Development of Iron Thin Films for Polarization Analysis of Ultracold Neutrons

2021-1-12

Hiroaki Akatsuka, Masahiro Hino, TUCAN collaboration

Contents

Introduction

- Purpose of the project
- Principle of UCN polarization measurement

Development and Evaluation of UCN polarization analyzer films

- Development of UCN polarization analyzer films
- B-H curve measurement by Vibrating Sample Magnetometry (VSM)
- Neutron reflectivity measurement

Conclusions and Outlook

Purpose of the project

Context

- UCN polarization films were tested in 2018, but did not achieve a good performance (polarization: 60% cf. Sean Hansen-Romu 2019)

Purpose

- Establish in-house production procedures of iron films for reliable preparation of high-performance films (in collaboration with Porf. M. Hino (KURNS, Kyoto Univ.))
- In addition to conventional aluminum substrate, investigate silicon substrate iron films
- Characterize the samples with complementary methods:
  Vibrating sample magnetometry, cold neutron reflectometry (for Si substrate), (-> this talk), UCN (-> next talk)

	Advantages	Disadvantages
Al substrate	・Results used in previous research ・Can be made thin (~ 20 um) (small absorption)	・Larger magnetic field required for saturation ・Neutron reflectivity measurement not possible
Si substrate	・Neutron reflectivity measurement possible ・Smaller magnetic field required for saturation	・Cannot be made thinner than < 0.1 mm (Absorption is about~ 2% larger than aluminum) •

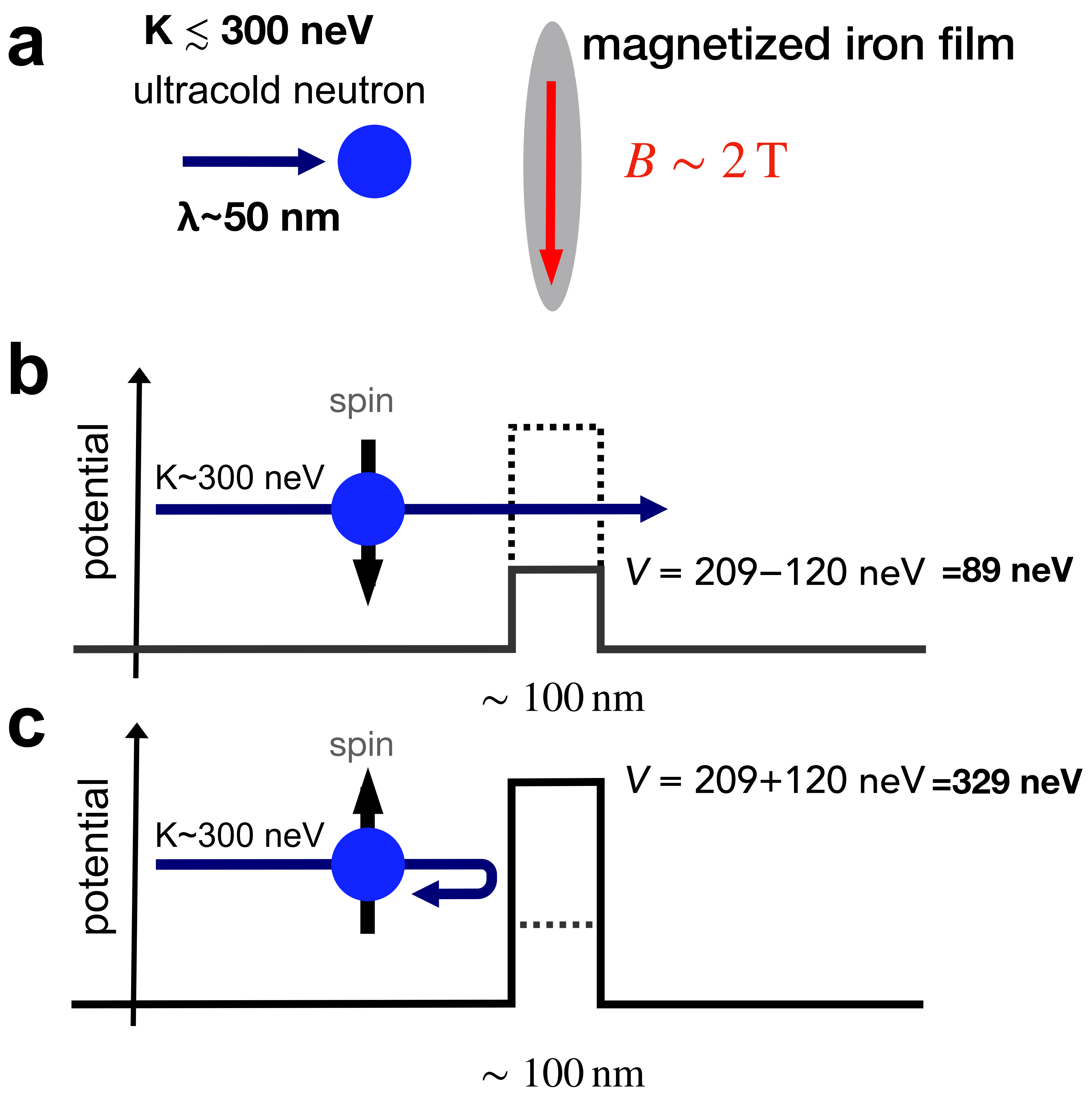
Principle of UCN spin analyzer

- UCN are polarized by a magnetized iron film
- The effective potential experienced by UCN:

$$V = V_F \pm \mu_n B = 209\,\mathrm{neV} \mp 60.3\,\mathrm{neV/T} \cdot B$$

- Fermi potential of Fe: $V_F \sim 209\,\mathrm{neV}$
- UCN kinetic energy $\lesssim 300\,\mathrm{neV}$

- **With ~ 2 T magnetization**
  → full separation of the UCN spin states
  → the film can be used **as a spin analyzer**

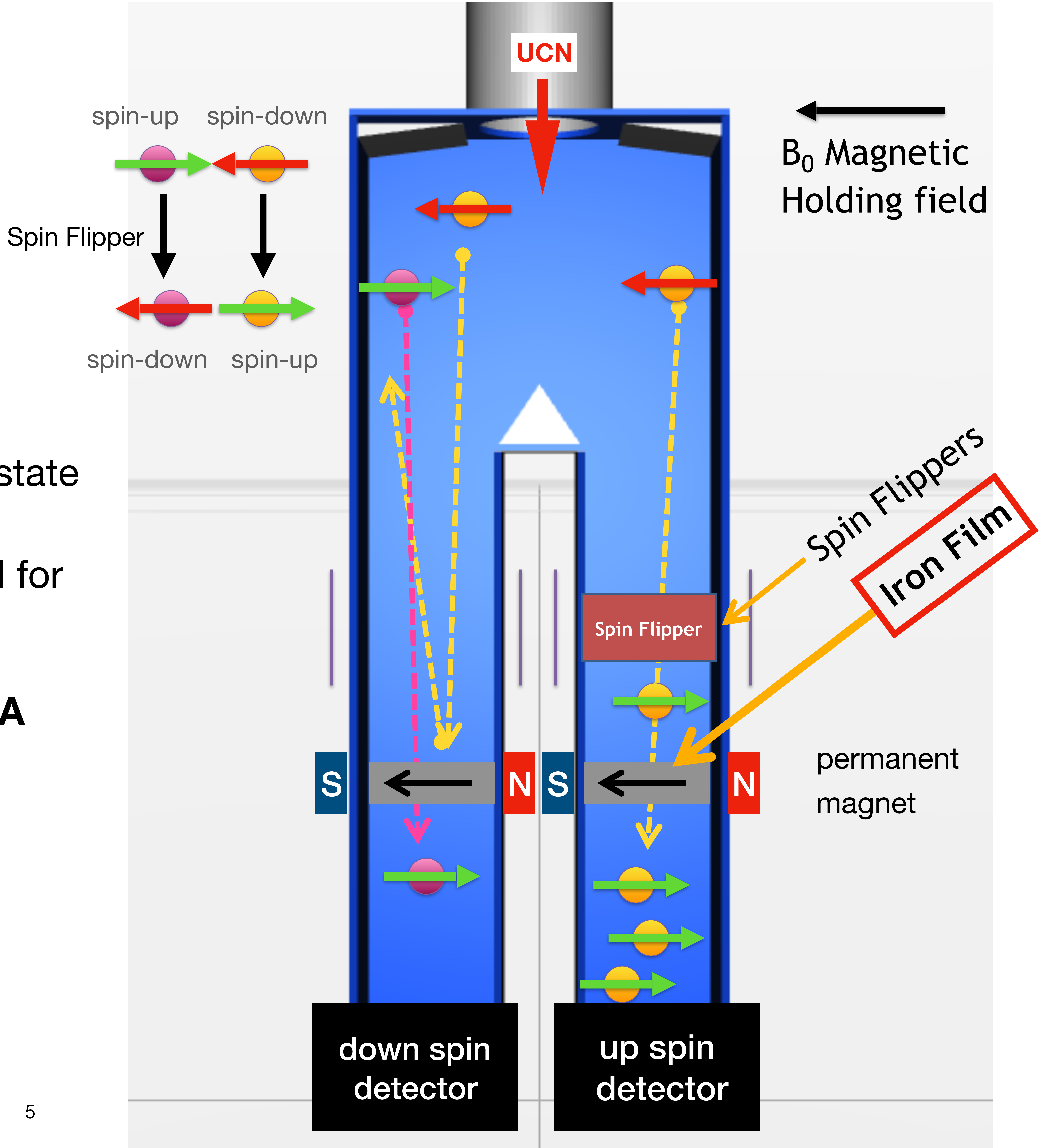


Simultaneous Spin Analyzer (SSA)

- **Simultaneous Spin Analyzer (SSA)**
  - Polarization analyzer
  - Thin Fe film in a permanent magnet: allows only a specific spin state to transmit
  - Simultaneous measurement of UCN in each spin state
    - Selection of the spin state by RF spin flipper
  - Measure the polarization from the number of UCN for each spin.

- **Requirements on the polarization films for the SSA**
  - Large saturation magnetization ($\sim 2\,\mathrm{T}$) (for high efficiency of spin analysis)
  - Saturate with a low magnetic field ($\lesssim 10\,\mathrm{mT}$)
    - Low leakage field
    - Compact device
  - Small absorption of UCN

S. Afach, et al, Euro. Phys. Jour. A 51, 143 (2015)



Development of polarization analysis film

Iron thin films were prepared using an ion beam sputtering system (IBS) at KURNS

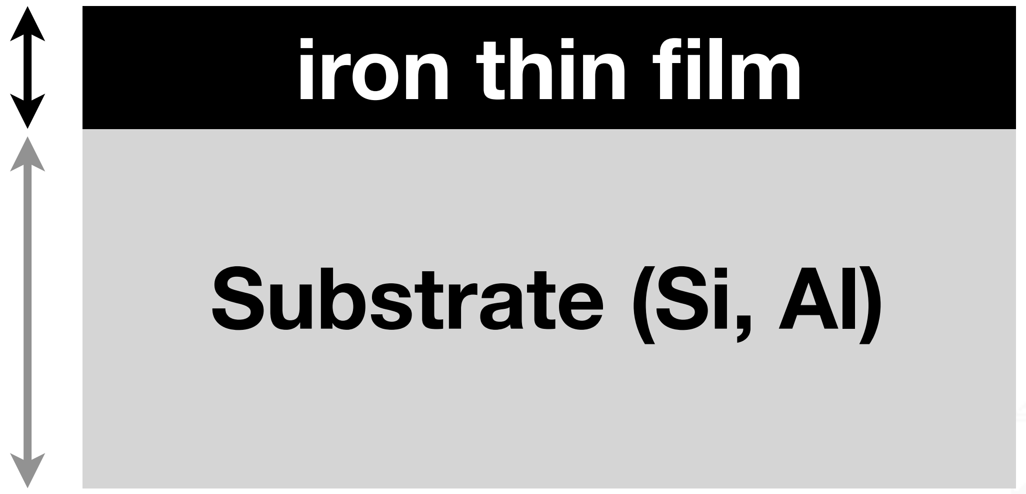
Produced sample

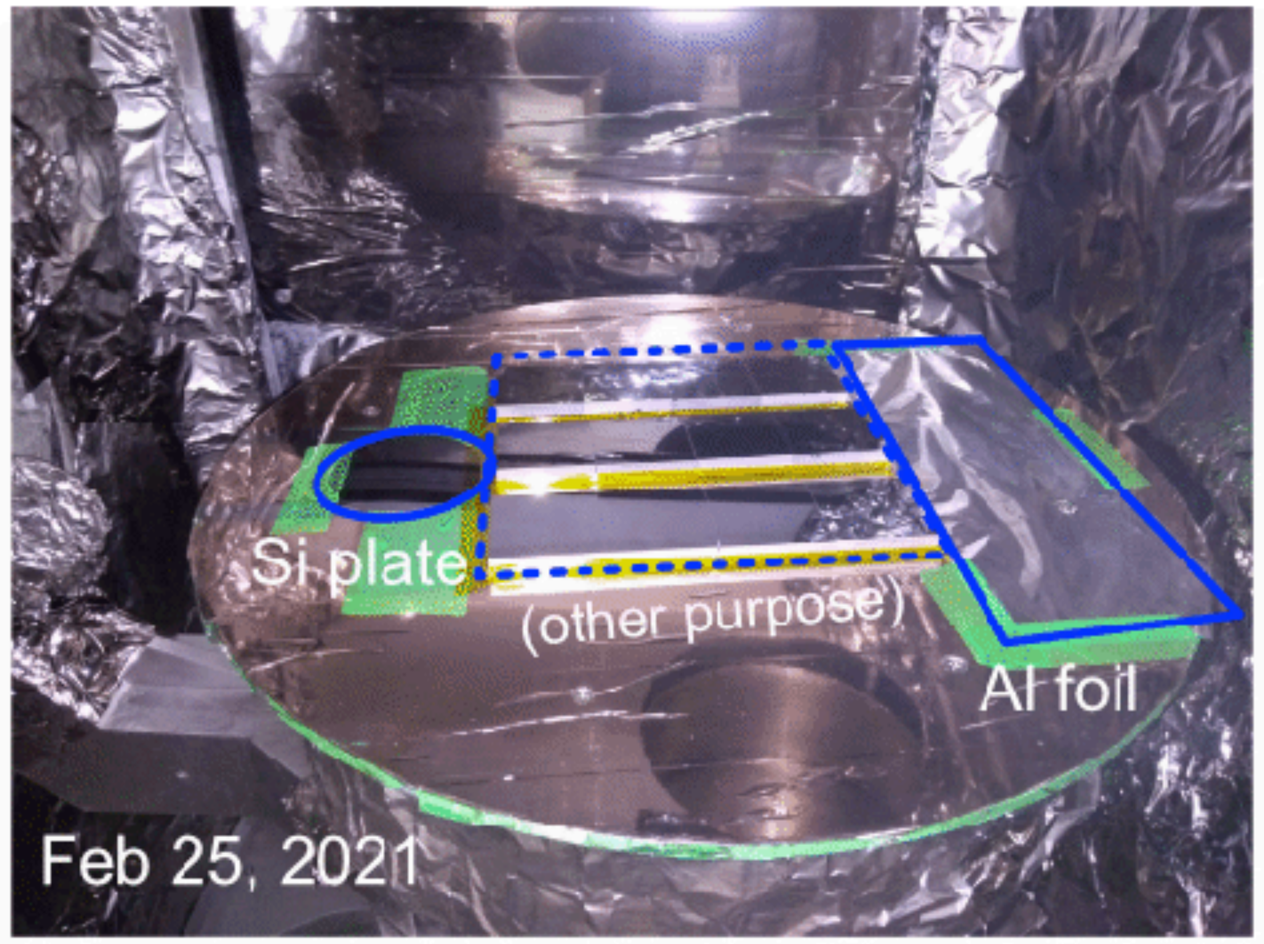
Iron thin film

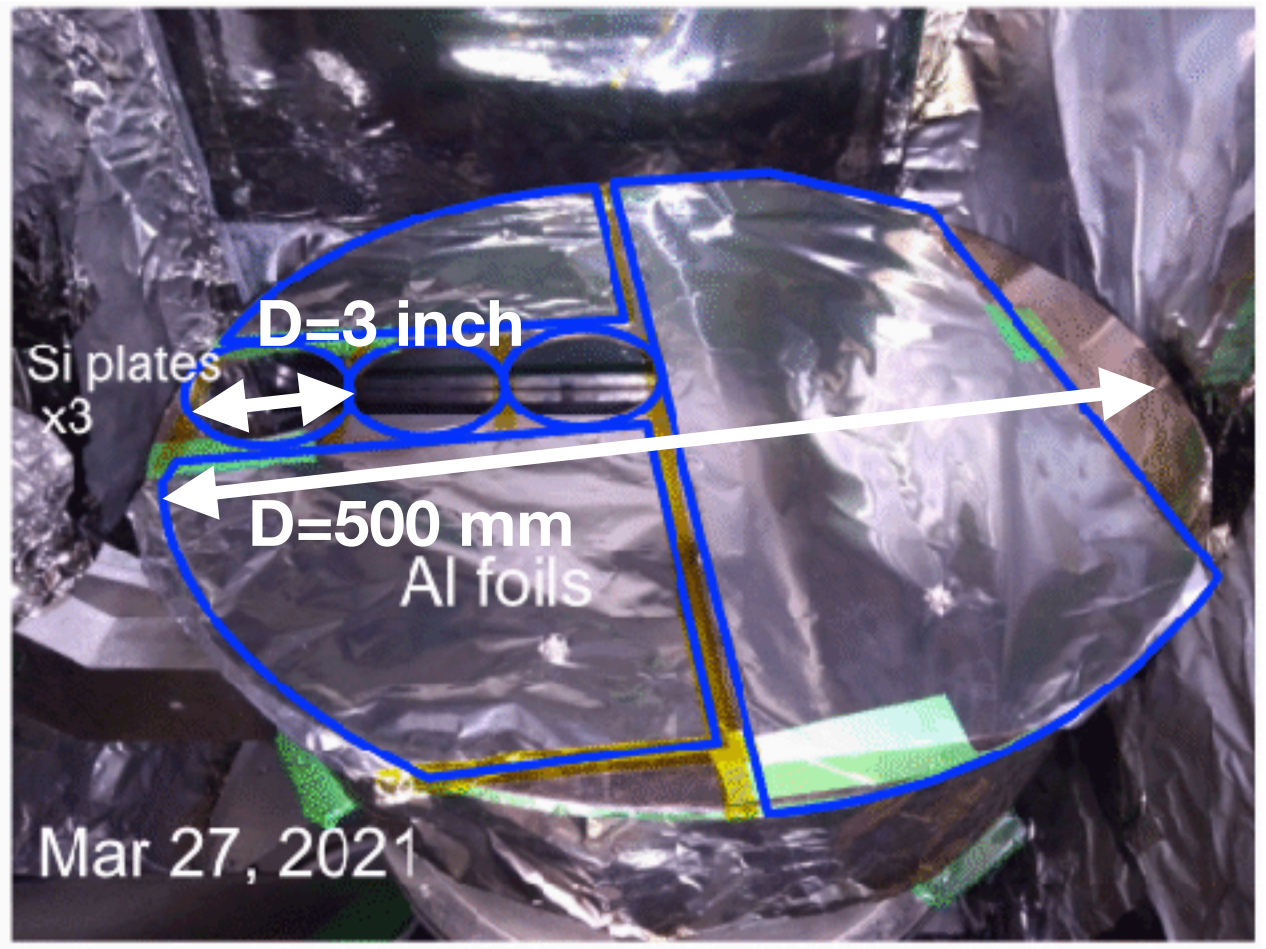
- thickness : 30, 50, 90 nm

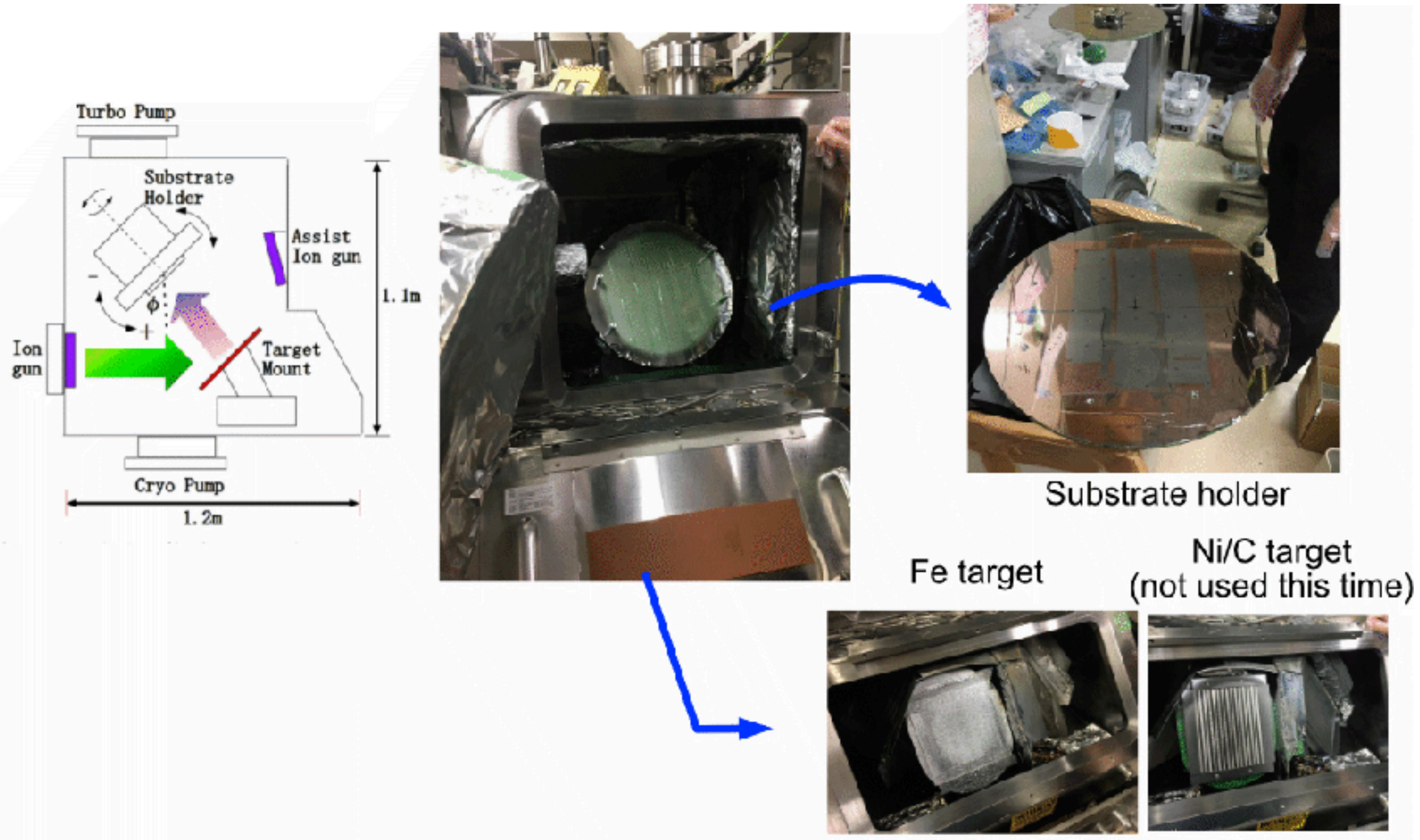
Substrates

- Si (thickness $380\ \mu$m)
- Al (thickness $25\ \mu$m)



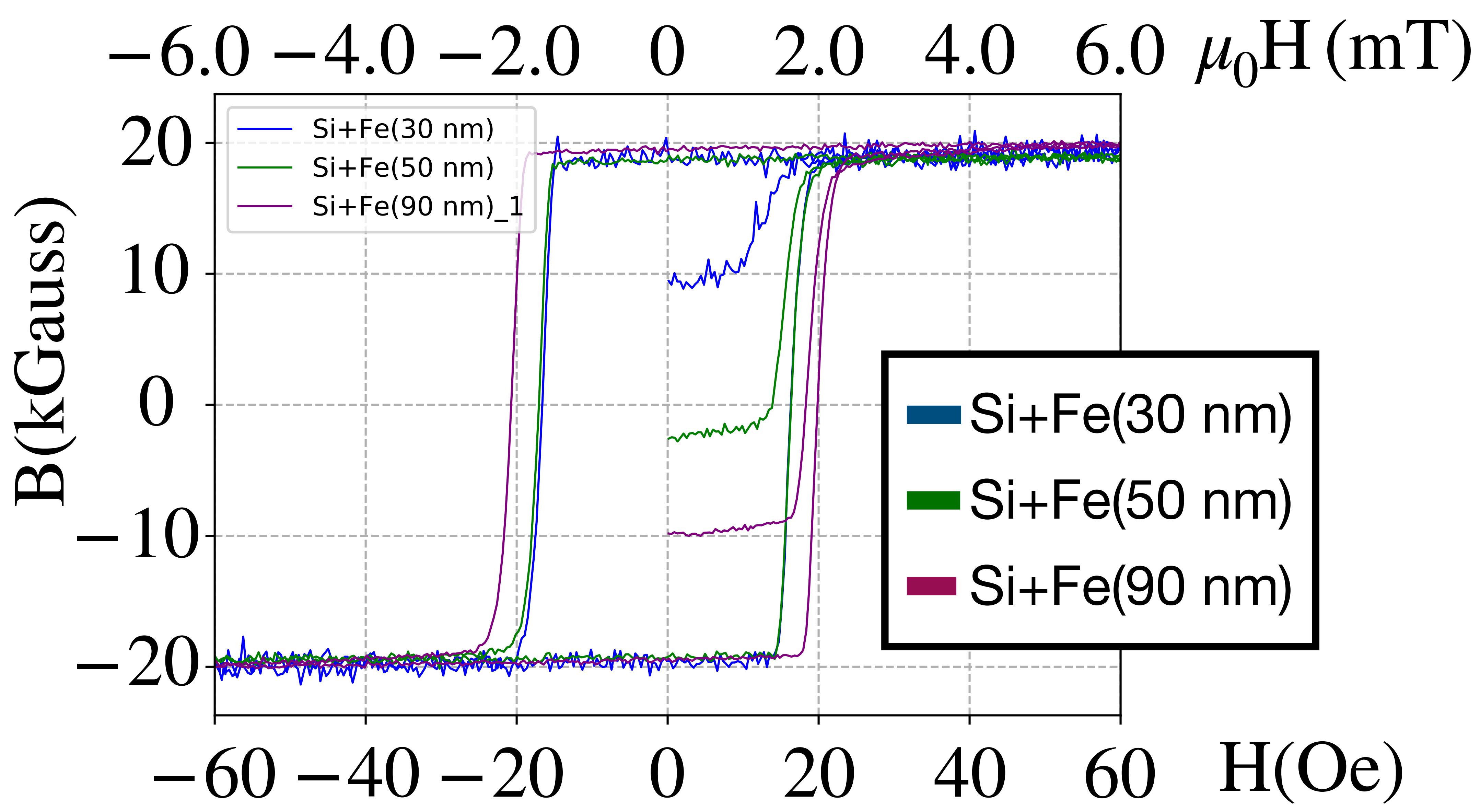


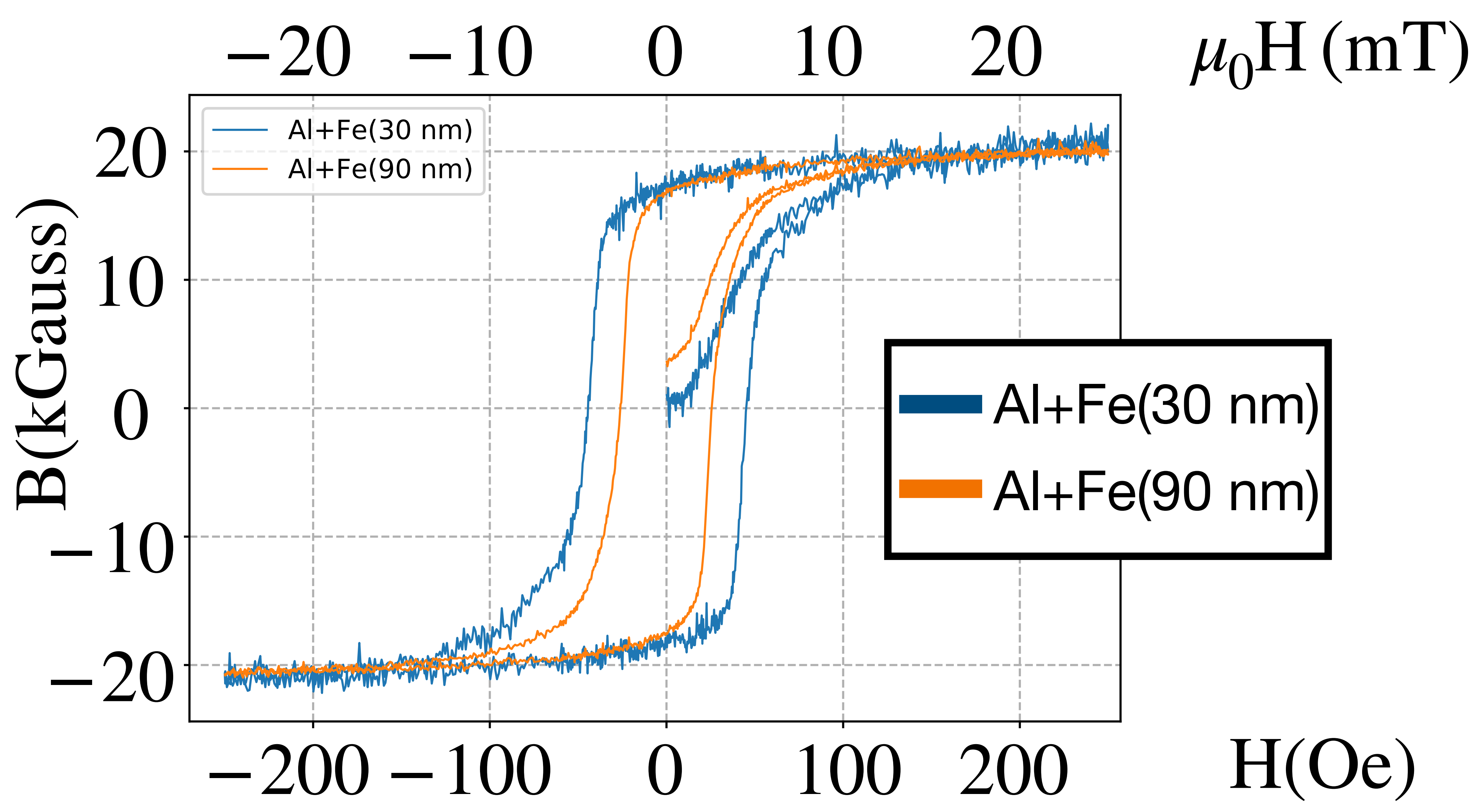




M. Hino et al, Nucl. Inst. Meth. A 797, 265 (2015)

BH curve measurement





H_c: Intersection of BH curve and B=0, H_s:H corresponding to 95% of B_{sat}

sample	Hc(Oe)	Hs(Oe)	μ0Hs(mT)
Si+Fe(30 nm)	16.5	29.8	2.98
Si+Fe(50 nm)	16.7	24.5	2.45
Si+Fe(90 nm)	20.3	45.5	4.55

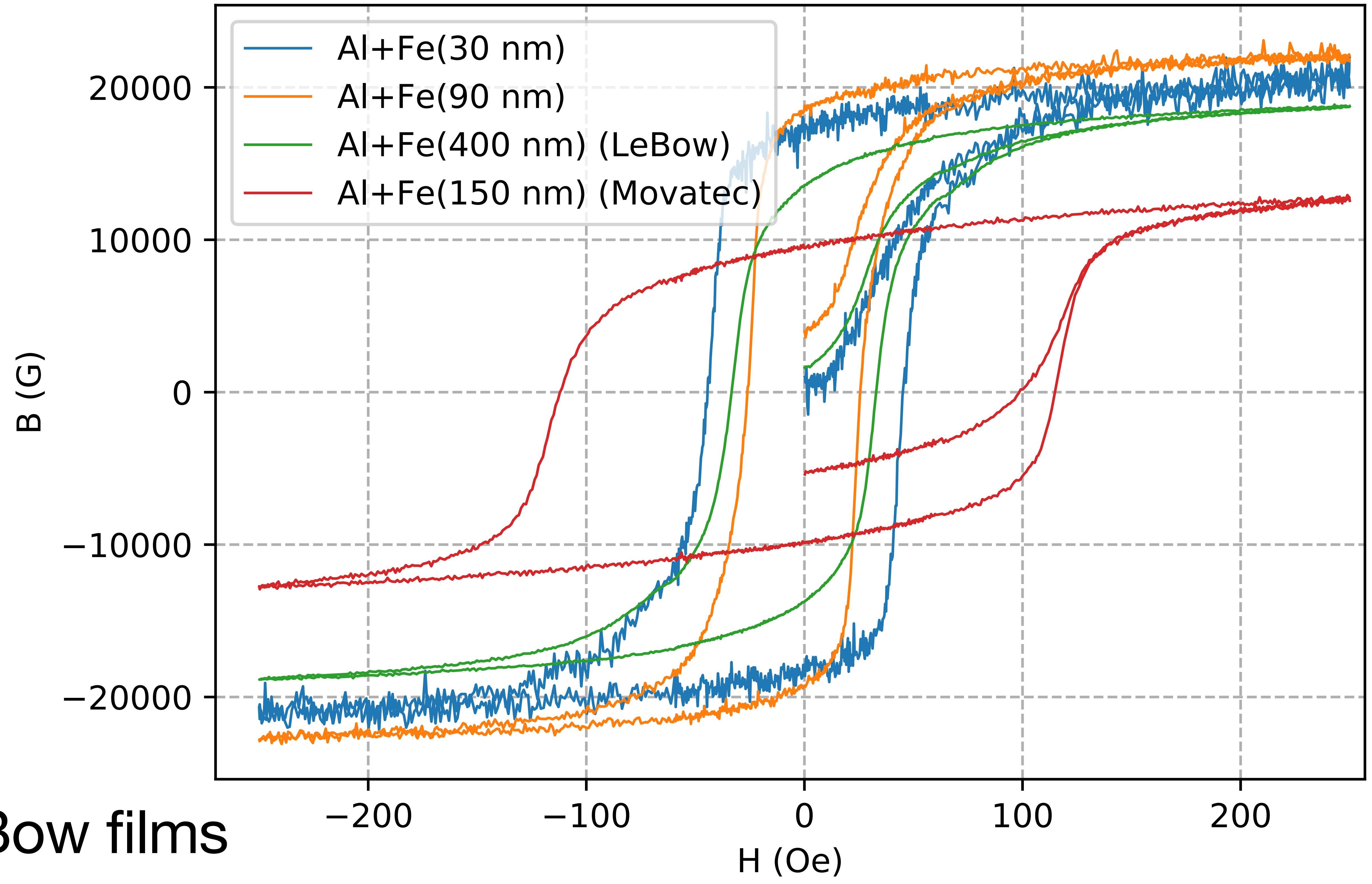
sample	Hc(Oe)	Hs(Oe)	μ0Hs(mT)
Al+Fe(30 nm)	45.0	159	15.9
Al+Fe(90 nm)	25.8	134	13.4

- BH curves of each sample were measured by Vibrating Sample Magnetometry (VSM)
- **Samples saturates with low magnetic fields (requirements : $\mu_0 H_s \lesssim 10\,\mathrm{mT}$)**
  - $\mu_0 H_s \lesssim 5\,\mathrm{mT}$ (Si substrate)
  - $\mu_0 H_s \lesssim 15\,\mathrm{mT}$ (Al substarte)

Comparison to previous TUCAN films

Sample	Hc (Oe)	Hs (Oe)
Al+Fe(30 nm) KURRI	25.8	29.8
Al+Fe(90 nm) KURRI	20.30	45.5
Al+Fe(400 nm) LeBow	33	161
Al+Fe(150 nm) Movatec	113	219

H_c: Intersection of BH curve and B=0,
H_s:H corresponding to 95% of B_{sat}



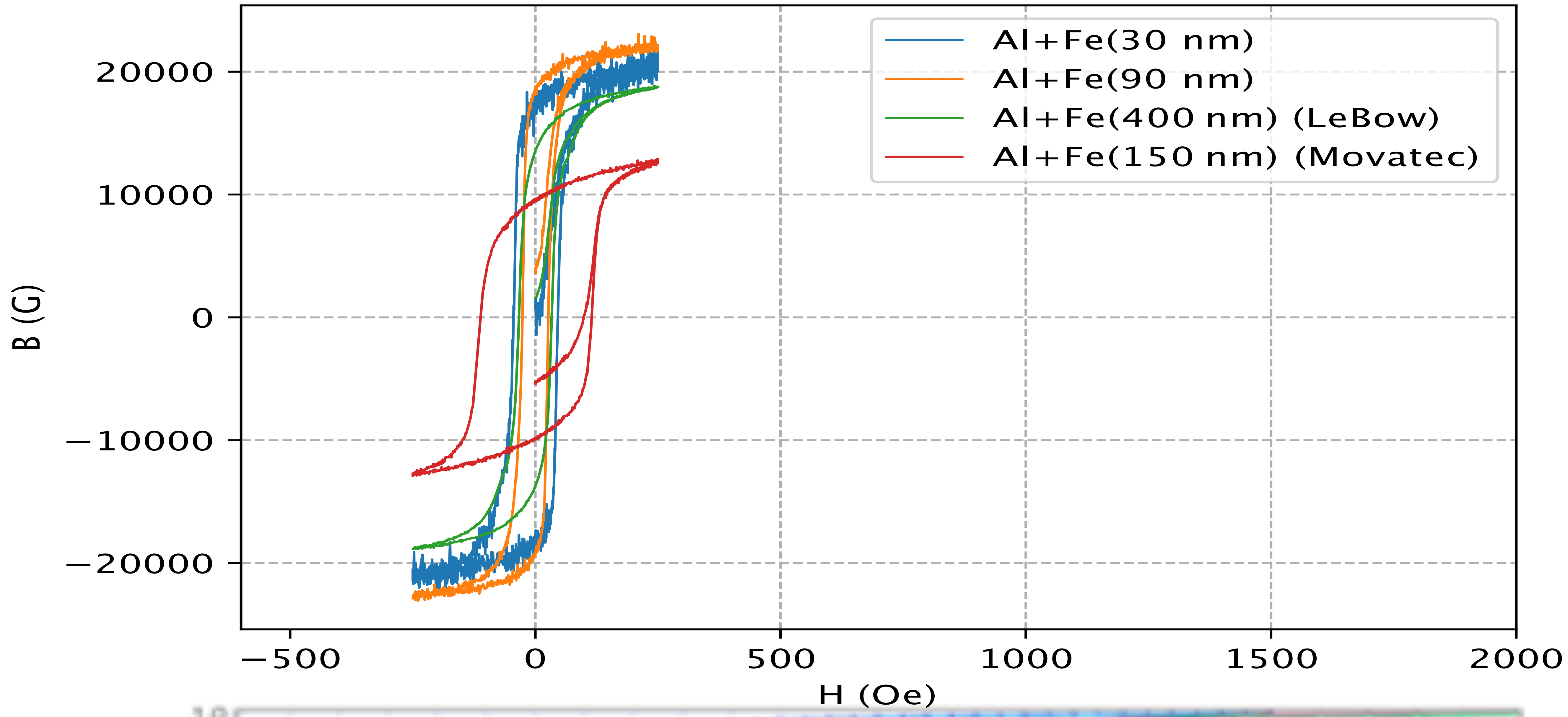
KURNS films saturated by a comparable field with LeBow films and much smaller magnetic field than the Movatec films.

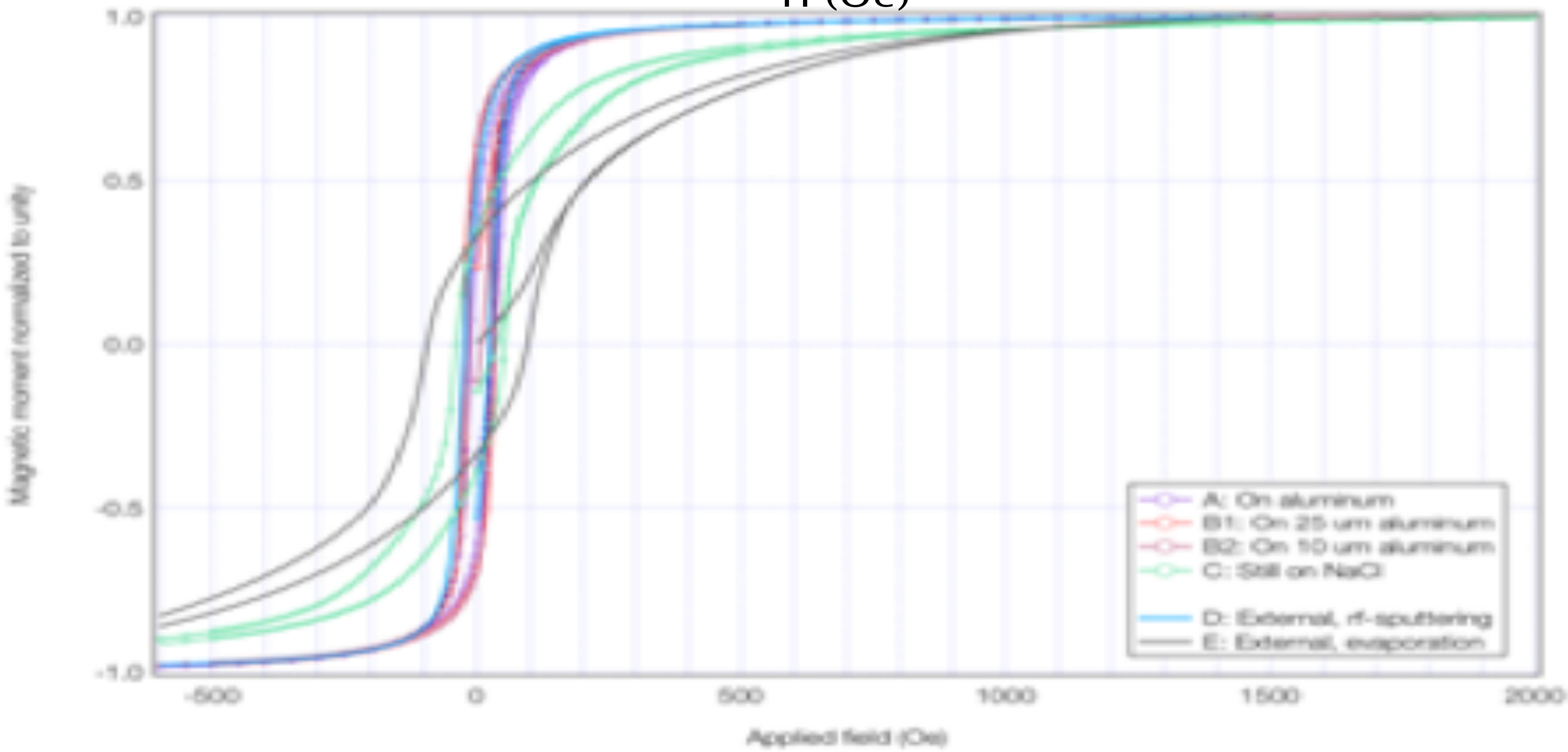
Thanks to Blair and Beatrice for sending the LeBow and Movatec foils!

Comments (Hino-san):
- Higher Hc of 30 nm than 90 nm is within lot-per-lot fluctuations. This level of fluctuations exist among different lots, but the quality is rather homogeneous in the same lot (see p.7)

Comparison to PSI films

- PSI film VSM measurement: annual report 2012
- Al-substrate films by KURNS are comparable to the PSI's.





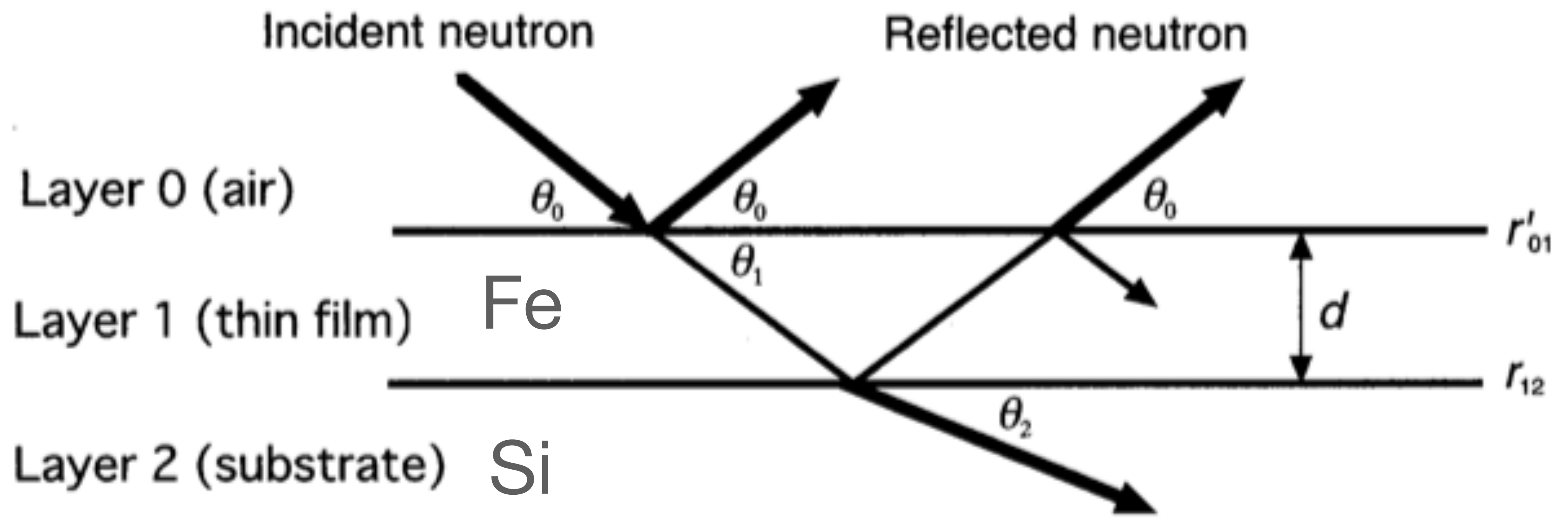
Neutron reflectometry

- Cold neutrons (wavelength $0.2 \sim 1\,\mathrm{nm}$) are injected to a sample and the reflectivity is measured.

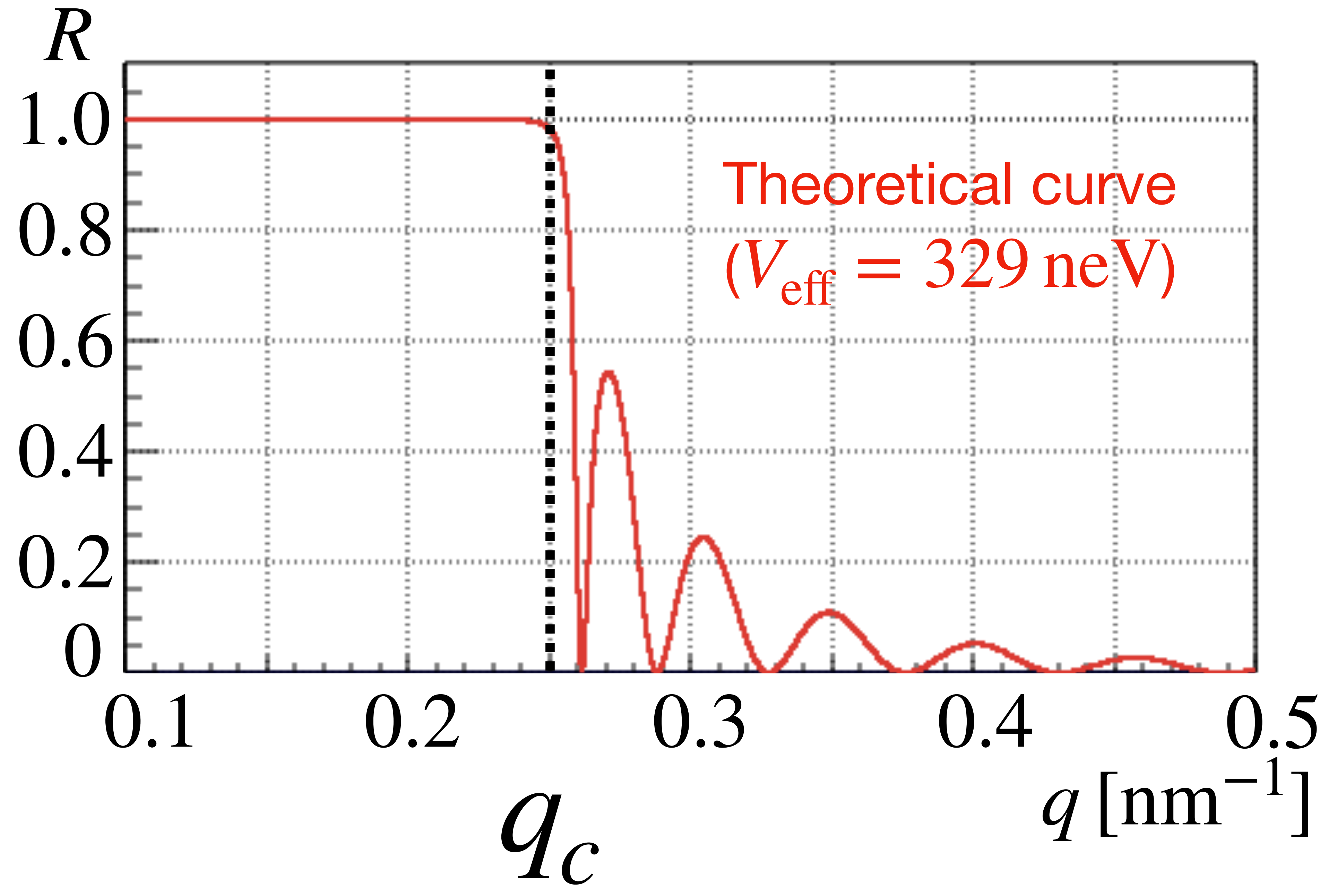
- From the reflectivity profile as a function of wave vector transfer $q = 4\pi \sin\theta_0/\lambda$, the critical value q_c can be determined.

- From the critical value q_c, the magnetic potential experienced by the neutron can be extracted.

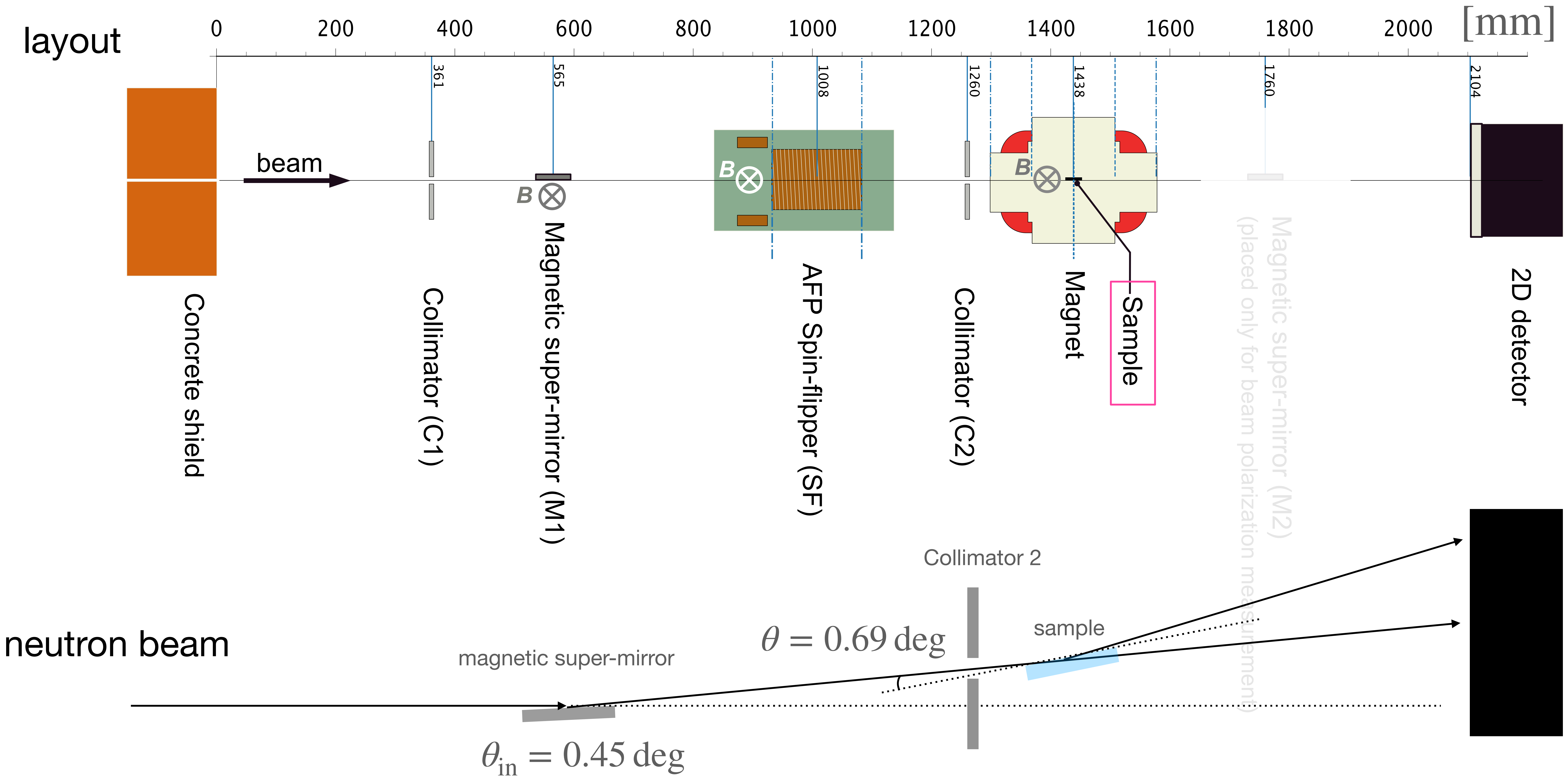
$$V_{\mathrm{eff}} = \frac{\hbar^2 q^2}{8 m_n} \qquad (m_n : \mathrm{neutron\,mass})$$



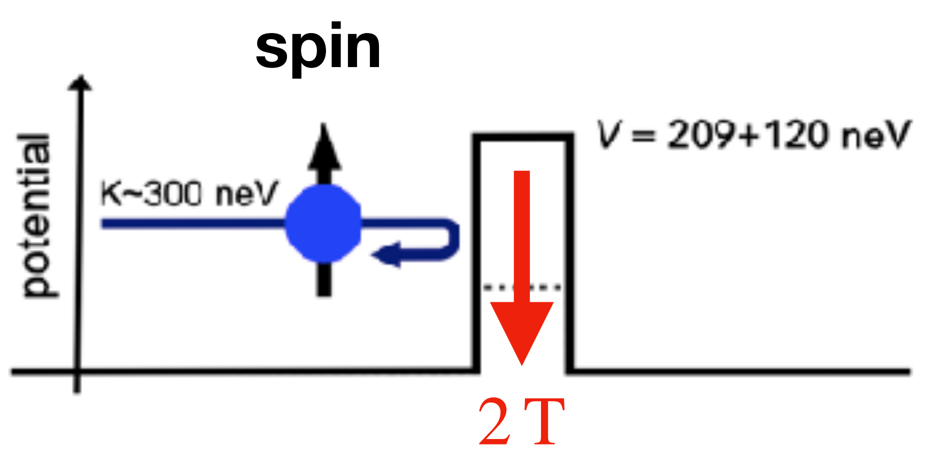
Journal of the Neutron Science Society of Japan "Ripples" Vol.18, No.4, 2008 Principle of neutron reflectometry Naoya Torikai and Masayasu Taketa

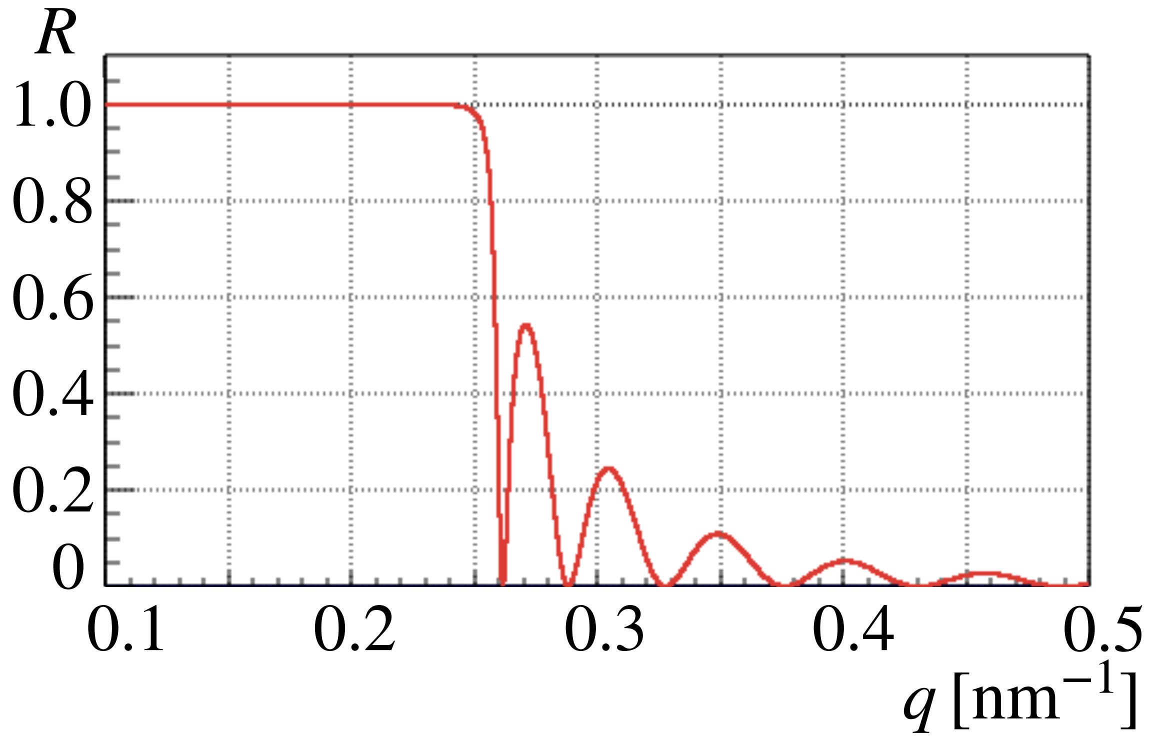


Neutron reflectivity measurement Setup (J-PARC/MLF BL05)



Reflectivity measurement of the sample



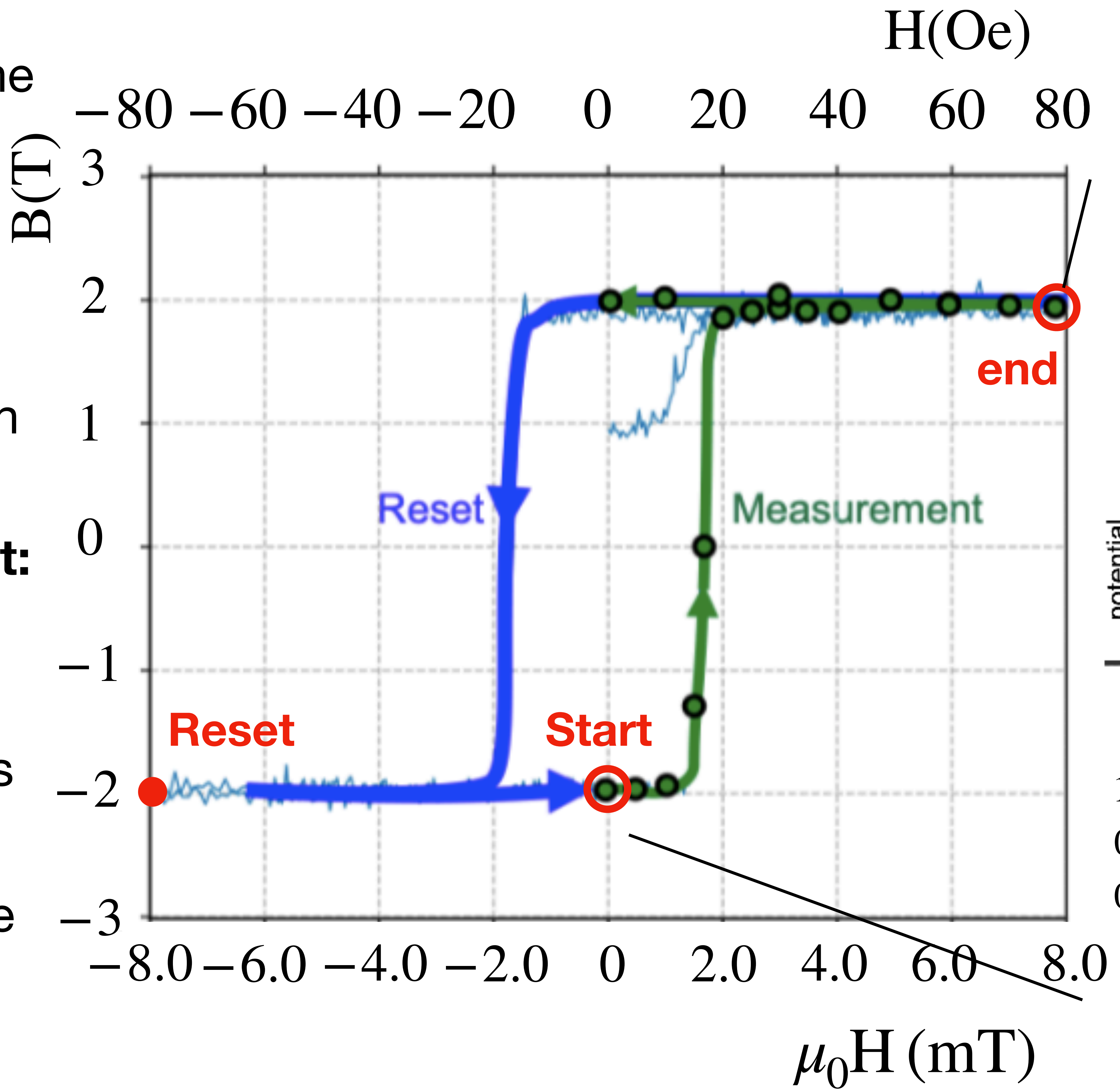


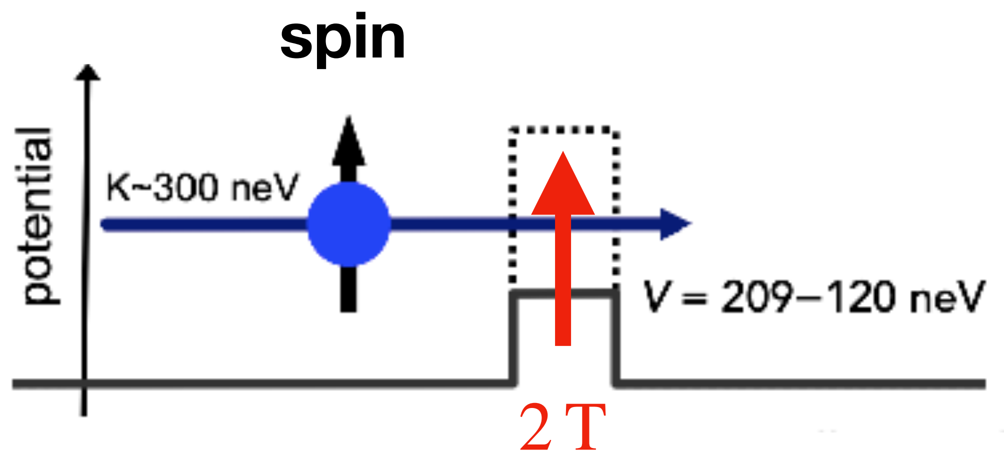
Measurement procedure:

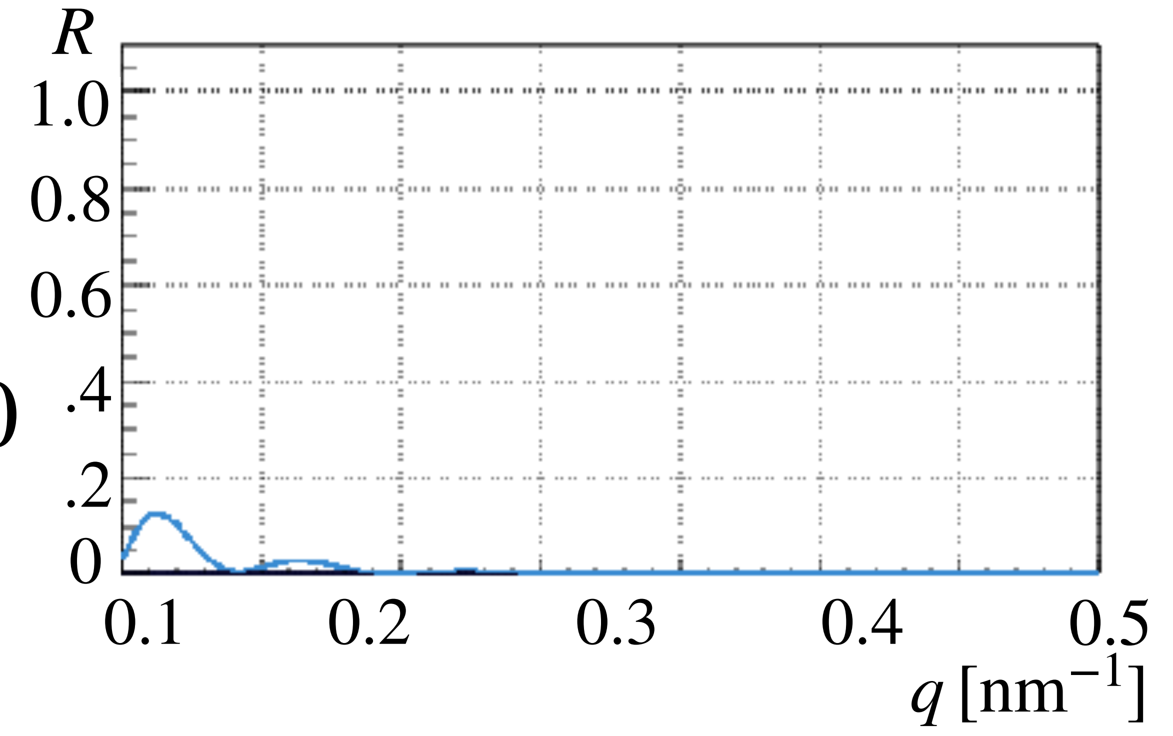
1. A magnetic field of $-8\ \mathrm{mT}$ was applied to the sample. (Reset)
2. The reflectivity R was measured while increasing the applied magnetic field.
   - The effective potential was determined from the reflectivity with the spin flipper on and off.

How to extract physical properties of interest:

- The critivcal value q_c of the reflectivity profile R(q)
  → The potential V_{eff} experienced by neutrons at saturation
- From the magnetic field at which the effective potential V_{eff} rises
  →Magnetic field required to saturate the film







Neutron reflectivity measurement results

Fe 90 nm + Si substrate
(Neutrons incident in each spin states
Reflectivity R_{down}, R_{up})

- Fitted with a function which takes into account the beam polarization
- Fitting results

  $V_{\mathrm{eff}} = 308(1)\,\mathrm{neV}$

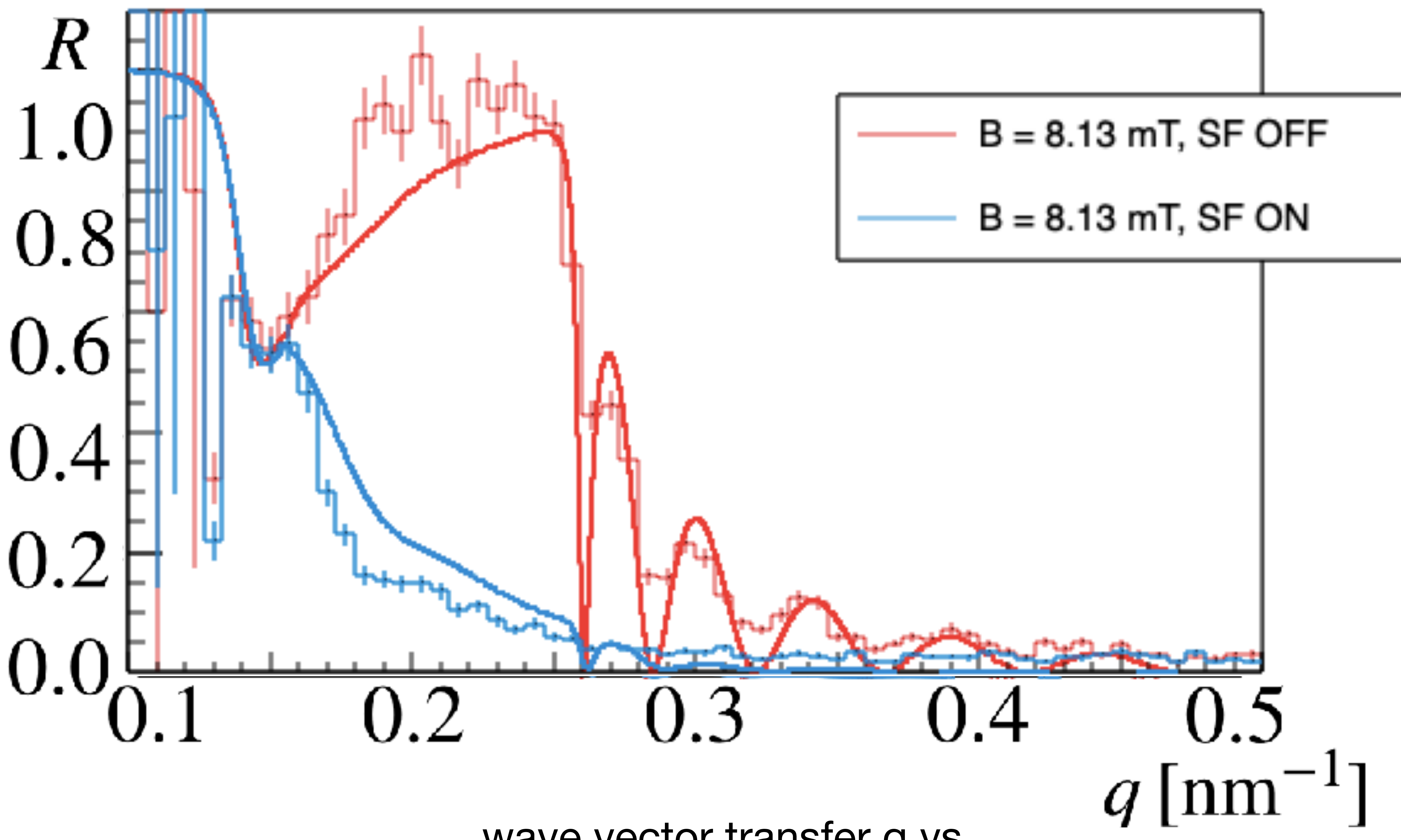
  (requirements: $V_{\mathrm{eff}} > 300\,\mathrm{neV} \gtrsim E_{\mathrm{UCN}}$)

  $\leftrightarrow$ Fe magnetization $2.02(1)\,\mathrm{T}$ (E_{UCN} : UCN energy)

  when 8 mT is applied

  (requirements : $\mu_0 \mathrm{H} \lesssim 10\,\mathrm{mT}$)

- **Enough saturation magnetization obtained to polarize UCN at sufficiently low magnetic field**



wave vector transfer q vs
Spin-up reflectivity R_{up},Spin-down reflectivity R_{down}
when 8mT is applied.
The global fit was performed using the Fermi potential of iron and the magnitude of the saturation magnetization as parameters.

Conclusion and outlook

- Development of UCN polarization analyzer for TUCAN
- Reflectivity measurement of the sample (Fe film and Si substrate)
  - $V_{\mathrm{eff}} \sim 308(1)\,\mathrm{neV}$ (requirements: $V_{\mathrm{eff}} \gtrsim 300\,\mathrm{neV} \gtrsim E_{\mathrm{UCN}}$), when 8 mT is applied. (requirements: $\mu_0\mathrm{H} \lesssim 10\,\mathrm{mT}$)
- **Successfully produced films that can be used for UCN polarization analysis**
- **The iron thin film on Si substrate was found to be magnetized at about 1/3 of the applied magnetic field compared to the PSI thin film**
- **Evaluation with UCNs are planned in spring 2022.**

Acknowledgements

Thank you for your attention!

NAGOYA UNIVERSITY

THE UNIVERSITY OF WINNIPEG

TRIUMF

UNBC UNIVERSITY OF NORTHERN BRITISH COLUMBIA

UBC THE UNIVERSITY OF BRITISH COLUMBIA

KEK

UNIVERSITY OF MANITOBA

RCNP

SFU SIMON FRASER UNIVERSITY ENGAGING THE WORLD

TUCAN
TRIUMF Ultra Cold
Advanced
Neutron source

JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE · FOUNDED 1932 ·

NSERC CRSNG

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION