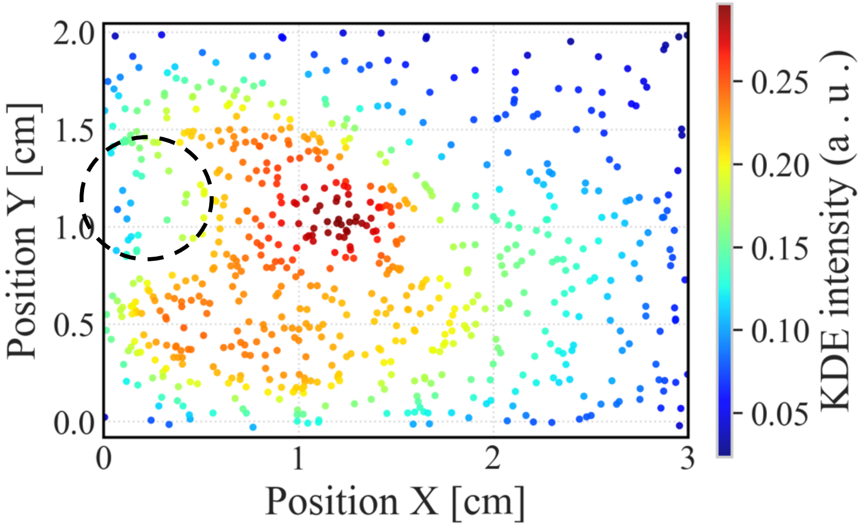
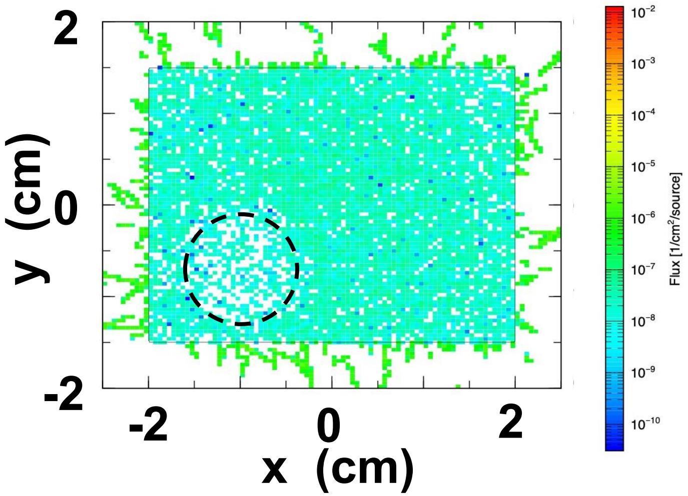
Progress on laser-driven spin polarized neutron beam generation

^{6}LiF sheet

Experiment result



Simulation result



Ryuya Yamada

u673006k@ecs.osaka-u.ac.jp

Institute of Laser Engineering, The University of Osaka.

Collaborators

Yasunobu Arikawa, Alessio Morace,
Akifumi Iwamoto, Akifumi Yogo,
Shinsuke Fujioka, Ryosuke Kodama

2022-2026 For the Next 50 YEARS
大阪大学
レーザー科学研究所
Institute of Laser Engineering, The University of Osaka

Hayato Kusano, Naoya Tamaki,
Rikimaru Kitamura, Fuka Nikaido,
Yuki Abe, Yasuhiro Kuramitsu

School/Graduate School of Engineering
The University of Osaka

Takehito Hayakawa, Yuji Fukuda,

調和ある多様性の創造 国立研究開発法人
QST 量子科学技術研究開発機構
National Institutes for Quantum Science and Technology

Contents

1. Method of spin-polarized neutron extraction
   in a laser-driven neutron source and laser-driven magnetic field.

2. Experiment and analysis of detector for spin-polarized neutron
   in high-power laser is conducted at ILE, Osaka.

3. Future work

Contents

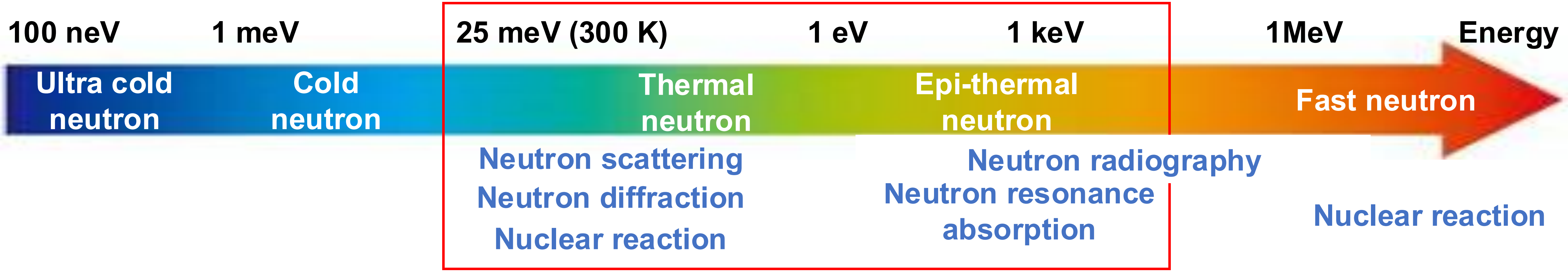
Spin-polarized neutron source has been expected to be unique particle source.

ILE, Osaka

Conventional: Nuclear reactor, Accelerator, Recent: Laser-driven neutron source

Features of laser-driven neutron source

- Wide range energy of neutron with meV~MeV.
- Short pulse
- Point source



Applications of spin-polarized neutron

- Magnetic substance
- Magnetic structure analysis of nano-order size
- Superconductors.

Polarized Neutron Scattering Tutorial.(book)
National Institute of Standards and Technology (NIST).

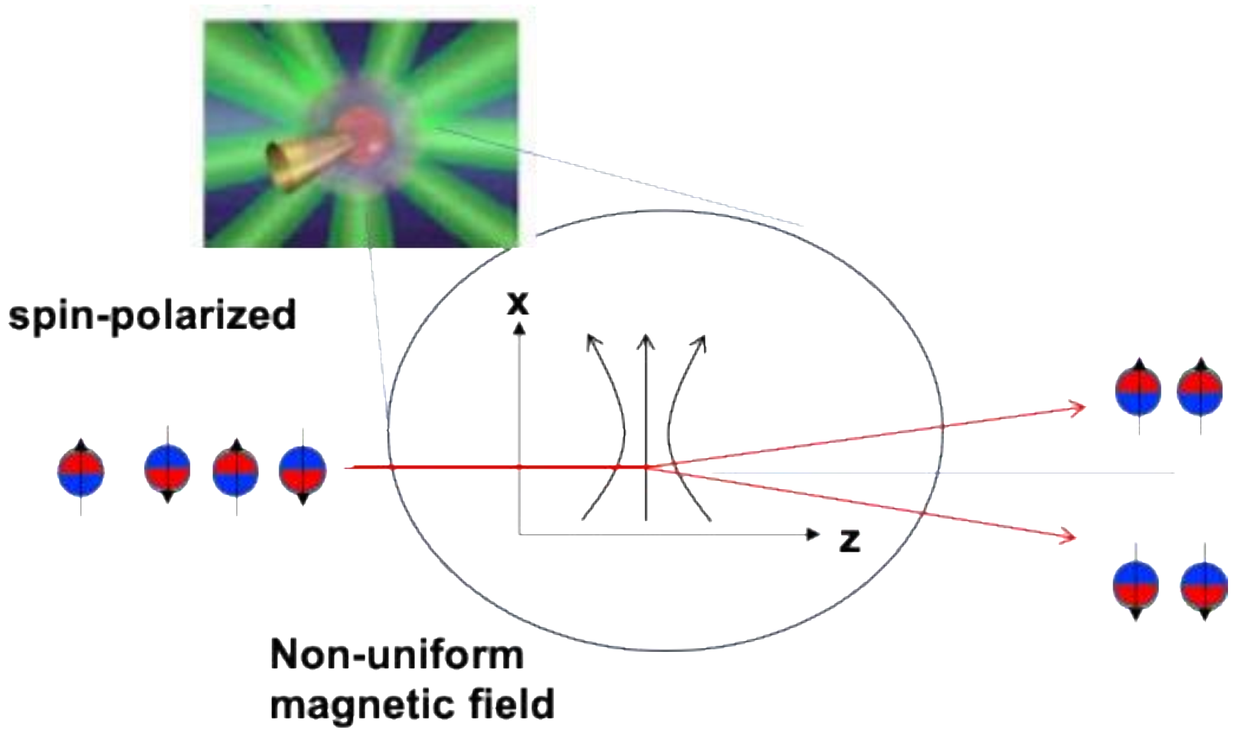
Magnetic field in the high-density plasma can be diagnosed by the spin-polarized neutron.

S.R. Mirfayzi, et, al, Sci. Rep, 2020.
S. R. Mirfayzi et, al., Appl. Phys. Lett. 2020.

Application of spin polarized neutron in high density plasma.
Imaging of laser-driven magnetic field.

Features of neutron

- High transmittance
- Affected by magnetic fields, while unaffected by electric fields

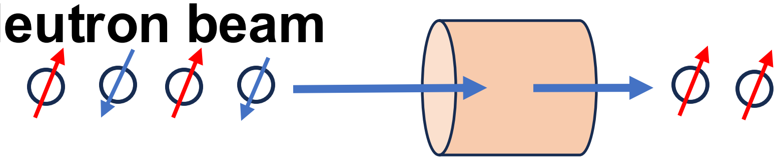


Neutron can penetrate high density matters.

Neutrons are deflected
by magnetic field gradient ($\theta \propto dB/dx \times Z$),
while not affected by E-field.

Extraction method of spin-polarized neutron.

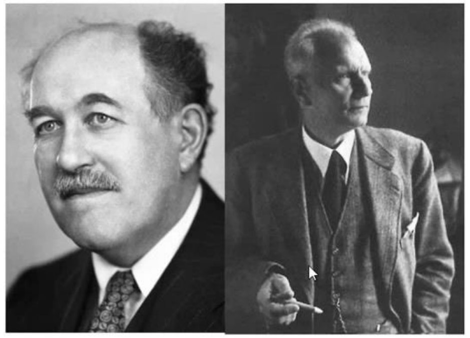
^{3}He spin filter is generally used for the generation of spin-polarized neutron beam.



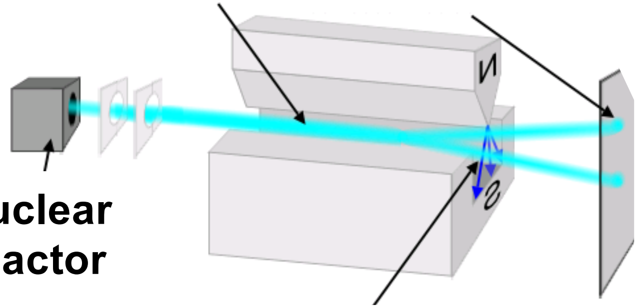
Drawback of the ^{3}He spin filter

- Complex generation devices (lasers, magnets)
- 100% spin-polarized neutrons are difficult to produce

In our study, aiming to extract spin-polarized neutron using Stern-Gerlach method (1922).



Otto Stern Walther Gerlach

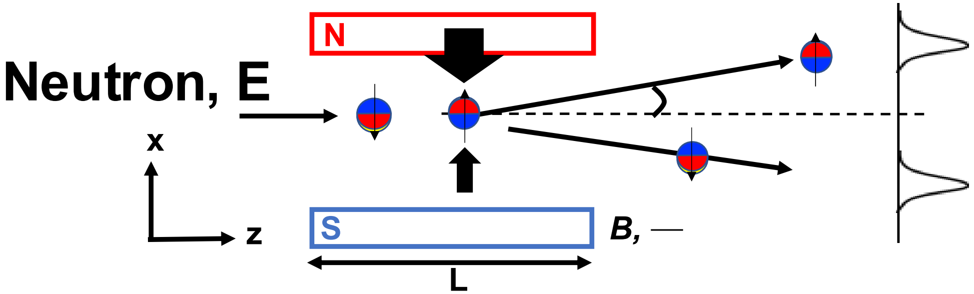


Spin polarized neutron are separated by magnetic field gradient

Combination of laser-driven neutron source and laser-driven magnetic field, 100% spin-polarized neutron is extracted.

Theoretical prediction of neutron polarization by magnetic field gradients

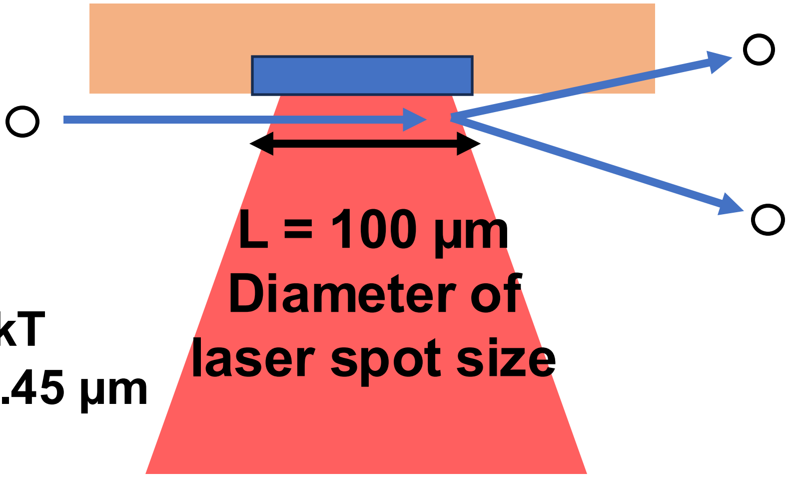
Neutron deflection angle θ is given by neutron polarization.



$$\theta = \pm 1.03 \times 10^{-7} L \cdot \frac{dB}{dx} \cdot \frac{1}{\sqrt{E}}$$

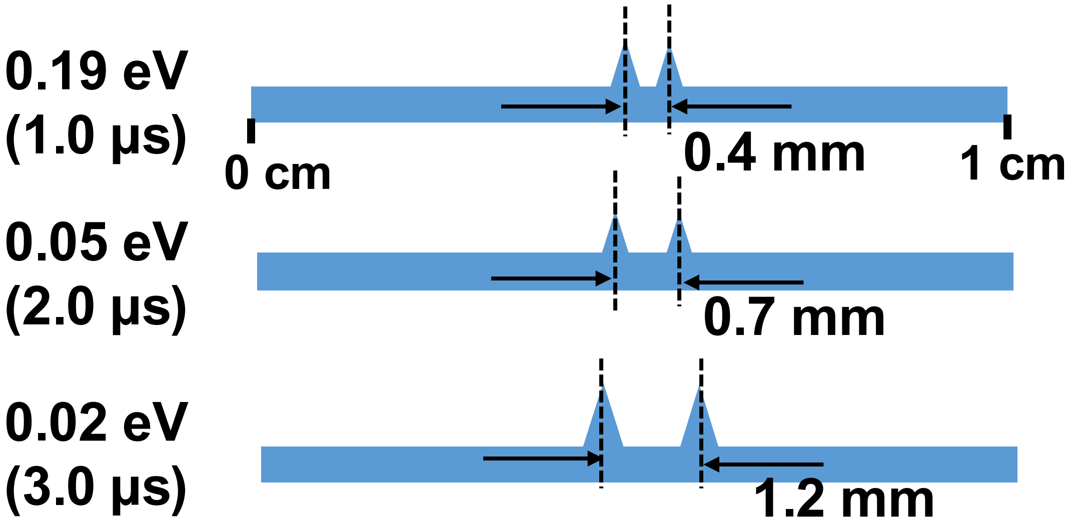
Thermal neutron shows bigger deflection.

Neutron
0.19 eV
0.05 eV
0.02 eV



B = 1kT
dx = 2.45 µm

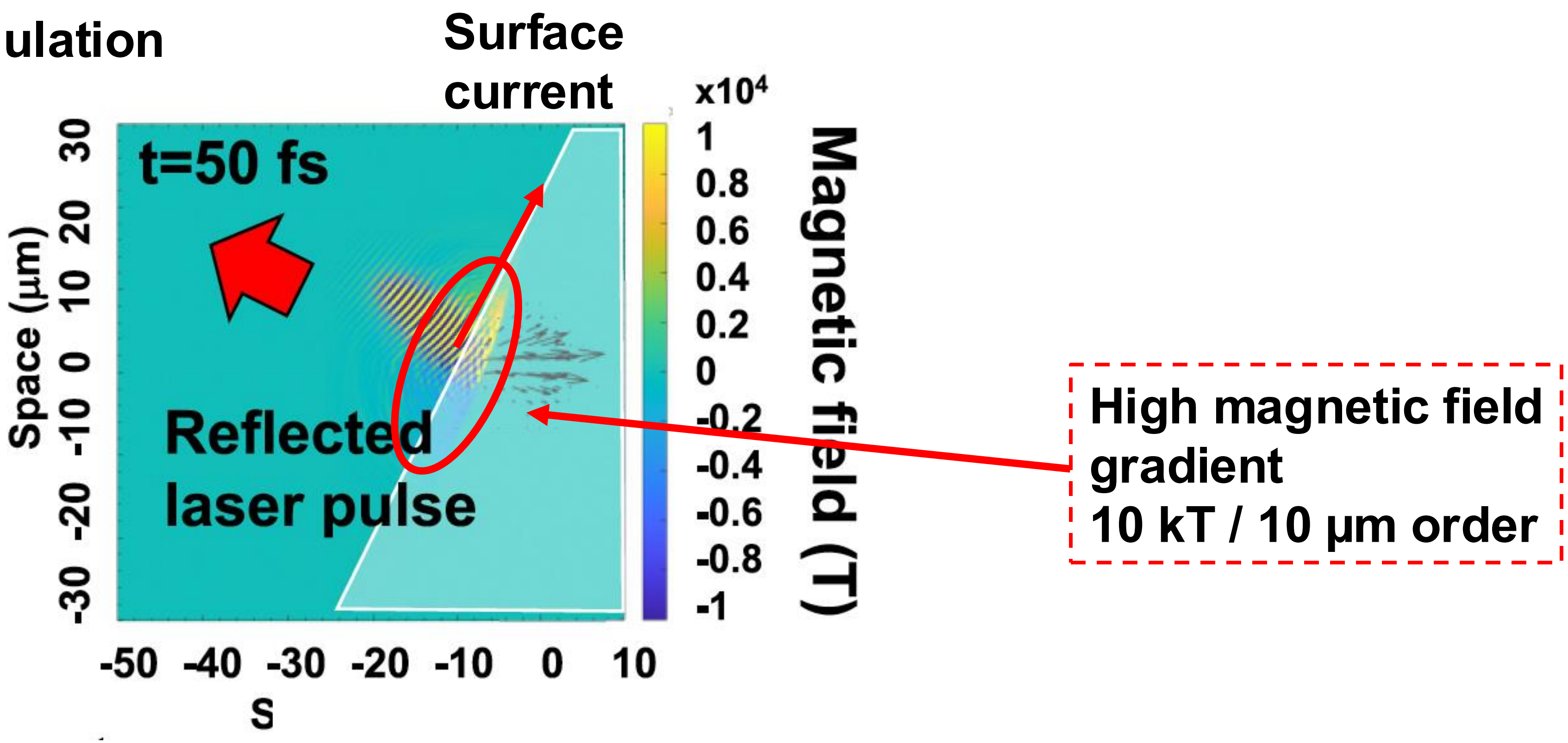
Split is showing less than ~1mm.



[1] Hiroki Morita, et, al,
Reviews of Modern Plasma Physics 2023

~kT magnetic field is generated by ultra intense laser

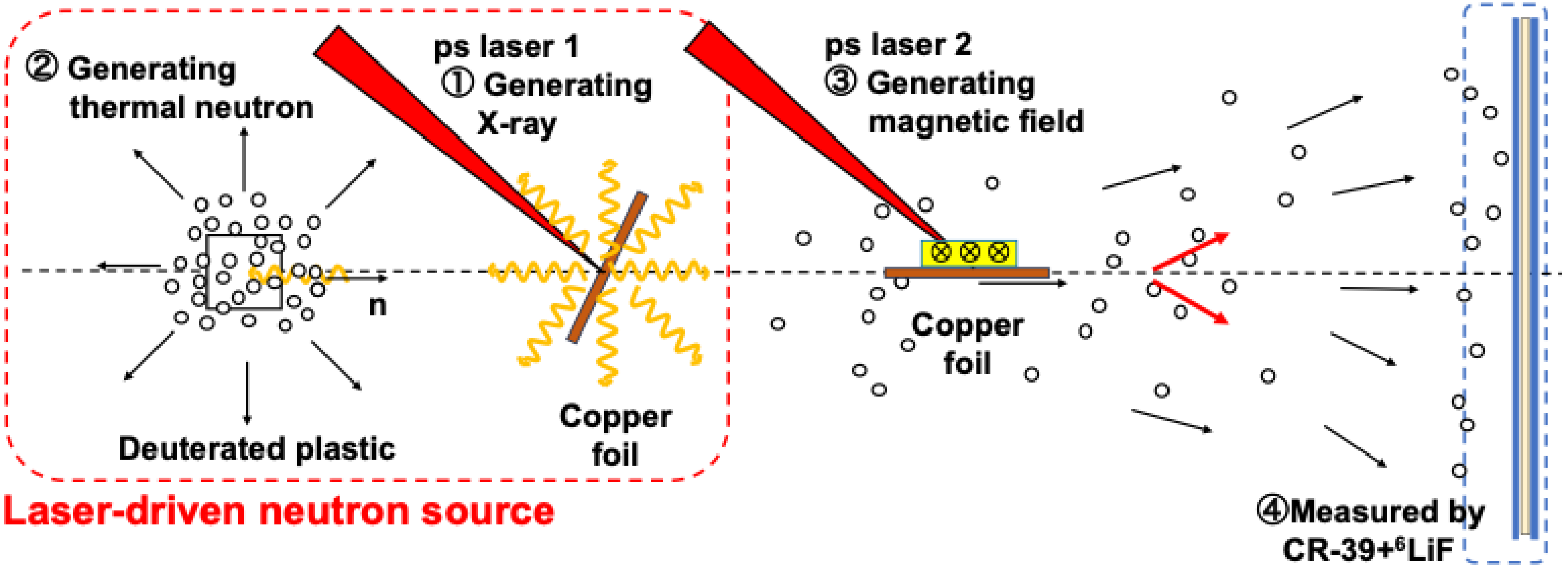
Particle-in-Cell simulation



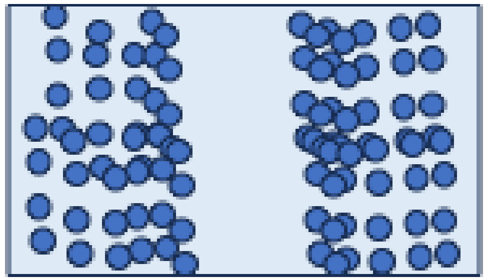
~kT order magnetic field is generated by ~ps laser
→ Using this magnetic field,
Spin-polarized neutron shows 1.0 mm distance of deflection.

Y. Arikawa et, al., Phy. Rev. Research.2023

Principle of the measurement.
High efficiency thermal neutron imaging detector is needed.



Predicted signal on CR-39



Requirement on the detection of spin-polarized neutron

1. Robust for noises
   (non-neutron particles and electro-magnetic pulse)
2. High efficiency for thermal neutron (~ 2.4 %)
3. High spatial resolution (~ 1 mm)
4. Large surface area

Contents

1. Method of spin-polarized neutron extraction
   in a laser-driven neutron source and laser-driven magnetic field.

2. Experiment and analysis of detector for spin-polarized neutron
   in high-power laser is conducted at ILE, Osaka.

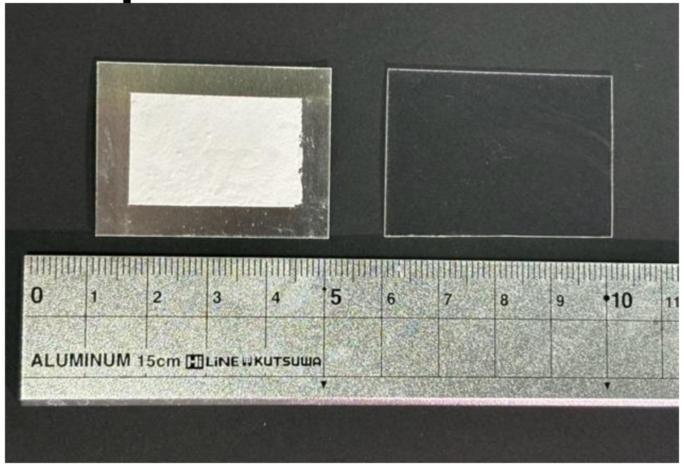
3. Future work

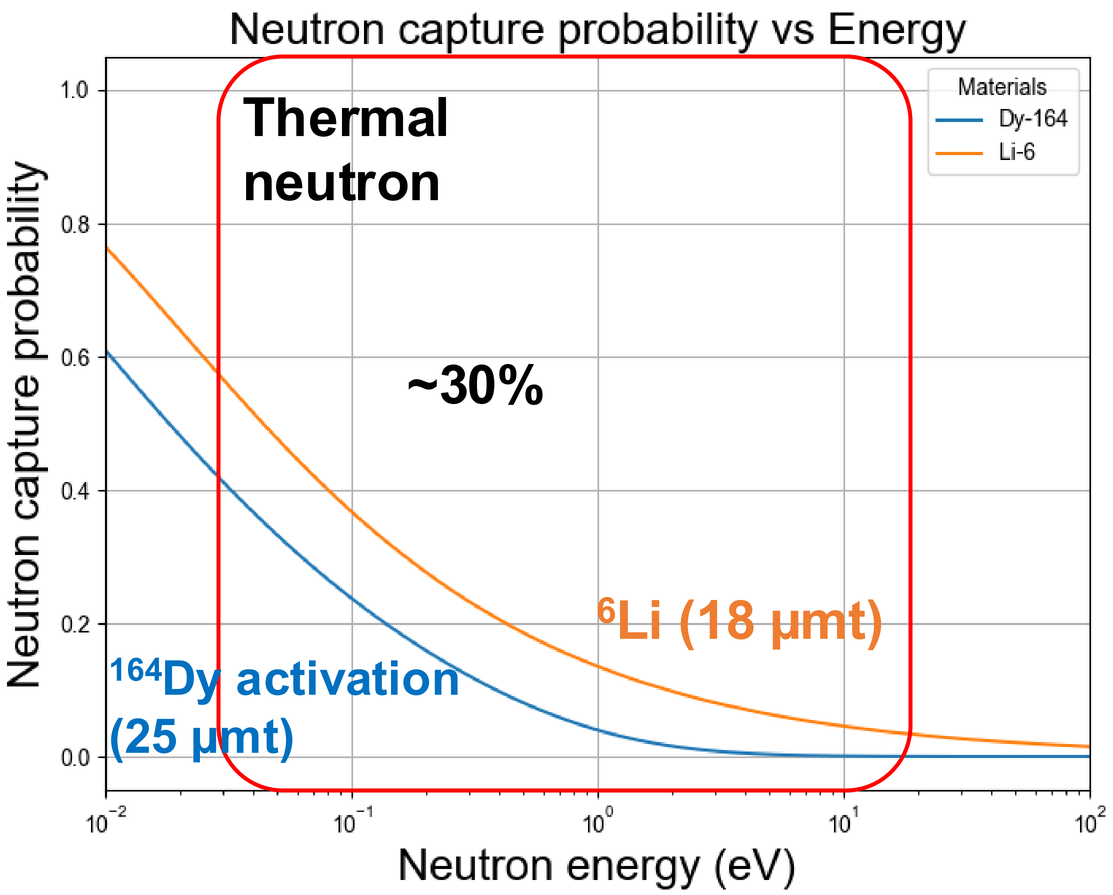
Thermal neutron imaging

High sensitivity and robust thermal neutron imaging detector by using ^{6}LiF and CR-39.

ILE, Osaka

Stack of ^{6}LiF plate and CR-39





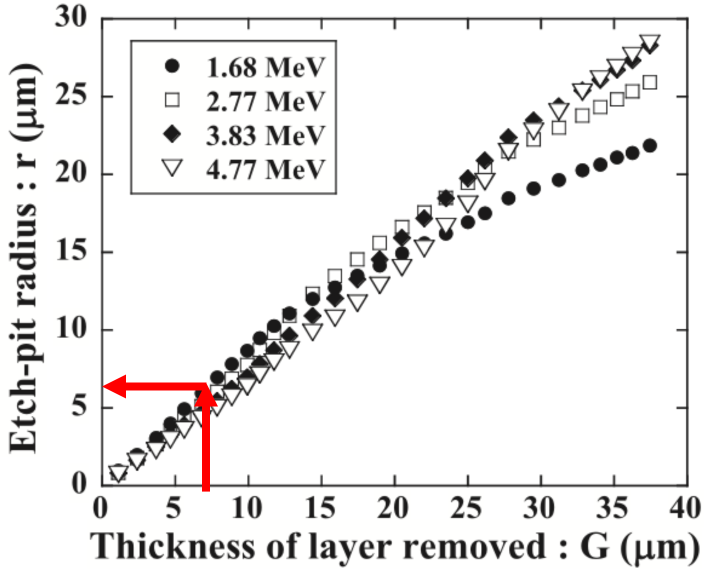
Merit

1. No sensitivity for X-ray and electromagnetic noise.
2. High sensitivity for thermal neutron.
3. High spatial resolution (~1 mm)
4. Easy and large area size. (~1 cm)

CR-39 + AI technique is introduced to discriminate neutron signal and backgrounds

ILE, Osaka

Alpha particle curve



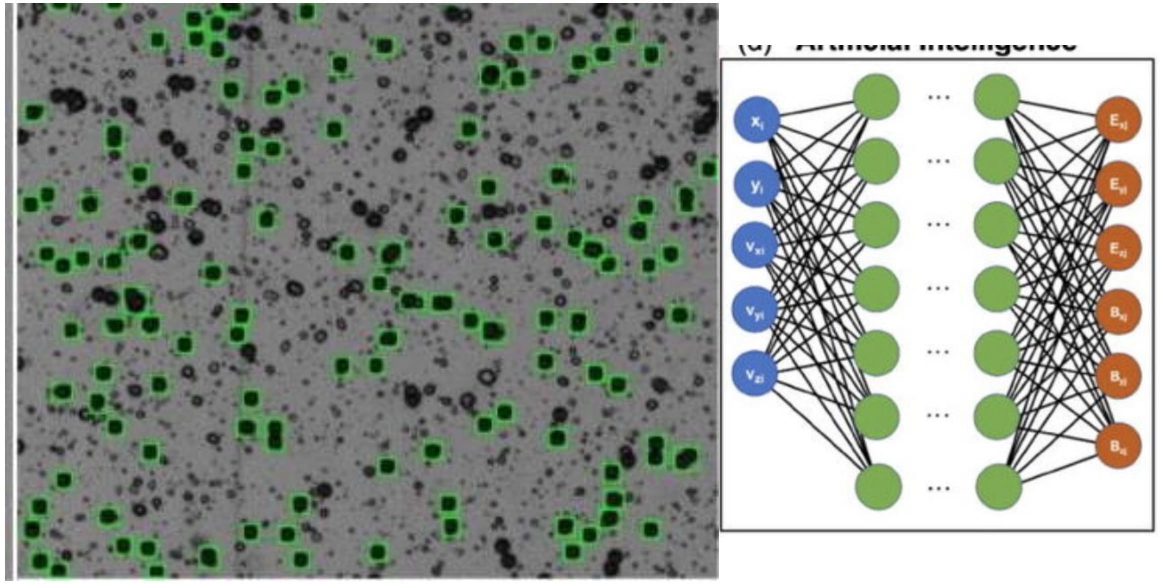
~ etching time

$^{6}Li + n_{(0.1eV)} \rightarrow \alpha + {}^{3}H + 4.79$ MeV

The energy of alpha particles is 2.05 MeV.

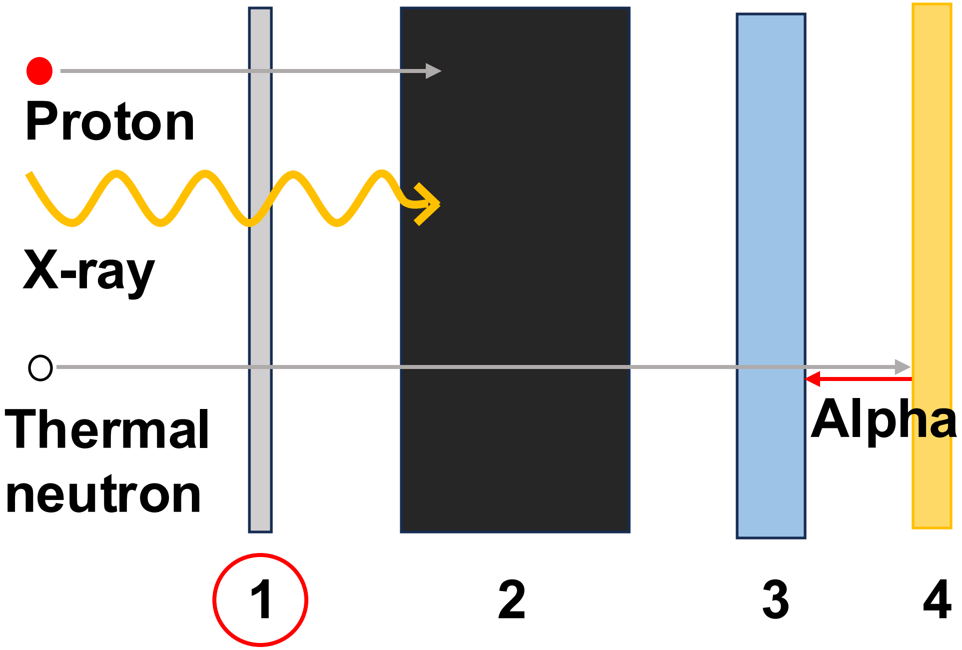
The pit size of thermal neutron ~14 μm is the neutron induced α particle

Deep learning is applied to distinguish pits of CR-39 [1-3]



[1]Y. Kuramitsu, et al., POP 2024
[2]M. Kanasaki, et,al, J.Plasma Fusion Res 2012
[3]T. Taguchi, et,al, Rev. Sci. Instrum. 2024.

The filter has been placed to attenuate the background signal and confirm thermal neutron signals.



Behind Al filter

1. Al (0.3mmt) : Attenuate protons
2. Pb (3mmt) : Absorb protons and X-ray
3. CR-39 : Detector
4. ^{6}LiF (0.5mmt) : Convert thermal neutron to α

Cd, Ag, Dy, Hf and Au have high attenuation for thermal neutron.

If there are shape of metal, thermal neutrons are detected.

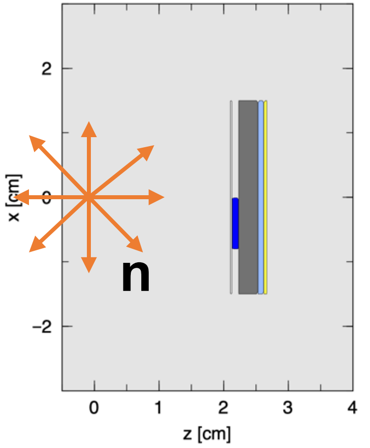
PHITS : Monte Carlo simulation

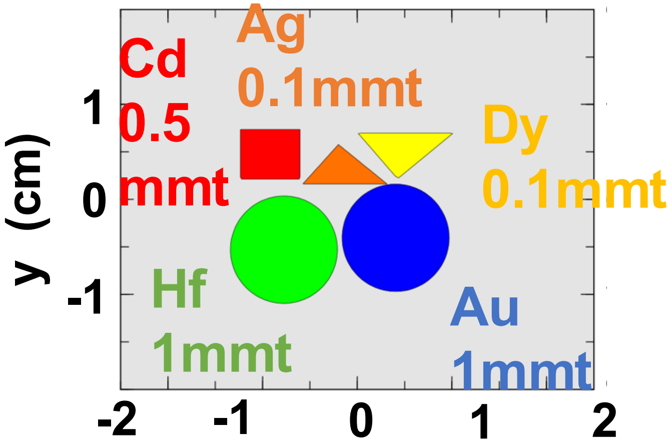
ILE, Osaka

PHITS
Particle and Heavy Ion Transport code System

Simulation setup

Thermal neutron injection

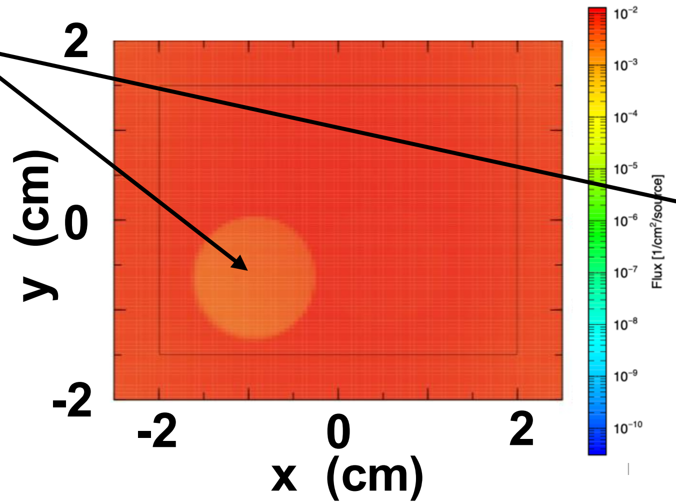




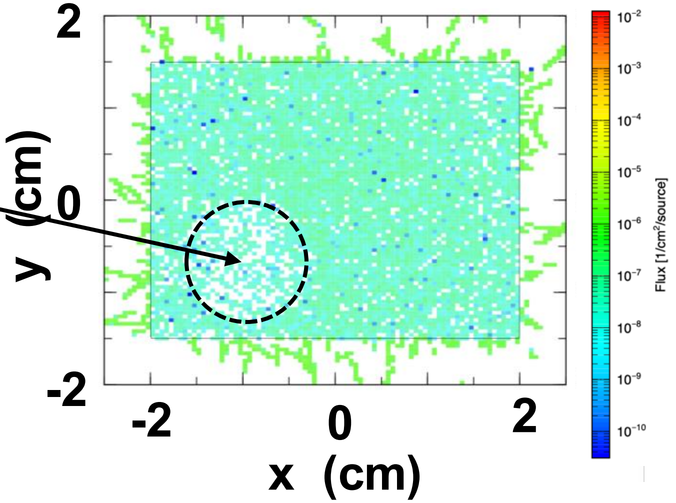
Experiment

Neutron flux map

Hf



Alpha particles
Simulated CR-39 signal



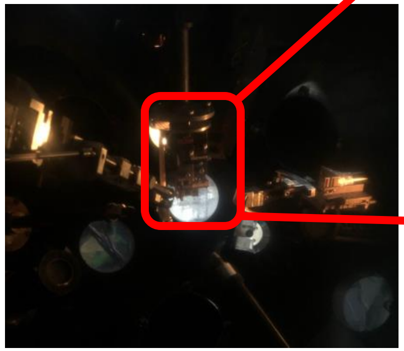
To evaluate of the spatial resolution of the detector Neutron absorption of the pattern is examined.

T. Sato, et,al,
J. Nucl. Sci. Technol. 2024

Thermal neutron generation experiment is conducted at LFEX laser facility.

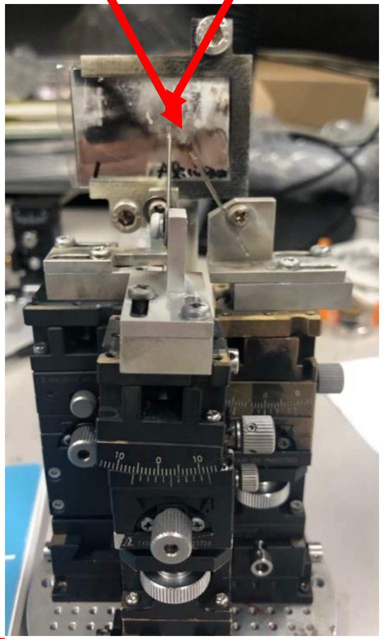
ILE, Osaka

Conducted in 2023

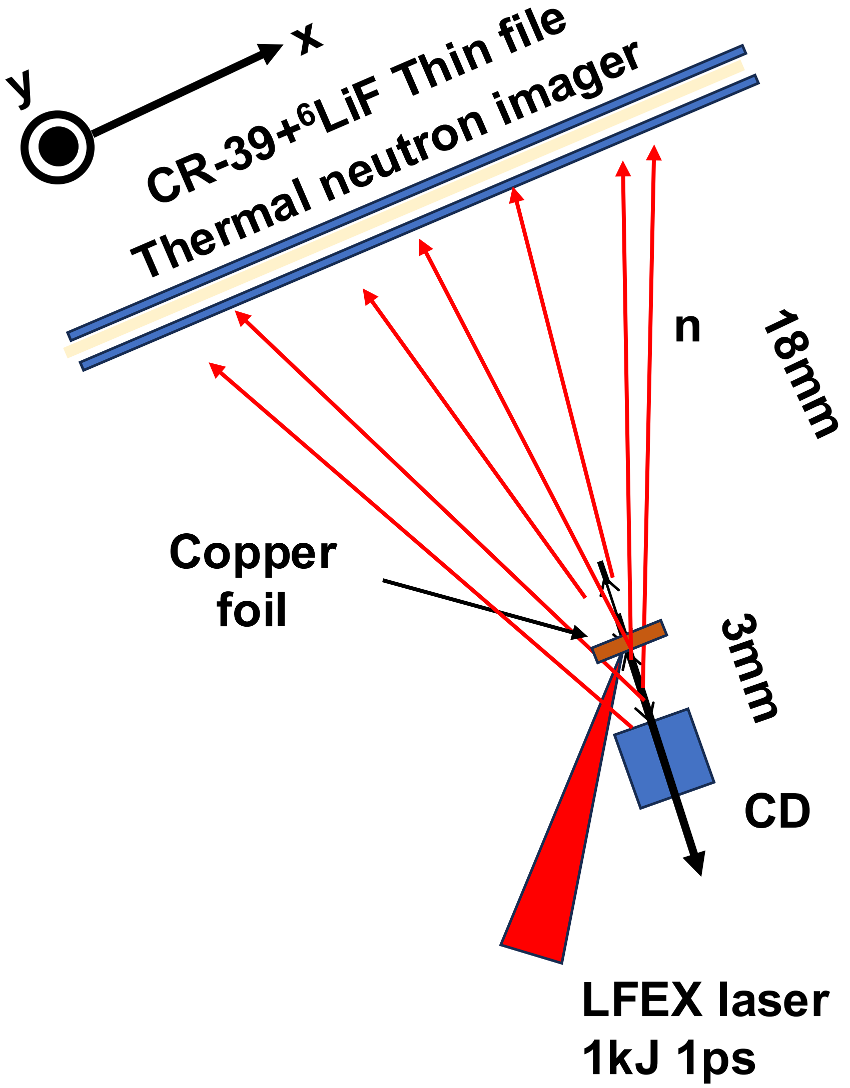


Target
1mmx1mmx20μmt
Copper foil

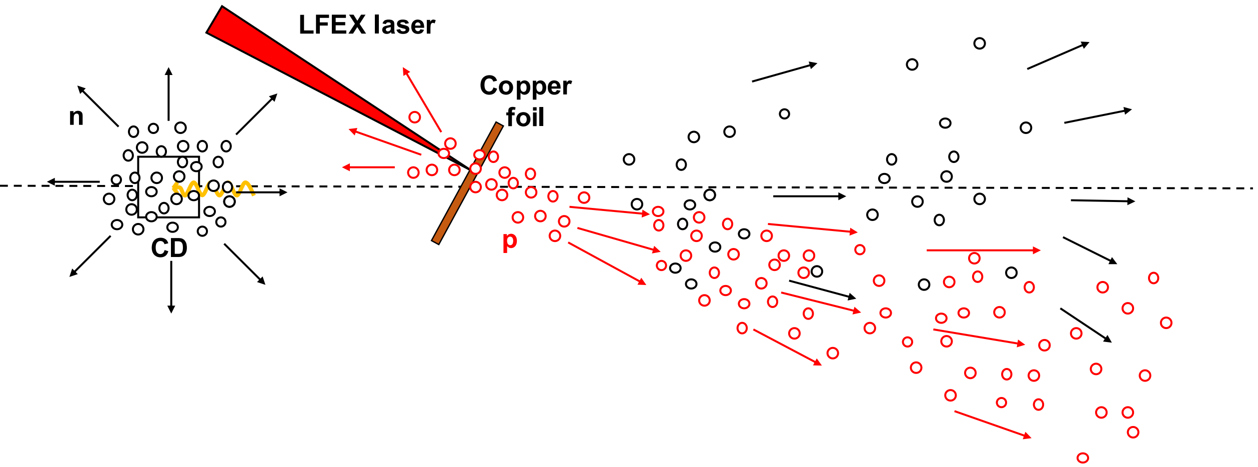
CD
2mmx2mmx2mmt



Experimental setup

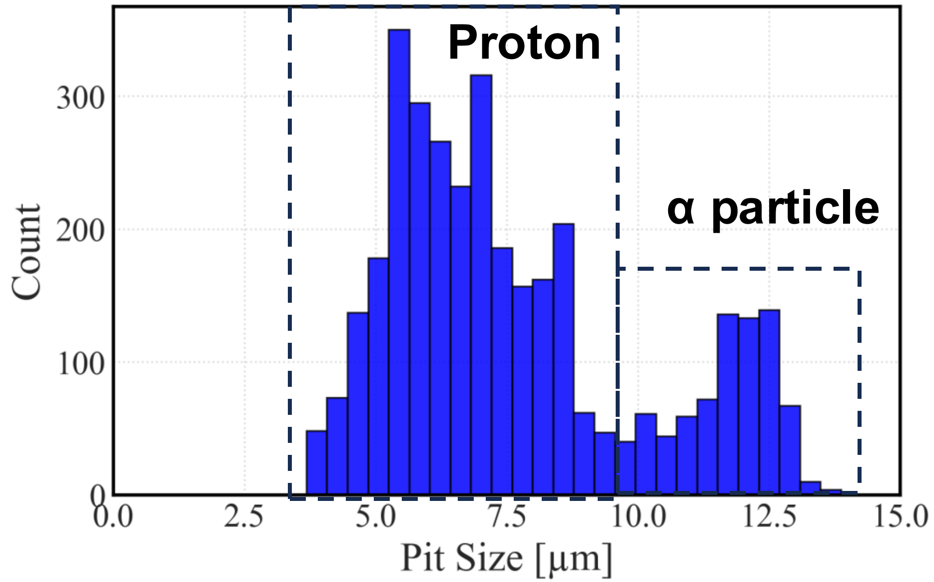


Other ions is generated by high-power laser and detected by CR-39. Thermal neutron can be discriminated by deep-learning.



The signal of proton come from TNSA by LFEX laser.

Experiment result of CR-39



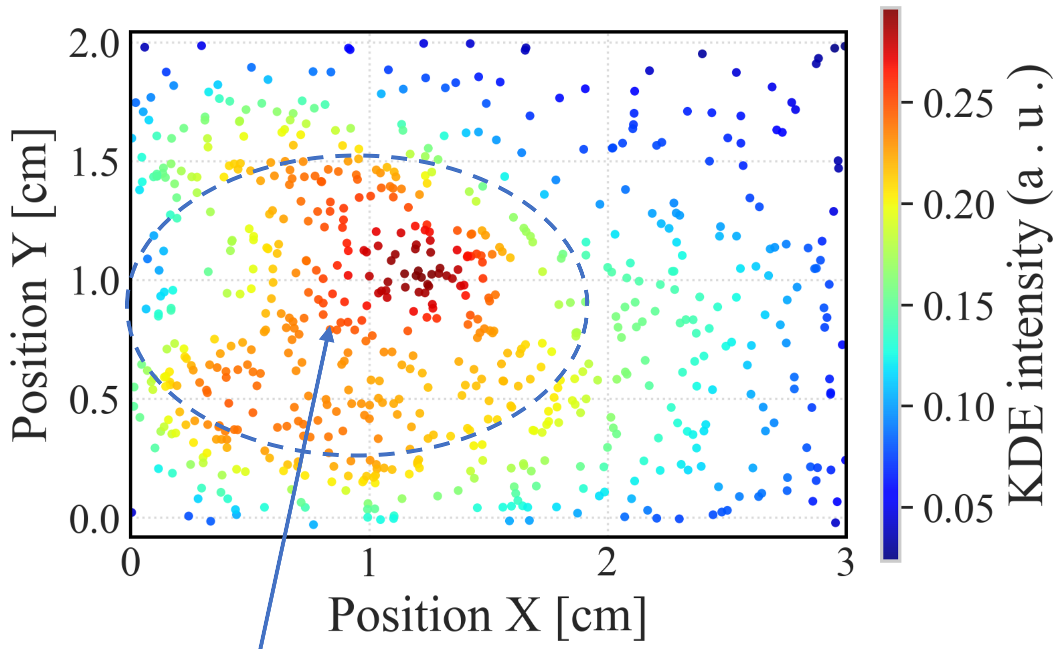
There are two different pit sizes.

[1]Y. Kuramitsu, et al., POP 2024
[2]M. Kanasaki, et,al, J.Plasma Fusion Res 2012
[3]T. Taguchi, et,al, Rev. Sci. Instrum. 2024.

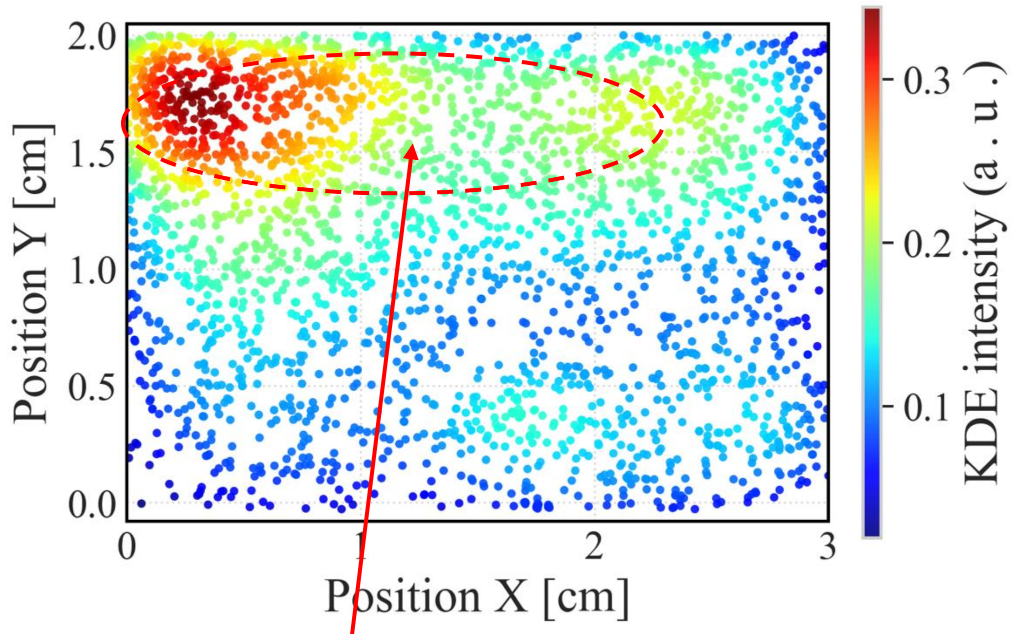
Experimental results by CR-39.
Neutron signal (n+Li→ α+T) is discriminated by pit size-AI technique.

ILE, Osaka

Alpha particle pit (>10μm)
Neutron



Proton pit (<10μm)
Noise



Thermal neutron signal from CD by d(γ,n)p
$^6Li + n \rightarrow \alpha + {}^3H$

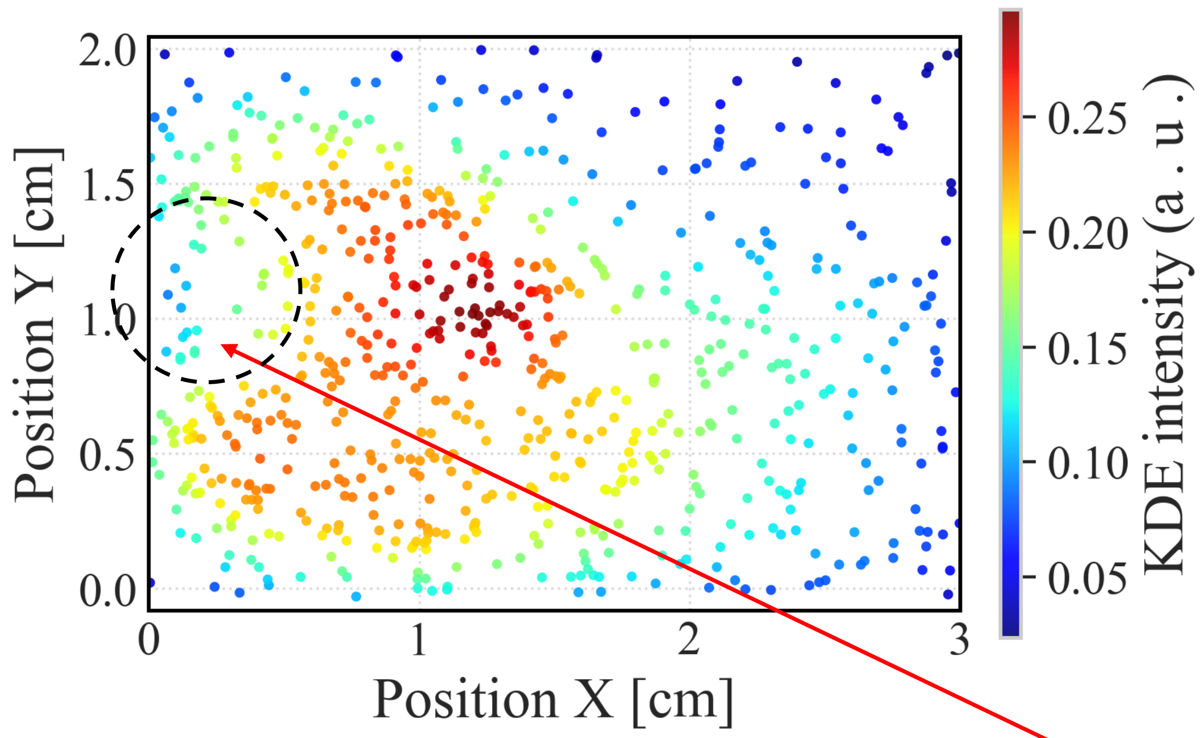
Proton signals from the copper foil target by LFEX laser

There are different distributions by the pit size.

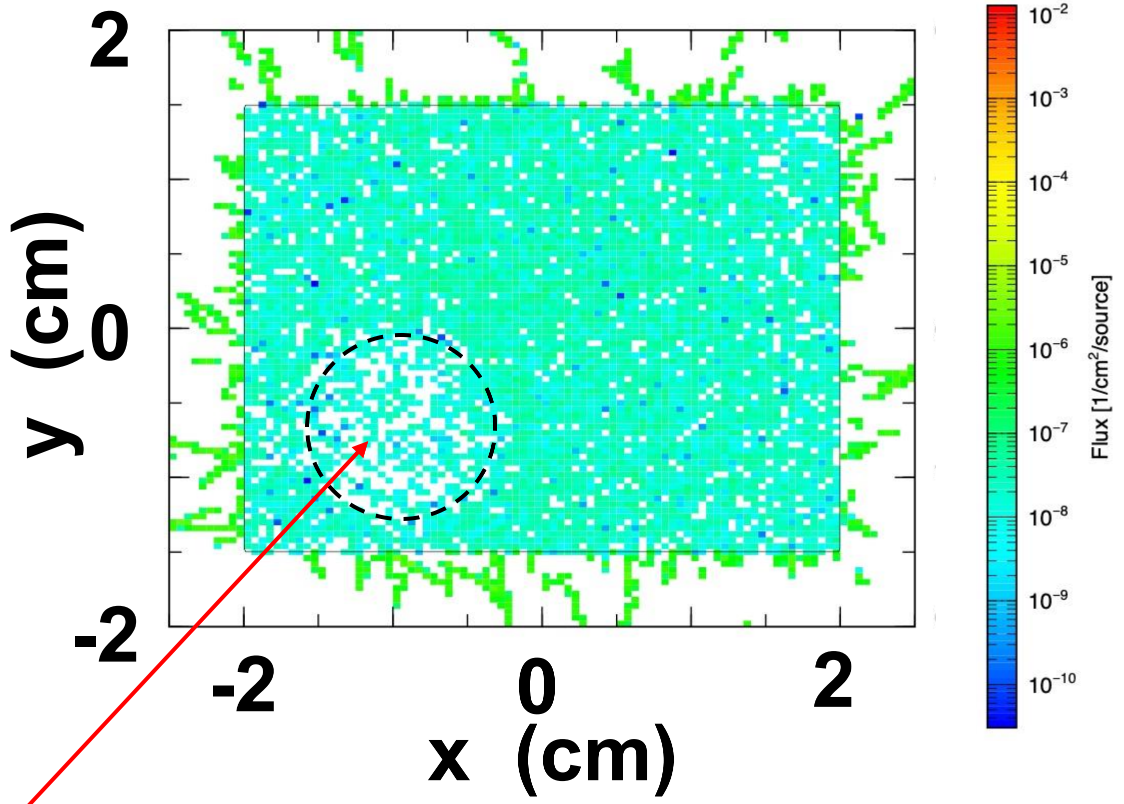
The thermal neutron imaging has been successfully observed.

ILE, Osaka

Experiment result
Alpha particles

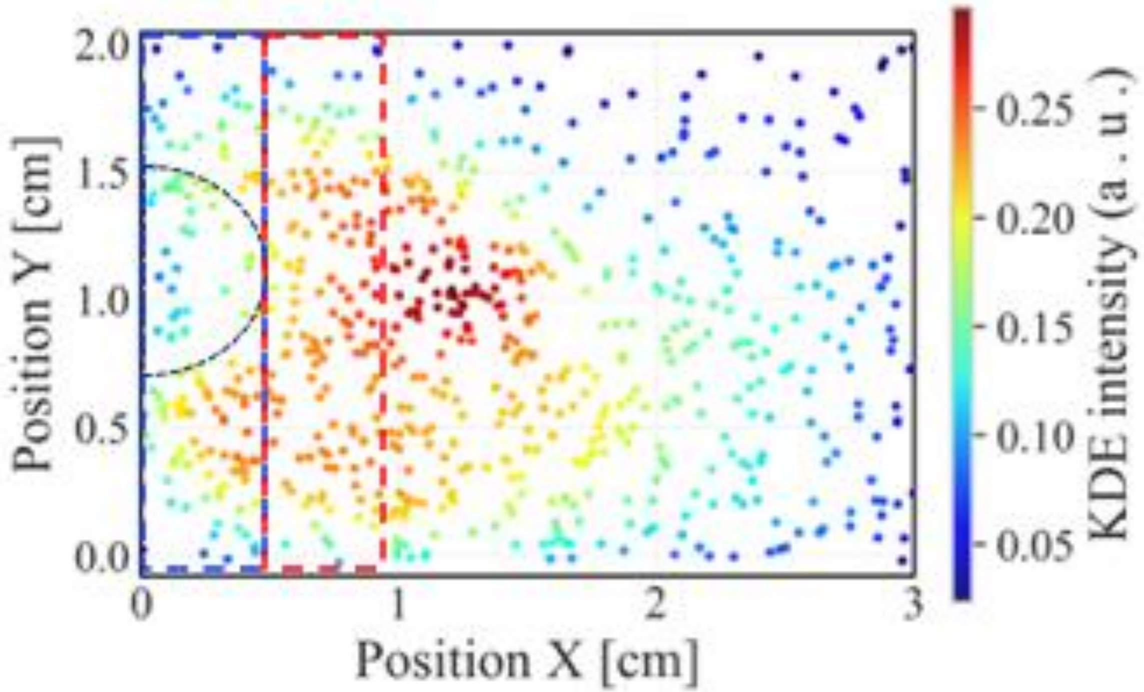


Simulation result
Alpha particles

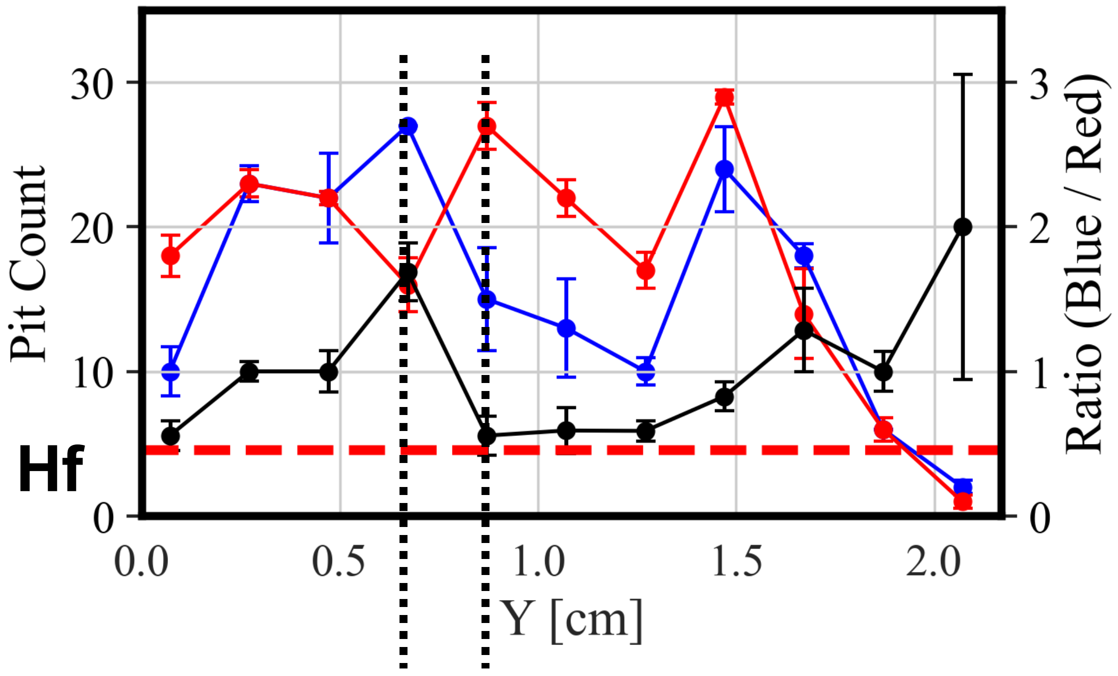


A circle appears on the CR-39 signal in the Hf region.

Spatial resolution estimation of the thermal neutron detection



With Hf No Hf



- Ratio from experiment is close to the Hf transmittance ratio.
- From transmittance of Hf, thermal neutron is detected by CR-39 and ^{6}LiF.
- ~2 mm spatial resolution thermal neutron detection is demonstrated.

Contents

1. Method of spin-polarized neutron extraction
   in a laser-driven neutron source and laser-driven magnetic field.

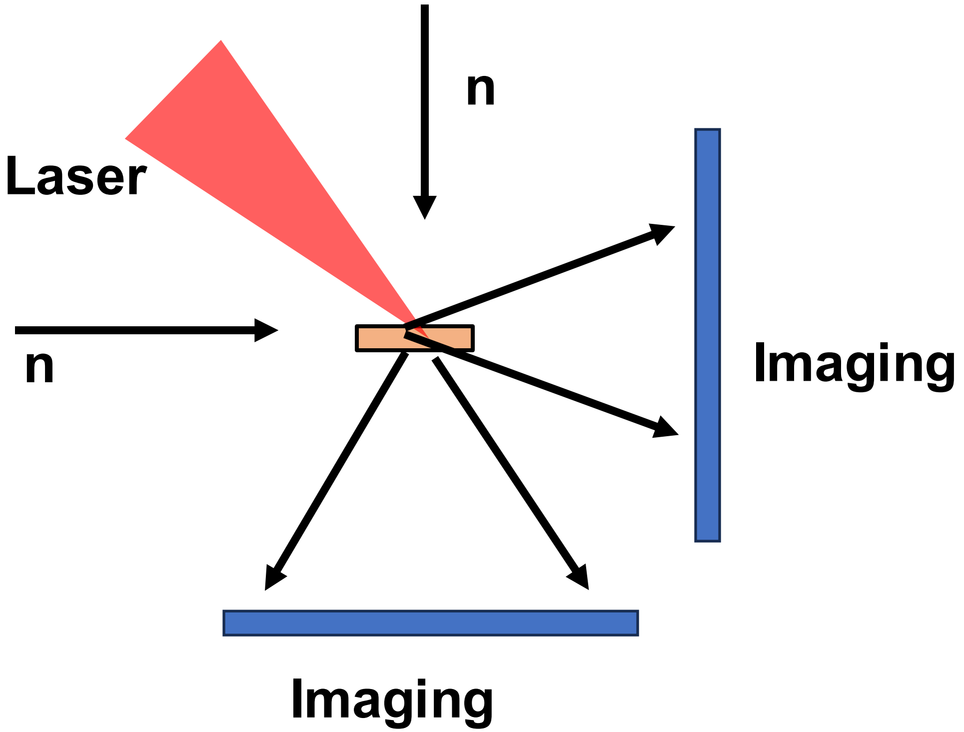
2. Experiment and analysis of detector for spin-polarized neutron
   in high-power laser is conducted at ILE, Osaka.

3. Future work

Future work
Spin-polarized neutron extraction experiment

Two ultra intense lasers
1. Generating thermal neutron generation.
2. Generating magnetic field.

3D scanning of magnetic field using spin-polarized neutron

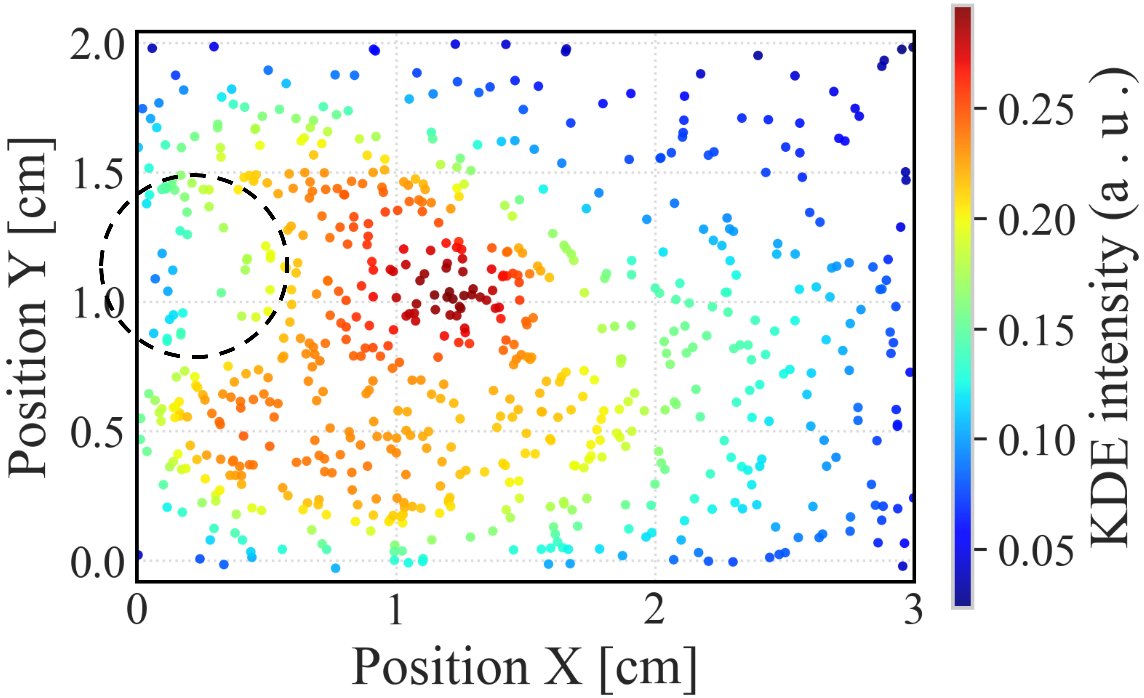


We will continue to develop the experimental setup.

Progress on laser-driven spin polarized neutron beam extraction

ILE, Osaka

- **Developing the detector for spin-polarized neutron**
- **Thermal neutron imaging has been successfully observed with CR-39 and ^{6}LiF from the attenuation rate of Hf.**



- **By using this detector, the spin-polarized neutron can be discriminated.**

Acknowledgement

- JST A-STEP (AS2721002c) and JST-Fusion Oriented Research for disruptive Science and Technology (Souhatsuteki Kenkyu Shien, Grant No. JPMJFR202K)
- This work was supported by JSPS KAKENHI Grant Number JP25K00983.
- This work was supported by JST SPRING, Grant Number JPMJSP2138.
- Grant-in-Aid for Scientific Research, the "PowerLaser DX Platform Project" (JPMXS0450300021) of the Ministry of Education, Culture, Sports, Scienceand Technology, and the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program, A.Advanced Research Networks (JPJSCCA20230003).
- This work was supported by “FiMEC”, JSPS KAKENHI Grant Number JP23K20038

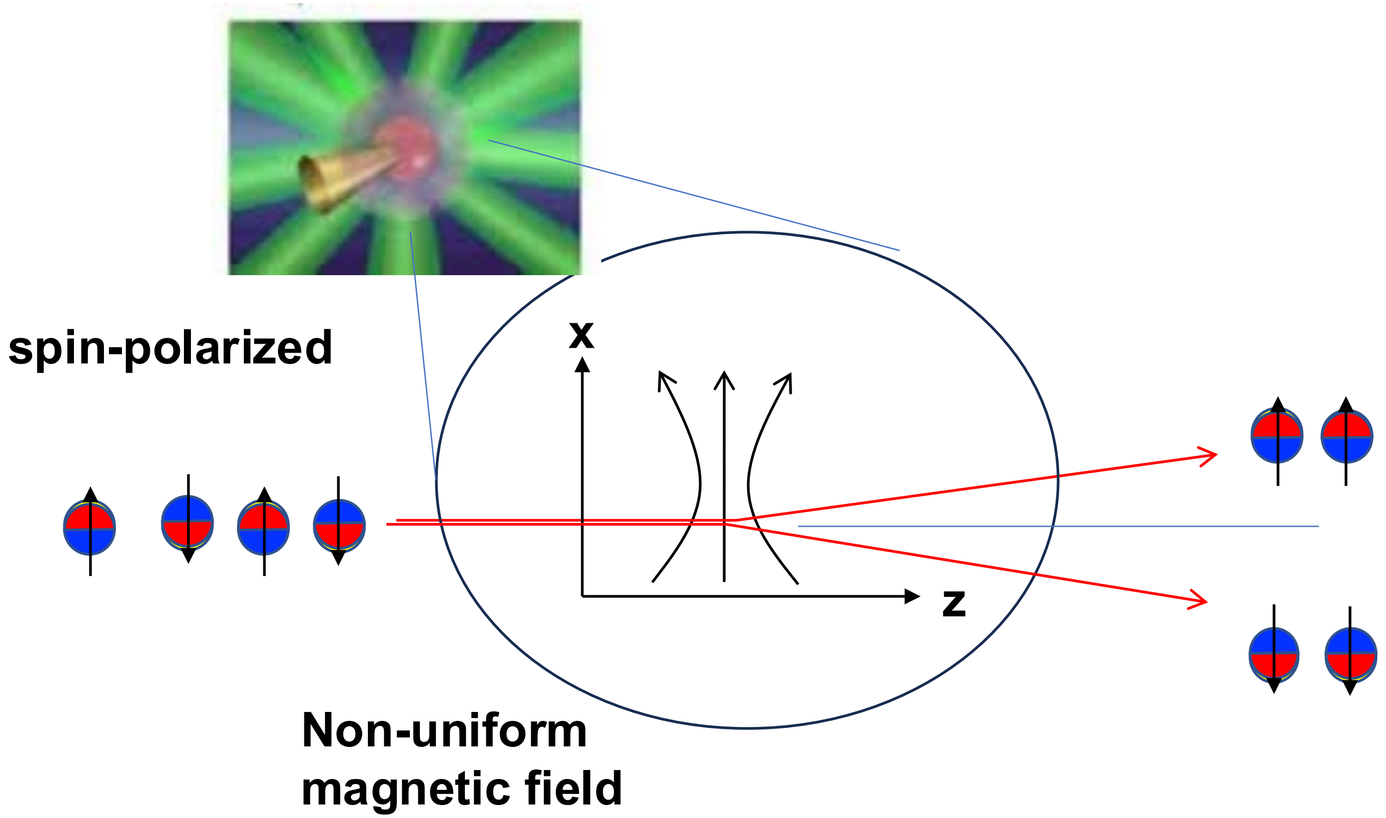
Thank you for your attention.

Application of spin polarized neutron in high density plasma. Imaging of laser-driven magnetic field.

ILE, Osaka

Features of neutron

- High transmittance
- Unaffected by electric fields, but affected by magnetic fields



Neutron can penetrate high der

Neutrons are deflected
by magnetic field gradient (θ ∝
while not affected by E-field.

Summary
Status on laser-driven spin polarized neutron generation

1. Spin-polarized neutron source has been expected to be unique particle source to diagnose magnetic field in the high-density plasmas.

2. The spin-polarized neutron can be extracted by using high power lasers.
   The split with ~1mm is expected for 1kT/10μm magnetic field.

3. As well as the generation,
   a diagnostics technique to discriminate the spin-polarized neutron is required.

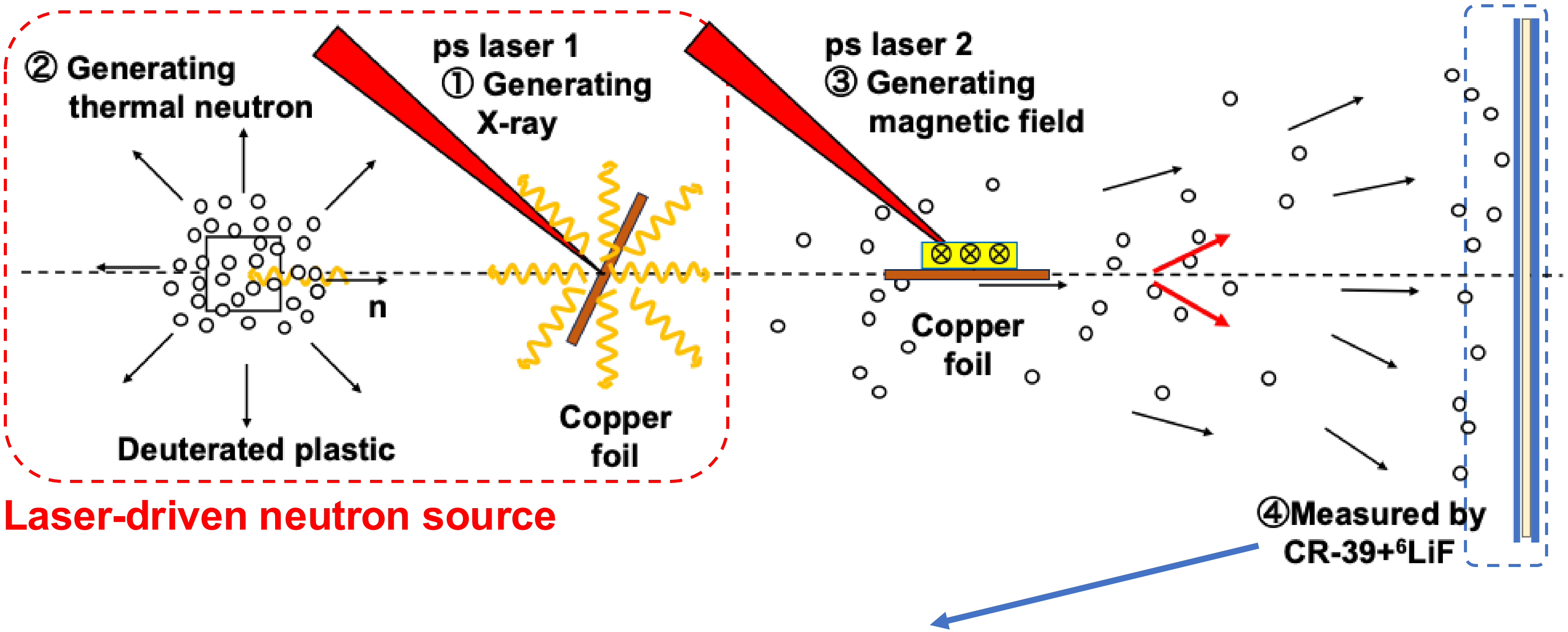
4. In this study a highly sensitive thermal-neutron detector
   by a combination of CR-39 and ^{6}LiF is developed.

5. Thermal neutron imaging has been successfully observed at the LFEX laser experiment.

6. The data represented enough spatial resolution and sensitivity
   for detecting the spin-polarized neutron.

Principle of the measurement.
High efficiency thermal neutron imaging detector is needed.

ILE, Osaka

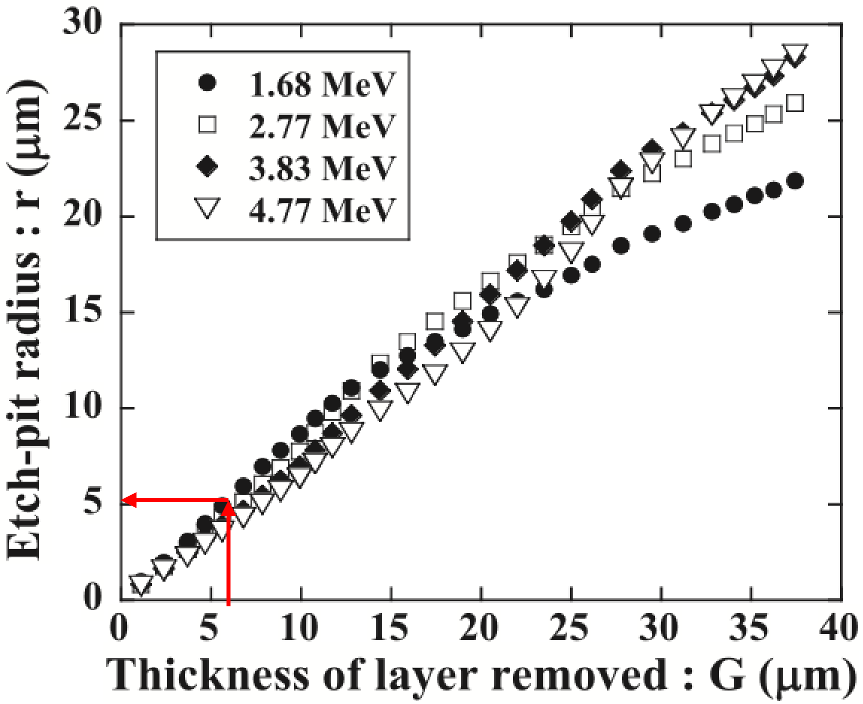


Requirement on the detection of spin-polarized neutron

1. Robust for noises (non-neutron particles and electro-magnetic pulse)
2. High efficiency for thermal neutron (~ 2.4%)
3. High spatial resolution (~ 1mm)
4. Large surface area

CR-39 + AI technique is introduced to discriminate neutron signal and backgrounds

Growth curve of pit size by the etching
Alpha particles

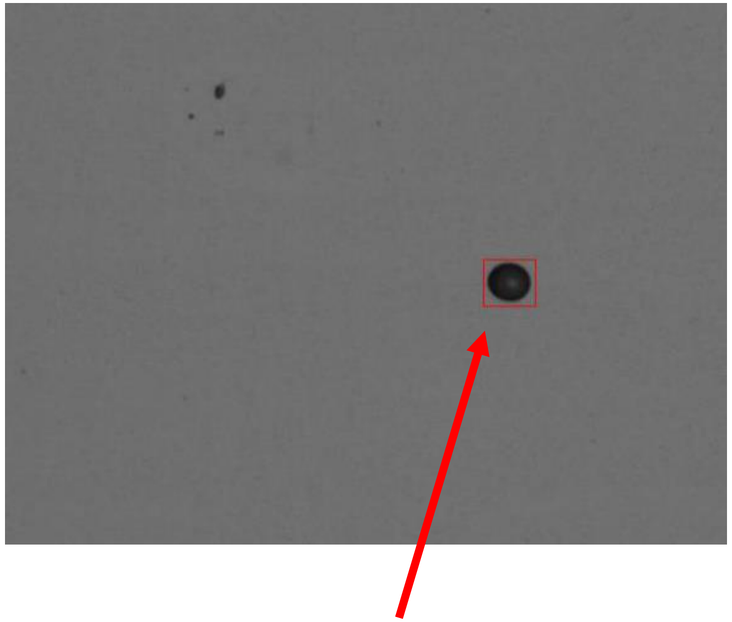


$^6Li + n \rightarrow \alpha + {}^3H + 4.79$ MeV

The energy of alpha particles is 2.05 MeV.

The pit size of
10~14 μm is the neutron induced α

Scan data on CR-39



Pits can be discriminated using deep learning

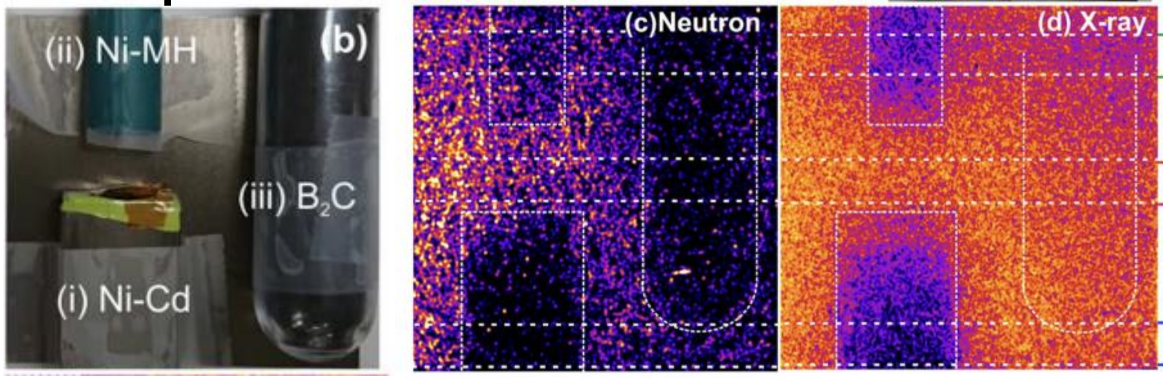
M. Kanasaki, et,al, J.Plasma Fusion Res 2012
T. Taguchi, et,al, Rev. Sci. Instrum. 2024.

Issues in the conventional thermal neutron detector.

ILE, Osaka

Activation measurement by Dysprosium using Imaging plate

The picture of samples | **Neutron imaging** | **X-ray imaging**

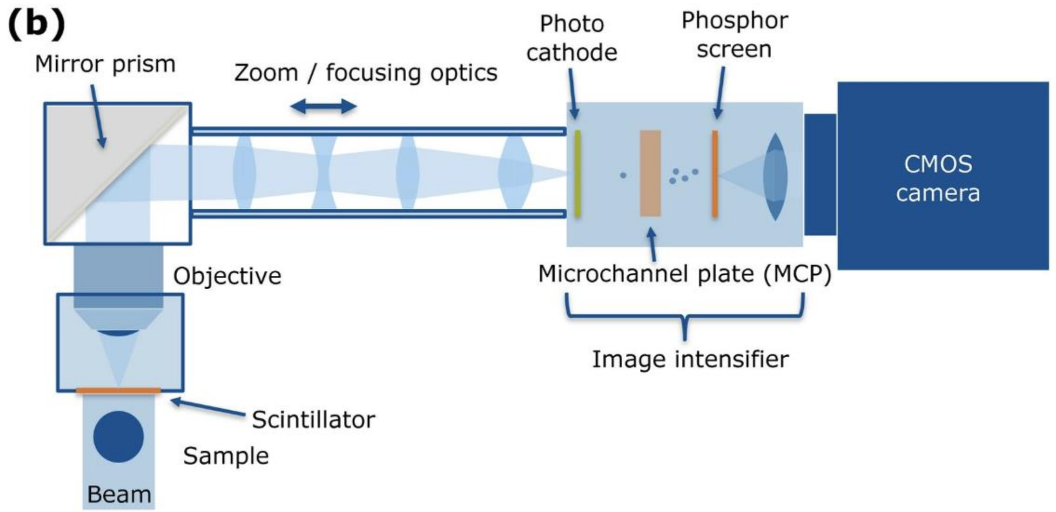


Merit: Easy setup, large area, sufficiently small background for non-neutrons (x-ray, electro-magnetic pulse)

Demerit: Small efficiency (activation to Imaging plate, Imaging plate fading,)

Akifumi Yogo, et,al, Applied Physics Express 2021

Detector with electricity (ICCD or CCD…)



Merit: High sensitivity

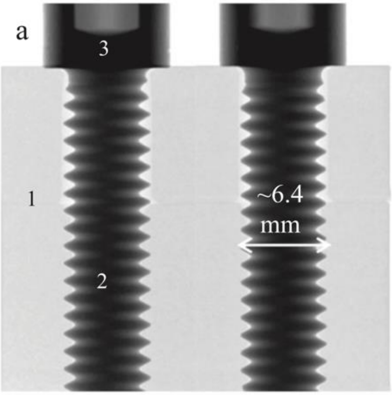
Demerit: Large noises on X-ray and electro-magnetic pulse, large electronics, it is hard to place it at close to the laser target.

Alex Gustschin, et,al, Scientific Reports 2024

Scintillator and ICCD methods have a noise issue.

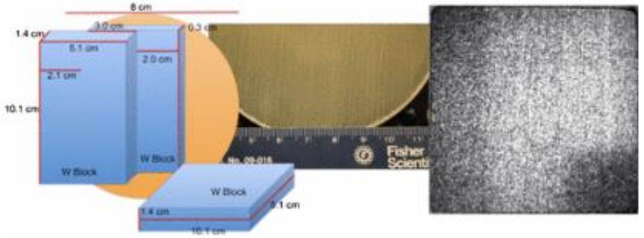
ILE, Osaka

High sensitivity scintillator detectors or MCP detectors



Accelerator-driven neutron source with MCP+CCD

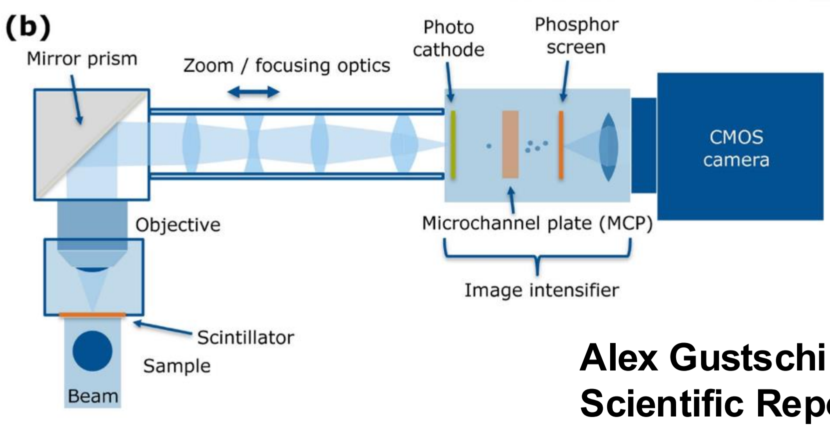
A. S. Tremsin, et,al,
Strain 2016



Laser-driven neutron source with Scintillator + ICCD

M.Roth, et,al,
Physical Review Letters 2013

Detector with electricity (ICCD or CCD…)

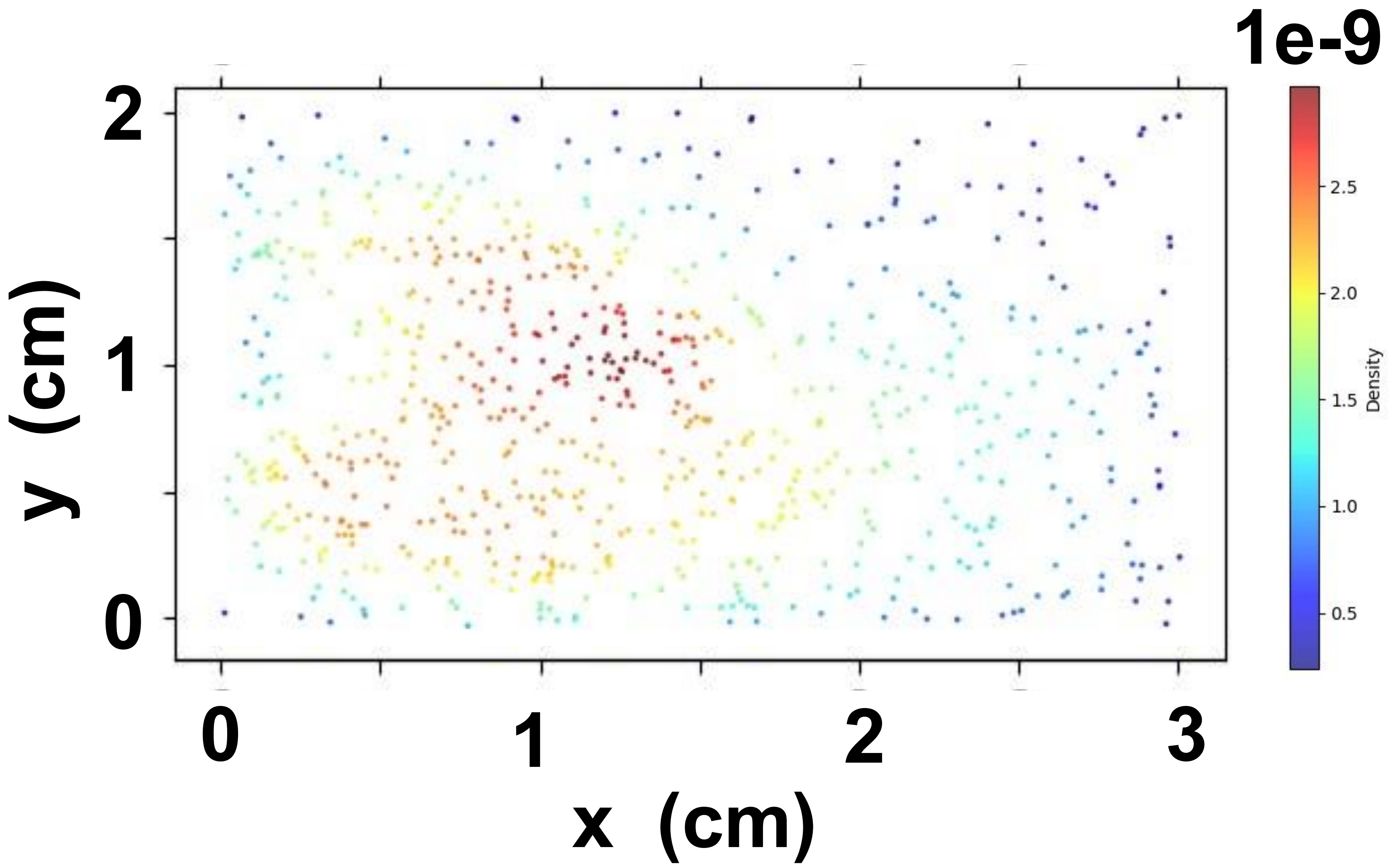


Alex Gustschin, et,al,
Scientific Reports 2024

Backgrounds from non-neutrons such as electrons, X-rays, protons, and electromagnetic noise are also issues to be removed.

Merit: High sensitivity

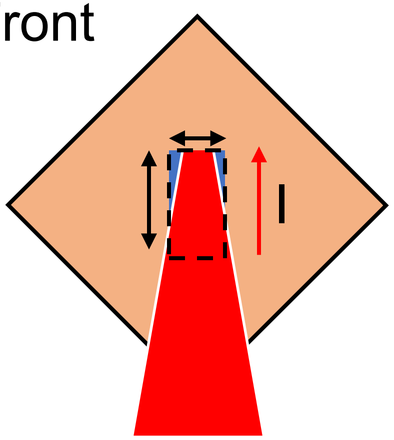
Demerit: Large noises on X-ray and electro-magnetic pulse, large electronics, it is hard to place it at close to the laser target. Small sensitivity.


1e-9
2
1
0
y (cm)
0
1
2
3
x (cm)
2.5
2.0
1.5
1.0
0.5
Density

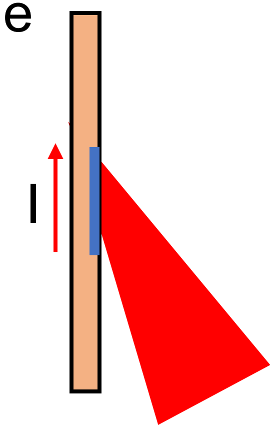
Order estimation of laser-driven surface current magnetic field by using nano second laser

ILE, Osaka

Front



Side



GEKKO laser condition: 1 kJ, 1.2 ns, 100 μm (spot size)

Laser intensity : 2.0 × 10^{16} W/cm^2,

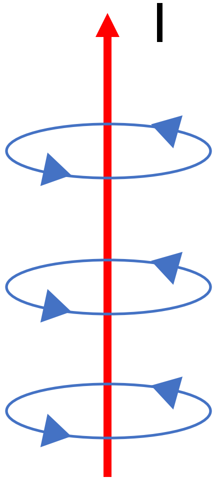
Electron energy: 2.04 keV

100 keV

Magnetic field generated by laser-driven recurrent

$$B = \frac{\mu_0 I}{2\pi r}$$

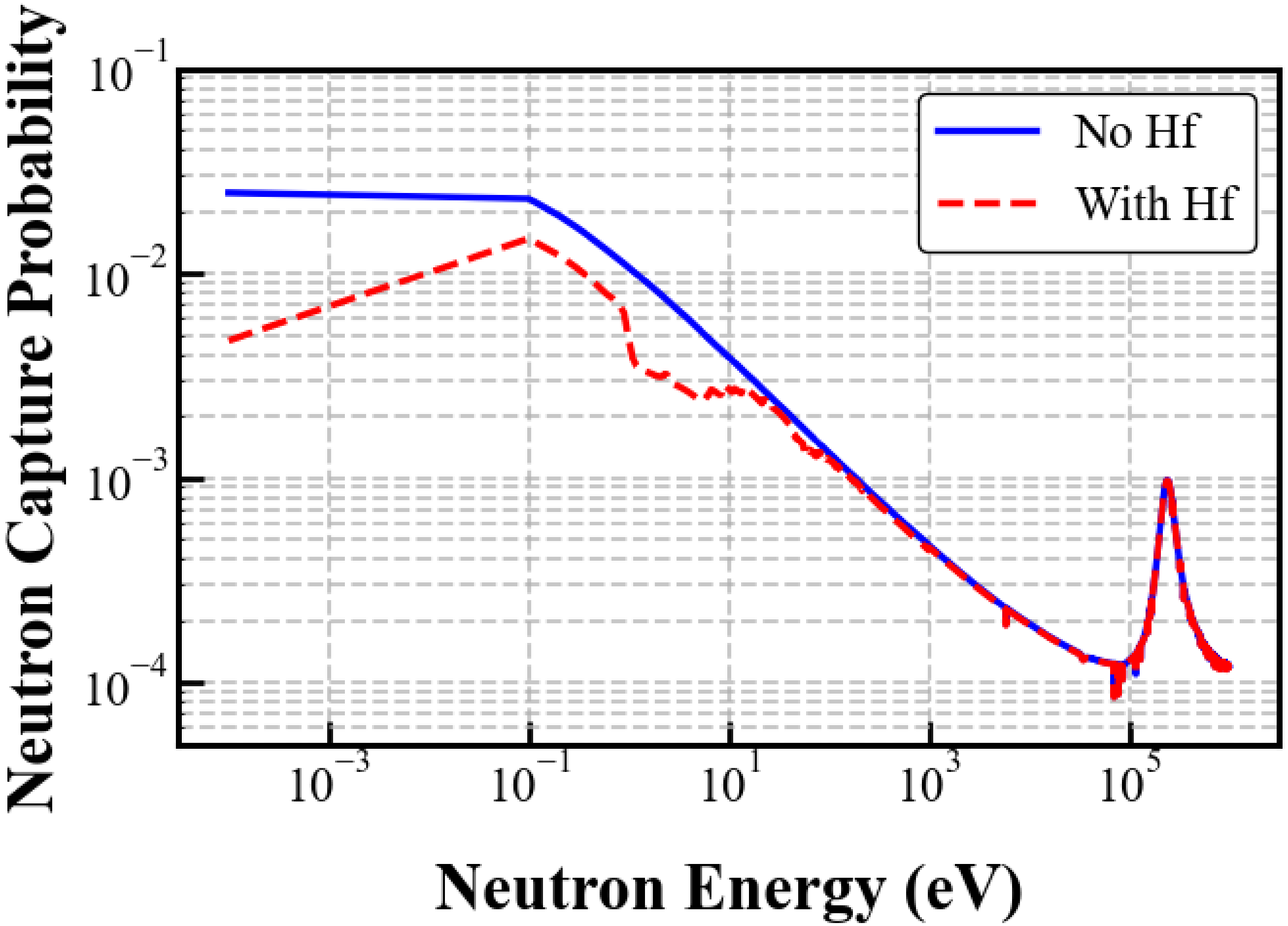
***r* = 2.35 μm (skin depth)**

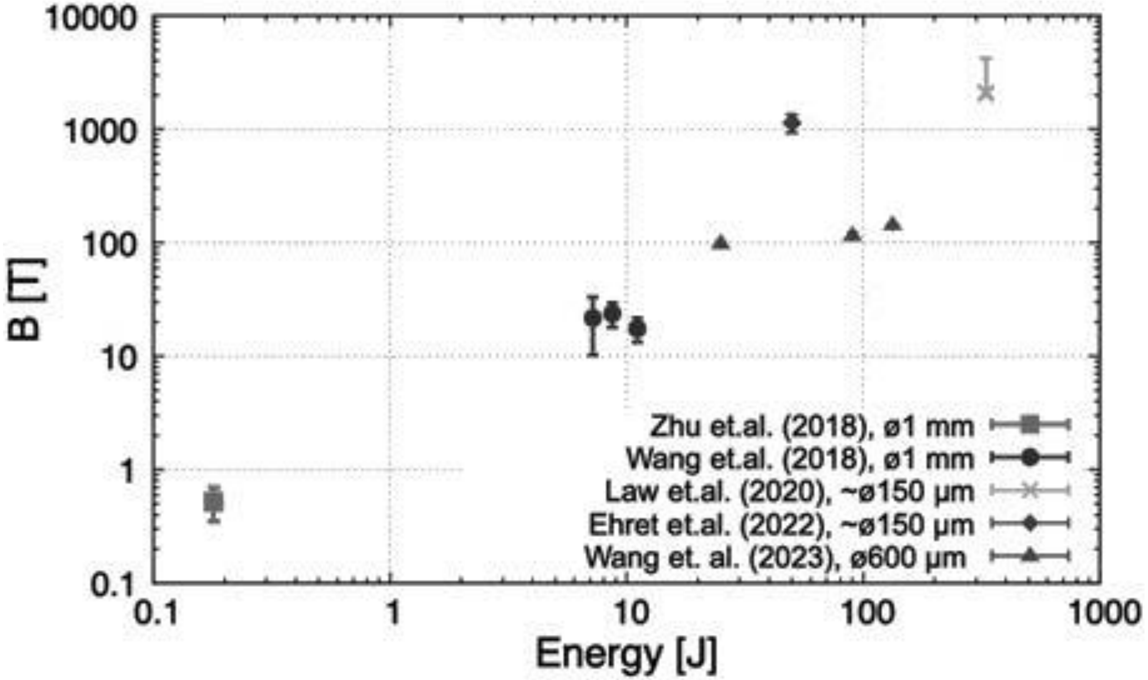


About electron Using ponderomotive force

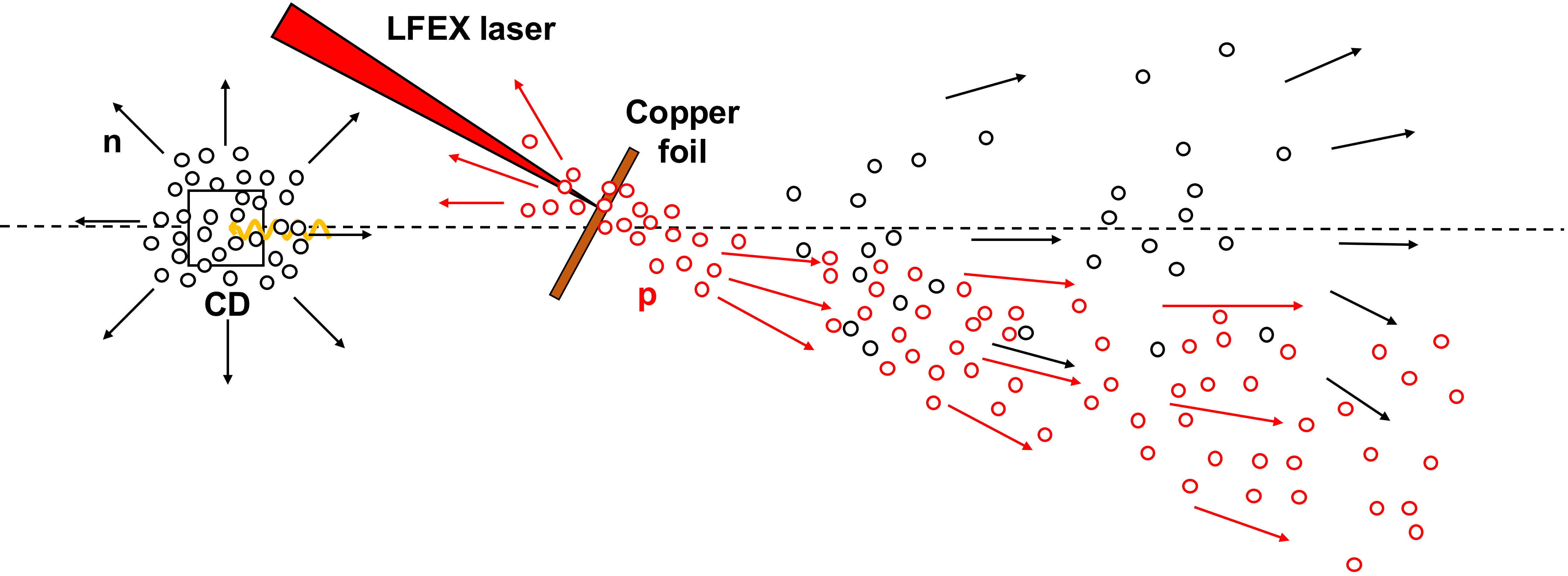
- ***Number: 1.217 × 10^{15}***
- ***Current: 1.949 × 10^5 A***

B = 16 kT

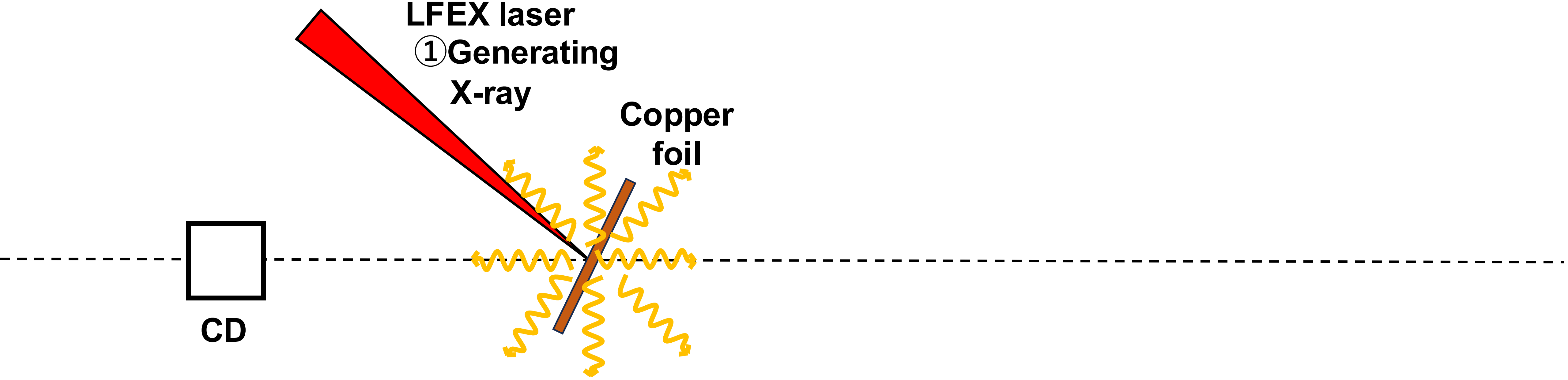

Neutron Capture Probability
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
Neutron Energy (eV)
No Hf
With Hf


10000
1000
100
10
1
0.1
B [T]
0.1
1
10
100
1000
Energy [J]
Zhu et.al. (2018), ø1 mm
Wang et.al. (2018), ø1 mm
Law et.al. (2020), ~ø150 µm
Ehret et.al. (2022), ~ø150 µm
Wang et. al. (2023), ø600 µm

Discussion
Why are there two distributions?

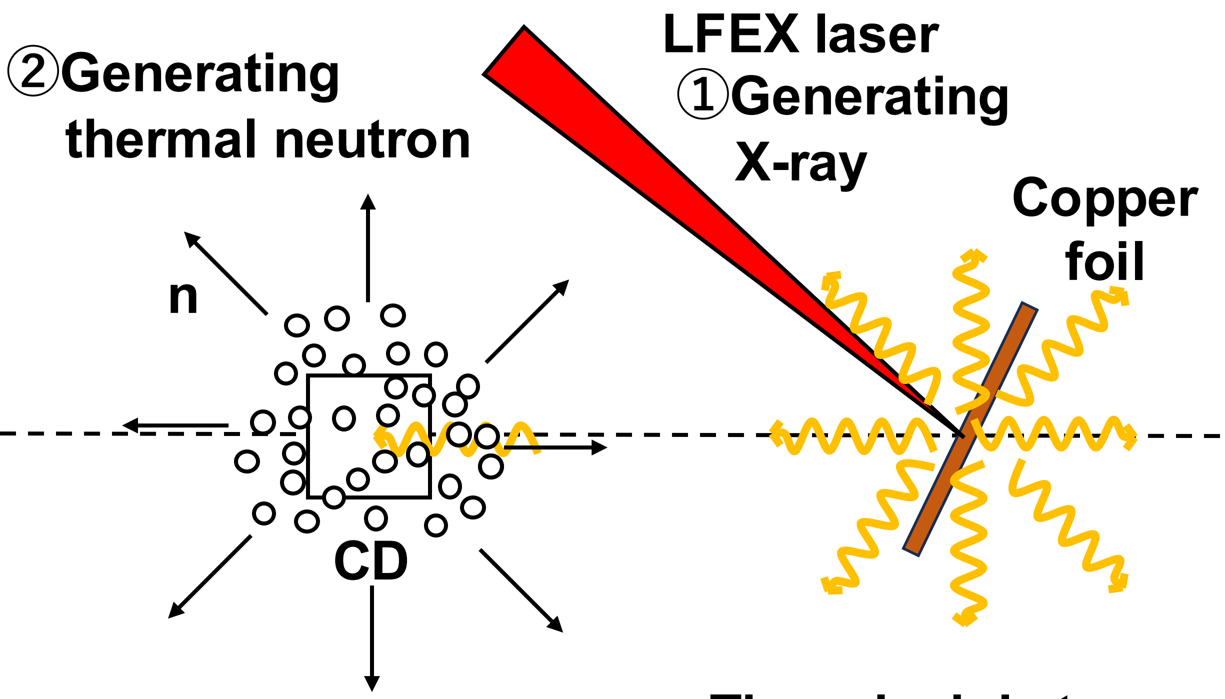


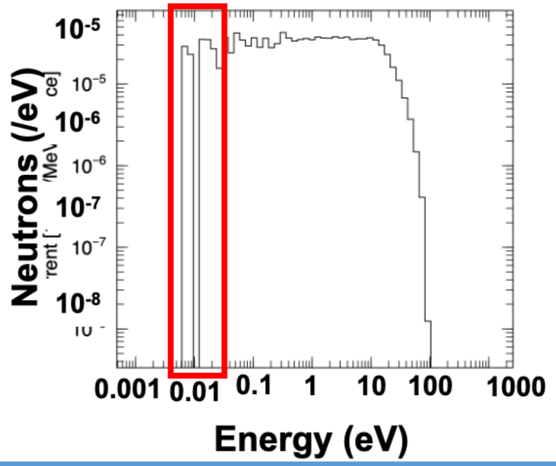
Principle of the measurement (1/3)



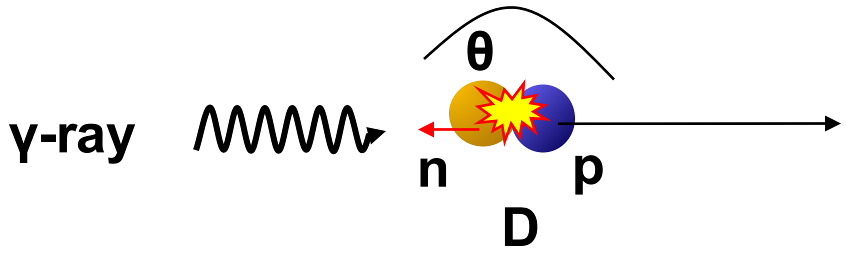
Principle of the measurement (2/3)

ILE, Osaka





The principle to generate the thermal neutron by photonuclear reaction



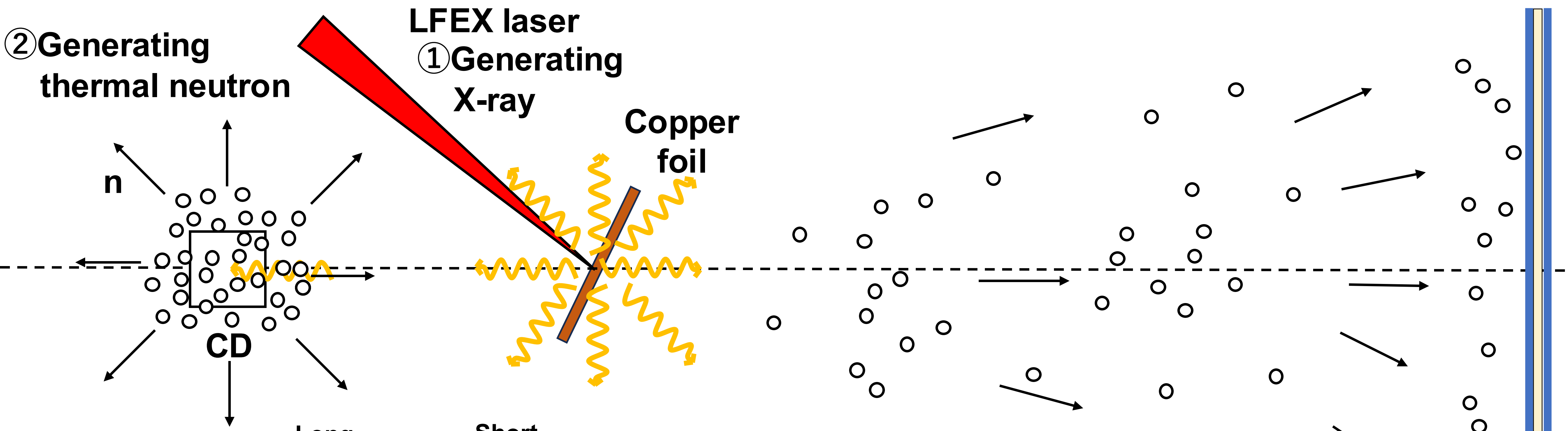
Point source
No moderator

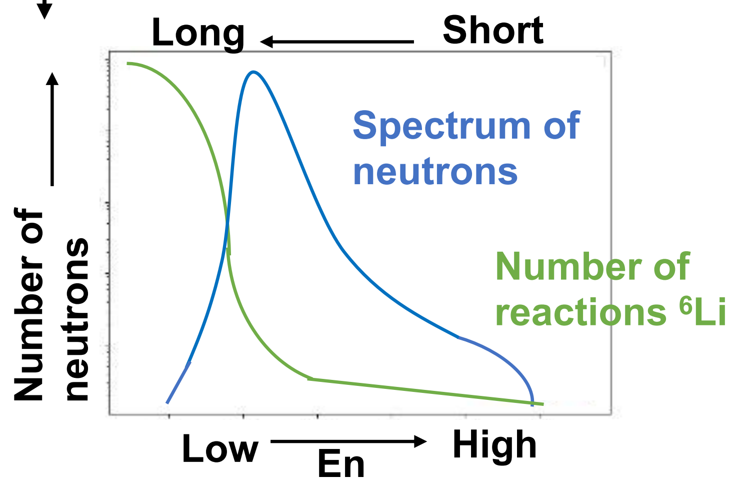
Direct generation of thermal neutrons

Thermal neutrons are emitted in the opposite direction of X-ray

Principle of the measurement (3/3)

ILE, Osaka





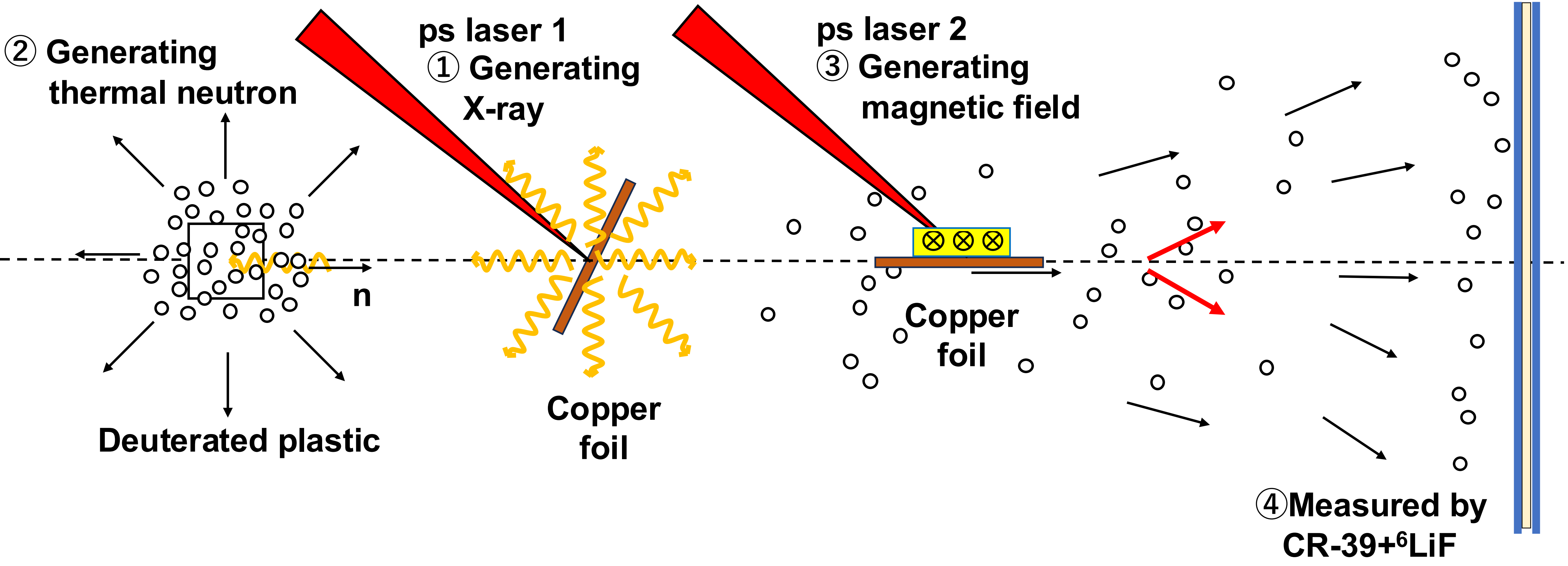
^{6}Li is high-sensitive to thermal neutrons.

$$n + {}^{6}Li \rightarrow T + \alpha$$

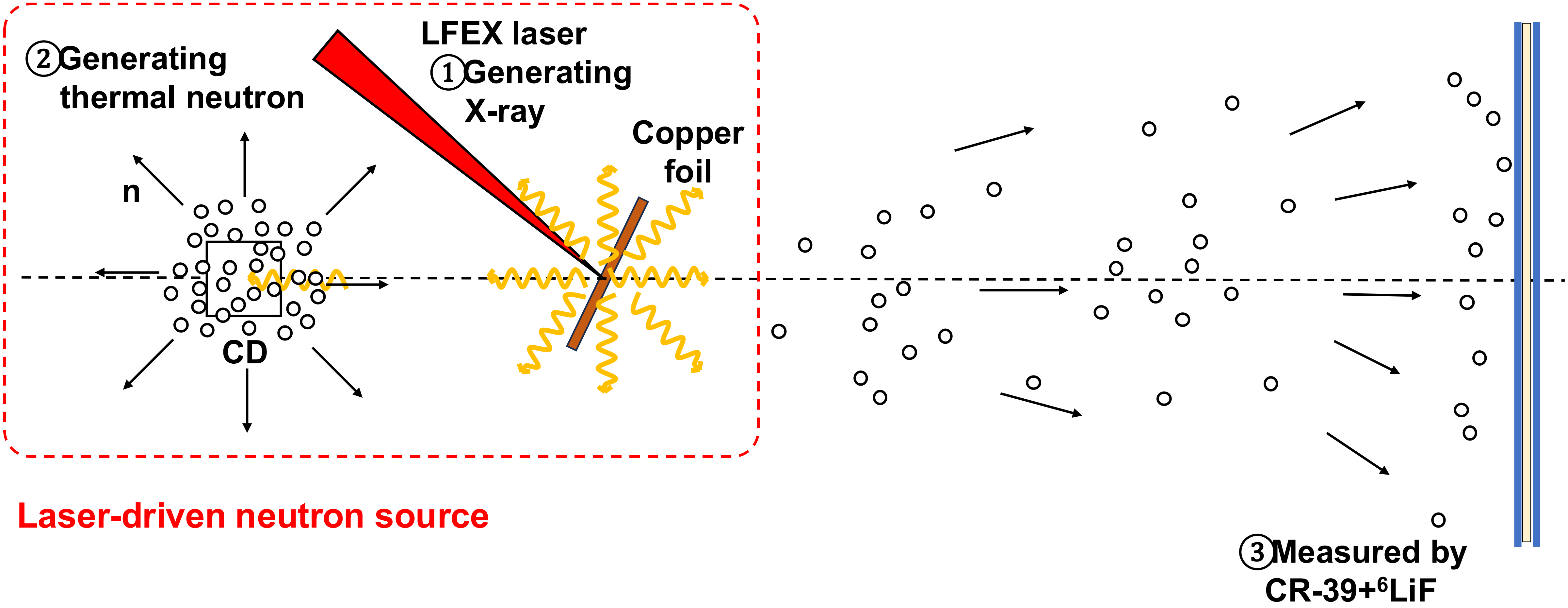
CR-39 detects α

The filter has been set up in front of the measurement.

Principle of the measurement (3/3)



Principle of the measurement



Laser-driven neutron source