Recent progress in the development of neutron multilayer optics at MLF

Ryuji Maruyama, J-PARC Center, Japan Atomic Energy Agency, 23rd October 2025

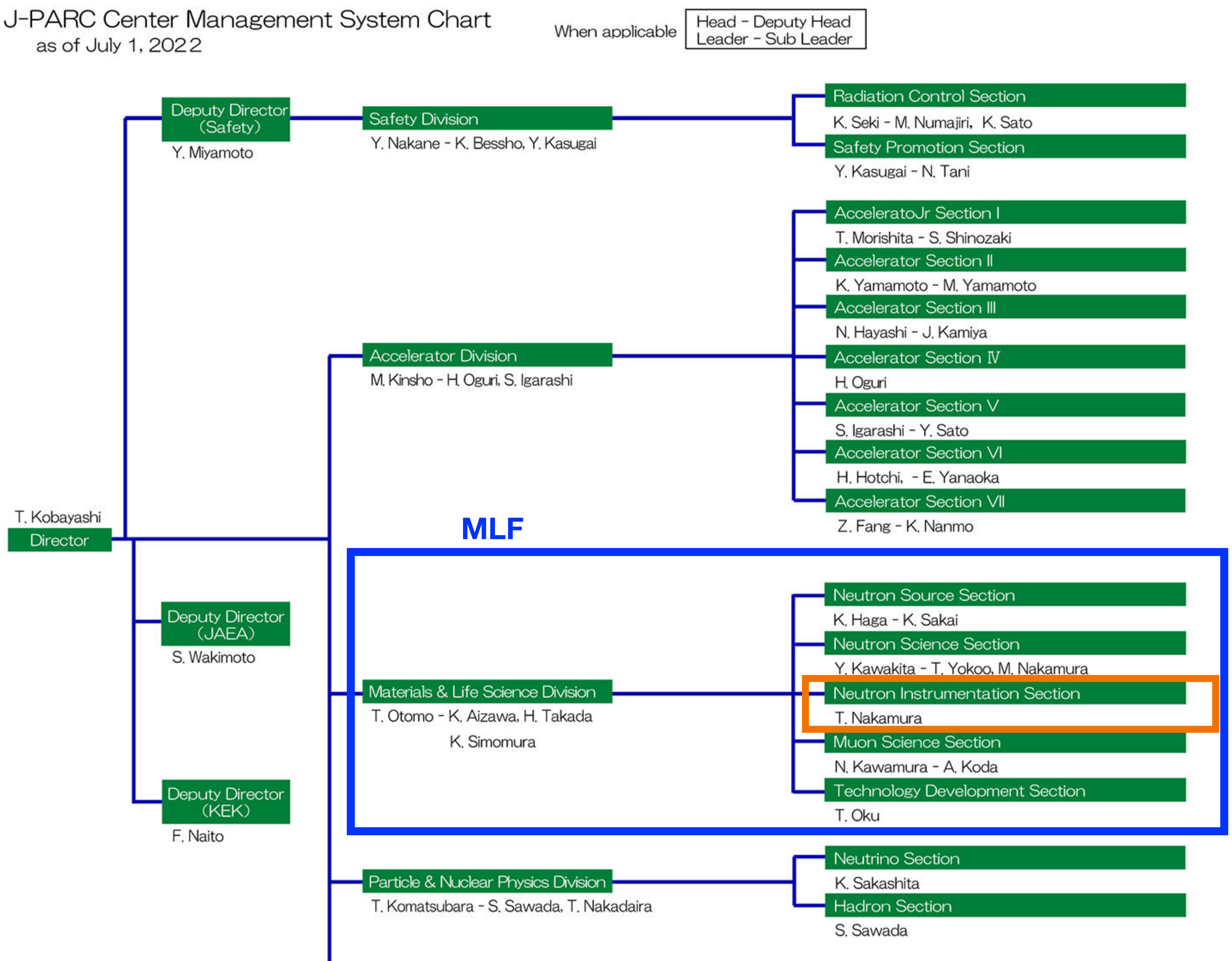
Outline

1. Introduction
2. Focusing supermirror for GISANS measurement at BL17
3. Wide-bandwidth polarizing supermirror due to ferromagnetic interlayer exchange coupling
4. Recent studies for further increase in bandwidth
5. Summary

Organization

Neutron instrumentation section,
MLF division,
J-PARC Center,
JAEA

In charge of the development of…
- **Neutron detector**
- **Neutron multilayer optics**



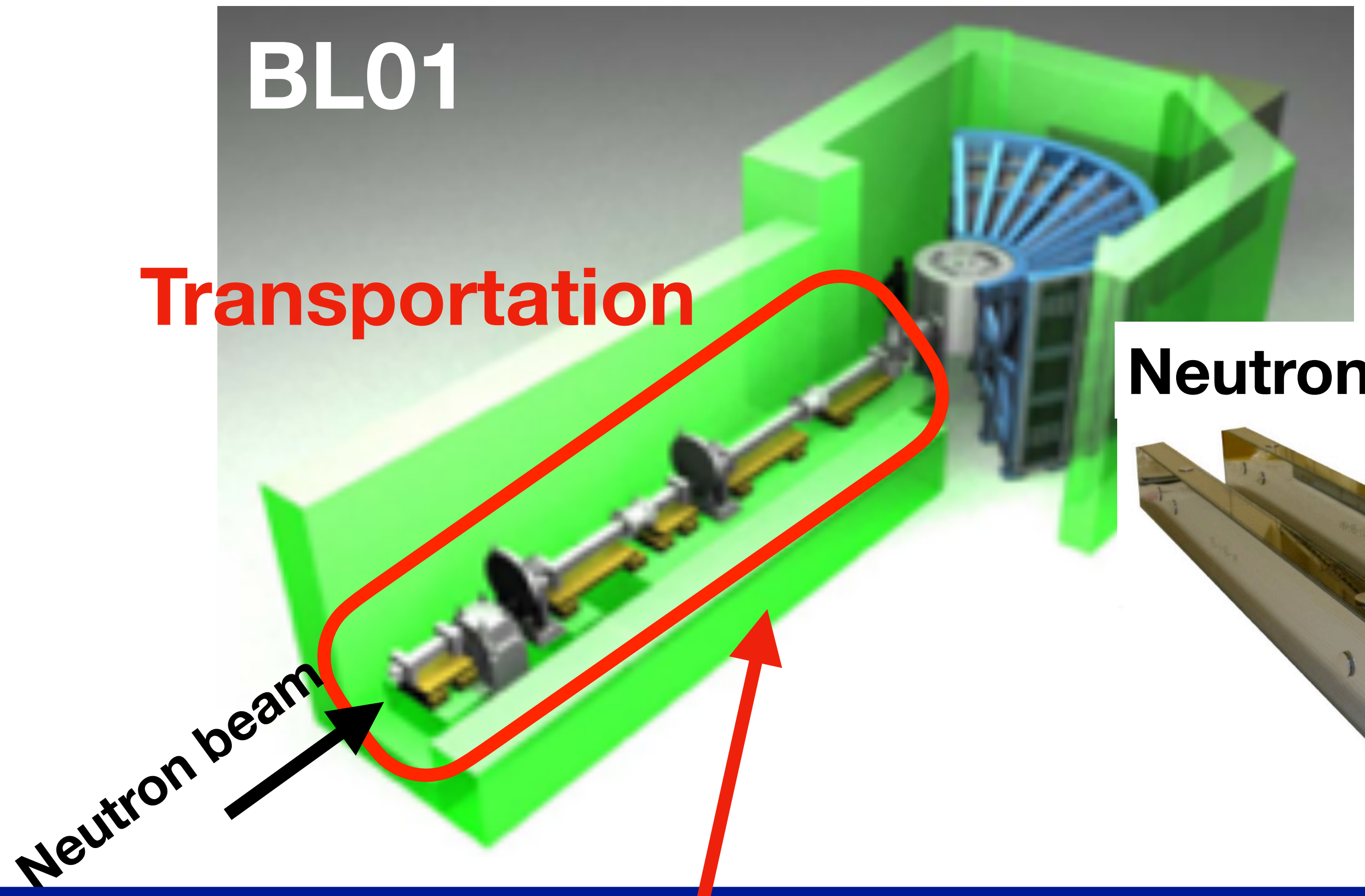
Collaborators

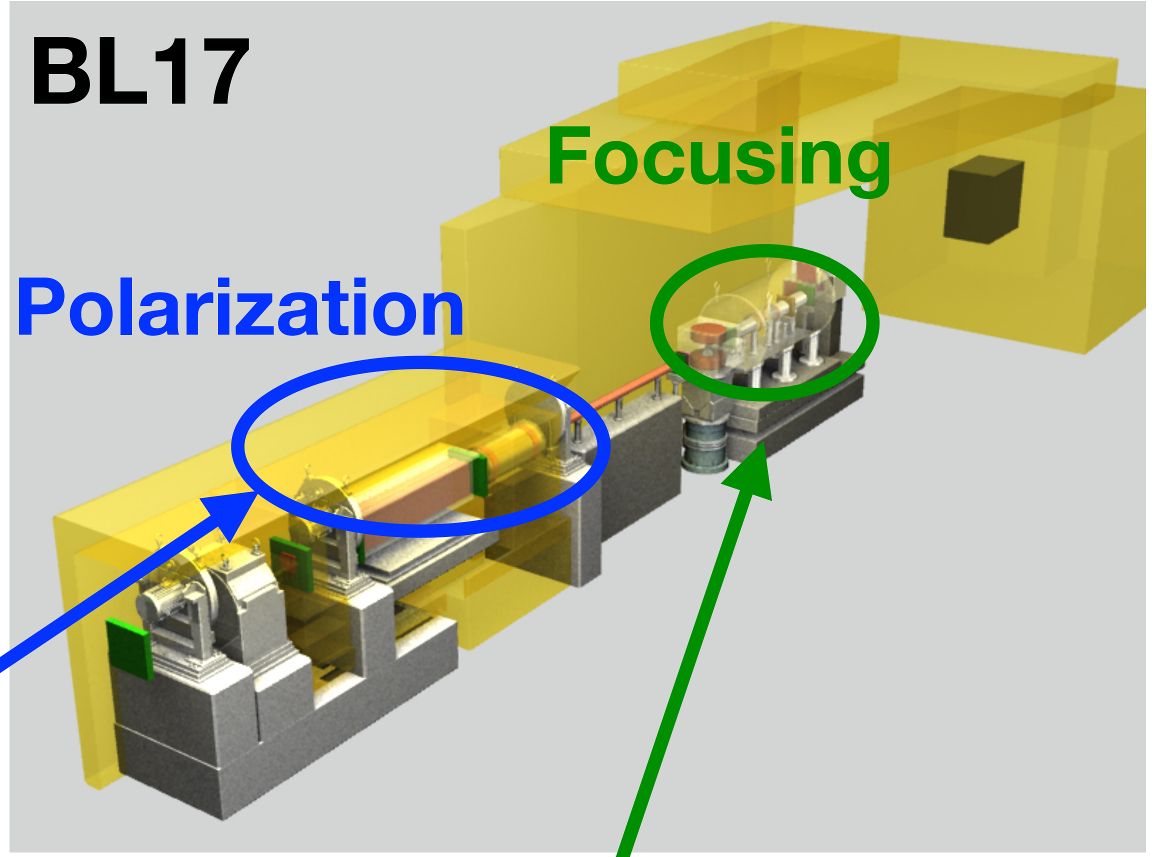
- **J-PARC, Japan**
  D. Yamazaki, K. Soyama, H. Aoki
- **JAEA, Japan**
  M. Takeda
- **CROSS, Japan**
  K. Akutsu-Suyama, T. Hanashima, N. Miyata, M. Ishikado
- **KEK, Japan**
  K. Amemiya
- **ILL, France**
  T. Bigault, T. Saerbeck, A. R. Wildes, C. D. Dewhurst, P. Courtois
- **ISIS, UK**
  D. Honecker
- **Uppsala Univ., Sweden**
  M. Wolff, A. Vorobiev, A. Devishvili, V. Kabanova
- **Linköping Univ., Sweden**
  F. Eriksson, N. Ghafoor, J. Birch

Our mission: Neutron multilayer optics

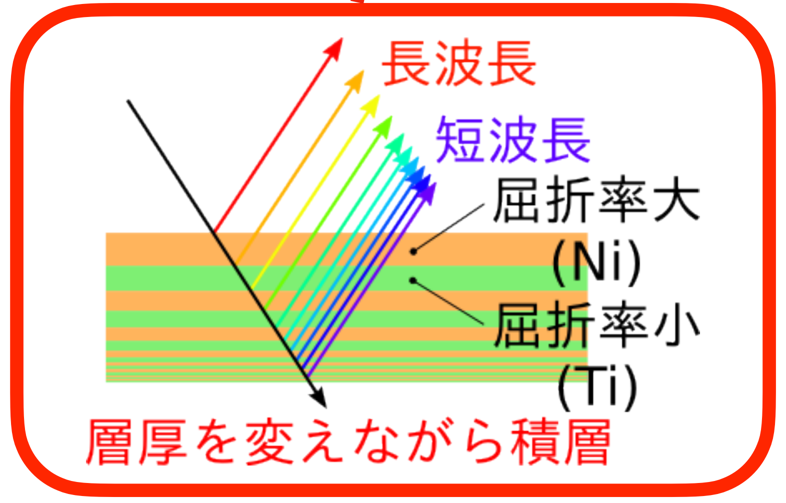
Aimed to contribute to the science conducted at MLF with multilayer based devices

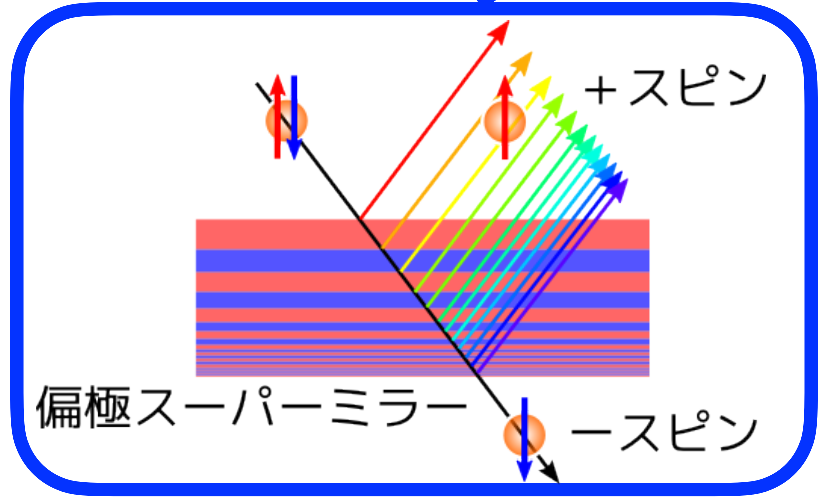
Neutron instruments at MLF

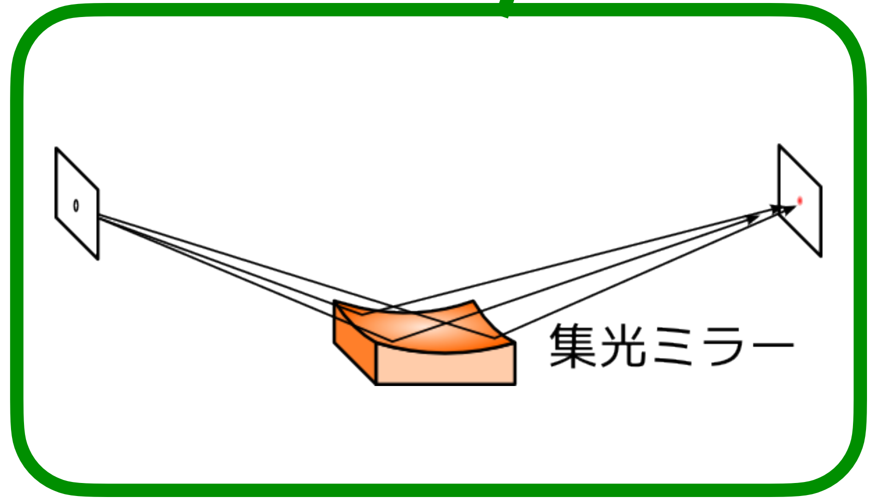




Devices







Science

- Strongly correlated sytem
- Battery materials
- Residual Stress

- Magnetism
- Spintronics
- Imaging

- High pressure science
- Soft matters
- Layered structures

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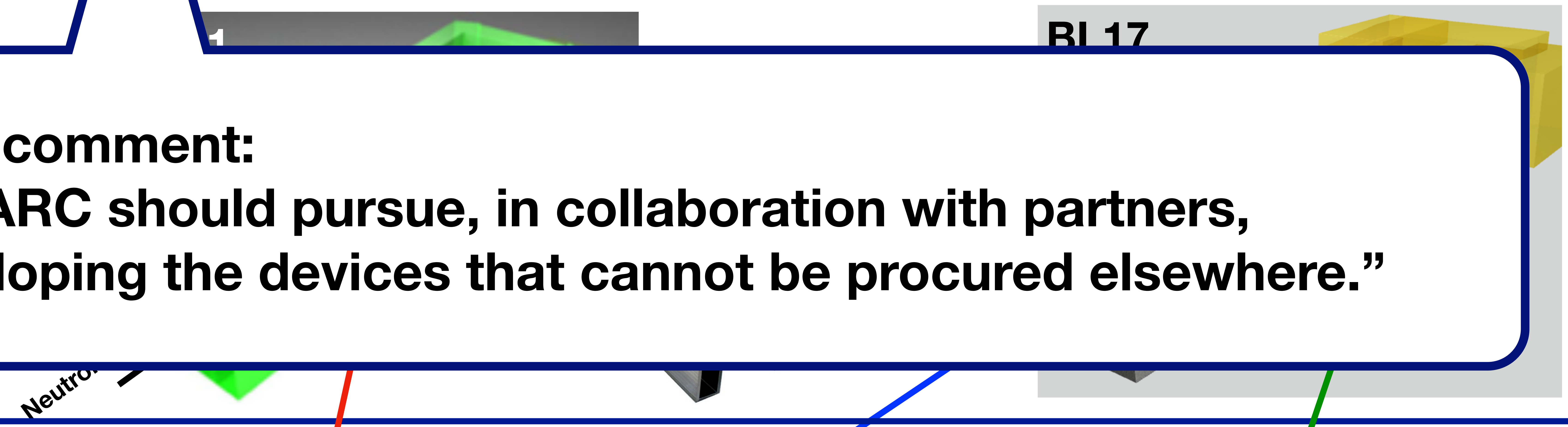
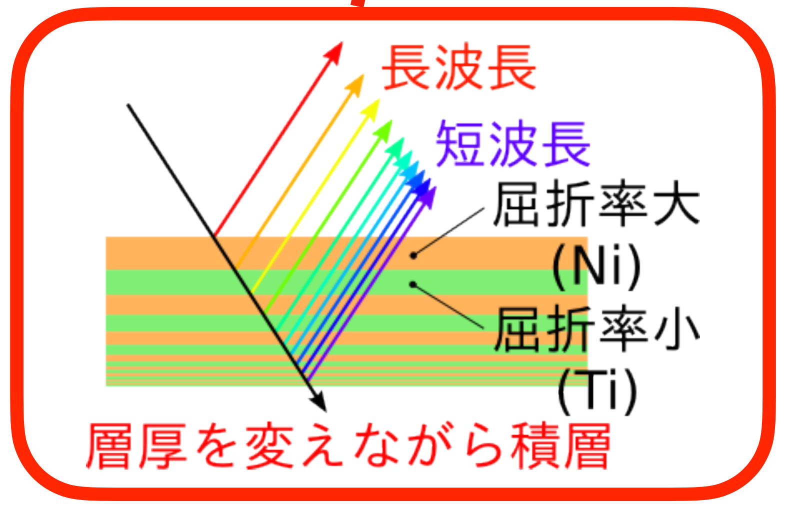
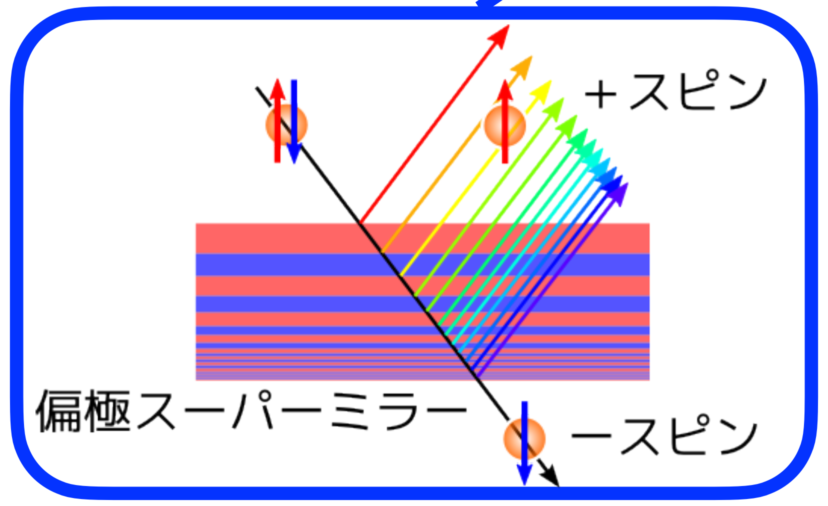
Neutron instr
at MLF

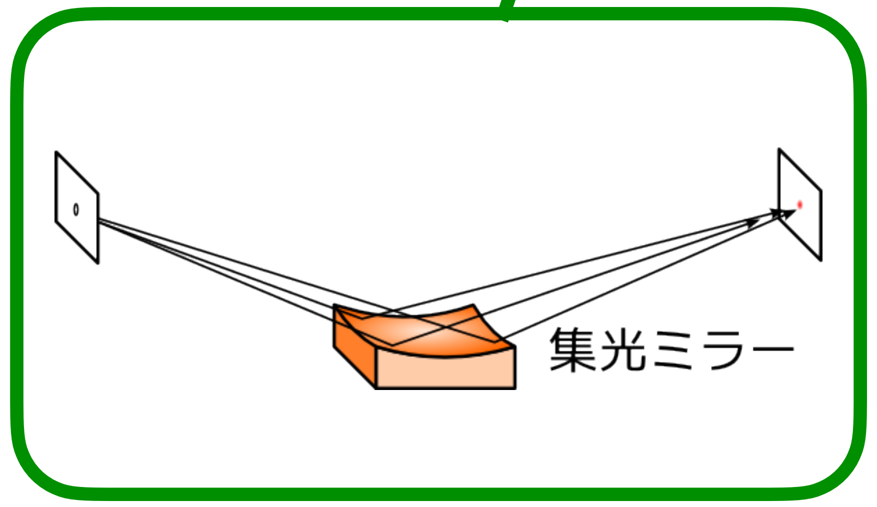


NAC comment:
"J-PARC should pursue, in collaboration with partners, developing the devices that cannot be procured elsewhere."

Devices







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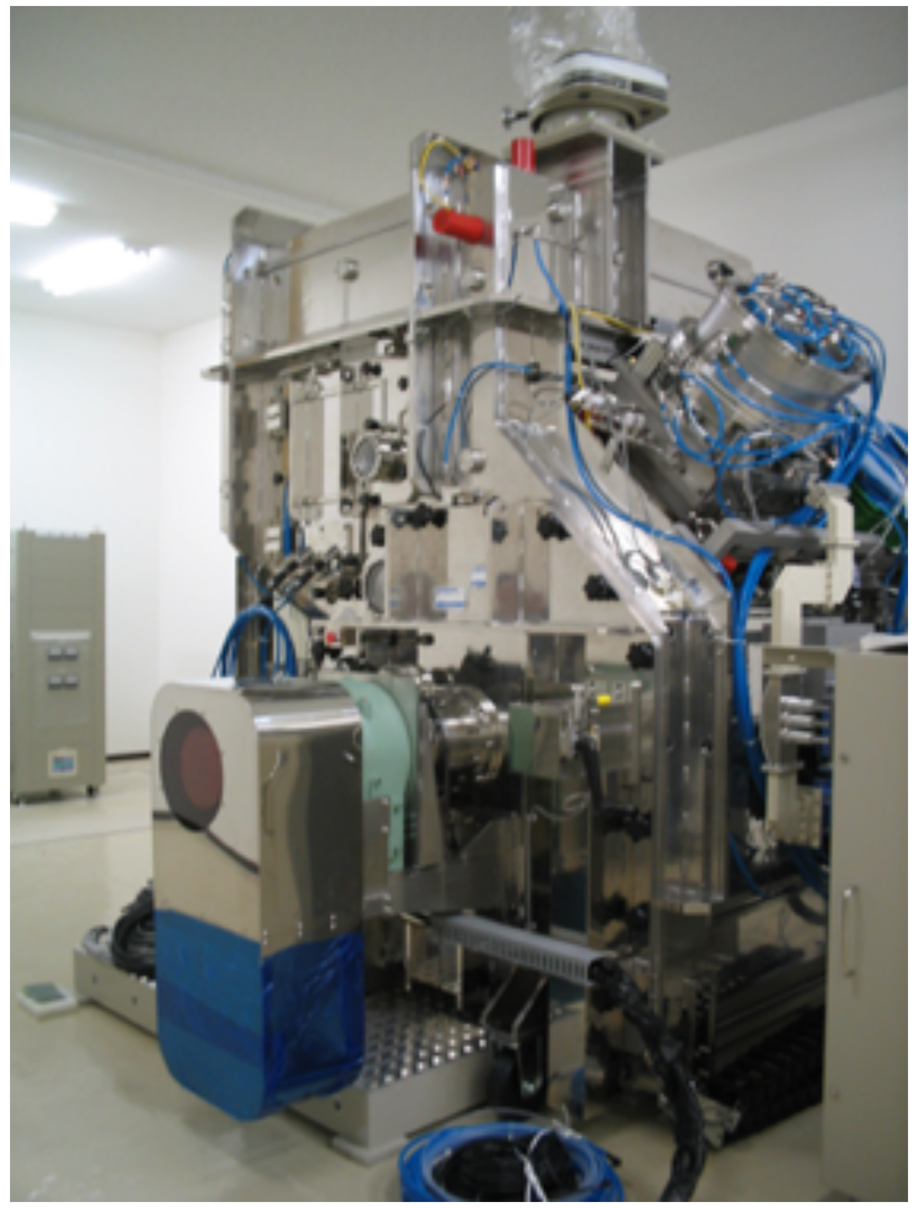
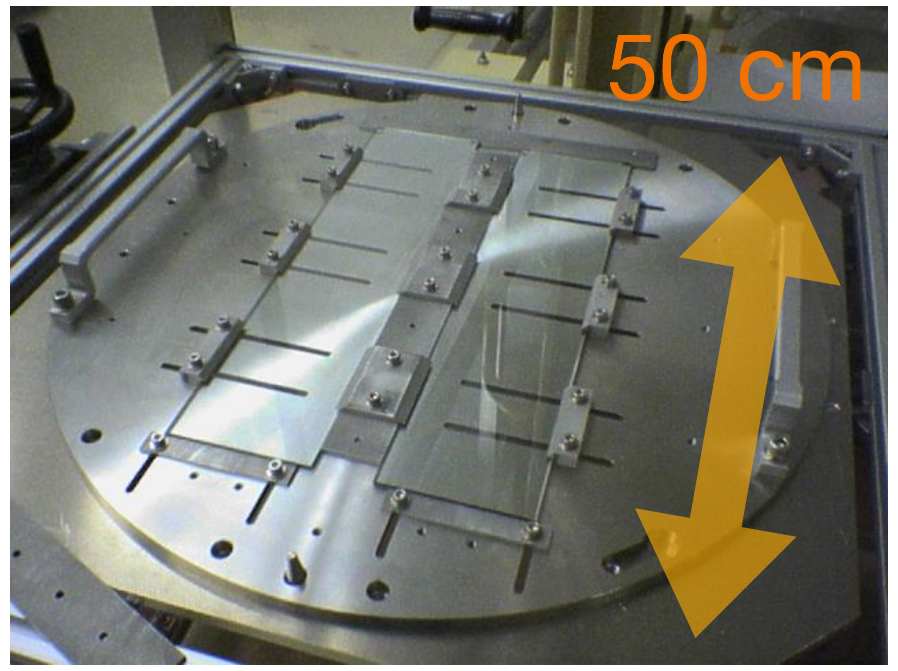
開発環境

大小2つのイオンビームスパッタ成膜装置

大面積成膜装置（実機製作用）





成膜可能面積：約2000cm^2

2m*l* x 2.5m*w* x 3.5m*h*

- 2013年頃まではMLF実験装置のガイド管製造に用いられていた
- GISANS用集光ミラー、回転楕円面ミラー等も

小型成膜装置（R&D用）

2010年頃@高温特研

装置移設＆大改造

- PLC　日立製→三菱製シーケンサ
- アナログ操作盤→タッチパネル
- 成膜制御PC　win2000→win10
- イオン源電源更新
- q-mass設置
- ドライポンプ、CP更新

2021年@JRB調整室B

長時間成膜が可能になり、
信頼性・再現性も向上

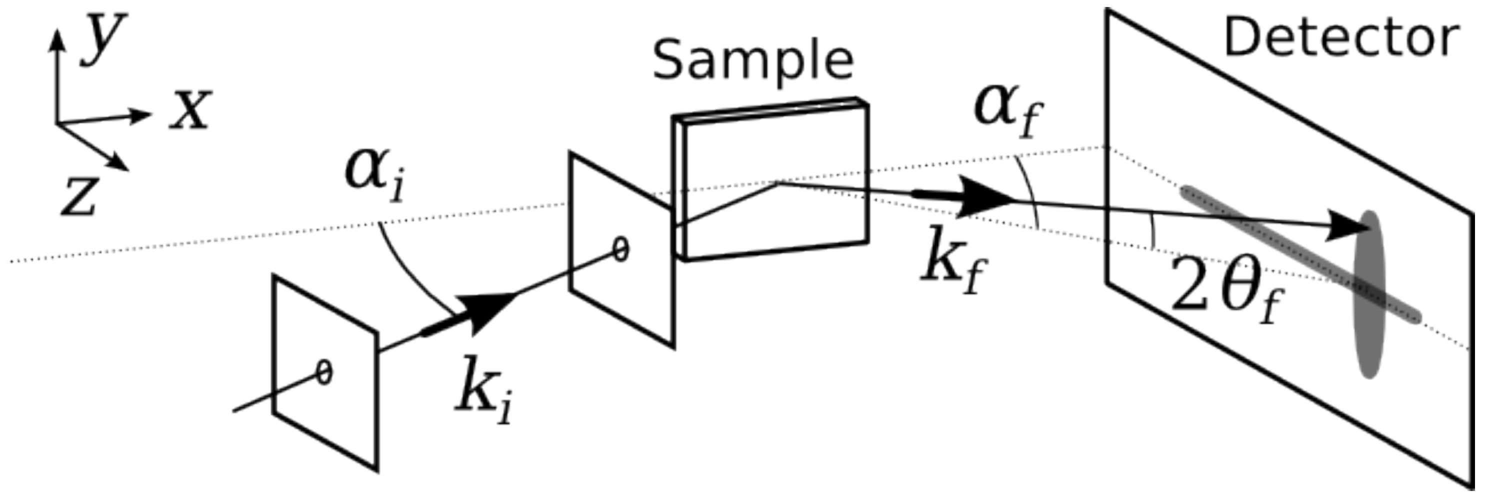
この他、X線反射率計、SQUID磁束計（CROSS）も重要

Focusing supermirror
An elliptic focusing supermirror for GISANS

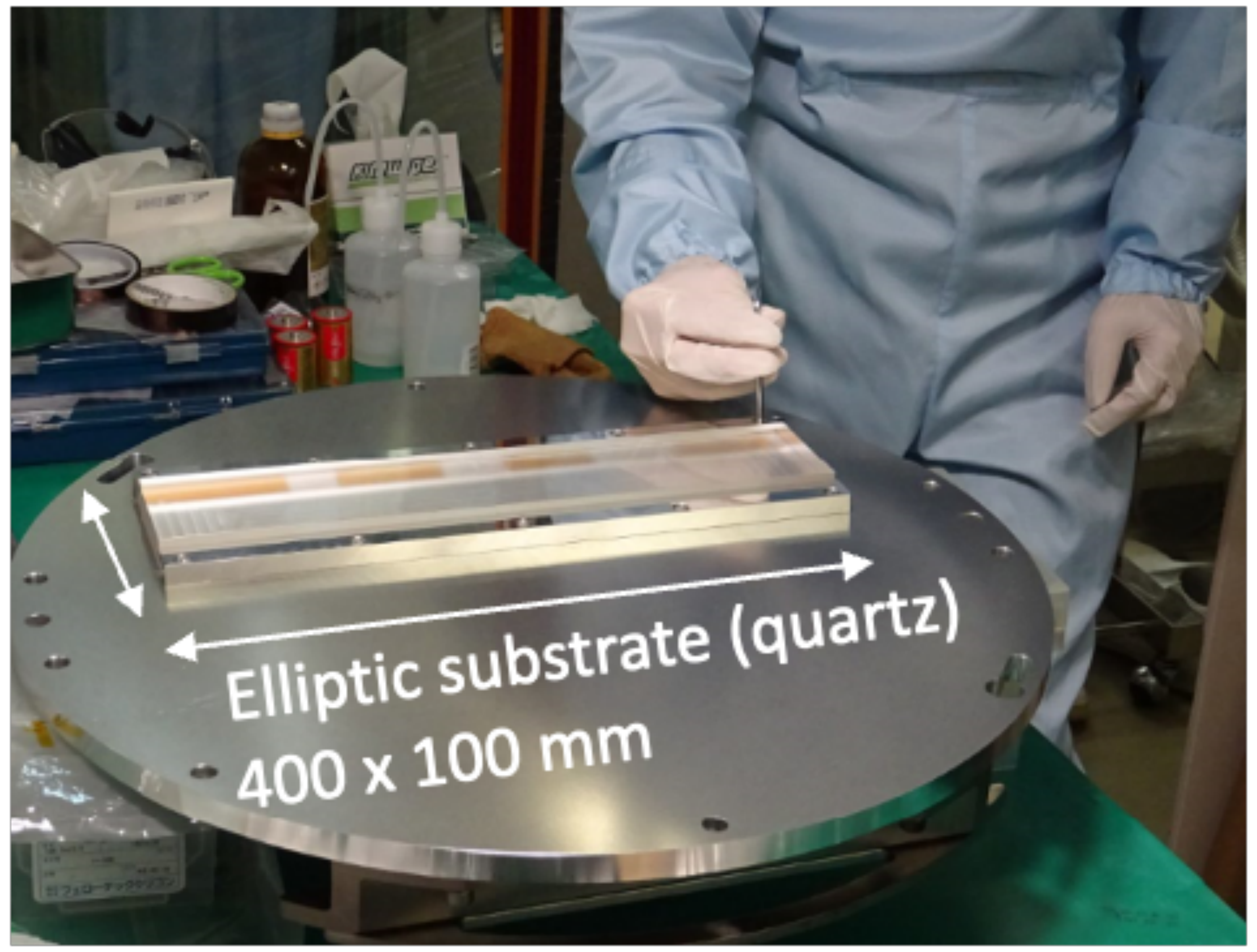
Dai Yamazaki

GISANS

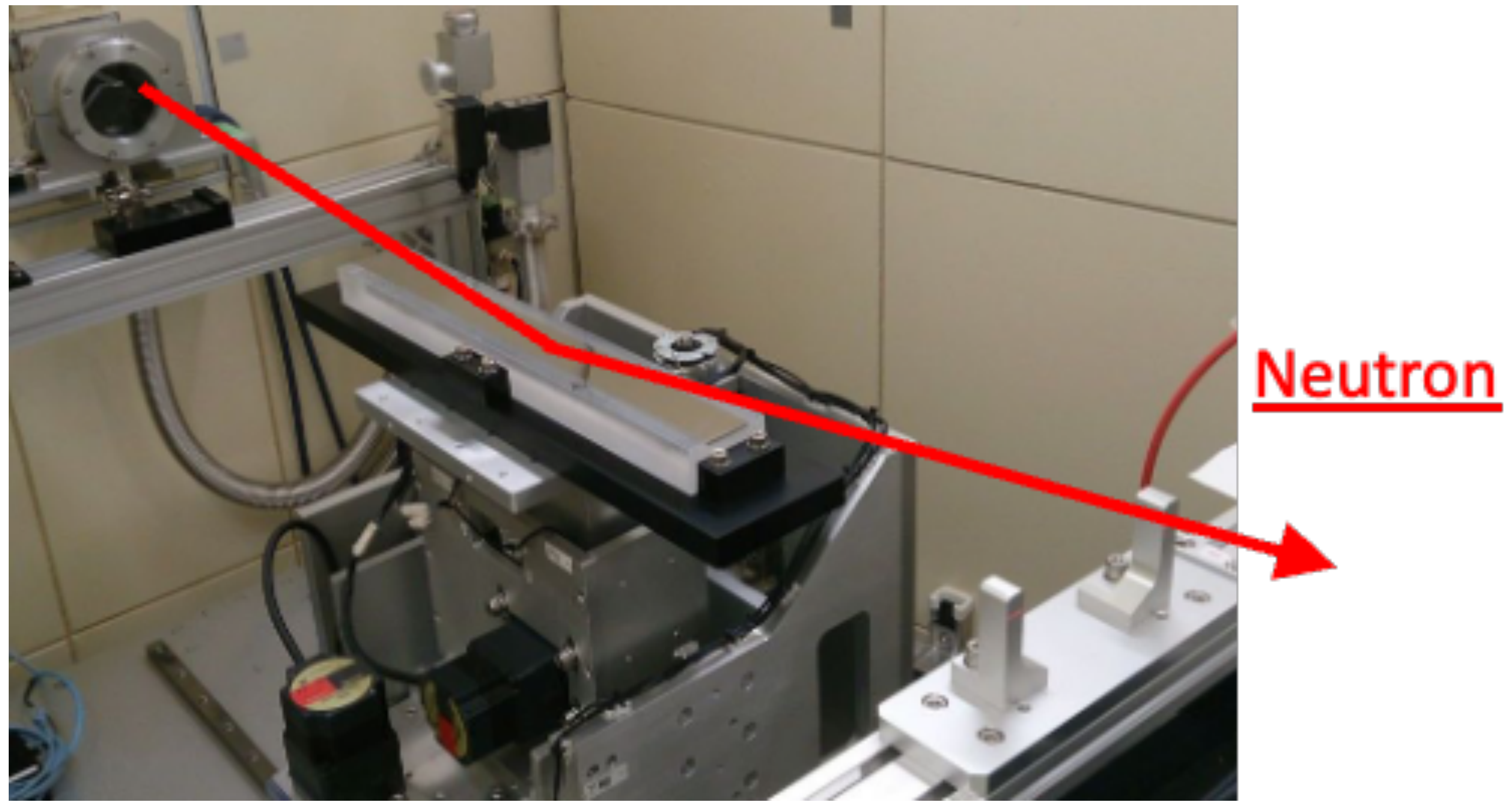
- An efficient probe for the in-plane structure with a length scale less than 1 μm.
- Neutron intensity is not enough in many cases.
- A neutron focusing supermirror is needed.



Grazing incidence small angle neutron scattering



NiC/Ti supermirror was deposited on the substrate with 1D elliptic shape

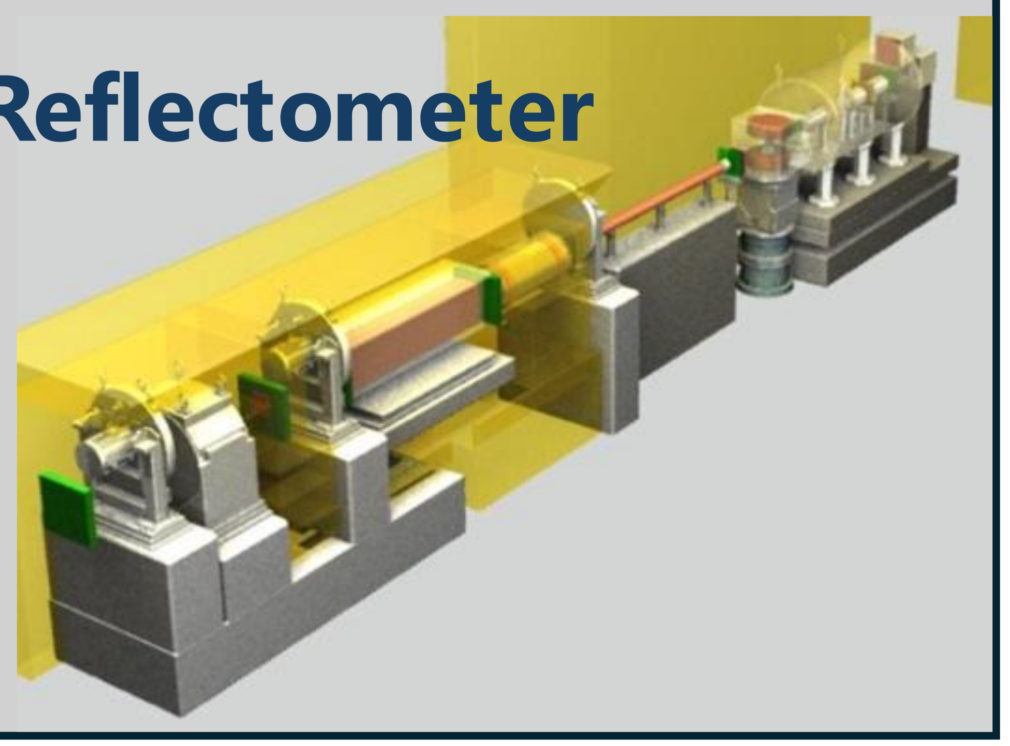


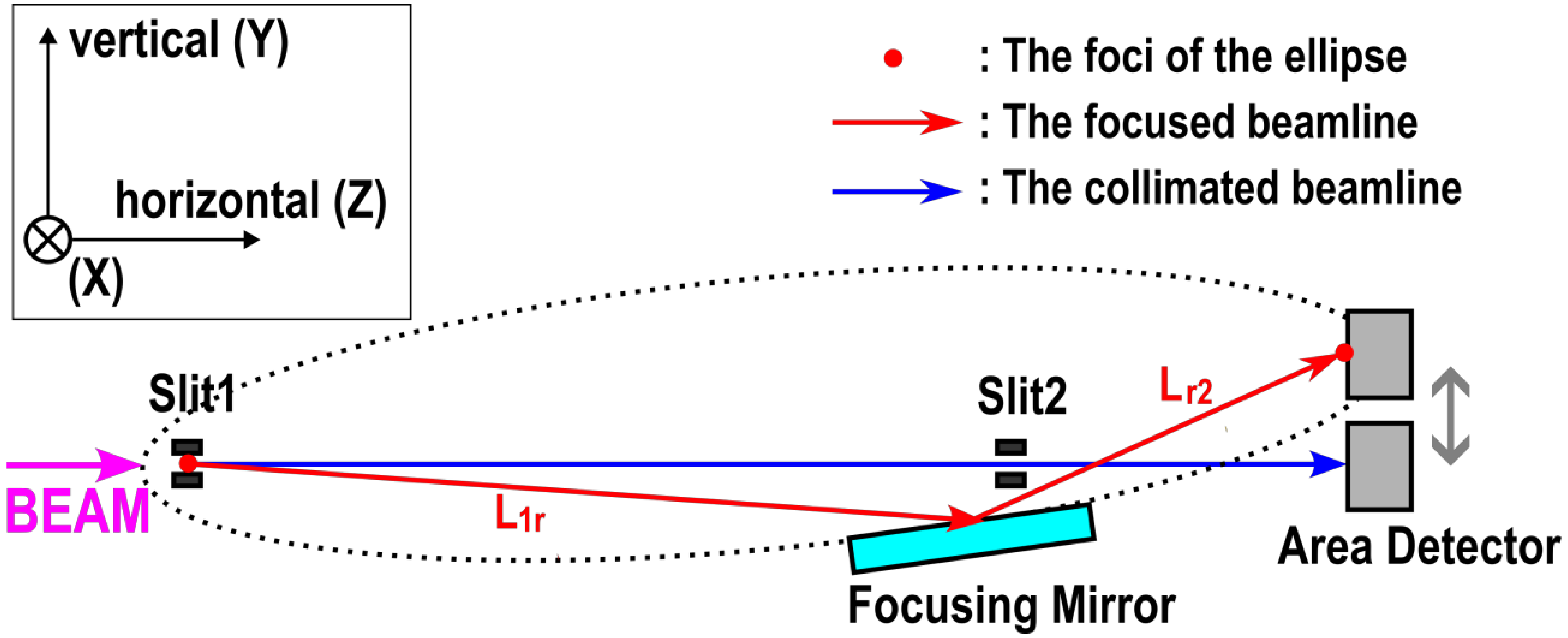
Neutron focusing test at BL17

A focusing supermirror for GISANS measurements at BL17

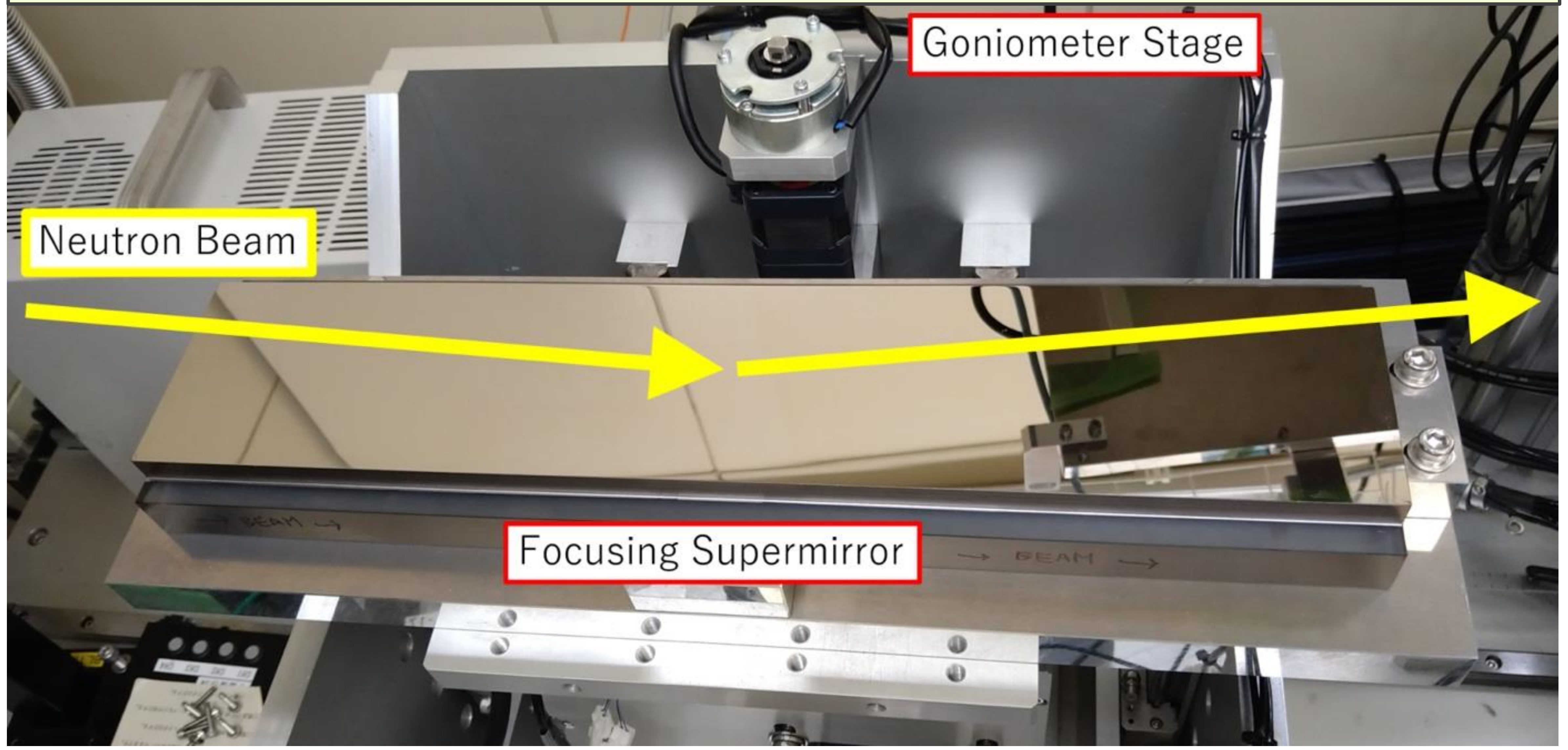
BL17:
Polarized Neutron Reflectometer
"SHARAKU"

vertical
sample geometry



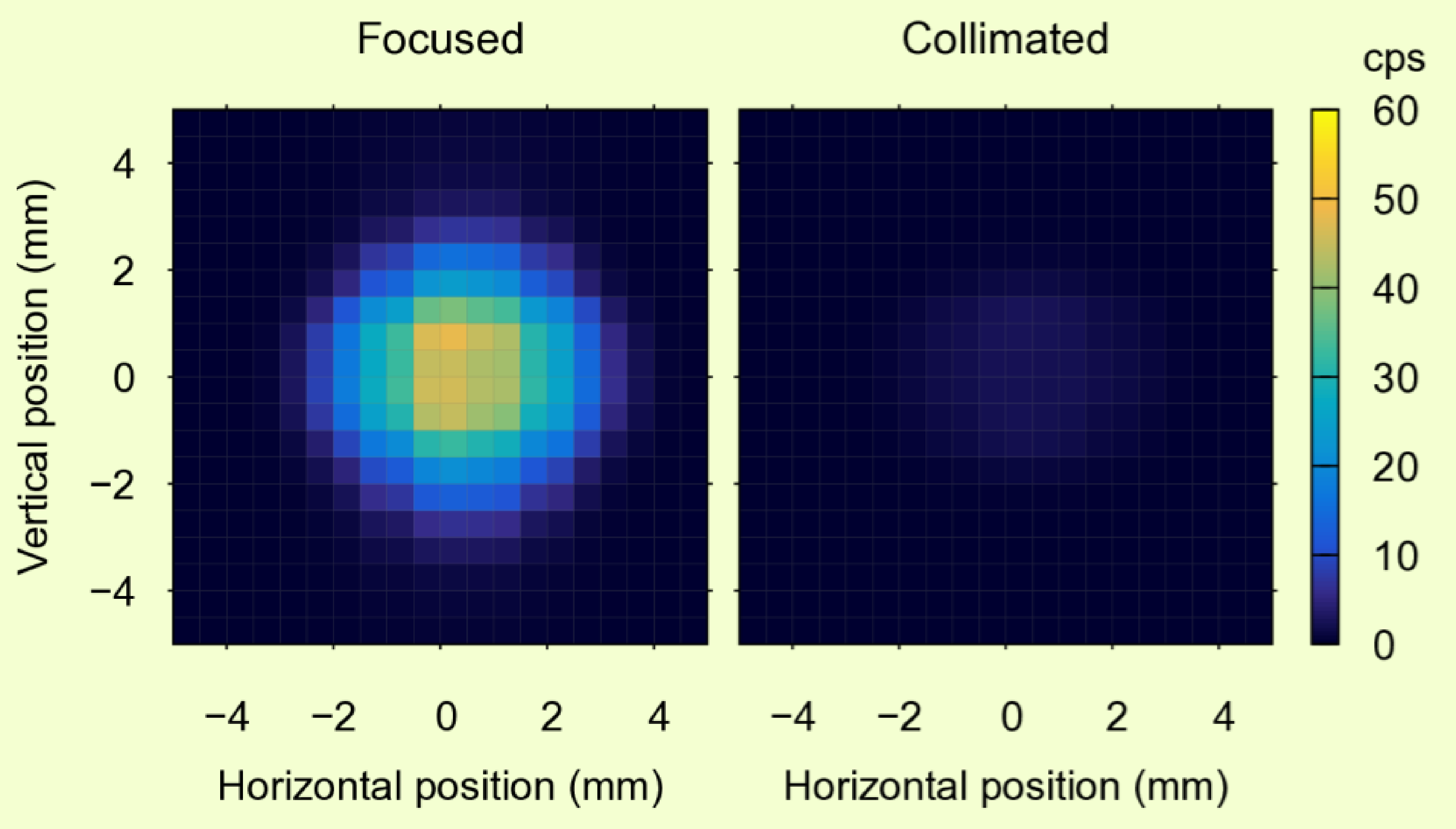


1-dimensional elliptic supermirror
for vertical beam focusing



the ellipsoid	(a=5525 mm, b=79.63 mm, θ= 72.59~76.89 deg)
1^{st} focus to mirror	L_{1r} = 6980 mm
mirror to 2^{nd} focus	L_{r2} = 4070 mm
incident angle	~ 0.856 deg
supermirror	NiC/Ti, m=4 (IBS coating)
substrate surface	roughness: 0.183 nm RMS
	figure error: 188.7 nm PV
substrate	400 x 50 mm^2, fused quartz

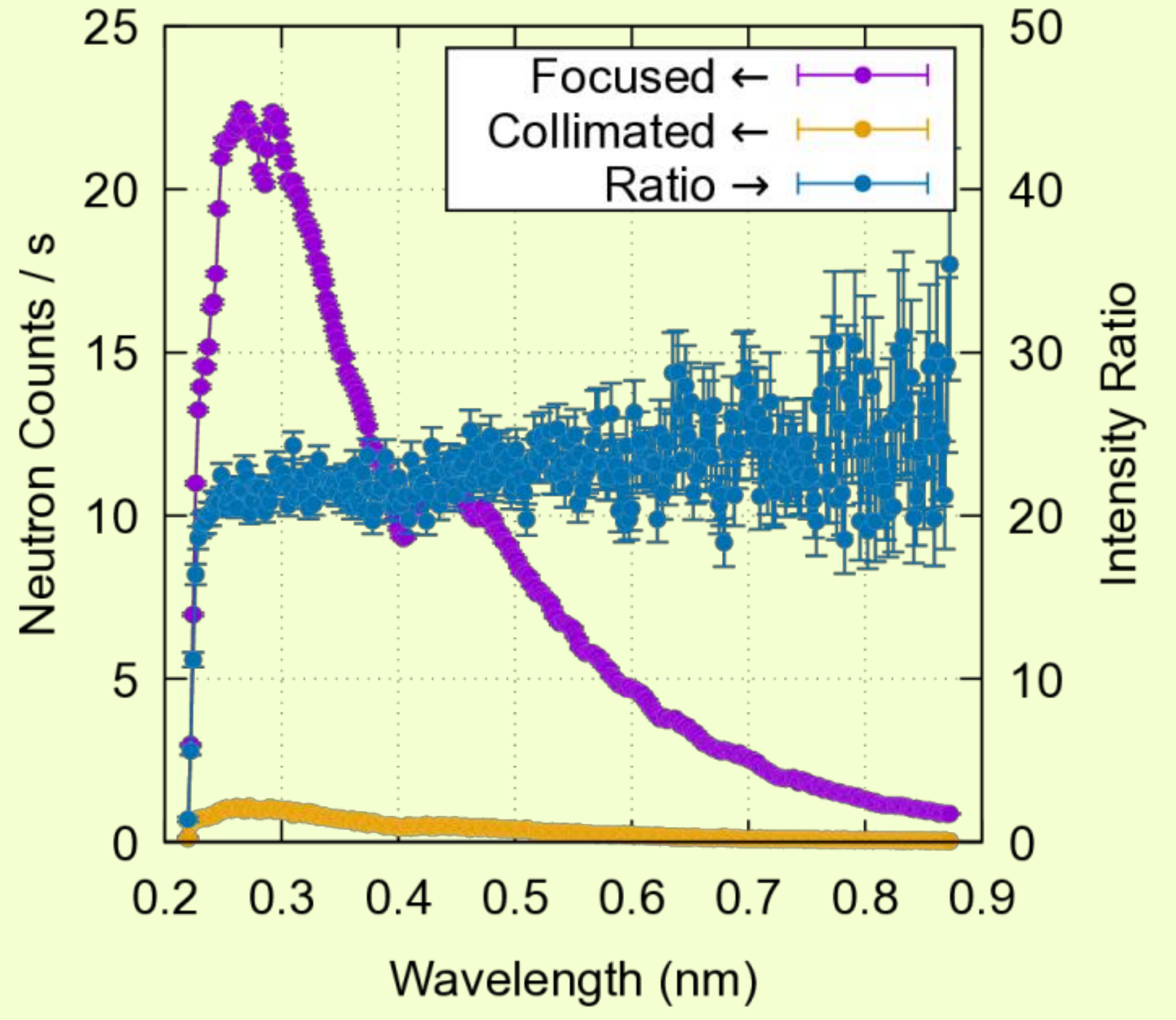
A focusing supermirror for GISANS measurements at BL17



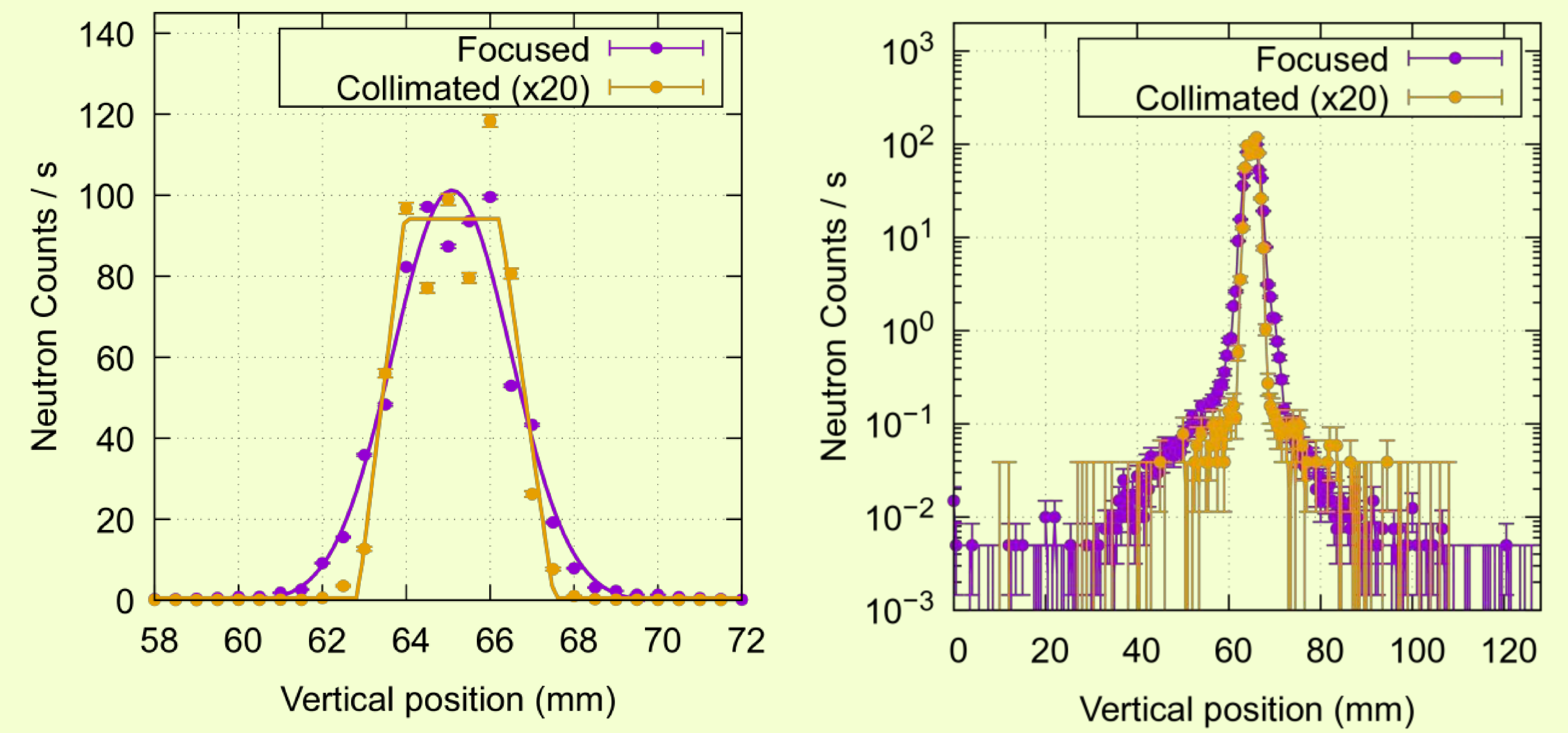
Measurement:
Focused spot vs Optimally collimated spot

Blurred spot due to …
- Mirror misalignment
- Detector resolution ~ 1.8 mm

Spot intensities vs Wavelength



Vertical cuts at the horizontal center



- ➢ Intensity Gain ~ 20 for λ > 0.23 nm
- ➢ S/B ratio ~ 500

Yamazaki et al., Quantum Beam Sci. **9**, 20 (2025).

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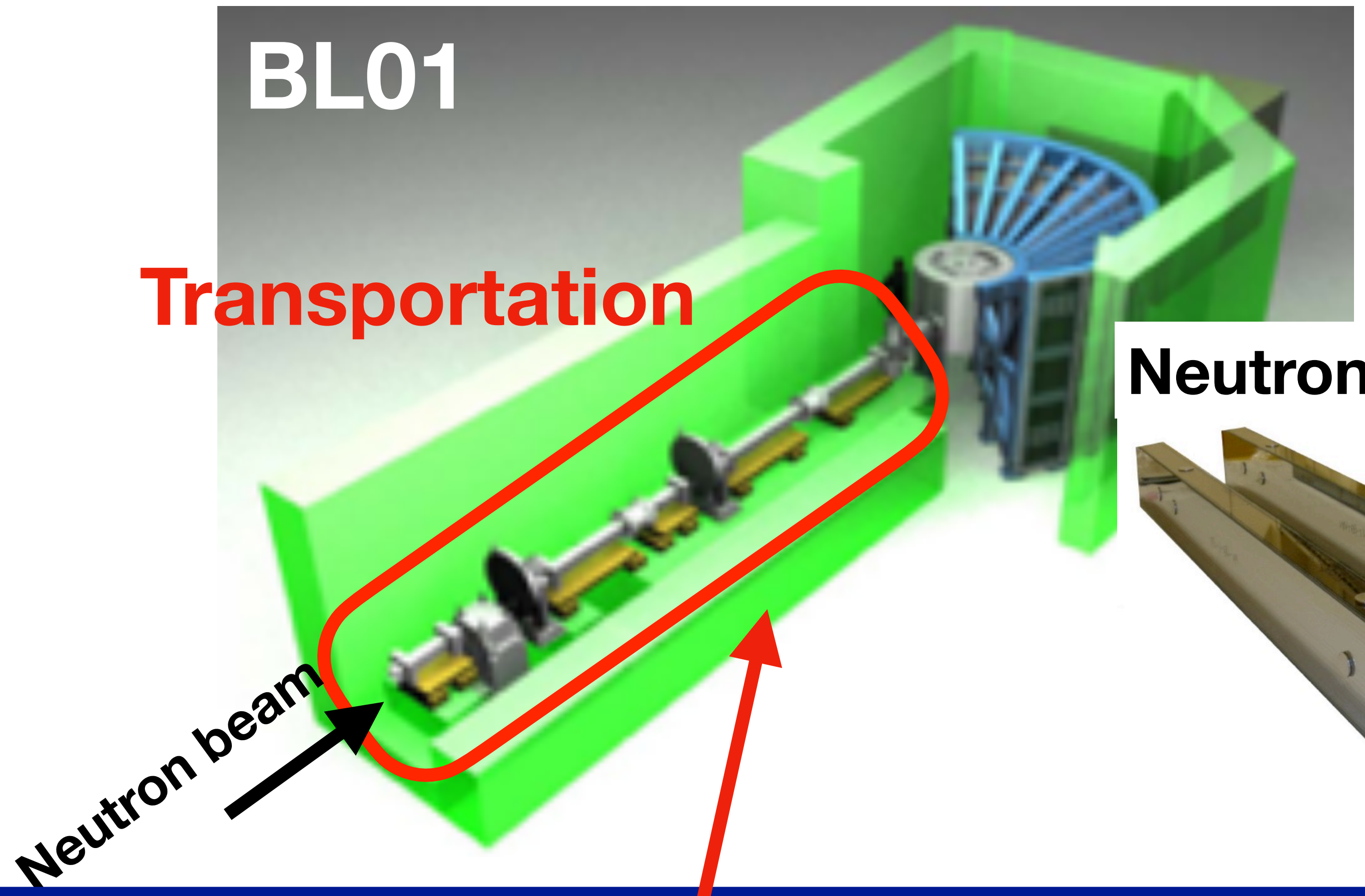

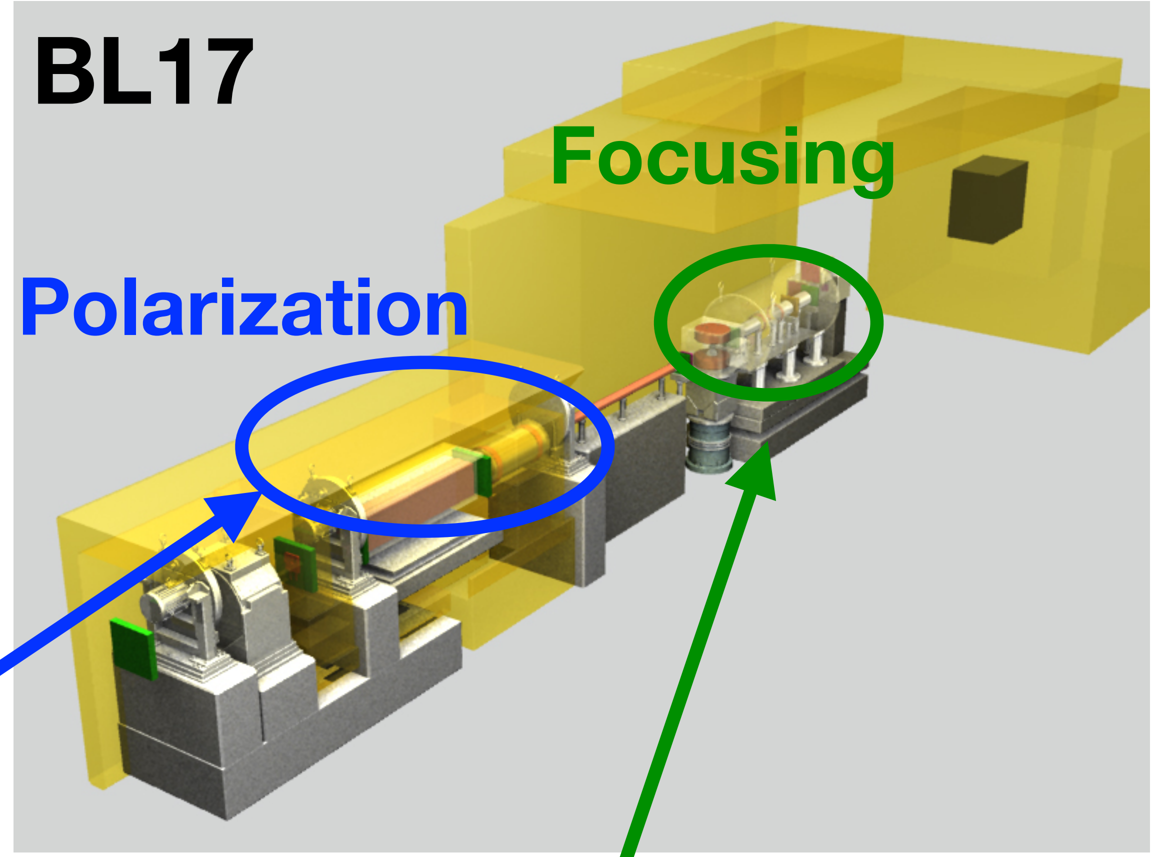

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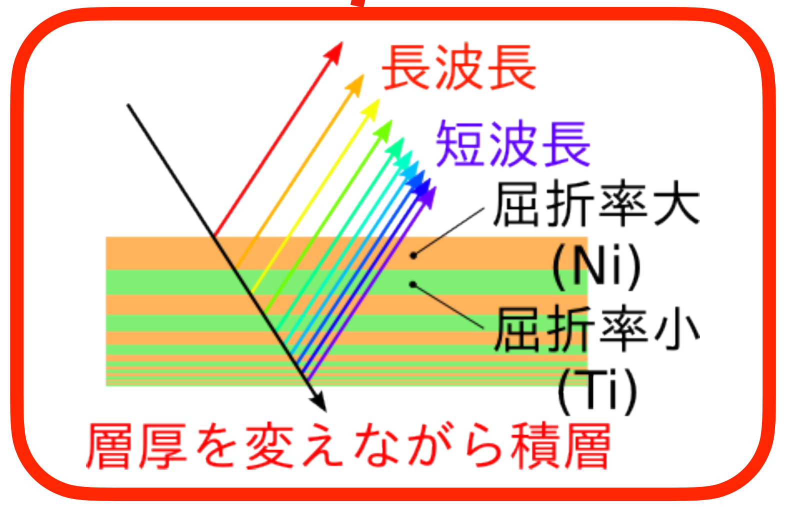

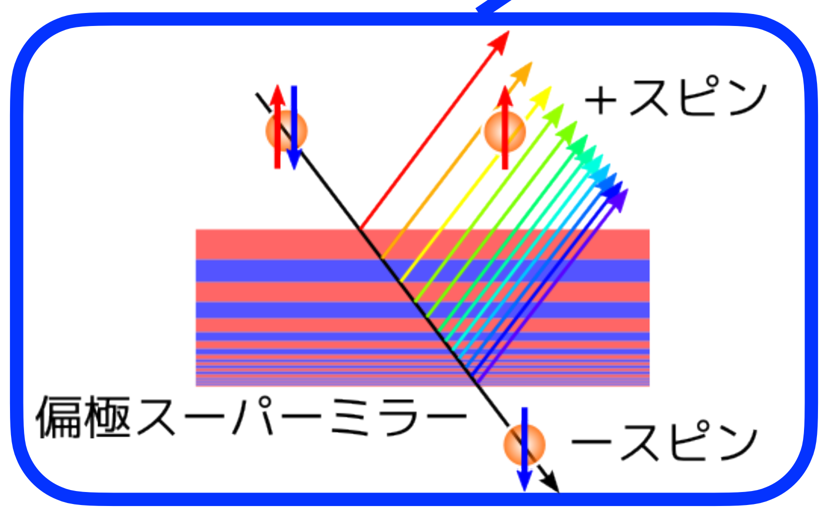

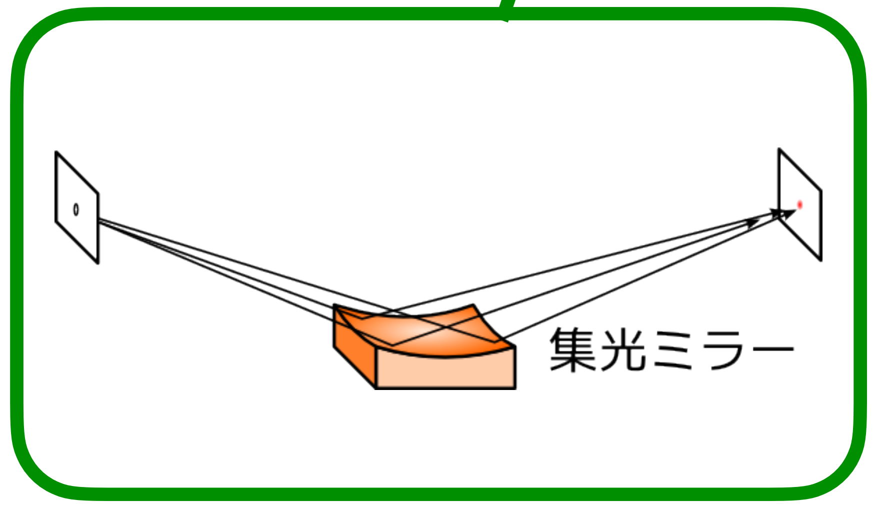

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Recent trends

Spallation neutron sources across the world

Science and Technology Facilities Council

ISIS Neutron and Muon Source
- Target Station 1 and 2

ISIS-II project (planned)

OAK RIDGE National Laboratory

Spallation Neutron Source
- Target Station 1
- **Target Station 2 (under construction)**

PAUL SCHERRER INSTITUT PSI

SINQ The Swiss Spallation Neutron Source

ess EUROPEAN SPALLATION SOURCE

European Spallation Source (under construction)

大強度陽子加速器施設 J-PARC Japan Proton Accelerator Research Complex

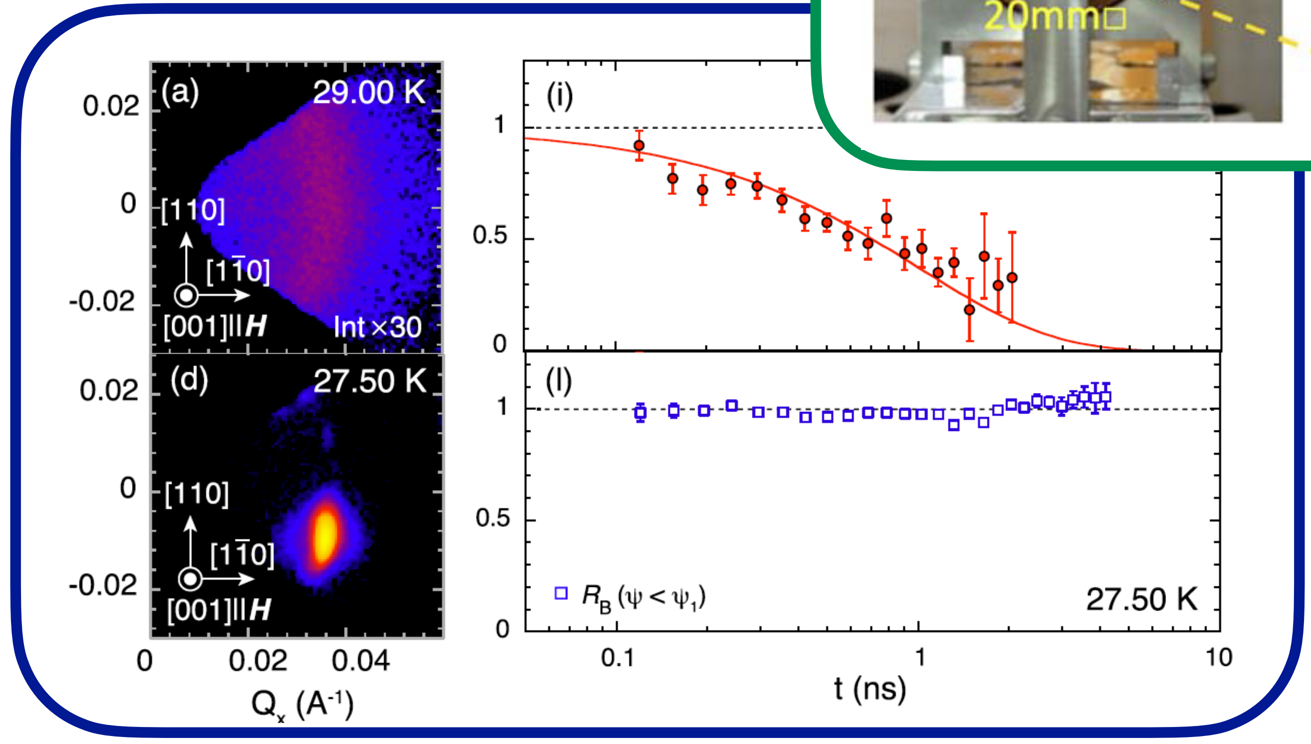
Material and Life Science Facility (MLF)
- Target Station 1
- **Target Station 2 (planned)**

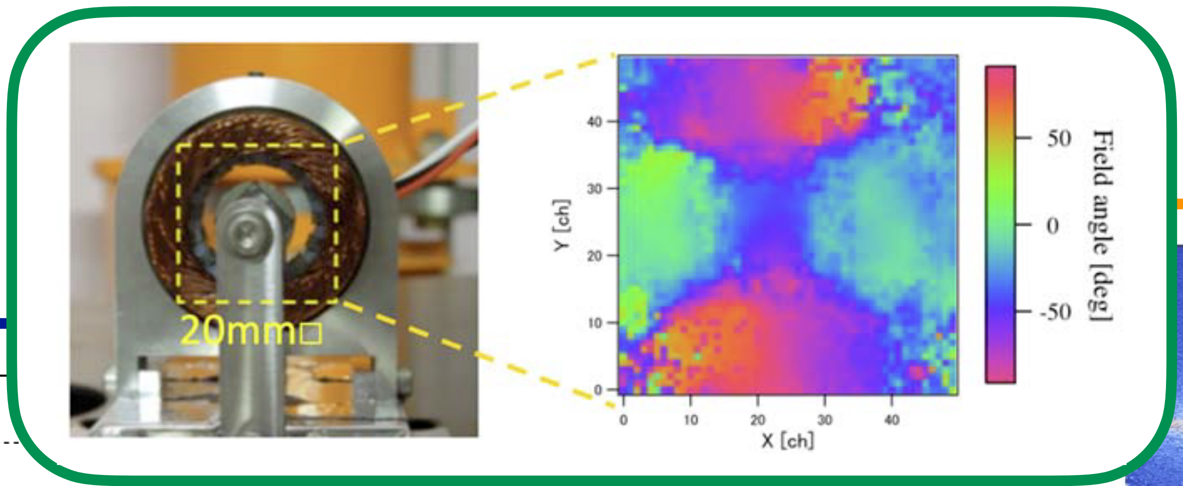
CSNS 中国散裂中子源 China Spallation Neutron Source

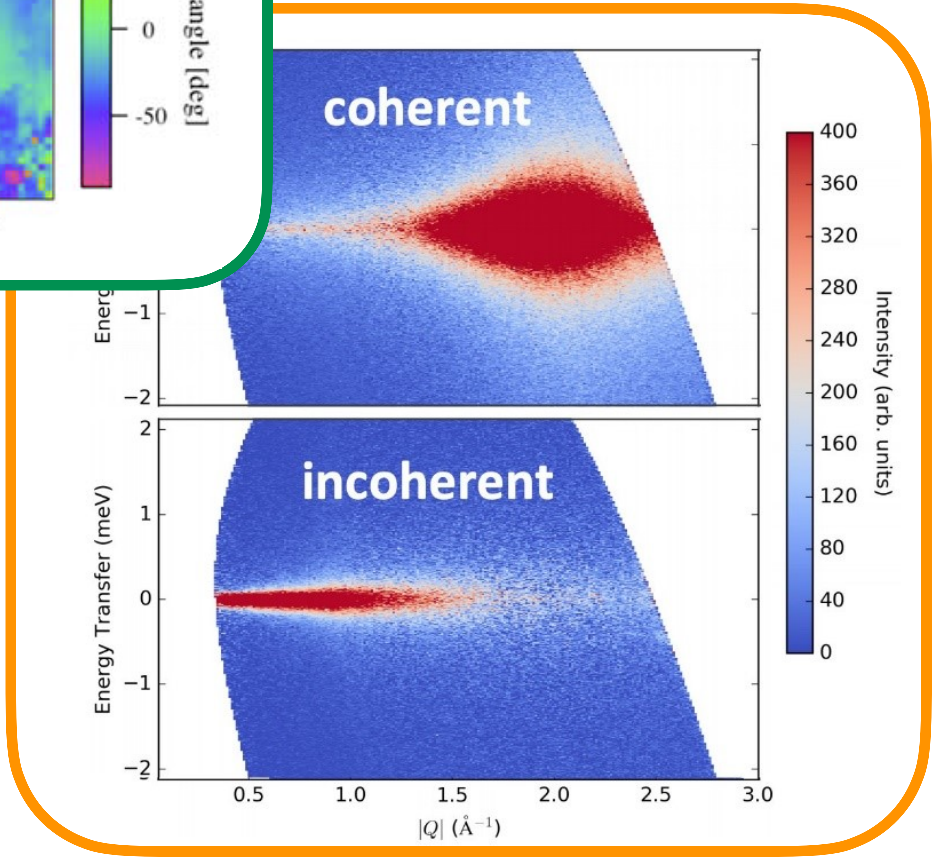
China Spallation Neutron Source (under construction)

Increasing demand for polarized neutrons

- Magnetic structures
- Dynamics of large-scale materials (nm—μm)
- Magnetic field analysis in a real device
- Coherent-incoherent separation
- etc…



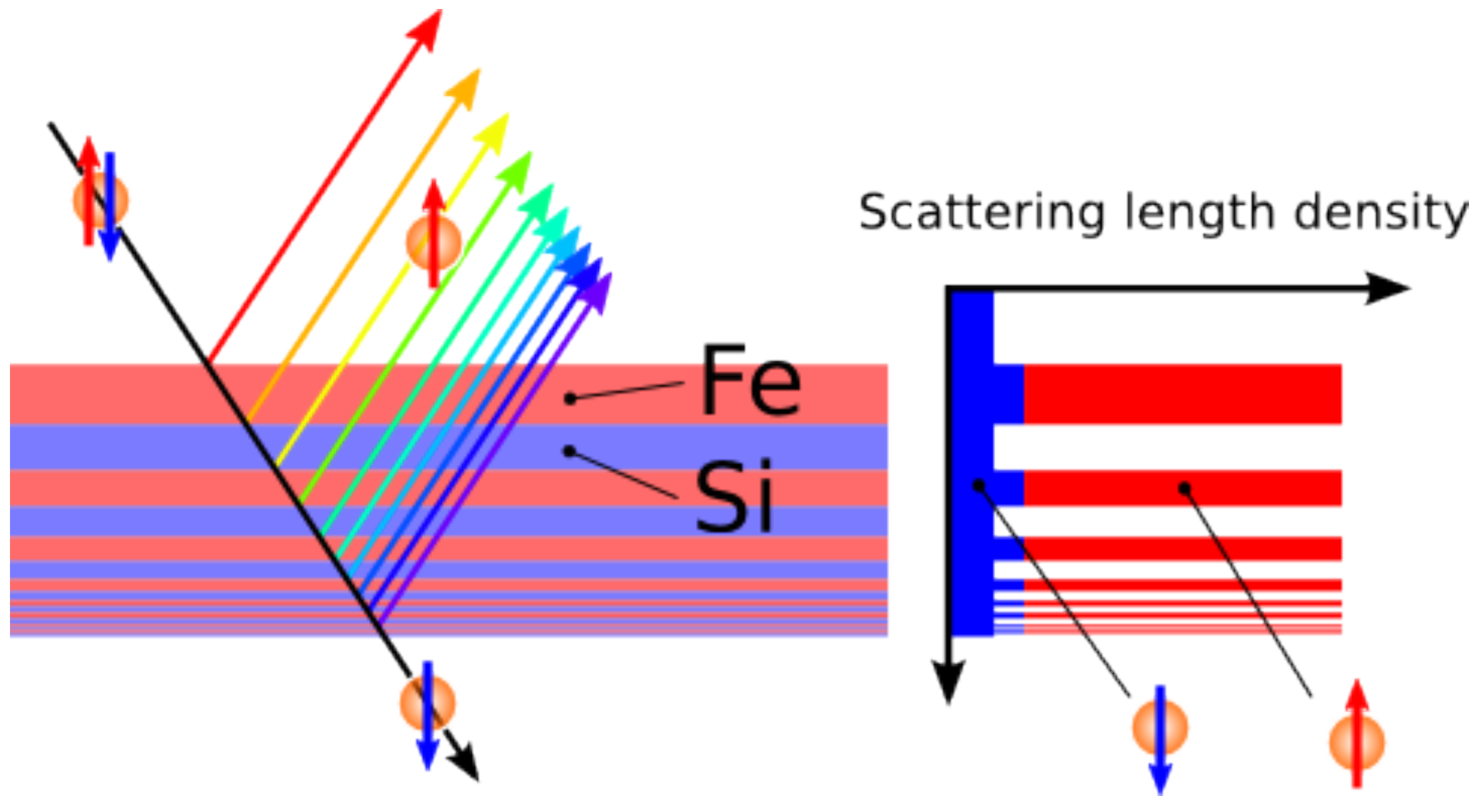




Neutron polarizing supermirror

How to polarize?

- A stack of alternating layers of ferromagnetic and non-magnetic materials
- A neutron beam is polarized by making use of the dependence of the scattering length density (SLD) on the neutron-spin



$$\text{SLD} = N(b_n \pm b_m)$$

N : Atomic number density

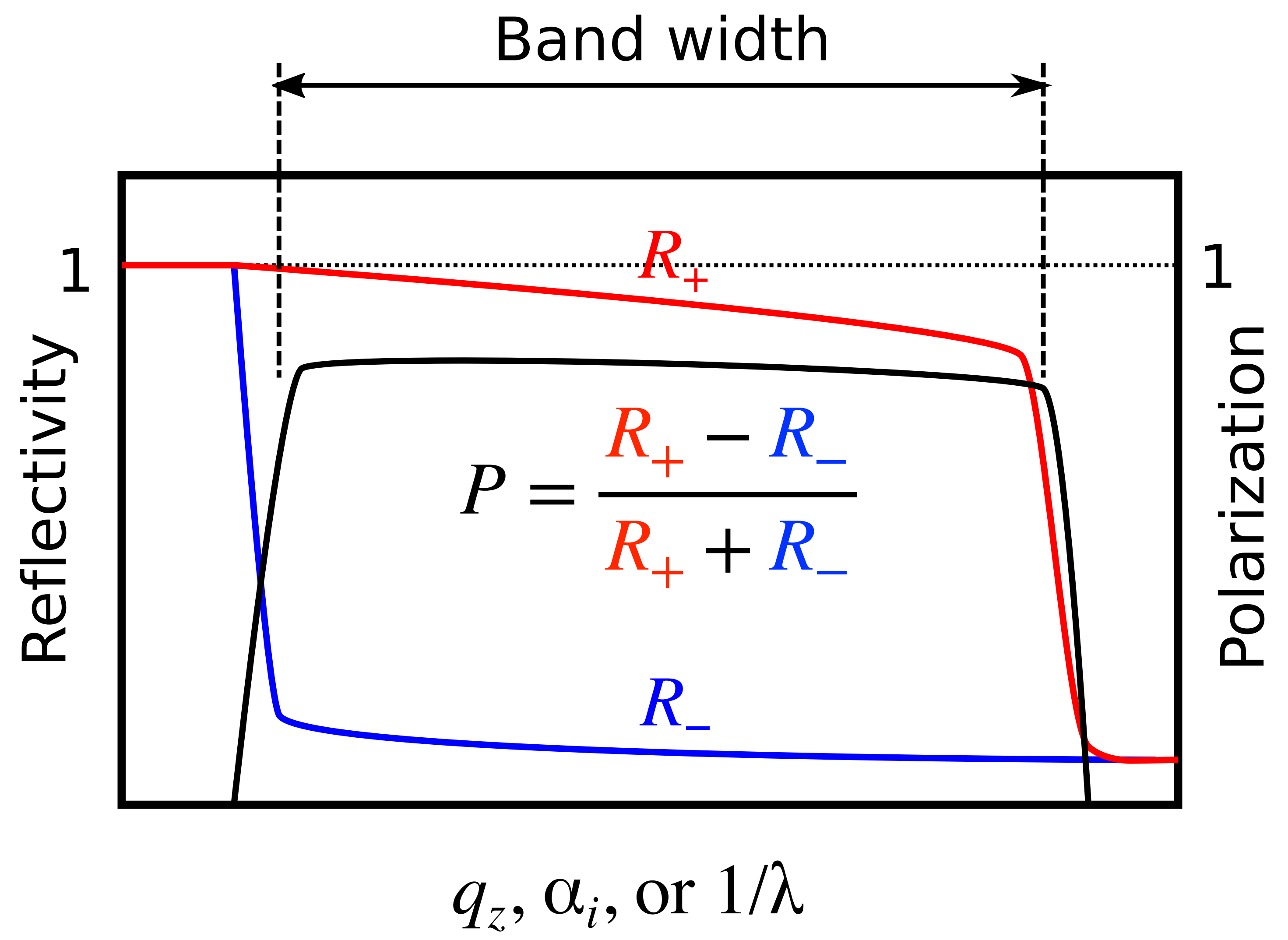
$b_{n(m)}$: Nuclear (Magnetic) scattering length

Advantages

- High polarization without loss of intensity
- Uniform polarization over a wide bandwidth
- Maintenance free

For higher performance…

- High polarization → SLD contrast matching
- High performance under low field → Magnetically soft layers
- Wide bandwidth → Thinner and more layers



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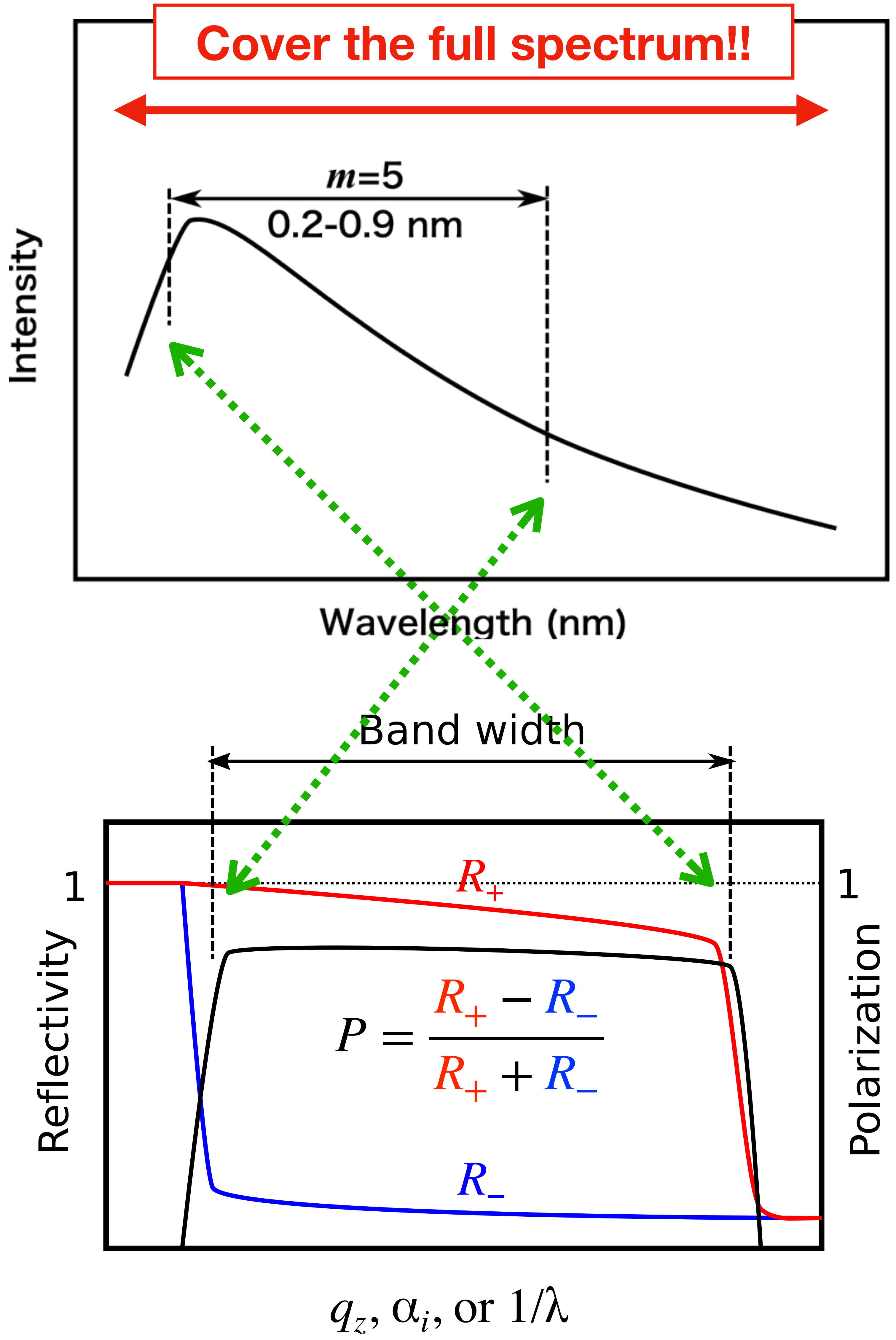
Spontaneous magnetization of Fe layer disappears at a thickness less than 3 nm…

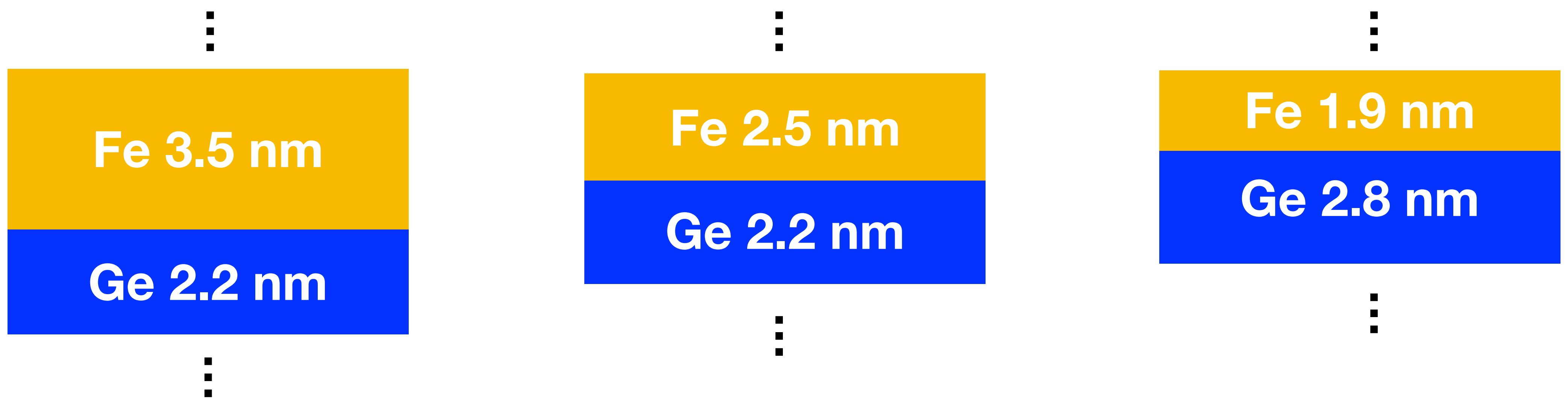


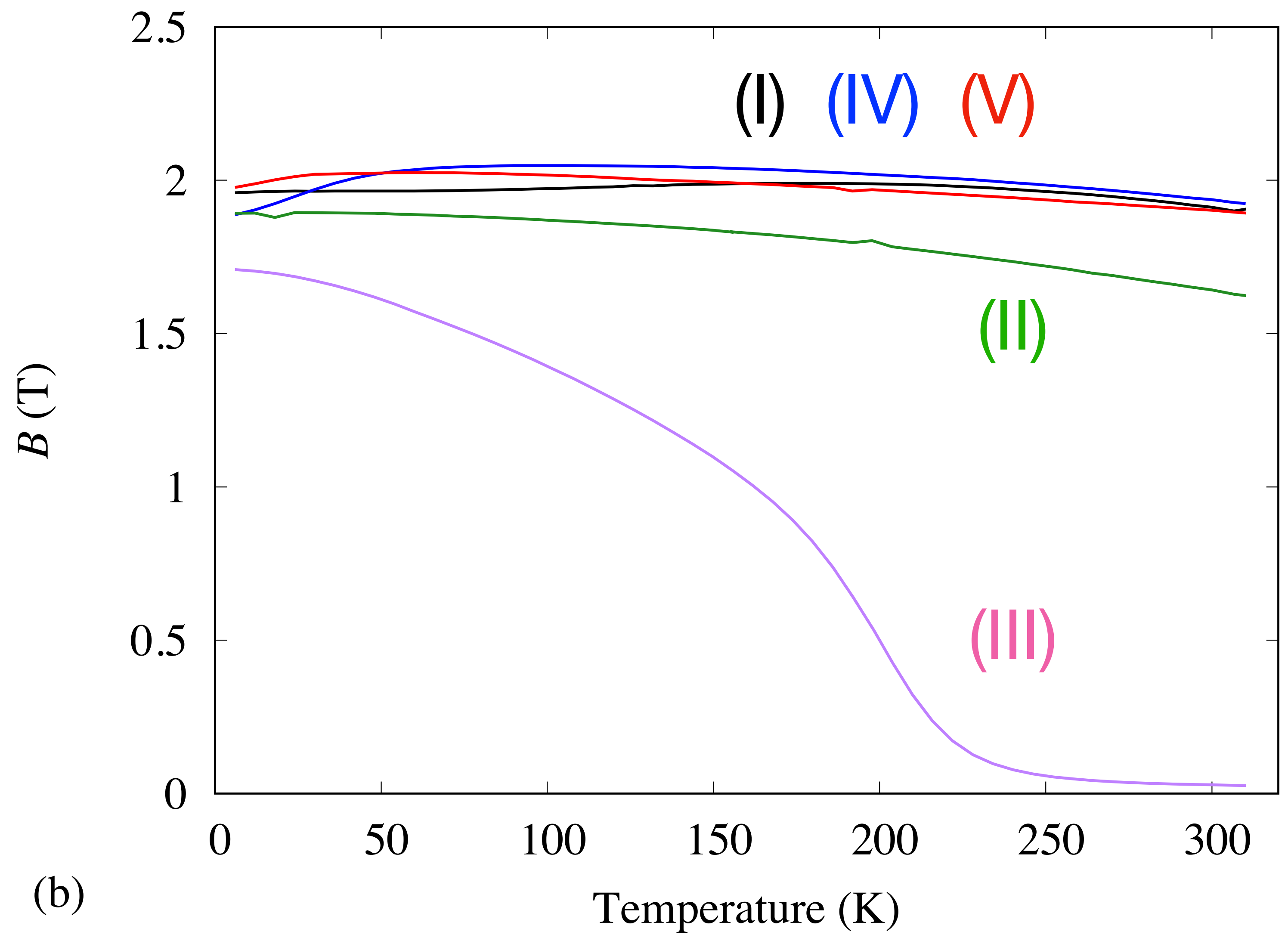
Magnetization measurement

Fe/Ge multilayers (50 bilayers)

When the Fe thickness is reduced to less than 3nm…

Sample (I) Sample (II) Sample (III)

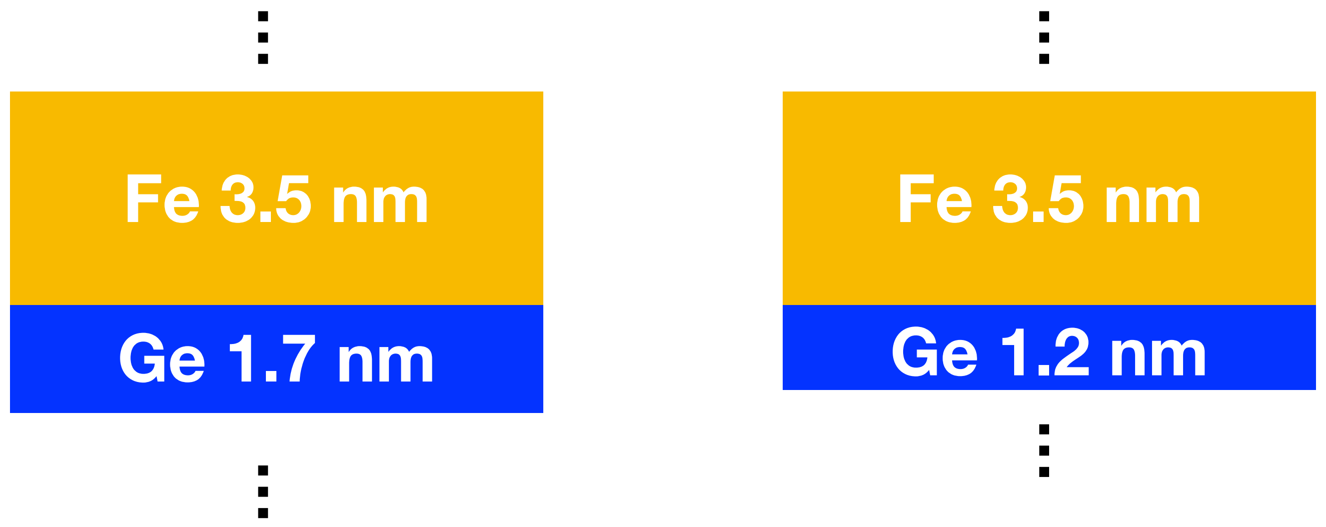


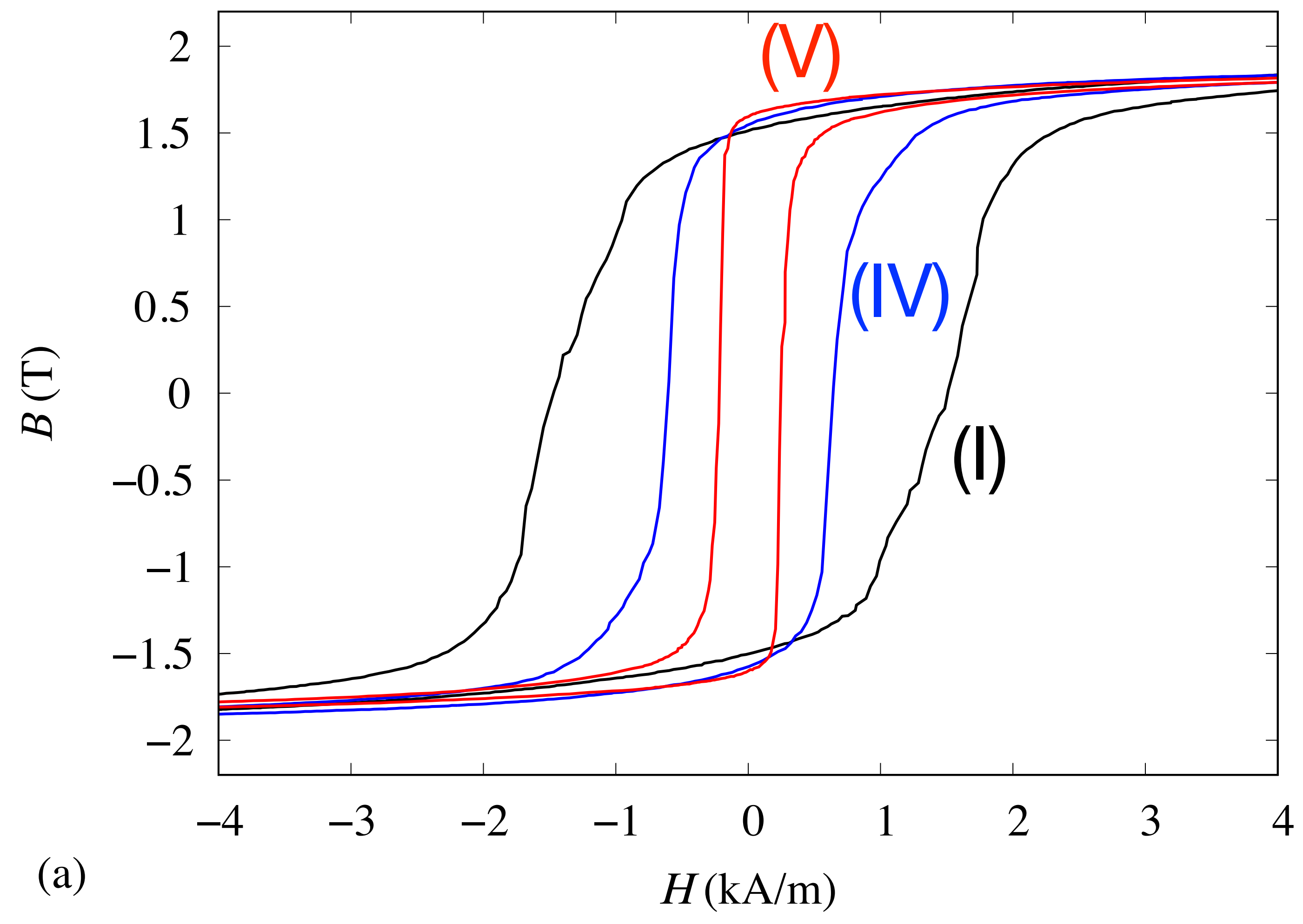


The Curie point : lower than room temperature

Instead, when we keep the Fe thickness and reduce the Ge thickness…

Sample (IV) Sample (V)



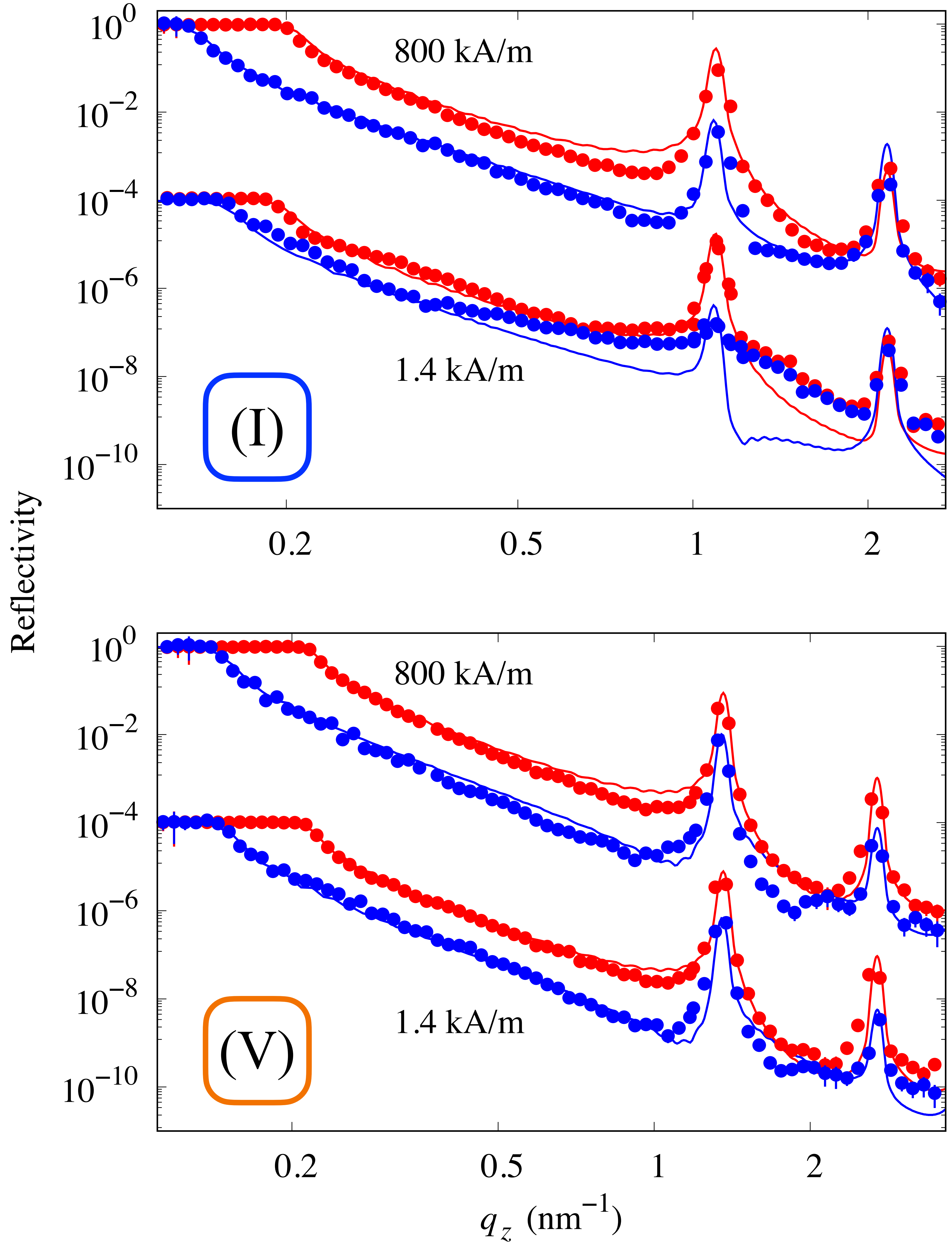


- The magnetization is kept at a value close to (I).
- The sample becomes soft with decreasing Ge thickness.

PNR measurement
BL17 at MLF

Samples: Fe/Ge multilayers (50 periods)
(I) Fe: 3.5 nm, Ge: 2.2 nm
(V) Fe: 3.5 nm, Ge: 1.2 nm

- No significant difference was observed between the PNR profiles…
- The out-of-plane structure averaged over the illuminated area does not differ.

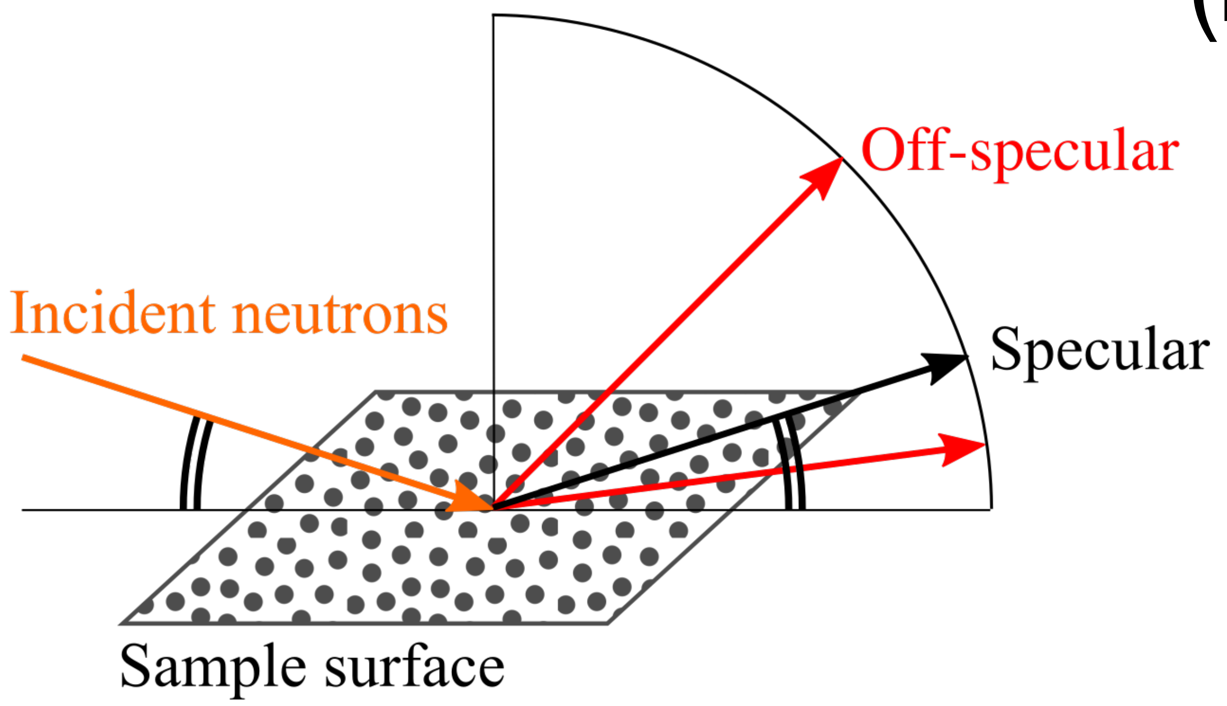


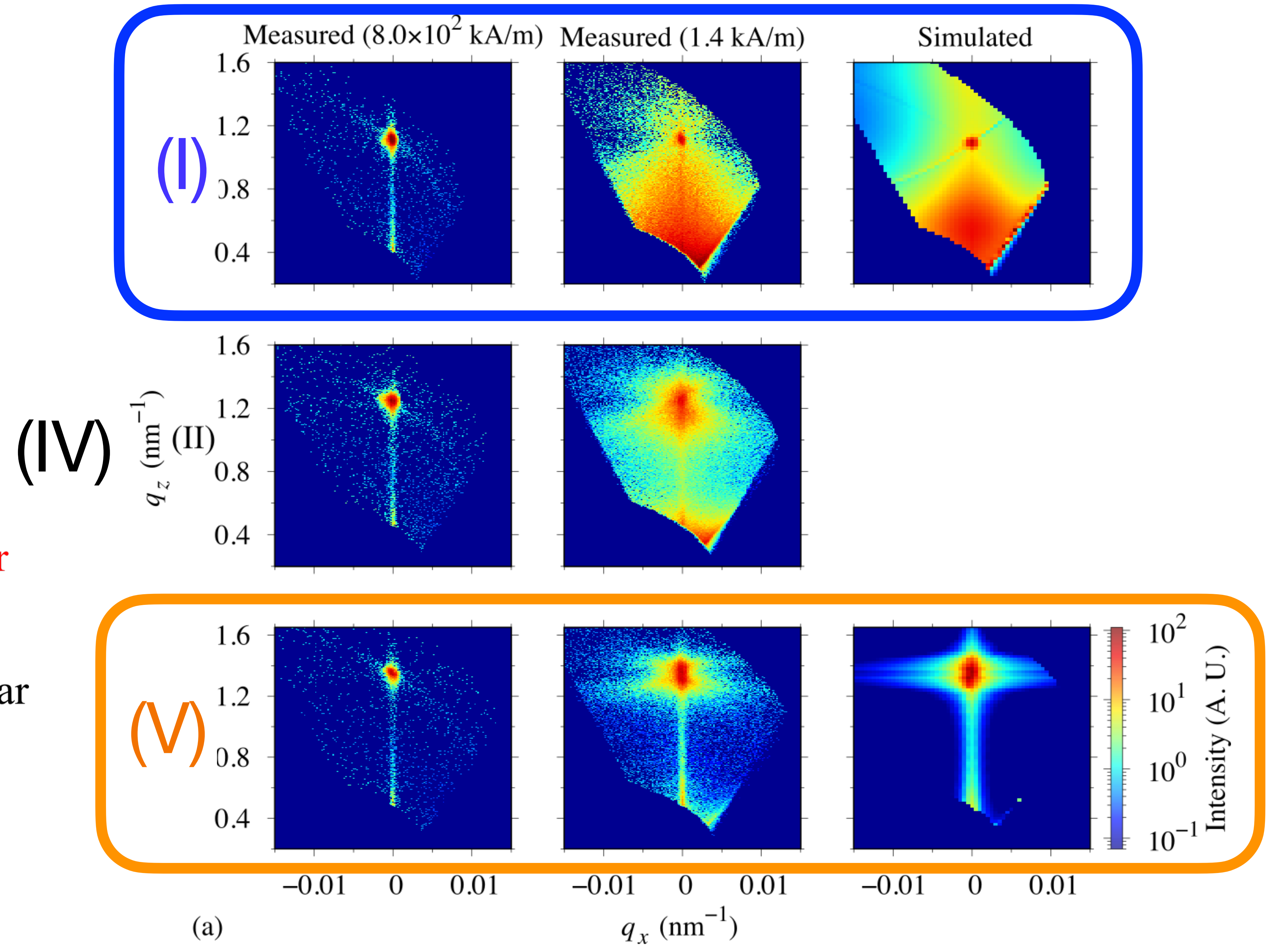
Polarized neutron off-specular scattering measurement

BL17 at MLF

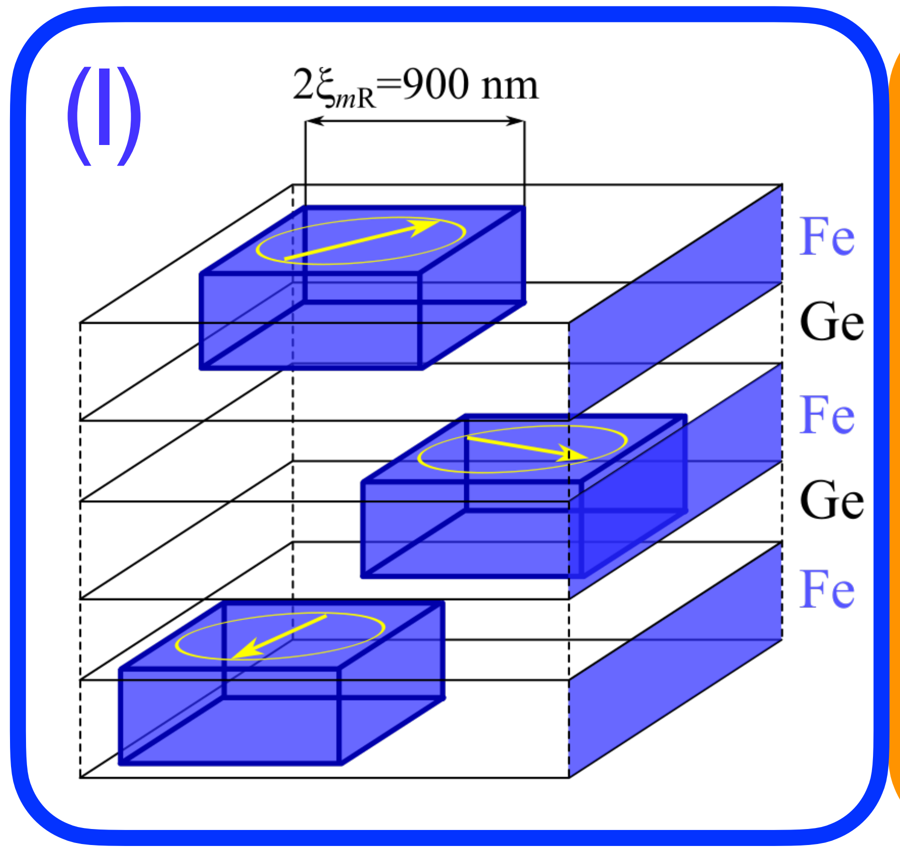
Samples: Fe/Ge multilayers (50 periods)

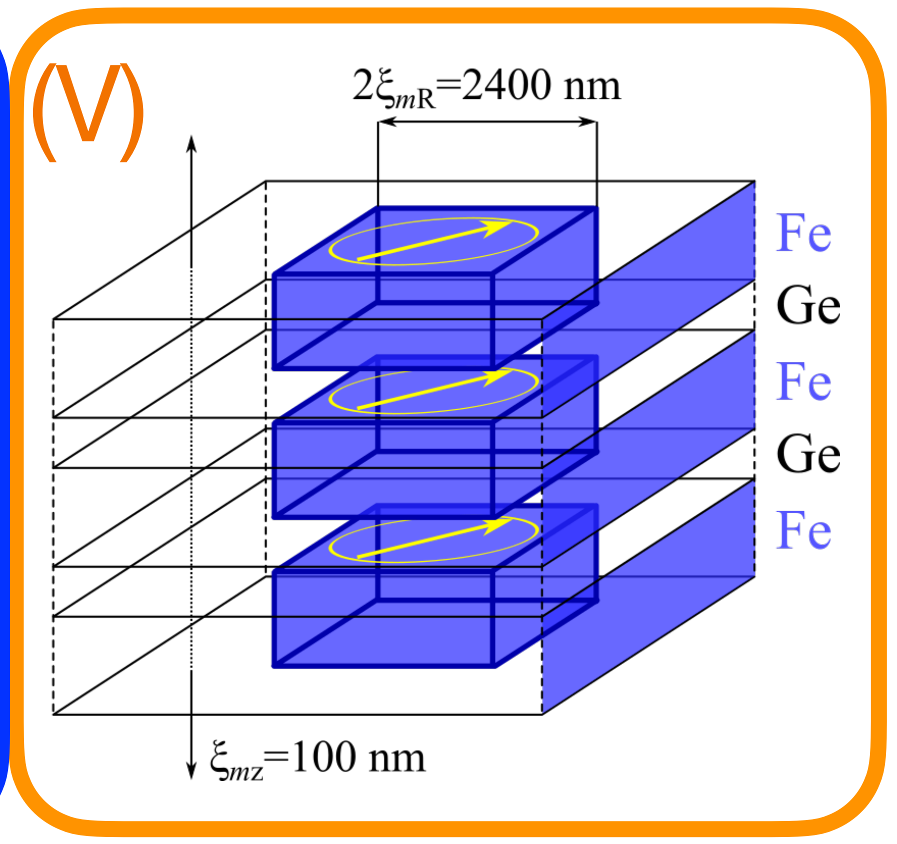
- (I) Fe: 3.5 nm, Ge: 2.2 nm
- (IV) Fe: 3.5 nm, Ge: 1.7 nm
- (V) Fe: 3.5 nm, Ge: 1.2 nm





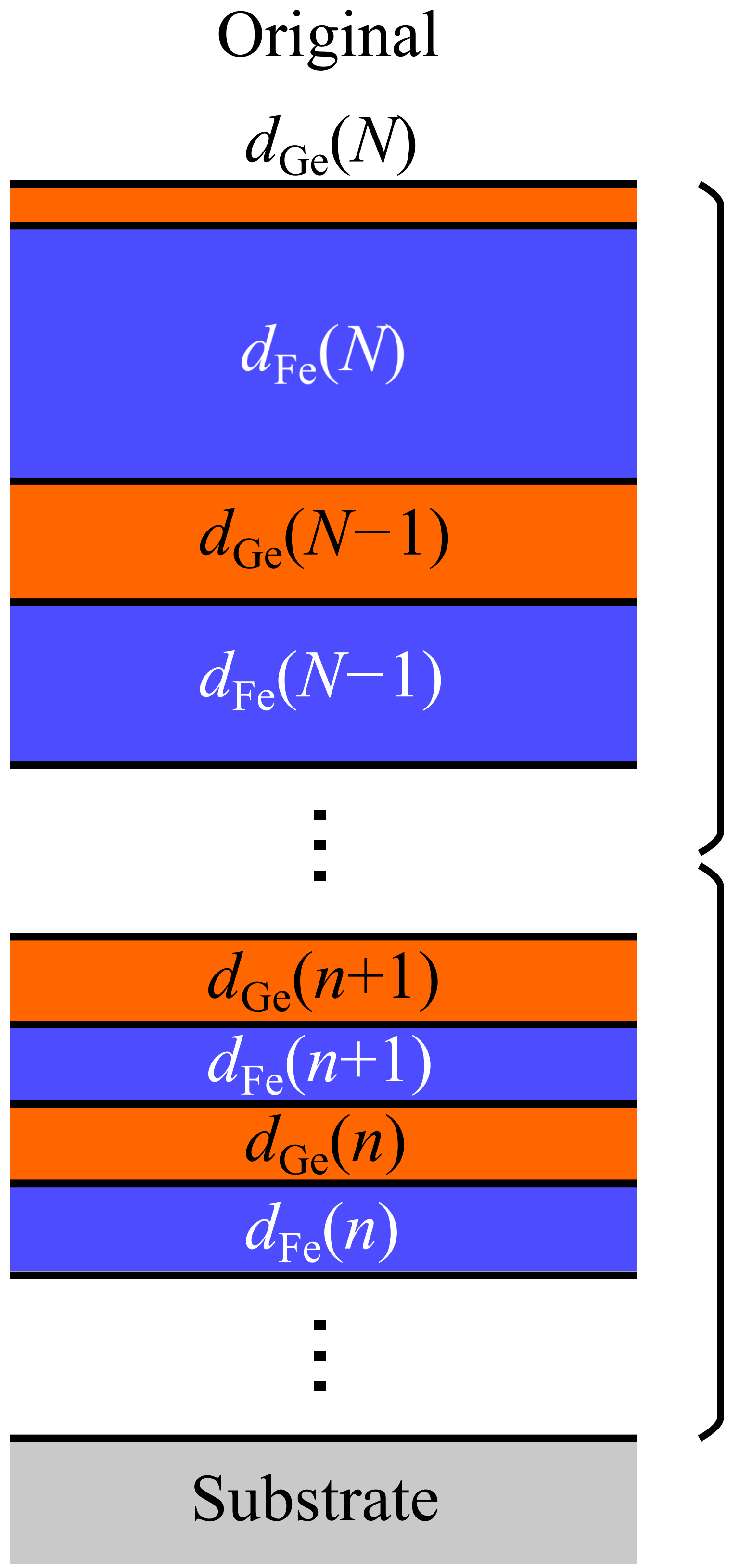
- **Ferromagnetic (FM) interlayer exchange coupling** is seen when the Ge layer thickness is less than 2 nm.
- FM interlayer exchange coupling contributes to the stable spontaneous magnetization and soft magnetic properties.
- This result offers a possibility to extend the bandwidth of the polarizing supermirror.





Design of layer thickness sequence

Aimed to a larger *m*-value



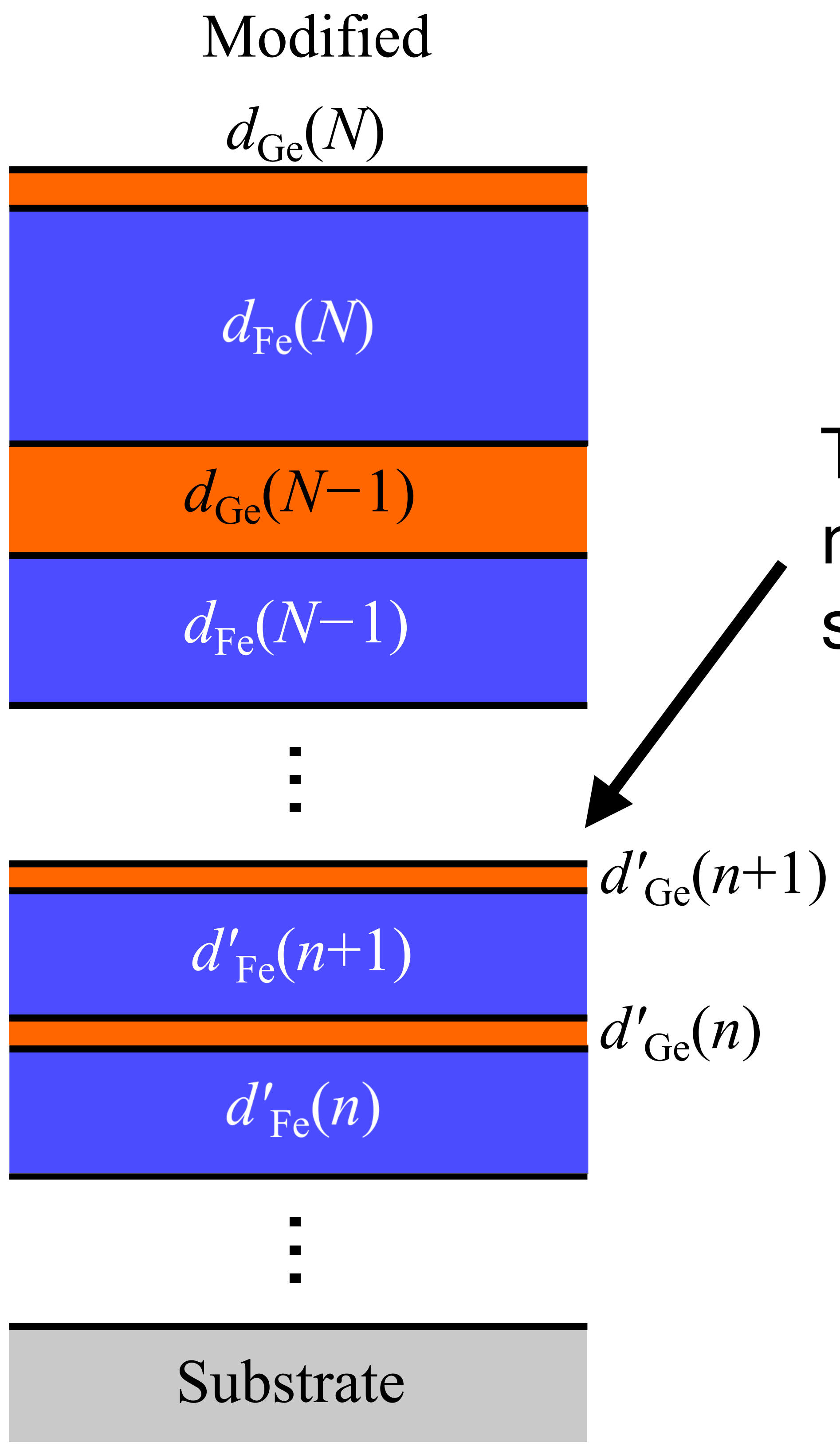
For $d_{Fe}(n) \geq 3.5$ nm

No modification

For $d_{Fe}(n) < 3.5$ nm

$d'_{Fe}(n) = 3.5$ nm

$d'_{Ge}(n) = d_{Ge}(n) + d_{Fe}(n) - d'_{Fe}(n)$



To stabilize the spontaneous magnetization and to obtain soft magnetic properties…

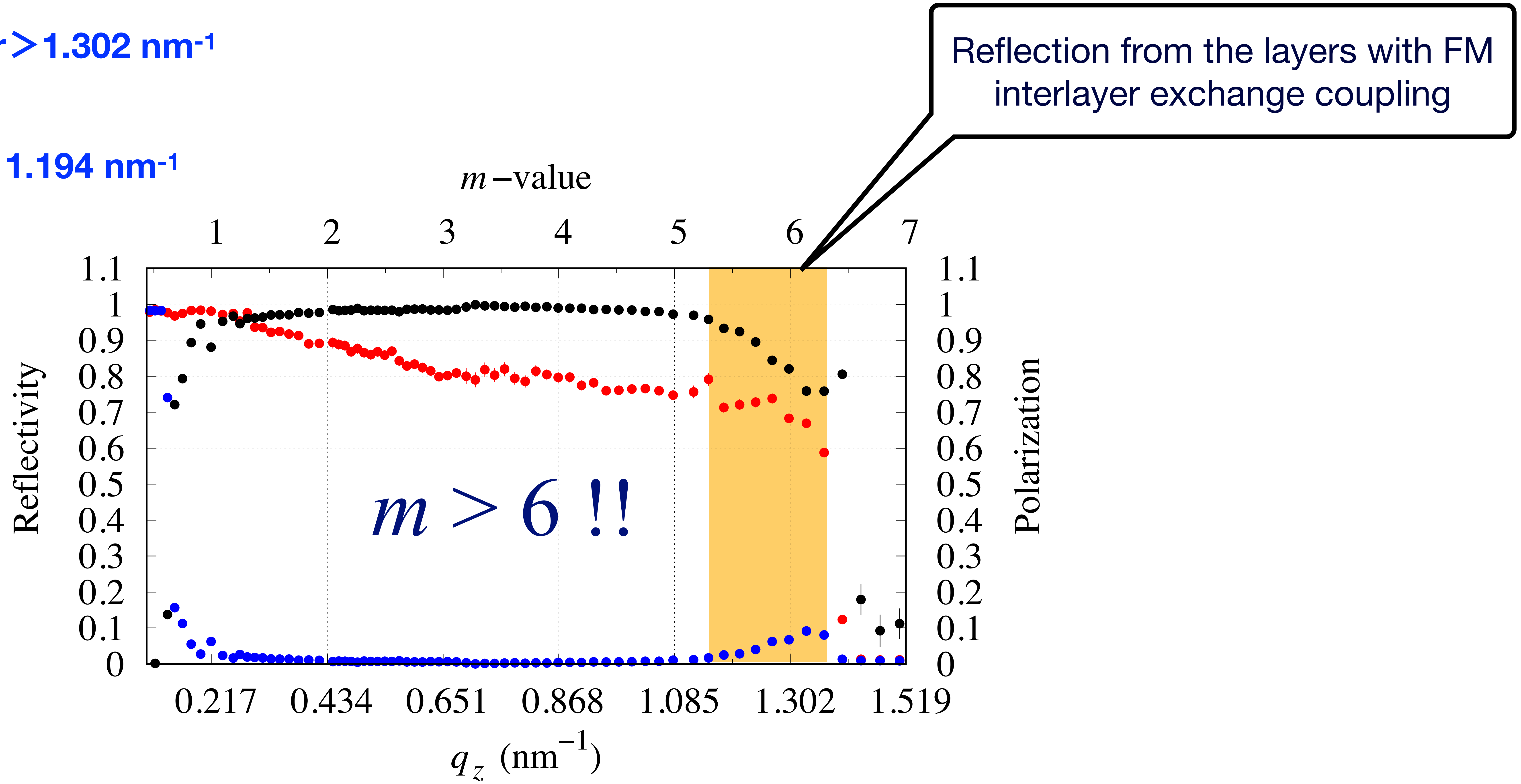
Hayter & Mook algorithm
Both thicknesses (Fe and Ge) are reduced.

Minimum Fe thickness: 3.5 nm
Instead, the thickness of Ge layer is reduced.

Performance test of polarizing supermirror

Measured at BL17

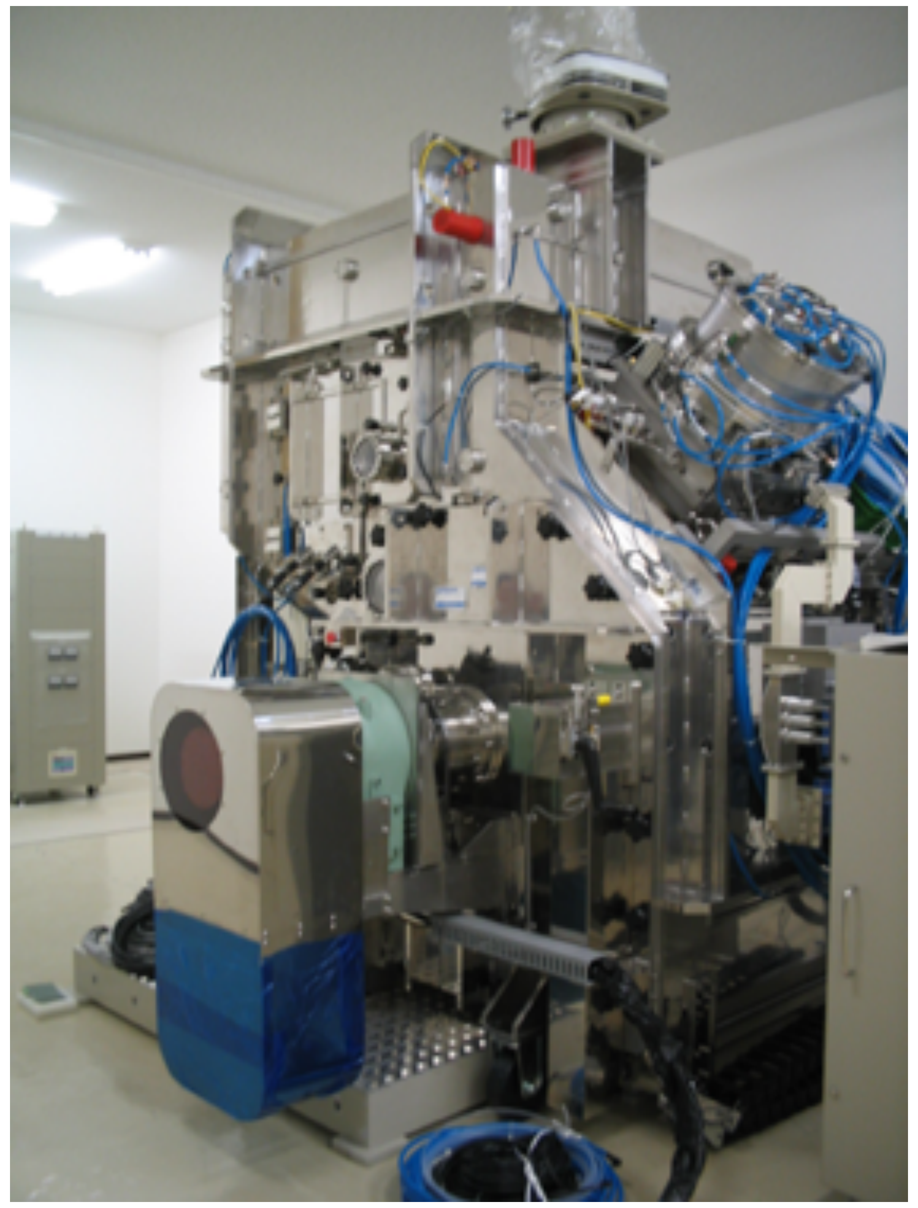
- Total number of layers: 10436
- Total thickness: 32μm
- **Critical momentum transfer ＞1.302 nm⁻¹**
- Spin-up reflectivity ＞ 0.70
- **Polarization：＞0.93 for q＜1.194 nm⁻¹**

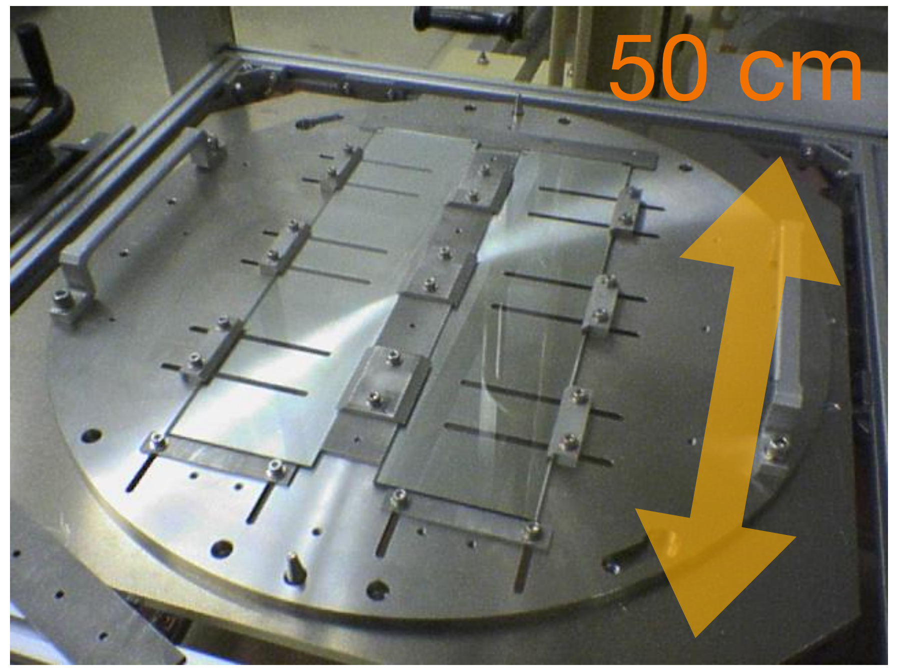


R. Maruyama *et al.*, J. Appl. Phys. **130**, 083904 (2021)

Polarizing supermirrors for MLF instruments

Large-scale ion-beam sputtering system



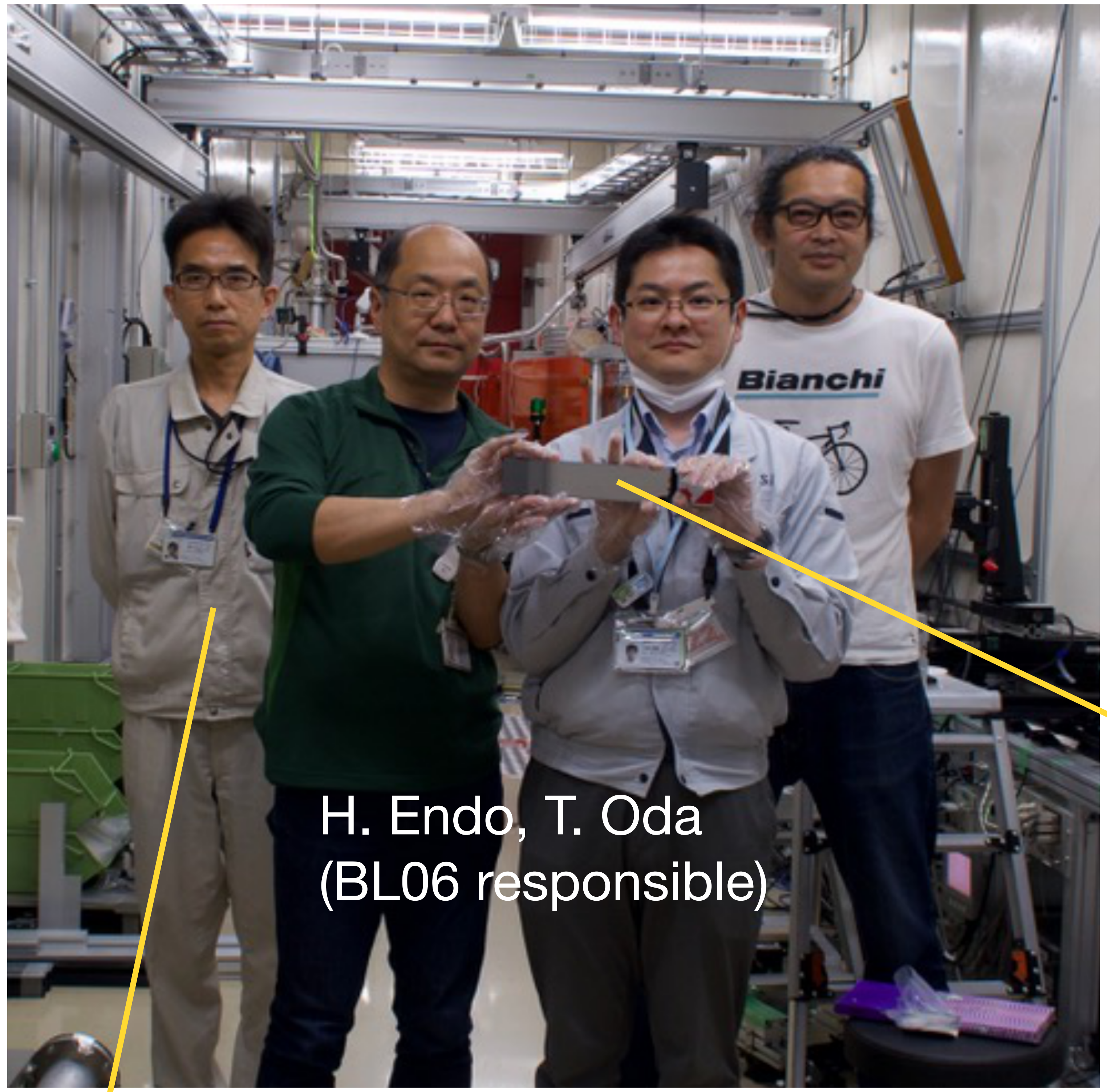


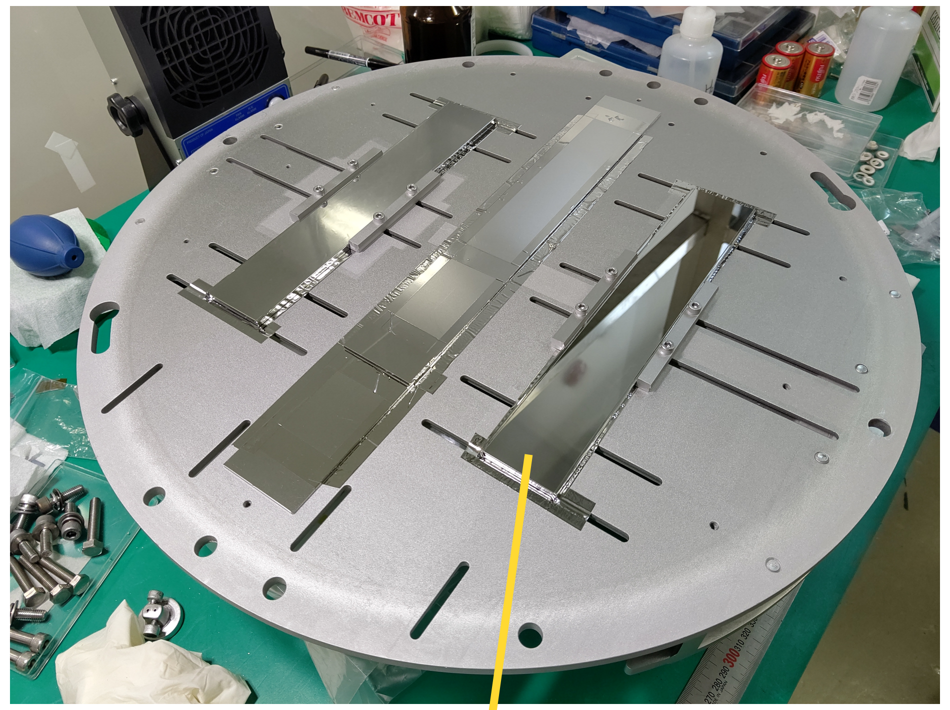
Deposition area: 2000 cm^2

2ml x 2.5mw x 3.5mh

- It was used in the production of the neutron guides for MLF instruments. (BL01, BL02, BL14, etc.)
- And for the fabrication of the focusing supermirrors

m=5 polarizing supermirrors for BL06 (MIEZE spin echo instrument)





Polarizing supermirror
(285 x 50 mm)

T. Miyauchi
(IBS system operation and maintenance)

Summary

- Focusing supermirror for GISANS measurement showed good focusing performance.

- The bandwidth of the polarizing supermirror was increased by using the ferromagnetic coupling occurring between neighboring Fe layers.

- Further studies are needed to cover the full spectrum of the neutron beam available at spallation source facilities across the world.