Development and Applications of Supermirror

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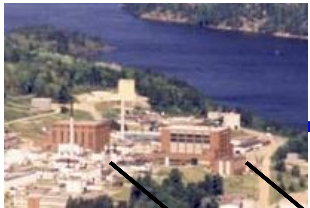
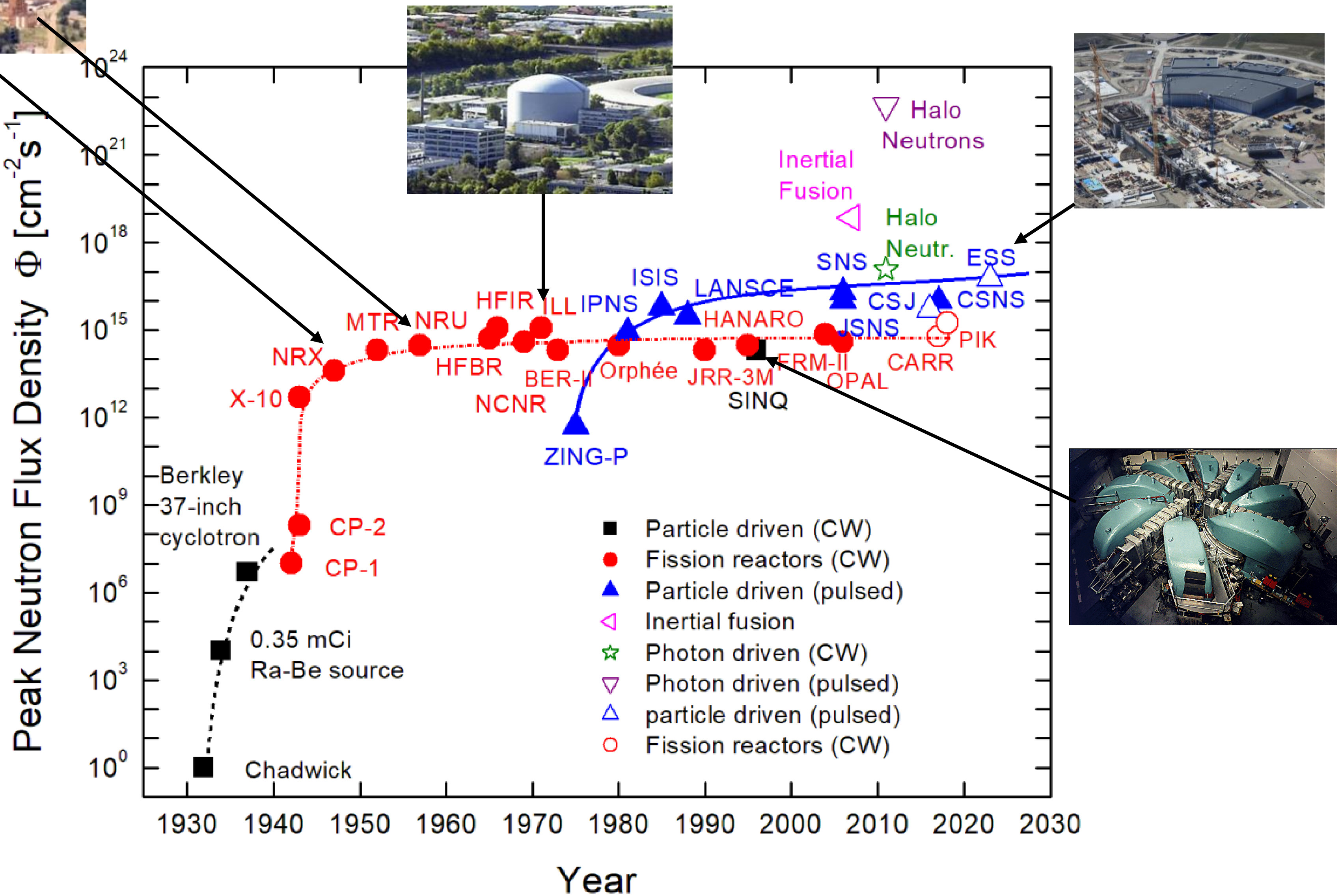
Stabilization of Flux Density at Low Level





P. Böni and W. Petry, ``Neutron Science with Highly Brilliant Beams'', in `Applications of Laser-Driven Particle Acceleration', edited by P. Bolton, K. Parodi, and J. Schreiber, CRC-Press Taylor & Francis, 2018, Boca Raton, FL, USA; https://www.crcpress.com/Applications-of-Laser-driven-Particle-Acceleration/Bolton-Parodi-Schreiber/p/book/9781498766418

Content

- Why supermirror ?
- How does supermirror work
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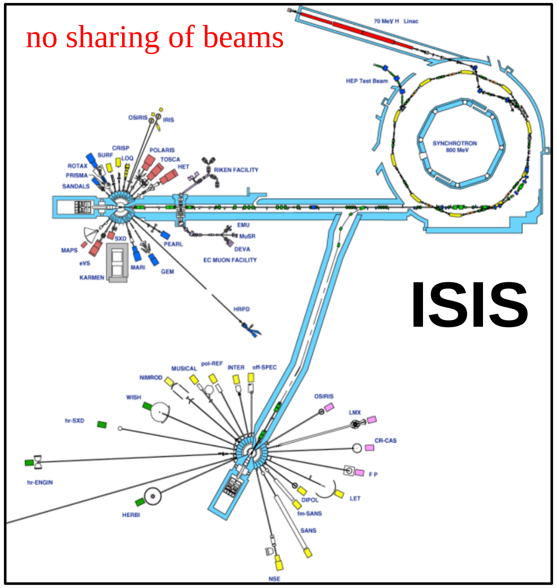
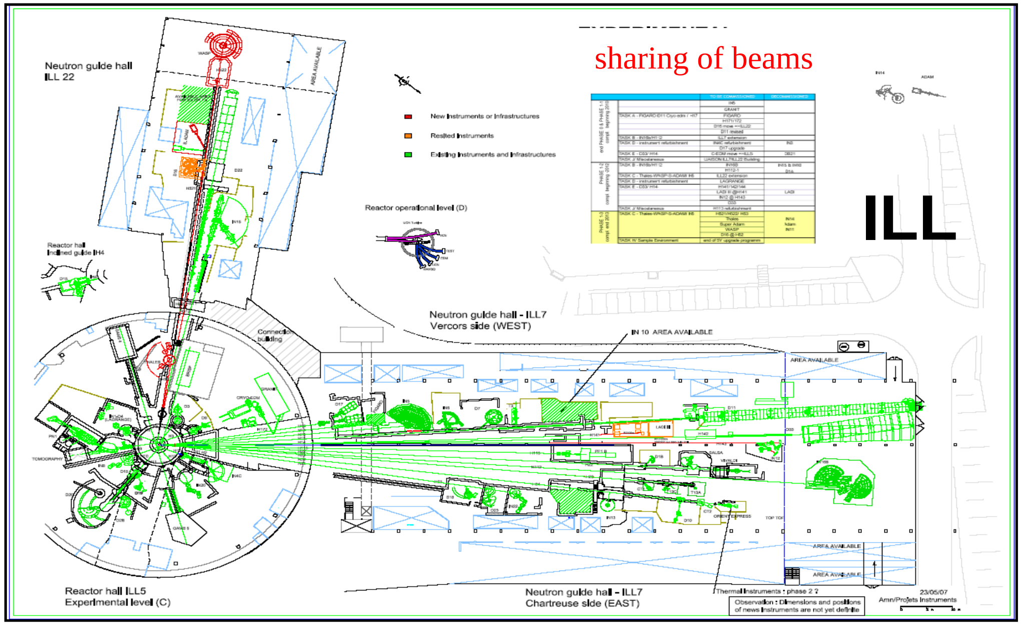
- Future
- Summary

Use Neutron Source as Efficient as Possible

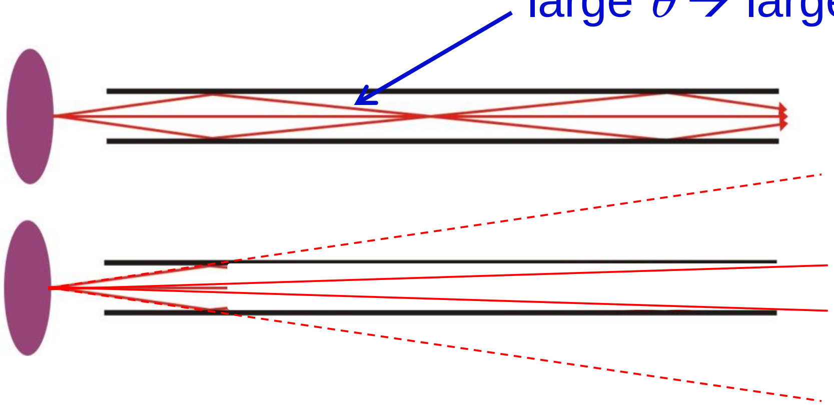




neutron guides:

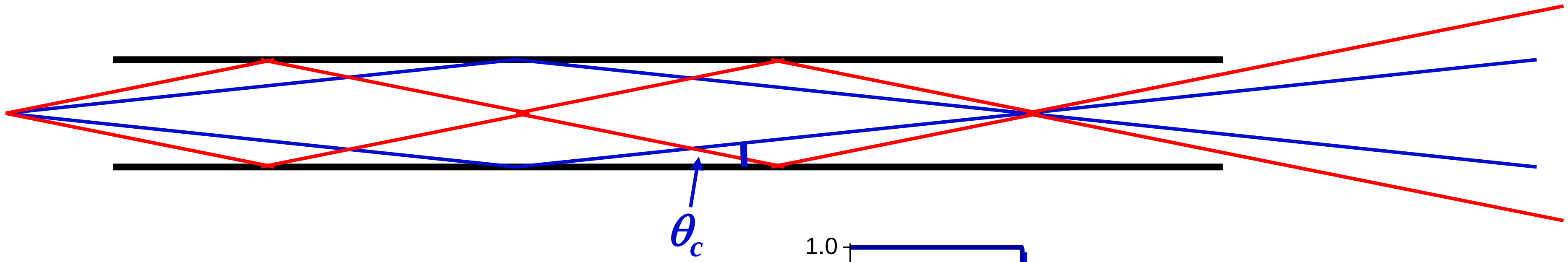
- transport of neutrons

large $\theta \rightarrow$ large flux density



Transport of Neutrons: Neutron Guides

internal reflection (compare with optical fiber): flux density $\propto \theta_c^2$



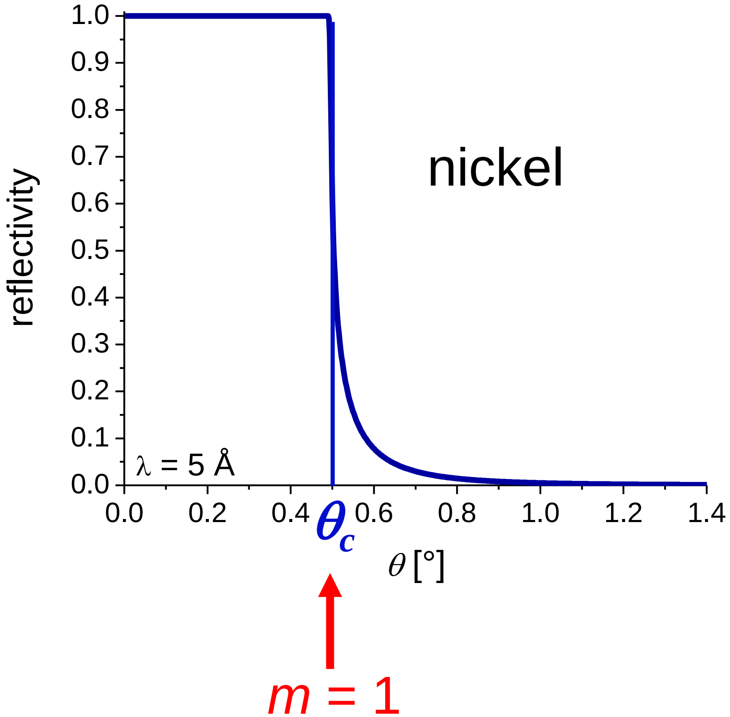
how large is θ_c?

- $n \cong 1 - 1{\cdot}10^{-5}$
- θ_c (^{0}) = 0.1$m\lambda$ (Å)

cold neutrons:

- λ = 5 Å, nickel coating

  → $\theta_c = 0.5^0$



n: index of refraction λ: wavelength of neutrons

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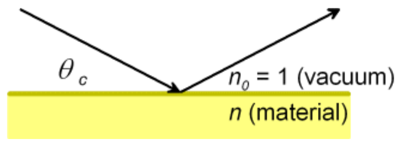
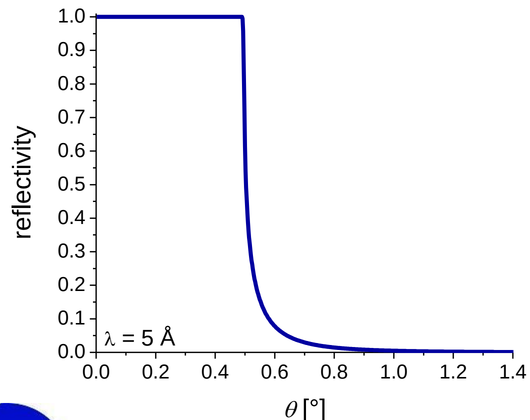
Invention of Supermirror

(Turchin 1967, Mezei 1976)

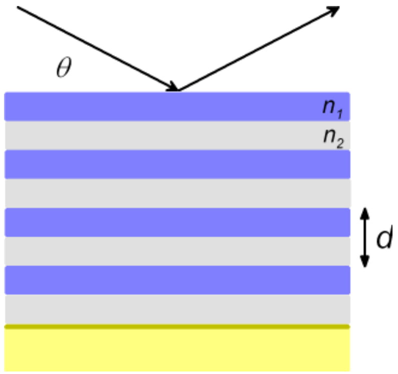
smooth surfaces



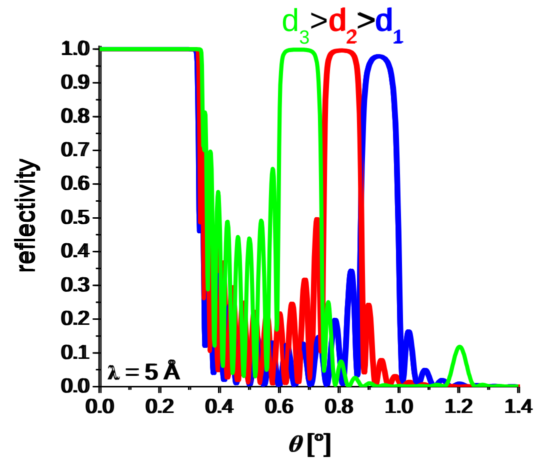
- refractive index $n < 1$
- total external reflection



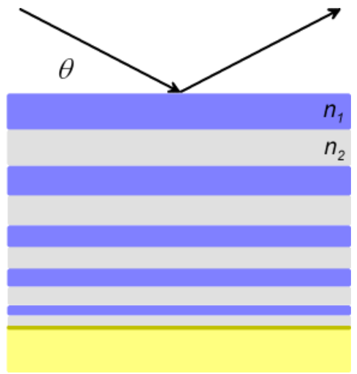
multilayer

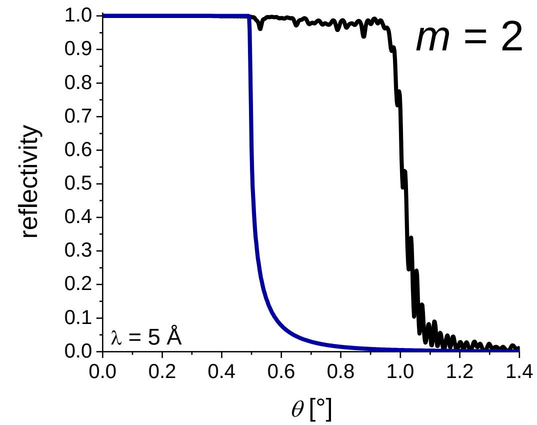


$$\lambda = 2d\sin\theta$$

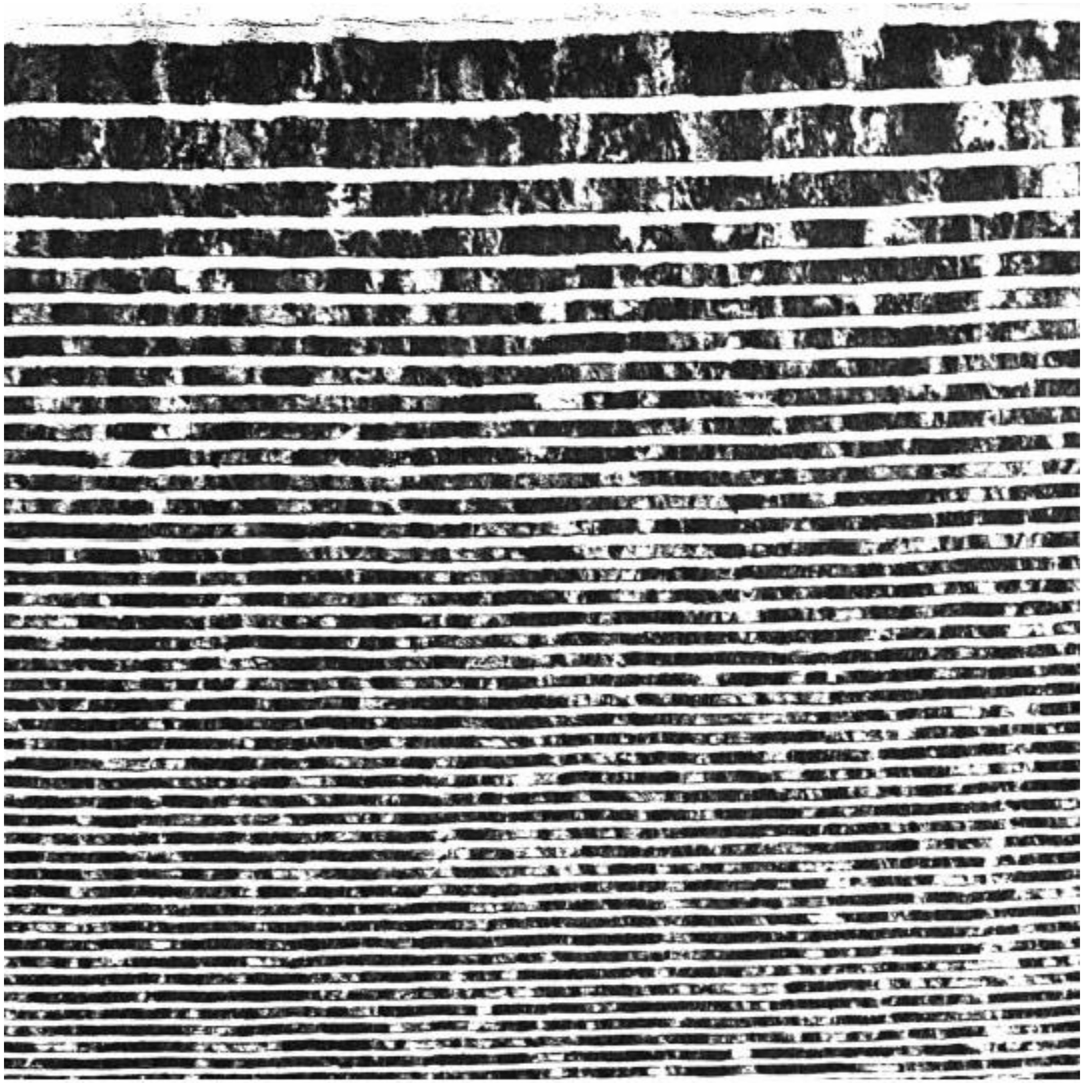


supermirror

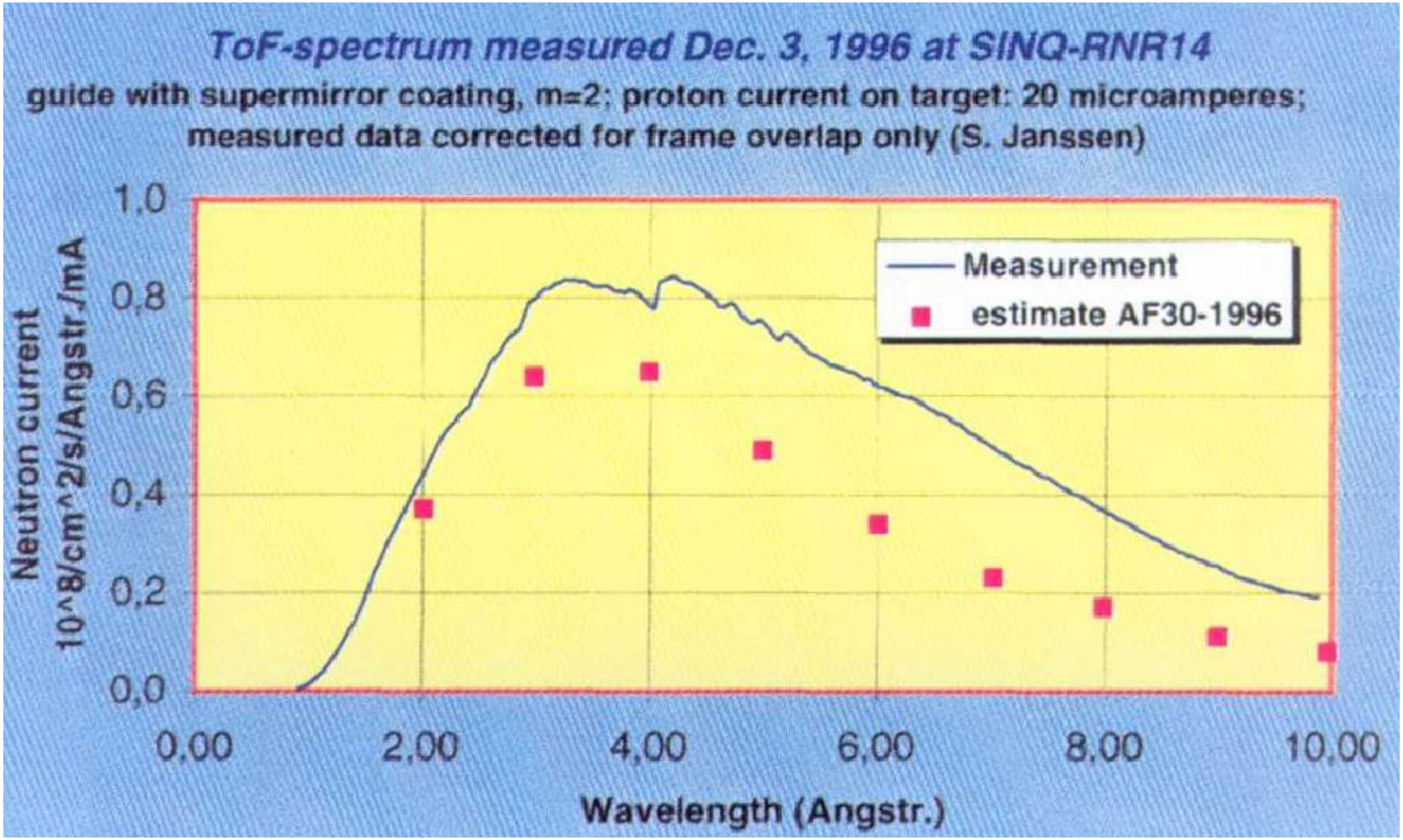




TEM on an m = 2 Supermirror



SINQ: 1st Neutron Source Based on SM-Technology



Proof of Concept

estimate: Francis Atchison, PSI

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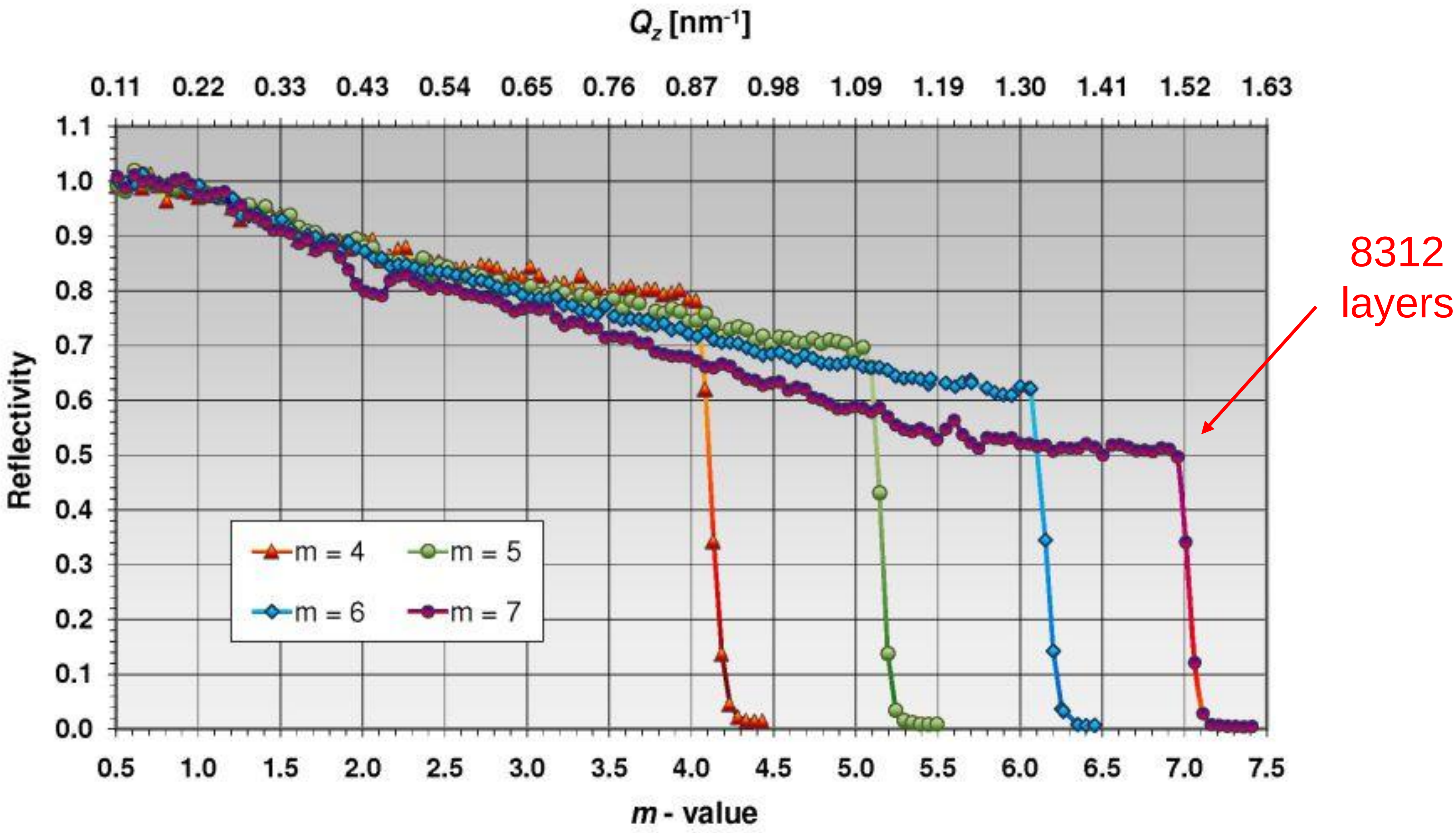
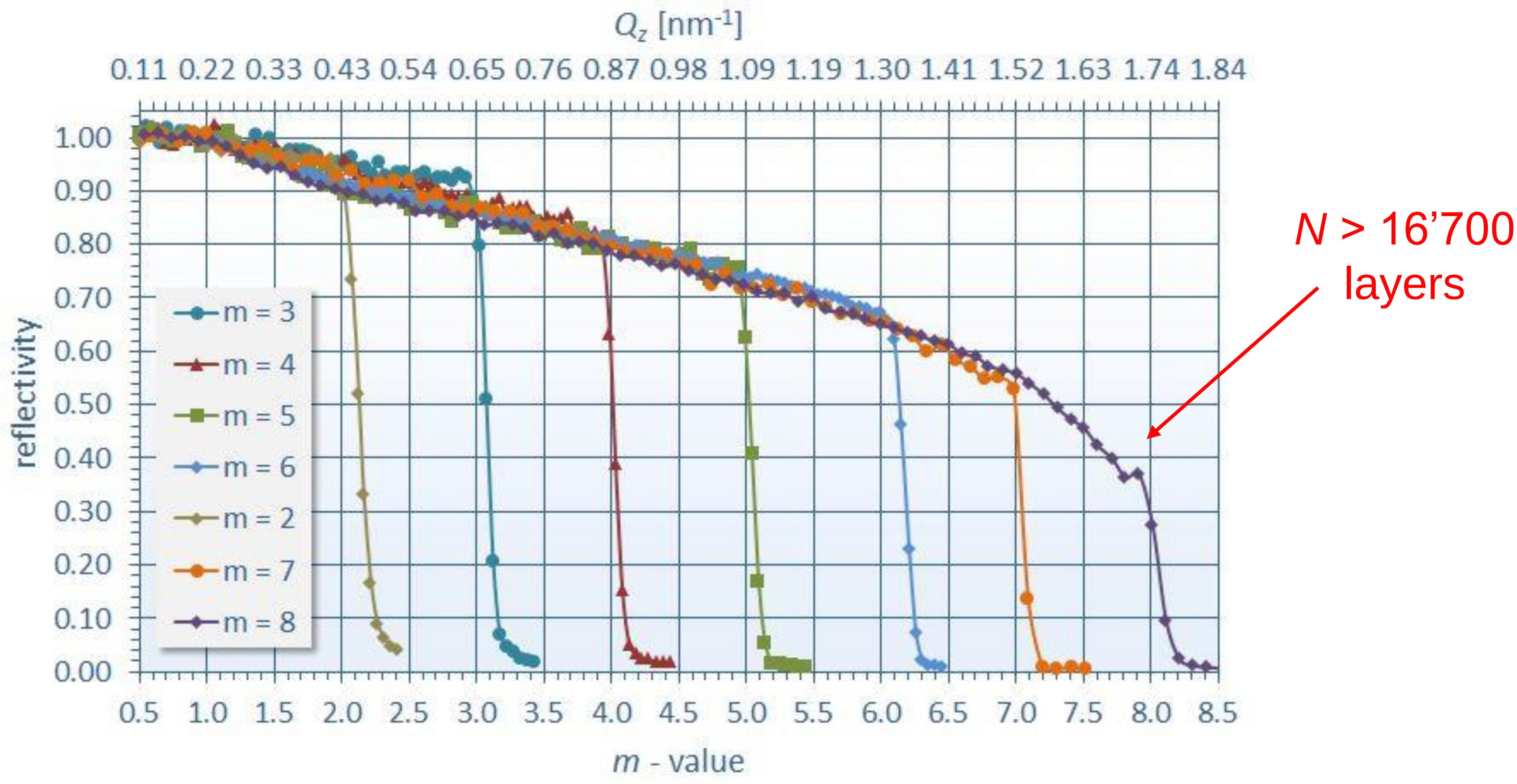
2009: Production Runs for VISION @ SNS



2016: Roughness Independent of *N*

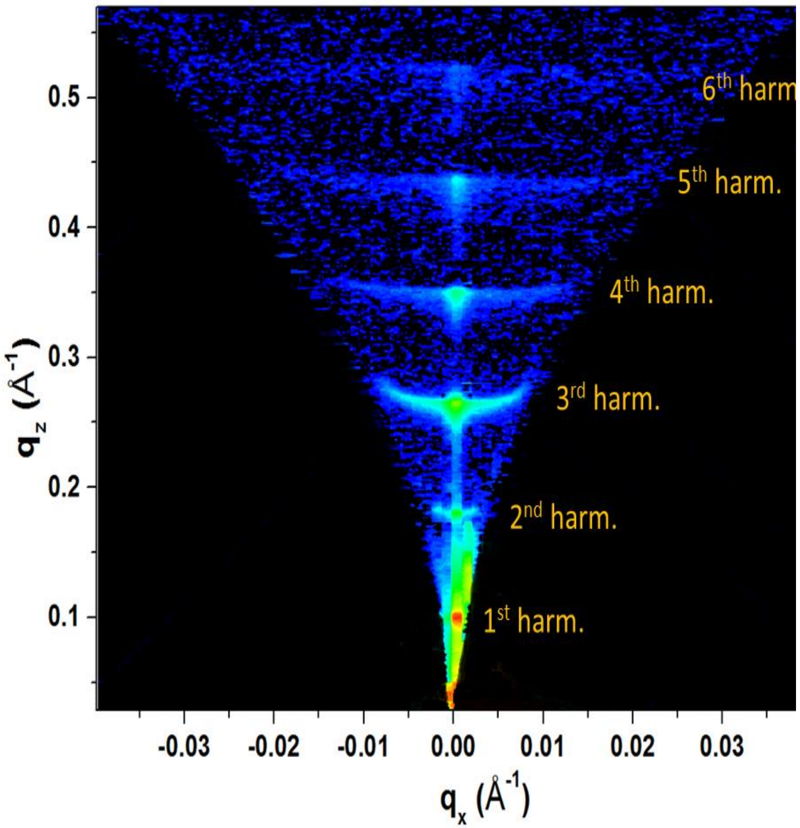


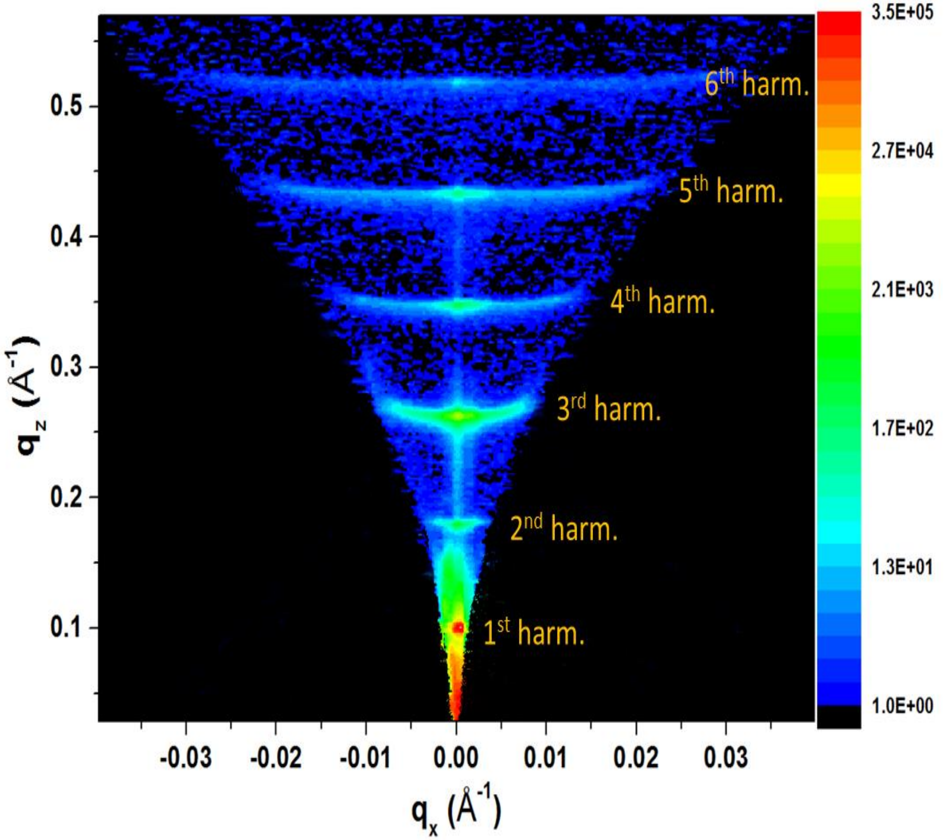
reflectivity of supermirror is fully understood and can be modelled

N: number of layers

C. Schanzer et al., JPCS 746, 012024 (2016); http://iopscience.iop.org/article/10.1088/1742-6596/746/1/012024/pdf

X-Ray Reflectivity of Supermirror $m = 4$

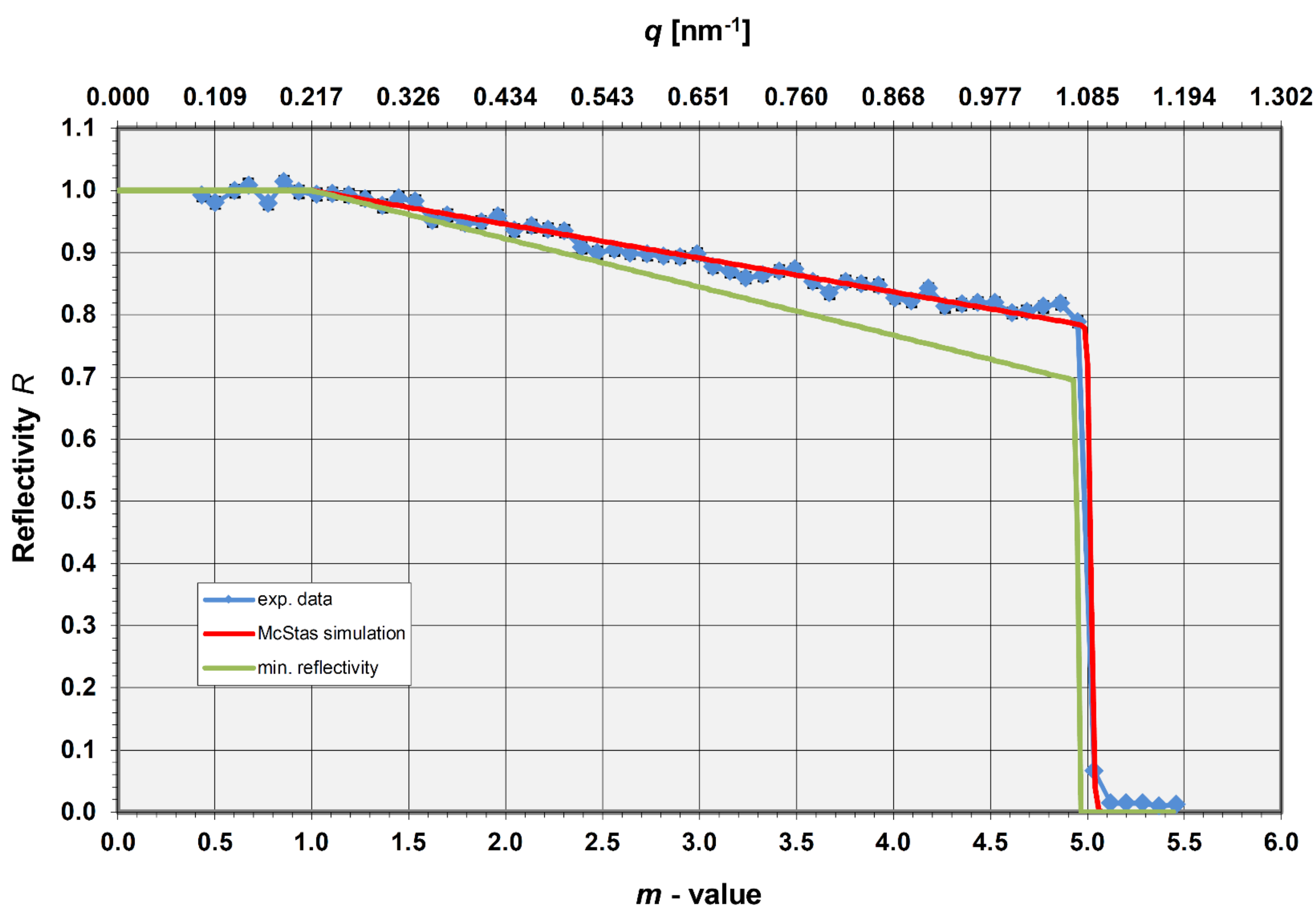




$R = 80\%$ $R = 60\%$

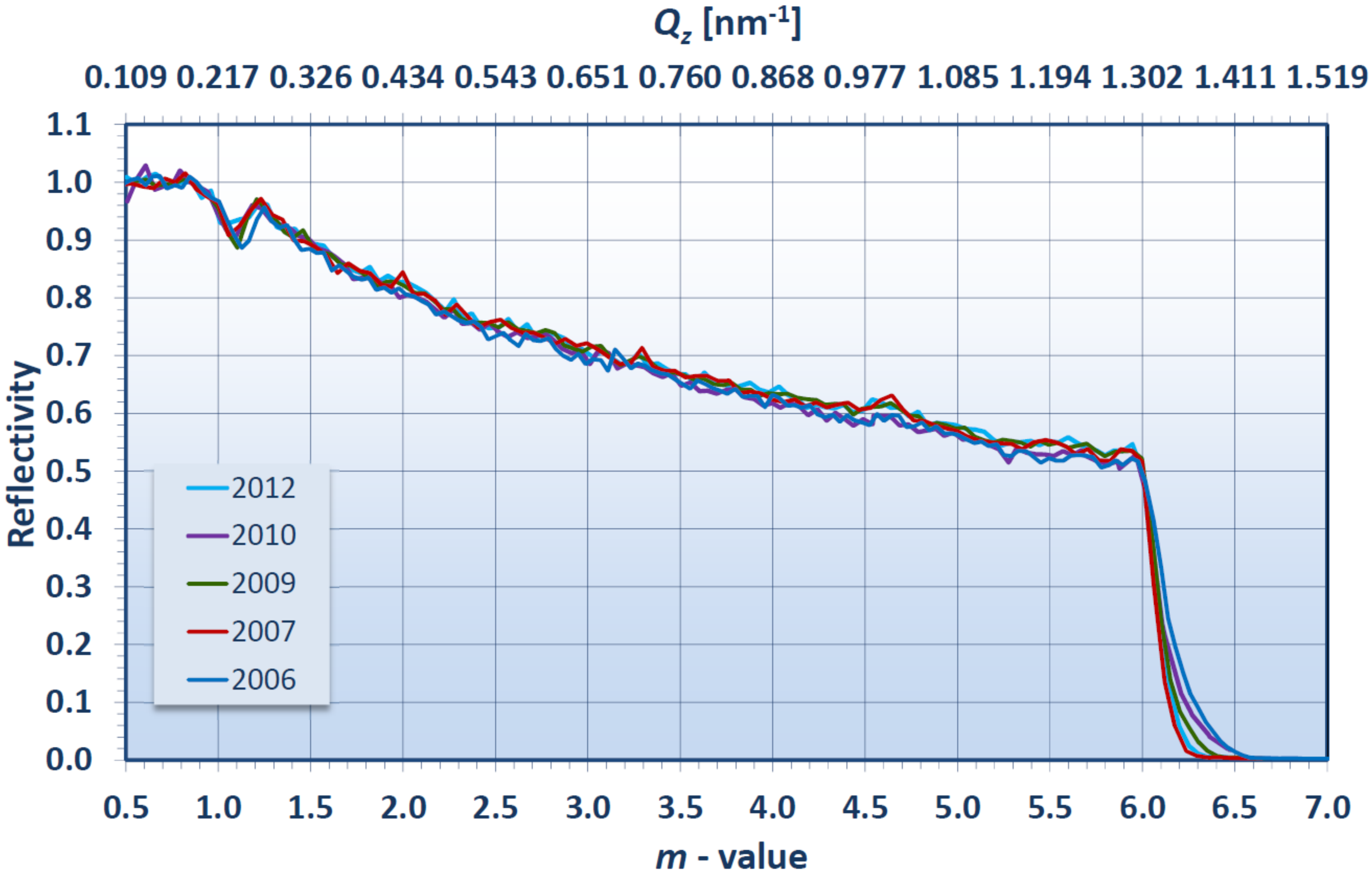
C. Schanzer, S. Valloppilly, and P. Böni, Nucl. Instr. Meth. A; https://doi.org/10.1016/j.nima.2019.162628

2018: Optimization of Supermirror *m* = 5

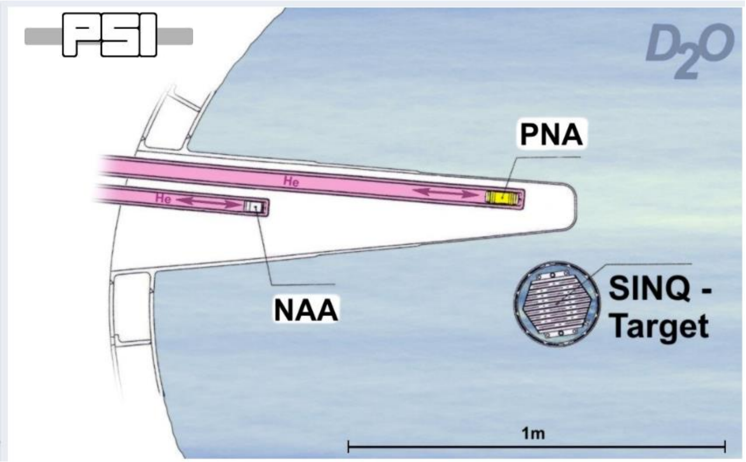


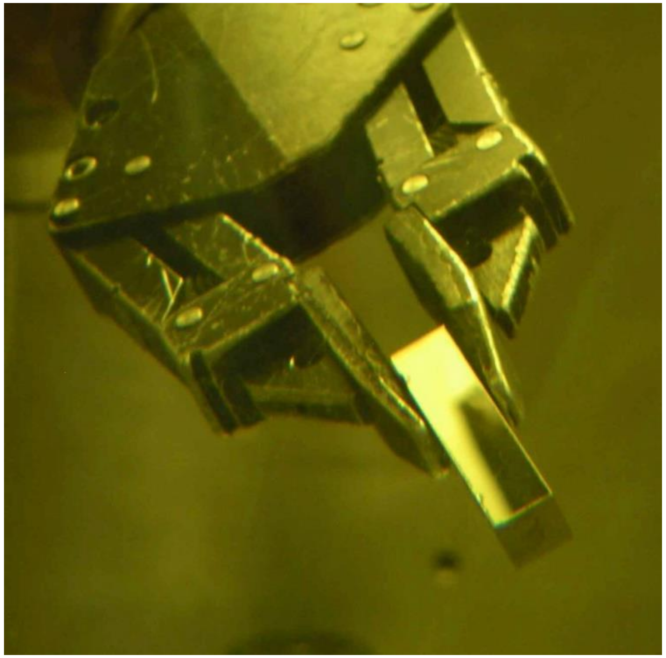
70% → 80%

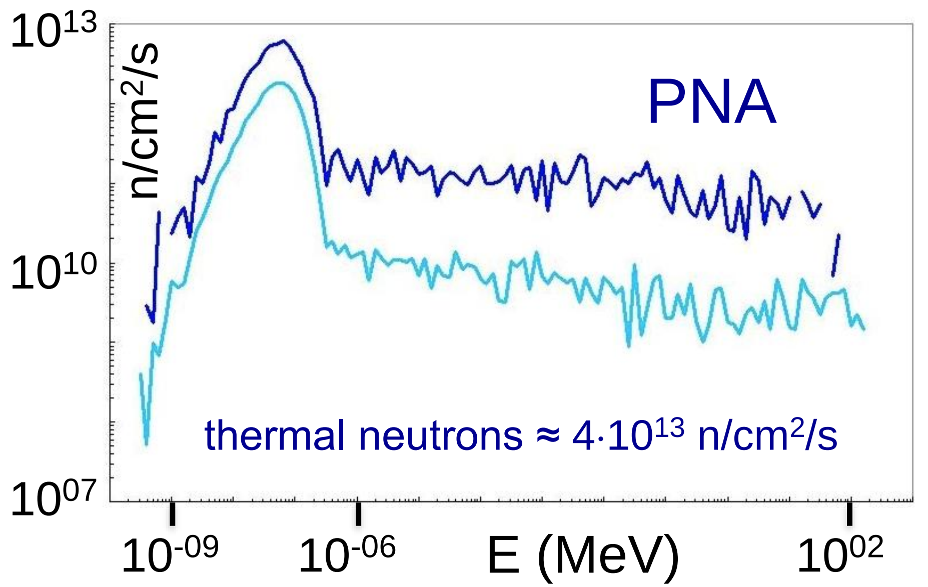
Long Term Stability: *m* = 6



Test: Irradiation of Supermirror on Aluminum





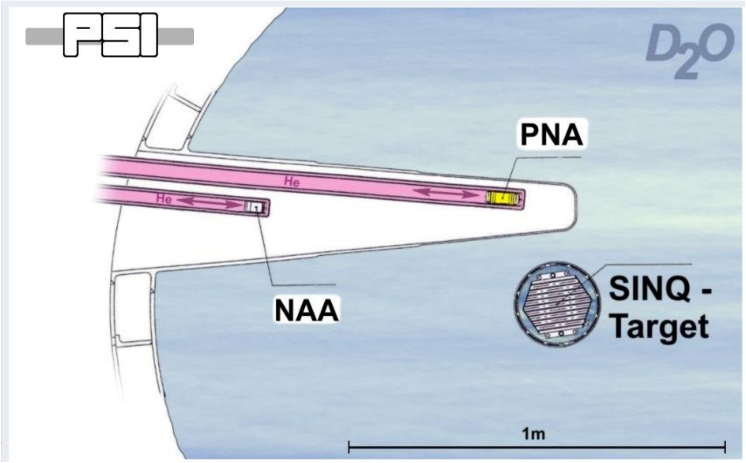


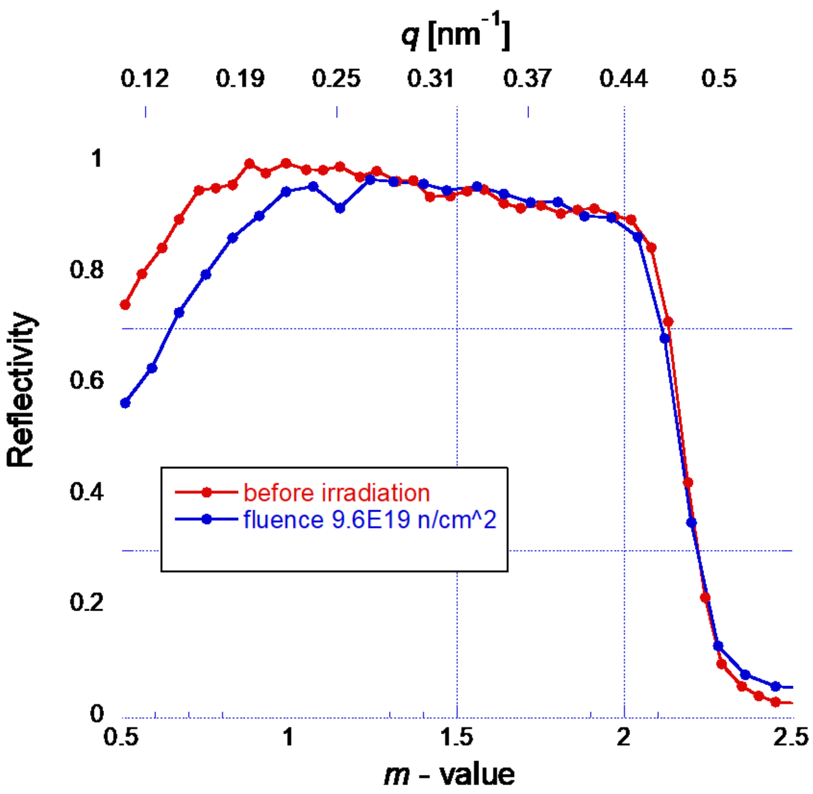
Irradiation: fluence $9.6 \cdot 10^{19}$ n/cm^2

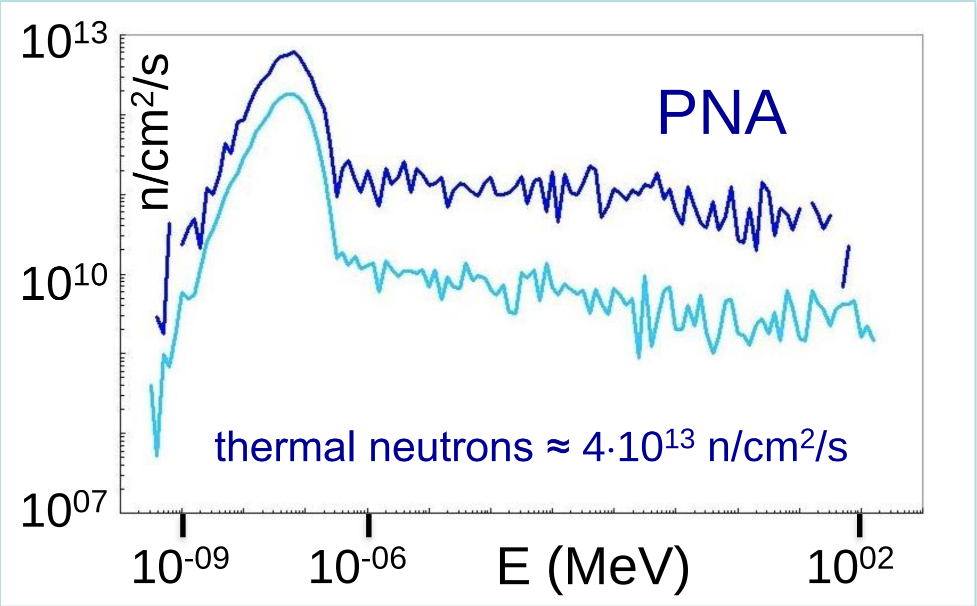
sample size: 10 x 10 x 50 mm^3

no visible degradation of surface of supermirror is observed

Irradiation of Supermirror on Aluminum







no degradation of reflectivity of supermirror is observed

Irradiation test: $9.6 \cdot 10^{19}$ n/cm^2

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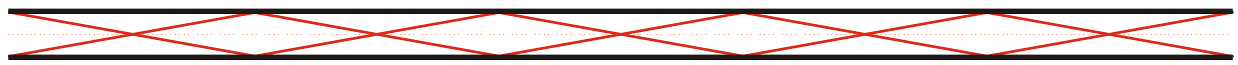
Guides: Artistic Glass Work / Standard Technology

Past and present: guides with constant cross section (straight or curved)



many reflections → significant losses: R^n ($0.9^{20} = 0.12$): BT << 1

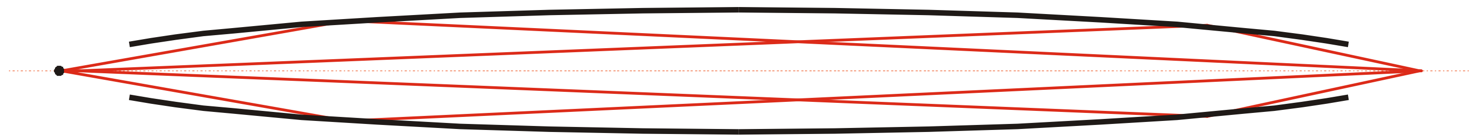
brilliance transfer:

$$BT = \frac{\text{brilliance at sample}}{\text{brilliance of source}}$$

H14 @ ILL 2011

Efficient Transport Using Elliptic Guides

Reduce number of reflections: elliptic guides



2 reflections* → reflection losses small
→ large solid angle possible

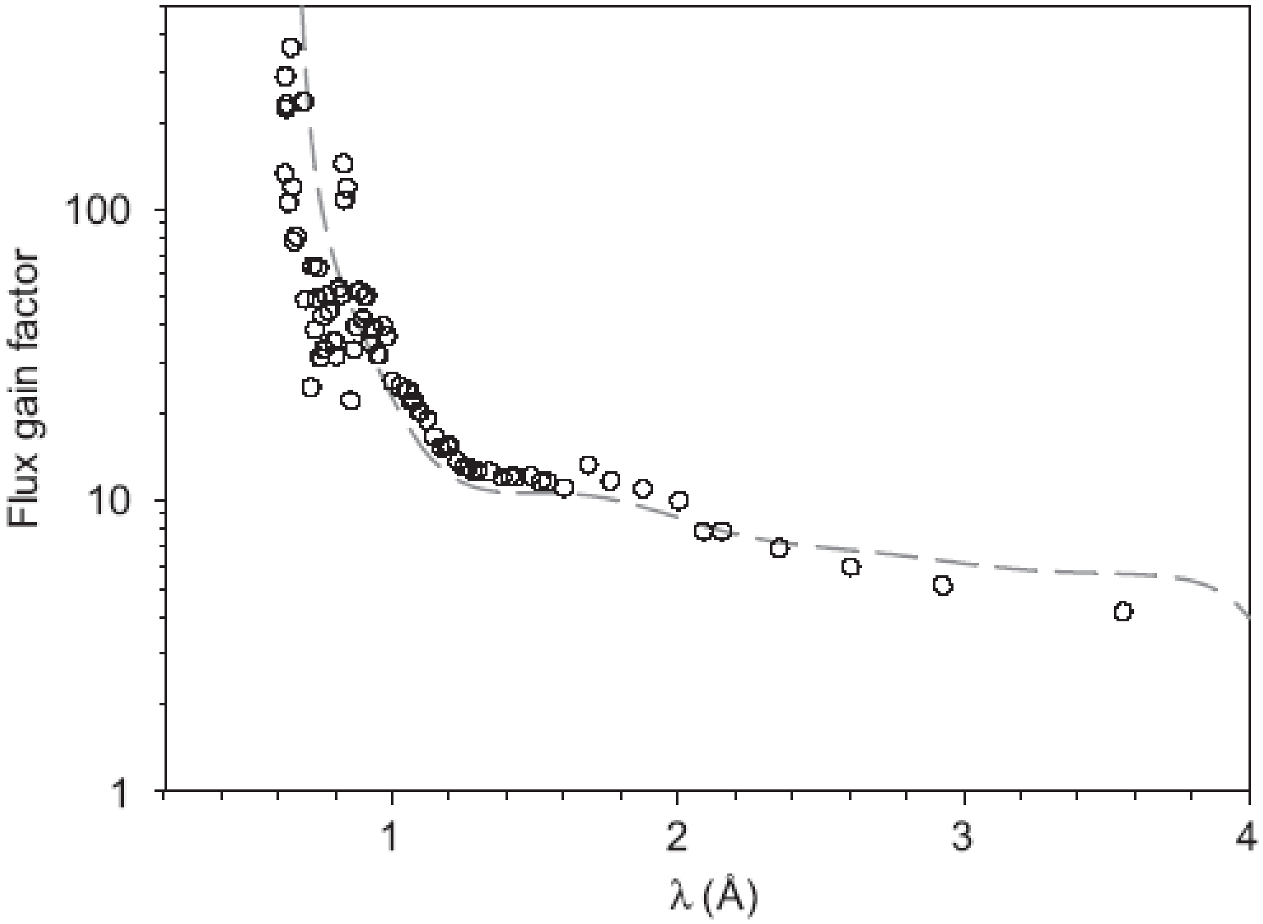
features:

- 90 m long
- graded coating
- truly curved
- installed: 2007

2007 HRPD @ ISIS

* if properly designed (is a controversial subject!)

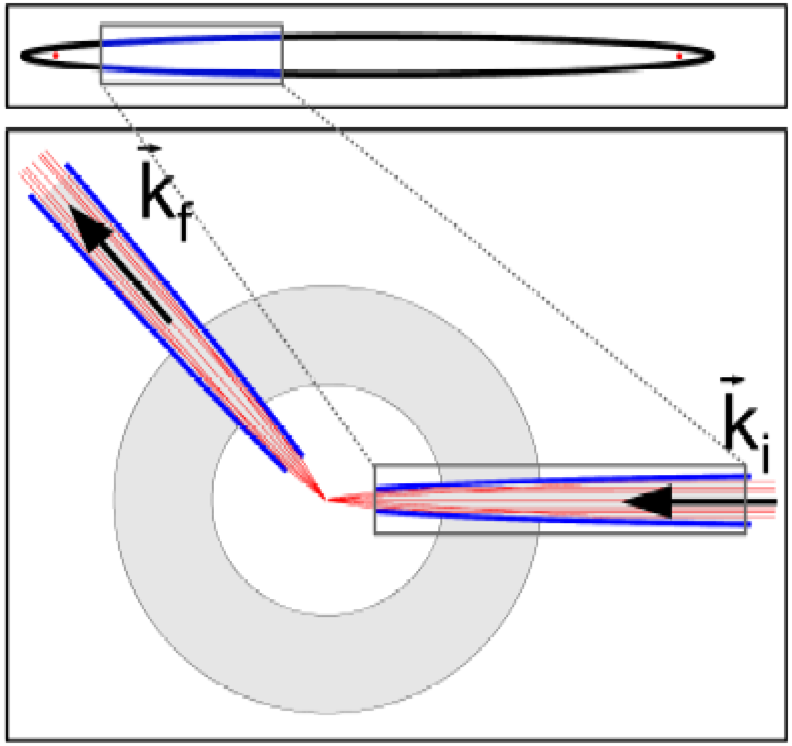
Significant Flux Gain at HRPD

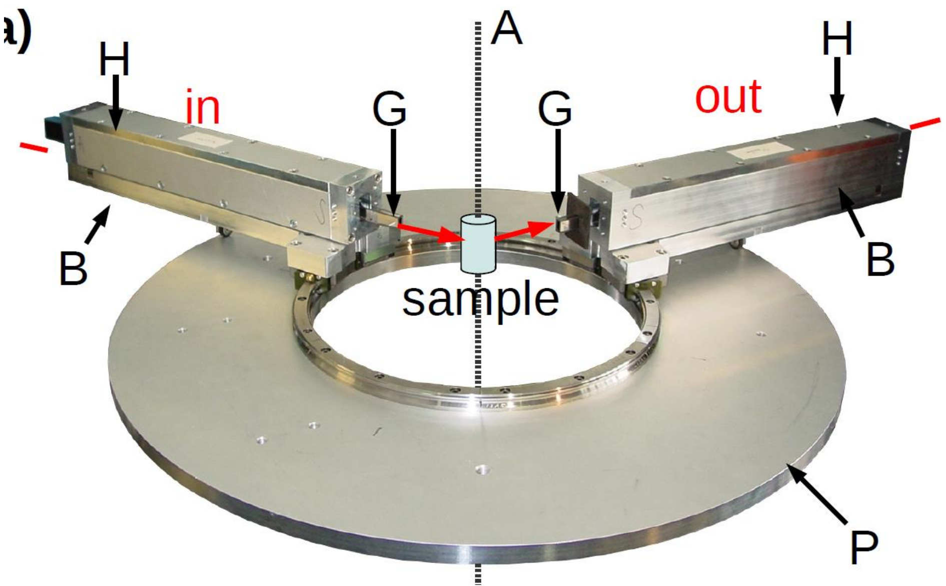


R. M. Ibberson, Nucl. Instrum. Methods A **600**, 47 (2009)

similar system has been installed at MLF @ J-PARC (SPICA)

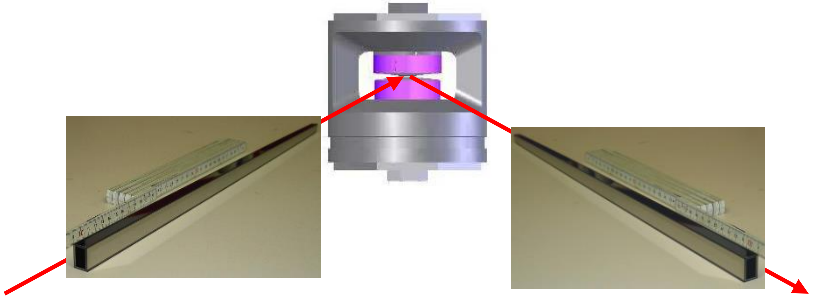
Small Samples: Use of Focusing Elliptic Guides





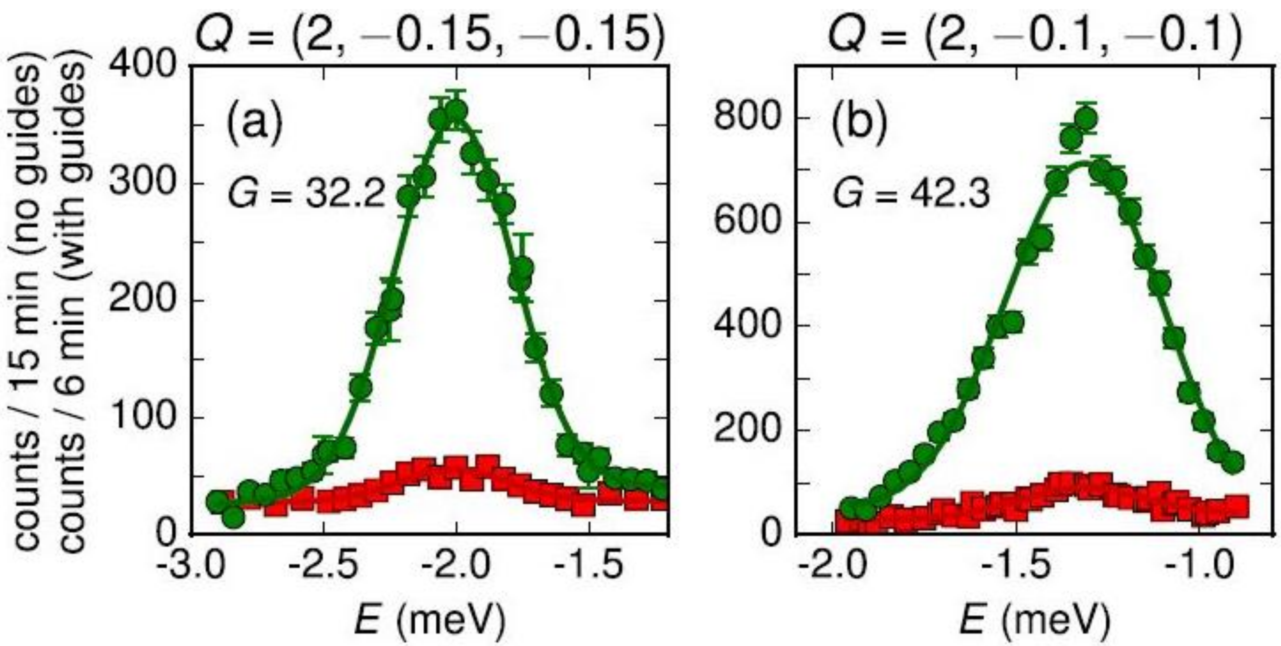
MIRA @ FRM II

→ focusing before
and
→ defocusing after sample



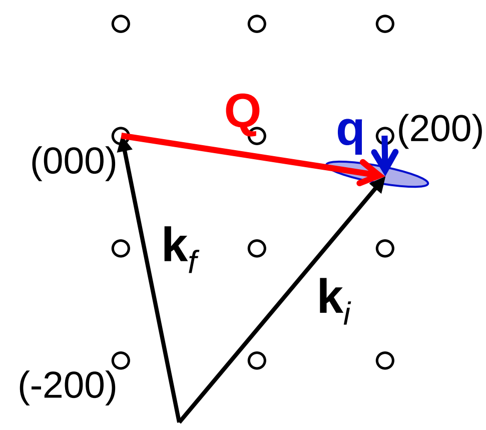
T. Adams et al., Applied Physics Letters **105**, 123505 (2014); http://dx.doi.org/10.1063/1.4896295

Focusing Setup: TA Phonons in Lead



Discussion:

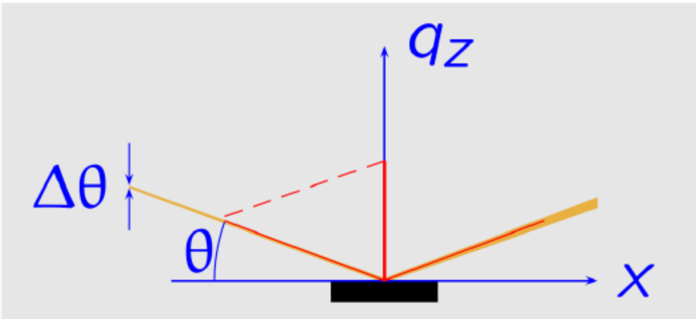
- large gains: $G_{TA} \cong 30 - 40$
- divergent beam does not spoil Q_y resolution
- can be installed at almost any beamline

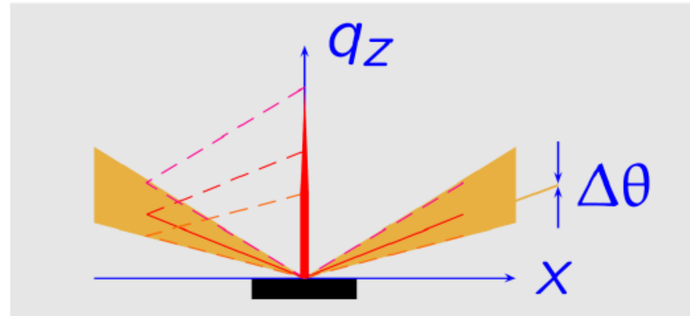


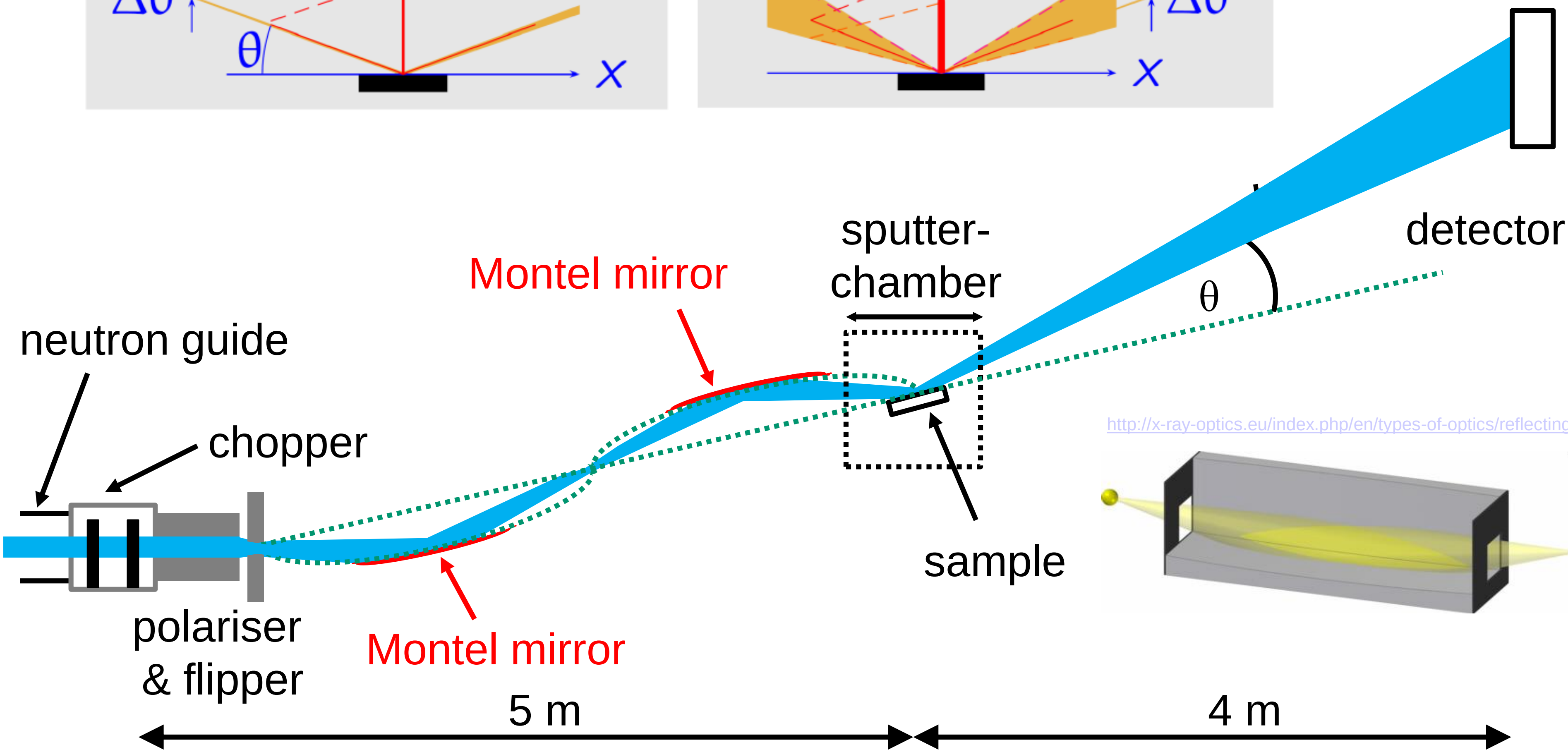
($V_{sample} = 2 \times 2.5 \times 2.5\ mm^3$)

G. Brandl et al., Applied Physics Letters **107**, 253505 (2015); http://dx.doi.org/10.1063/1.4938503

Elliptic Montel Mirrors: Selene @ SINQ



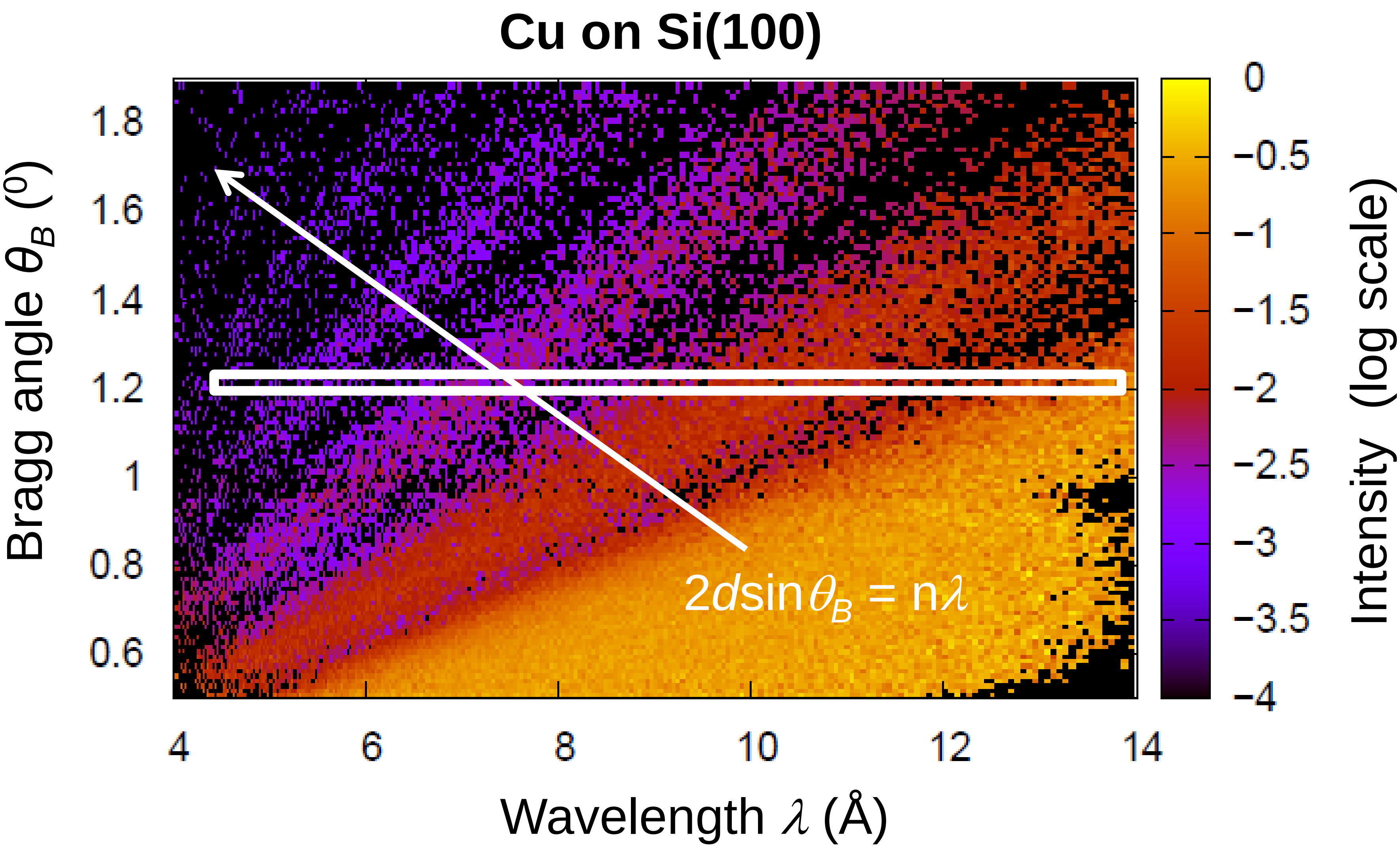




J. Stahn et al., Nucl. Instr. Meth. A **634**, S12-S16 (2011); https://doi.org/10.1016/j.nima.2010.06.221

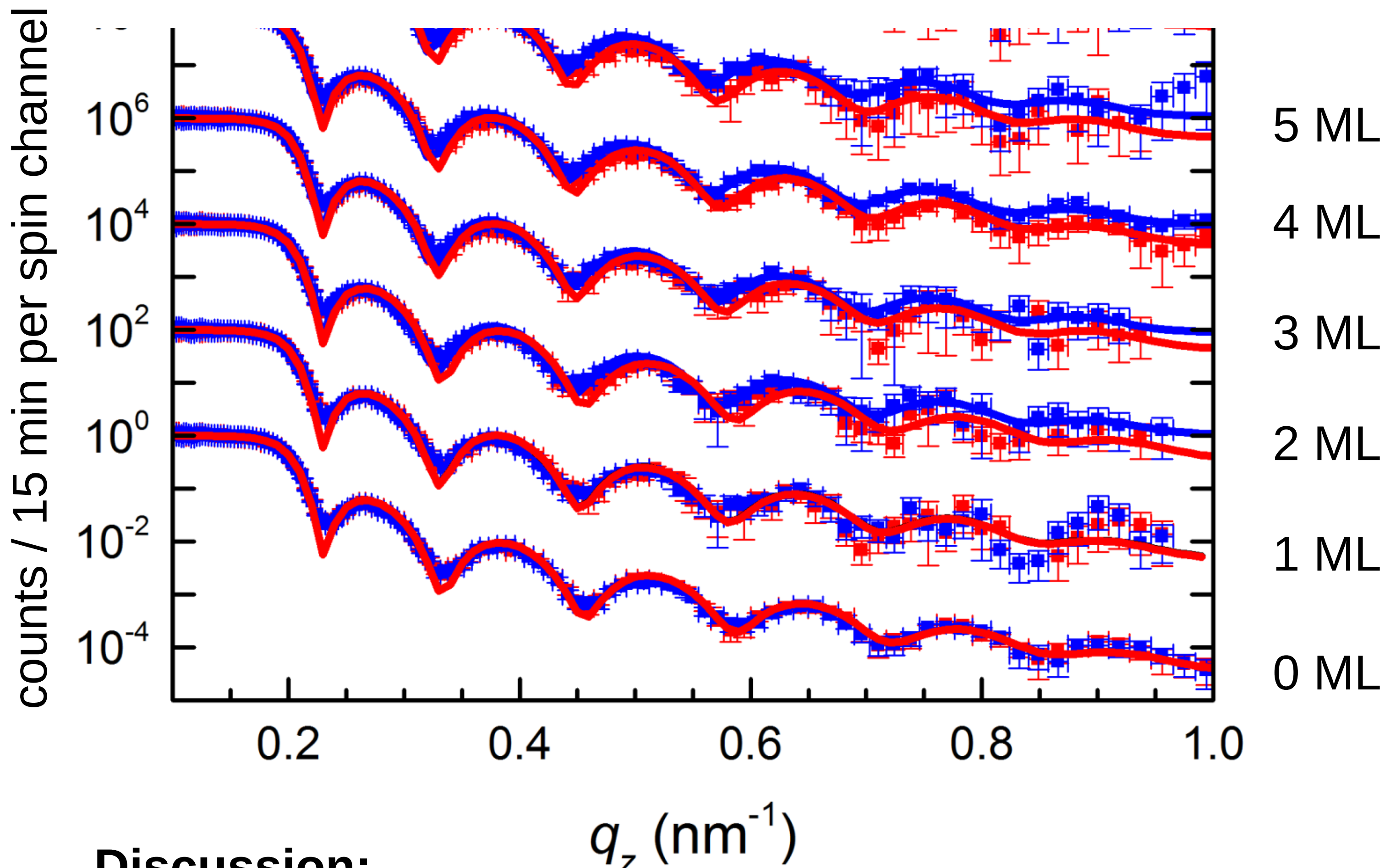
Installation of *In-situ* Chamber at AMOR

Raw Data: Monolayers Fe (Selene @ AMOR)



W. Kreuzpaintner et al., Phys. Rev. Appl. **7**, 054004 (2017); https://doi.org/10.1103/PhysRevApplied.7.054004

Monolayers of Fe on Si-Cu: Selene @ AMOR

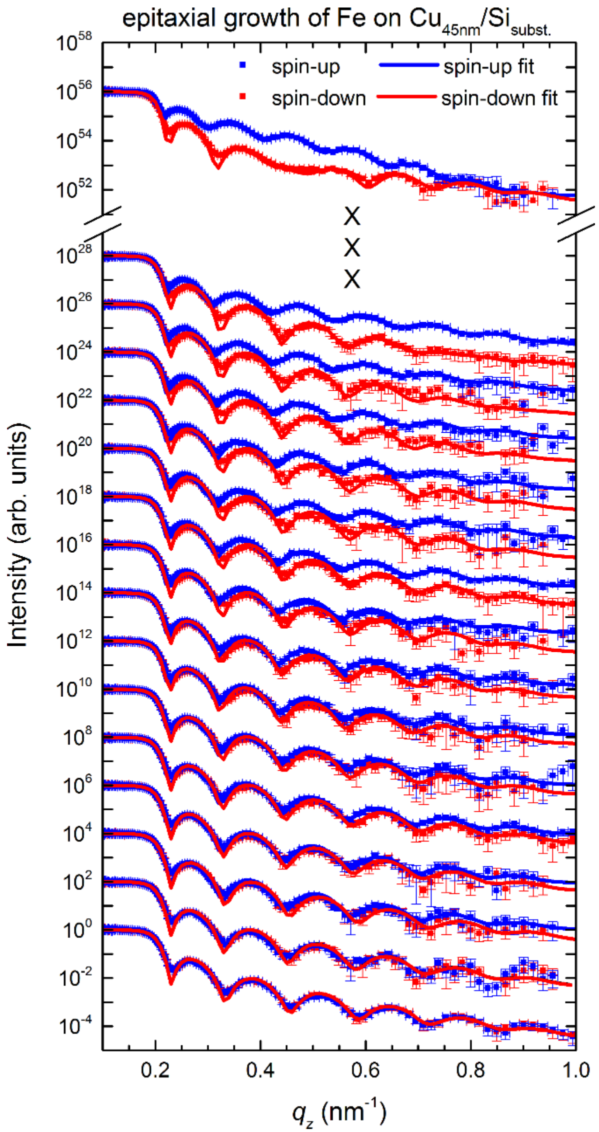


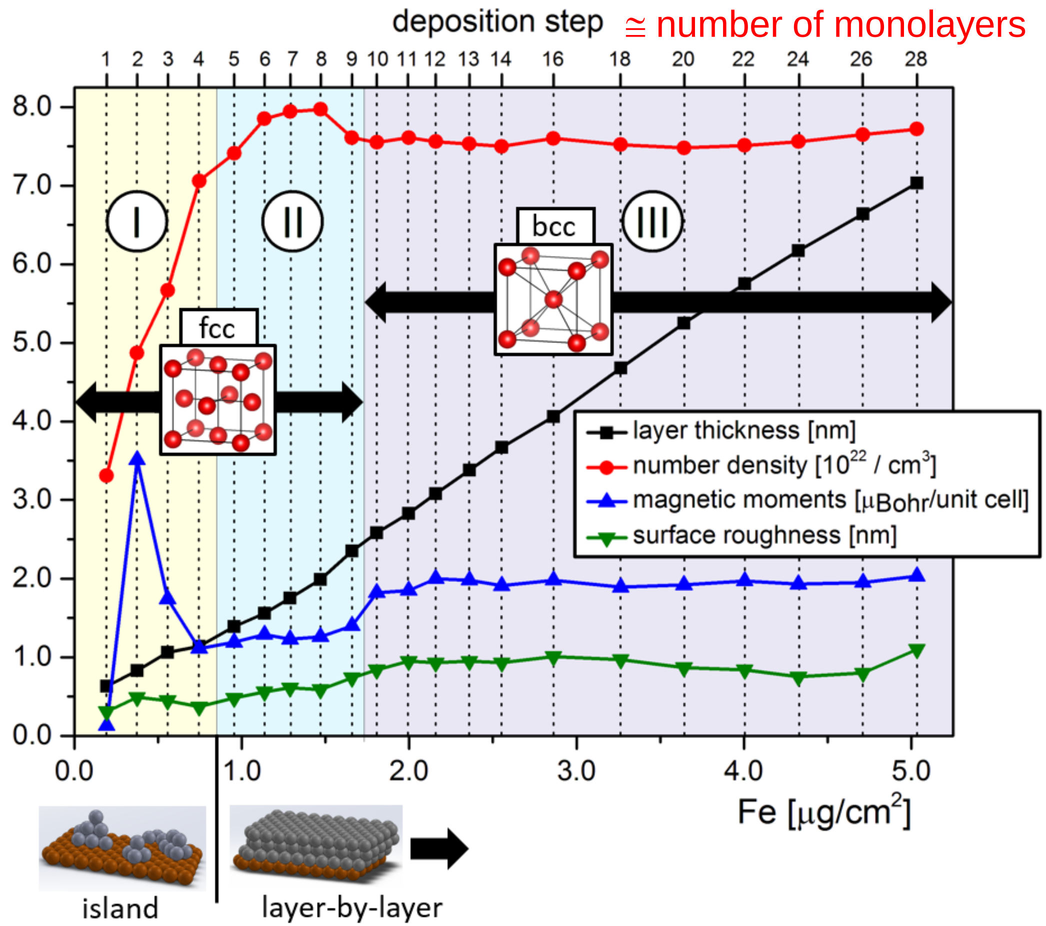
Discussion:

- new Selene @ SINQ: ≅ 1 min / spin channel
- ESTIA at ESS: ≅ 0.5 sec / spin channel

W. Kreuzpaintner et al., Phys. Rev. Appl. **7**, 054004 (2017); https://doi.org/10.1103/PhysRevApplied.7.054004

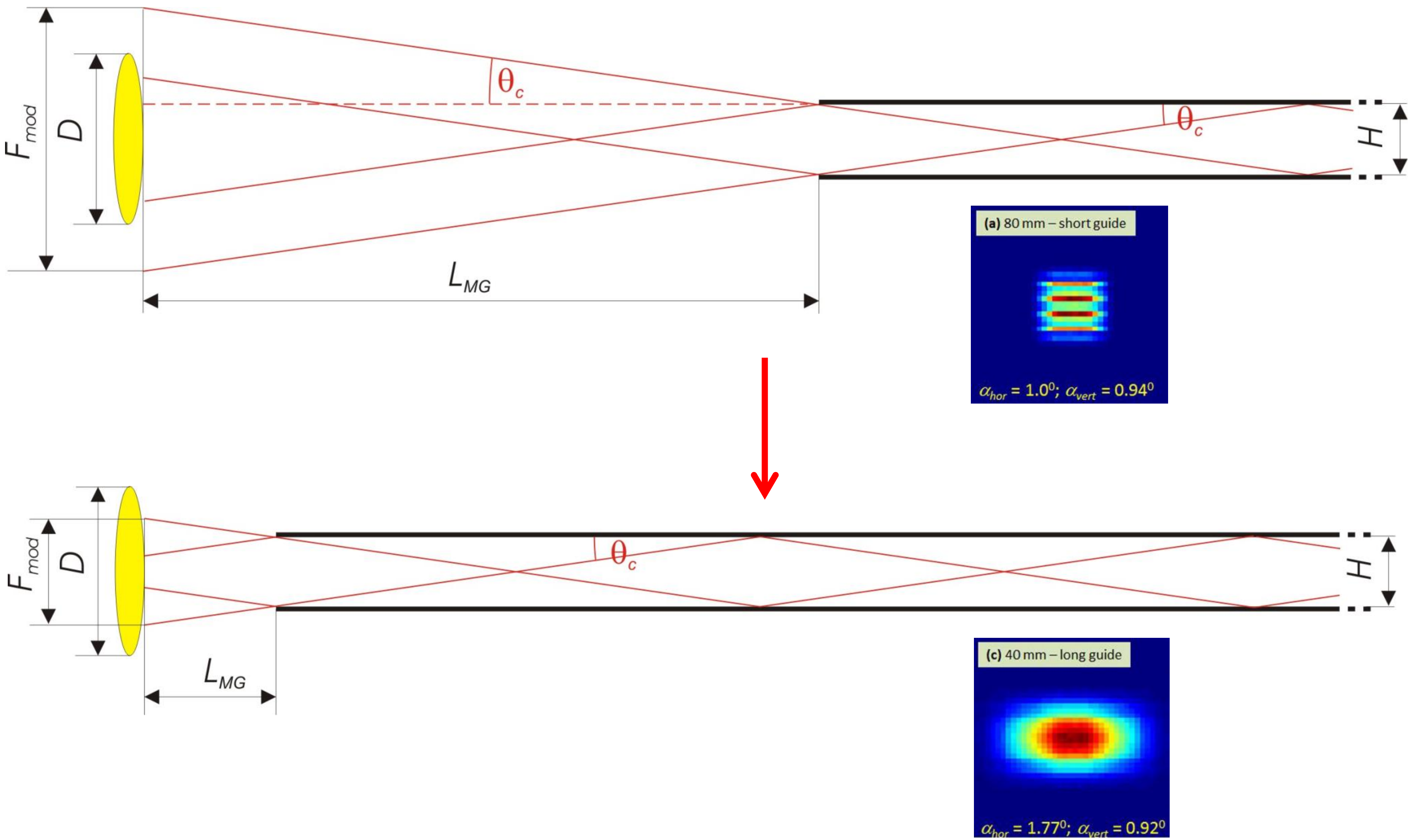
Montel Mirrors Combined with *In-situ* Sputtering





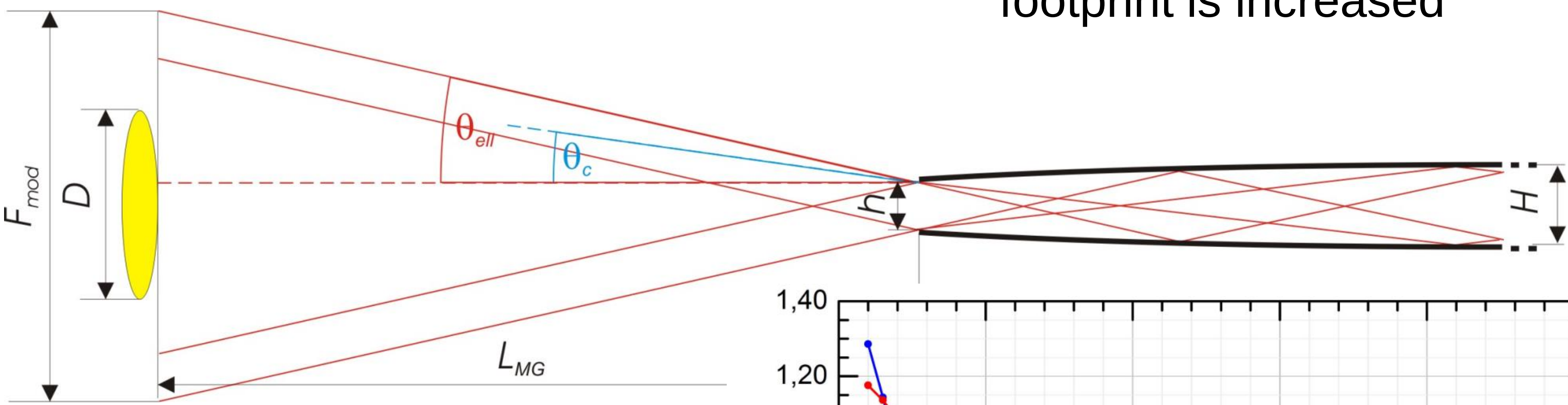
W. Kreuzpaintner et al., Phys. Rev. Appl. **7**, 054004 (2017); https://doi.org/10.1103/PhysRevApplied.7.054004

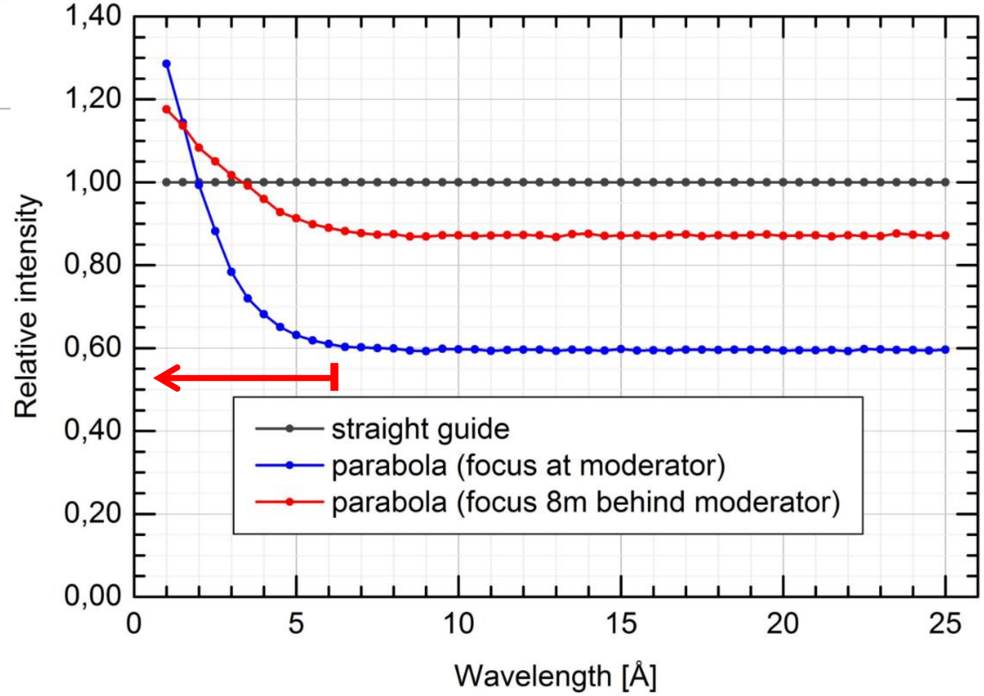
Full Illumination: Move Guide Close to Moderator



Extraction of Neutrons Using Tapered Guides?

Liouville: $H\theta_H = h\theta_h$ = const → divergence is increased
footprint is increased





move entrance of guide close to moderator

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Supermirror: Is there a Limitation on *m*?

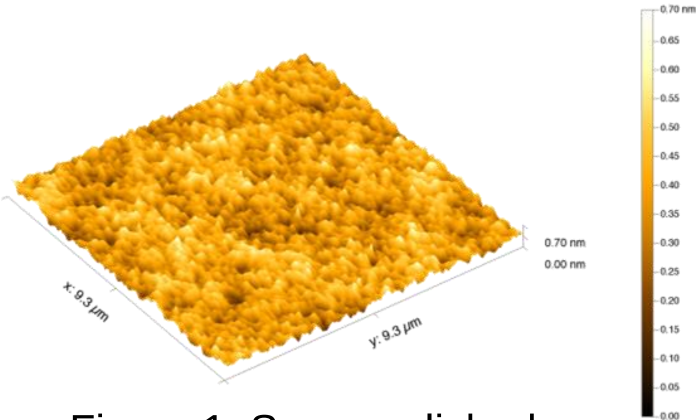
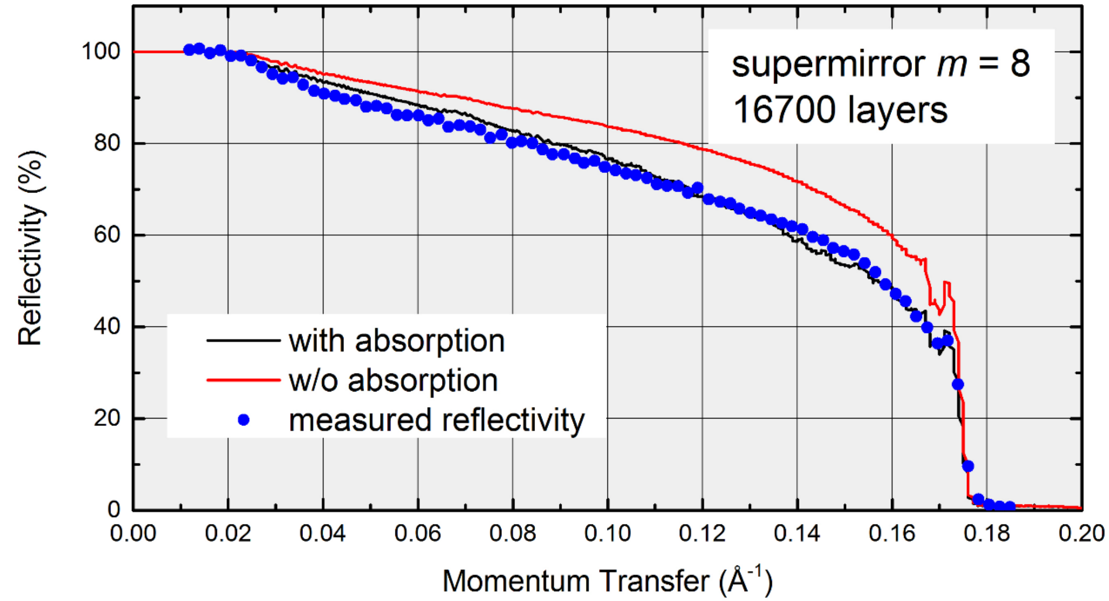


Figure 1. Super-polished substrate characterized by AFM. RMS roughness over scan area of 10 × 10 µm² is σ < 1 Å.

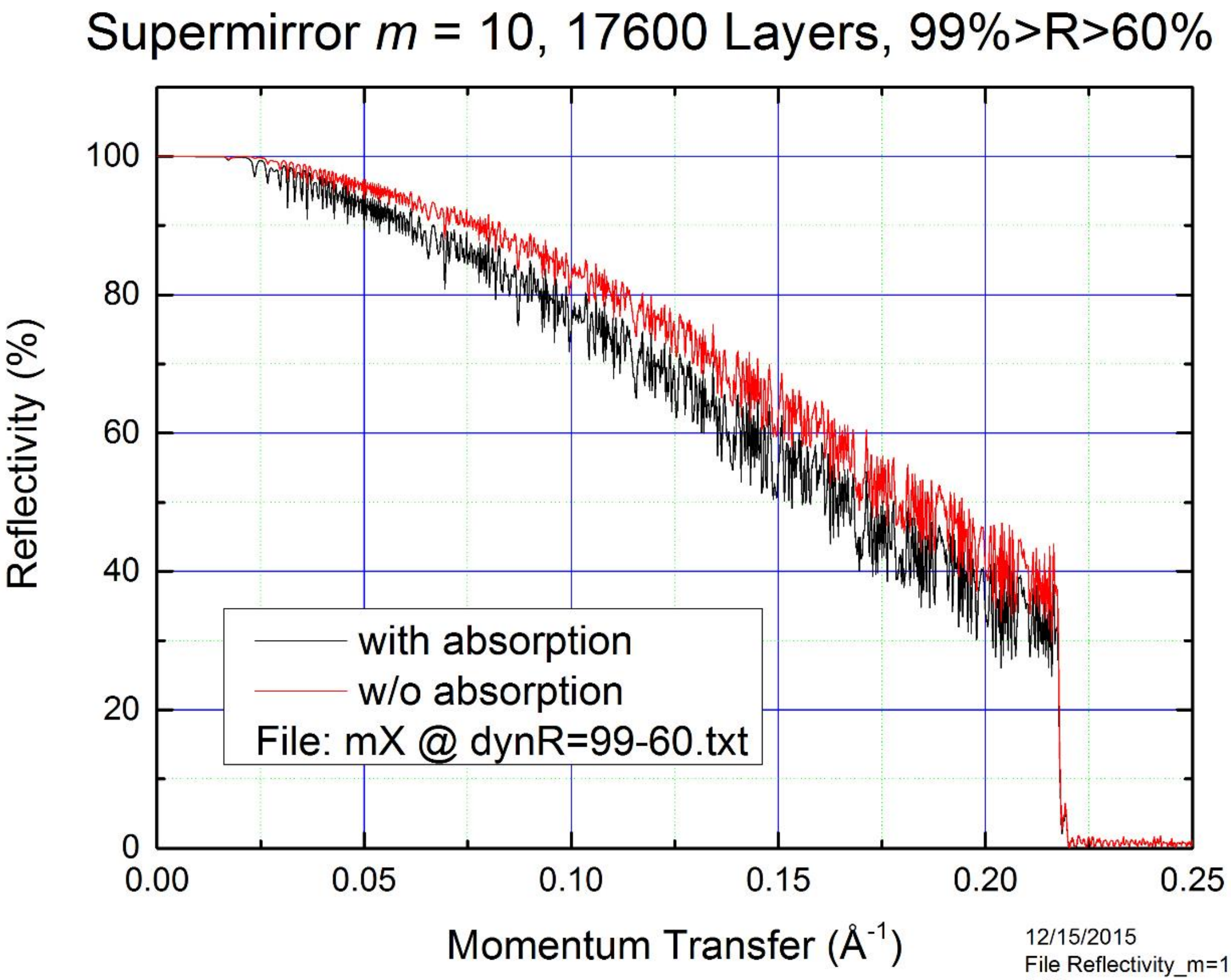


Challenges:

• sharp interfaces (not required)	solved
• low roughness	solved
• substrates with low roughness	solved
• absorption	major challenge

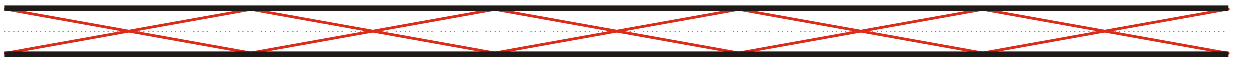
C. Schanzer et al., JPCS 746, 012024 (2016); http://iopscience.iop.org/article/10.1088/1742-6596/746/1/012024/pdf

The mX Mirror Project: *m* = 10



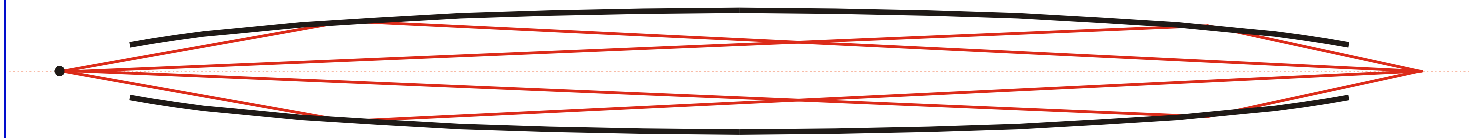
12/15/2015
File Reflectivity_m=10_Simulation_var
A99

Development of Neutron Guide Optics

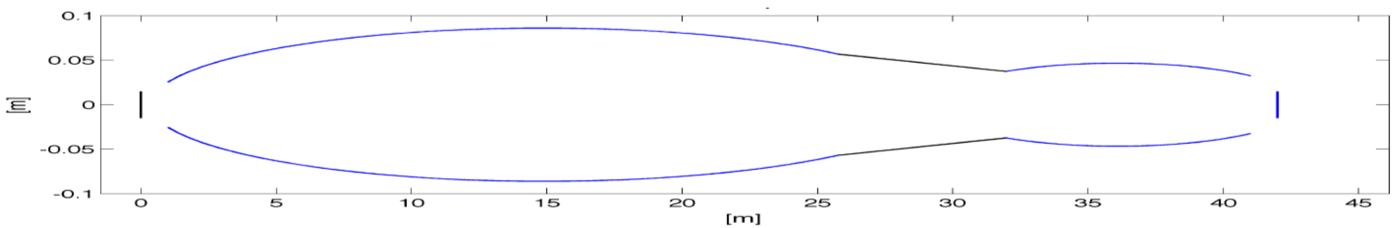


advantage: gravitational effects usually not important

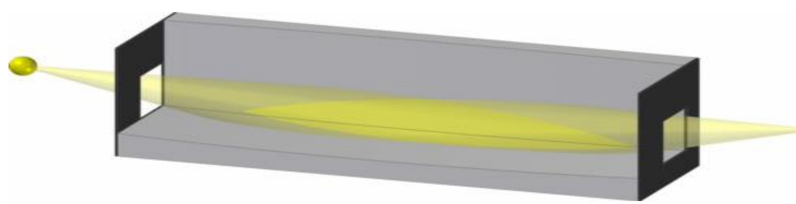
ILL, SINQ, etc



ISIS, J-PARC

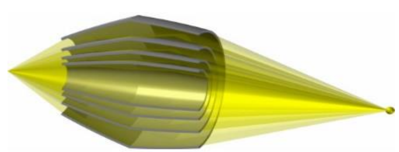


ESS



http://x-ray-optics.eu/index.php/en/types-of-optics/reflecting-optics/curved-mirrors

SINQ → ESS



http://x-ray-optics.eu/index.php/en/types-of-optics/reflecting-optics/curved-mirrors

B. Khaykovich et al.: optics for imaging

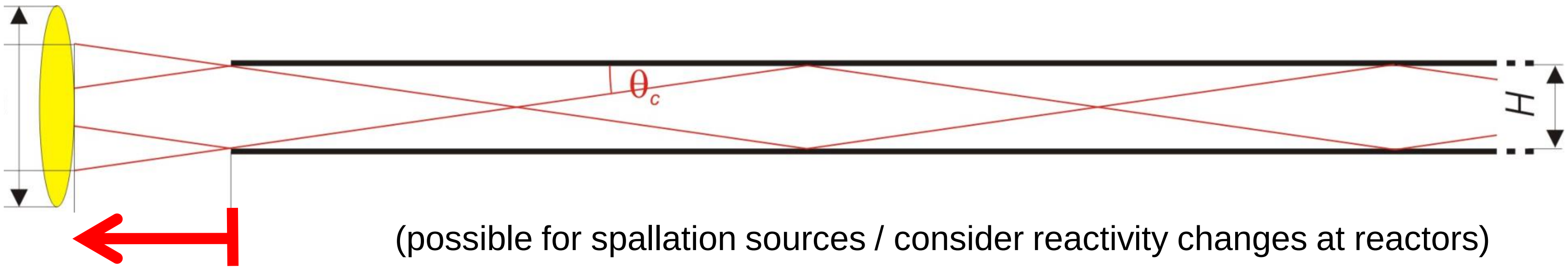
see also talk by **O. Zimmer**

Pau Jorba et al., J. Magn. Magn. Mater. **475**, 176 (2019); https://doi.org/10.1016/j.jmmm.2018.11.086
B. Khaykovich et al., Nucl. Instr. Meth. A **631**, 98 (2011): https://doi.org/10.1016/j.nima.2010.11.110

Beam Extraction

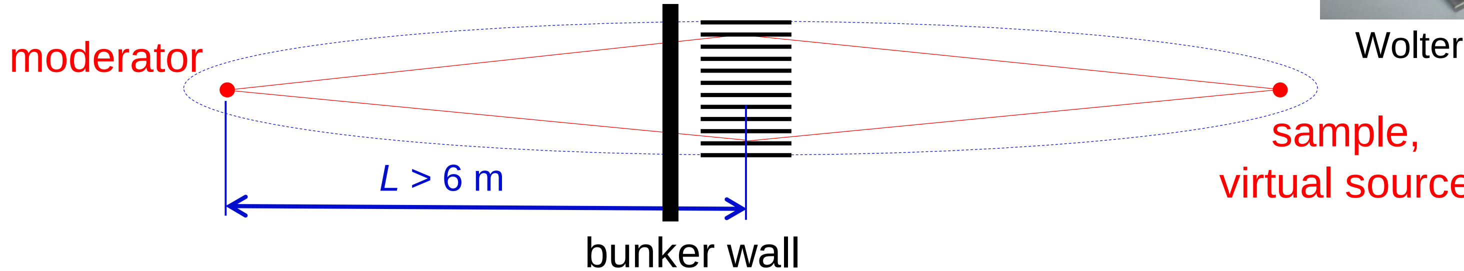
2 options for efficient extraction:

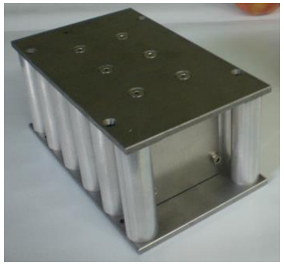
- extend guides (tapered/not tapered) close to moderator (new sources)
- reduction of background due to decreased beam window



(possible for spallation sources / consider reactivity changes at reactors)

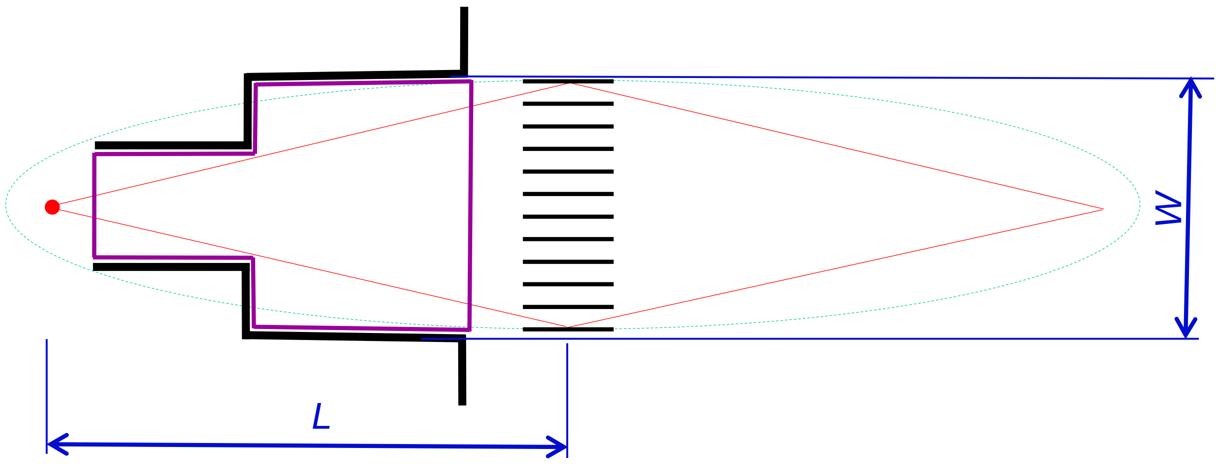
- Wolter optics (optional: Montel)
  (avoid illumination losses at existing sources)
- reduction of background (small beam extracted)
- optics may be placed outside biological shielding

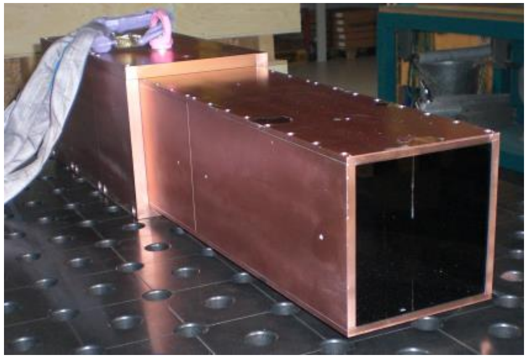




Wolter optics

Experience: Design Large Beam Inserts





Insert made from copper

example: cold neutrons

- L = 6 m
- λ = 5 Å
- m = 3
- divergence: 3^0

→ D = 311 mm + mechanics

× 2 for elliptic guides

example: hot neutrons

- L = 6 m
- λ = 0.5 Å
- m = 8
- divergence: 0.8^0

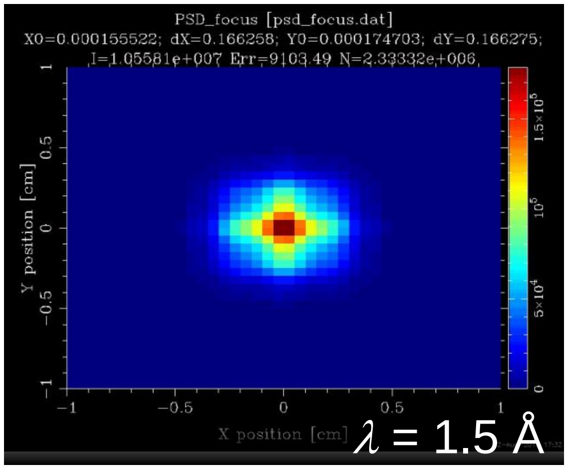
→ D = 83 mm + mechanics

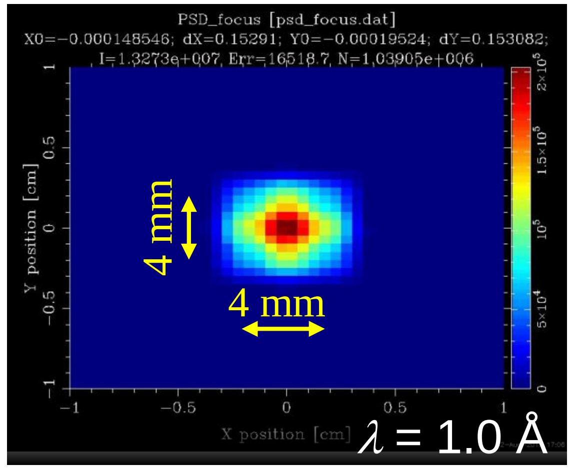
× 2 for elliptic guides

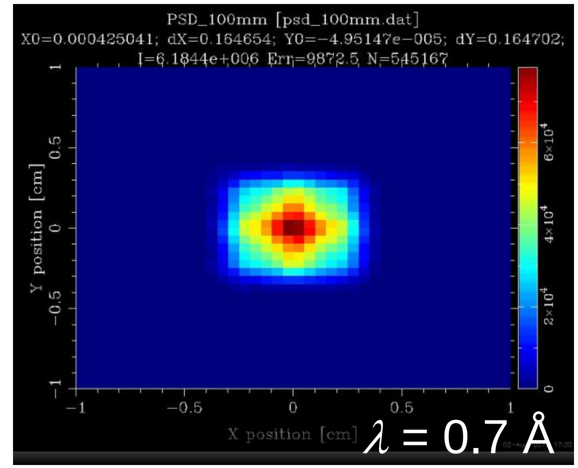
Focusing of Hot Neutrons

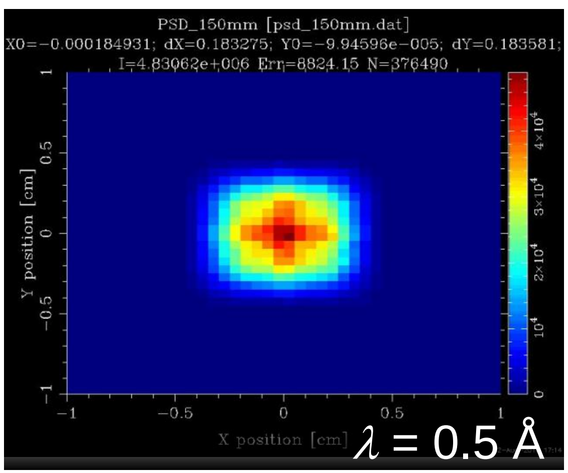
Paramters of focusing guide:

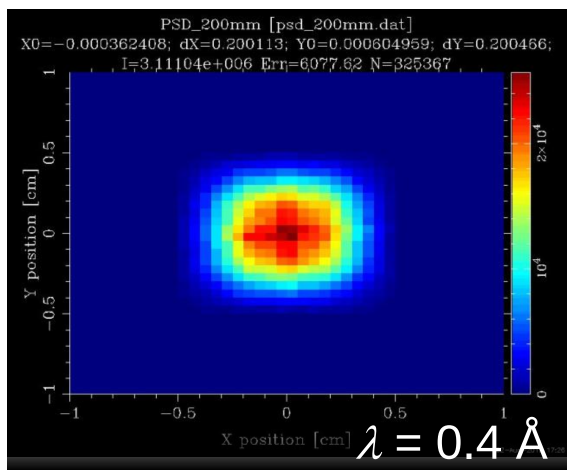
- L = 500 mm
- m = 7.0 / R = 51%
- $w_{in} = h_{in}$ = 15 mm
- $w_{out} = h_{out}$ = 5.6 mm

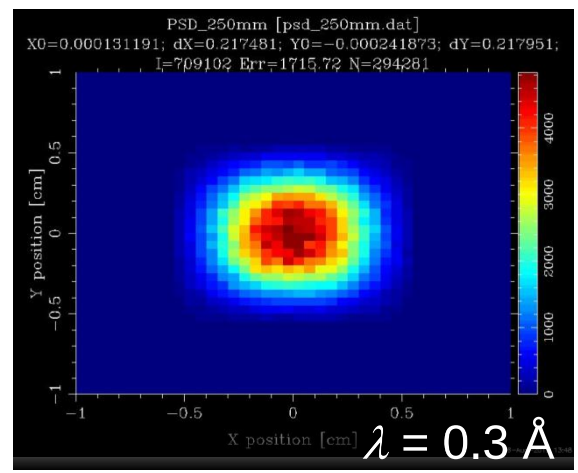




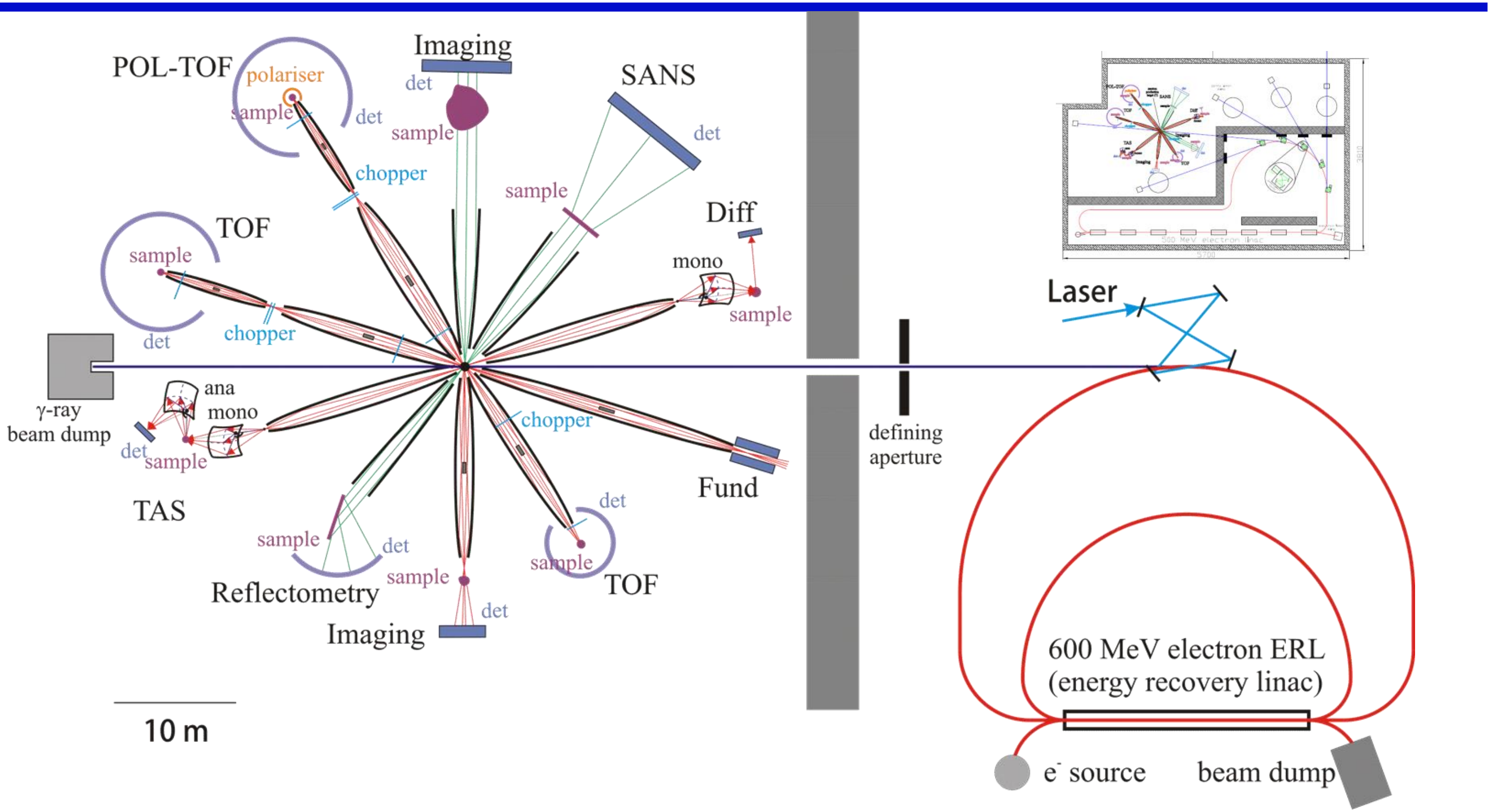








Compact Sources: Halo Neutrons



Discussion:

- no moderator required
- flux scales with power of ERL

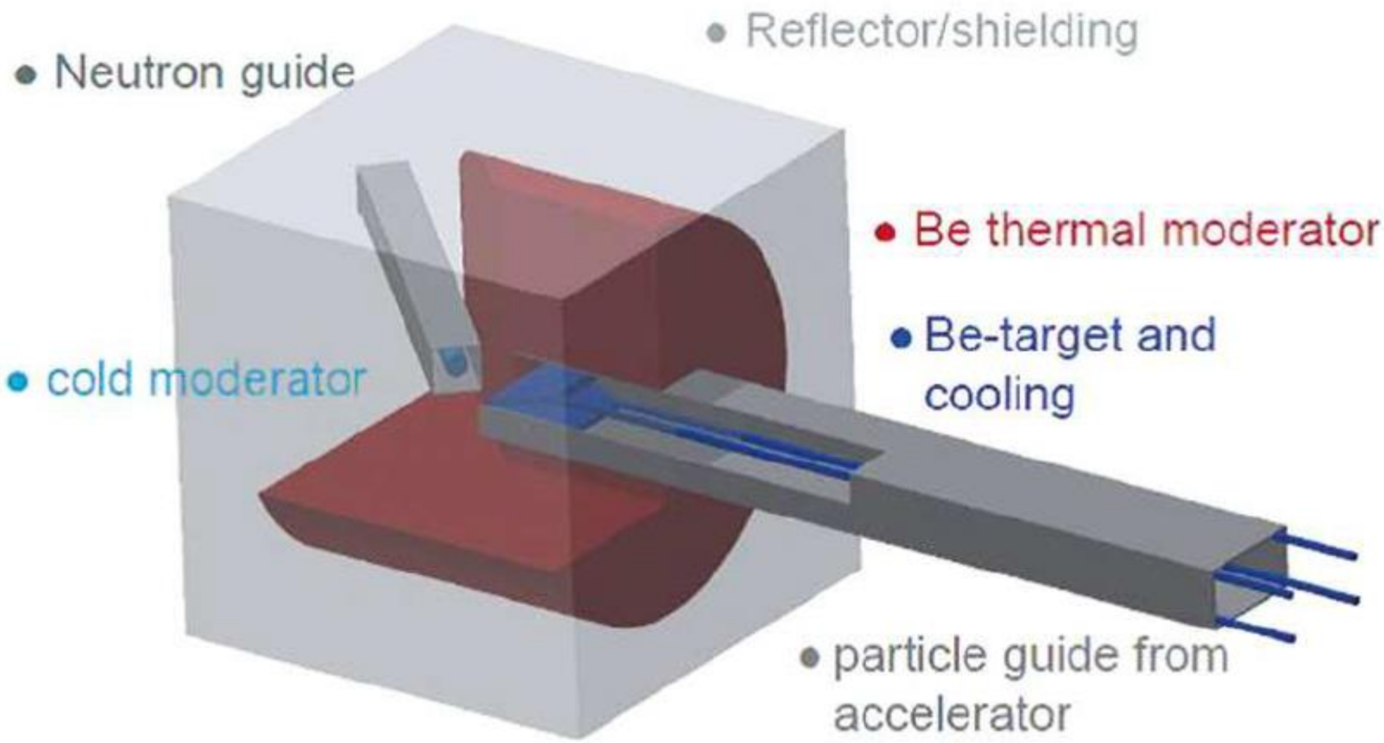
$B_{CW} \cong 10^5\ s^{-1}\ mm^{-2}\ mrad^{-2}\ (0.1\%BW)^{-1}$

$B_{pulsed} \cong 10^{11} s^{-1}\ mm^{-2}\ mrad^{-2}\ (0.1\%BW)^{-1}$

D. Habs et al., Applied Physics B **103**, 485–499 (2011); https://link.springer.com/article/10.1007/s00340-010-4276-3

Jülich High-Brilliance Neutron Source Project

U. Rücker, T. Cronert, J. Voigt, J. P. Dabruck, P.-E. Doege, J. Ulrich, R. Nabbi, Y. Beßler, M. Butzek, M. Büscher, C. Lange, M. Klaus, T. Gutberlet, and T. Brückel



Question: Brilliance??

U. Rücker et al., Eur. Phys. J. Plus 131, 19 (2016); https://doi.org/10.1140/epjp/i2016-16019-5

Content

- Why supermirror?
- How does supermirror work
- Fabrication of supermirror
- Applications of supermirror
- Future
- Summary

Summary

Supermirror is essential: optimize for

- large *m*, high reflectivity *R* (limitation: absorption)
- polarizing mirrors / band pass mirrors
- long lifetime, irradiation resistant, stress-free
- advanced optics available

Some comments:

- design beamline backwards: physics → neutron source
- accept Liouville theorem: extract only useful neutrons
- maintain dense phase space / optimize brilliance transfer
- develop new optical concepts (Montel, Wolter, etc.)
- adaptive optics (adjustment of beam size, divergence)
- be aware: neutron sources are aged when taken into operation
  (who buys a 10 years old car?)
- wishful thinking: avoid moderation process, use accelerator

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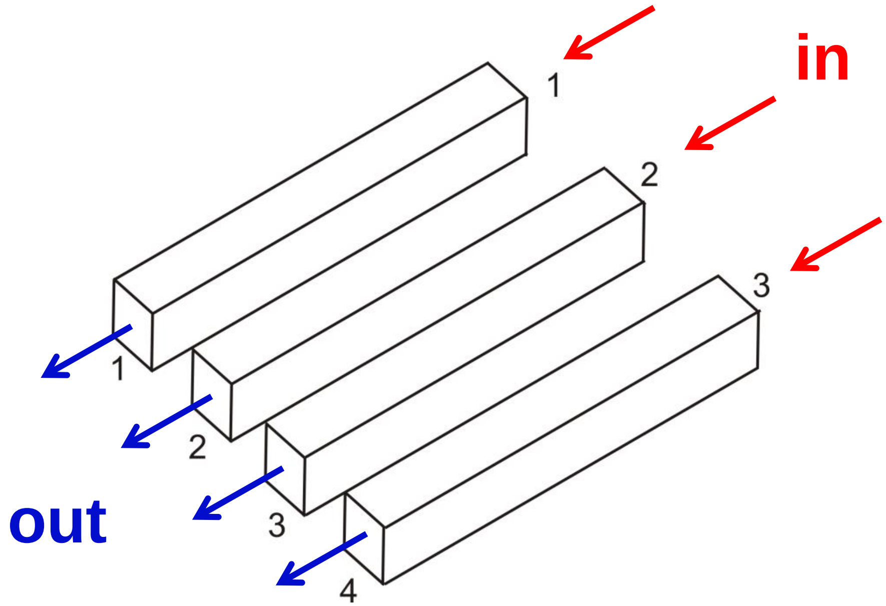
- Tobias Weber (TUM)
- Robert Georgii
- Oliver Zimmer (ILL)



Thank you for your patience