AN INTRODUCTION TO NEUTRON GUIDE OPTICS

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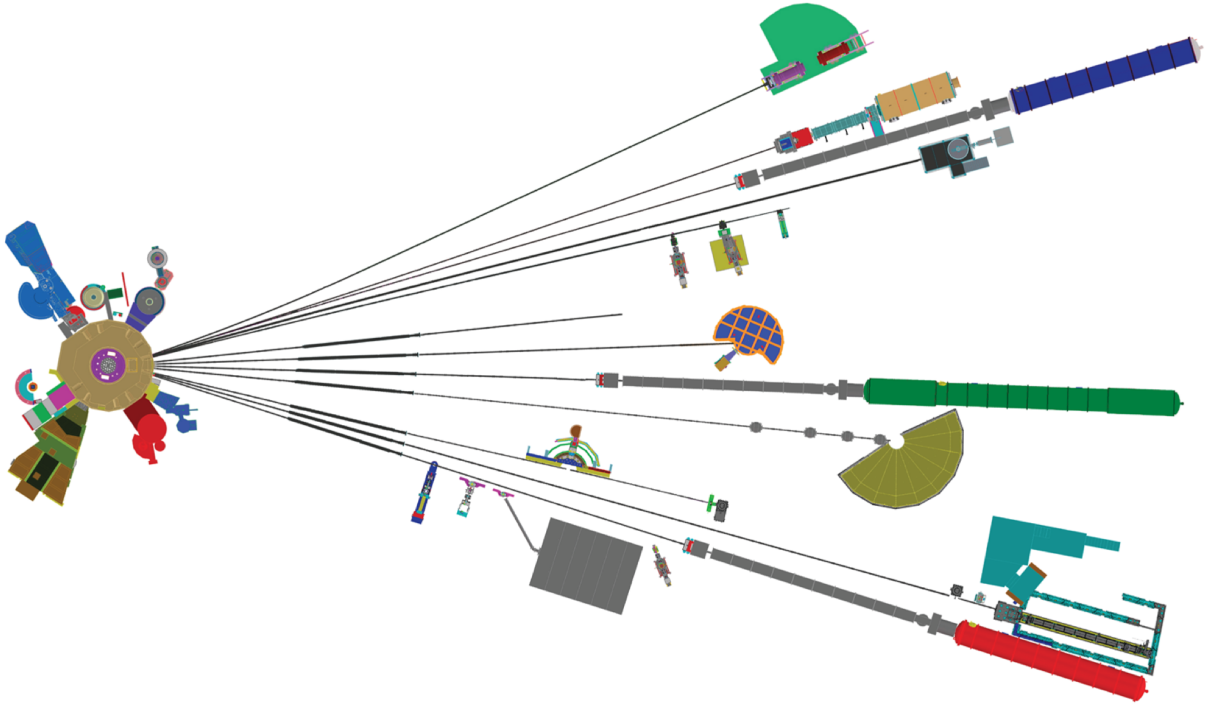

Jeremy Cook

Physicist, Research Facility Operations Group

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NEUTRON GUIDE OPTICS
OUTLINE

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- What are neutron guides and what do they do?
- Neutron optical properties
- Neutron reflective coatings
- Neutron guide substrates
- Neutron guide geometries and performance
- Transmission mirror devices
- Polarizing devices
- Windows, misalignments, cost estimates

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NEUTRON GUIDE OPTICS

WHAT DO NEUTRON GUIDES DO?

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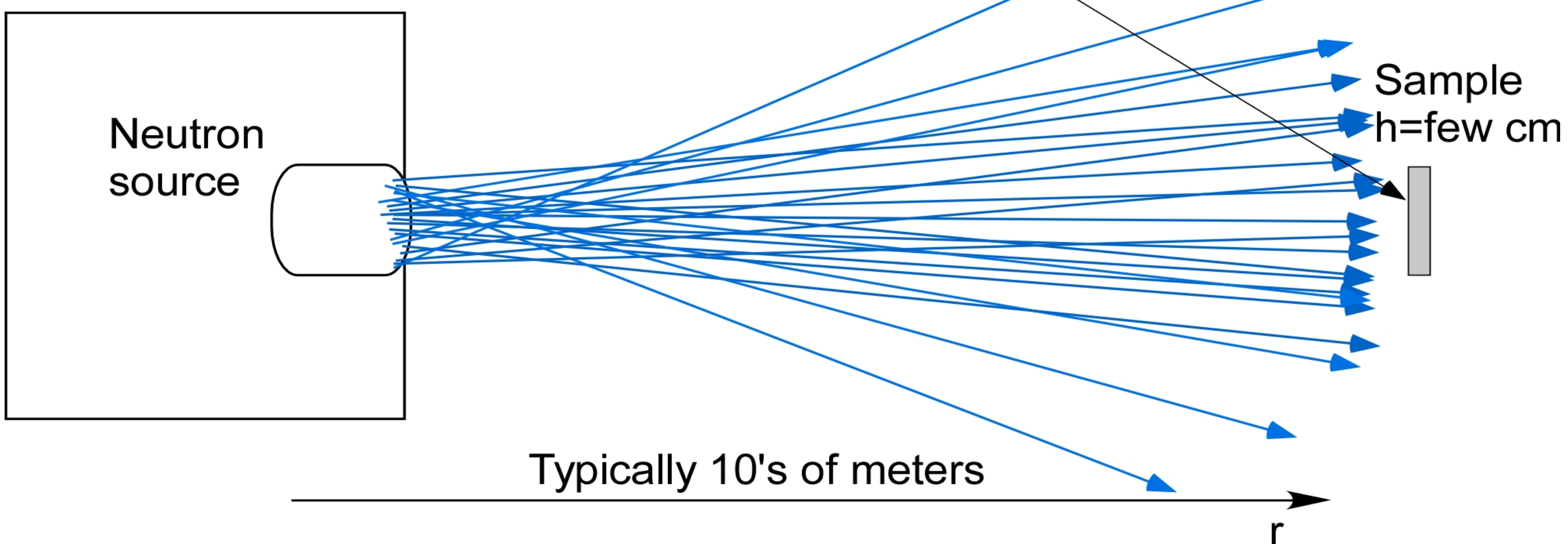
- Instruments physically large (often displaced radially 10's m from source), samples ~ few cm in size – neutron guides **concentrate** the neutron beam **enhancing neutron flux (ns/unit area) at sample**



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WHAT DO NEUTRON GUIDES DO?

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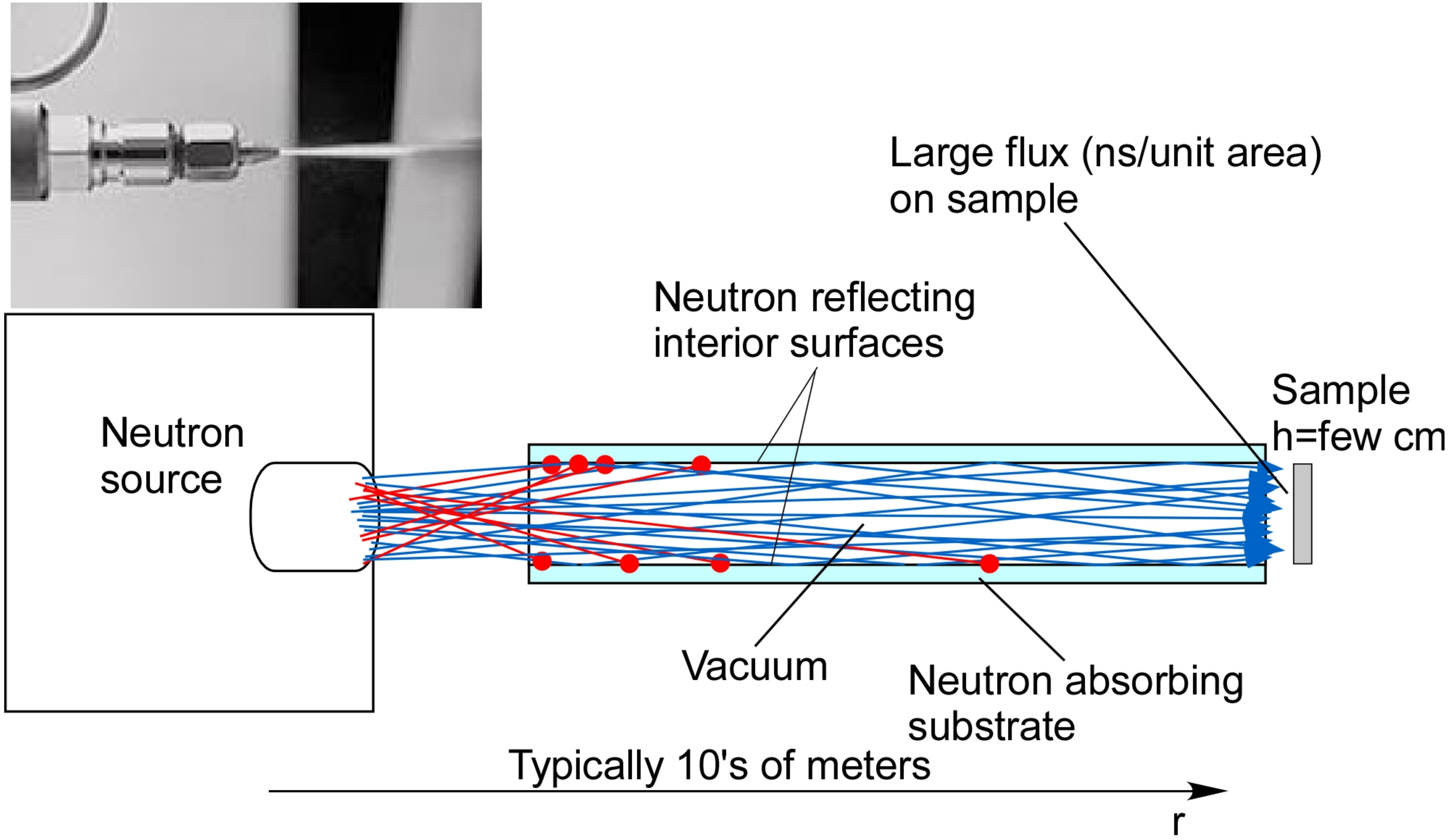

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HOW?

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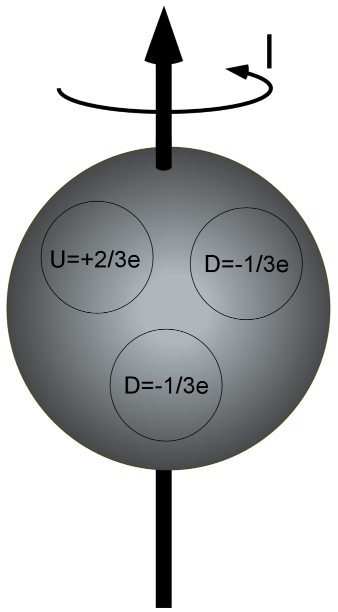
- Neutrons are uncharged – cannot redirect them easily like a charged particle beam
- BUT neutrons *DO* have **spin** a **magnetic moment**
  - Trajectory can be changed by *non-uniform* magnetic field (*refractive* optics).
  - Hexapole magnetic focusing devices exist ***but one neutron spin state is focused, the other is defocused***
- Neutron guides use *reflective* optics



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WAVE-LIKE PROPERTIES OF NEUTRONS

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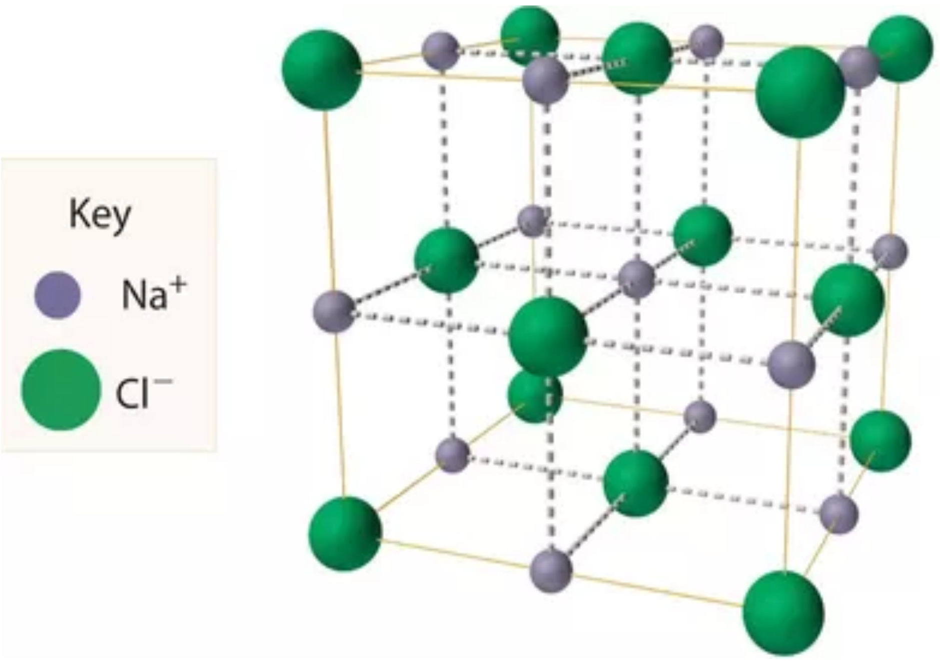
- Wavelengths of *thermal-cold* neutrons typically several Angstroms Å [1Å = 0.1 nm]
- Atomic spacings typically several Å (e.g. NaCl has nearest Na-Cl separation 2.8 Å)



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WAVE-LIKE PROPERTIES OF NEUTRONS

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- Wavelength λ of neutron

$$\lambda = \frac{h}{m_n v_n}$$

h=Planck's constant, m_n=mass of neutron, v_n=velocity of neutron

$$E_n = \frac{1}{2} m_n v_n^2$$

- Neutron energy

$$E_n\left[\text{meV}\right] = \frac{81.804207}{\left(\lambda\left[\mathring{\text{A}}\right]\right)^2} \qquad v_n\left[\text{ms}^{-1}\right] = \frac{3956.034}{\lambda\left[\mathring{\text{A}}\right]}$$

Neutron cross-sections usually quoted at v_n=2200 ms^{-1} (E_n=25.3 meV, λ=1.7982 Å)

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WAVE-LIKE PROPERTIES OF NEUTRONS

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λ [Å]	Energy	Velocity [ms^{-1}]
10^{-4}	8.18 MeV	3.956×10^{7}
10^{-3}	81.8 keV	3.956×10^{6}
10^{-2}	0.818 keV	3.956×10^{5}
0.1	8.180 eV	39560.34
0.5	327.22 meV	7912
1	81.804 meV	3956
1.7982	**25.299 meV**	**2200**
2	20.451 meV	1978
4	5.113 meV	**989.0**
5	3.272 meV	791.2
6	2.272 meV	659.3
9	**1.010 meV**	439.6

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THE OPTICS OF NEUTRONS

NEUTRON GUIDE OPTICS
REFRACTION AND TOTAL REFLECTION OF NEUTRONS

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- Neutron has *wave-like* properties: Can assign a ***refractive index***, n, for their passage through a medium (ignoring absorption usually ok)

$$n \approx 1 - \lambda^2 \frac{Nb}{2\pi}$$

$$Nb = \text{“}scattering\ \ length\ density\text{”}\ \text{of medium}$$

- n=1 for vacuum, also for air, He (to good approx.)

- *n very slightly less than 1* for dense media ($1 - n \approx 10^{-6}$)

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REFRACTION AND TOTAL REFLECTION OF NEUTRONS

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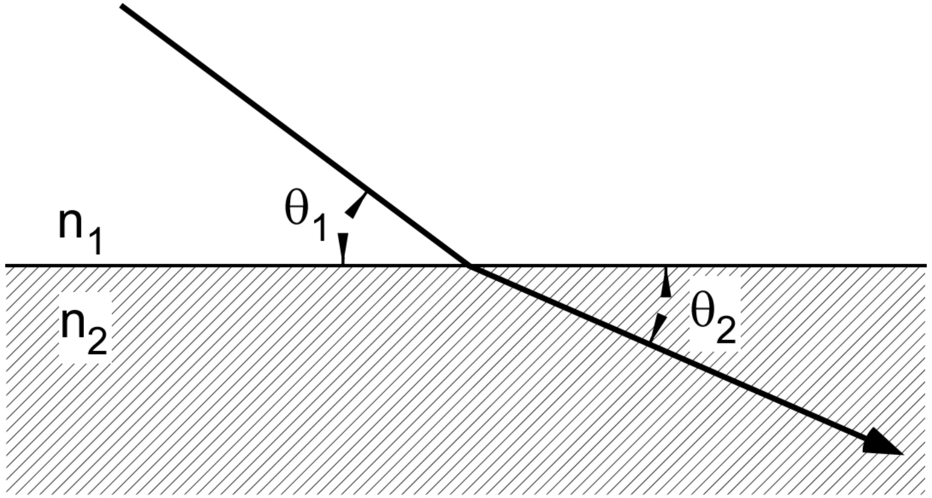
- Snell's law

$$\frac{n_1}{n_2} = \frac{\cos\theta_2}{\cos\theta_1}$$



$$n_i \approx 1 - \lambda^2 \frac{N_i b_i}{2\pi}$$

For *vacuum/air* $n_1 = n_{vac} = 1$

For dense medium $n_2 = n_{med} < 1$

$$\therefore \theta_{med} = \theta_2 < \theta_{vac}$$

$$\cos\theta_{vac} = n_{med}\cos\theta_{med}$$

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REFRACTION AND TOTAL REFLECTION OF NEUTRONS

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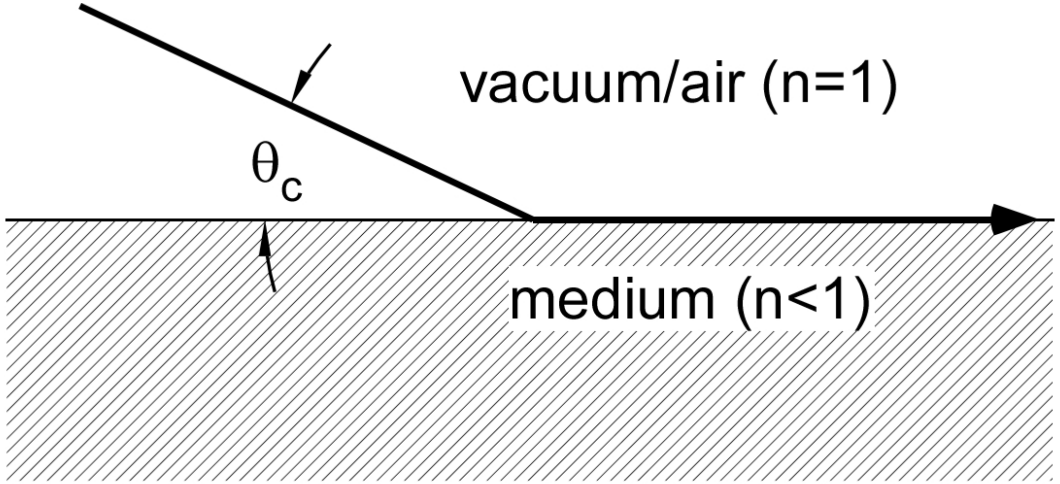
- Transition from refraction to ***total reflection*** occurs when:
  and $\theta_{med} = 0 \quad \left(\cos\theta_{med} = 1\right) \quad \theta_{vac} = \theta_c$



$\therefore \quad \cos\theta_c = n_{med}$

θ_c is the "***critical angle***"

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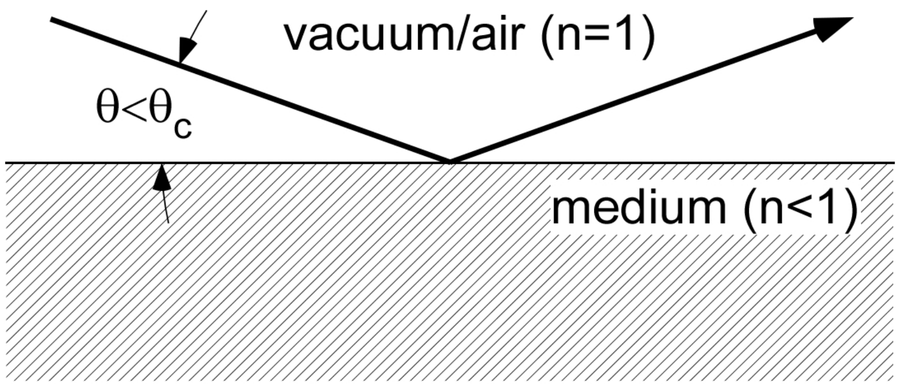
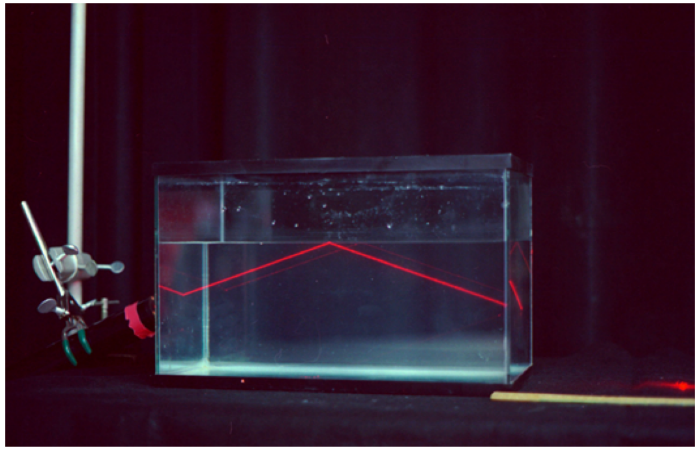
TOTAL REFLECTION AND CRITICAL ANGLE



$\theta < \theta_c$



- **Total (external) reflection** occurs on going from *less dense* (vacuum) to *more dense* (mirror) interface

- Drop "*med*" subscript for ***neutron guides:***
  - Dealing with n=1 for vacuum/He/air
  - n (and N,b) henceforth refer to the *dense medium* (reflective coating)

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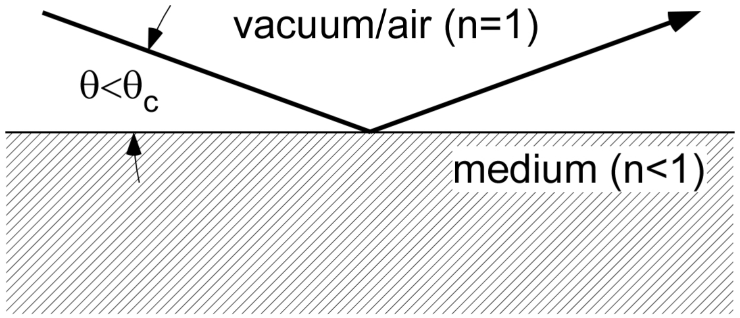
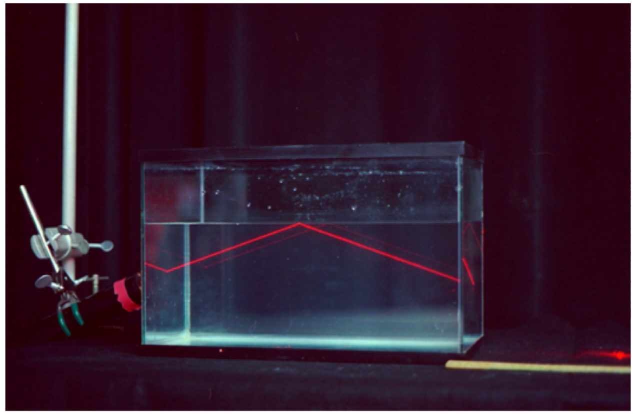
TOTAL REFLECTION AND CRITICAL ANGLE



$$\theta < \theta_c$$



- 1- n very small (≈ 10^{-6}) ⇒ ***small angle approximation*** applies:

$$\cos\theta_c \approx 1 - \frac{\theta_c^2}{2} \quad = n = 1 - \lambda^2 \frac{Nb}{2\pi} \qquad \Rightarrow \frac{\theta_c}{\lambda} \approx \sqrt{\frac{Nb}{\pi}}$$

$$\theta_c(\lambda) \propto \lambda$$

- In 2-dimensions: Solid angle ~ $\theta_{c,x}(\lambda)\theta_{c,y}(\lambda)$

  ∴ (idealized) **solid angle of acceptance of guide ~ λ^2**

  (**<u>guide naturally filters out fast neutrons</u>**)

NEUTRON GUIDE OPTICS
REFLECTIVITY

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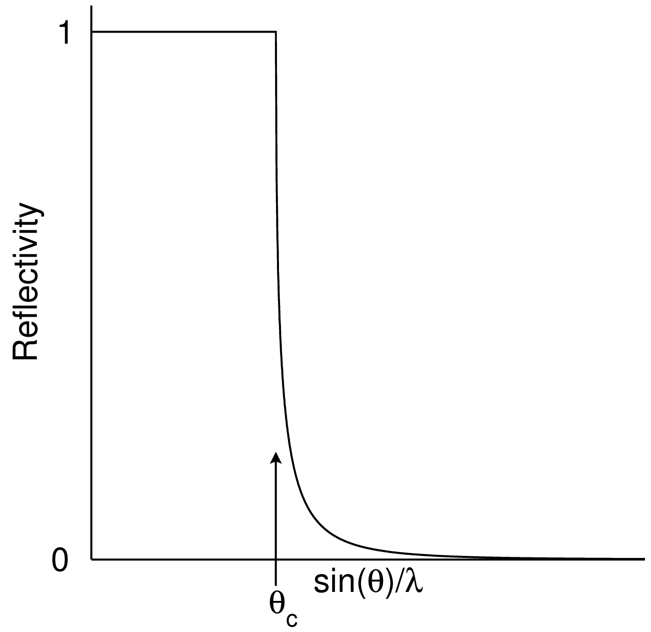
- **Fresnel's law reflectivity**

$$R(\theta < \theta_c) = 1$$

$$R(\theta \geq \theta_c) = \left| \frac{\sin\theta_1 - \left(n^2 - \cos^2\theta_1\right)^{\frac{1}{2}}}{\sin\theta_1 + \left(n^2 - \cos^2\theta_1\right)^{\frac{1}{2}}} \right|^2 \equiv \left| \frac{\sin\theta_1 - \left(\cos^2\theta_c - \cos^2\theta_1\right)^{\frac{1}{2}}}{\sin\theta_1 + \left(\cos^2\theta_c - \cos^2\theta_1\right)^{\frac{1}{2}}} \right|^2$$



- Often plot reflectivity against ***wavevector transfer Q***

$$Q = \frac{4\pi}{\lambda}\sin\theta \quad \approx 4\pi\frac{\theta}{\lambda}$$

- Note ***critical Q*** is

$$Q_c \approx 4\pi\frac{\theta_c}{\lambda} \quad = 4\sqrt{\pi N b}$$

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REFLECTIVITY LIMITS AND CRITICAL ANGLE

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- **Largest critical angle** for **largest scattering length density** ***Nb***

Material	N or ⟨N⟩ ($\times 10^{22}$ cm^{-3})	b or ⟨b⟩ (fm)	Nb or $S_i N_i b_i$ ($\times 10^{-6}$ Å^2)	"m" ≡ q_c/q_c(nat Ni)
Be	12.34	7.79	9.61	1.01
Fe	8.48	9.45	8.01	0.92
Ni (reference)	**9.13**	**10.3(1)**	**9.41**	**1.00**
^{58}Ni	9.11	14.4(1)	13.1	1.18
Cu	8.49	7.72	6.55	0.83
Borkron® NZK7 glass	7.36	5.26	3.87	0.64

$$\frac{\theta_c}{\lambda} \approx \sqrt{\frac{Nb}{\pi}}$$

- Largest θ_c in *naturally-occurring* elements (except Be which is not practical) is for **Ni** (^{58}Ni isotope is larger)
- θ_c(nat Ni)/λ = 1.73 mrads Å^{-1} (≈0.1° Å^{-1})
- θ_c(^{58}Ni)/λ = 2.04 mrads Å^{-1} (≈0.12° Å^{-1})
- **θ_c for guides usually referenced to nat. Ni via factor "*m*"**

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NEUTRON GUIDE OPTICS

DEFINITIONS: "FULLY-ILLUMINATED"

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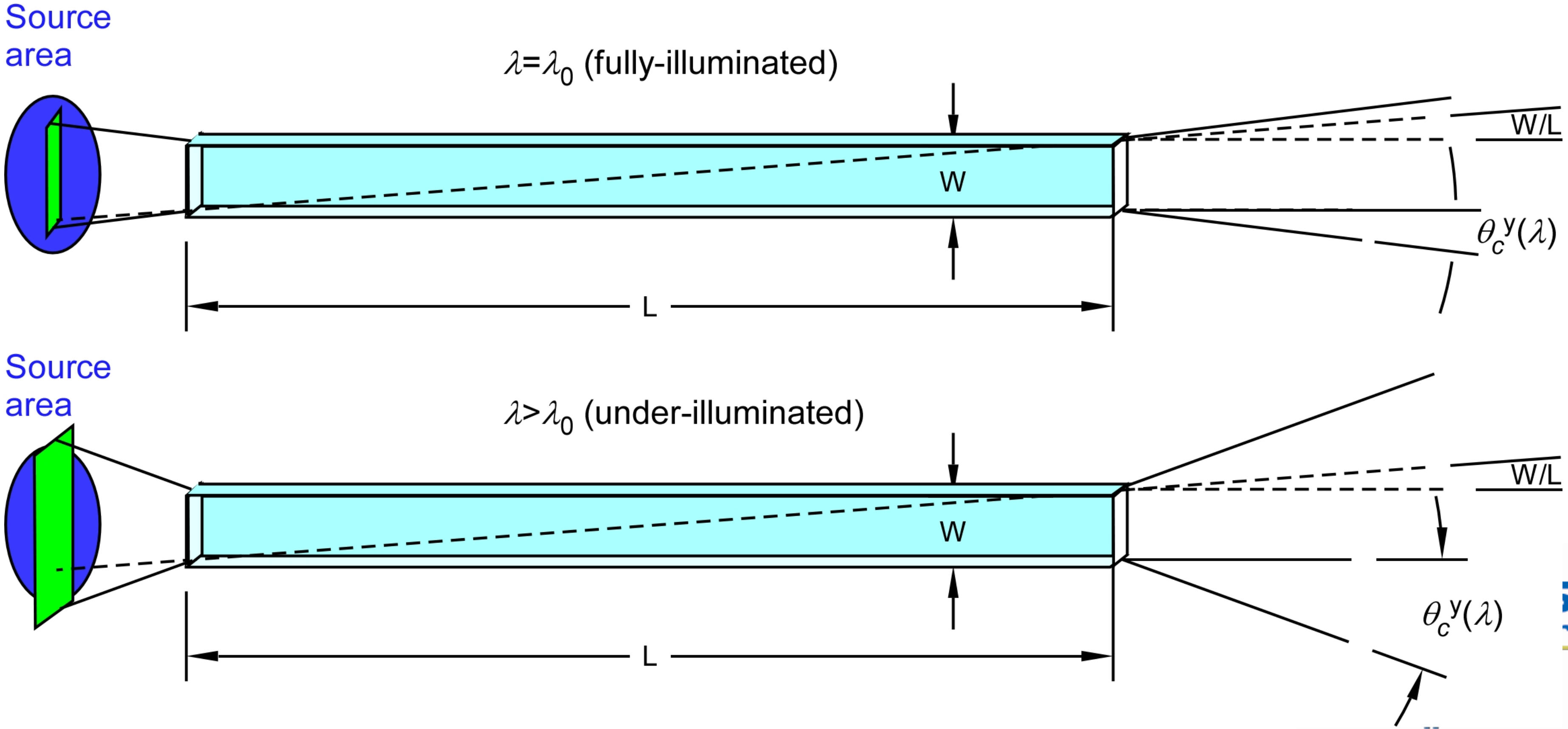
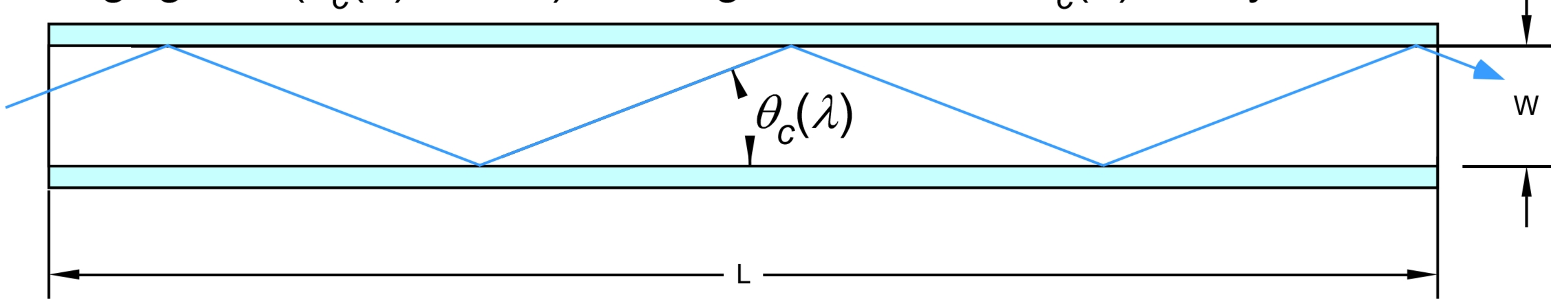
- "Fully-illuminated" ⇒ What can be accepted by the guide is not limited by the boundaries of the source: Think "**infinite source**"
- Usually wish to fully-illuminate to **reasonably long wavelength** or for **max acceptable beam divergence**



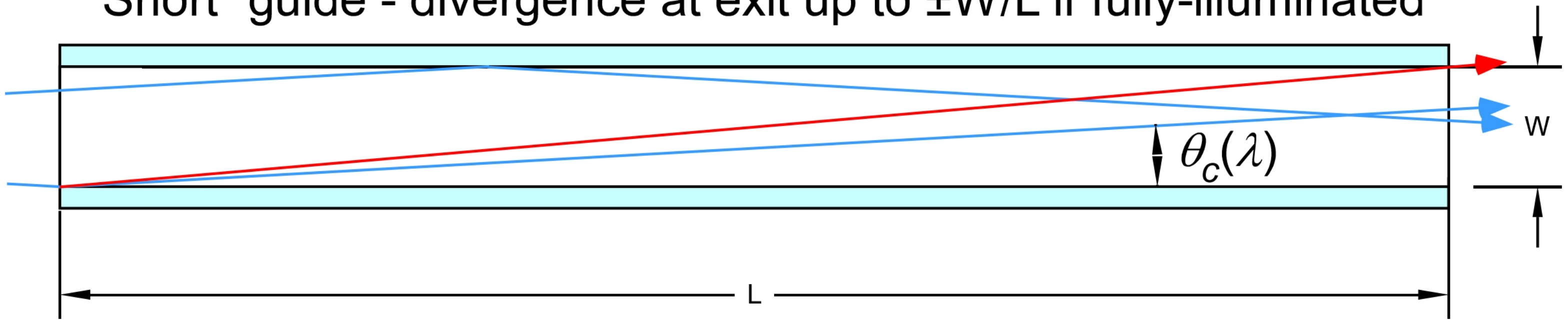
NEUTRON GUIDE OPTICS

DEFINITIONS: "LONG" STRAIGHT GUIDES

"Long" guide ($\theta_c(\lambda) > W/L$) - divergence at exit $\pm\theta_c(\lambda)$ if fully-illuminated



"Short" guide - divergence at exit up to ±W/L if fully-illuminated



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NEUTRON GUIDE OPTICS

SIMPLE EXAMPLE “LONG” STRAIGHT GUIDE

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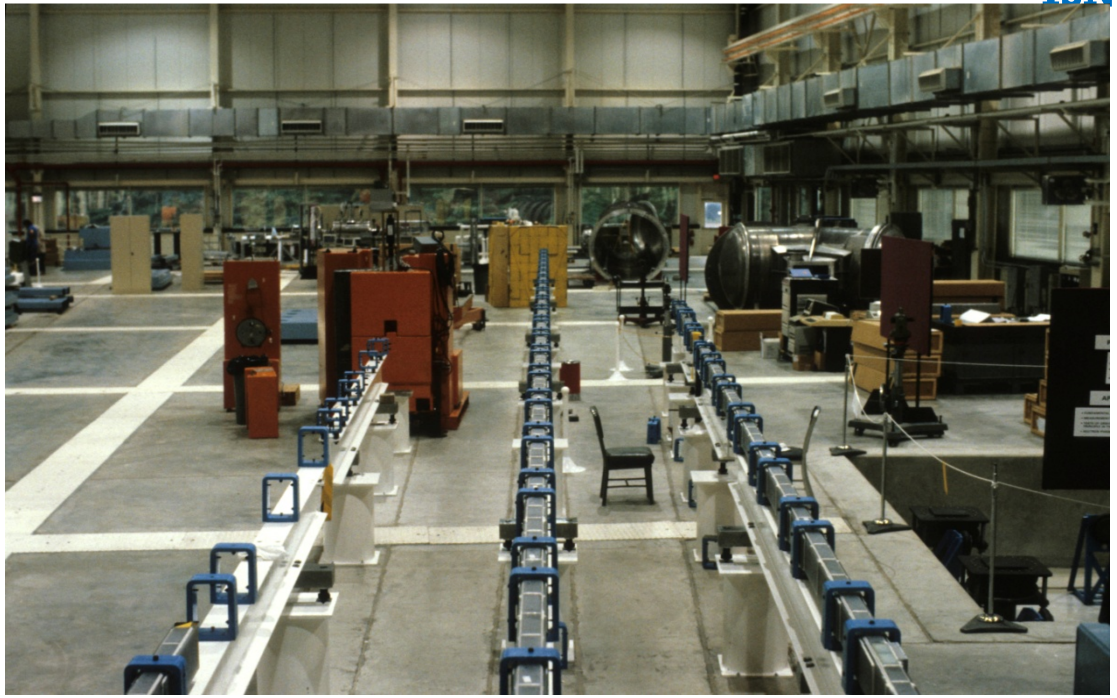
- First guides at NCNR (CNRF) early 1990’s were straight-sided and not curved



- IDEALIZED transmission ~ $\theta_c^2 \propto \lambda^2$
- NG3,5,6,7 are ^{58}Ni, $\theta_c(^{58}\text{Ni})/\theta_c(\text{Ni}) = 1.18 \Rightarrow$ ideal gain ^{58}Ni/Ni = $1.18^2 \approx 1.4$
- Flux gain is at the expense of <u>increased divergence</u>

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NEUTRON GUIDE OPTICS
EXTEND THE LIMITS OF CRITICAL ANGLE?

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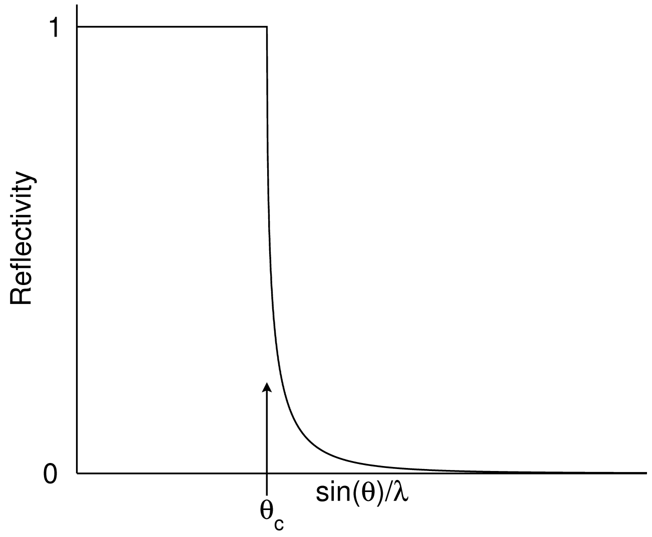
- Fresnel's law reflectivity
  - Very high reflectivity below θ_c
  - θ_c is fundamentally **limited by physical and nuclear properties of material**



- Can we somehow increase the naturally-limited critical angle by factor *m*?
  - e.g. m=2 ⟹ idealized gain wrt Ni =m^2 = 4
  - m=3, gain=9 etc.
- Yes! – Can do this artificially with ***supermirrors***

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SUPER MIRRORS

NEUTRON GUIDE OPTICS

ARTIFICIALLY EXTENDING THE LIMITS OF CRITICAL ANGLE

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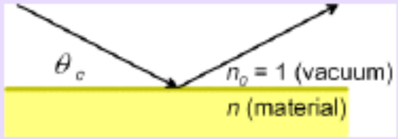
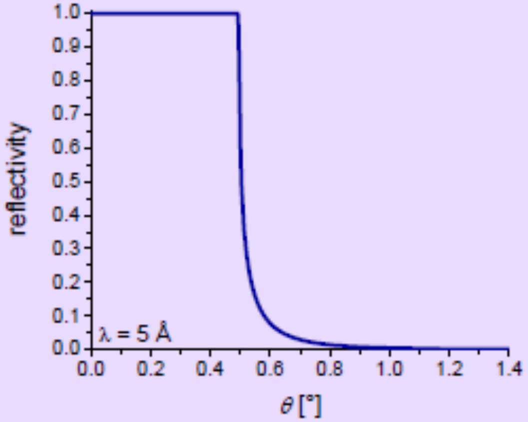
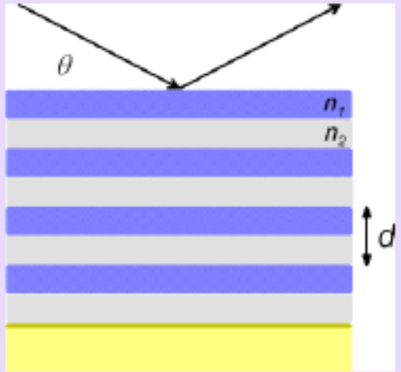
@ smooth surfaces



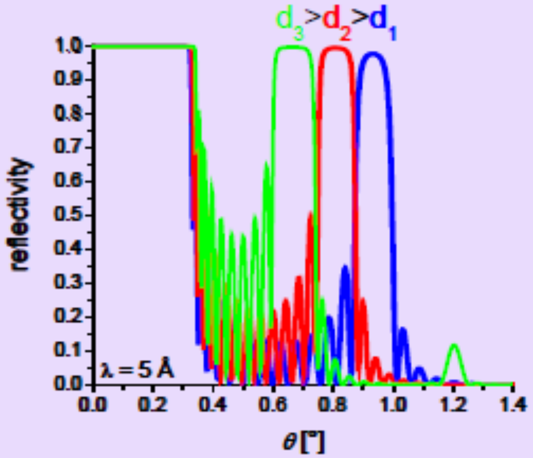
- refractive index $n < 1$
- total external reflection
  e.g. Ni θ_c = 0.1 °/Å



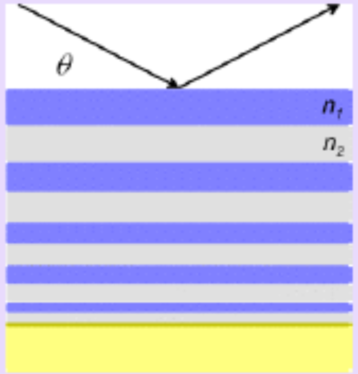
@ multilayer

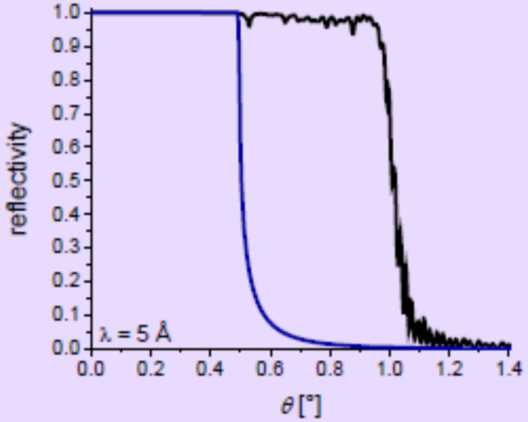


$$\lambda = 2d \sin\theta$$



@ supermirror





Slide due to P. Böni

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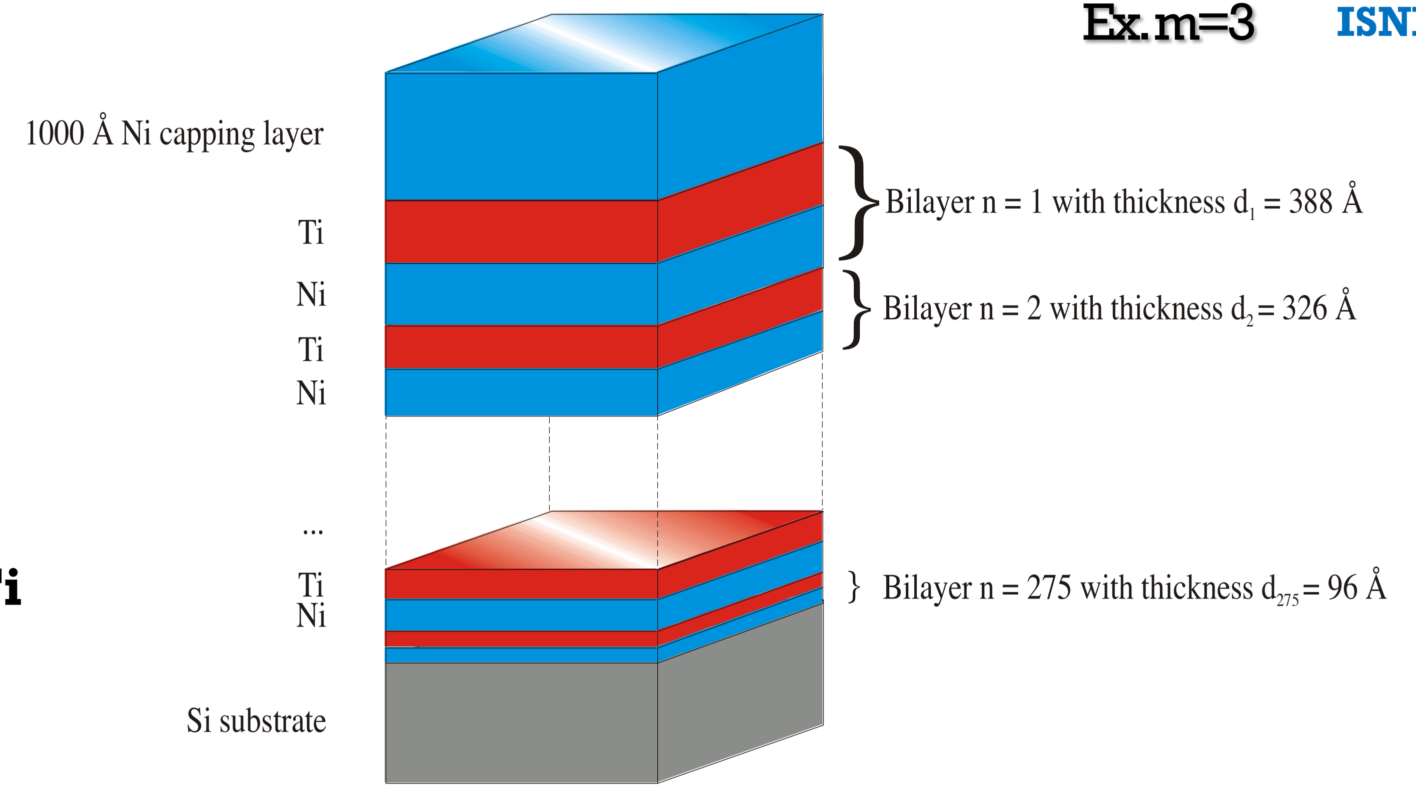
SUPERMIRRORS

Ex. m=3 ISNIE

Mezei's Supermirror Design Recipe

$$d(n) = \frac{d_c^{Ni}}{\sqrt[4]{n}}$$

- Alternating layers of "**high contrast**" materials
- e.g. **Ni (*Nb*=9.41×10^{-6} Å^{-2})** and **Ti (*Nb*=-1.91×10^{-6} Å^{-2})**



- Relies on coherent (in-phase) neutron scattering from different layers
  - Each *d*-spacing reflects a different Q (different angle for a given wavelength or different wavelength for a given angle)

Figure from C. Rehm

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SUPERMIRRORS

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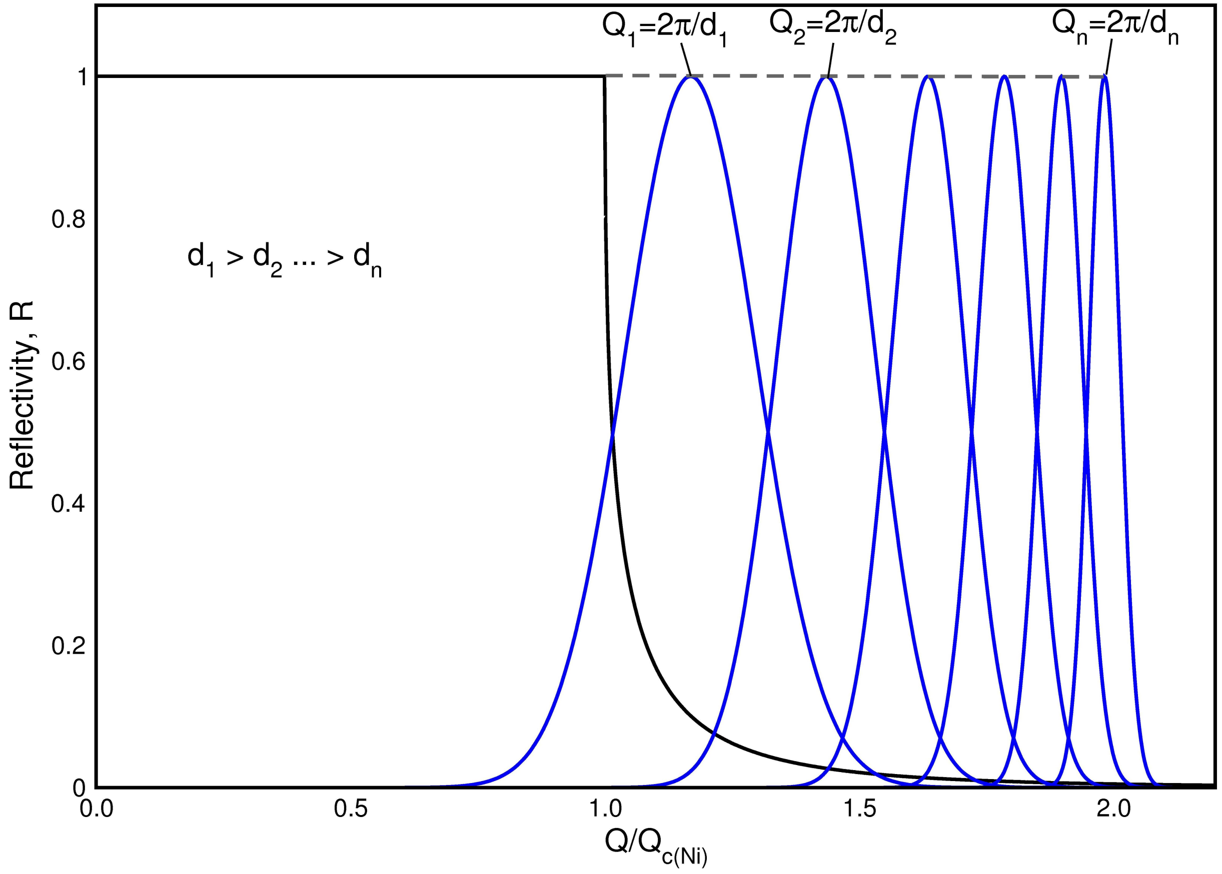
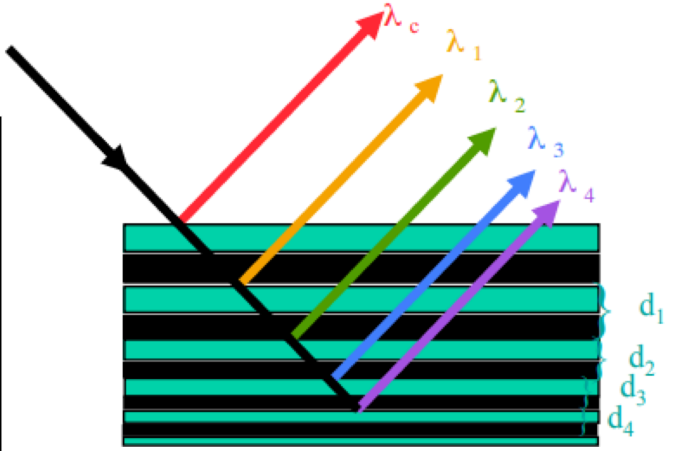
- d_i are chosen such that the corresponding Bragg peaks intersect at half-height
- "m" defines the ratio of the effective supermirror reflectivity cutoff wrt nat. Ni (e.g. m=3 ⇒ $Q_c(SM)/Q_c(Ni)=3$)

e.g. Ni-Ti supermirror





Fixed θ

$$Q \approx 4\pi \frac{\theta}{\lambda}$$

$d_1 > d_2 > d_3$,

$\lambda_1 > \lambda_2 > \lambda_3$,

$Q_1 < Q_2 < Q_3$, etc.

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SUPERMIRRORS

- Number of required layers increases rapidly with increasing *m*

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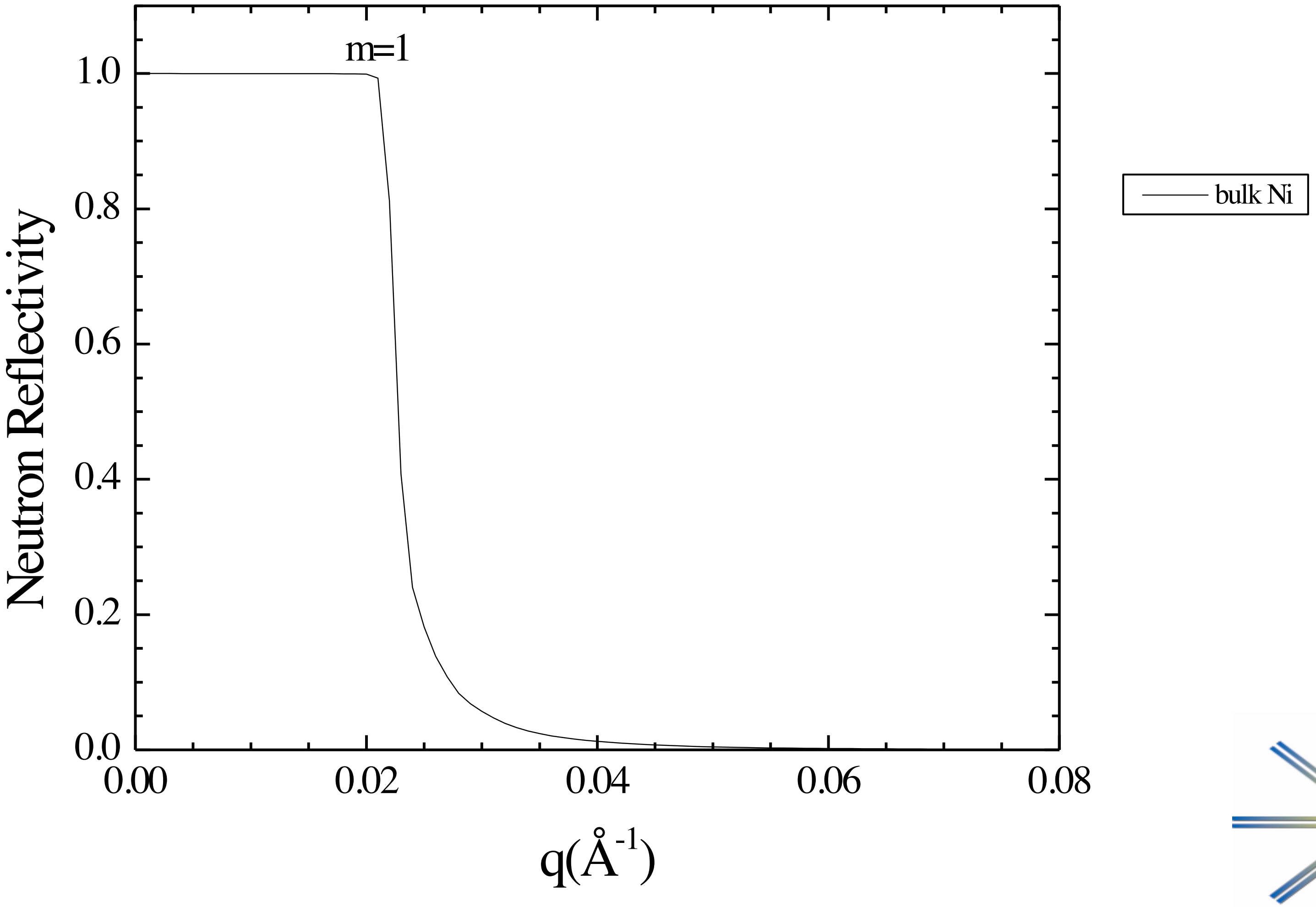

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SUPERMIRRORS

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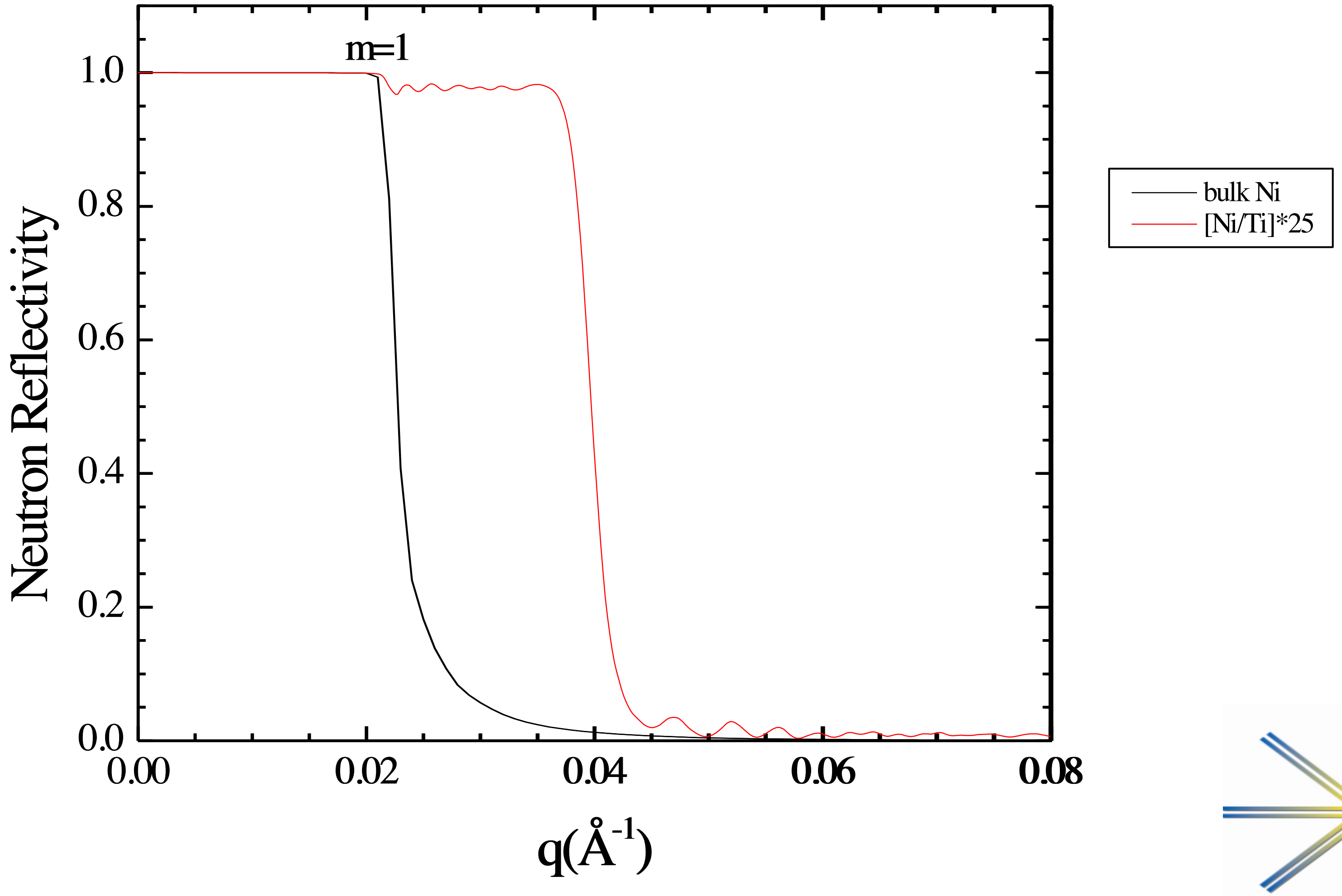

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SUPERMIRRORS

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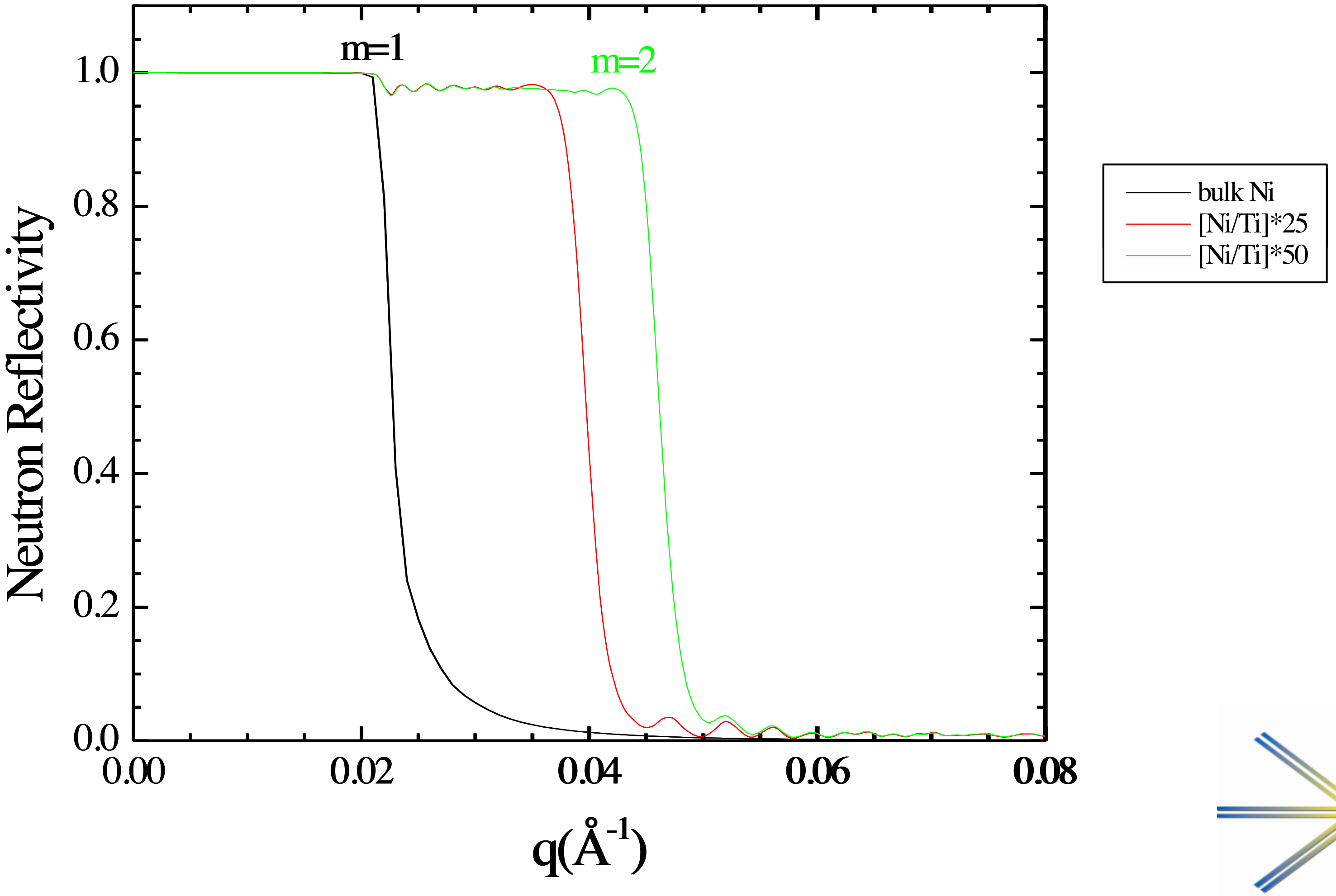

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SUPERMIRRORS

- Number of required layers increases rapidly with increasing *m*

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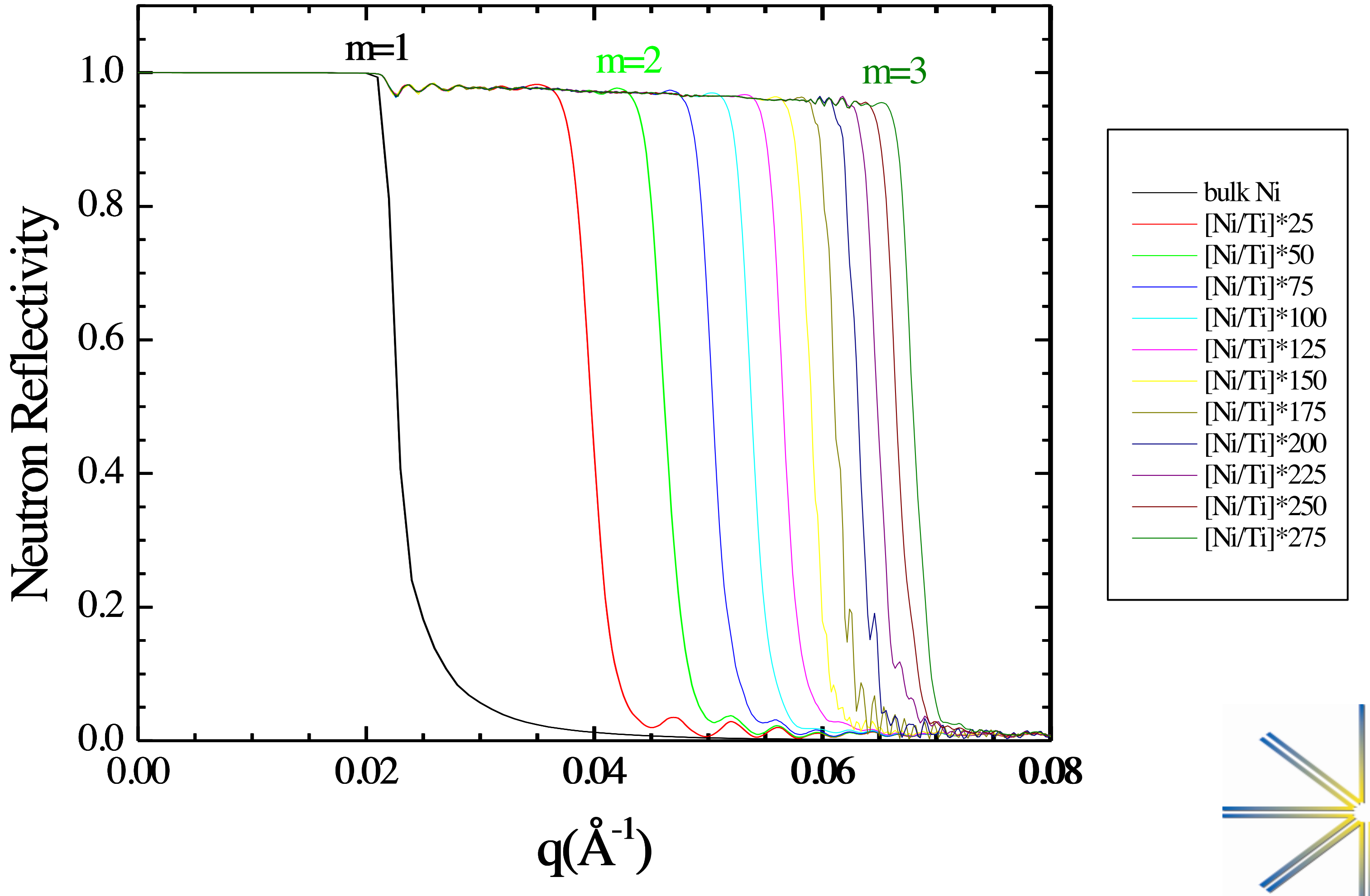

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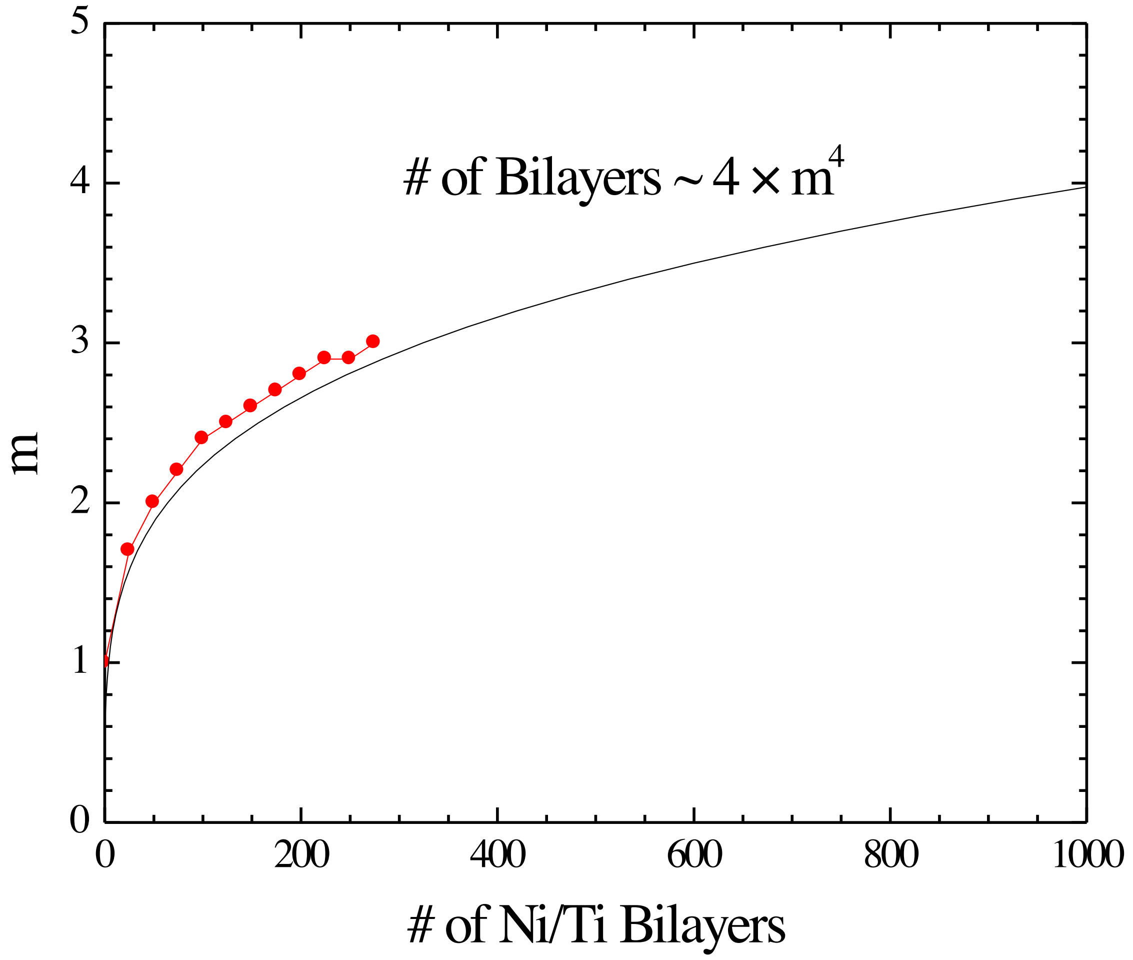
SUPERMIRRORS

- Number of required layers increases rapidly with increasing *m* ($\sim m^4$) - influences cost



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SUPERMIRRORS

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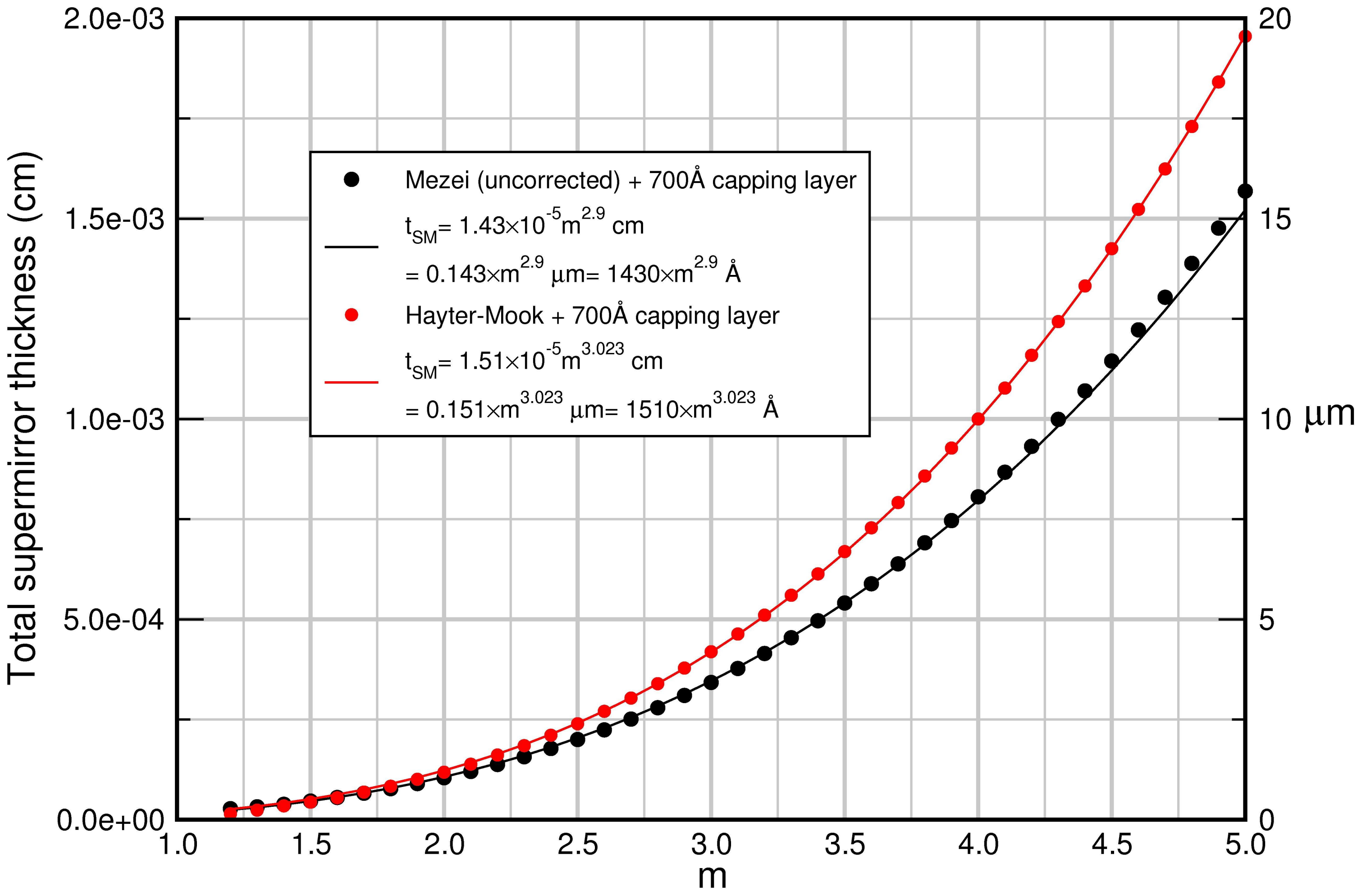
- Thickness of supermirror increases ~m^3



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COATING TYPES

NEUTRON GUIDE OPTICS
TYPES OF SUPERMIRROR

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- Common (non-polarizing guides): **Ni-Ti**
- Polarizing
  - **Fe/Si**
  - **FeCoV / TiN** (problem activation of Co (^{60}Co $T_{1/2}$>5 yrs)
  - Require > 100 Gauss (0.01 T) magnetic field in "easy magnetization direction" (plane of supermirror) to saturate polarization
- Non-magnetic **Ni(Mo)/Ti** (special applications)

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SUPERMIRROR COATINGS

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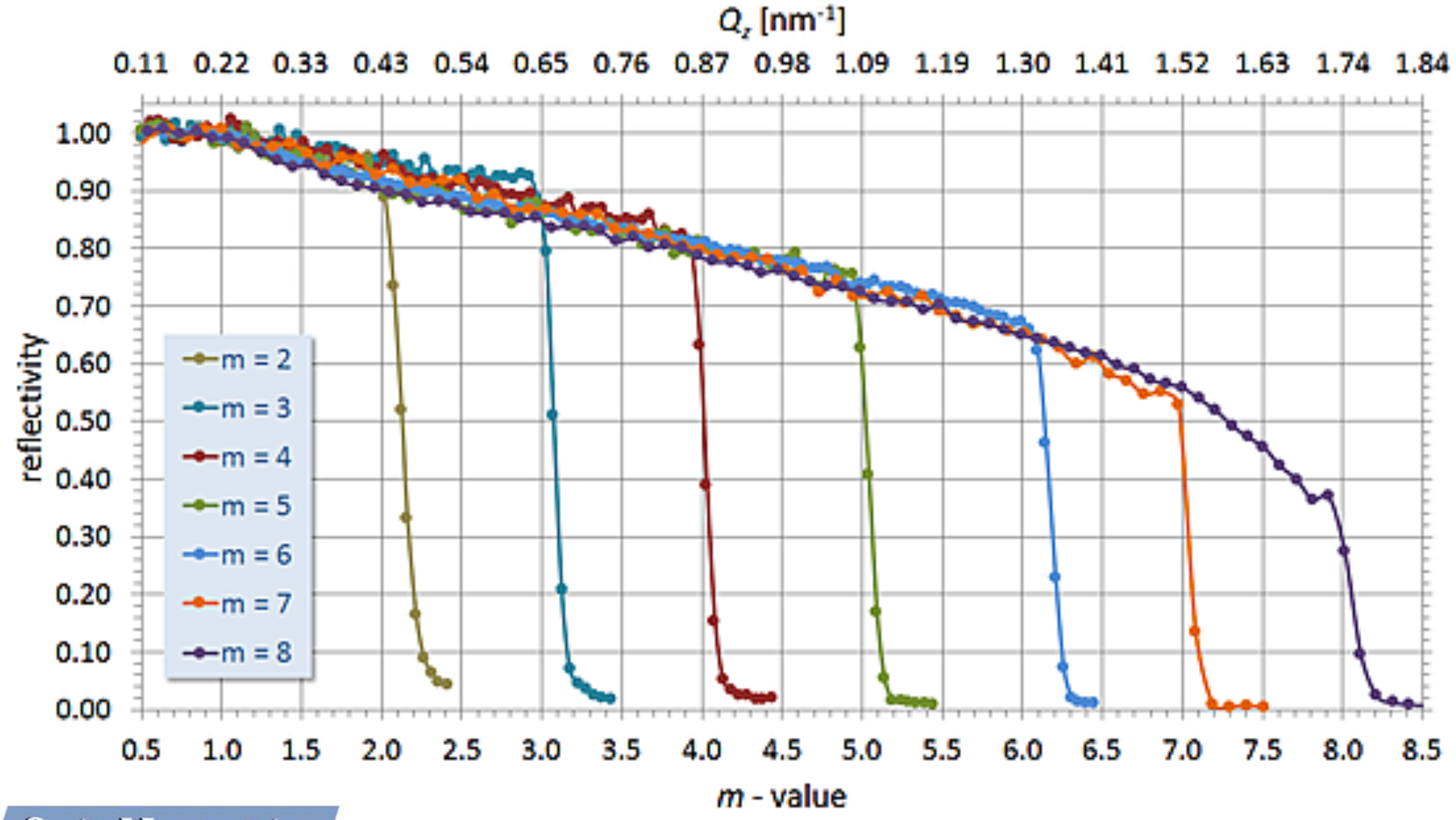

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SUPERMIRROR COATINGS

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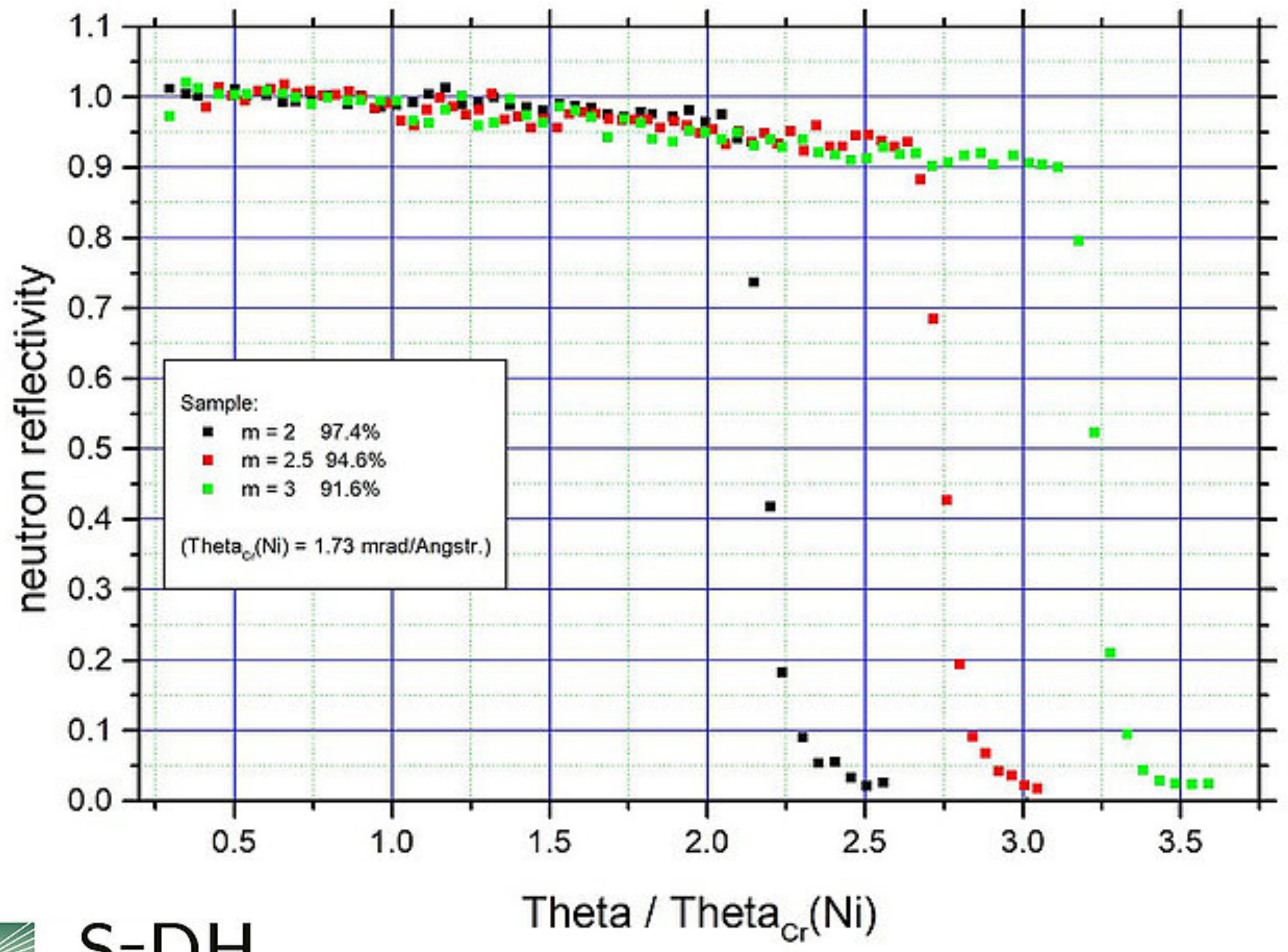

S-DH

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POLARIZING SUPERMIRROR COATINGS

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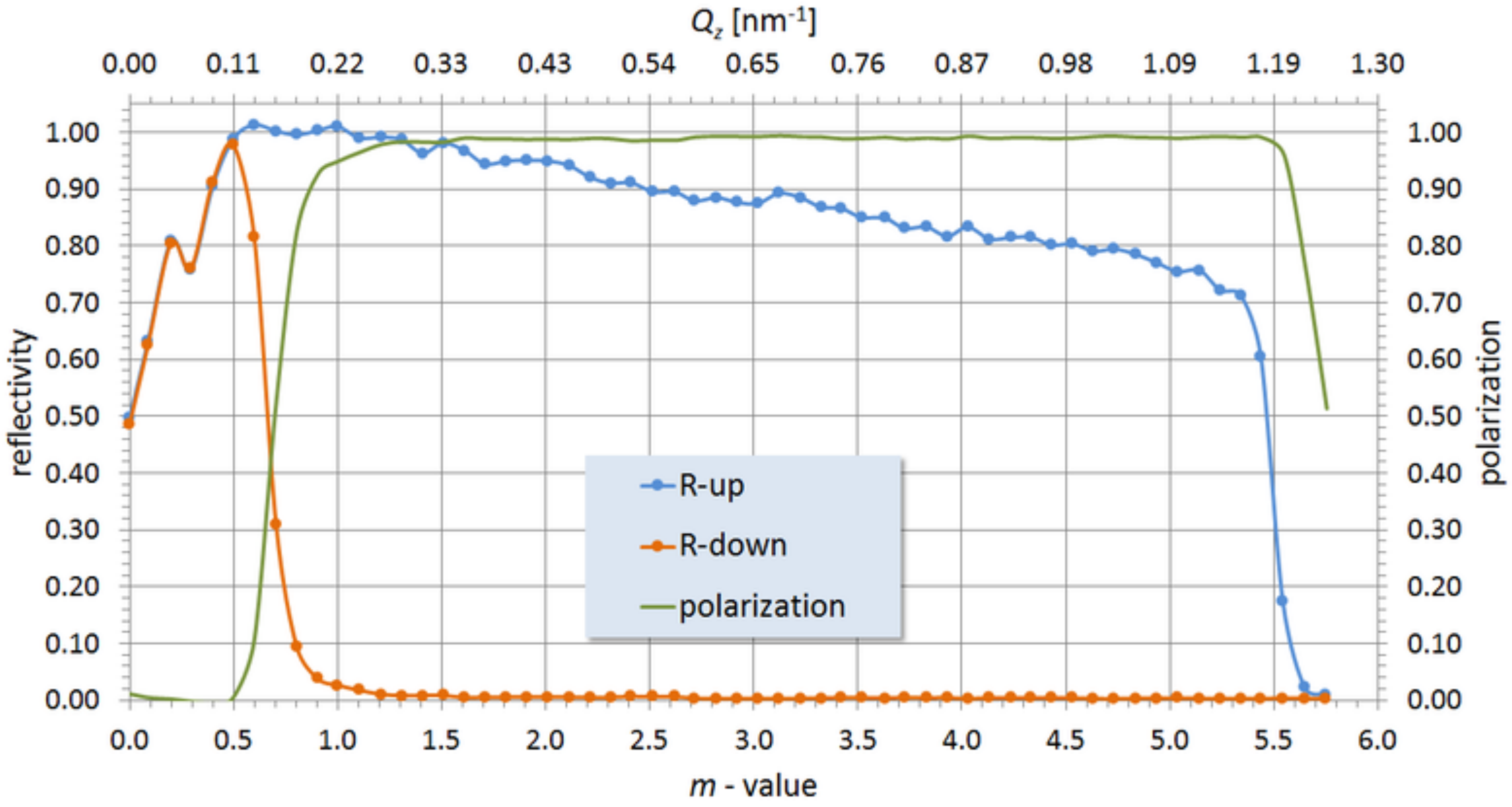
Polarizing: Fe/Si, m=5.5



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SUPERMIRRORS

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- NCNR guides 3, 5, 6, 7 are currently ^{58}Ni
  - will be upgraded with supermirror guides (5,6), 7 (m=2 through confinement)
  - curved (6)
  - bi-elliptical (5)

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GUIDE LOSSES

NEUTRON GUIDE OPTICS

REALITY! REFLECTIVITY AND OTHER LOSSES

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- Reflectivity of all coatings < 1 because of imperfections
  - Surface roughness has to be on Å scale (leads to off-specular reflections)
    - Effect can be approximated by factor **exp($-Q^2\langle u^2\rangle$)** where $\langle u^2\rangle$ **is the mean squared roughness**
    - Controlling roughness particularly important for **high *m*** supermirrors (large Q)
  - Interdiffusion of layers (supermirrors)
  - Absorption of neutrons in reflecting layers
  - Surface roughness and interdiffusion are significantly improved by "**reactive sputtering**"
    - ex. For Ni-Ti supermirrors Ni layer is deposited in a partial pressure of air or carbon is added

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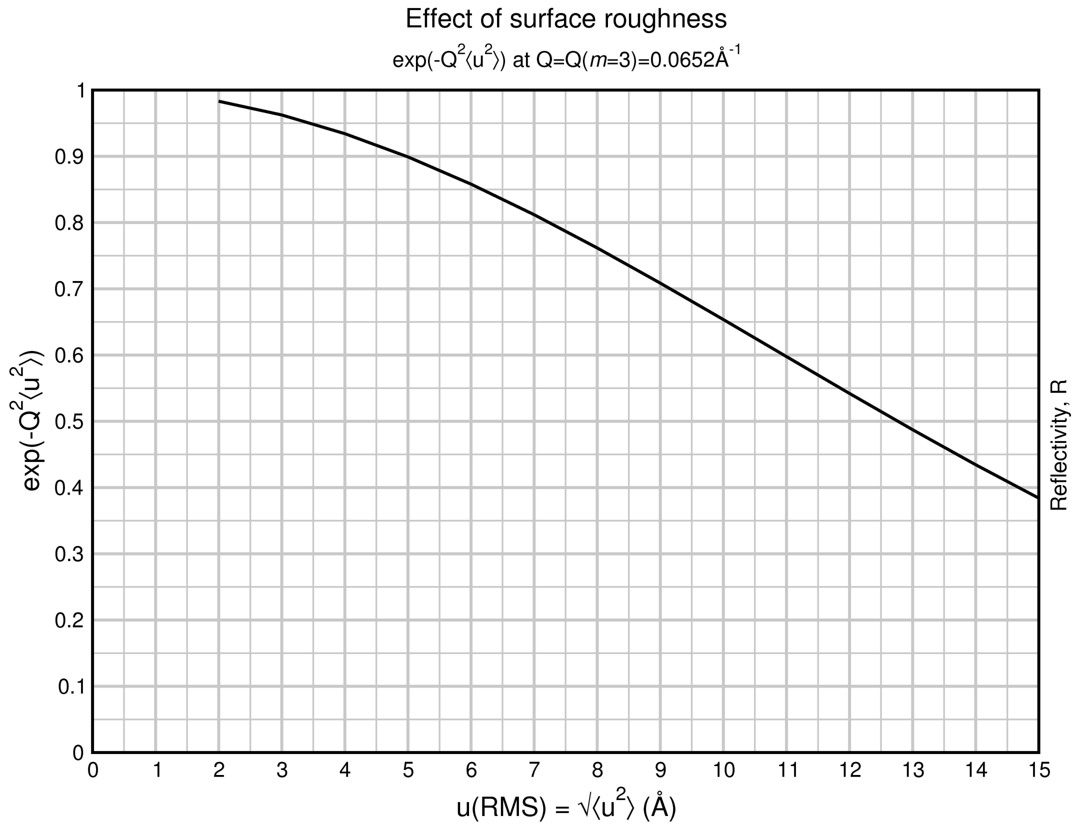
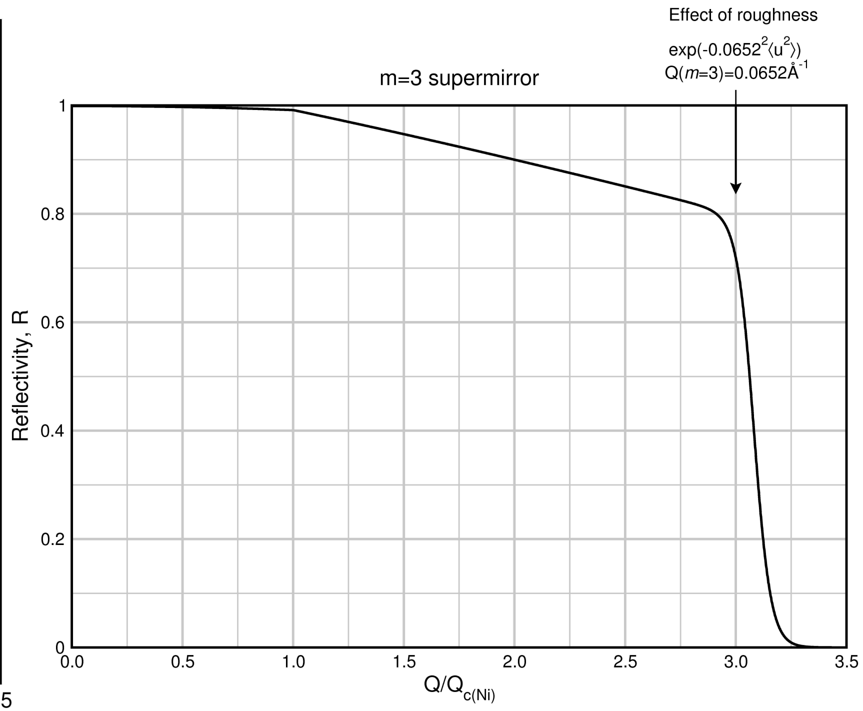
NEUTRON GUIDE OPTICS
REALITY! REFLECTIVITY AND OTHER LOSSES

- Example of effect of surface roughness at Q=Q(m=3)=0.0652Å





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NEUTRON GUIDE OPTICS

REALITY! REFLECTIVITY AND OTHER LOSSES

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- Other sources of losses in guides
  - Misalignments (angular and spatial)
  - Waviness of substrates (long-range undulations of substrate surface redirects neutron away from intended direction)
  - (Often ~ 0.1 mrad level of angular precision required for the above)
  - Intrinsic manufacturing imprecision (e.g. cross-section ~±0.01 mm, degree of parallelism etc., substrates are selected for low waviness)
  - Oxidation, overheating of mirrors/ supermirrors
  - Poor vacuum

- Reflectivity losses can be very large when a large number of reflections, n_r, are required for transmission

$$T \sim R^{n_r}$$

- Redirection of neutron trajectory also blows up with increasing n_r etc.

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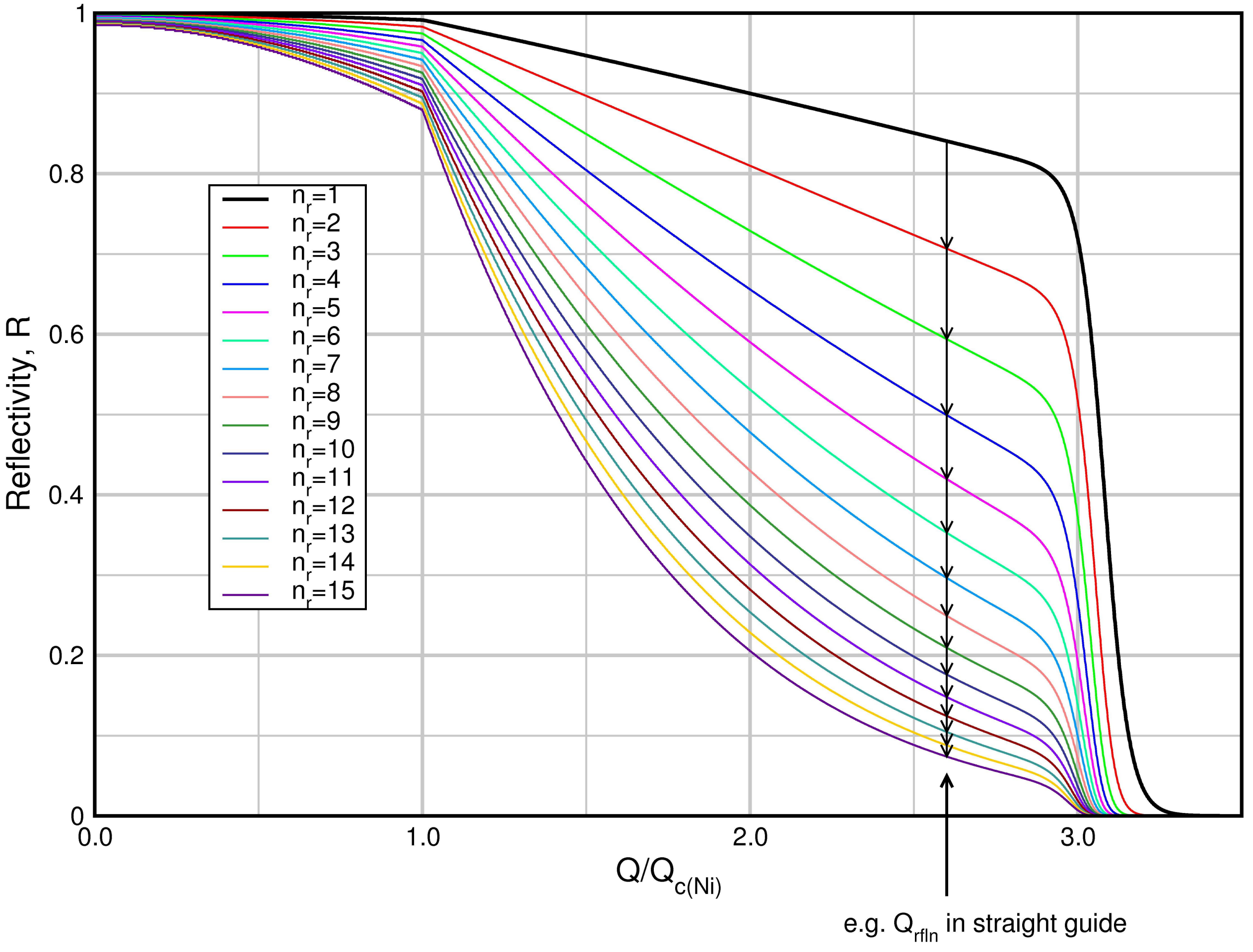
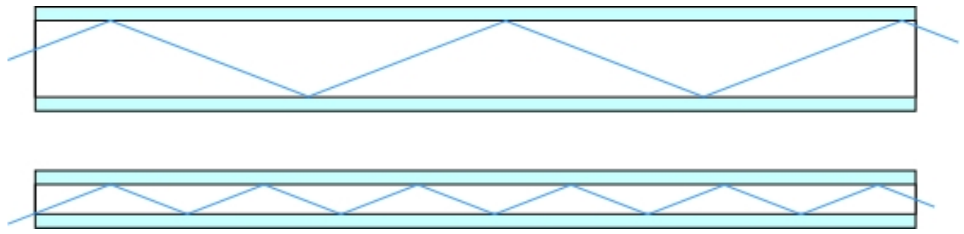
NEUTRON GUIDE OPTICS

REALITY! REFLECTIVITY AND OTHER LOSSES

ISNIE



$$Q \approx 4\pi \frac{\theta}{\lambda}$$



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SUBSTRATES

NEUTRON GUIDE OPTICS

TYPES OF SUBSTRATE

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- ~ Å (0.1 nm) level roughness required
- Borated glass (usually bonded with radiation-resistant epoxy)
  - Borkron NZK7 and NBK optical glass – superpolished (more resistant to high flux neutron irradiation than borofloat)
  - Borofloat – floated on molten metal
  - Embrittlement due to $^{10}B(n,\alpha)^{7}Li$ reaction (charged particle track displaces atoms in glass structure (cascades))
  - Thermal neutron beam cannot escape the guide, easily-shielded gamma radiation
- Non-borated glass
  - e.g. soda-lime float glass: No α-related embrittlement but higher energy gamma spectrum from e.g. Na, Si, may be some neutron transmission near source
- Silicon
  - Produces hard gammas but can be made thin
  - Thin substrates can be bent on a figure (e.g. elliptical or other forms)
- Metallic (very low roughness ~1Å rms now available)
  - Aluminum (produces hard gamma spectrum – more shielding challenges than borated substrates) – good heat conduction and radiation heat removal in very high flux
  - Copper, steel (can also shield gammas from supermirror inside)
  - Possibility to weld Al without significant distortion (we are told)

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NEUTRON GUIDE OPTICS

CHOICE OF SUBSTRATE?

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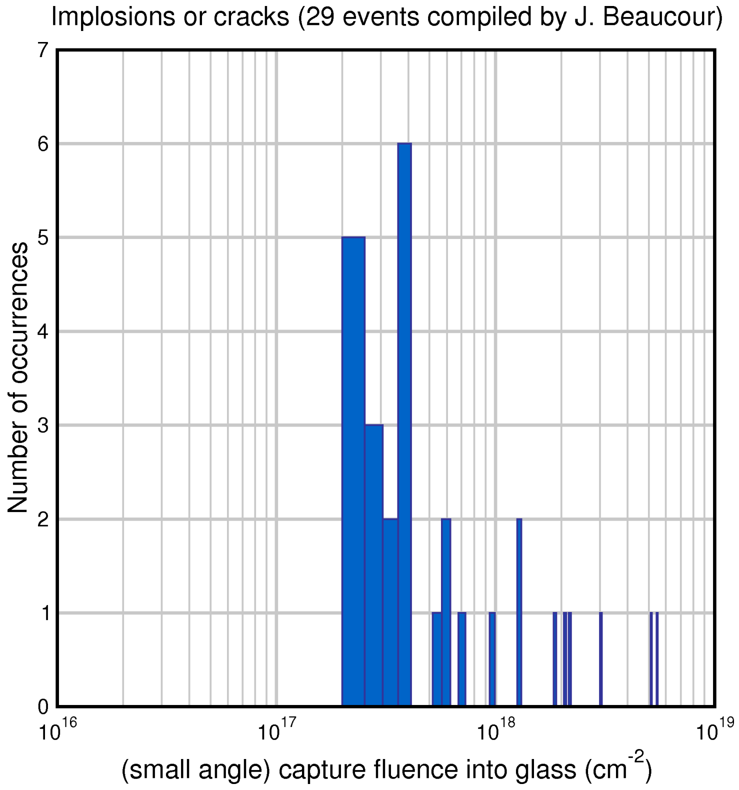
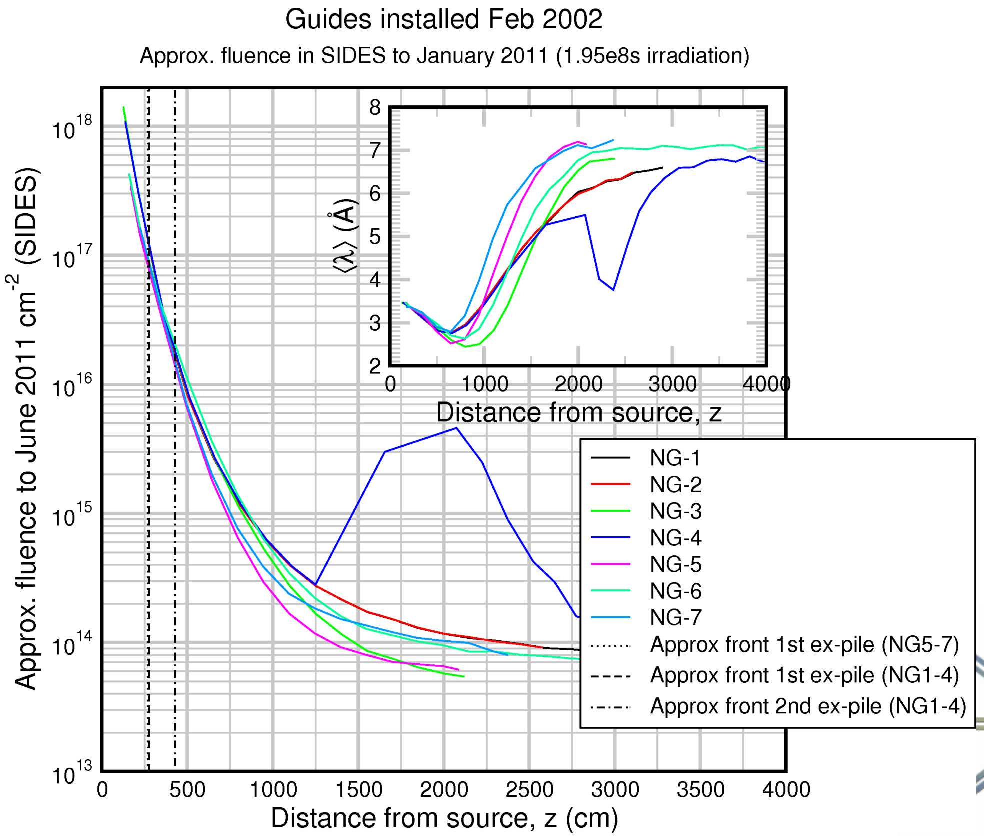
- Borkron (NZK7 or NBK7)
  - Should not exceed ~10^{17} cm^{-2} lifetime neutron fluence – embrittlement from (n,α) reaction
  - First Borkron NIST guides outside of inpile have been known to break under their own weight when removed
  - Must protect exposed ends of guides (borated Al mask) even 10's of m from source (risk of implosion for evacuated guides)





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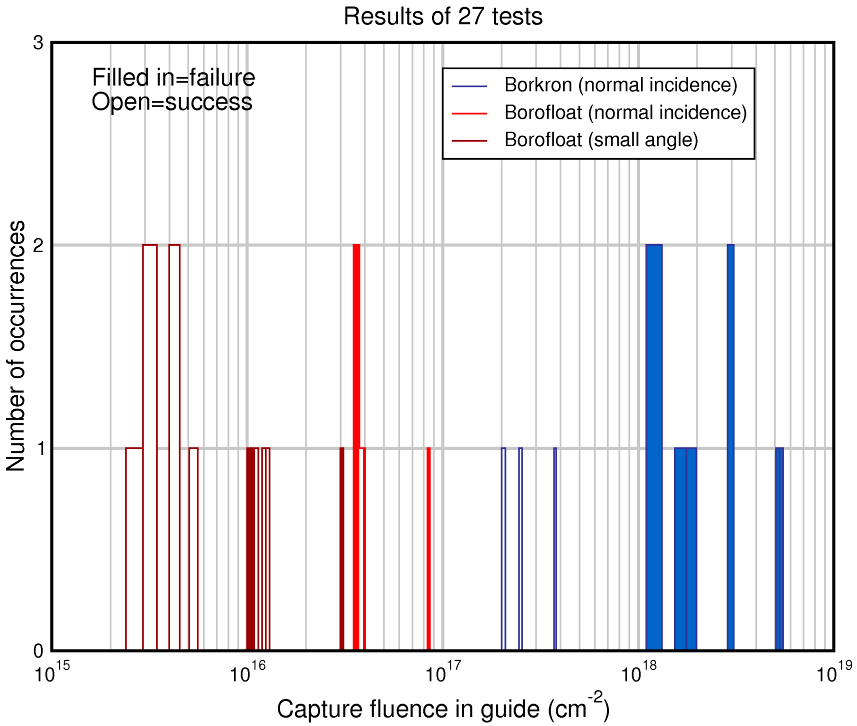
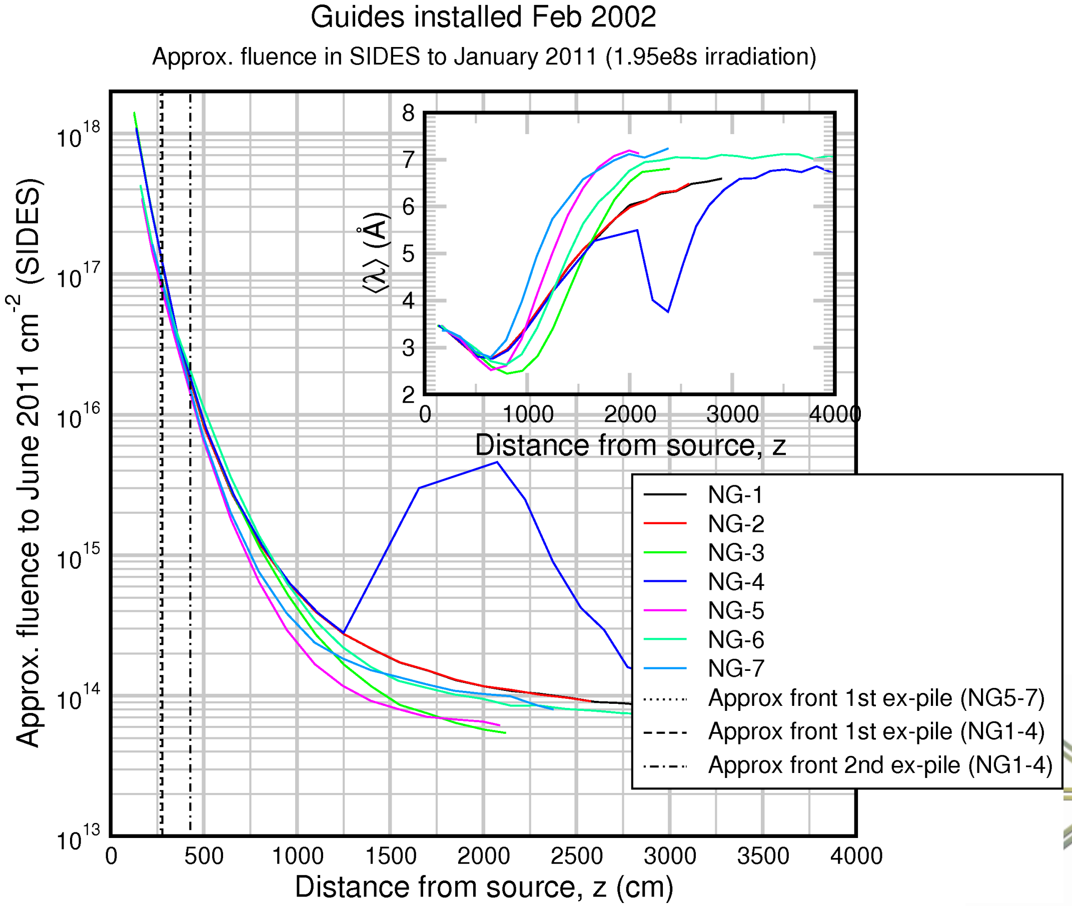
NEUTRON GUIDE OPTICS

CHOICE OF SUBSTRATE?

ISNIE

- Borofloat
  - Appears to have significantly shorter lifetime wrt n irradiation than Borkron 1-2 orders of magnitude (cannot use close to source)
  - Must protect exposed ends of guides (borated Al mask) even 10's of m from source (risk of implosion for evacuated guides)





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NEUTRON GUIDE OPTICS

CHOICE OF SUBSTRATE?

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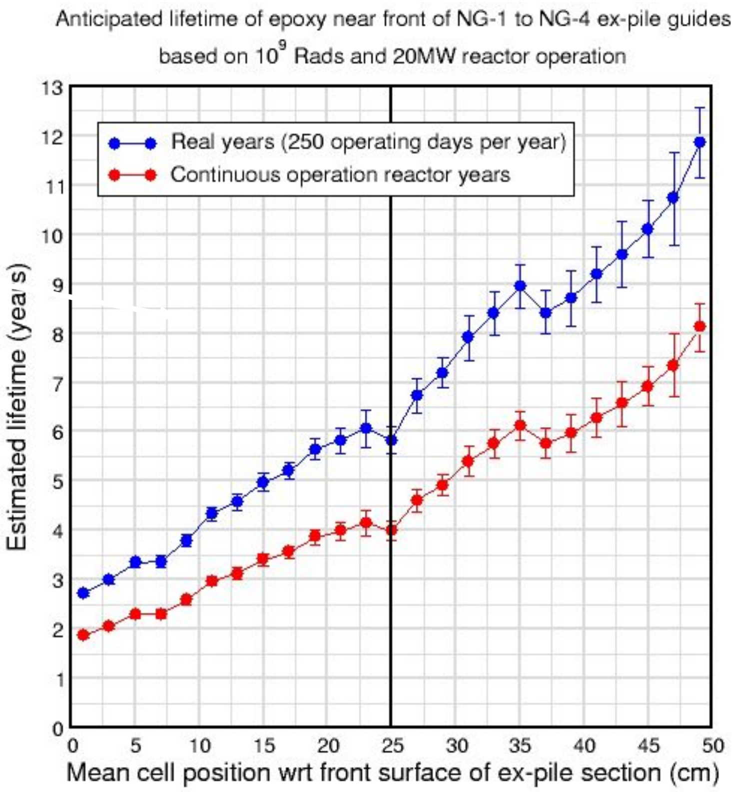
- Soda Lime float glass (boron-free)
  - Used on first in-pile guides at NIST
  - Does not suffer from embrittlement from $^{10}B(n,\alpha)^{7}Li$ reaction
  - Epoxy in highest radiation estimated exceed lifetime (radiation damage) – fears of in-pile collapse after 2011 mag 5.8 earthquake near Richmond VA!

- Estimate in **first *ex-pile*** element based on 10^9 rad lifetime
- **Float glass NG1-4 in-pile epoxy should be totally shot!**



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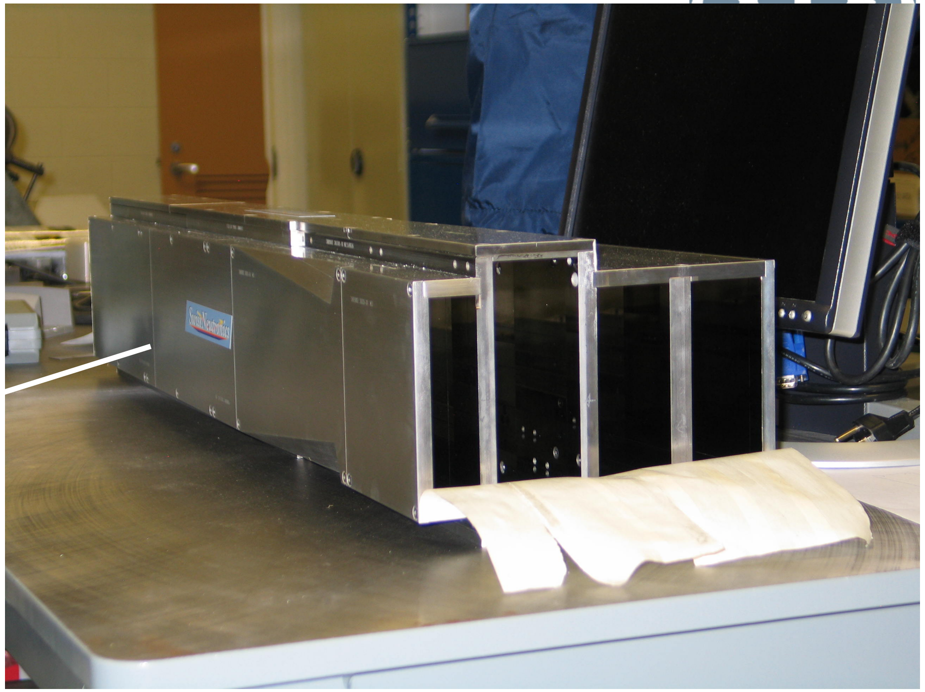
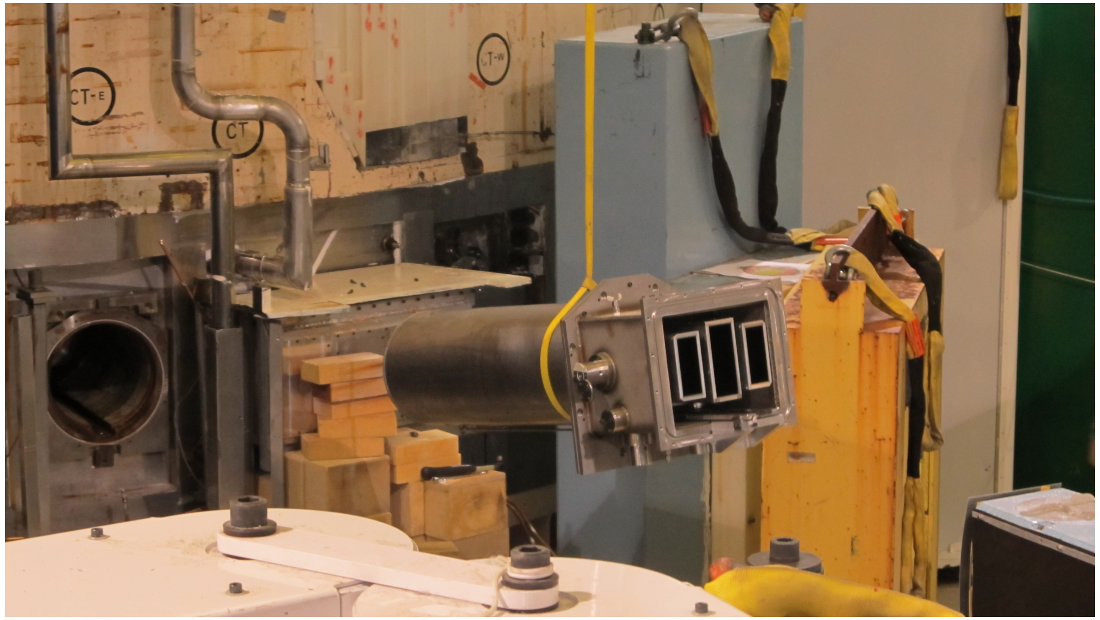
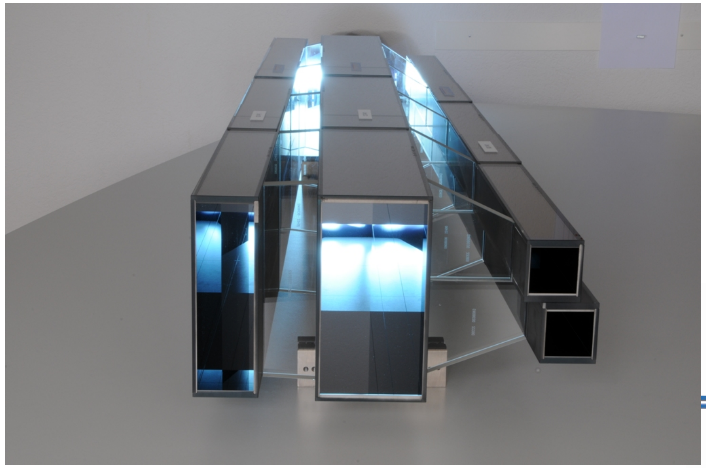
NEUTRON GUIDE OPTICS

CHOICE OF SUBSTRATE?

- **Aluminum**
  - Material selected for all new in-pile (non-evacuated) guides at NIST
  - Indefinite substrate lifetime
  - Much lower risk of breakage than glass (**future CTW ex-pile monolith sections will be Al**)
  - Very low roughness







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TYPES OF GUIDE

NEUTRON GUIDE OPTICS

COMMON TYPES OF GUIDE

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- **Straight**
  - Direct line of sight to the source
  - Often require cooled crystal filters to eliminate fast neutron and gamma beam contamination
- **Curved** (eliminate line of sight to source – lower beam contamination)
  - Often polygonal approximation to circular arc, non-uniform spatial-angular distribution at exit
  - Curved-straight (improves spatial-angular uniformity of beam)
  - "Phase Space Tailoring" guide – variant of curved-straight: Can produce **almost perfect beam uniformity** above a given wavelength (NGBl and NGBu SANS at NCNR)
- **Other line-of-sight elimination**
  - "Optical filter" designs (e.g. NG-4)
- **Profiled** (focusing/ defocusing) – parabolic, elliptical, general shape
  - Can be produced on bent silicon substrates if small scale
  - Can use polygonal approximation to profile (e.g. 0.5m linearly tapered sections used for NGC at NCNR)

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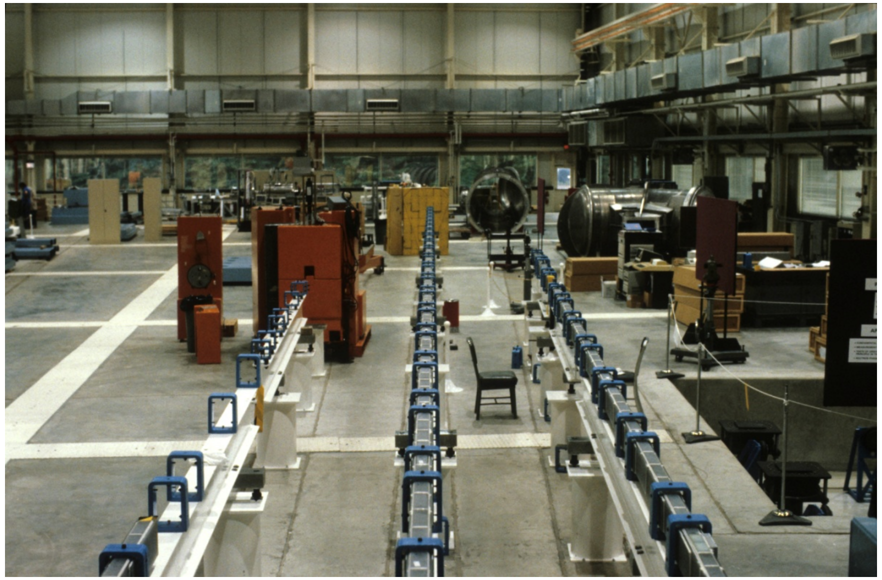
NEUTRON GUIDE OPTICS
STRAIGHT GUIDES

ISNIE

- All original NCNR guides (NG1-7) through confinement are straight
- Unwanted fast neutrons and gammas emitted from the source eliminated by cooled crystal filters
  - e.g. Polycrystalline beryllium strongly scatters λ < 4Å neutrons (transmits λ > 4Å)
  - Bismuth attenuates gammas but good thermal neutron transmission
  - Also sapphire, quartz, MgO, Si, graphite etc. for fast neutrons
- NG4 & 5 have "optical filters" to eliminate direct lines of sight from the guide exit to the source



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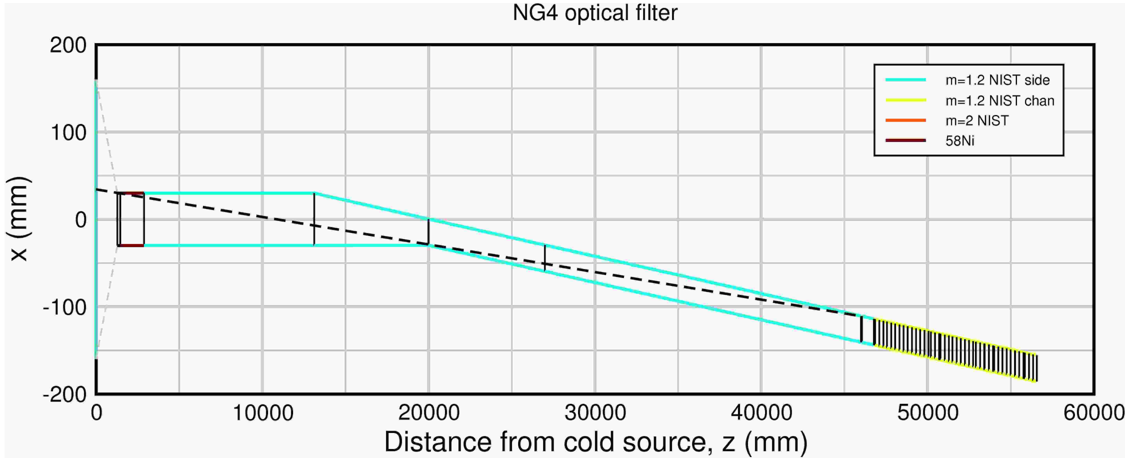
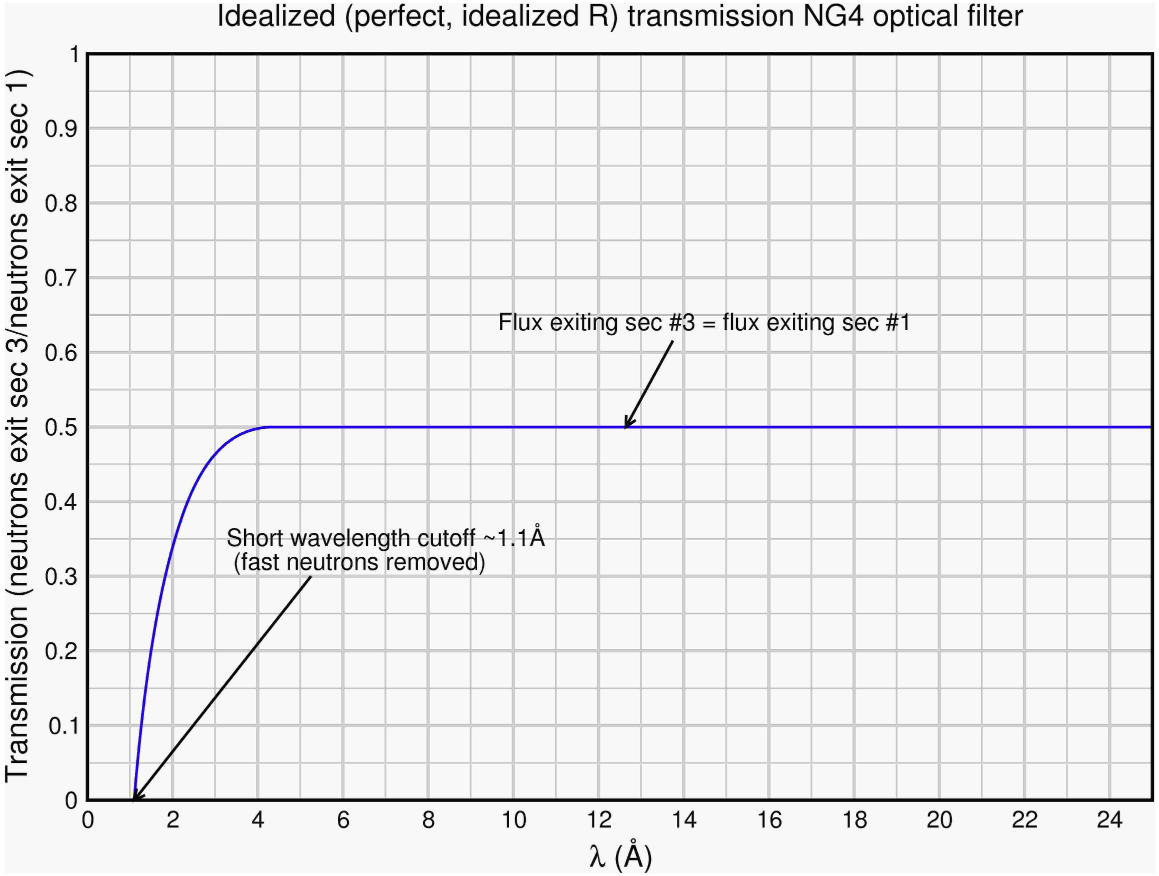
NEUTRON GUIDE OPTICS

OPTICAL FILTERS (NG4 AND NG5)

NG4

"Optical filter" kink eliminates direct line of sight (cold neutrons follow kink, fast neutrons and gammas go straight on and get lost in shielding)

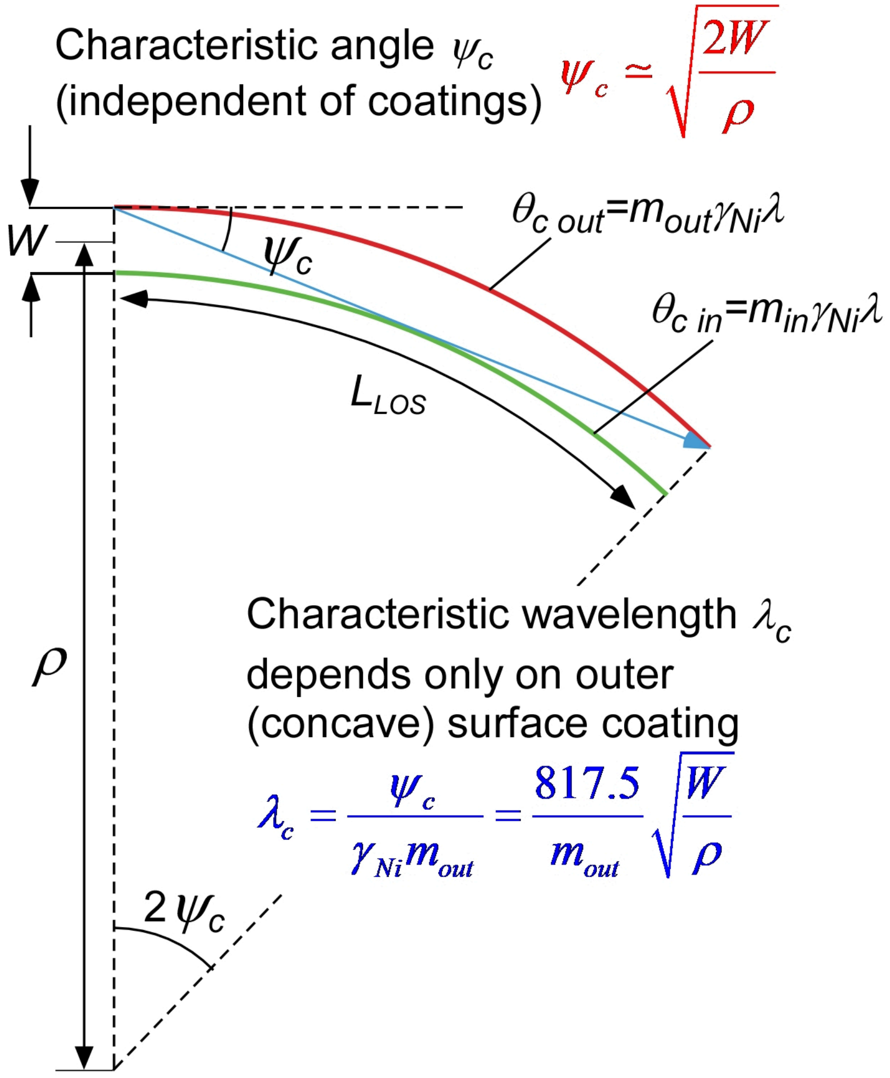




NEUTRON GUIDE OPTICS

CURVED GUIDES

ISNIE



- Avoid direct line of sight with curved guide

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NEUTRON GUIDE OPTICS

CURVED GUIDES

ISNIE

- Advantages
  - Reduce fast neutron and gamma contamination
  - W=width of guide, ρ=radius of curvature $L_{LOS} \approx \sqrt{8W\rho}$
  - NGBl W=5cm, ρ=780.6m, $L_{LOS}\approx$17.7m
  - Increase separation of instruments: Lateral displacement of guide exit $D=\rho(1-\cos(L/\rho))$
    - If L/ρ small $D\approx L^2/2\rho \Rightarrow$ displacement at end of line of sight $\approx 4W$ (e.g. NGBl, **20cm at L_{LOS}**=17.7m, ≈**80cm at 2L_{LOS}**=35.3m, ≈**1.8m at 3L_{LOS}**=53m etc.)
  - Possible to use lower m on inner radius than outer radius

- Disadvantages
  - Non-uniform spatial-angular distribution of neutrons at exit (improves with increasing λ)
  - Short wavelength "cutoff" theoretically in limit of $\lambda\rightarrow 0$

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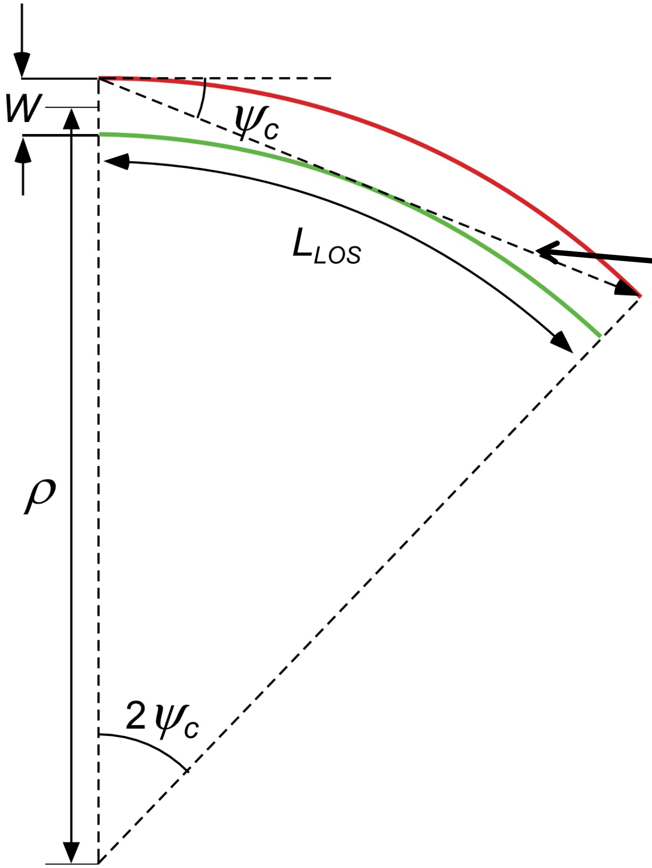
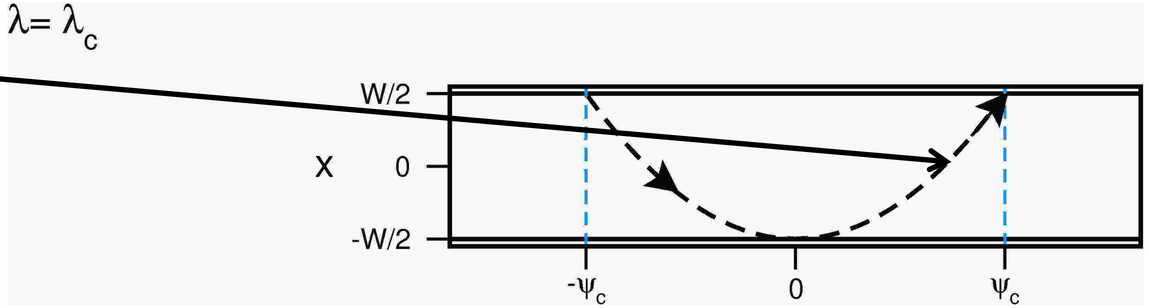
NEUTRON GUIDE OPTICS

CURVED GUIDES

- Neutron spatial-angular distributions (no line of sight)





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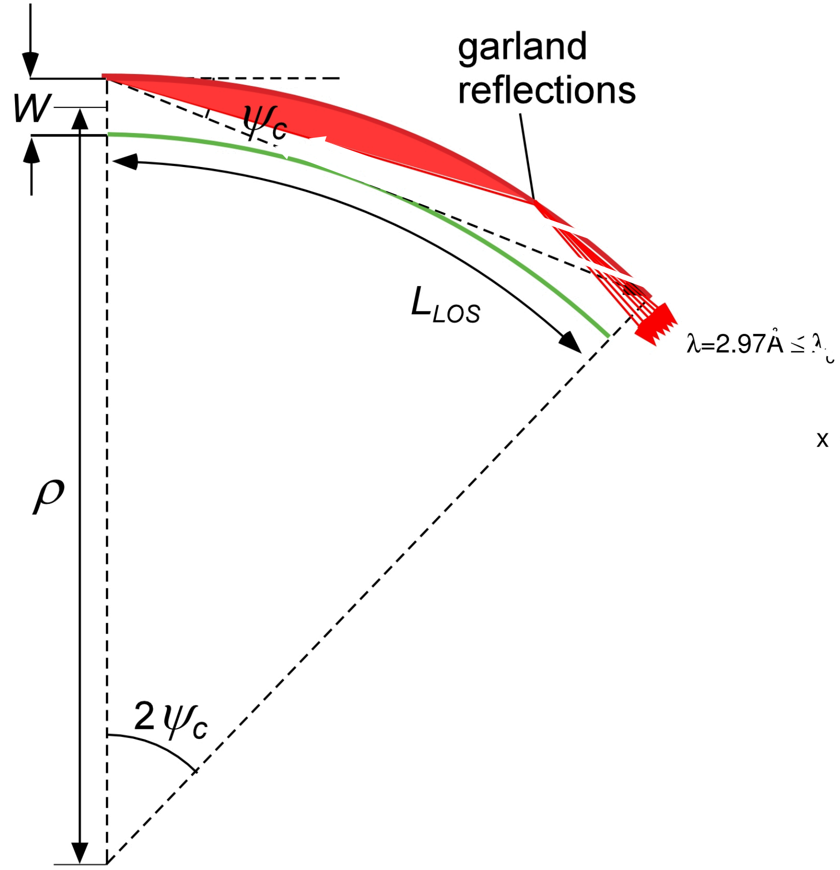
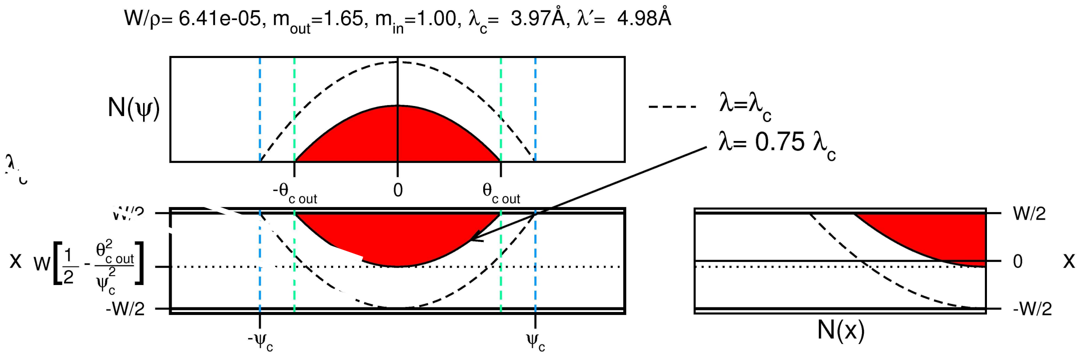
CURVED GUIDES

- Neutron spatial-angular distributions (no line of sight)

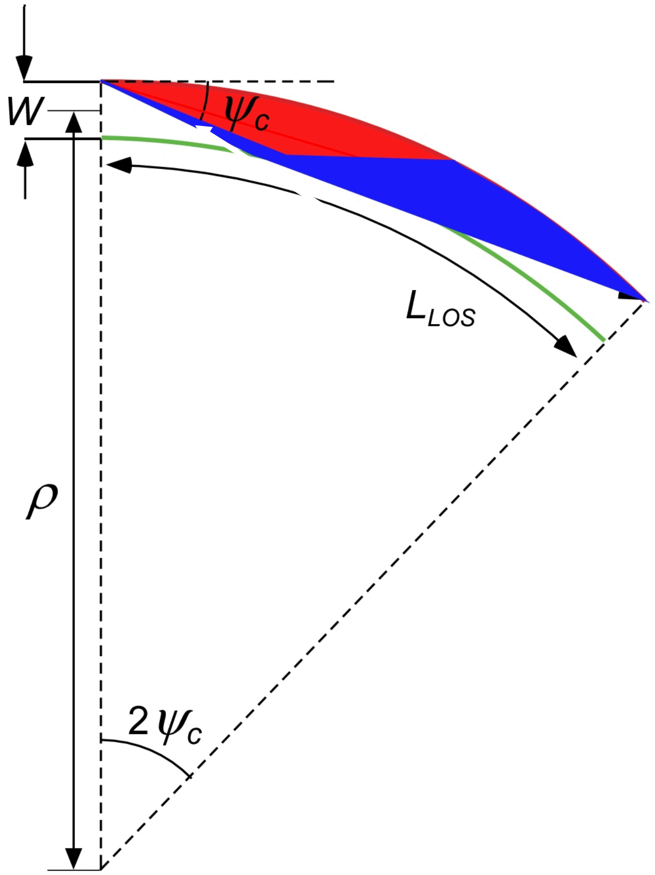




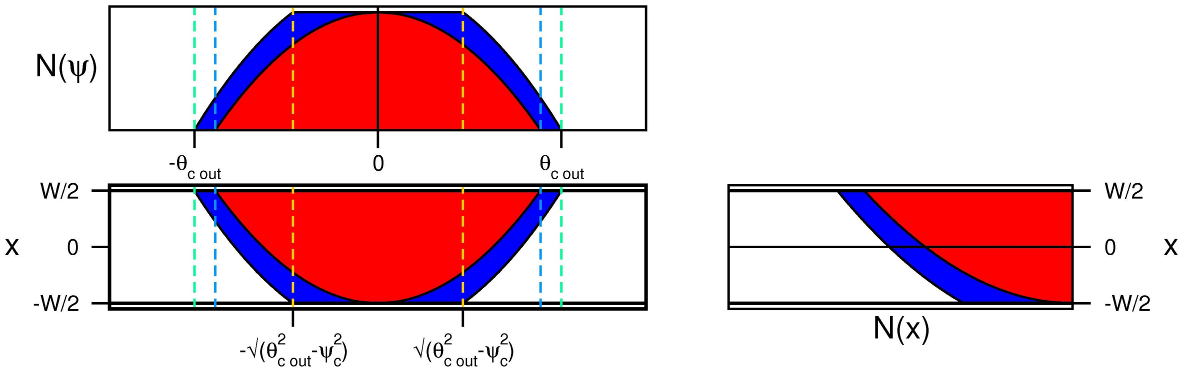
NEUTRON GUIDE OPTICS

CURVED GUIDES

- Neutron spatial-angular distributions (no line of sight)



$\lambda_c < \lambda = 4.48\text{Å} \leq \lambda'$



NEUTRON GUIDE OPTICS

CURVED GUIDES

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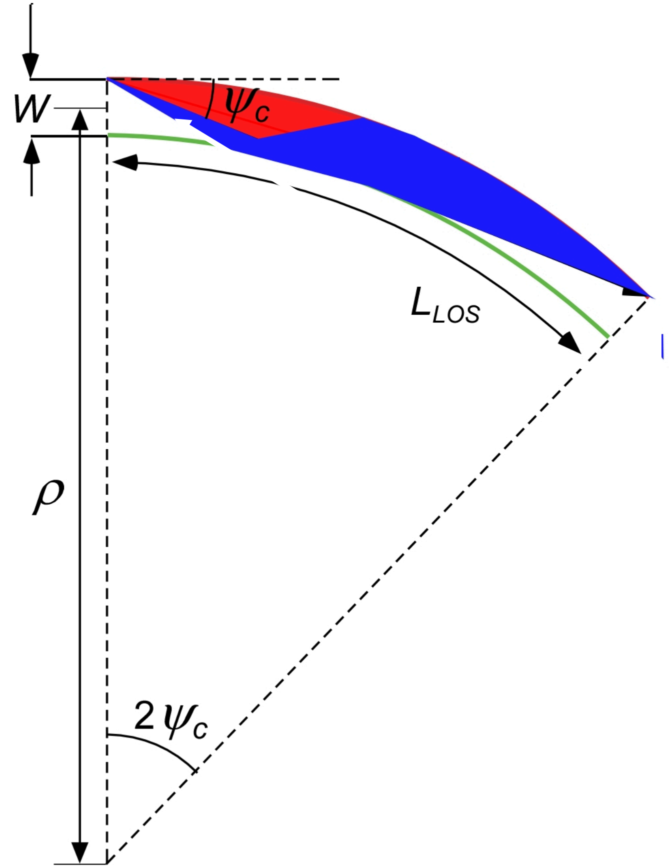
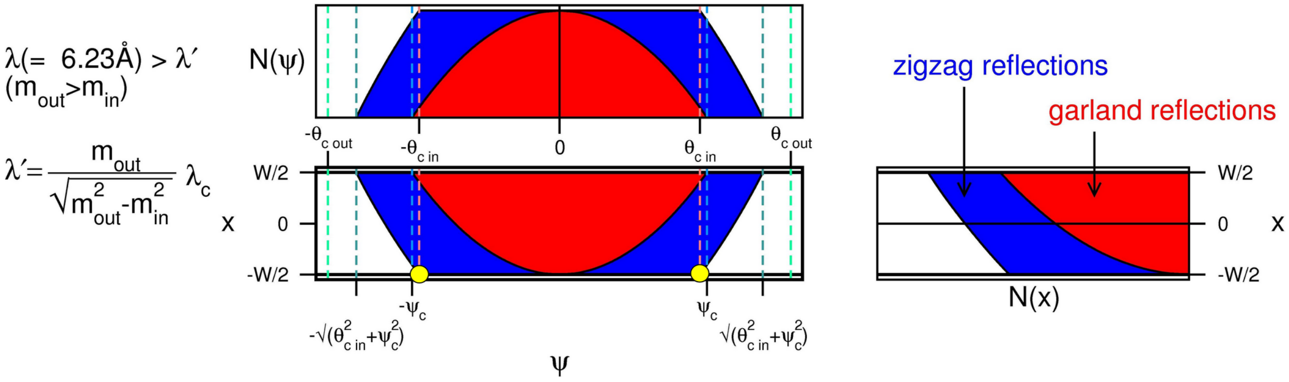
- Neutron spatial-angular distributions (no line of sight)
- If $m_{out} > m_{in}$, λ' exists

$$\lambda' = \lambda_c \frac{m_{out}}{\sqrt{m_{out}^2 - m_{in}^2}}$$





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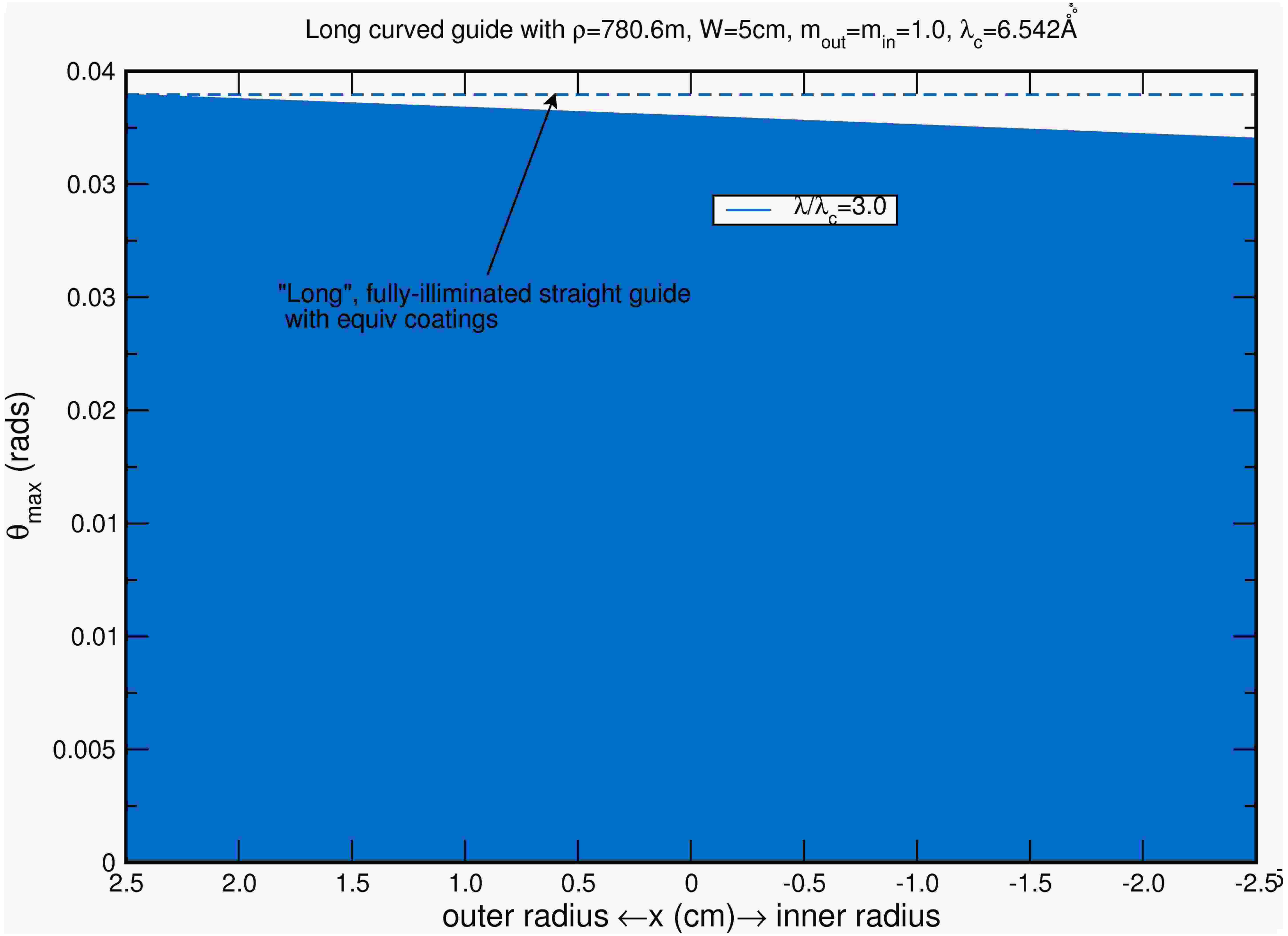
NEUTRON GUIDE OPTICS

CURVED GUIDES

- Neutron spatial-angular distributions (no line of sight)



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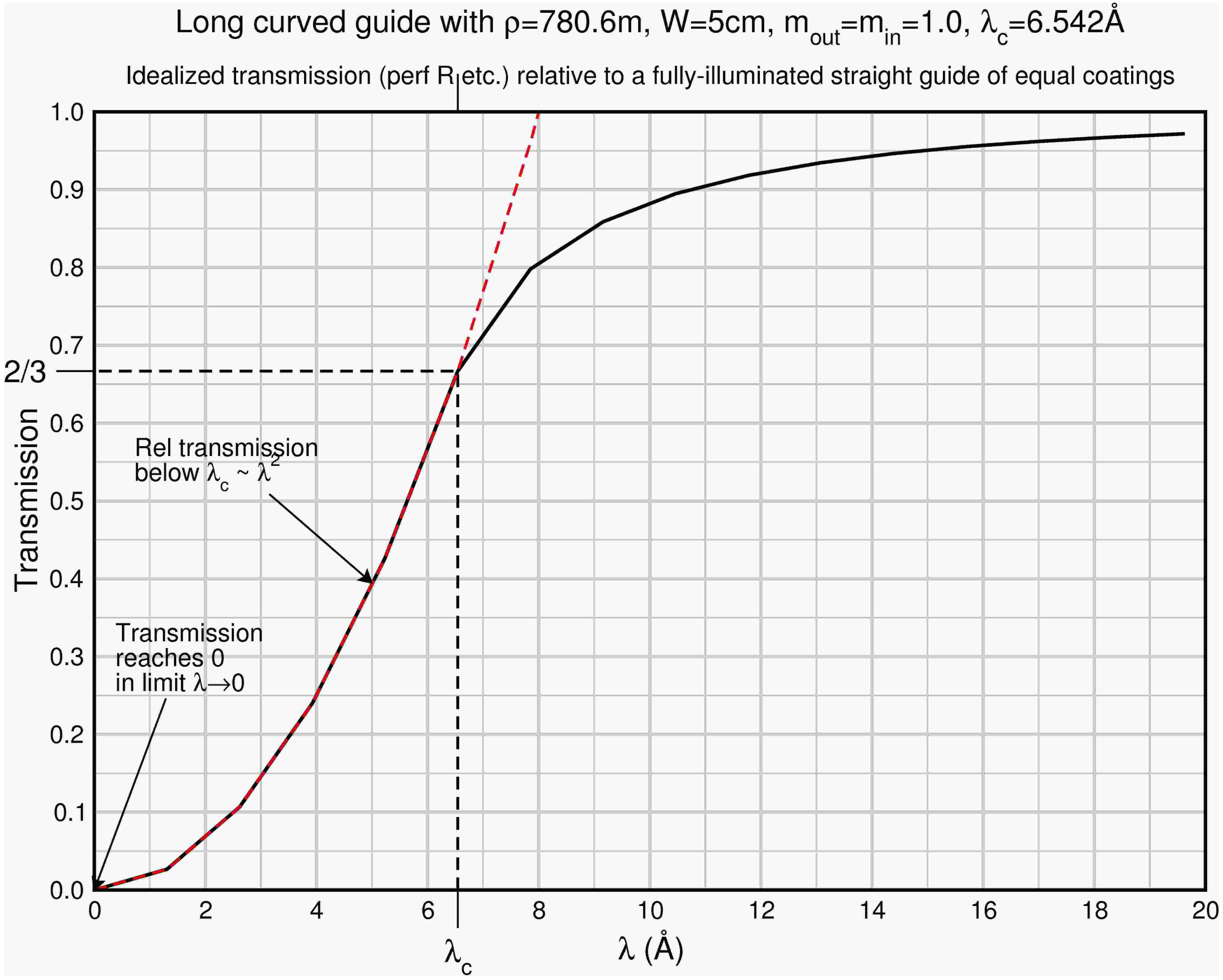
CURVED GUIDES



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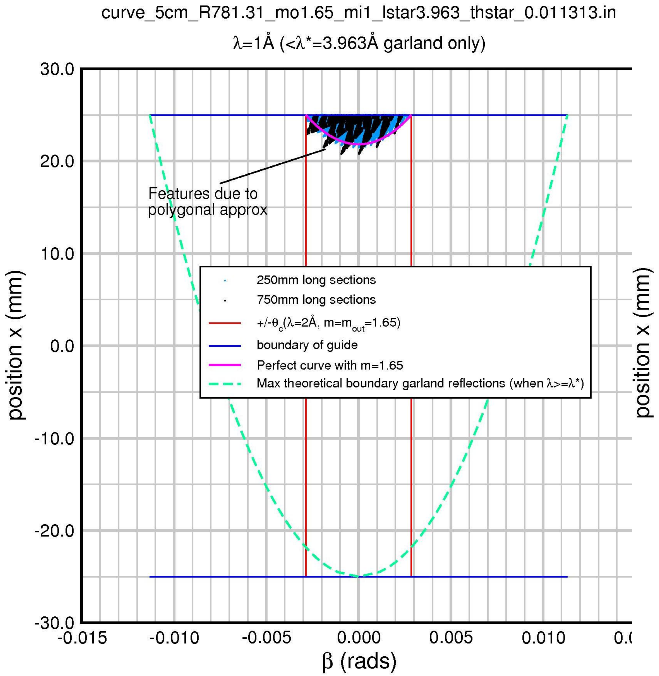
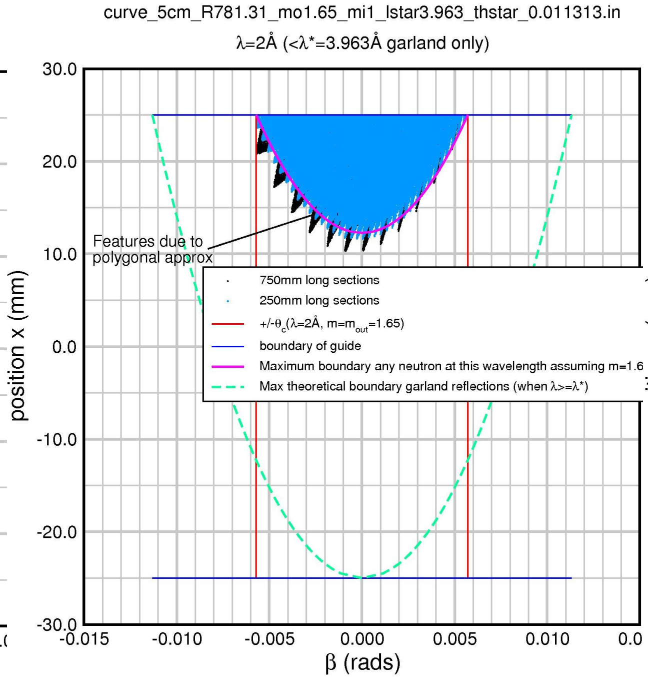
NEUTRON GUIDE OPTICS

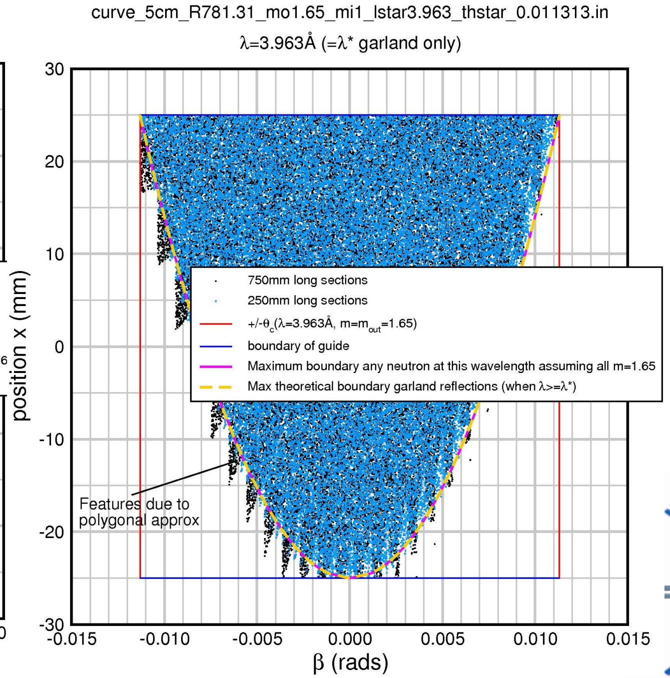
CURVED GUIDES – EFFECT OF POLYGONAL APPROXIMATION

- Usually use a polygonal approximation for curved guide (straight sections with angular offsets)
- Puts jagged edges and holes in acceptance diagram (gets more exaggerated as λ reduces or length of elements increase for a given ρ (bend angle becomes increasing fraction of θ_c)

Example similar to NG-Bl (ρ =781m) with 750mm (bend angle=0.055°) or 250mm elements (bend angle=0.0183°) and λ=1Å, 2Å, or $\lambda=\lambda_c\approx$4Å)







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CURVED GUIDES – EFFECT OF POLYGONAL APPROXIMATION

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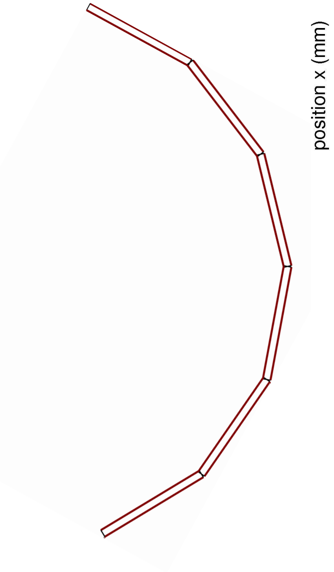
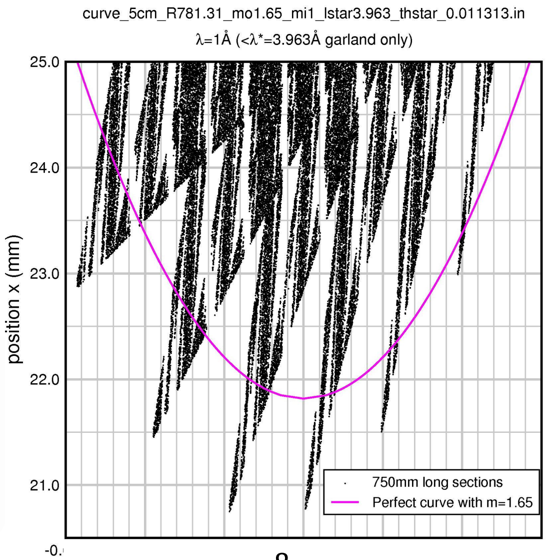
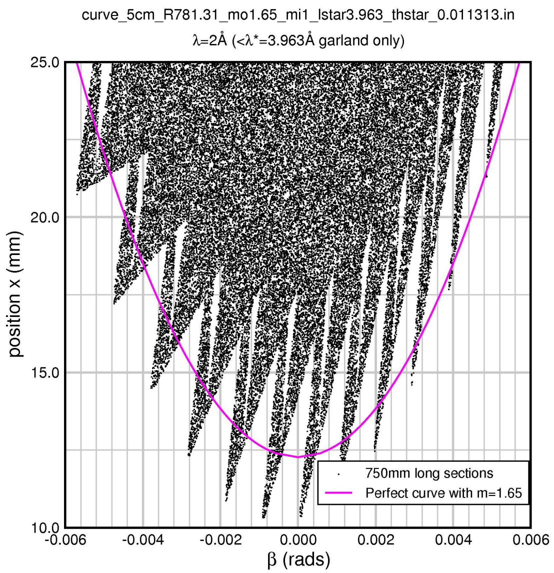
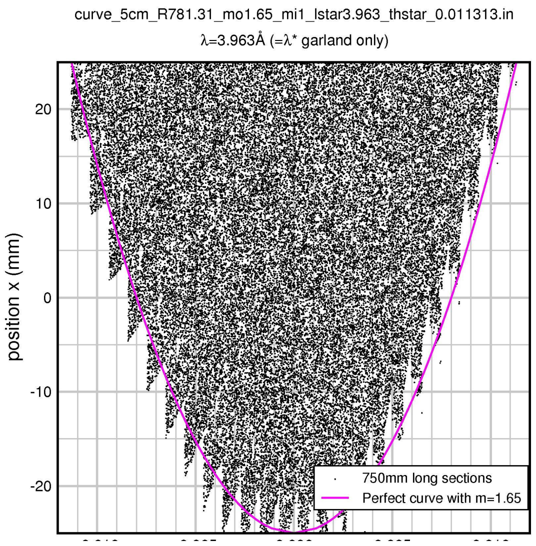


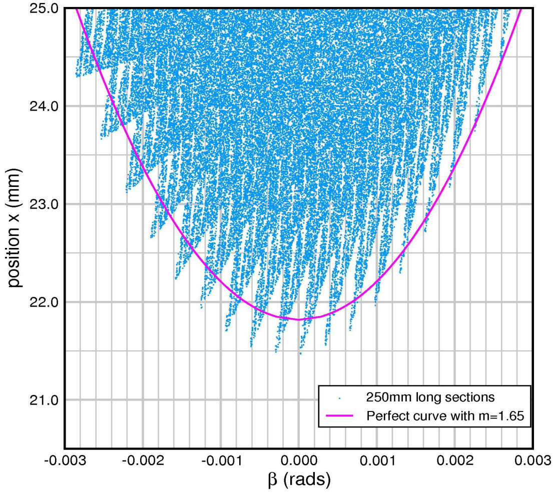


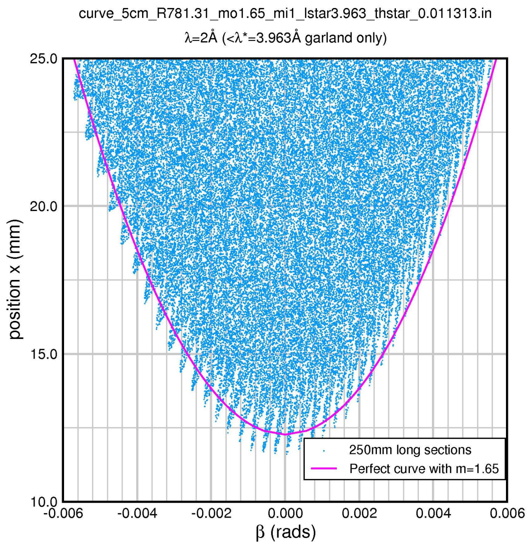


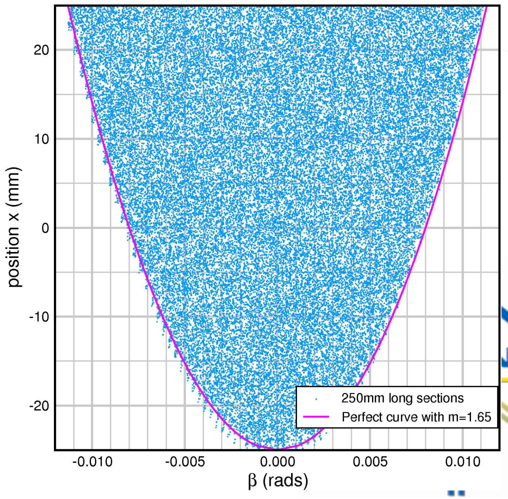


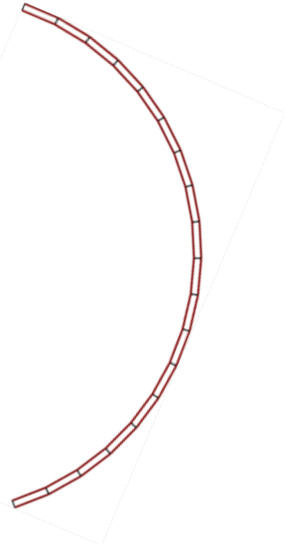
$\lambda=\lambda_c\approx 4Å$, l=750mm

$\lambda=\lambda_c\approx 4Å$, l=250mm









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NEUTRON GUIDE OPTICS

CURVED-STRAIGHT GUIDES

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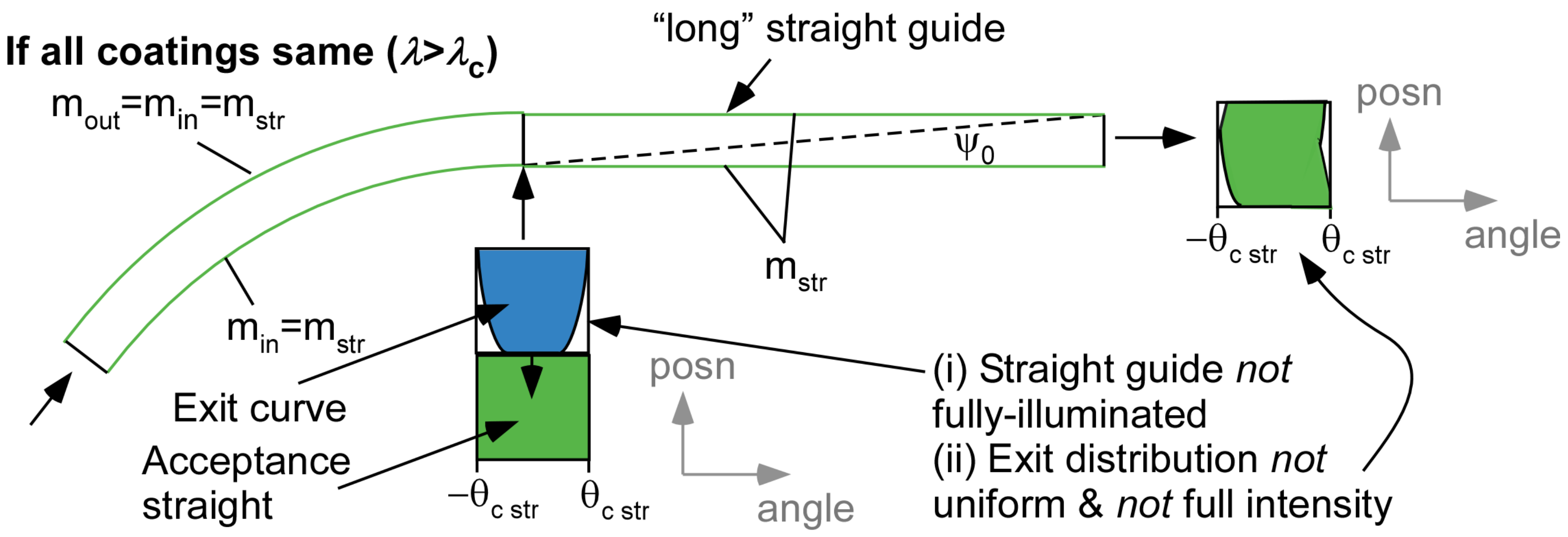
- With fixed *m* coatings improves but does not cure spatial-angular non-uniformity



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Neutron guide optics

Some tricks: PST guide concept (limited div guides)

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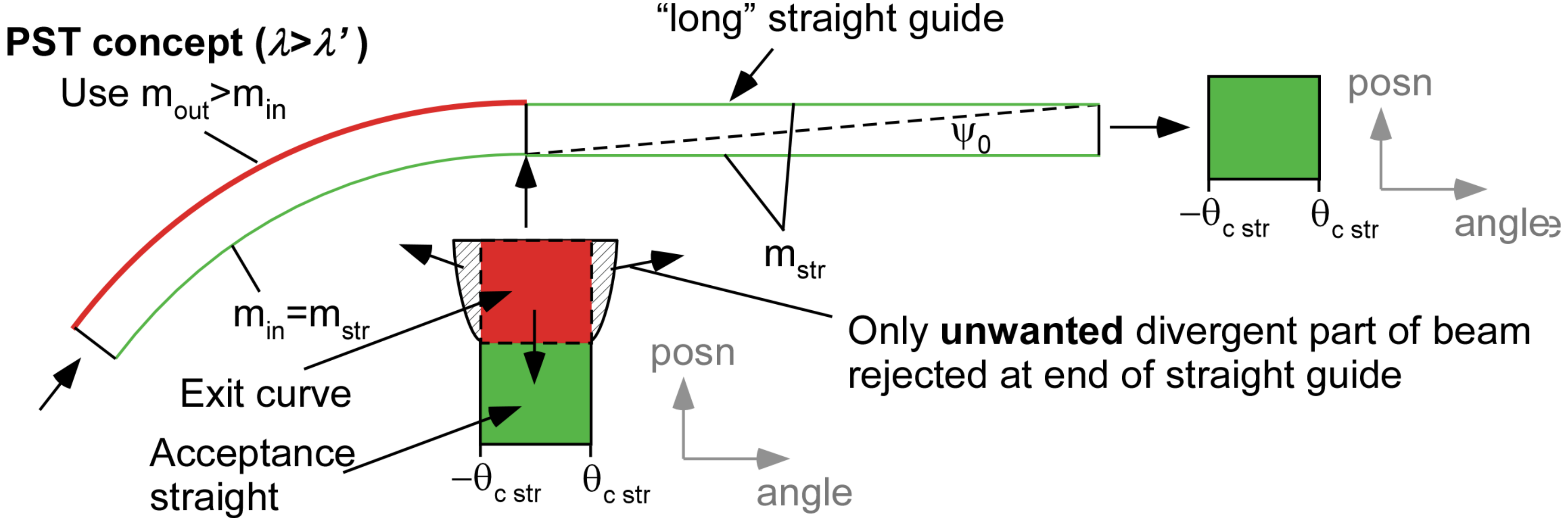
THEN straight part fully-illuminated for all $\lambda > \lambda'$

- Uniform beam at exit
- Required divergence at exit
- Intensity like straight guide *without* xtal filt

$$\lambda' = \lambda_c \frac{m_{out}}{\sqrt{m_{out}^2 - m_{in}^2}} = \frac{1}{\gamma_{Ni}} \sqrt{\frac{2W}{\rho\left(m_{out}^2 - m_{in}^2\right)}}$$



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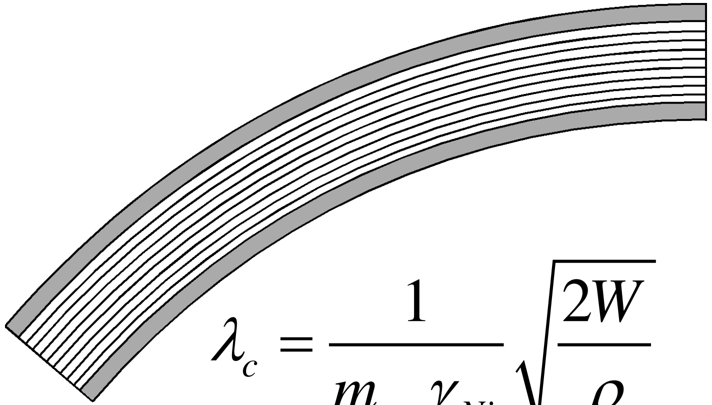
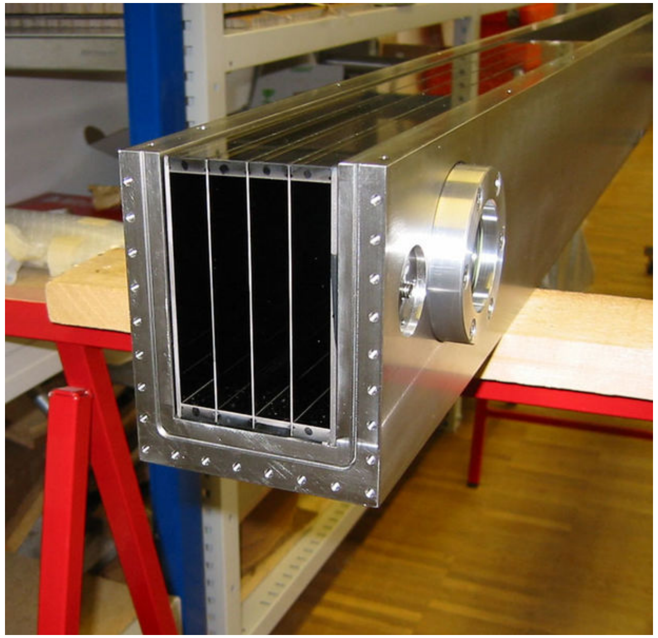
BENDERS

NEUTRON GUIDE OPTICS

BENDERS



$$\lambda_c = \frac{1}{m_{out}\gamma_{Ni}}\sqrt{\frac{2W}{\rho}}$$



- Allow larger deflection in restricted space than equivalent curved guide (NGA')
- Decreasing λ_c increases transmission (reduce W, increase ρ, increase m_{out}) but decreasing $W \Rightarrow$ more channels, more blanking – find optimum
- Increasing λ_c decreases short wavelength background
- Can also be polarizing

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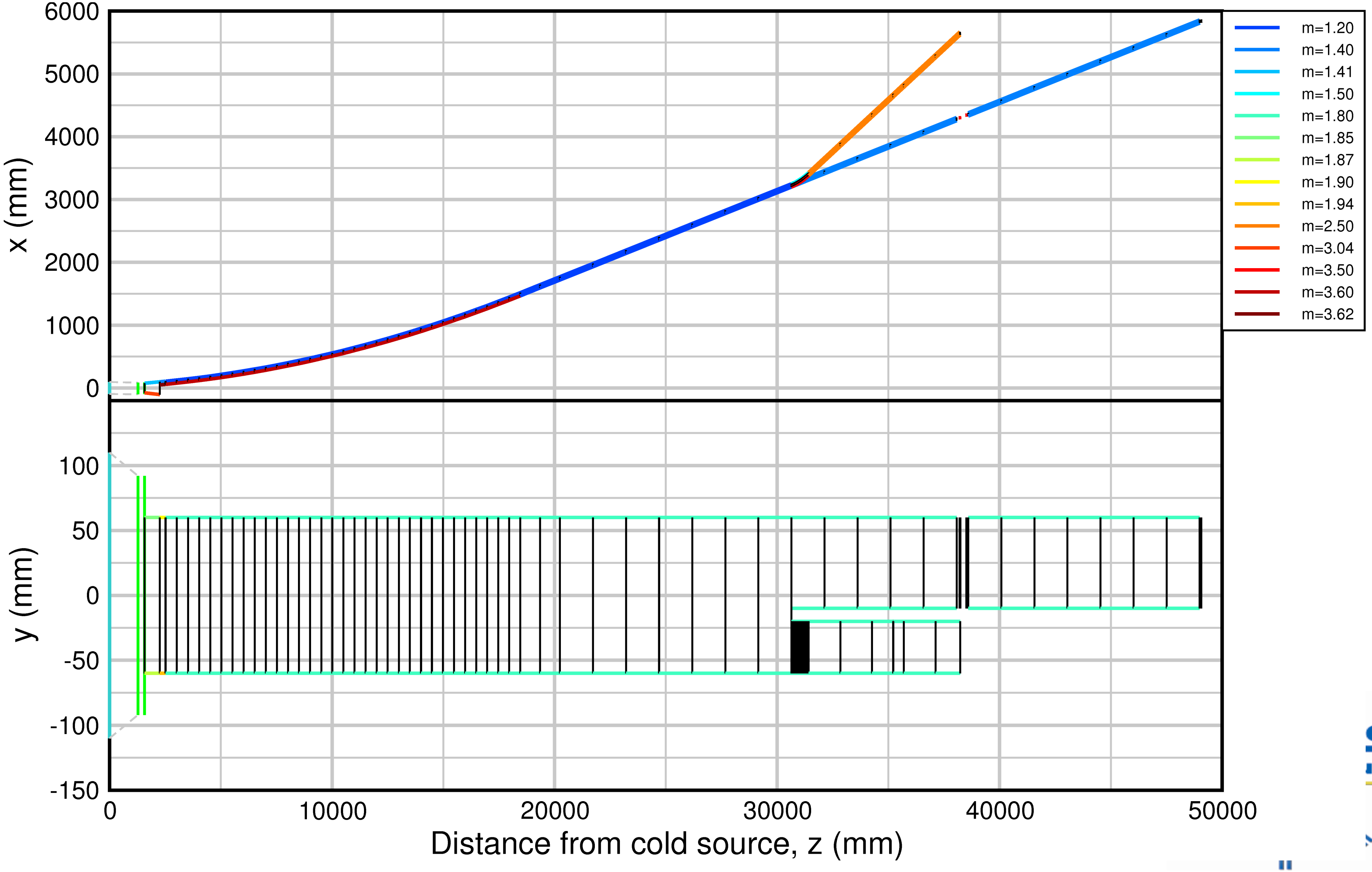
NGA´ for NDP



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NGA´ for NDP

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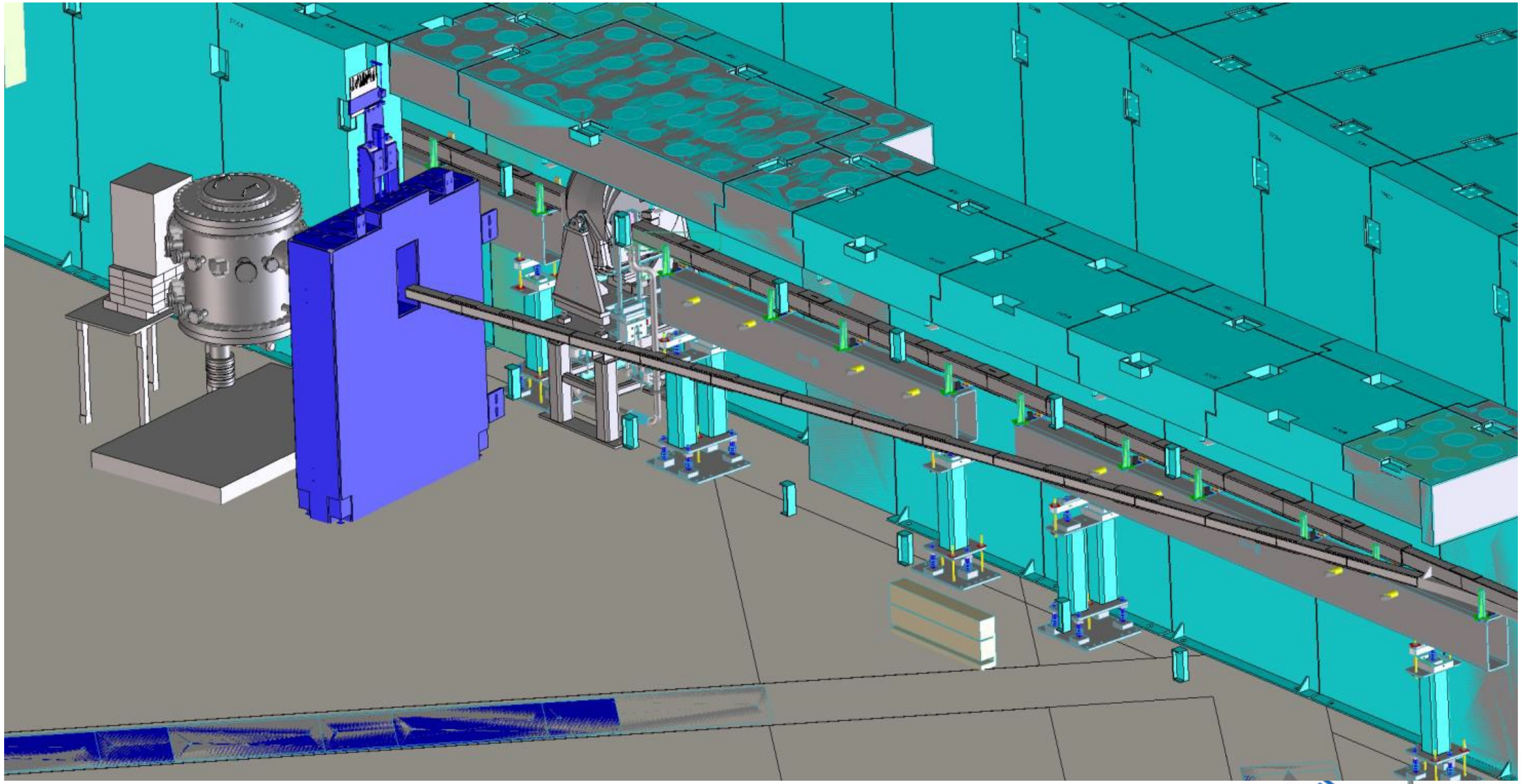

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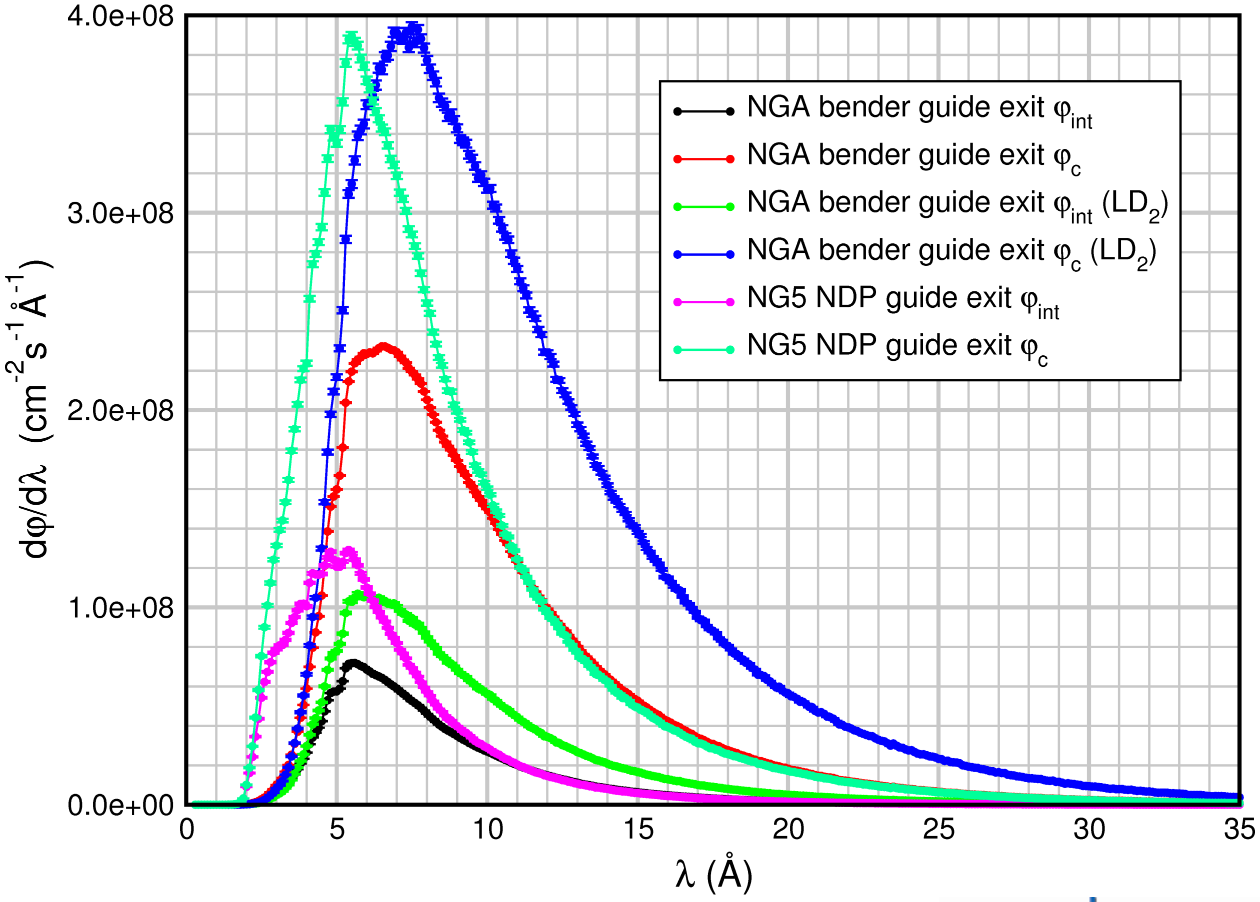
NGA´ for NDP

	ϕ_c (x10^9 cm^{-2} s^{-1})	J_c (x10^{10} /s)
D_2 NGA′	**3.7**	7.3
NGA′	1.9	3.7
NG5	**2.7**	2.4



The NGA´ beam will be very cold and very clean (already out of line of sight of feed guide)

⇒ low background

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NEUTRON GUIDE OPTICS

FOCUSING AND PROFILED GUIDES

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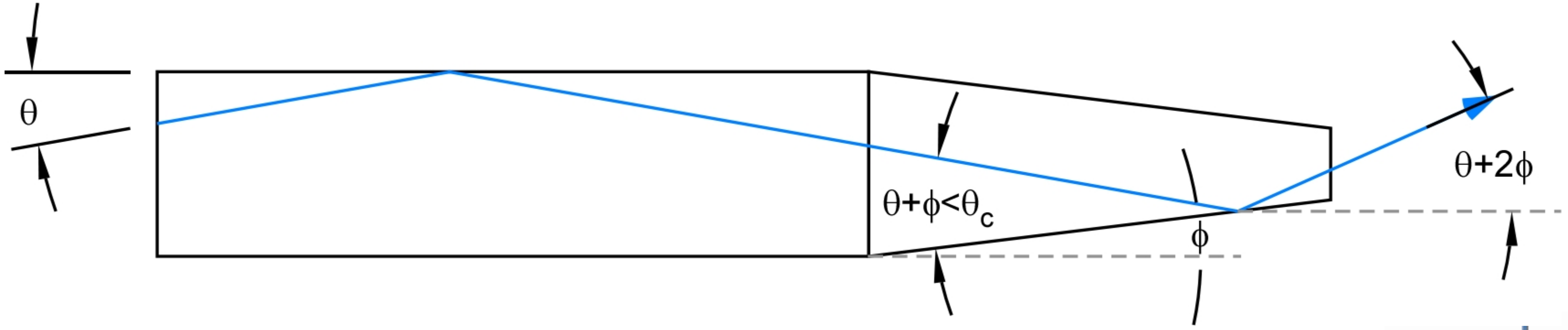
- **Linear taper**
  - Most early focusing guides were linearly tapered (can taper in both directions)
  - Focus (max flux) is physically at exit of taper
  - Focusing compresses beam in size (flux increases) **but beam divergence increases** (unavoidable consequence of Liouville's theorem) – sometimes undesirable
  - Eventually critical angle limits what can be reflected



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NEUTRON GUIDE OPTICS
FOCUSING AND PROFILED GUIDES

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- **Elliptical, parabolic, general form, etc.**
- Elliptical: foci can be beyond guide exit
- Ellipse: Can think of "focusing on source and/or sample"
- Ellipse with point source at one focus transmits with (at most) 1 reflection to sample placed at other focus
- Unreflected still defocusing (divergence depends on solid angle of direct view)
- Transmission efficiency high because few reflections from source to sample
- Have extended sources and samples ⇒ multiple reflections and possibly structure in source image (often want uniform neutron distributions at sample)

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FOCUSING AND PROFILED GUIDES

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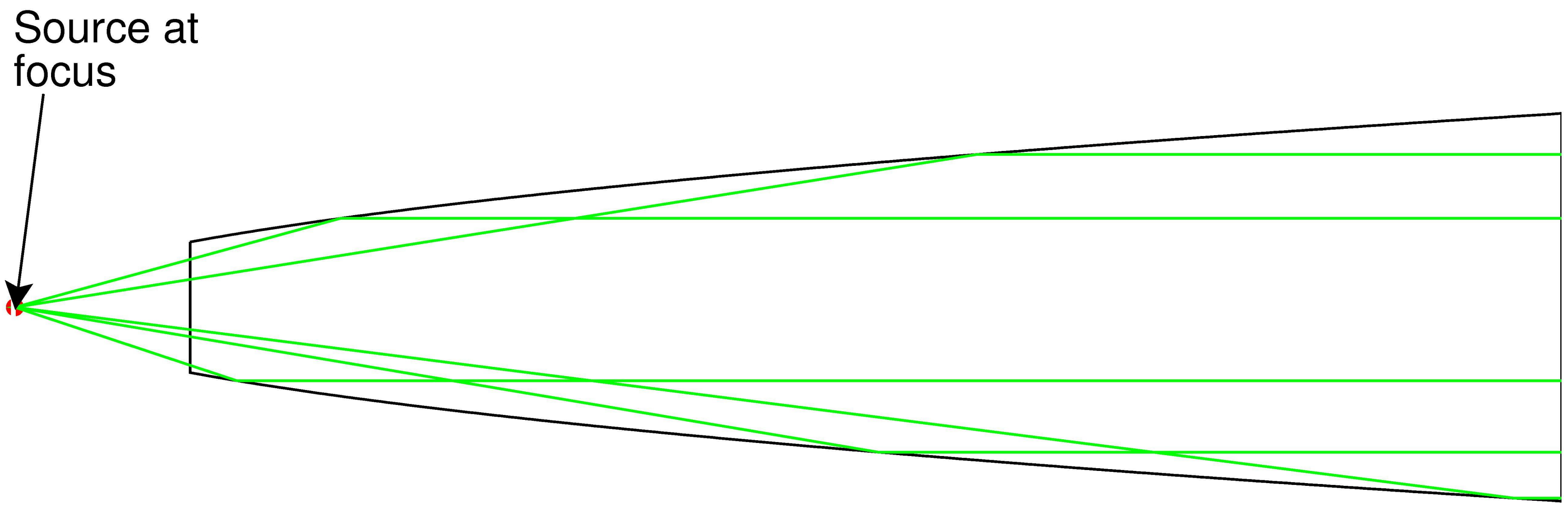
- **Parabolic**
- Can think of "focusing on source" (time-reversal)
- With point source at focus converts small divergent source beam into broad parallel beam (reflected component)
- Un-reflected still divergent depending on solid angle of direct view
- Transmission efficiency high because few reflections from source to sample
- Neutron experiments have use extended sources



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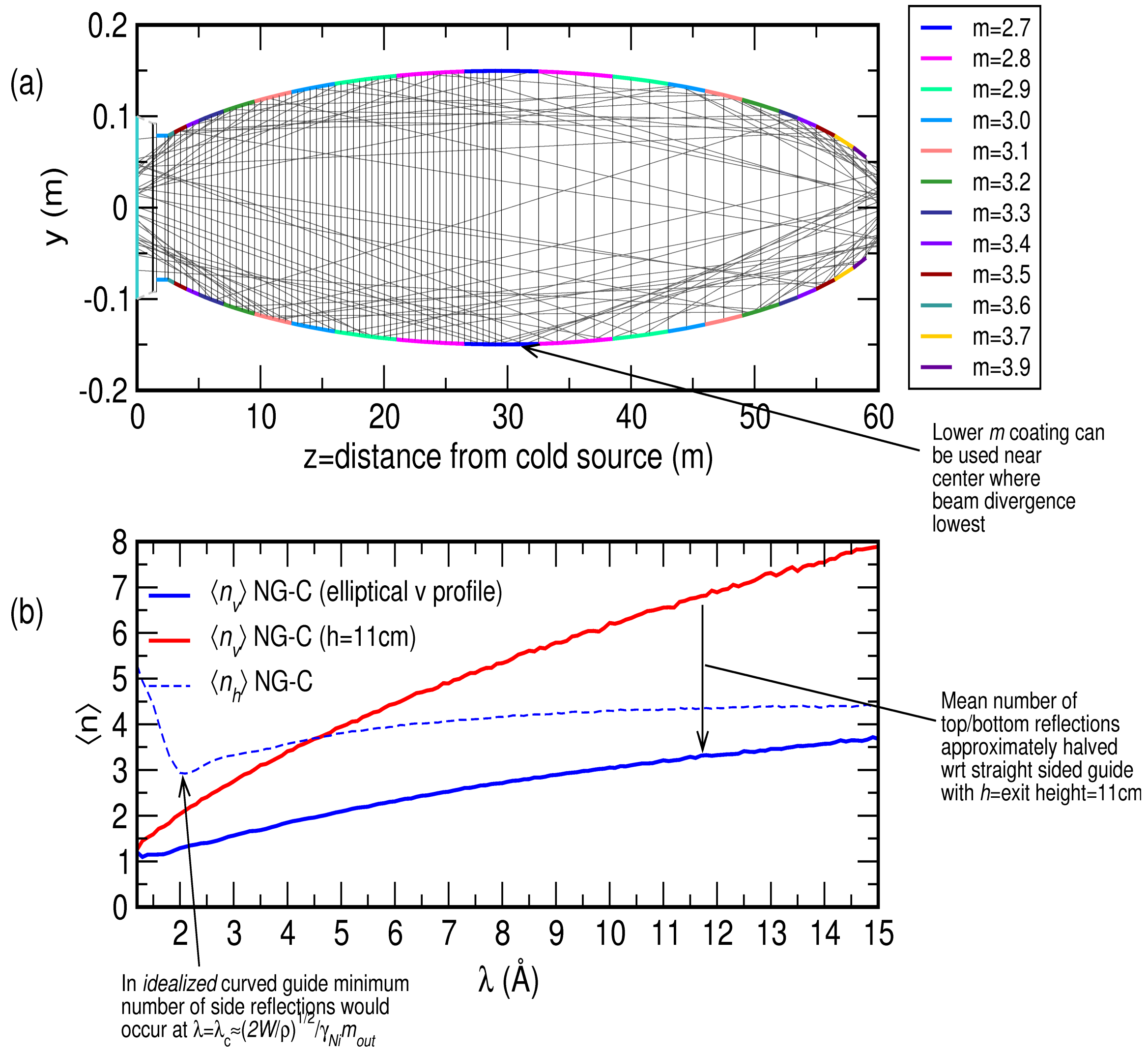
NEUTRON GUIDE OPTICS

ELLIPTICAL GUIDES AT NCNR

ISNIE



- **NGC elliptical in vertical plane (increases transmission efficiency), graded *m***

1. Ellipse accepts narrower divergent beam from source
2. Converts to wider less divergent beam in the center
   a) Allows long distances traveled with reduced number of contacts (losses) at the guide walls
   b) Also permits lower *m* to be used near center.
3. Refocuses beam near exit increasing the flux and reduces the beam size (but divergence increases)

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ELLIPTICAL GUIDES AT NCNR

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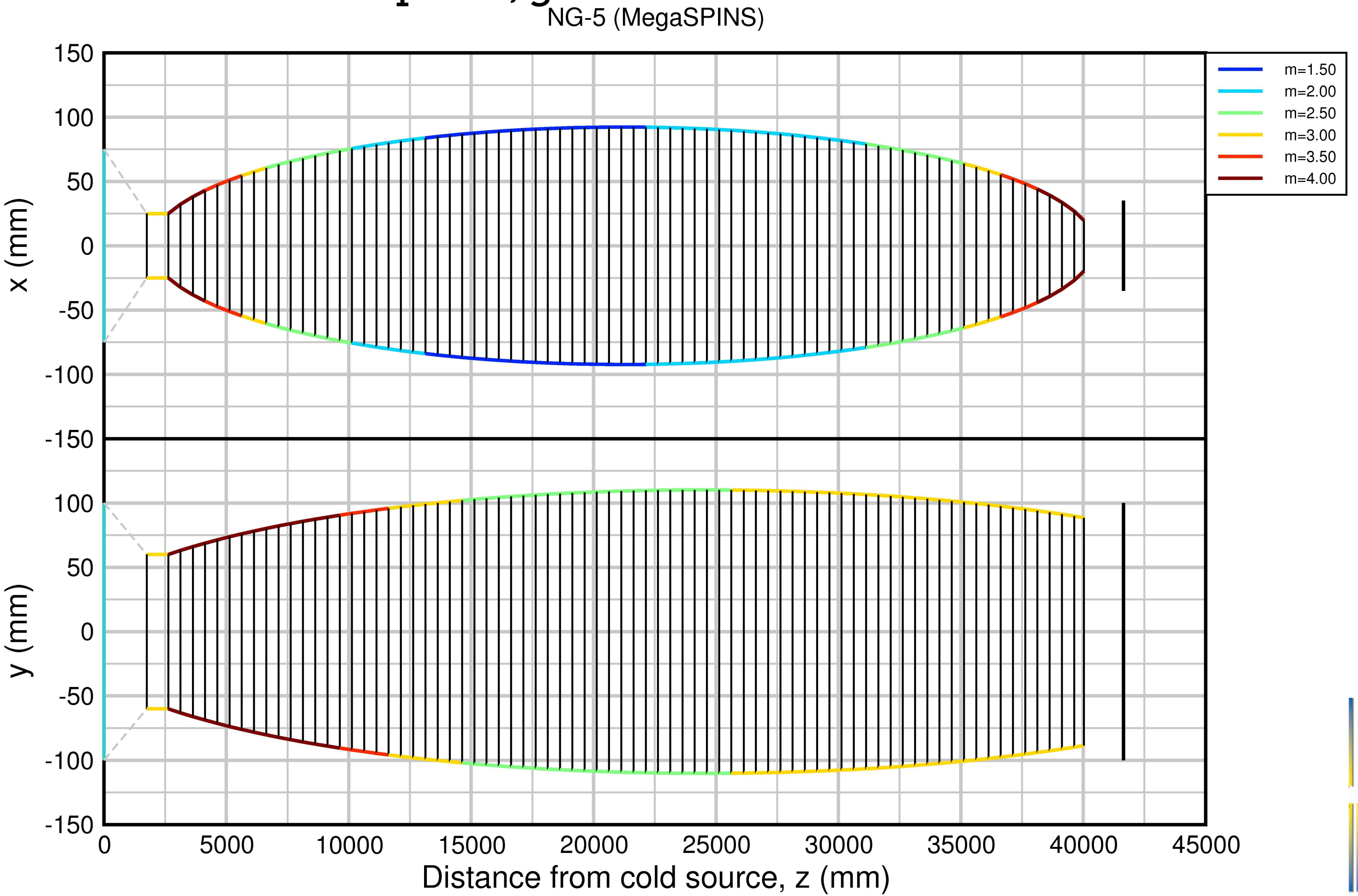
- NG5 will be bi-elliptical, graded *m*



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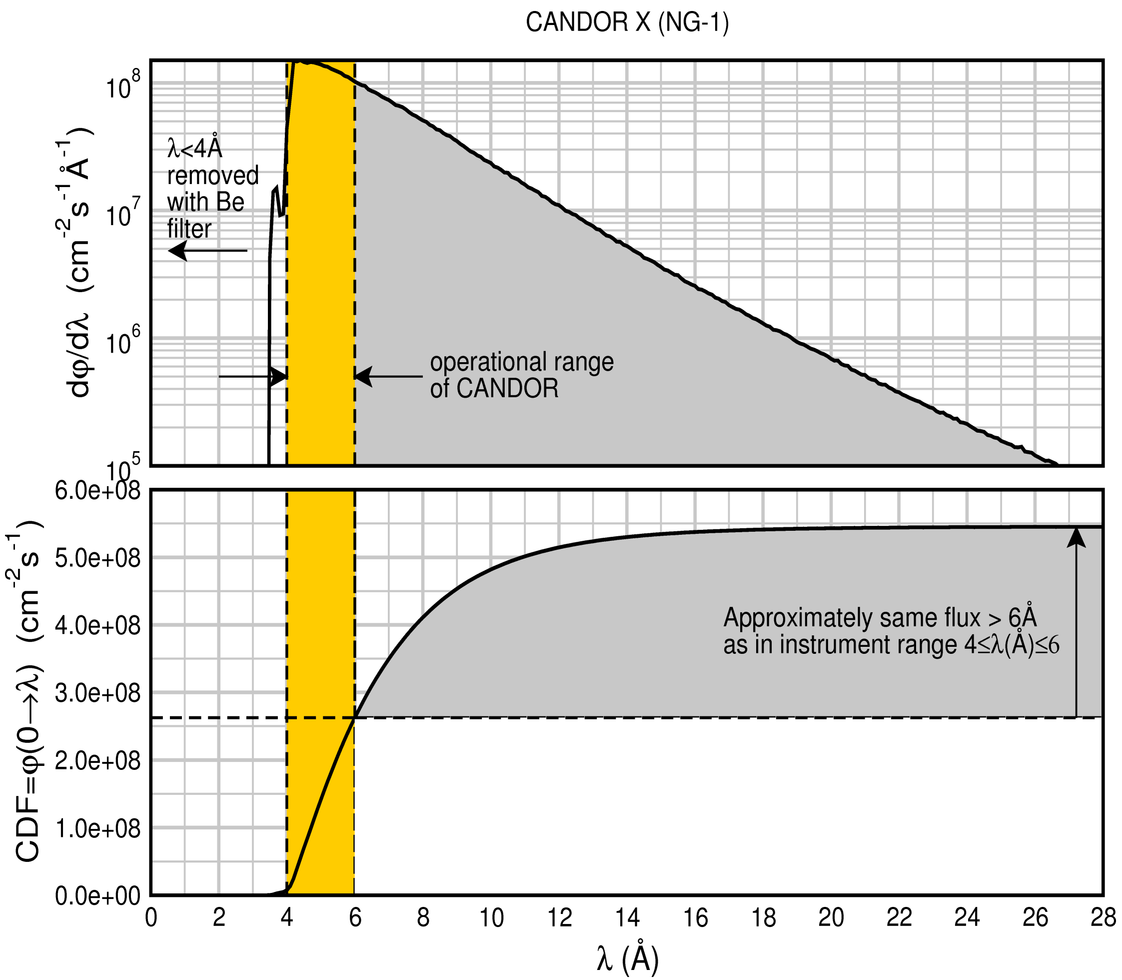
LONG WAVELENGTH CUTOFF DEVICE FOR CANDOR

ISNIE



- CANDOR instrument at NCNR uses **ONLY wavelength range between 4 and 6Å**
- Wavelengths **outside of this range** only contribute to **instrumental background**
- Eliminate $\lambda < 4$Å very effectively with Be filter
- Want to reduce wavelengths with $\lambda >$ 6Å with minimal penalty to $\lambda \leq 6$Å

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X-DEFLECTOR (CANDOR)

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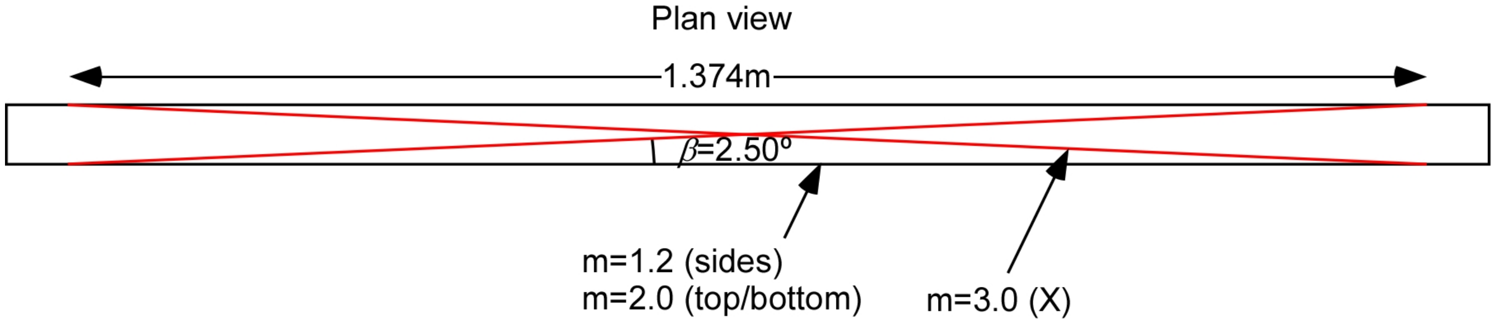

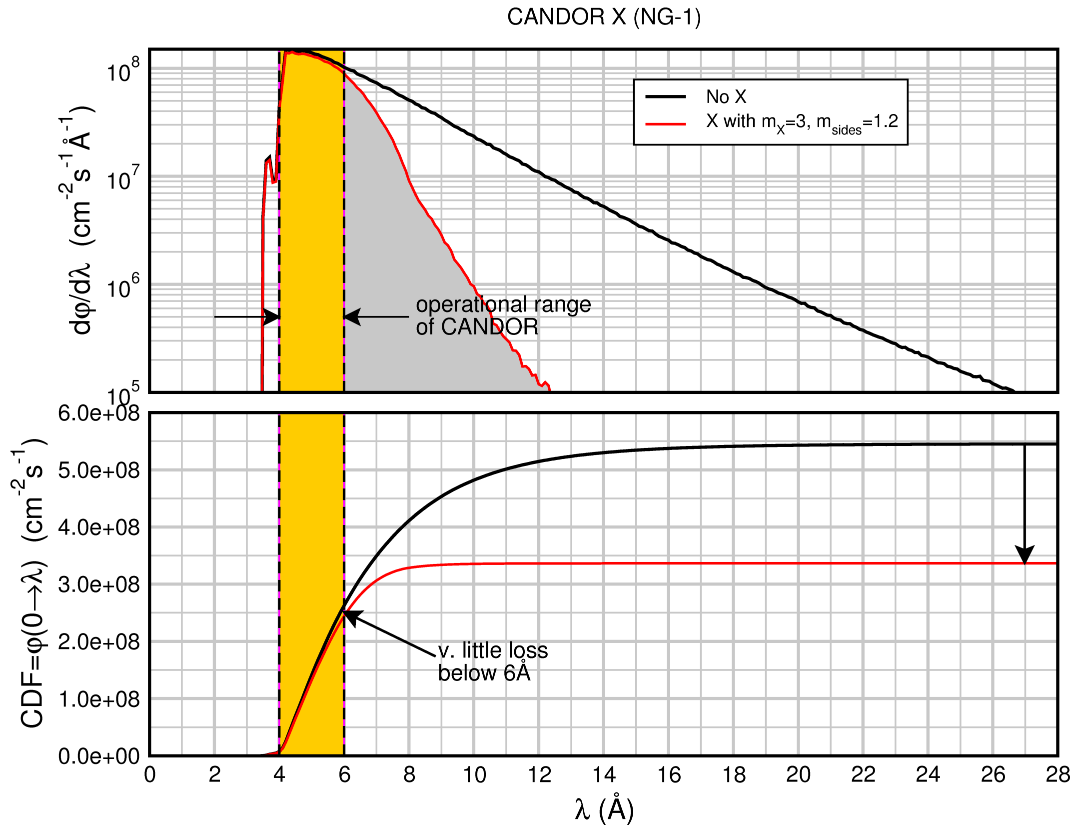

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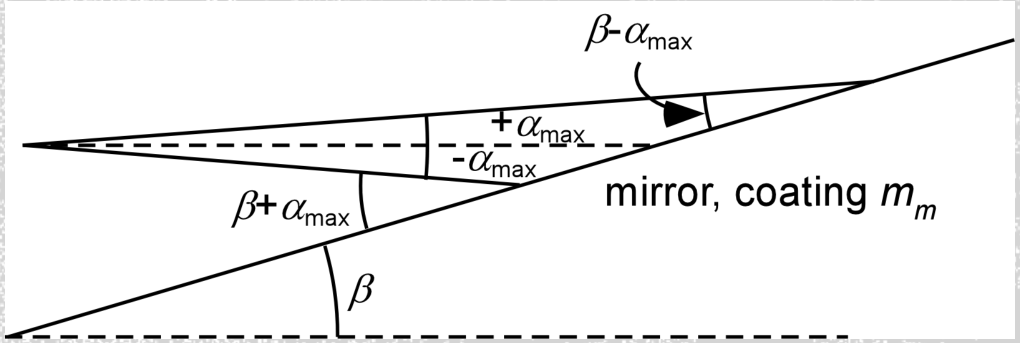
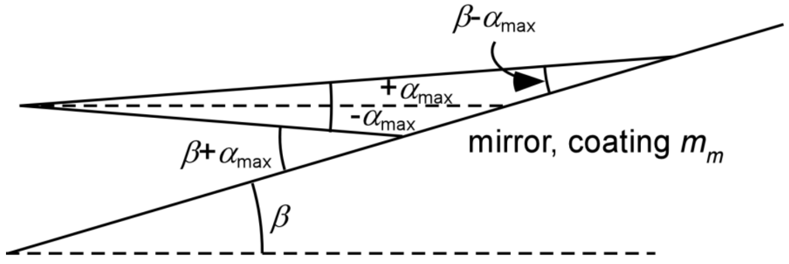
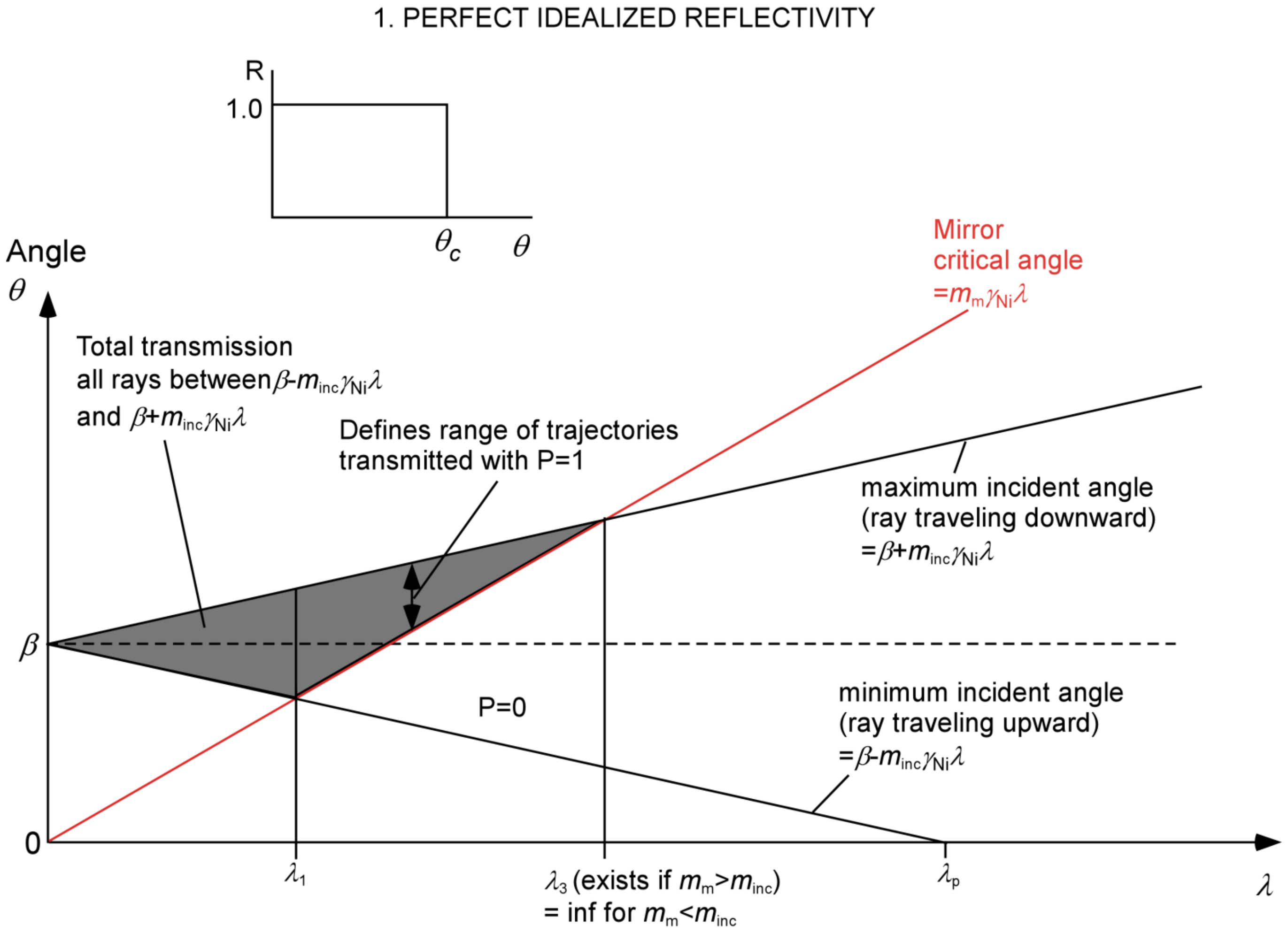
SPECIAL DEVICES
LONG WAVELENGTH CUTOFF



Special devices

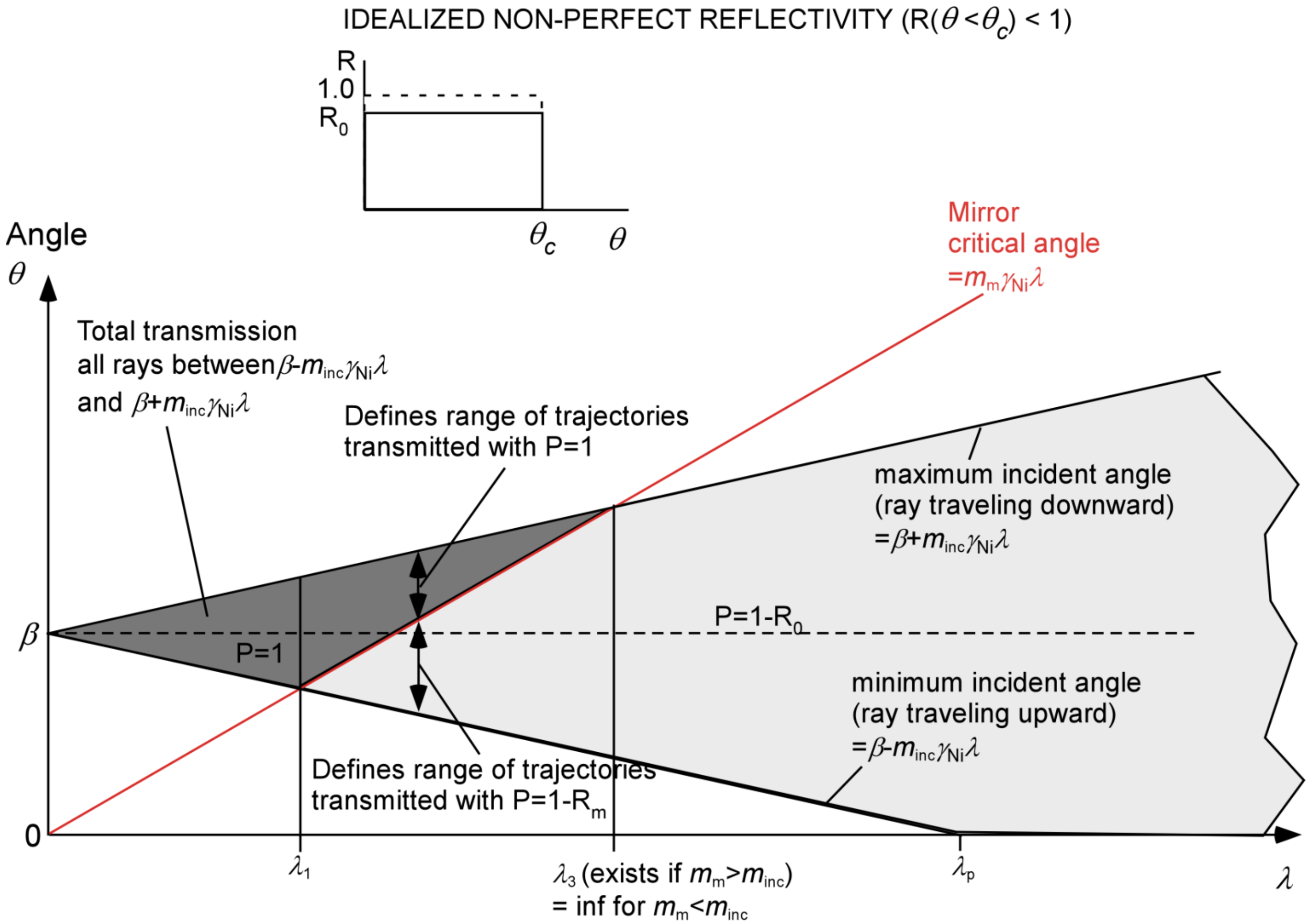
Long wavelength cutoff device (perfect R, transmission)

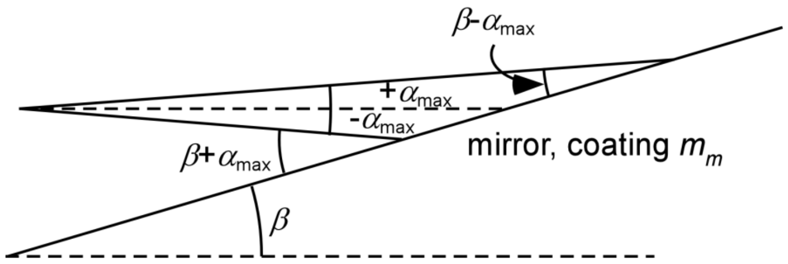




Neutron guide optics

Long wavelength cutoff device (imperfect R, transmission)





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Neutron guide optics
"V" or "X" (may be asymmetric)

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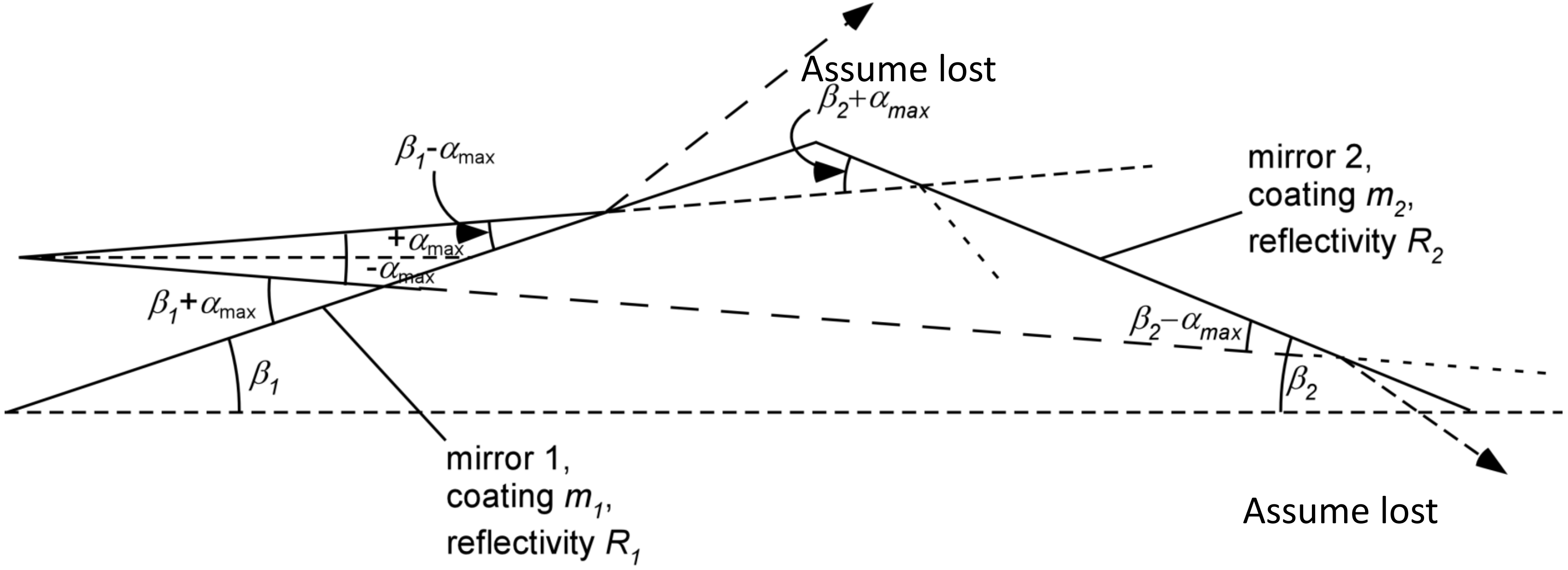

Ignore physical length of device for now

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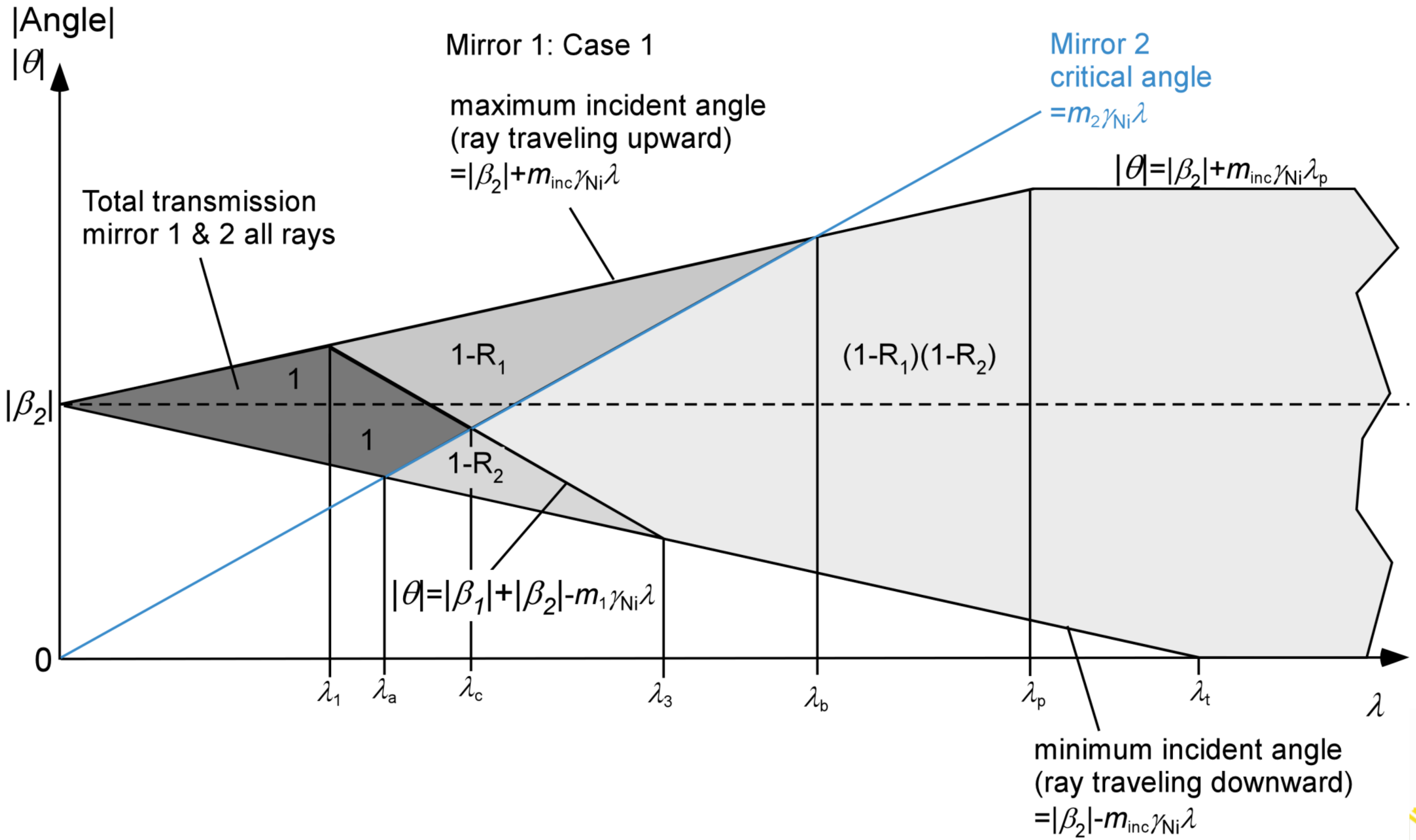
Neutron guide optics
"V" or "X" (may be asymmetric)

ISNIE



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SPECIAL DEVICES
POLARIZERS

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POLARIZING DEVICES – POLARIZING GUIDES

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- Polarizing guide (Fe/Si, FeCoV / TiN supermirror) – typically require several 100 Gauss magnetic field in "easy magnetization direction" (plane of supermirror) to "saturate" magnetization in desired direction

Polarizing guide at FRM2, Munich

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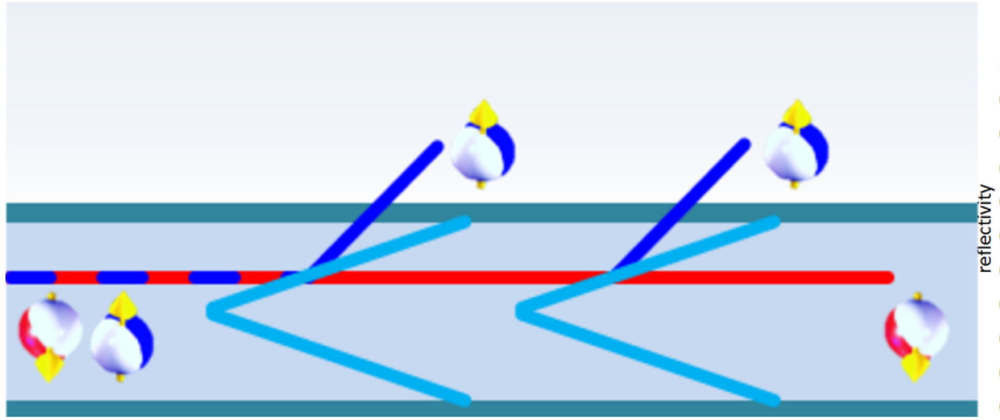
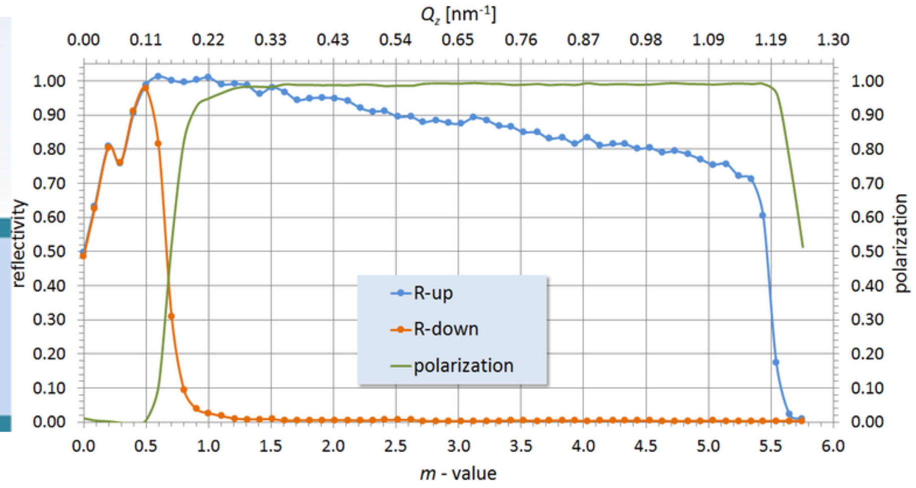
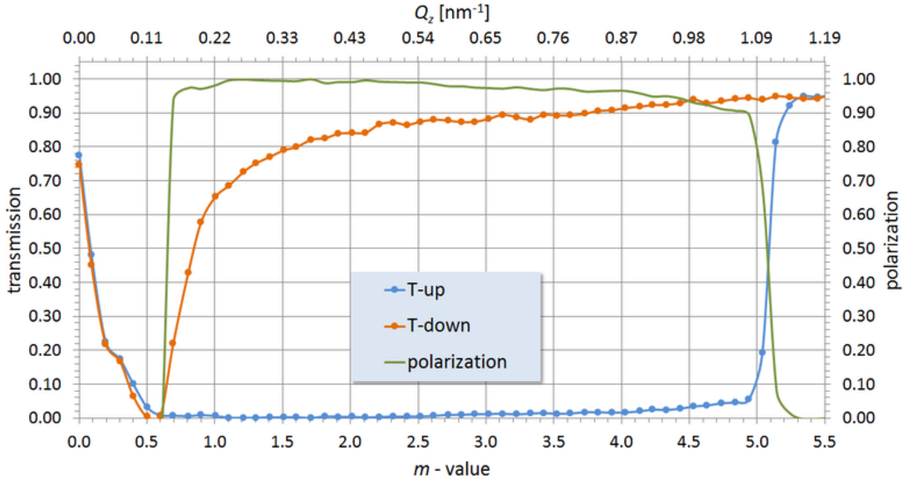
POLARIZING DEVICES – V-POLARIZER

- Polarizing: Fe/Si, FeCoV / TiN (problem activation of Co (^{60}Co $T_{1/2}$>5 yrs) – require few Gauss magnetic field in "easy magnetization direction" (plane of supermirror)







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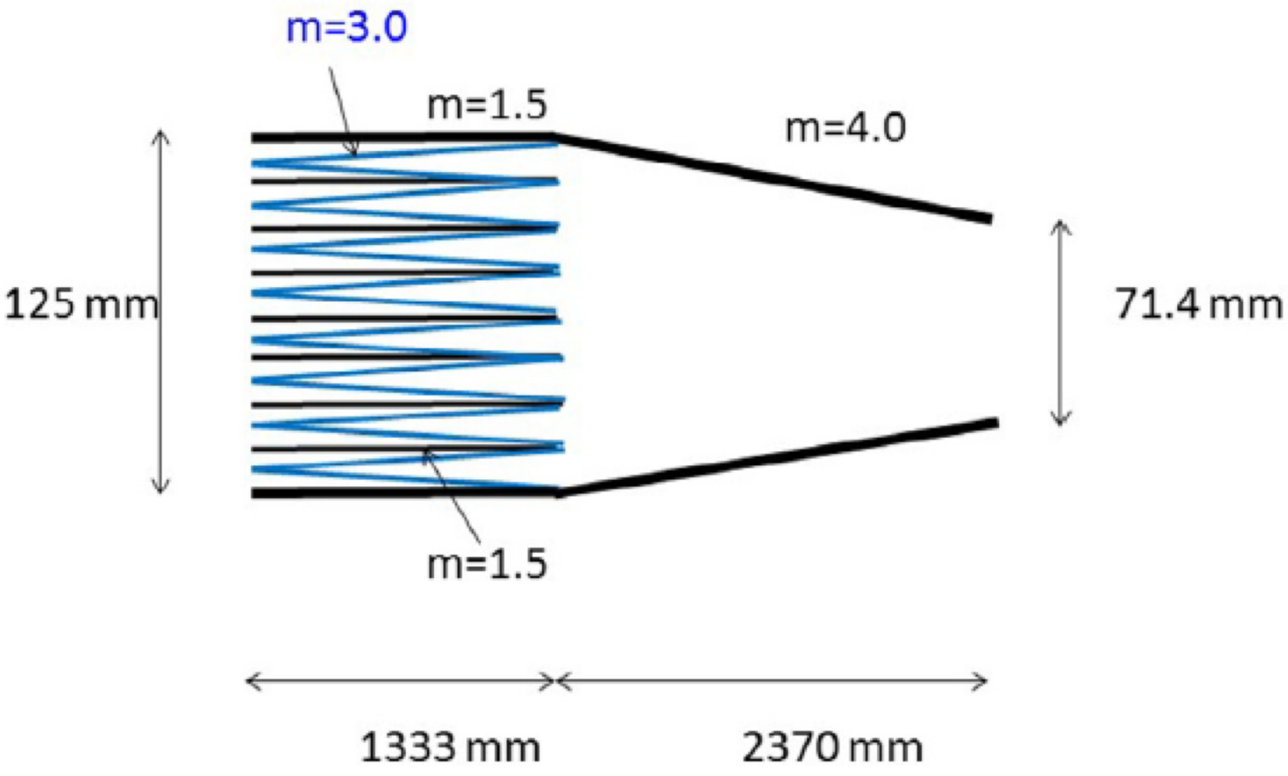
POLARIZING DEVICES – V-POLARIZER …

ISNIE

R.R. Gainov, F. Mezei, J. Füzi, M. Russina
Nuclear Inst. and Methods in Physics Research, A 930 (2019) 42–48



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- Because of the small angles required for the V's devices can be long
- May be remedied by placing multiple adjacent shorter V's

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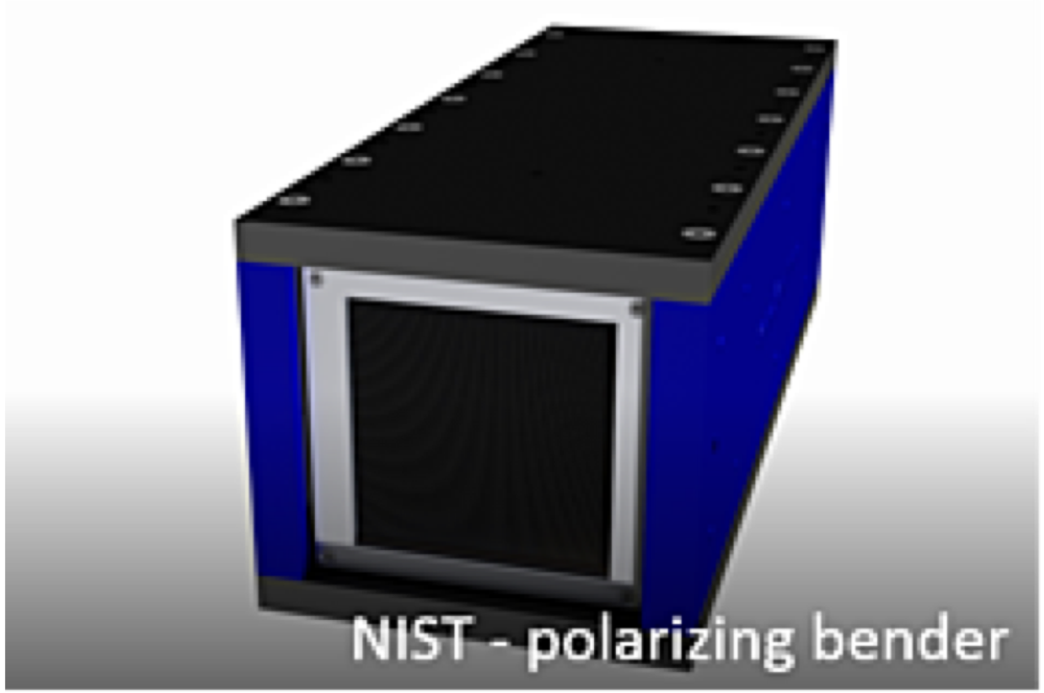
POLARIZING DEVICES – POLARIZING BENDER

- Otto Schärpf (ILL 1980's)



Polarizing bender - NIST (2013)

Bender design

Number of channels:	60
Path/Profile:	truly curved
Radius of curvature:	11160 mm
Cross-section:	106 mm(*w*) x 100 mm (*h*)
Length:	402 mm
Width of channels:	1.37 mm
Thickness of blades:	0.3 mm
Coating of blades:	Fe/Si, m = 2.5

Specials

Magnetic casing with B = 450G

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WINDOWS

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GUIDE WINDOWS

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- Must have high thermal/cold neutron transmission (low scattering and absorption)
- Most materials have "1/*v*" absorption (absorption cross-section increases ∝ λ)

$$\sigma_a(v_n) \approx \sigma_{a,2200} \frac{2200}{v_n\left[\mathrm{ms}^{-1}\right]} \quad \text{or} \quad \sigma_a(\lambda) \approx \sigma_{a,2200} \frac{\lambda\left[\mathrm{\mathring{A}}\right]}{1.7982}$$

$$T = \exp\left(-\Sigma_a t\right), \qquad \Sigma_a = \sum_i N_i \sigma_{a,i}$$

- Usually assume that *any* scattering loses neutron from the beam so

$$T \approx \exp\left(-\Sigma_t t\right), \qquad \Sigma_t = \sum_i N_i \left(\sigma_{a,i} + \sigma_{s,i}\right)$$

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GUIDE WINDOWS

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- Windows are "thin" (exponent is small) so

$$T \approx \exp\left(-\Sigma_t t\right) \quad \approx 1 - \Sigma_t t$$

- This means that the absorption probability $\approx \Sigma_a t$, so **prompt gamma production and activation rate ∝ $t\lambda$ (minimize t!)**
- Common materials for guide windows Al (Al6061-T6), Mg (AZ31B – 3% Al, 1% Zn), Be
- Note neutron activation of Al, ^{28}Al $T_{1/2}$=2.3 minutes
  - Saturation activity is reached after a few minutes of irradiation
  - Should wait at least 20 minutes before approach after beam off

MISALIGNMENT

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EFFECTS OF MISALIGNMENTS

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- Spatial misalignments
  - Lose transmittable area of beam
  - Steps can block non-negligible preceding reflecting surface due to small reflection angles
- Angular misalignments
  - Can be cumulative increasing error of intended trajectory
  - Cause additional trajectories to exceed critical angle
- Causes
  - Manufacturing defects - machining, measurement accuracy limitations (also substrate waviness, parallelism)
  - Installation errors
  - Building settlement
- Effects of both types of misalignment tend to decrease with increasing wavelength (e.g. for instance if angular offset $\ll$ critical angle) BUT longer wavelengths tend to reflect more on the average (depends on design)
- Effects can be estimated in simulations

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BONUS
COSTING APPROXIMATIONS

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(VERY) APPROXIMATE GUIDE COSTS!

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- "Home-made" algorithm based on purchased guide data and some guesses (zero knowledge of proprietary cost algorithms!)
- Over-dependence fraught with danger (many variables, including load and market constraints which are NOT factored in)
- For rough initial budget estimates only – **only for standard or simple tapered elements**
- **I will deny all knowledge of this in cases of failure!**

Glass cost ,

$$C_{glass} = C_{fixed} + L(\mathrm{m})\left(C_l + C_{pol}\,\max\left[w_{ent}(\mathrm{cm}), w_{ex}(\mathrm{cm}), h_{ent}(\mathrm{cm}), h_{ex}(\mathrm{cm})\right]\right)$$

where $C_{fixed} = \$415$, $C_{pol} = \$656\mathrm{m}^{-1}\mathrm{cm}^{-1}$ (polishing) and

1 Non-tapered or singly tapered

$C_l = \$7963$

2 Doubly-tapered

$C_l = \$9555$

Supermirror/coating cost for side i

$$C_{coat,i} = C_{m,i} A_i \left(m^2\right)$$

where

$$C_{m,i} = \begin{cases} \$1700 m^{2.9} & \text{SM} \\ \$1700 & \text{Nat Ni} \\ \$5806 & {}^{58}\text{Ni} \end{cases}$$

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END

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