Development and Applications of Supermirror

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Stabilization of Flux Density at Low Level

Content

• Why supermirror?
• How does supermirror work
• Fabrication of supermirror
• Applications of supermirror
• 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 $\theta_c$?
• $n \approx 1 - 1 \cdot 10^{-5}$
• $\theta_c (0) = 0.1 m \lambda$ (Å)

cold neutrons:
• $\lambda = 5$ Å, nickel coating
  $\rightarrow \theta_c = 0.5^0$

$n$: index of refraction
$\lambda$: wavelength of neutrons
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Invention of Supermirror

- smooth surfaces
- multilayer
- supermirror

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

$\lambda = 2d\sin\theta$

(Turchin 1967, Mezei 1976)
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

\[ Q_z [\text{nm}^{-1}] \]

Reflectivity

\[ m \text{- value} \]

8312 layers
2016: Roughness Independent of $N$

reflectivity of supermirror is fully understood and can be modelled

$N > 16'700$ layers
X-Ray Reflectivity of Supermirror $m = 4$

\[ R = 80\% \quad \text{and} \quad R = 60\% \]
2018: Optimization of Supermirror $m = 5$

70% → 80%
Long Term Stability: $m = 6$
Test: Irradiation of Supermirror on Aluminum

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

sample size: $10 \times 10 \times 50 \text{ mm}^3$

no visible degradation of surface of supermirror is observed

[Diagram showing PSI, D$_2$O, PNA, NAA, and SINQ-Target]

PNA

thermal neutrons $\approx 4 \times 10^{13} \text{n/cm}^2/\text{s}$
Irradiation test: $9.6 \times 10^{19}$ n/cm$^2$

**Irradiation of Supermirror on Aluminum**

No degradation of reflectivity of supermirror is observed.

**Graph:**
- Reflectivity vs. $m$-value
- Two curves: before irradiation and fluence $9.6 \times 10^{19}$ n/cm$^2$

**Holographic neutron imaging:**
- PNA
- Thermal neutrons ≈ $4 \times 10^{13}$ n/cm$^2$/s
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Guides: Artistic Glass Work / Standard Technology

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

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

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


similar system has been installed at MLF @ J-PARC (SPICA)
→ focusing before
and
→ defocusing after sample
Focusing Setup: TA Phonons in Lead

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

$V_{sample} = 2 \times 2.5 \times 2.5 \text{ mm}^3$
Elliptic Montel Mirrors: Selene @ SINQ

- Neutron guide
- Chopper
- Polariser & flipper
- Montel mirror
- Sputter-chamber
- Sample
- Detector

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)

\[ 2d \sin \theta_B = n \lambda \]
Monolayers of Fe on Si-Cu: Selene @ AMOR

Discussion:
• new Selene @ SINQ: $\approx 1$ min / spin channel
• ESTIA at ESS: $\approx 0.5$ sec / spin channel
Montel Mirrors Combined with *In-situ* Sputtering

Full Illumination: Move Guide Close to Moderator

\[ \theta_c \]

\[ L_{MG} \]

\[ F_{mod} \]

\[ D \]

\[ H \]

(a) 80 mm – short guide
\[ \alpha_{hor} = 1.0^\circ; \alpha_{vert} = 0.94^\circ \]

(c) 40 mm – long guide
\[ \alpha_{hor} = 1.77^\circ; \alpha_{vert} = 0.92^\circ \]
Extraction of Neutrons Using Tapered Guides?

Liouville: $H\theta_H = h\theta_h = \text{const}$

- 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 $10 \times 10 \, \mu\text{m}^2$ is $\sigma < 1 \, \text{Å}$.

Challenges:
- sharp interfaces (not required): solved
- low roughness: solved
- substrates with low roughness: solved
- absorption: major challenge

The $mX$ Mirror Project: $m = 10$

Supermirror $m = 10$, 17600 Layers, 99%>$R>$60%

Reflectivity (%)

Momentum Transfer ($\text{Å}^{-1}$)

- with absorption
- w/o absorption

File: mX @ dynR=99-60.txt

12/15/2015
File Reflectivity_m=10_Simulation_var A99
Development of Neutron Guide Optics

ILL, SINQ, etc

ISIS, J-PARC

ESS

SINQ → ESS

B. Khaykovich et al.: optics for imaging

see also talk by O. Zimmer


advantage: gravitational effects usually not important

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
Experience: Design Large Beam Inserts

example: cold neutrons
- $L = 6 \text{ m}$
- $\lambda = 5 \text{ Å}$
- $m = 3$
- divergence: $3^0$

$\rightarrow \ D = 311 \text{ mm} + \text{ mechanics}$

$\times 2$ for elliptic guides

example: hot neutrons
- $L = 6 \text{ m}$
- $\lambda = 0.5 \text{ Å}$
- $m = 8$
- divergence: $0.8^0$

$\rightarrow \ D = 83 \text{ mm} + \text{ mechanics}$

$\times 2$ for elliptic guides

Insert made from copper
Focusing of Hot Neutrons

Parameters of focusing guide:

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

\[ \lambda = 1.5 \text{ Å} \]
\[ \lambda = 1.0 \text{ Å} \]
\[ \lambda = 0.7 \text{ Å} \]
\[ \lambda = 0.5 \text{ Å} \]
\[ \lambda = 0.4 \text{ Å} \]
\[ \lambda = 0.3 \text{ Å} \]
Discussion:

- no moderator required
- flux scales with power of ERL

\[ B_{\text{CW}} \approx 10^5 \text{ s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2} (0.1\%\text{BW})^{-1} \]

\[ B_{\text{pulsed}} \approx 10^{11} \text{s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2} (0.1\%\text{BW})^{-1} \]
Jülich High-Brilliance Neutron Source Project


Question: Brilliance??
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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 $\rightarrow$ 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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