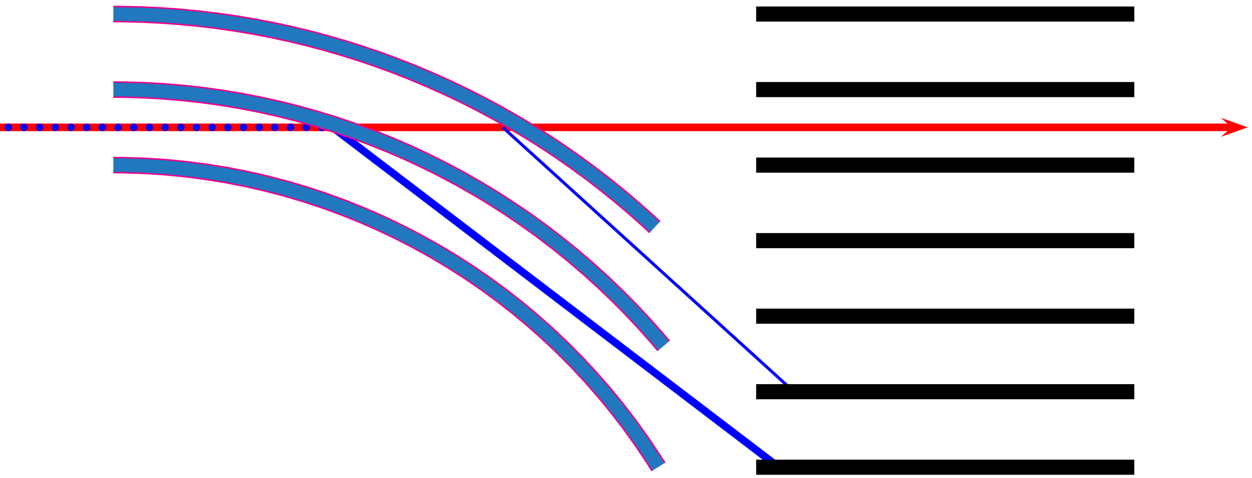
- both sides of substrates coated

- several substrates in sequence

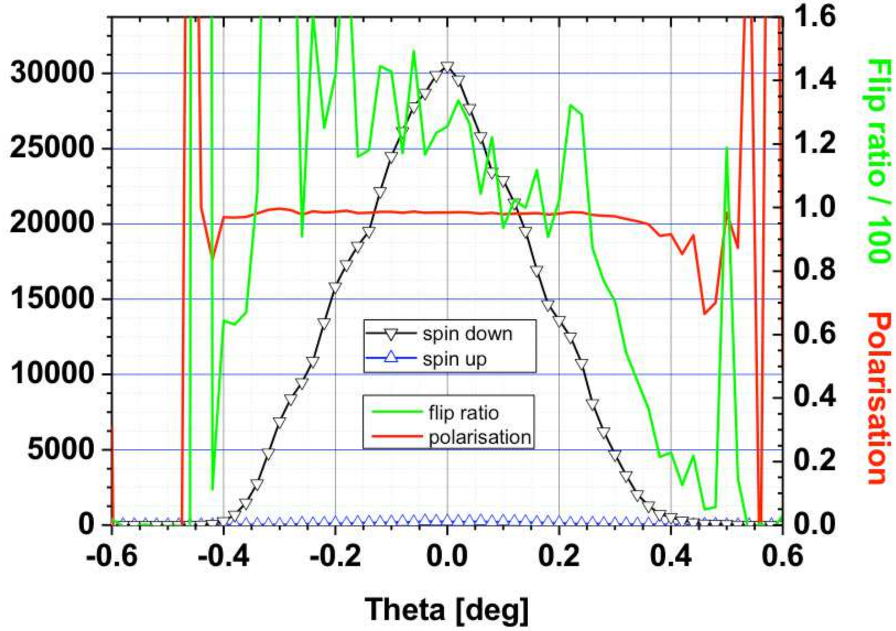
$\Rightarrow$ reduced intensity

transmission bender + collimator

$$\frac{\text{length}}{\text{width}} \approx 300$$



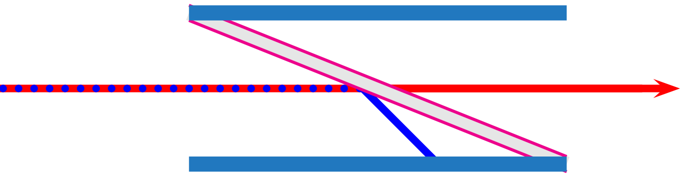
- straight trajectory
- dark areas due to substrates



T. Krist: solid-state transmission bender + collimator

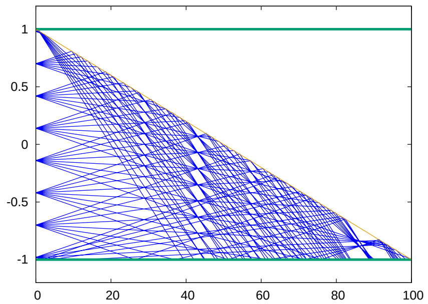
cavity

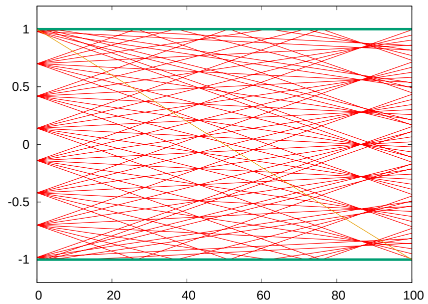
$$\frac{\text{length}}{\text{width}} \approx 50$$

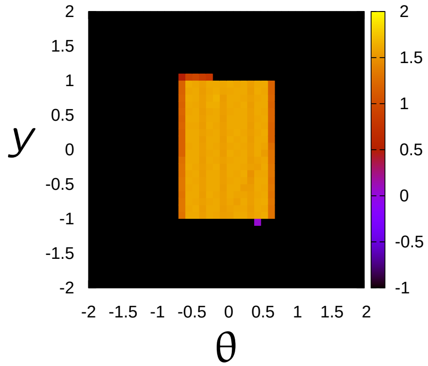


$|+\rangle$ $|-\rangle$ $|-\rangle$

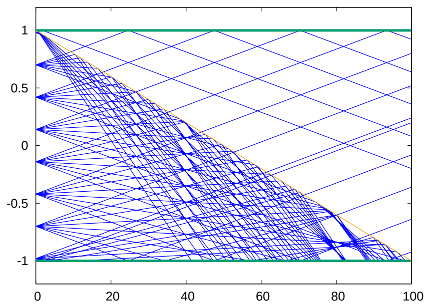
optimum parameters



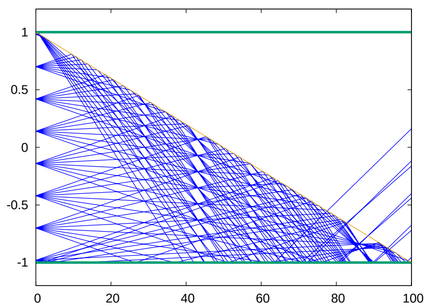




too large $\delta\theta$



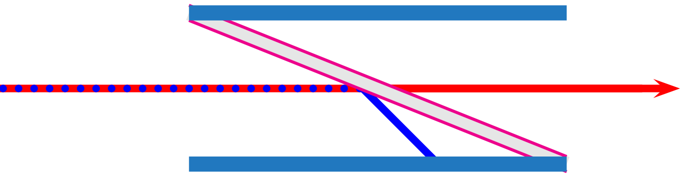
too high m_{channel}



polarisers - based on SM

cavity

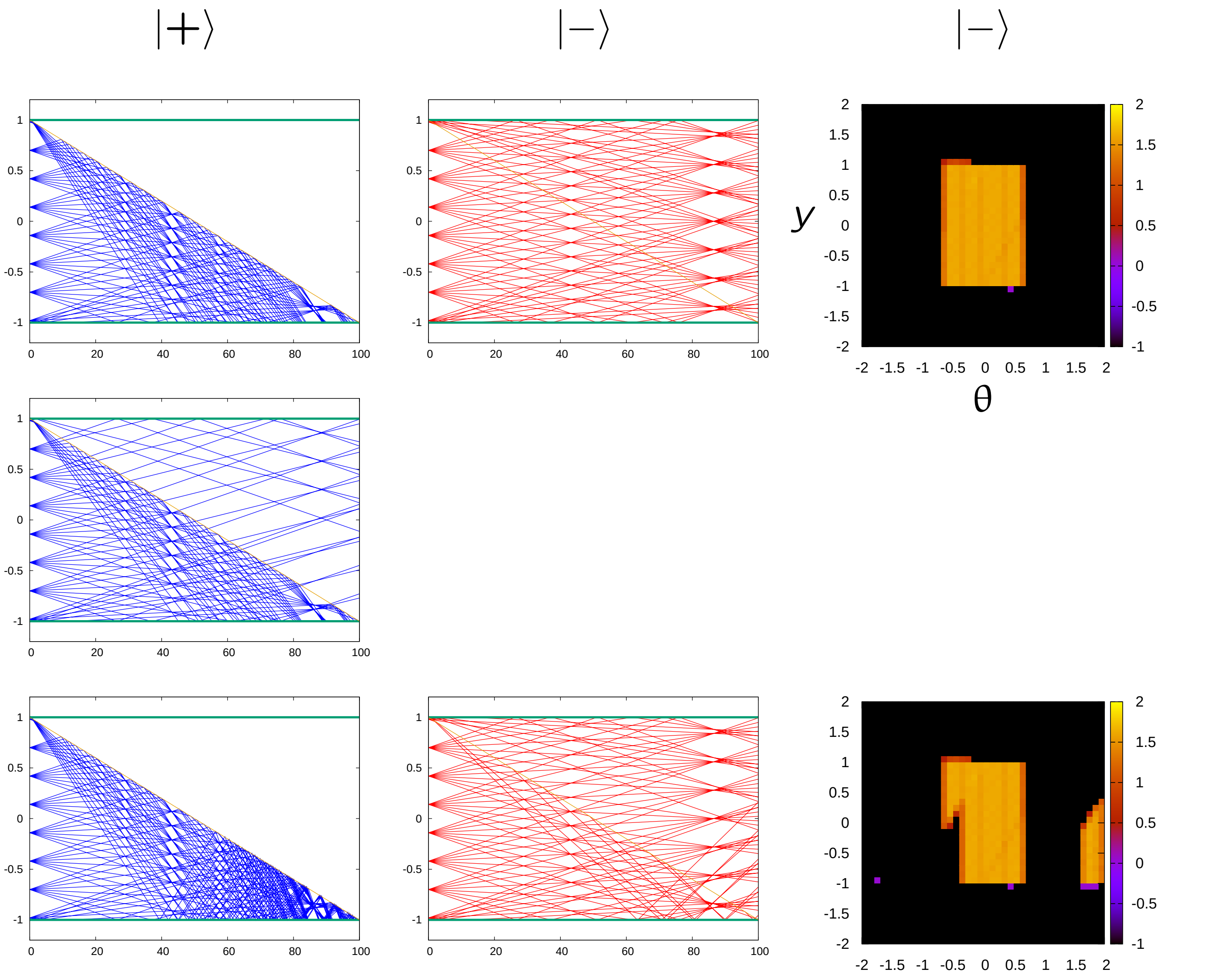
$$\frac{\text{length}}{\text{width}} \approx 50$$



optimum parameters

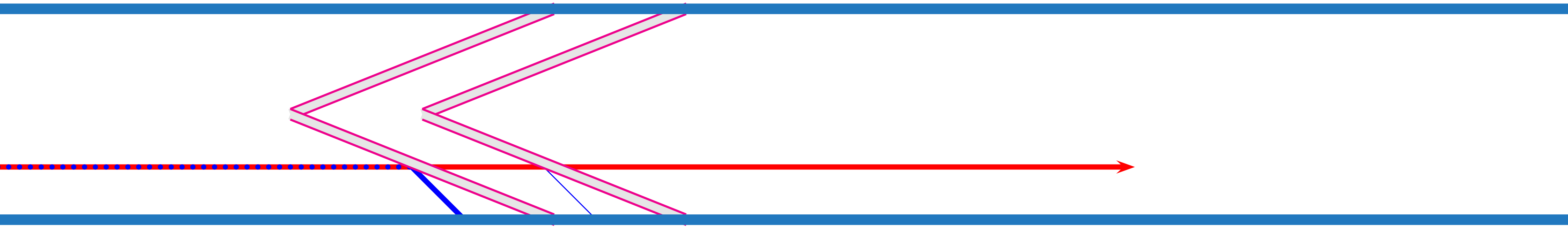
too low λ

too high λ



V-cavity

$$\frac{\text{length}}{\text{width}} \approx 30$$



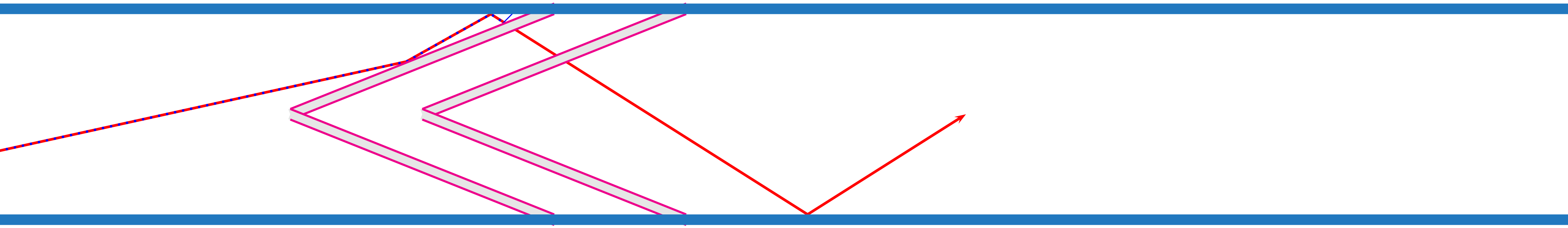
- straight beam geometry

F. Mezei et al.: Physica B **180-181**, 1005 (1992)

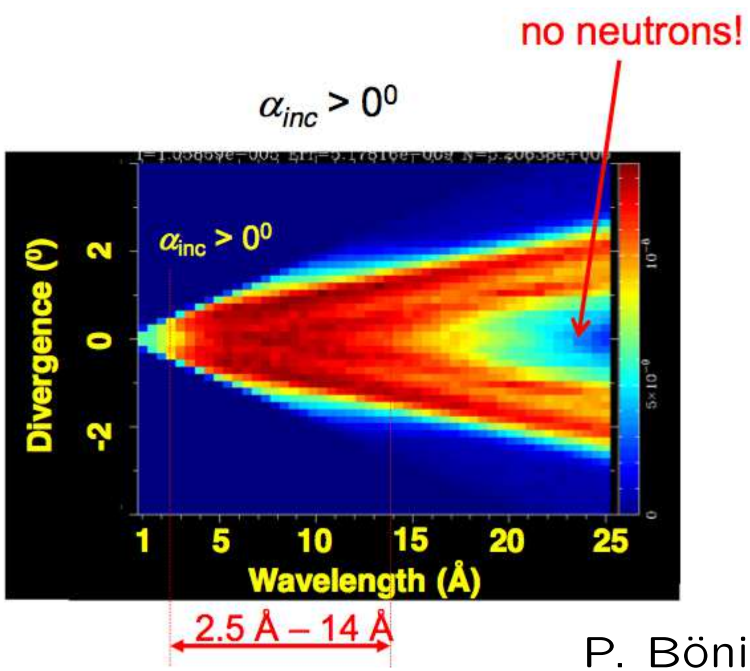
polarisers - based on SM

V-cavity

$$\frac{\text{length}}{\text{width}} \approx 30$$



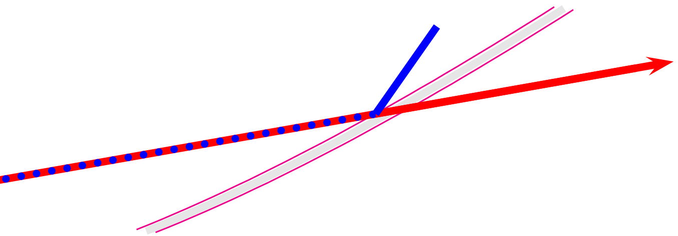
- straight beam geometry phase space affected
- $\Delta\lambda/\lambda_{\min} \approx 5$
- $P \approx$ **99%**



F. Mezei et al.: Physica B **180-181**, 1005 (1992)

P. Böni

equiangular spiral

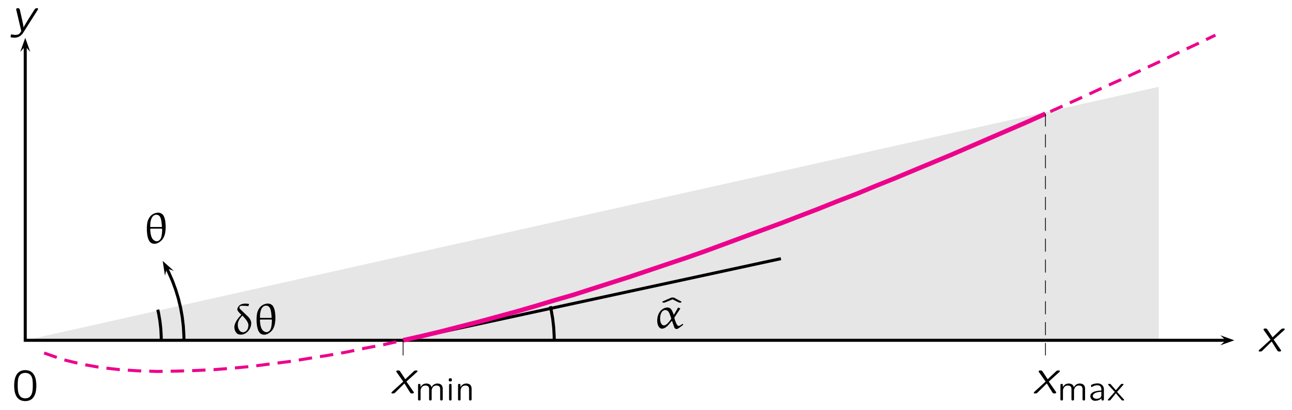


for beams { emerging from / focused to } a narrow area

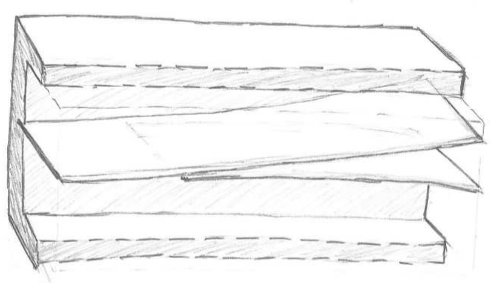
- same ω for all trajectories

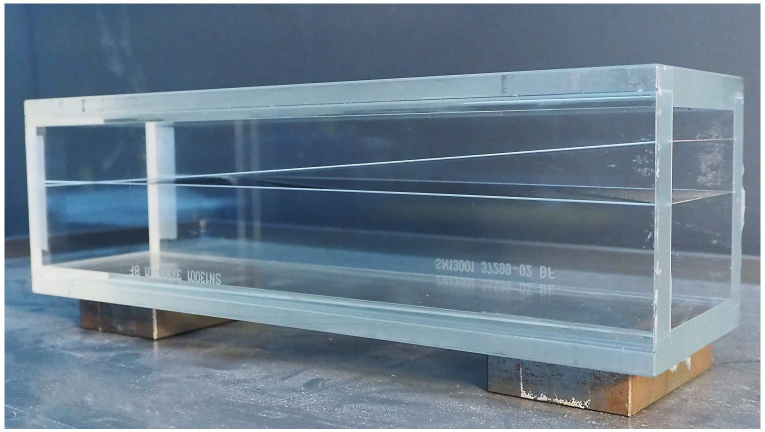
$\rightarrow$ flexibility for ω, m, λ

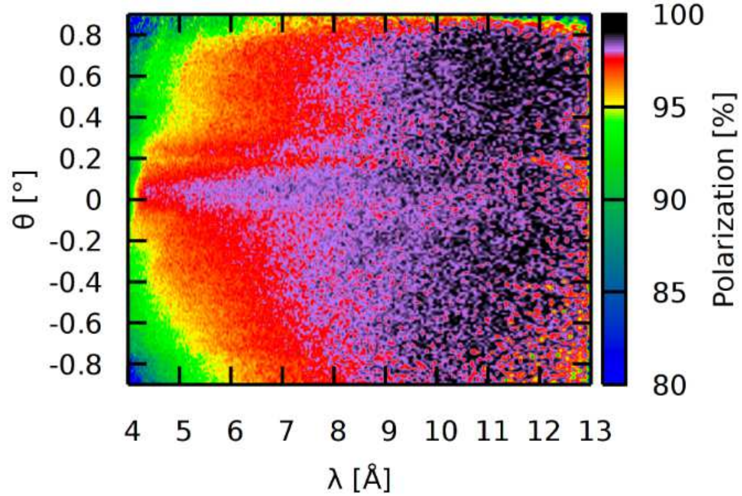
- phase space hardly affected



prototype at PSI







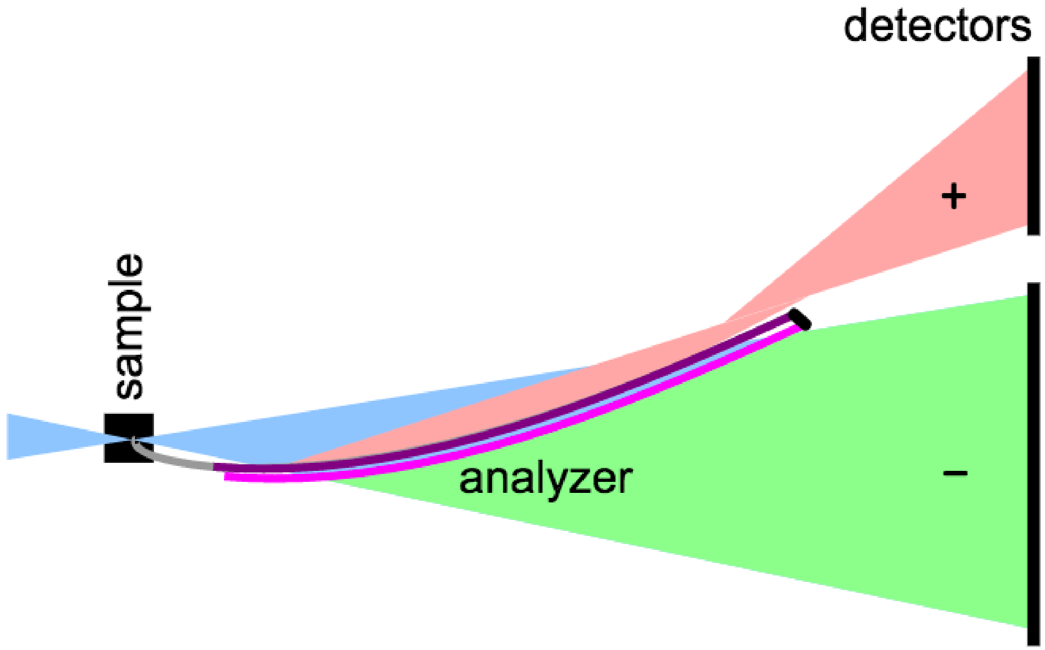
J. Stahn, A. Glavic: Journal of Physics: Conference Series **862**, 012007 (2017)

using Reflected and Transmitted beam

- split neutron guide for 2 polarised instruments (at HMI / HZB)

F. Mezei et al.: Physica B **213-214**, 393 (1995)

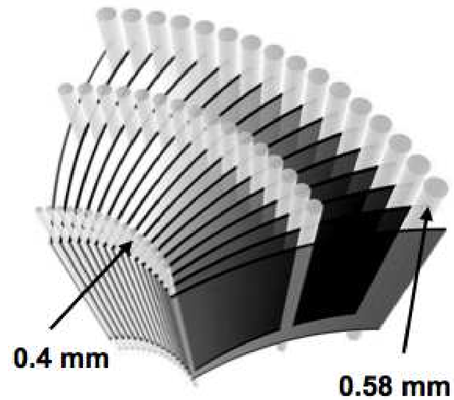
- suggested analyser for Estia@ESS



A. Glavic

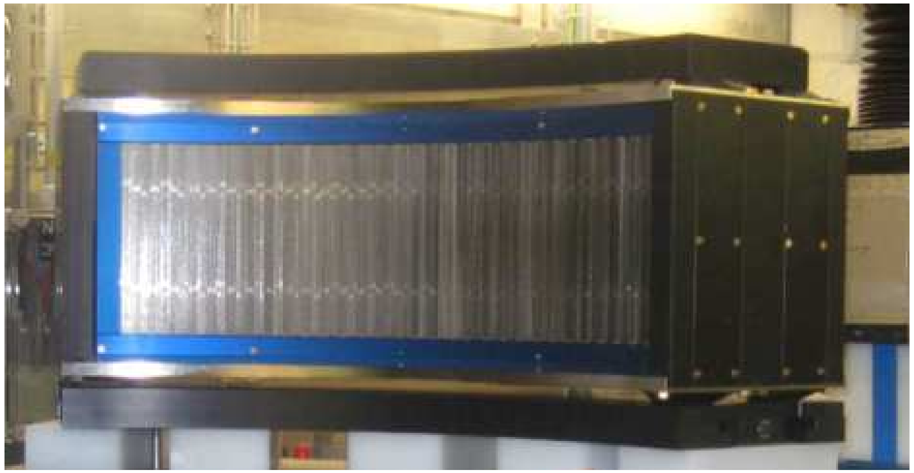
wide-angle analysers

stack of cavities / benders / spirals pointing towards the sample



challanges:

- avoid / minimise black angles
- provide a high magnetisation field
- reduce losses



example: Hyspec analyser by PSI

60° coverage with 1000 benders

$P \approx 95\%$

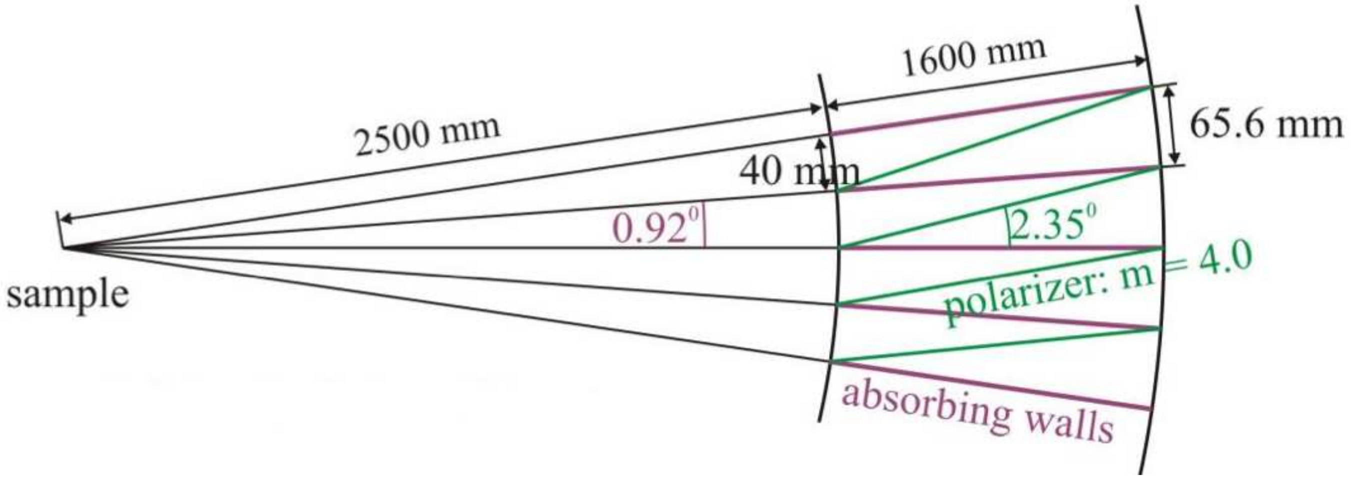
transmission $= 10\%$ to 45% for $\lambda \in [2, 5]$ Å

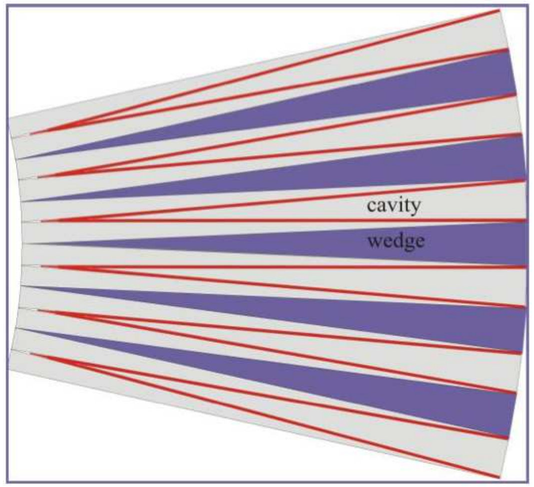
wide-angle analysers

study for MIEZE@ESS

$\lambda > 6$ Å

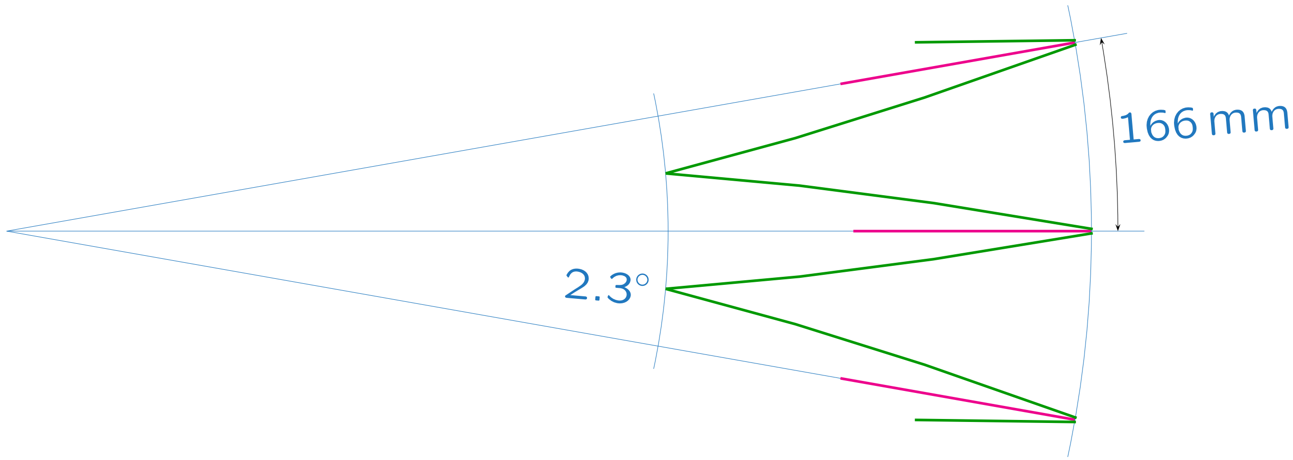
by P. Böni



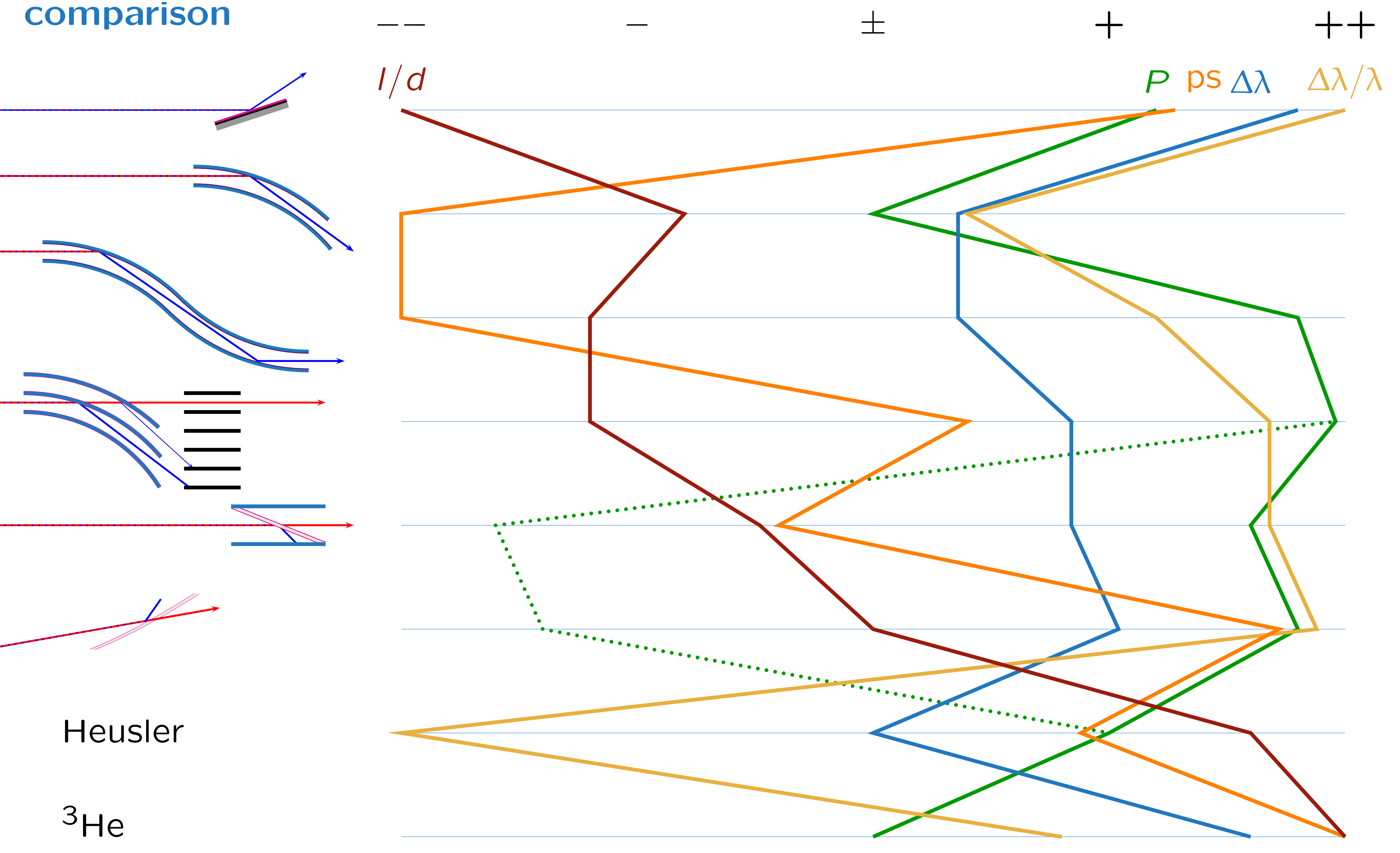


optimisation of shape using an equiangular spiral:

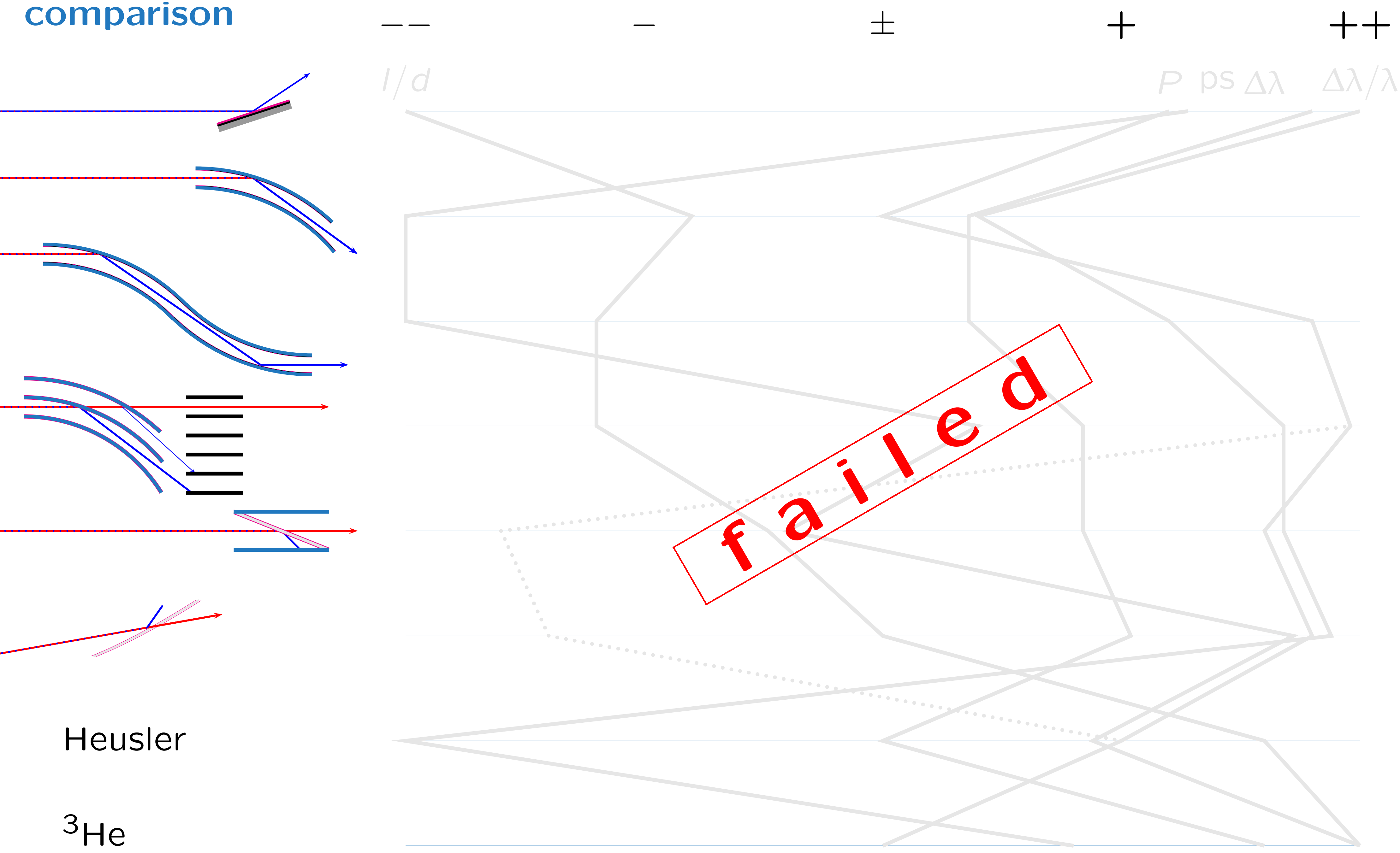
$\lambda \in [6, 48]$ Å



comparison



comparison

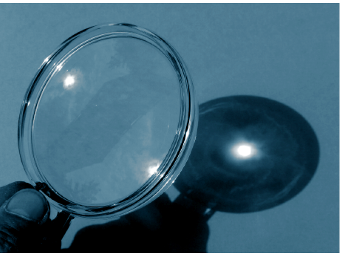


basics

- reflectometry
- supermirrors
- polarising coatings

polarisers

- overview
- reflective coatings
- comparison

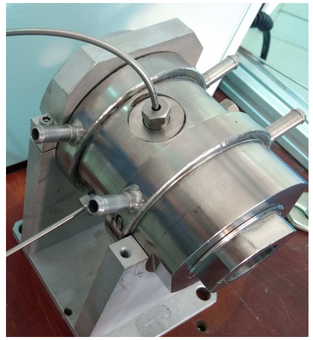


focusing optics

- refractive
- reflective

motivation

higher flux on small samples

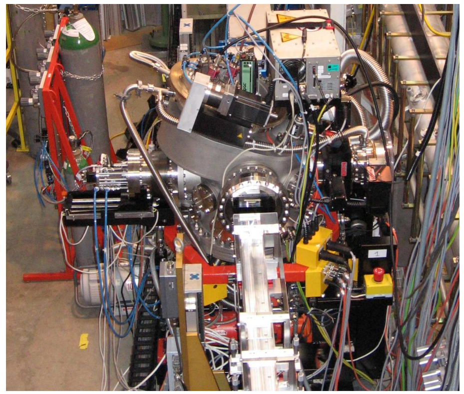


no illumination of sample environment

control over phase space / trajectories

selection of area on / within sample

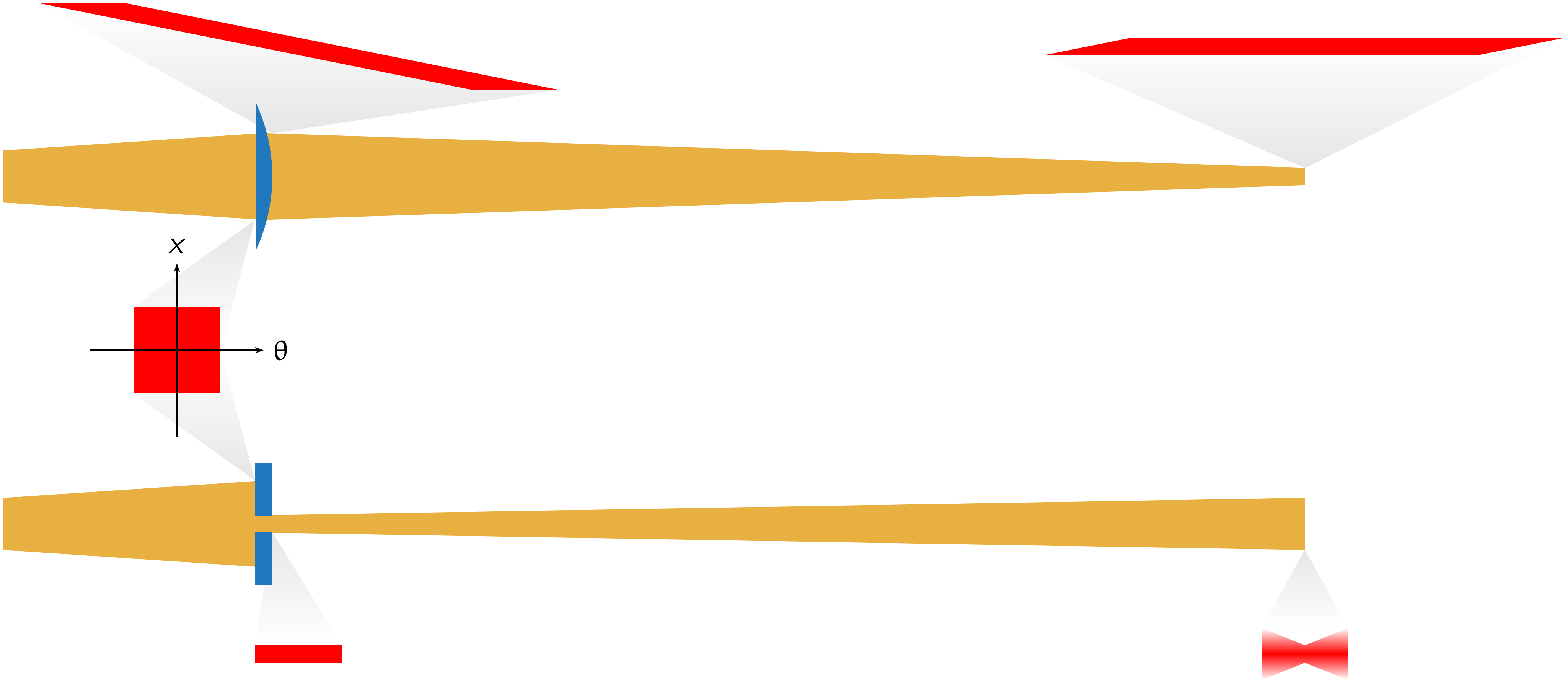
deal with small sources



remote footprint control

focusing optics

reshapes the phase space of a n-beam (an ensemble of neutrons)
to a **small spatial extent** at a given position



shading optics

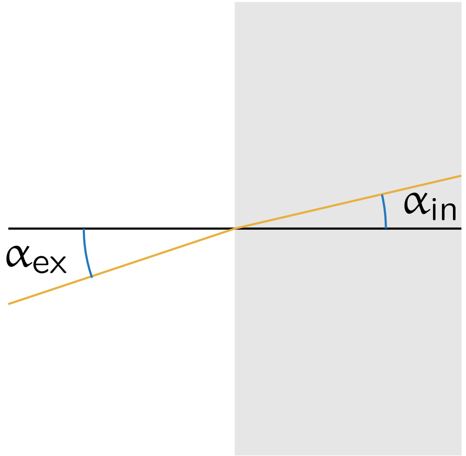
reshapes the phase space by restricting it in space (slit) focusing optics vs. shading optics

high costs (needs high precision)
lower transmission
convenient beam manipulation
real focusing
aberration

robust
flexible
high transmission
high background

refractive optics

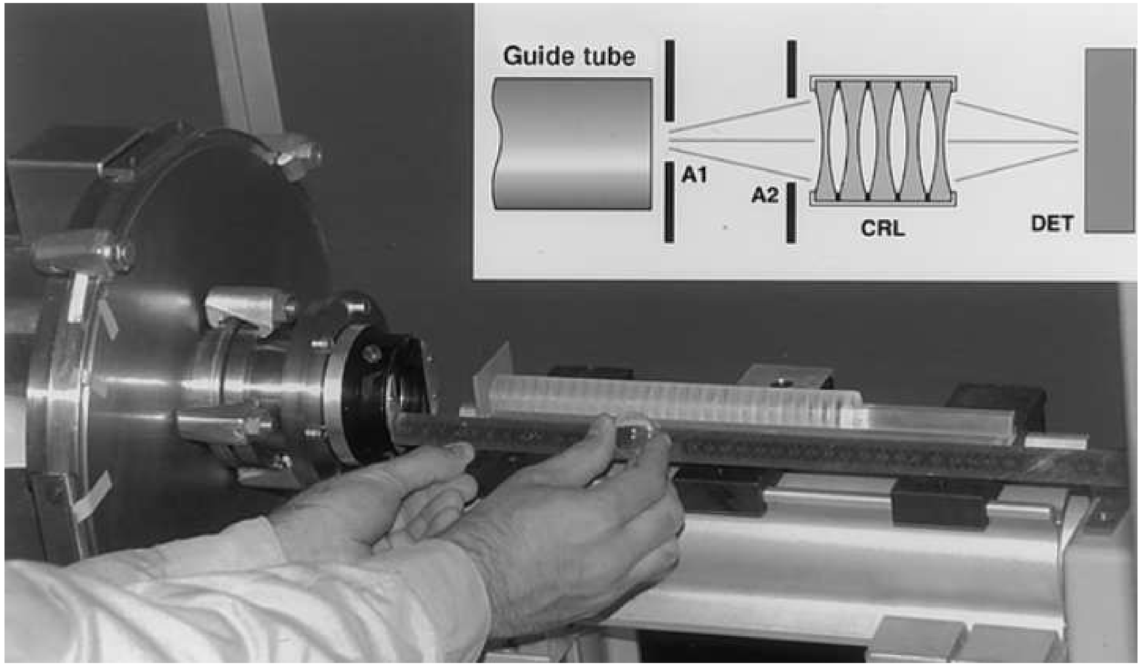
$n \approx 0.99999 \ldots 1$ for all bulk materials



Snell's law: $n = \dfrac{\sin \alpha_{ex}}{\sin \alpha_{in}}$

$\Rightarrow \alpha_{in} \approx n\, \alpha_{ex}$ close to normal incidence

- used for SANS

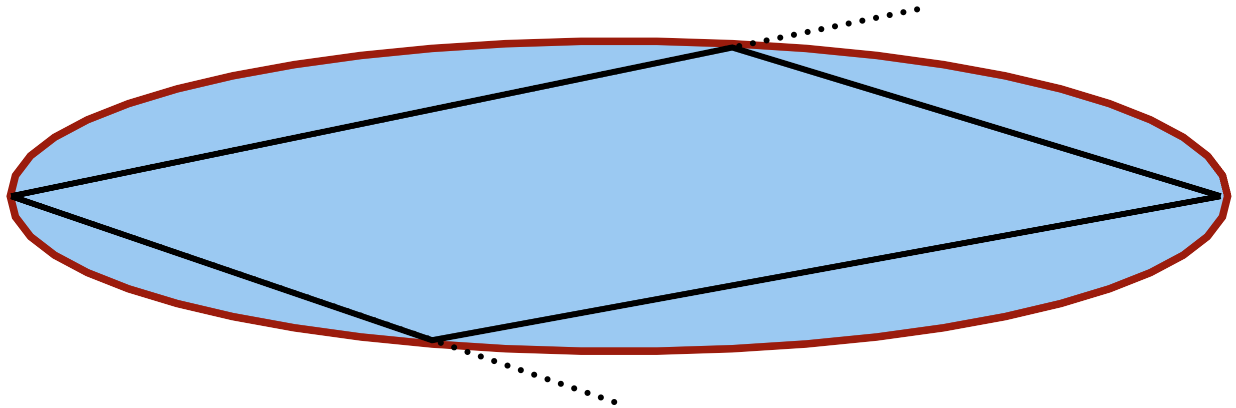


M. R. Eskildsen et al. nature 391, 563 (1998)

reflective optics

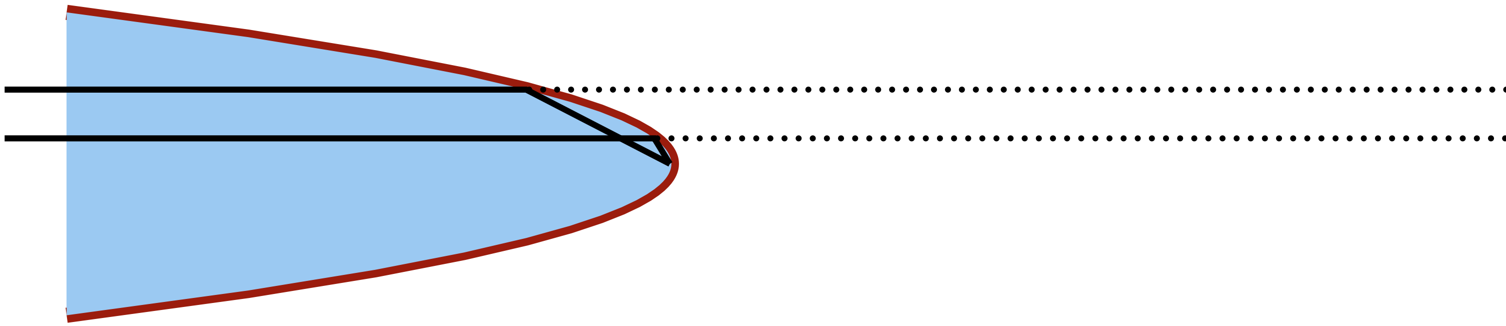
elliptic

divergent to convergent



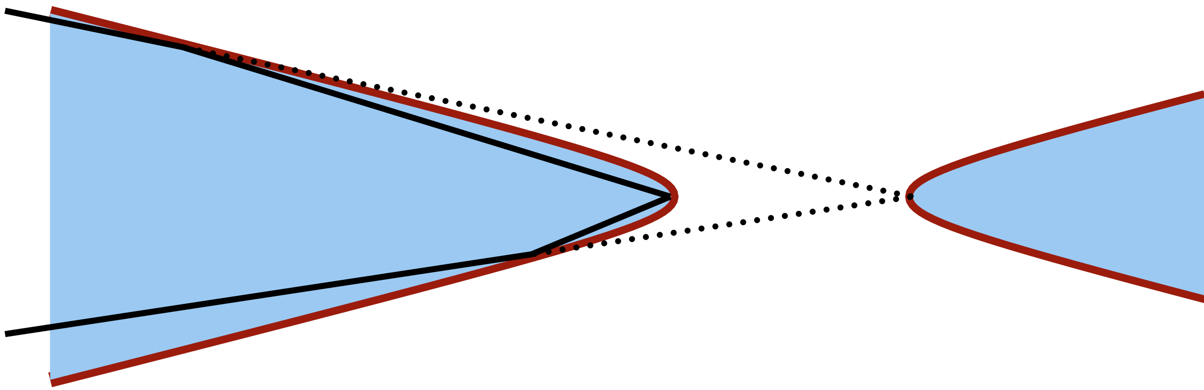
parabolic

parallel to convergent

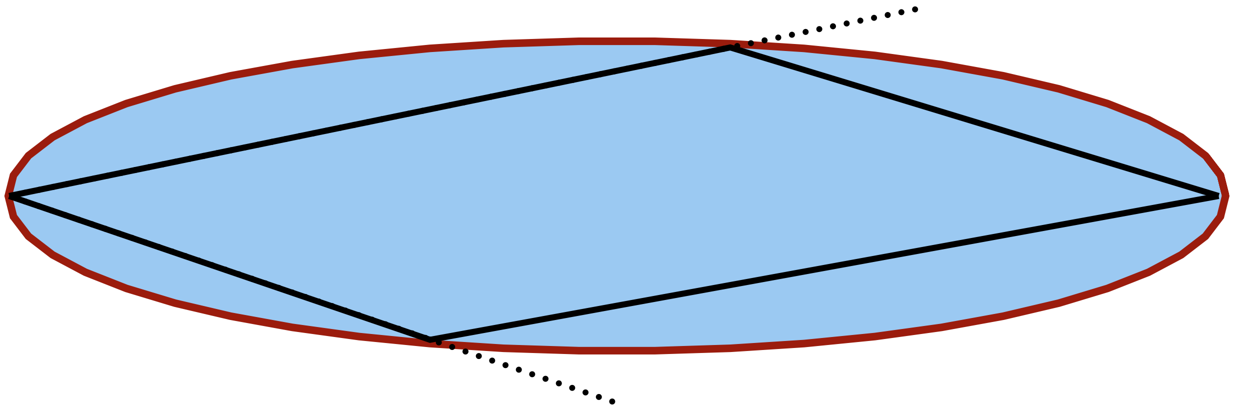


hyperbolic

convergent to convergent



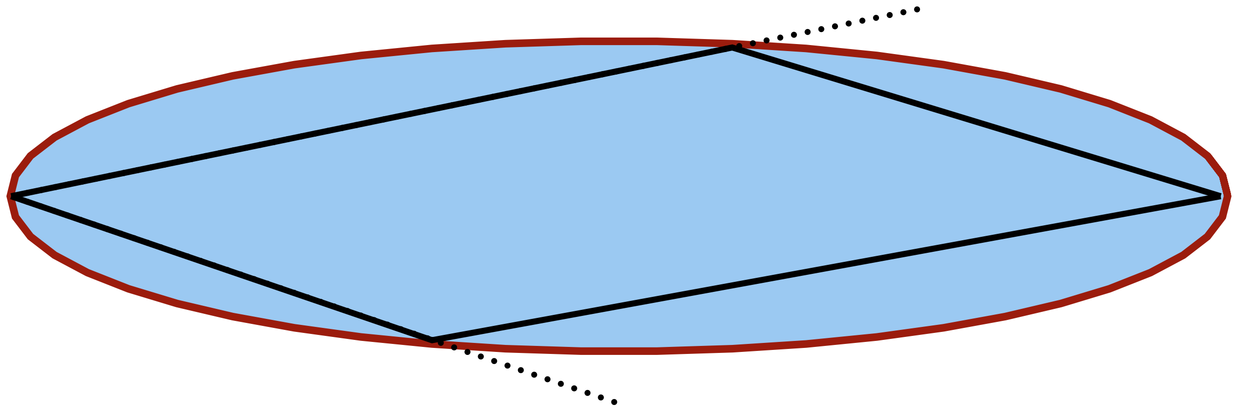
reflective focusing optics



elliptic

divergent to convergent

reflective focusing optics



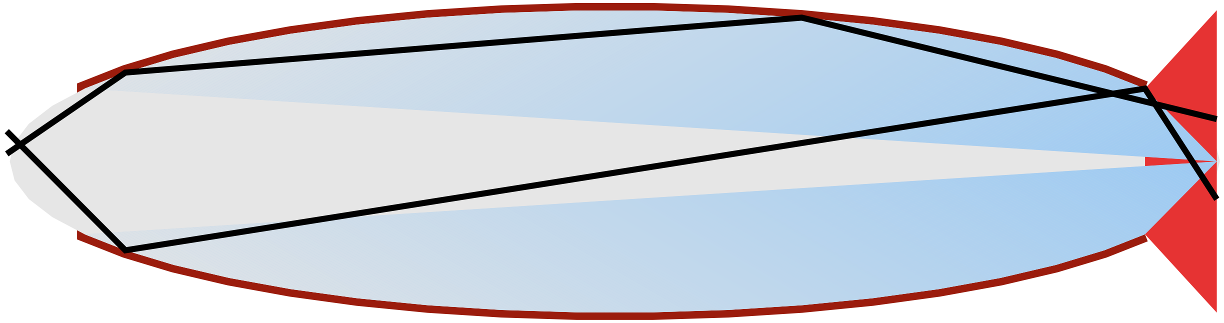
elliptic

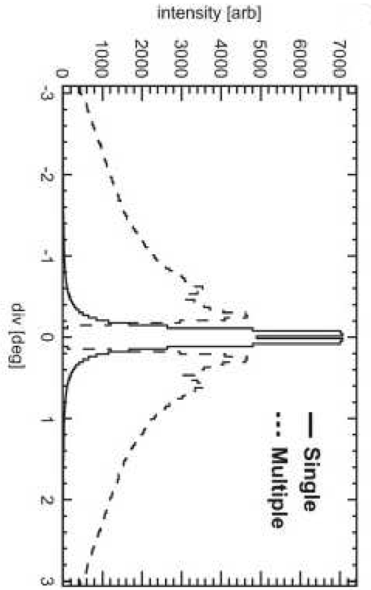
divergent to convergent ?

early reflections suffer the most from coma aberration

⇒ multiple reflections

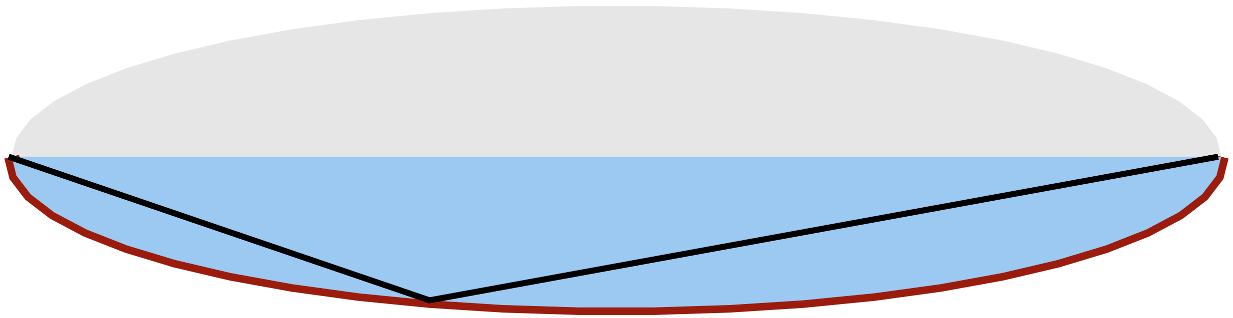
⇒ non-convergent beam behind guide exit



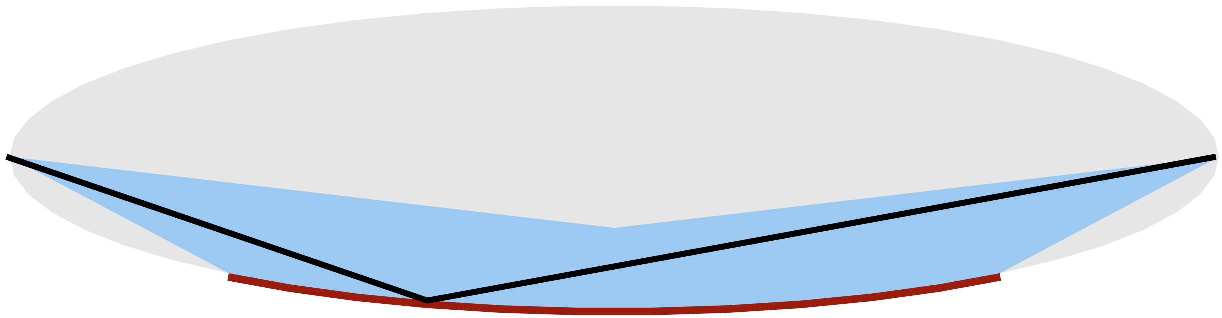


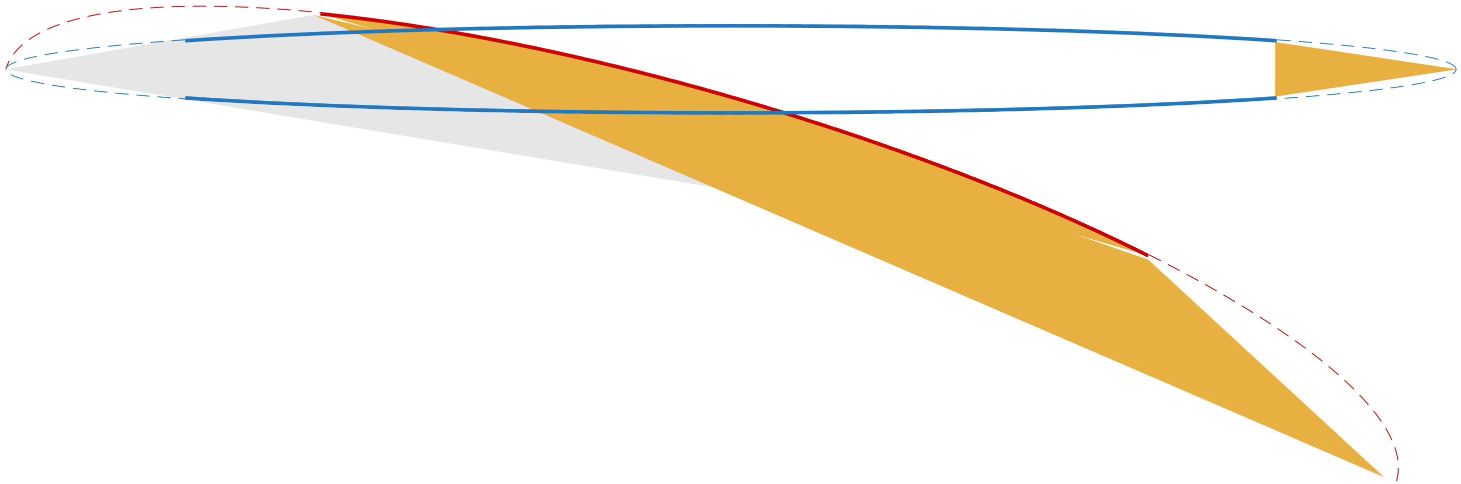
L. Cusssen *et al.*: NIM A **705**, 121 (2013)

reflective focusing optics

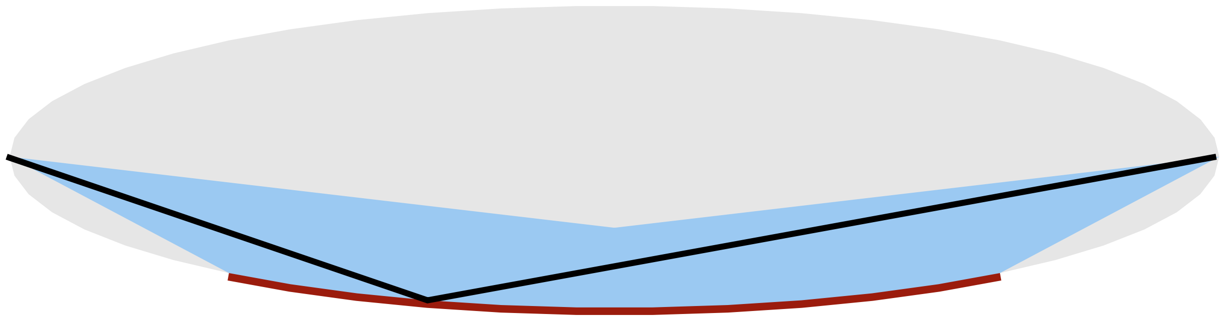


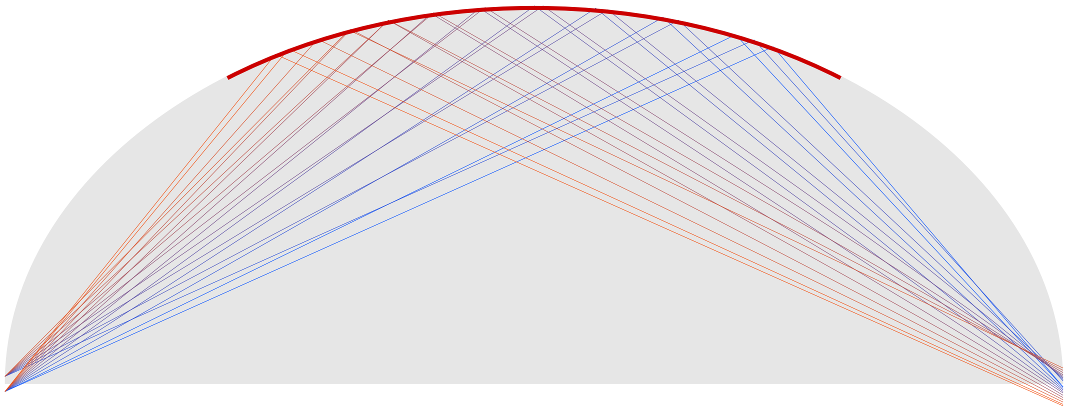
reflective focusing optics





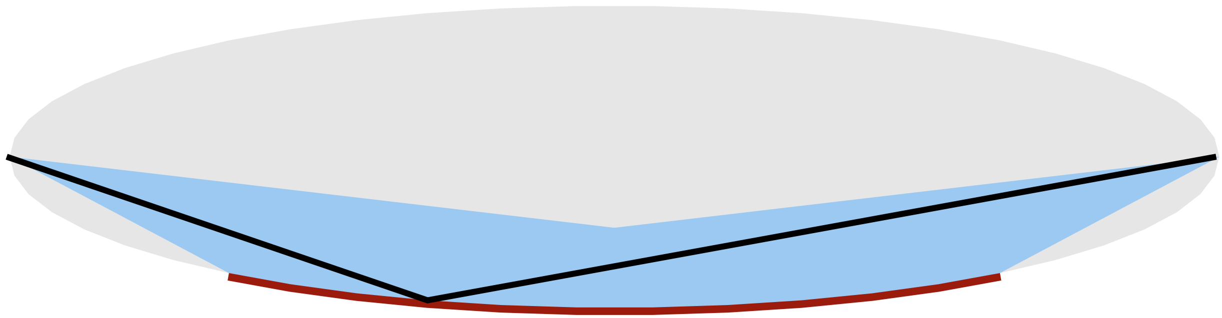
coma aberration

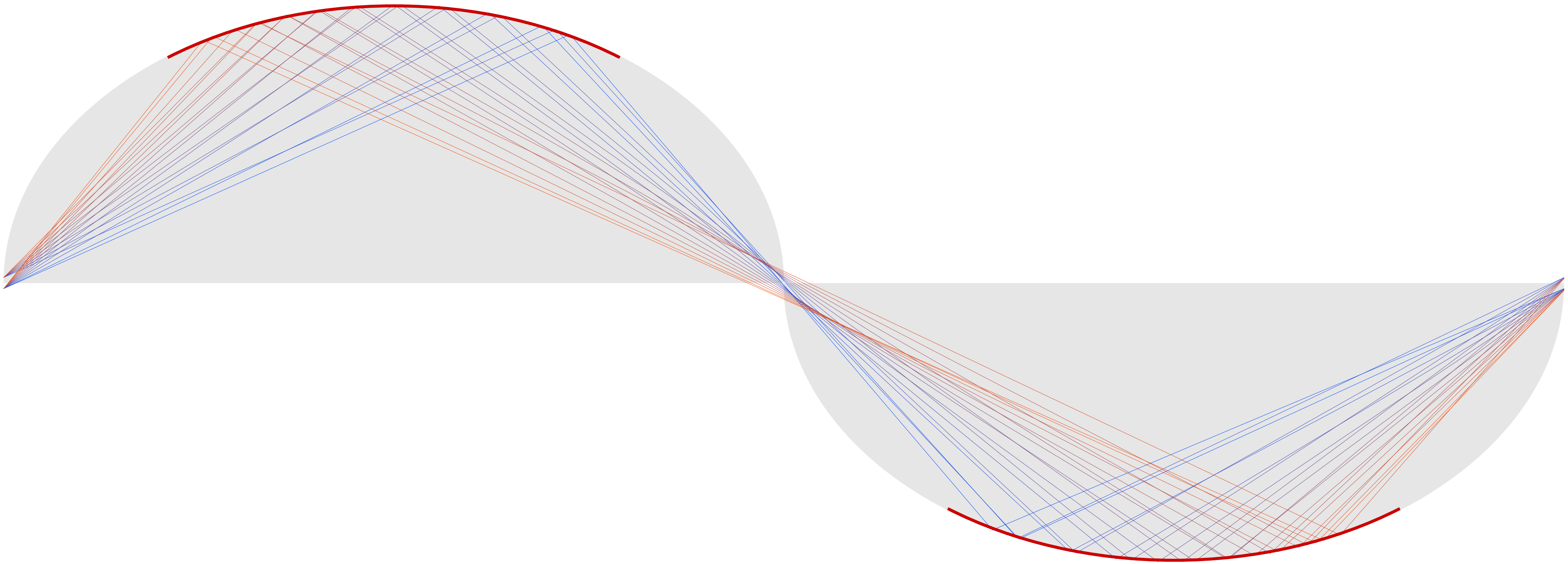




coma aberration

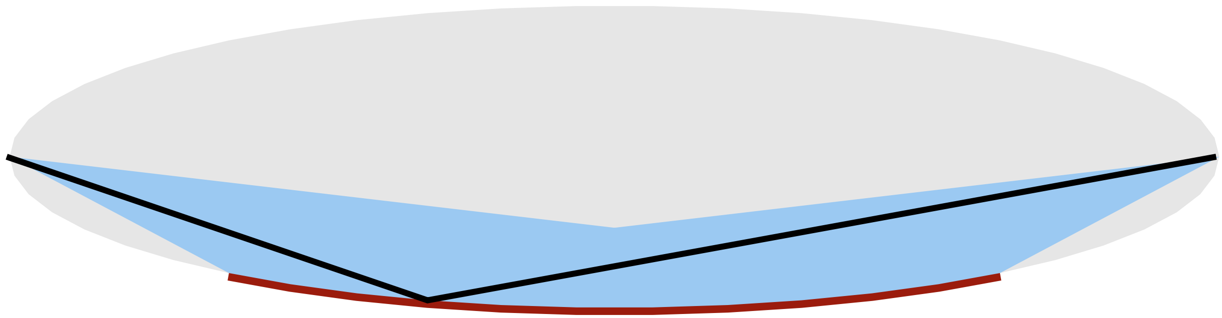
. . . and its correction

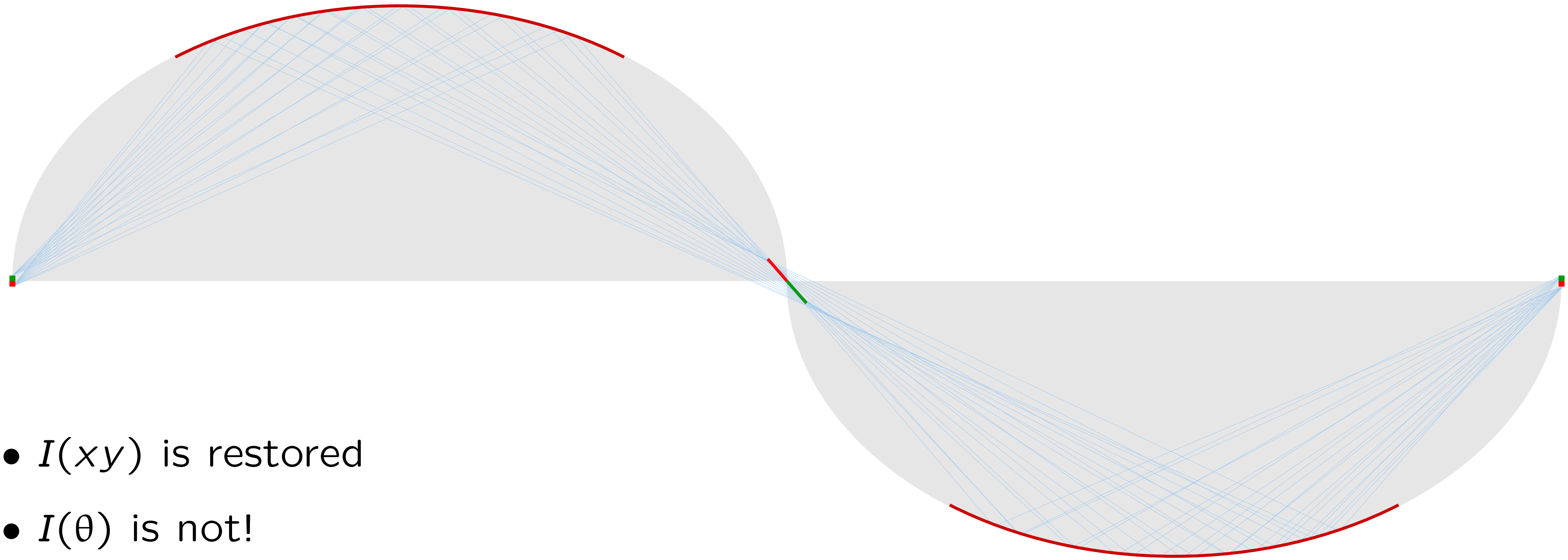




coma aberration

. . . and its correction





- $I(xy)$ is restored
- $I(\theta)$ is not!

Selene guide

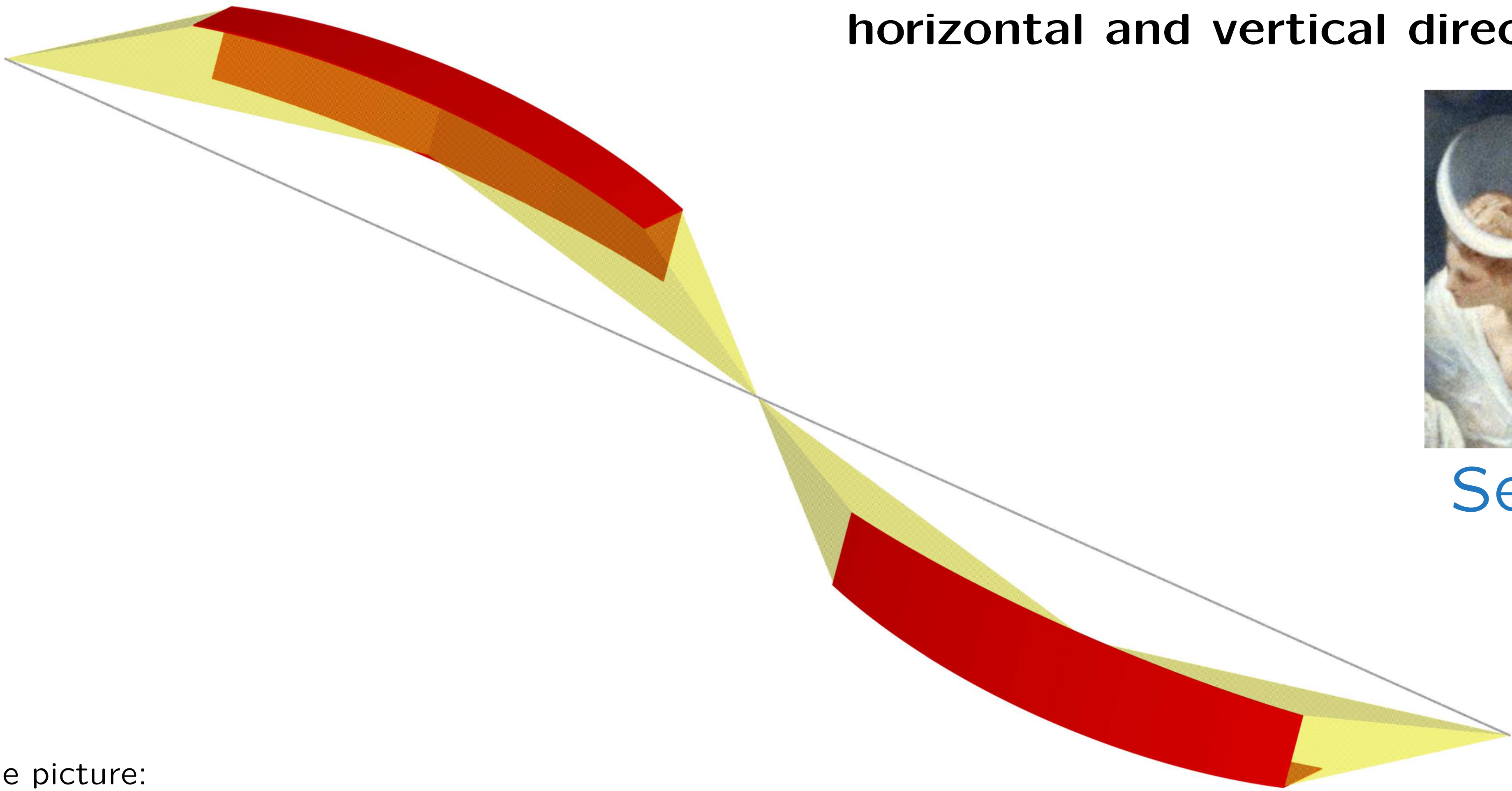
point-to-point focusing

with

2 subsequent elliptical reflectors

for

horizontal and vertical direction



Selene

Selene picture:
ceiling painting in the Ny Carlsberg Glyptotek, København

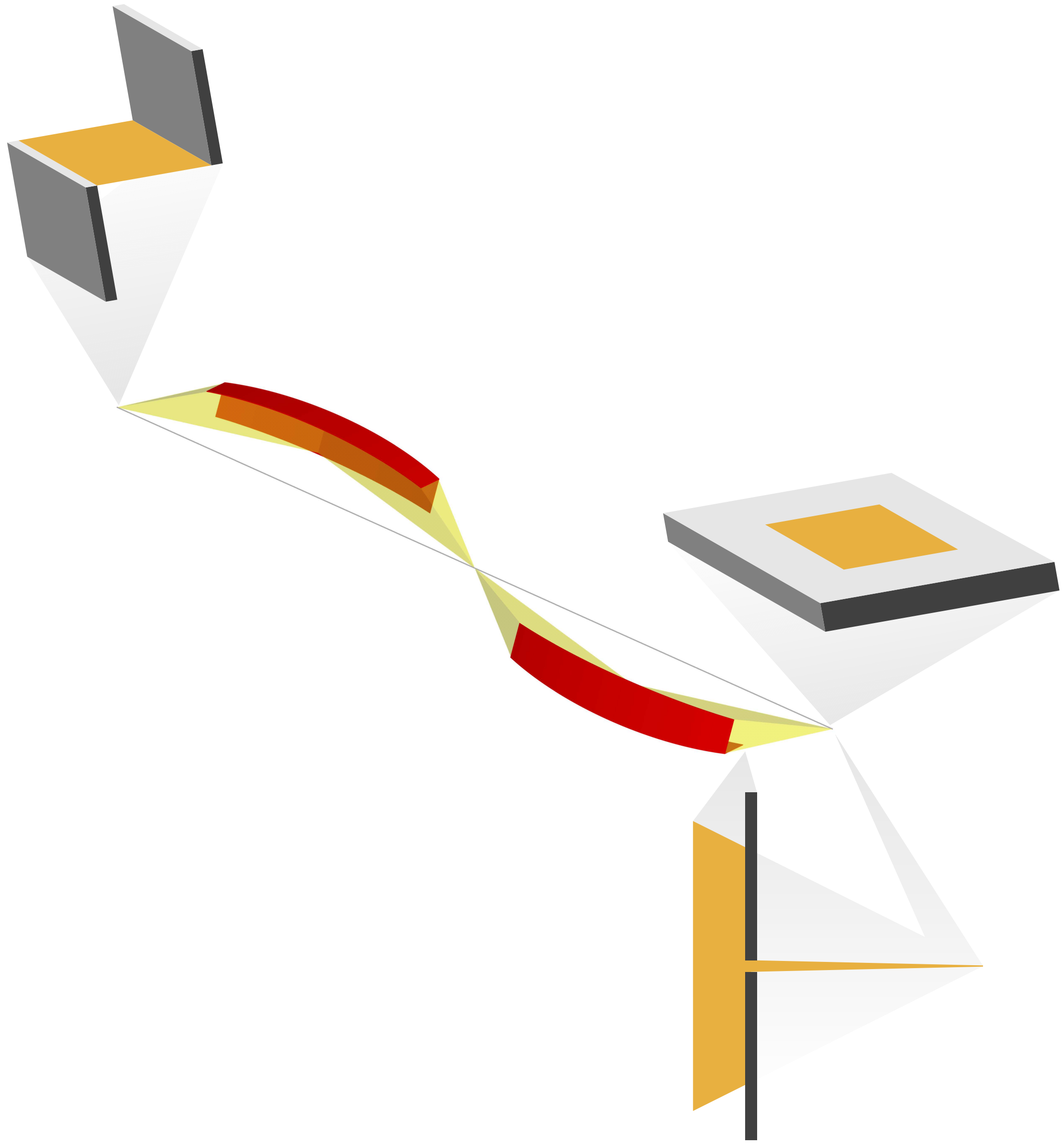
Selene guide

decoupling of

- spot-size

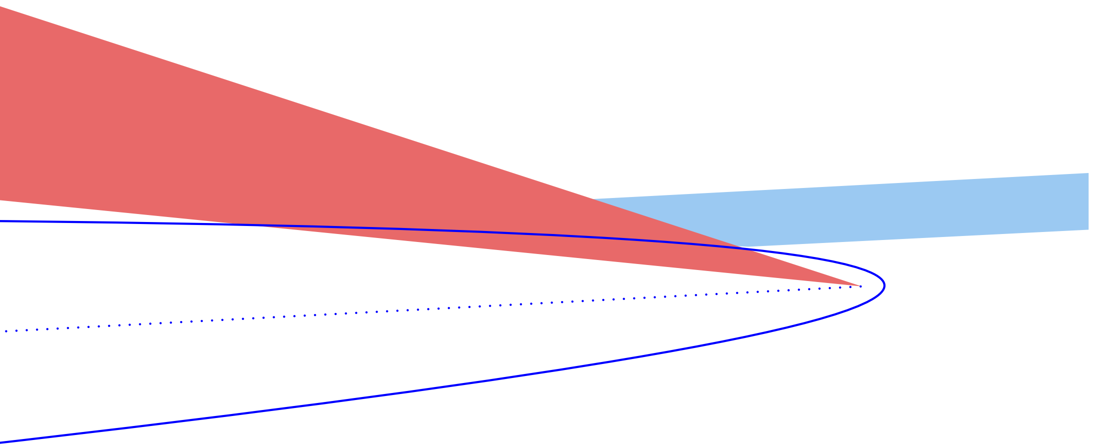
and

- divergence



focusing optics – reflective

condenser: parabolic deflector to generate a parallel beam



parabola axis ⇒ beam direction

focal length ⇒ beam width

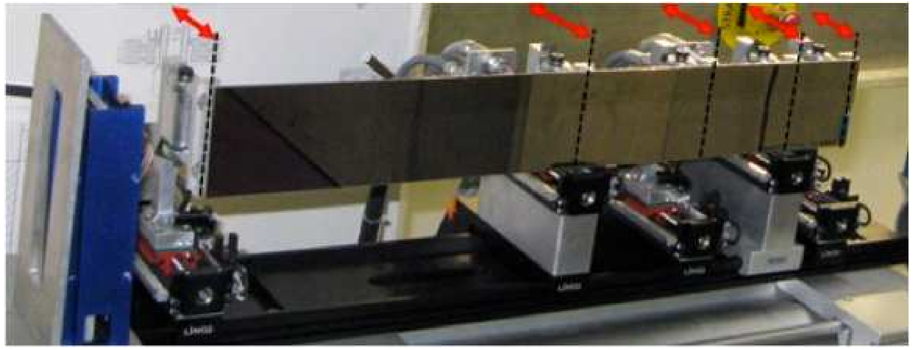
beam width & spot size ⇒ divergence

no collimator needed

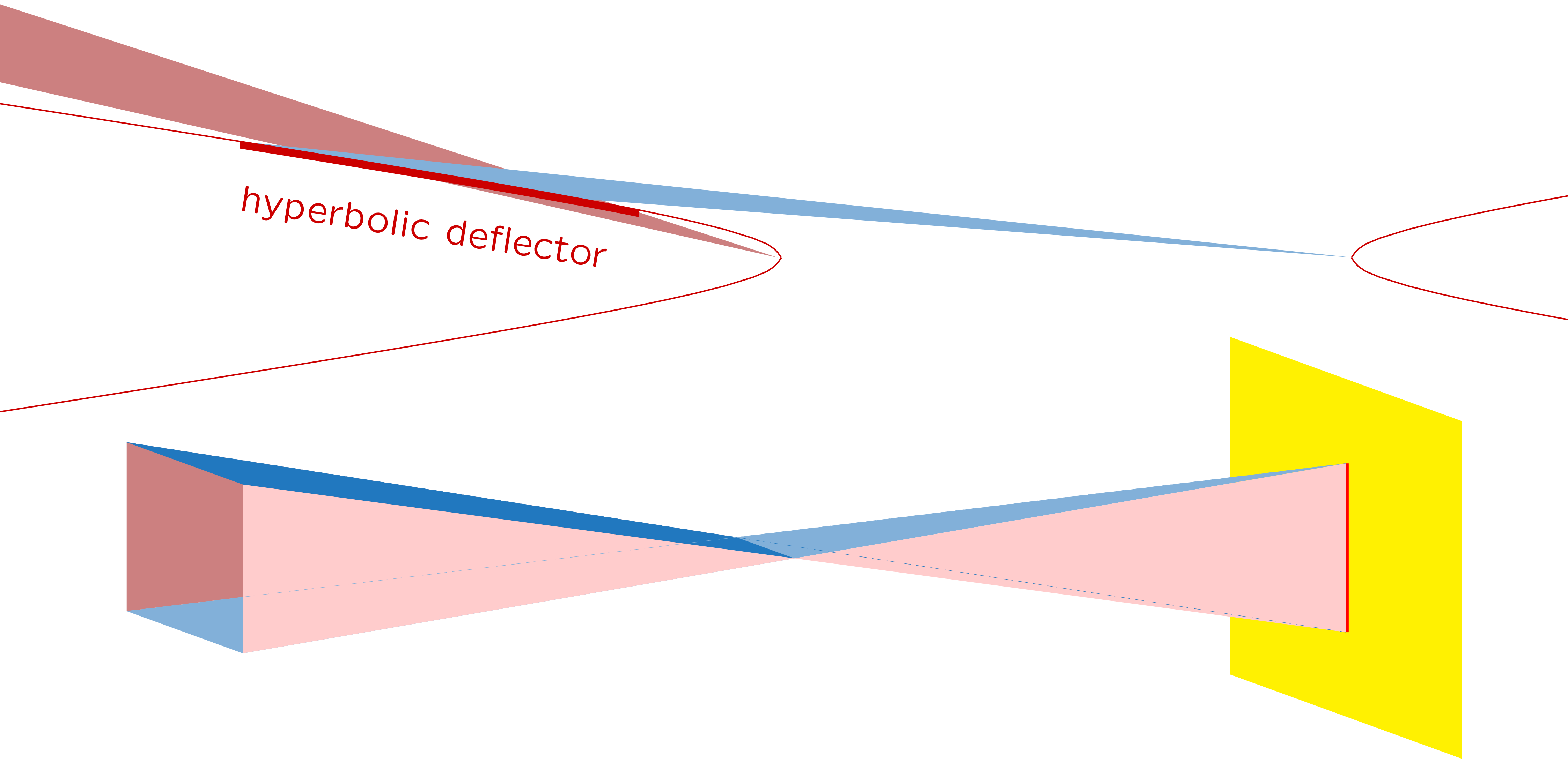
tunable

adaptive parabola (convex)
focal spot with 170 μm reached

(PSI, early version)

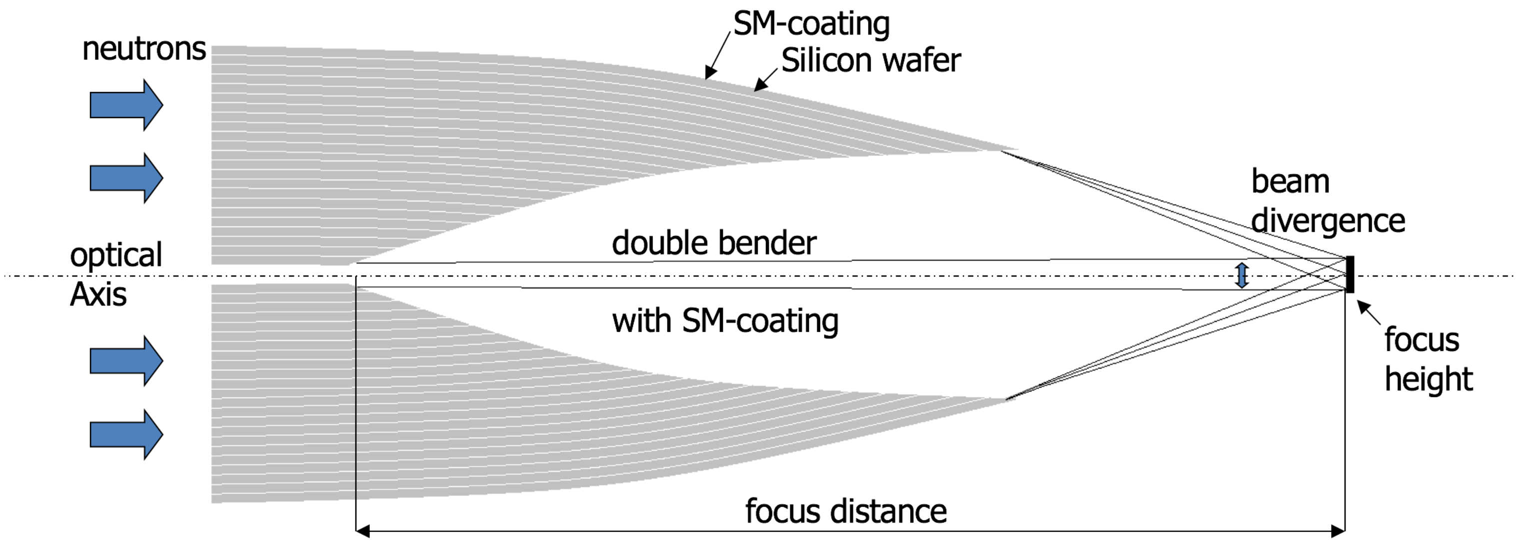


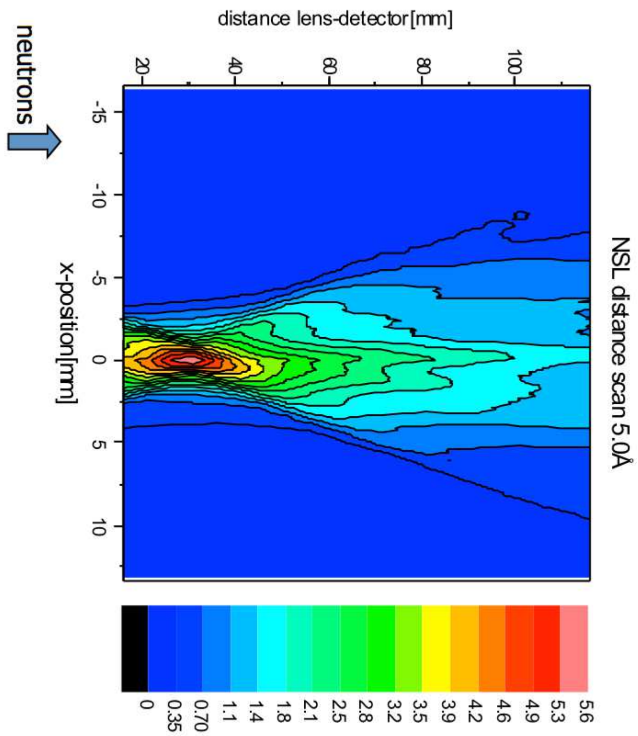
astigmatic focusing: focusing to the detector by shifting the focal point



focusing optics – reflective

solid-state neutron lense





T. Krist et al.: N.I.M. A **634**, S104 (2011)

focusing optics - discussion

focusing results in . . .

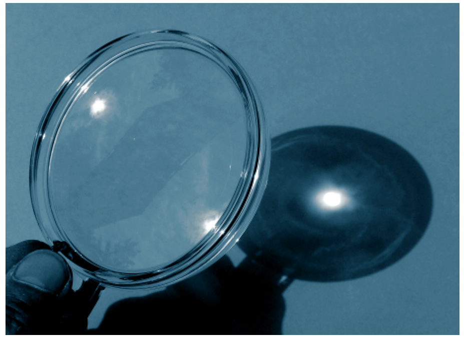
. . . no gain in brilliance

. . . a defined footprint

. . . a clean beam

homogeneous

uni-modal angular or spatial distribution



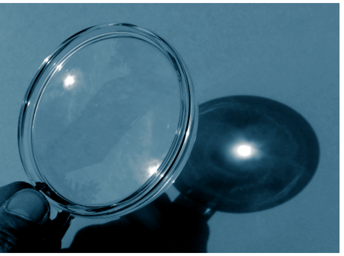
non-perfect optics

$\Rightarrow$ reduction of resolution / transmission

works best for small samples

weak aberration

thanks to



Thomas Krist	HZB
Peter Böni	TUM
Uwe Filges	PSI
Artur Glavic	PSI

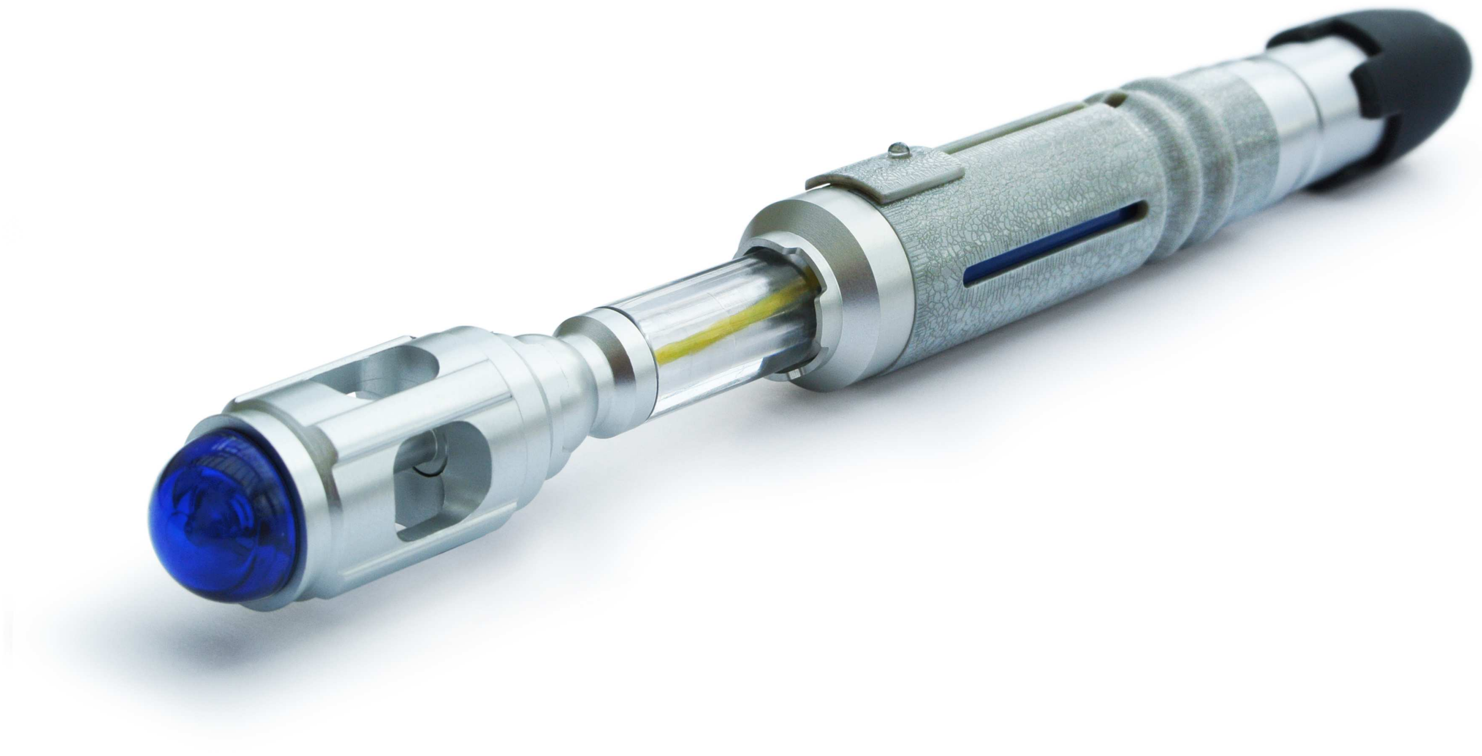
for discussions and for

contributing to these slides

PNCMI 2016 proceedings: Journal of Physics – Conference Series **862** (2017)

sonic screwdriver used by the Doctor to

reverse the polarity of the neutron flow



There must be a similar device to polarise it!