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U.S. DEPARTMENT OF ENERGY

BNCT lithium beam driver

The project started FY2023

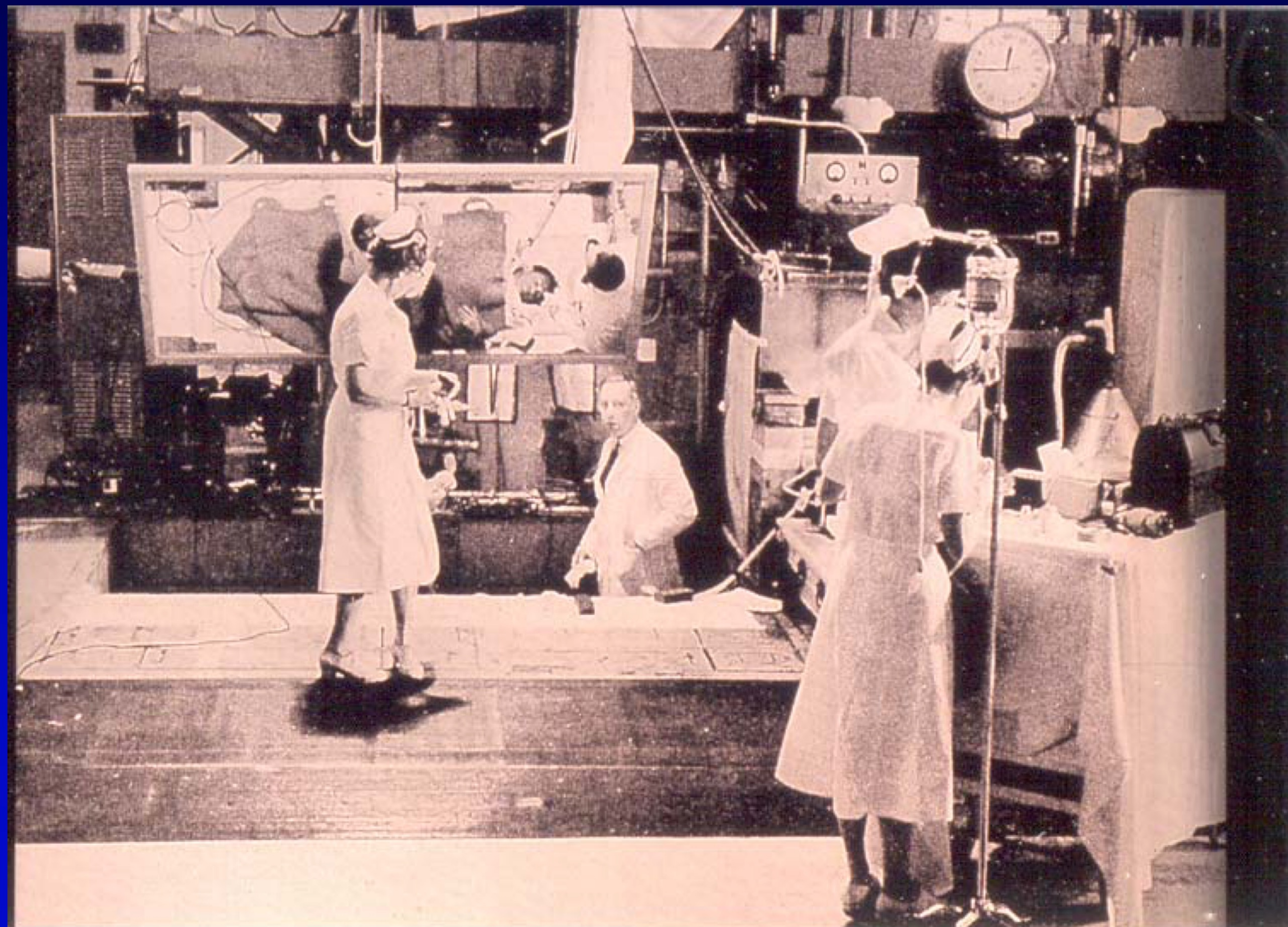
Many requests for participation.
ANSTO, GSI, Wollongong Uni., Science Institute of Tokyo, Okayama Uni., Osaka Uni., Nagaoka UT, Columbia U. Darmstadt tech.

Multiple invited talks.

Masahiro Okamura

Dec. 17, 2024

BNCT Clinical Trial: ~1953



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BGRR Clinical Trial: 1951-1959

BNCT Clinical Trial: 1959-1961

Brookhaven Medical Research Reactor

Beam shutter

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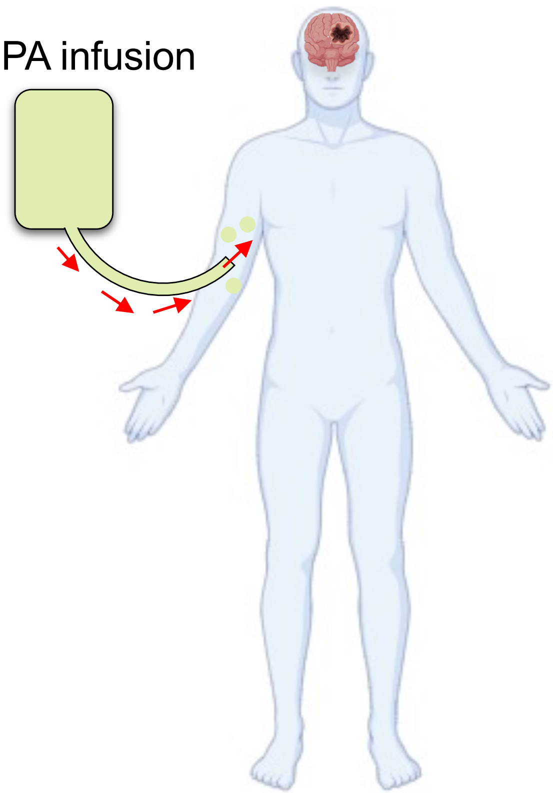
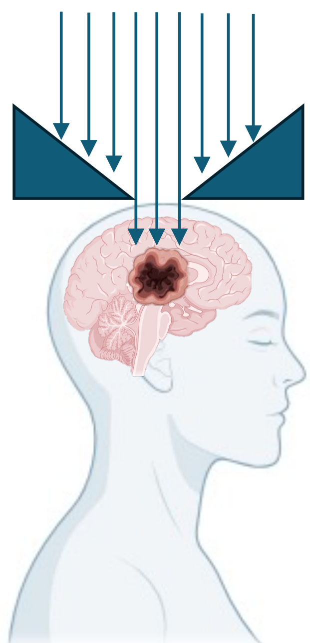
Background

Boron Neutron Capture Therapy (BNCT)

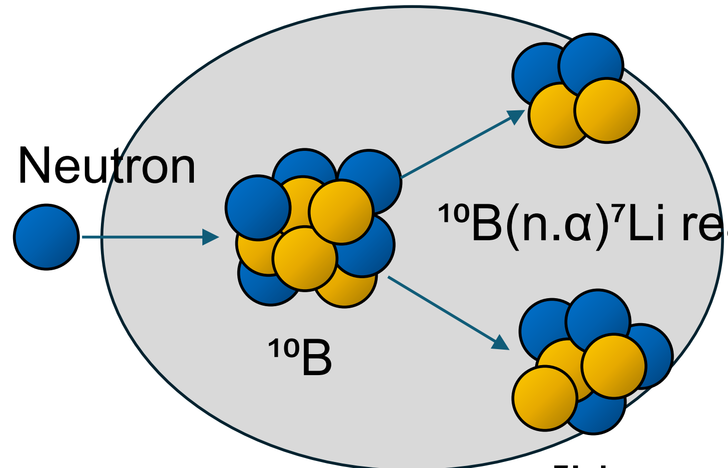
1. Boron compound IV infusion



2. Neutron beam irradiation



3. Transmuted particles destroy tumor cell nuclei



- Neutron Beam reacts with boron-10
- Destroy tumor cells from inside
- Safety passes through surrounding tissue
- Treatment time ~ 1 hour

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BNCT is one of the promising applications of the compact neutron source using an intense Li ion beam driver.

Neutron generators with proton driver

- Neutron generation with Li or Be target
- 2 - 30 MeV proton energy
- 10 – 30 m long
- Higher neutron flux compared with other types of compact sources

Example of application: Accelerator Based-BNCT(AB-BNCT) *1

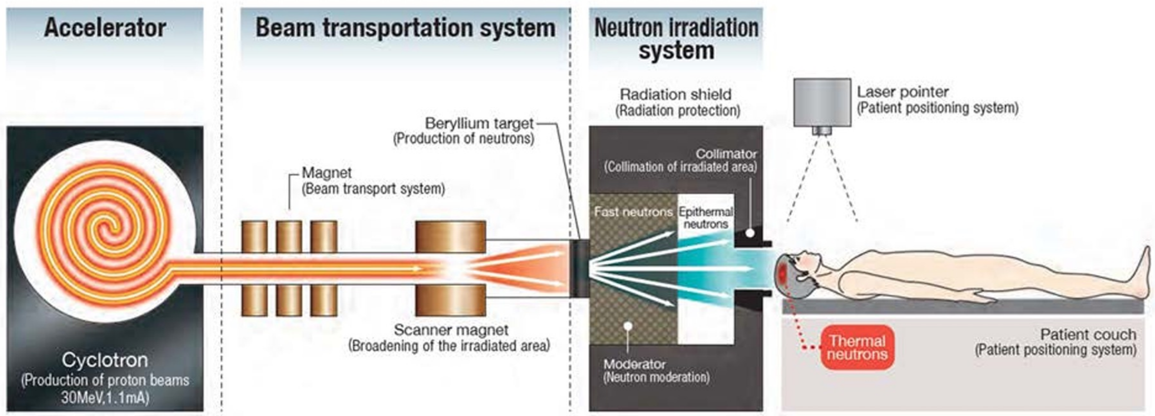


FIG. 1. Schematic diagram of an AB-BNCT system showing the principal components of the accelerator, beam transport, and the target and moderator inside the shielded neutron irradiation system (beam shaper assembly) emitting a therapeutic neutron 'beam' for a carefully positioned patient (courtesy of Osaka Prefecture, Japan).

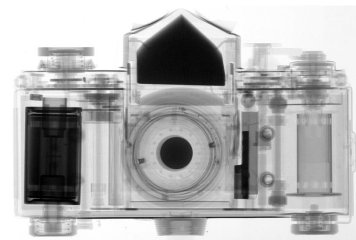
*1 International Atomic Energy Agency (IAEA), "Advances in Boron Neutron Capture Therapy", 2023

Background

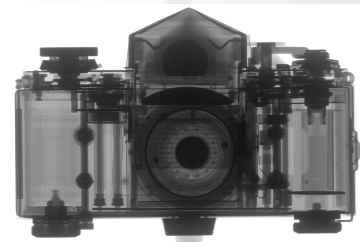
Demand for compact accelerator driven neutron generator

Recently, as nuclear reactors are being retired, compact accelerator driven neutron generators are getting more desired.

Radiography *1



Neutron imaging



X-ray imaging

No reactor

- Updating the reactors has been prevented by nuclear non-proliferation policies and the impact of past accidents

Low cost

- Spallation source is expensive and machine time is limited

Wide range of applications

- Nondestructive inspection
  - Residual stress in train rails and aircraft parts
  - Hidden failures of buildings and bridges
  - Cargo inspection
  - Neutron imaging
- Boron neutron capture therapy (BNCT)
- Detector development

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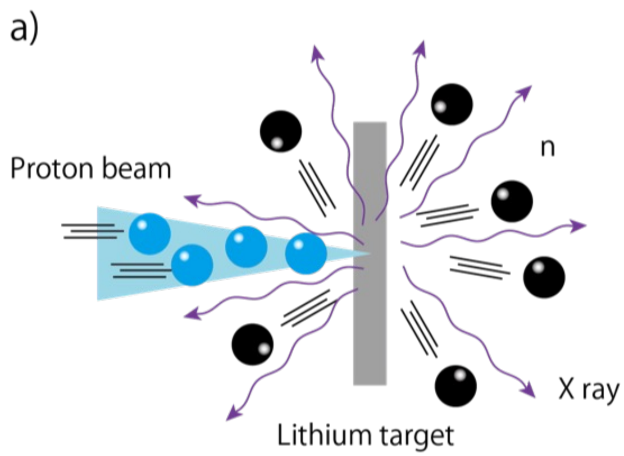
*1 Web page of the Paul Scherrer Institute (PSI), https://www.psi.ch/en/niag/what-is-neutron-imaging
*2 Web page of Japanese Society of Neutron Capture Therapy (JSNCT), http://www.jsnct.jp/e/about_nct/

Inverse kinematics

Neutron production with proton beam



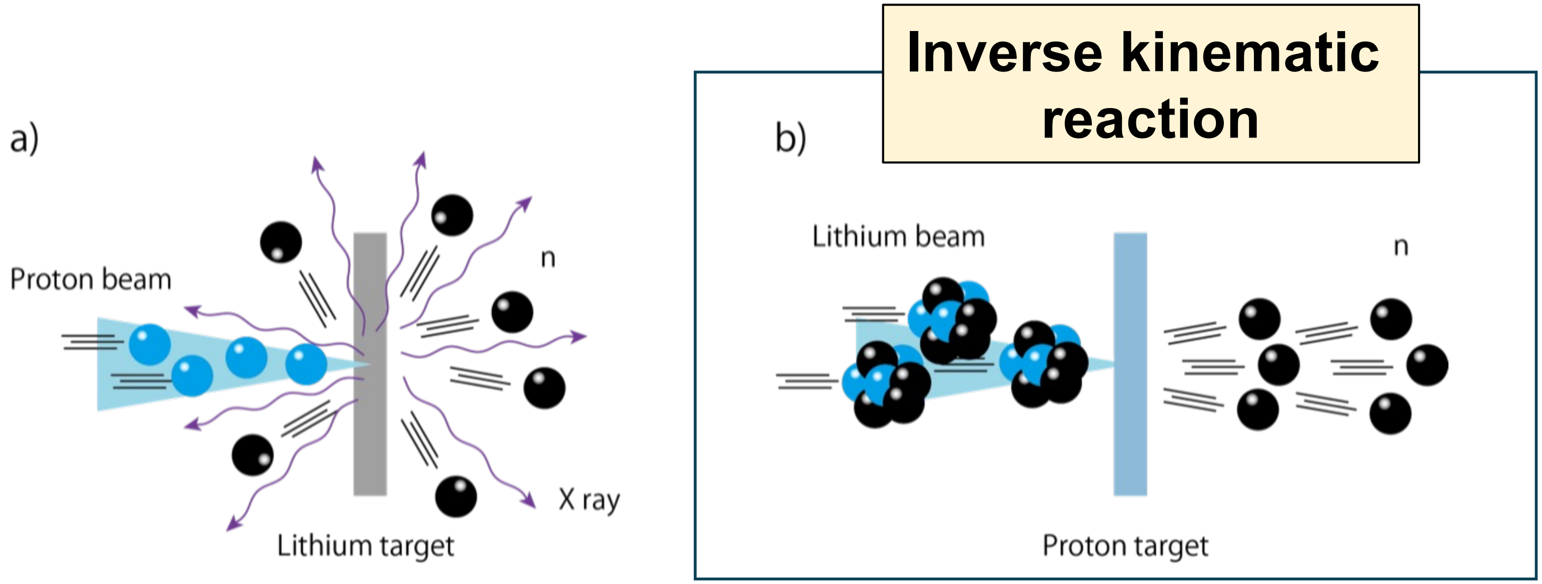
$$^{7}\mathrm{Li} + \mathrm{p} \rightarrow {}^{7}\mathrm{Be} + \mathrm{n} - 1.64\ \mathrm{MeV}$$
$$^{9}\mathrm{Be} + \mathrm{p} \rightarrow {}^{9}\mathrm{B} + \mathrm{n} - 1.85\ \mathrm{MeV}$$

Y. Zuo, et al, "Neutron yields of thick Be target bombarded with low energy deuterons"

- These reactions are endothermic and undesired radiations could be small if beam energy is near the thresholds.
- However, since the proton is lighter than the target atoms, the neutrons are produced in the 4 π direction and only a small fraction can be used for the application.

Background

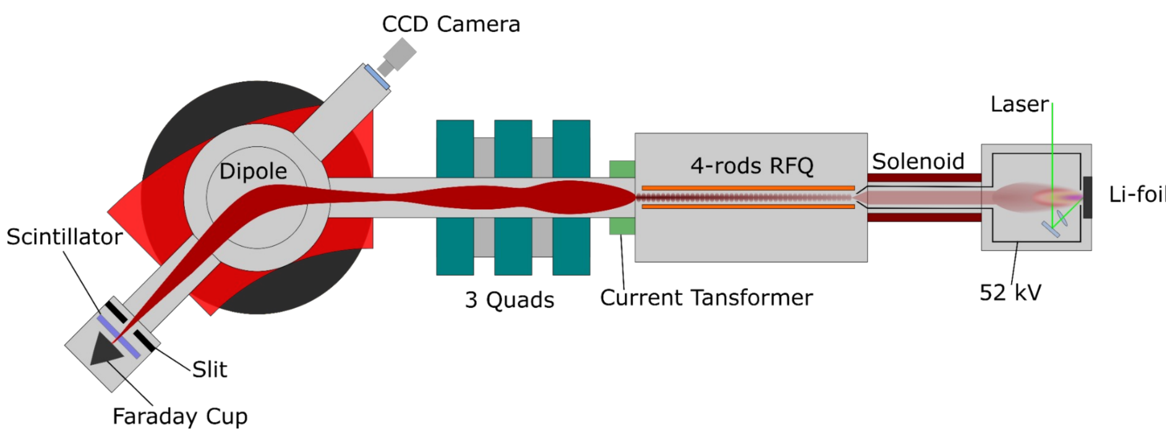
Neutron source with Li ion driver

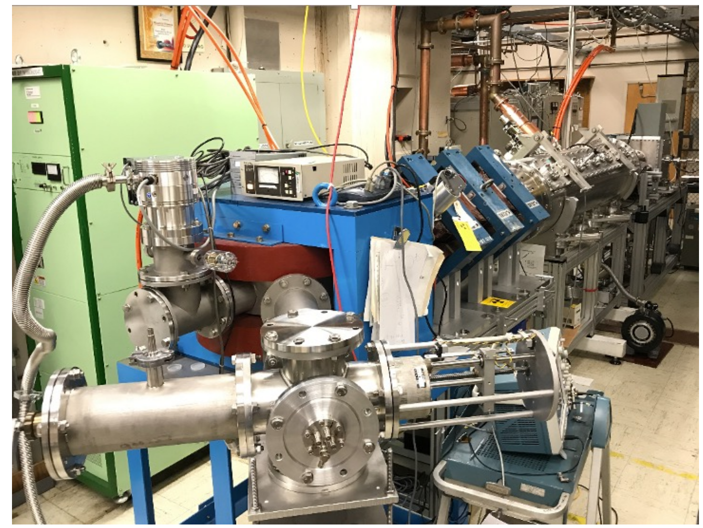


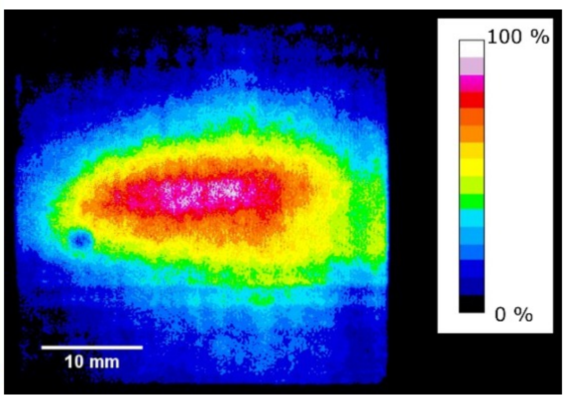
- If heavy ions are injected, neutrons are directed to forward because of the high gravity center velocity.
- Neutron flux at large angles is reduced drastically
- Smaller number of unwanted radiation and smaller shielding -> clean neutron source

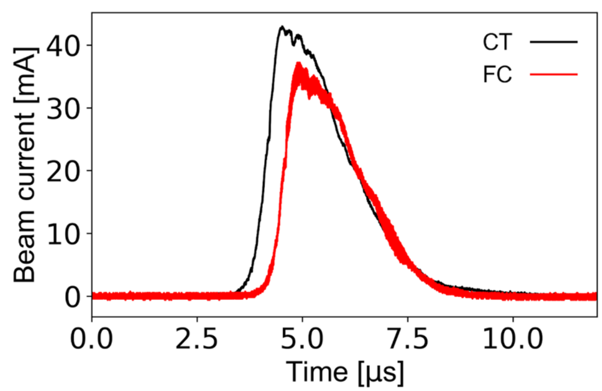
Background

Success of 35 mA beam acceleration by first stage accelerator (RFQ linac)







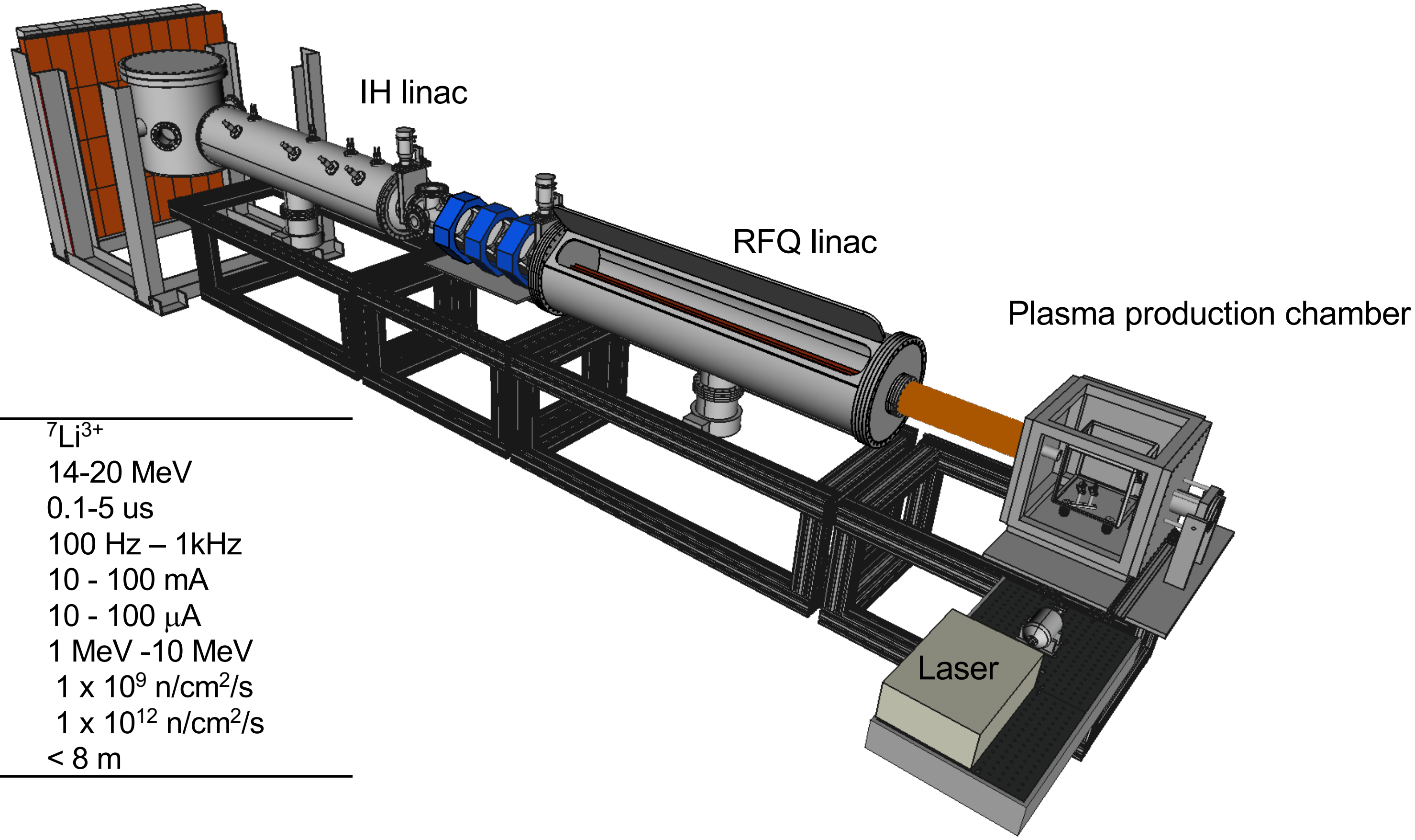


35 mA of $^{7}Li^{3+}$ was accelerated (world record).

Tandem ~ μA, ECR ~ mA

*1 M. Okamura, et al. Demonstration of an intense lithium beam for forward-directed pulsed neutron generation. Sci. Reports 12, DOI: 10.1038/s41598-022-18270-0 (2022). Publisher: Nature Research.

Compact neutron source using intense Li ion beam driver



Ion	$^{7}Li^{3+}$
Ion beam energy	14-20 MeV
Beam pulse width	0.1-5 us
Repetition rate	100 Hz – 1kHz
Peak ion beam current	10 - 100 mA
Average ion beam current	10 - 100 μA
Neutron energy	1 MeV -10 MeV
Average neutron flux	1 x 10^{9} n/cm^{2}/s
Peak neutron flux	1 x 10^{12} n/cm^{2}/s
Length	< 8 m

Advantage1: Forward-directed neutrons = very small number of unwanted neutrons, small shielding
Advantage2: Short beam pulse = Background separation by TOF method

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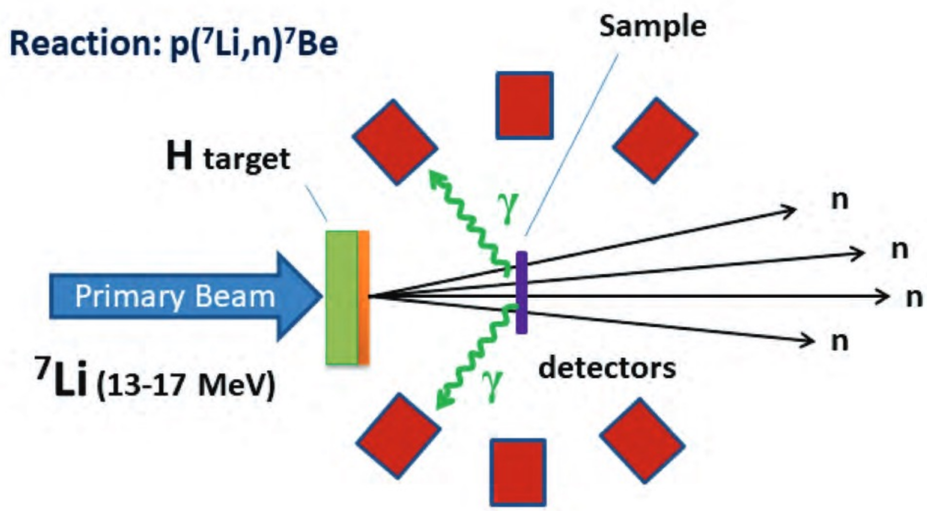
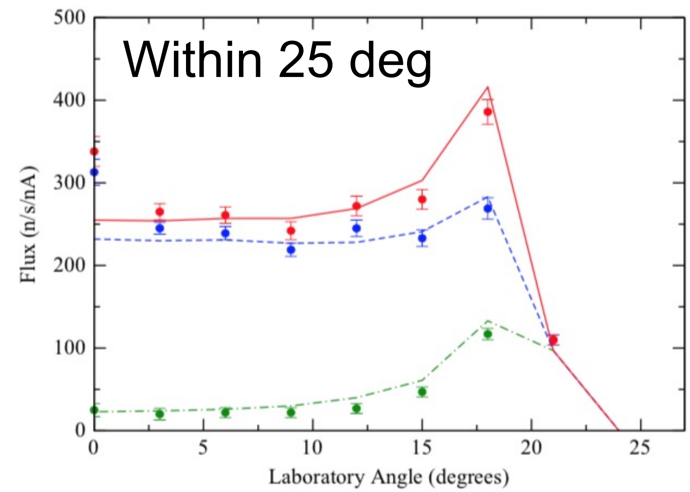
The LICORNE at ALTO in France





Angular distribution of neutron flux

10^7/sr/s

- Advantage

The kinematic focusing technique clearly offers some distinct advantages over standard isotropic quasi-monoenergetic sources:

1. The focusing enhances the available neutron flux by a factor of between 25 and 100.
2. The lack of neutron emission at most angles results in much lower fast and thermal scattered neutron backgrounds in the experimental hall.

- Disadvantage (conventionalheavy ion machine)

available beam current of ^{7}Li is much lower than that available for protons in the non-inverse reaction, because of the relative difficulty of extraction of ^{7}Li-ions from the ion source. Secondly,

Proton ~ mA, Tandem ~ nA, ECR ~ μA

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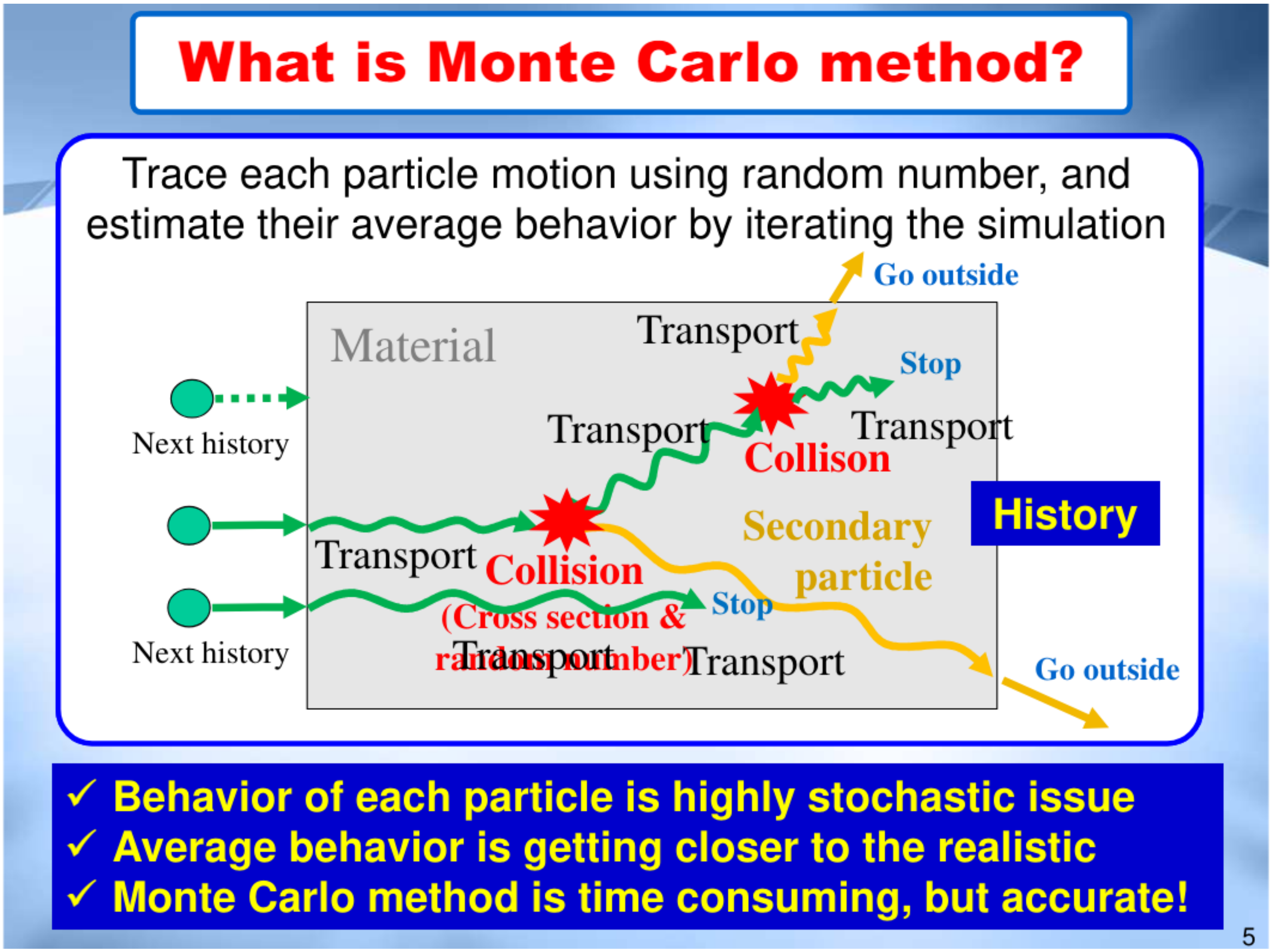
*1 chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.in2p3.cnrs.fr/sites/institut_in2p3/files/page/2020-04/3-Pres-LEBOIS_ld.pdf
*2 M. Lebois *et al.*,*Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 735, pp. 145–151, 2014.

Recent activity – Simulation study –

For the design of an accelerator-based neutron source, we are aiming to reproduce the neutron source by using Monte Carlo Method. (in progress)



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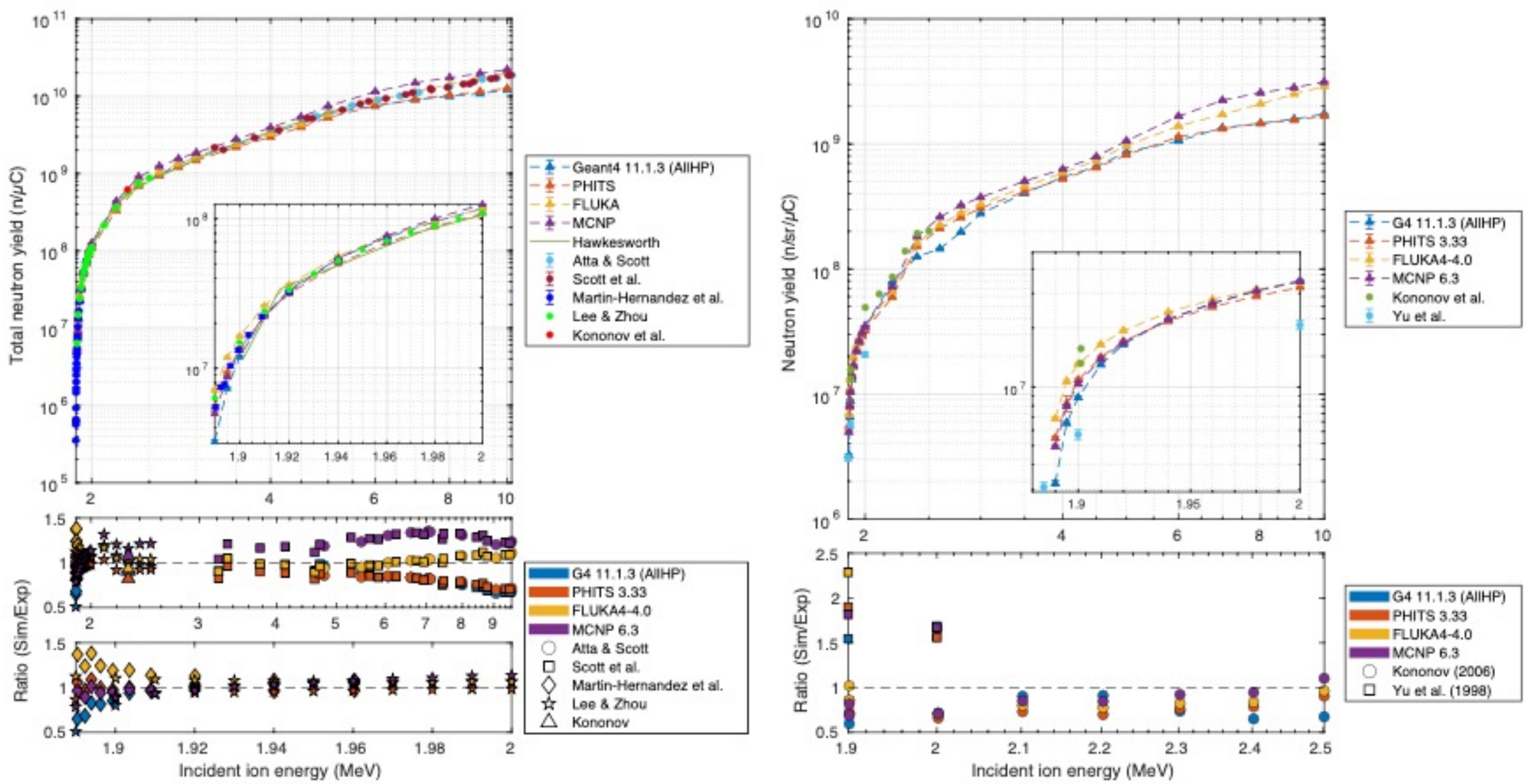
https://phits.jaea.go.jp/lec/phits-introduction-en.pdf

Example of Proton Driver case



(a) Total yield **(b)** Yield at 0°

Figure 5. Neutron yield for the $^{7}Li(p,n)^{7}Be$ reaction from incident proton energies of 1.89 MeV to 10 MeV. (a) Total neutron yield from each MC code compared to reference data from Hawkesworth [51], Atta and Scott [58], Scott [59], Martin-Hernandez et al. (2019) [60], Lee and Zhou (1999) [61] and Kononov et al. (2006) [62]. (b) Neutron yield in the forward direction ($\theta = 0°$) from each code is compared to reference data from Kononov et al. (2006) [62] and Yu et al. (1998) [63].

Provided by Sherryn McLeod (ANSTO/Wollongong U.)

Example of Lithium Driver case

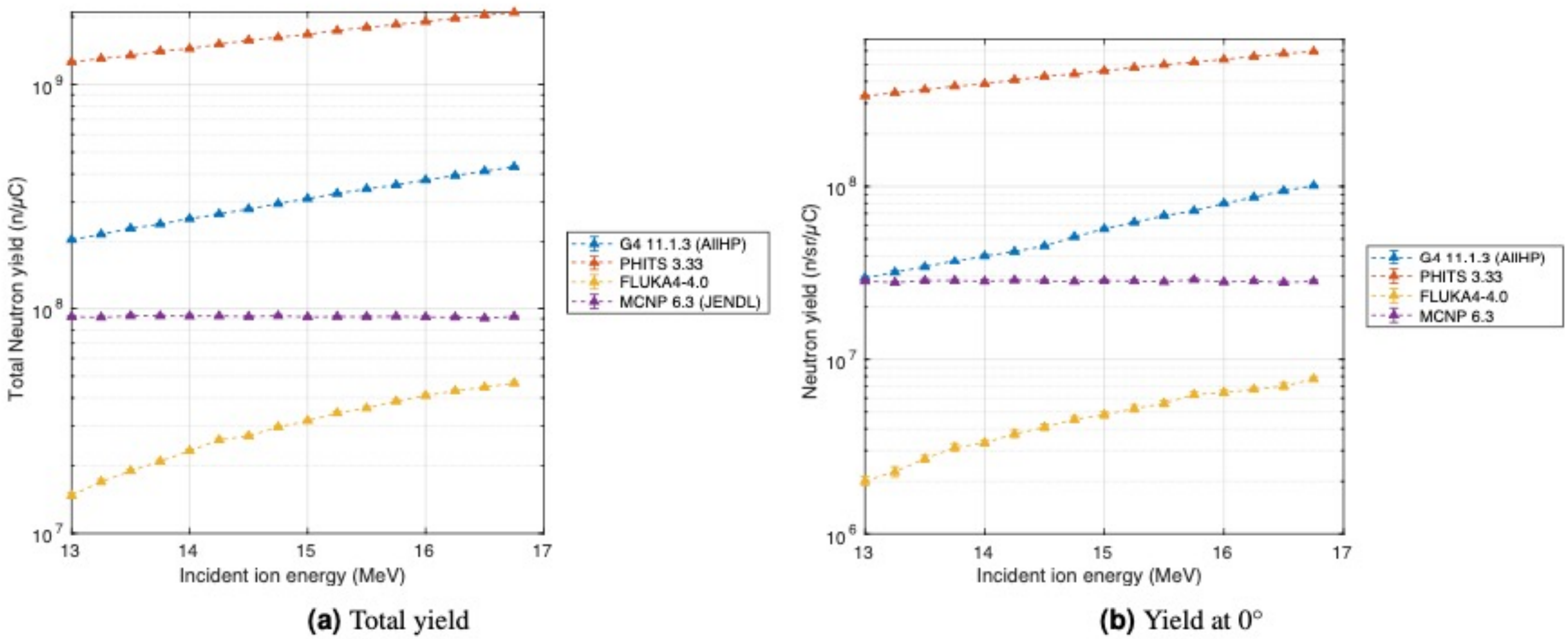


Figure 8. Neutron yield for the p(^{7}Li,n)^{7}Be reaction from incident lithium ions with energies ranging from 13 MeV to 16.5 MeV. Li ions of charge 3+ have been used to calculate yield, in accordance with the Li beam reported by Okamura et al. [19]. (a) Total neutron yield. (b) Neutron yield in the forward direction ($\theta = 0$).

None of the software could simulate

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Provided by Sherryn McLeod (ANSTO/Wollongong U.)

Recent activity – Simulation study –

<Configuration>

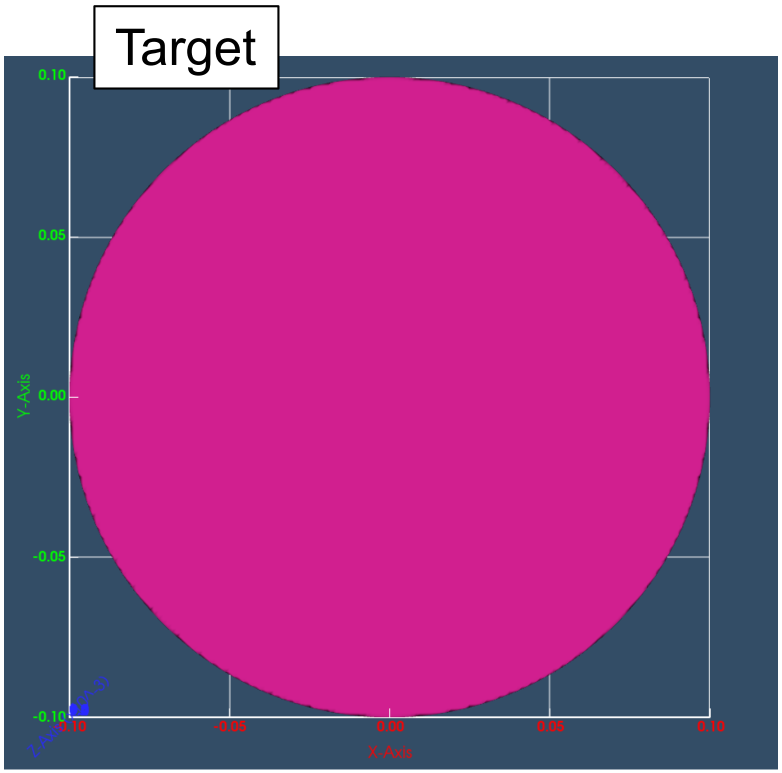
<u>Basic configuration for this study</u>

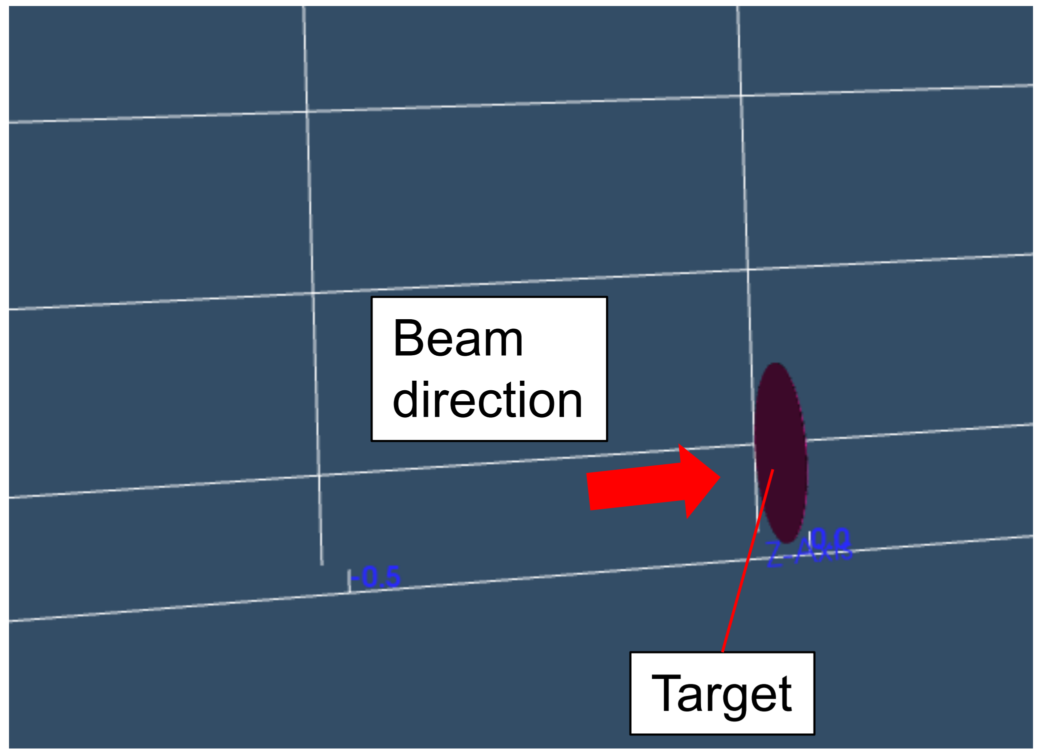
Target material: Polypropylene $(C3H6)n$, Density: 0.9 g/cm^3

Target thickness: 12 μm

Beam specie: Li^{3+},

Beam energy : 13, 13.5, 14, 15, 16, 17, 18, 19, 20, 26, 30, 40, 50, 56 MeV



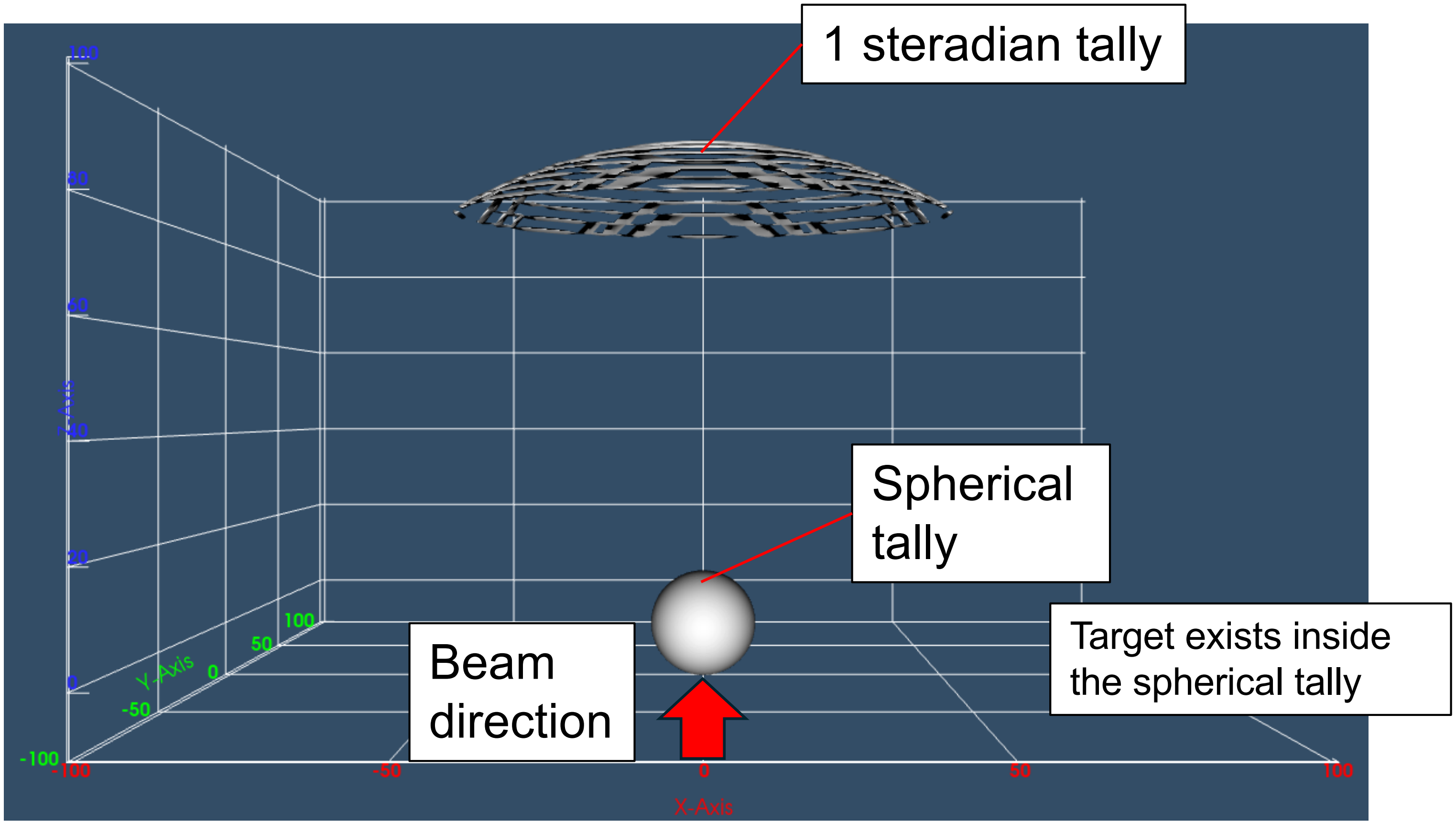


Recent activity – Simulation study –

<Configuration>

<u>Other tallies in the simulation</u>

The spherical tally and the 1 steradian tally are also defined.
The target exists inside the spherical tally.



Recent activity – Simulation study –

<Configuration>

Basic information for this simulation

The inverse kinematic reaction between Lithium and proton, p (Li^7, n) Be^7, generates neutrons. When neutrons are generated, Be-7 is also generated.

The threshold energy for this reaction is 13.098 MeV.

At first, this study evaluates the difference between nuclear reaction models on neutron production.

The nuclear reaction models that can be used in PHITS code

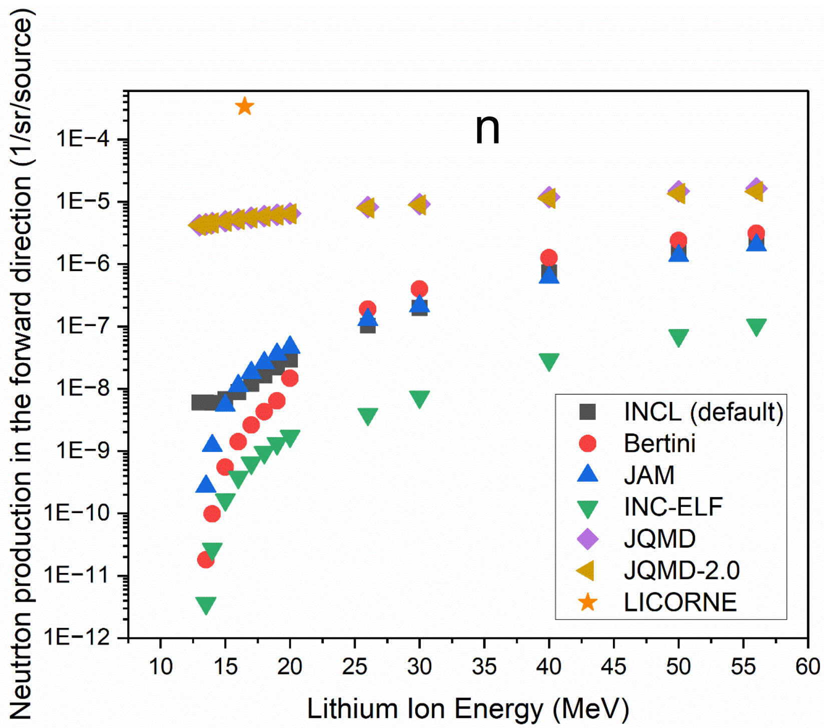
- INCL (default)
- Bertini
- JAM
- INC-ELF
- JQMD
- JQMD-2.0

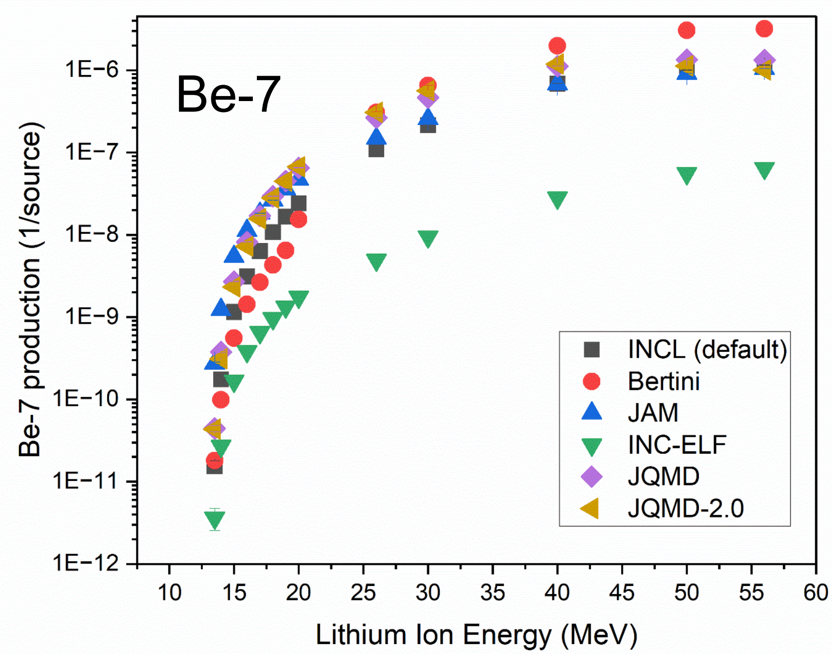
Recent activity – Simulation study –

PHITS
Particle and Heavy Ion Transport code System

<Result>

Neutron production in the forward direction (1 sr cone) and Be-7 production in each nuclear model.





Neutron production and Be-7 production are much lower than the experimental value in the prior study.

Additionally, large discrepancies are observed among the nuclear reaction models.

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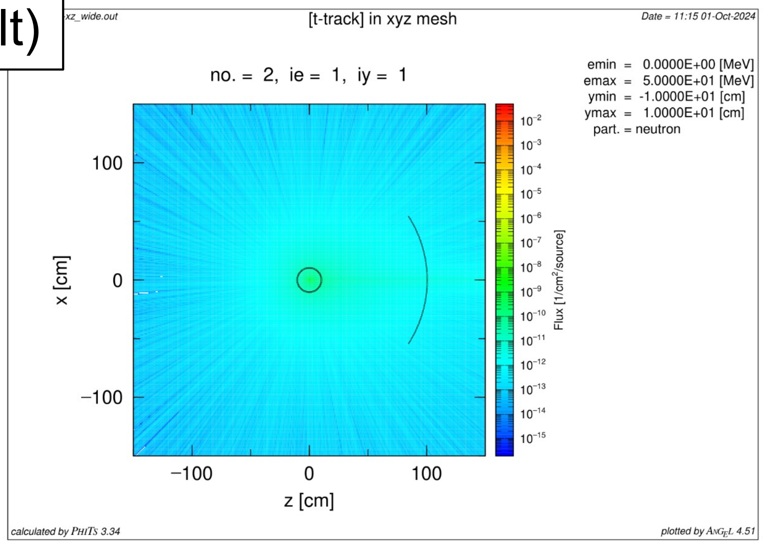
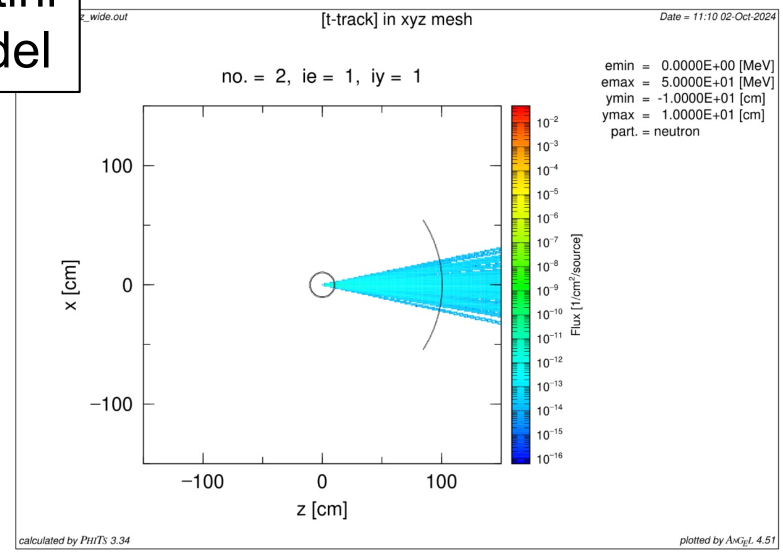
Recent activity – Simulation study – <Result>

Neutron distribution in each nuclear model. (Beam energy: 14 MeV)

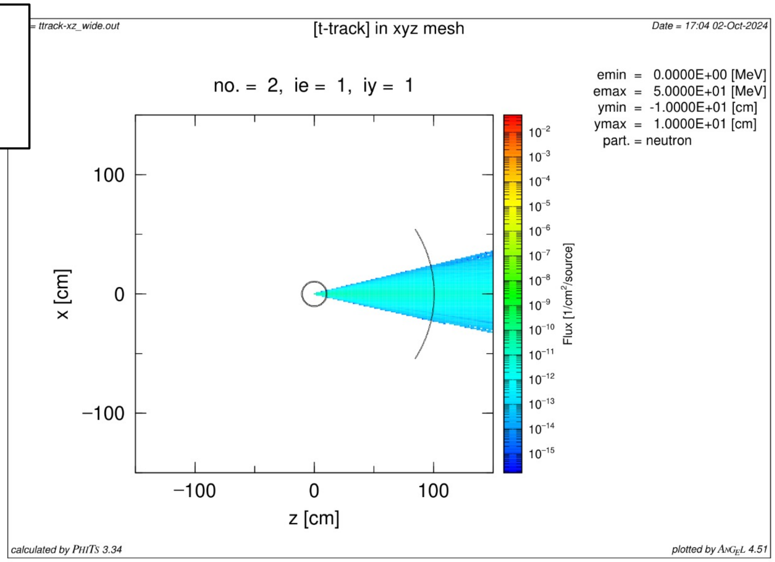
INCL
(default)



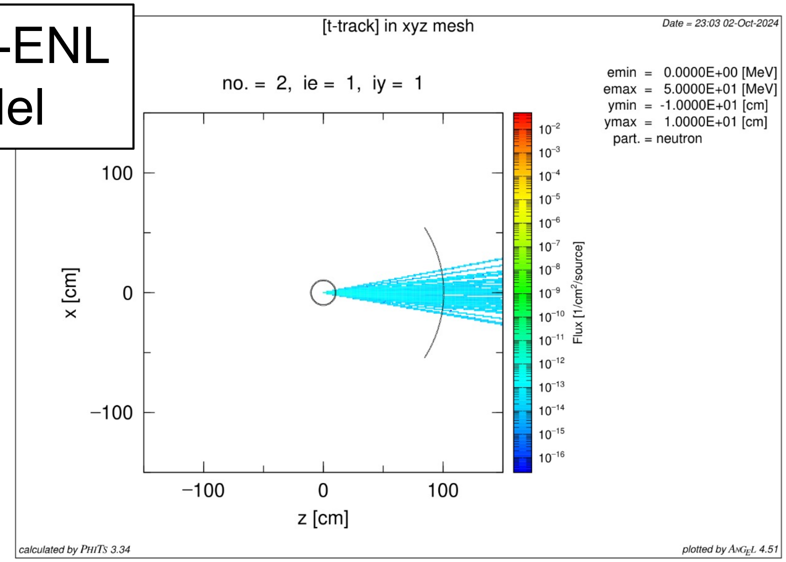
Bertini
model



JAM
model



INC-ENL
model

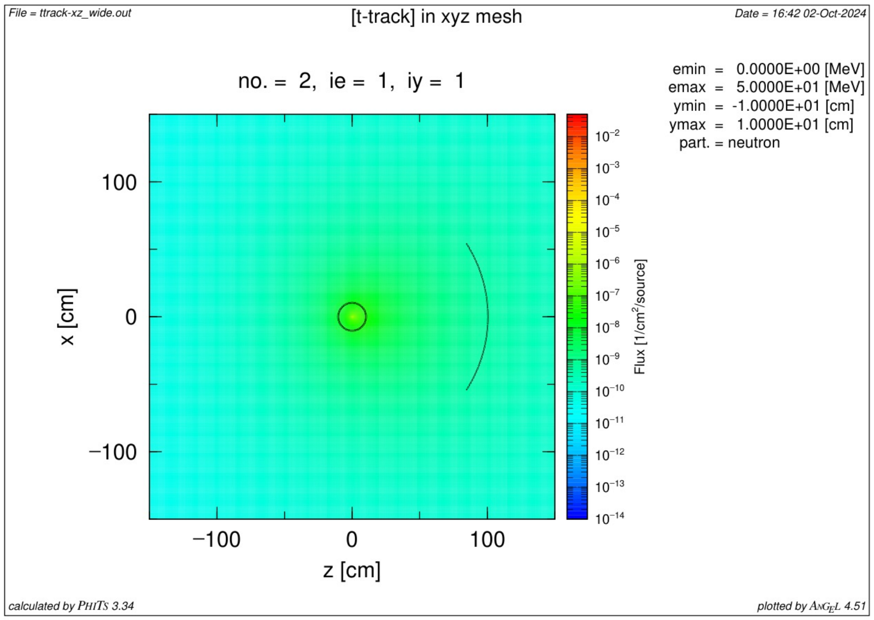


The result of the INCL model does not match the feature of the inverse kinematic reaction.

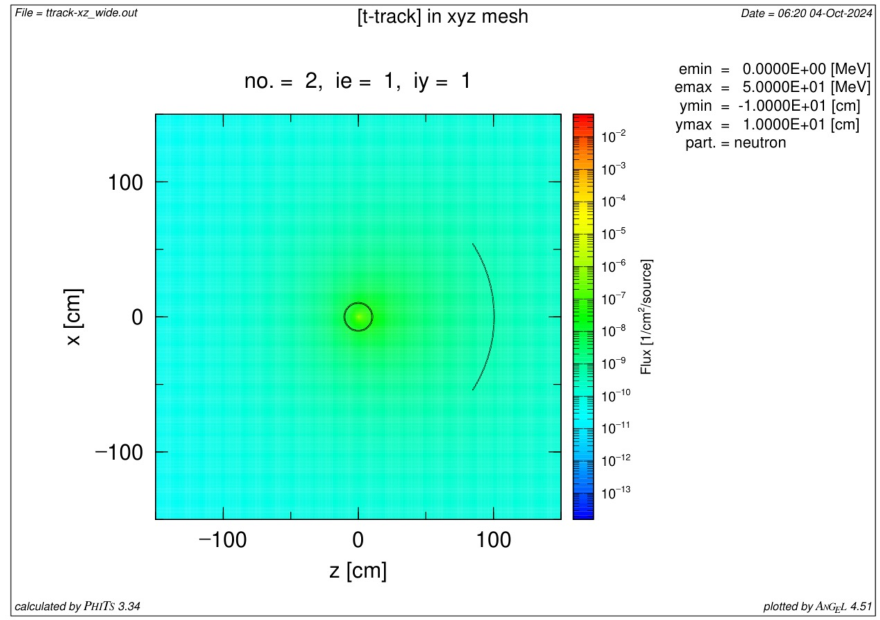
Recent activity – Simulation study – <Result>

Neutron distribution in each nuclear model. (Beam energy: 14 MeV)

JQMD



JQMD2.0



The results of the JQMD and JQMD2.0 do not match the feature of the inverse kinematic reaction.
INCL, JQMD, and JQMD2.0 make the reaction between carbon and lithium, which emit neutrons in this case. Therefore, the neutron distributions do not agree with the feature of the inverse kinematic reaction.

Nuclear reaction models are unsuitable for the inverse kinematic reaction; p (Li^7, n) Be^7.

Recent activity – Simulation study –

<Frag data(Nuclear data format)>

The nuclear reaction models could NOT be used for the inverse kinematic reaction; p (Li^7, n) Be^7.
There are no available cross-section data of this inverse kinematic reaction.
⇒ We need to make the cross-section data for the inverse kinematic reaction.

The Frag data was made for the inverse kinematic reaction; p(7Li, n)7Be.
(Frag data is the cross-section data format for the PHITS code.)

Specification of new frag data

- Just made for neutron production by p(7Li, n)Be
- Energy range: Threshold energy to 16.45 MeV

Table 1
Main characteristics of the p(^{7}Li,n)^{7}Be reaction. Neutrons produced in each channel are labeled n_i to indicate they are produced with different kinematics.

Type of exit channel	Q-value (MeV)	Threshold energy (MeV)	Primary 0° neutron energy
$n_0 + {}^7_4Be$	−1.644	13.098	1.44
$n_1 + {}^7_4Be^*(0.429\ MeV)$	−2.073	16.513	3.84
$n_2 + {}^3_2He + {}^4_2He$	−3.230	25.726	8.18
$n_3 + {}^7_4Be^*(4.57\ MeV)$	−6.214	49.489	18.79

M. Leboisetal./NuclearInstrumentsandMethodsinPhysicsResearchA735(2014)145–151

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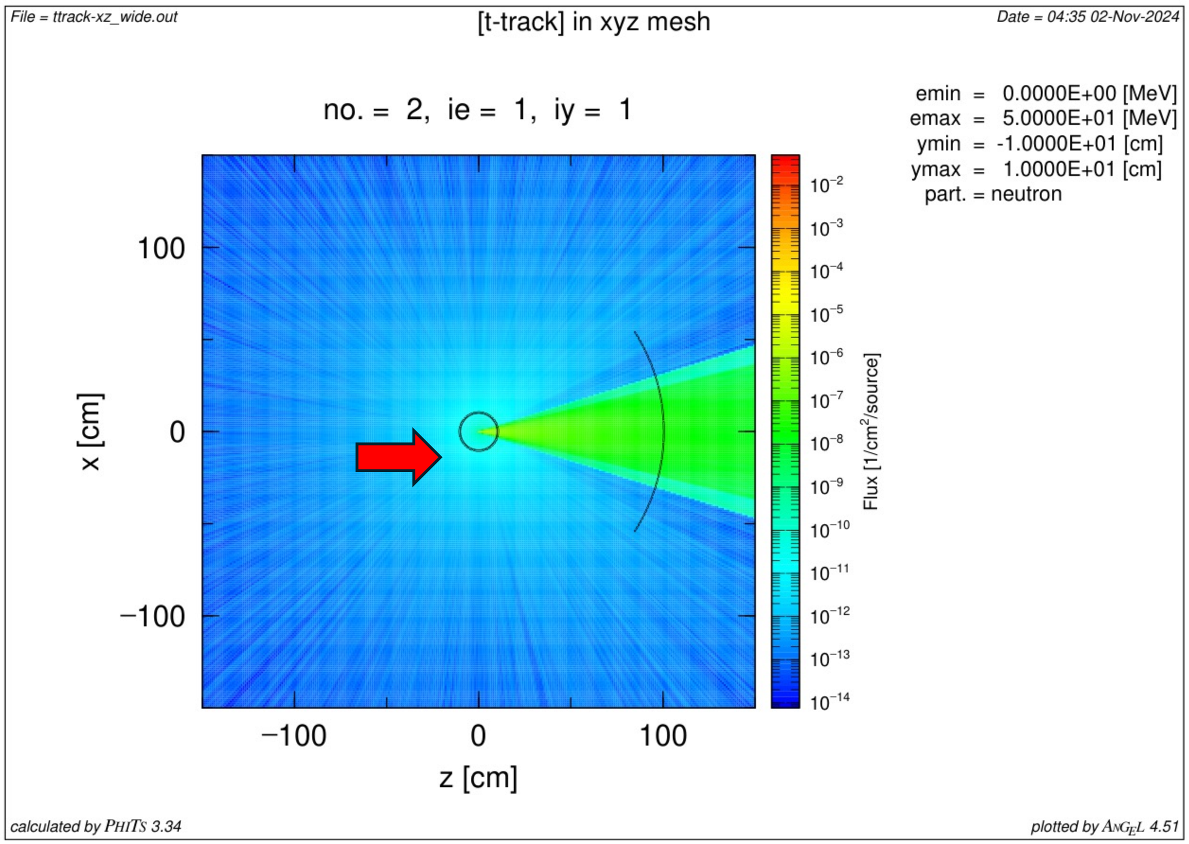
Recent activity – Simulation study –

<Result>

<u>The result of the simulation using the new Frag data</u>

Default setting (INCL model) and frag data. (14 MeV Lithium beam)



Target: 12 μm polypropylene

The target exits in the center of the drawing.

The red arrow means the beam direction.

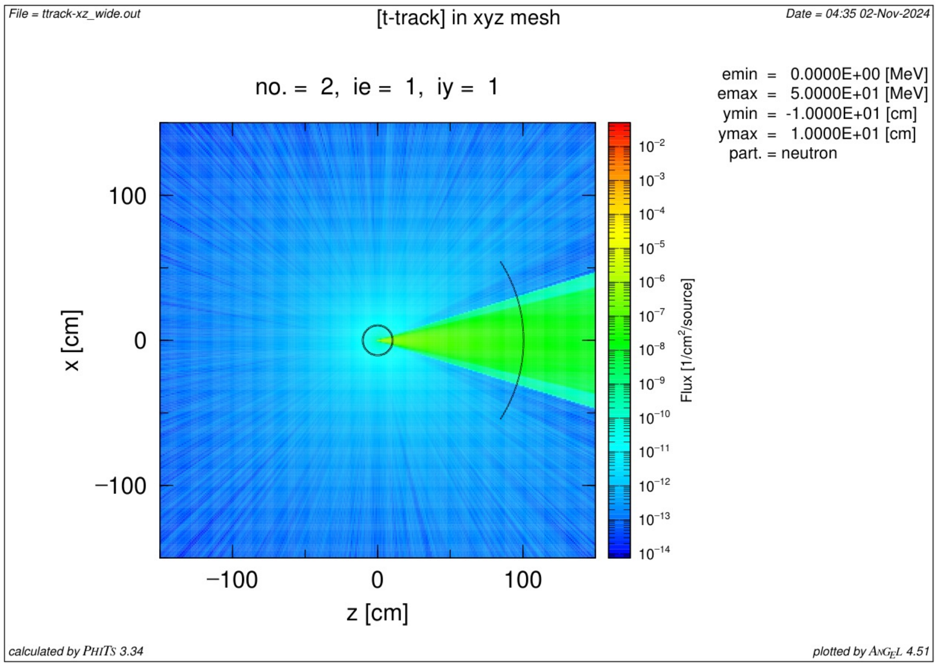
The neutron cone in the forward direction was observed.

Recent activity – Simulation study –

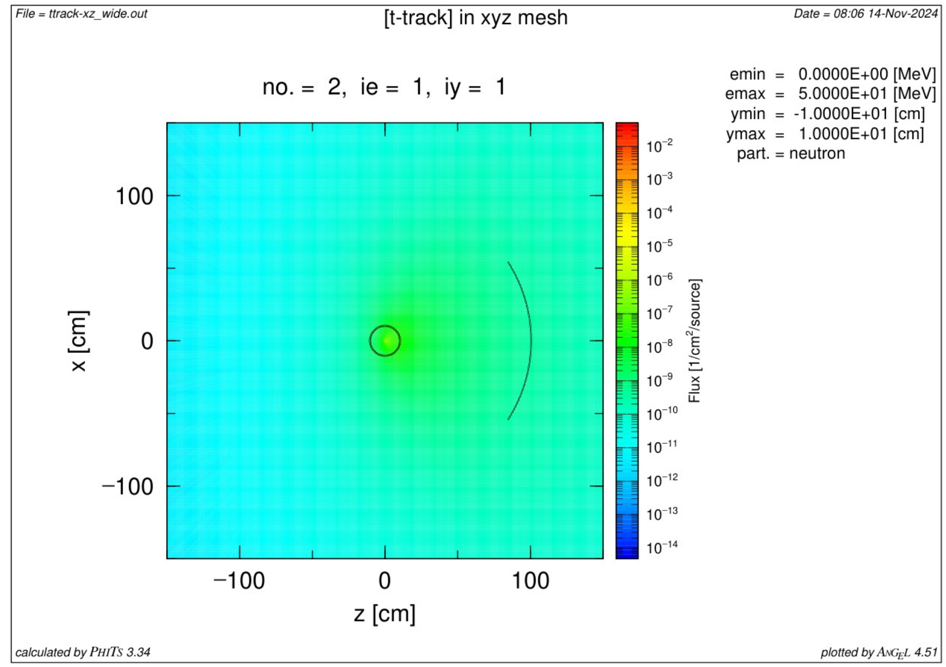
<Result>

<u>Comparison with the proton-beam case</u>

14 MeV(2 MeV/n) of Lithium-beam
(New Frag data, 12μm polypropylene target)



2 MeV/n of Proton-beam
(JENDL5, 12μm Lithium target)



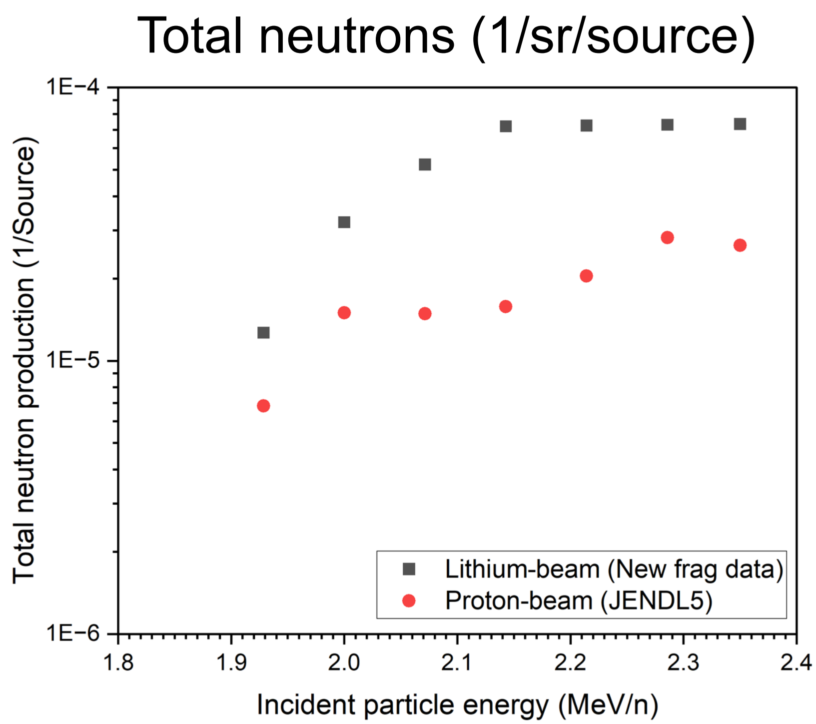
In the lithium beam case, the neutron cone was well observed in the forward direction.
In the proton case, neutrons are emitted to every directions.

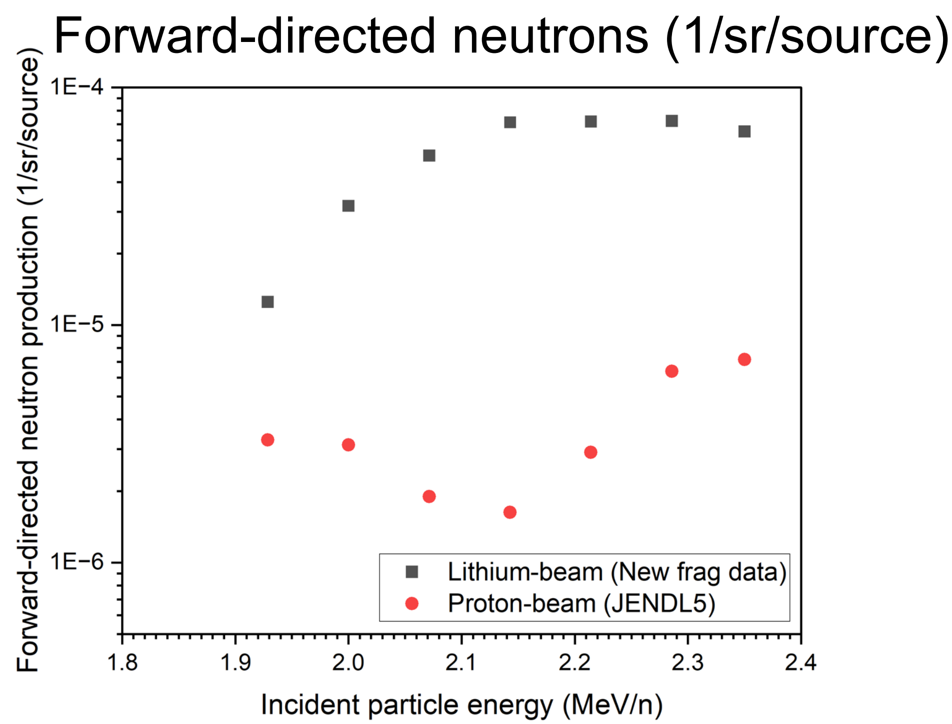
Recent activity – Simulation study –

<Result>

<u>Comparison with the proton-beam case</u>

- Lithium beam case/ New Frag data, 12μm polypropylene target
- Proton beam case/ JENDL5, 12μm Lithium target



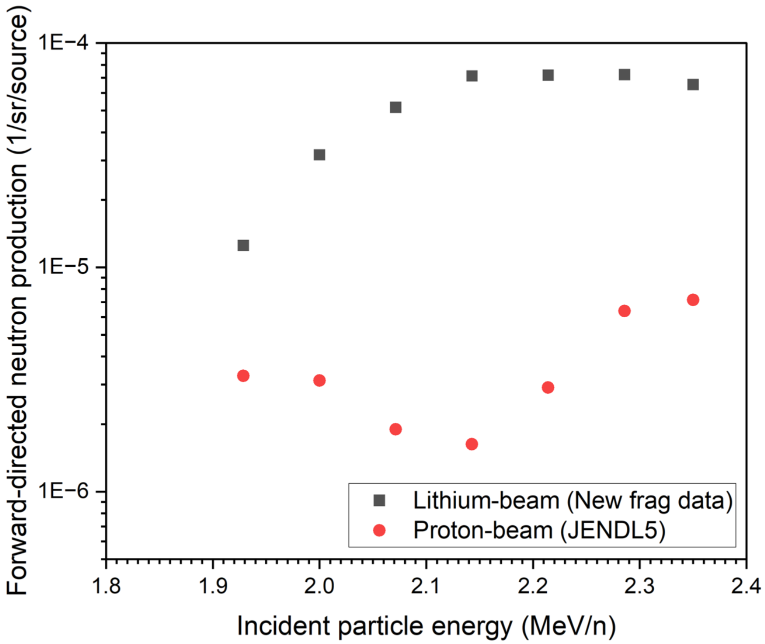


In the lithium beam case, the great enhancement of forward-directed neutrons is observed.

Recent activity – Simulation study –

<Result>

Forward-directed neutrons (1/sr/source)



At 2.35 MeV/n(16.45 MeV), the new frag data result shows a neutron flux of 6.54×10^{-5} (1/sr/source) in the forward direction.

If the average current is 100 nA, a neutron flux in the forward direction is estimated to be 1.36×10^{7} (/sr/source).

In the LICORNE paper*, 7×10^{7} (/sr/source) of neutron flux in the forward direction is reported in the case of 16.5 MeV, 100 nA.

⇒ The same order of neutron production in the forward direction is confirmed.

*J.N. Wilson et al, Physics Procedia 59 (2014) 31 – 36

Recent activity – Simulation study –

PHITS
Particle and Heavy Ion Transport code System

<Conclusion>

- In PHITS code, Bertini model, JAM model, and INC-ENL model agree with the feature of the inverse kinematic reaction in terms of neutron distribution.
- However, neutron production is underestimated in the PHITS code. (In particular, lower energy region; 20 MeV or less).
- The nuclear reaction models are unsuitable for this inverse kinematic reaction.
- The Frag data (user-define data) shows the reasonable result in the initial simulation trial. Further investigation is required.

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Recent activity – Experimental study –

Neutron production experiment was conducted using the Tandem van de Graaf accelerator to evaluate an angular neutron distribution in the case of the inverse kinematic reaction; $p(^{7}Li, n)^{7}Be$.

Basic information on the experiment

- Beam specie: $^{7}Li^{3+}$
- Beam energy: up to 56 MeV
- Beam current: up to 65 nA
- Target material: Polypropylene $(C_3H_6)_n$

Tandem van de Graaf accelerator at BNL

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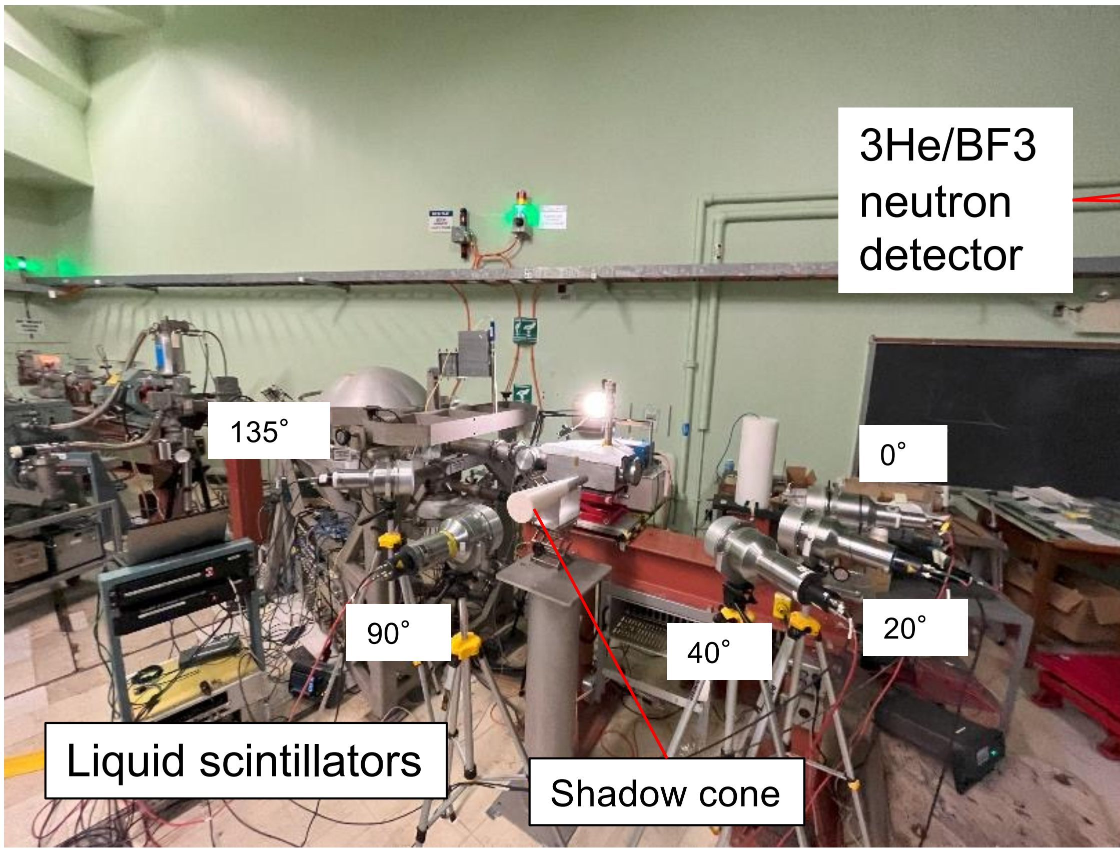
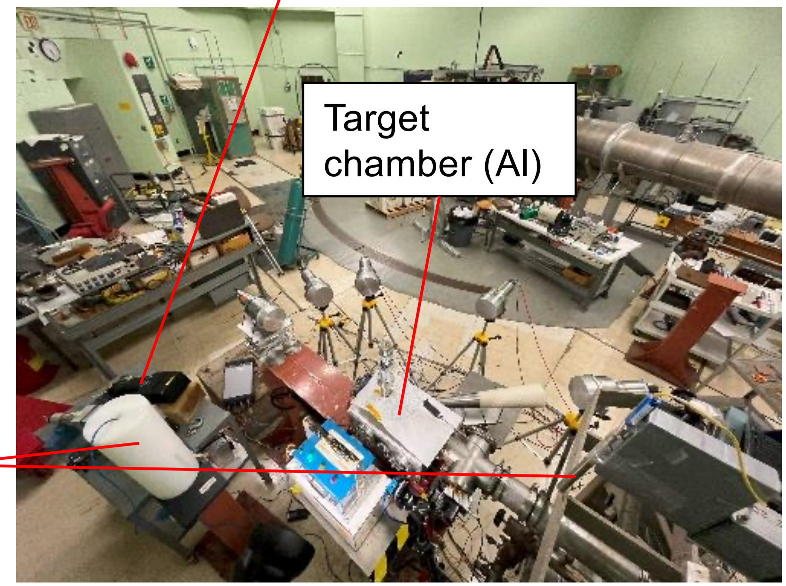
Recent activity – Experimental study –

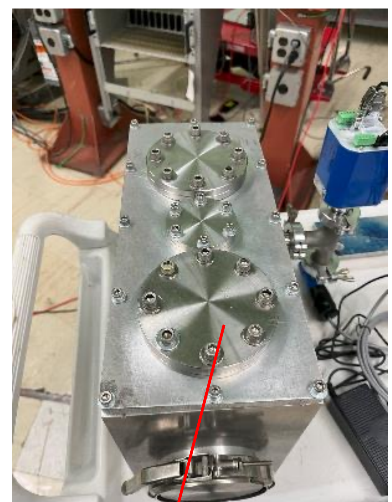
<Configuration>

The polypropylene target was installed inside the aluminum chamber at the end of the beamline.

The inverse kinematic reaction, p (Li⁷, n) Be⁷, was induced on the target.







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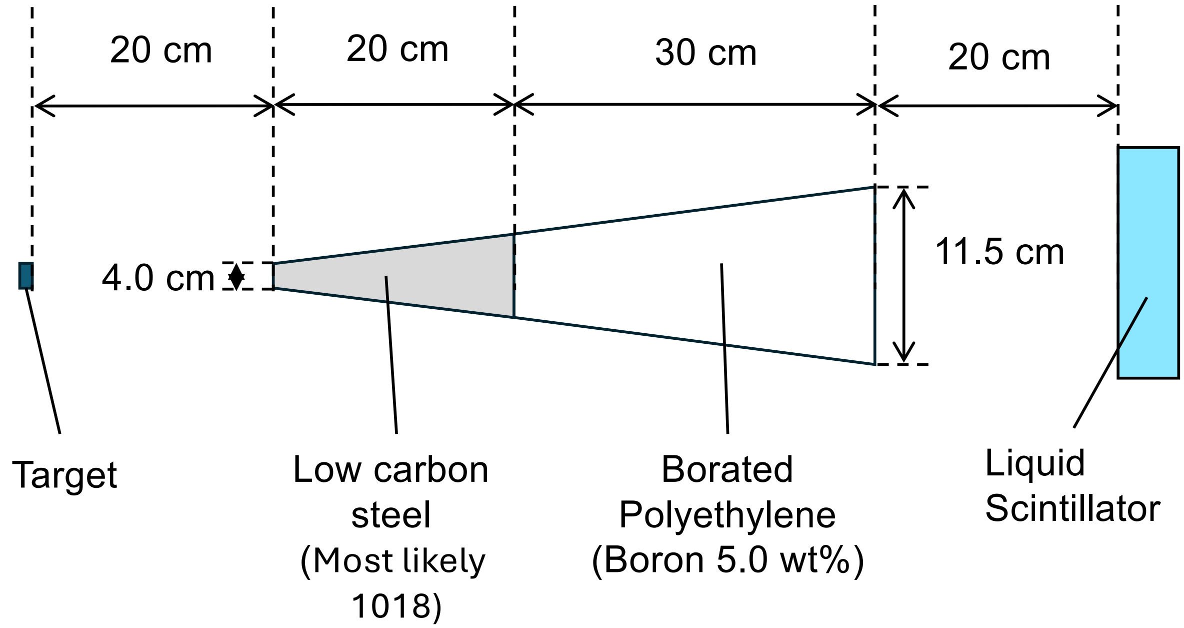
0 degrees means the beam direction.

Recent activity – Experimental study –

<Configuration>

The shadow-cone was in front of the liquid scintillator to shield radiations from the target.



With shadow cone: Neutrons from the room and the experimental setups.
Without shadow cone: Neutrons from the target, the room, and the experimental setups.

⇒ By comparing the radiation signals with/without the shadow cone, the neutron flux from the target can be calculated.

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Recent activity – Experimental study –

<Setup of the BF3/He3 neutron detector>

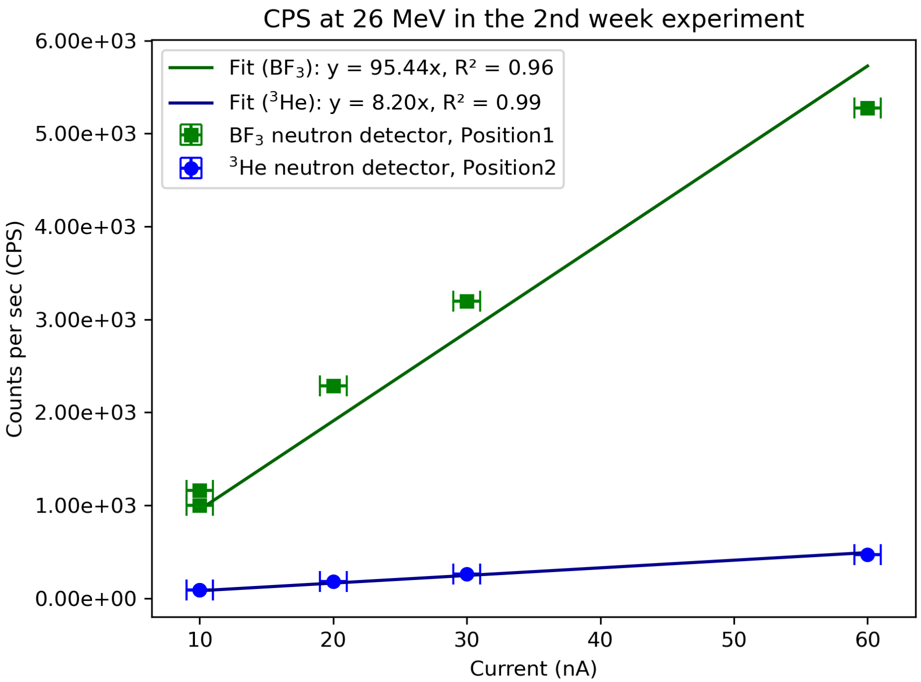
◆ Position1
- Distance from the target to the detector: 1.0 m
- Setting Angle: 50° (with the polyethylene block)

◆ Position2
- Back scattering side (As shown in the photo)

◆Position1

◆Position2

<Result of the BF3/He3 neutron detector>



Neutron production by the collision between lithium beam and polypropylene was observed.

The linearity between the CPS and the current was observed.
(CPS: current per second)

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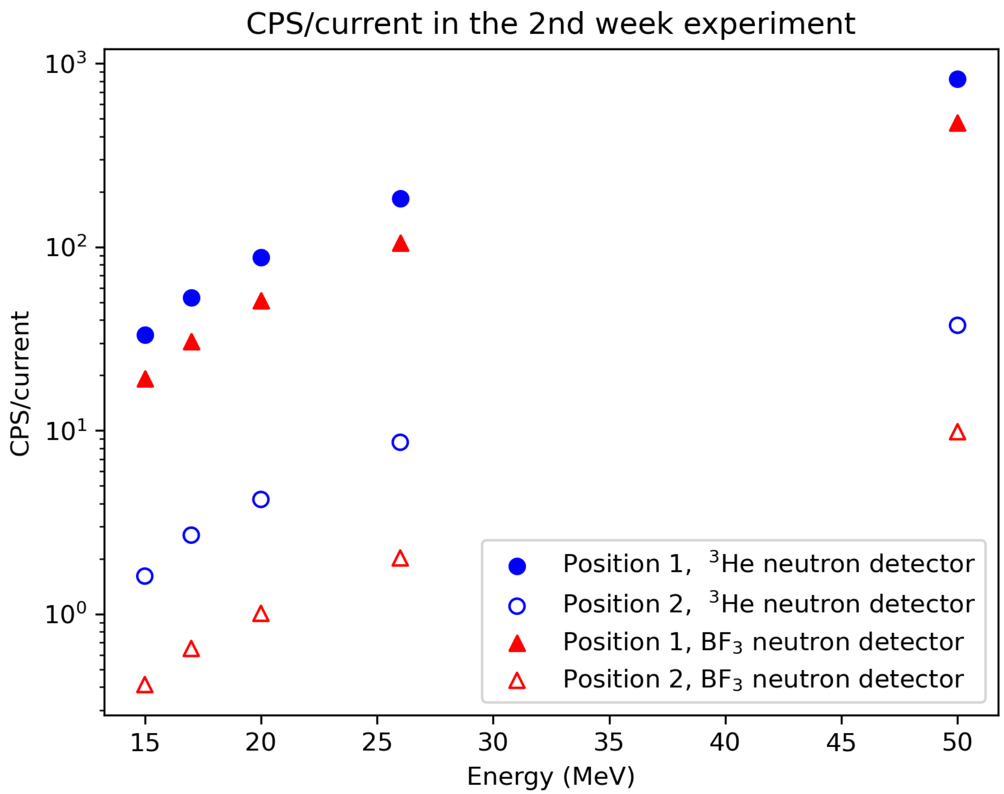
Recent activity – Experimental study –

<Result of the BF3/He3 neutron detector>

The positions of the detectors were exchanged in the middle of the measurement at each beam condition.



The CPS/current value strongly depends on the beam energy.

◆Position1

◆Position2

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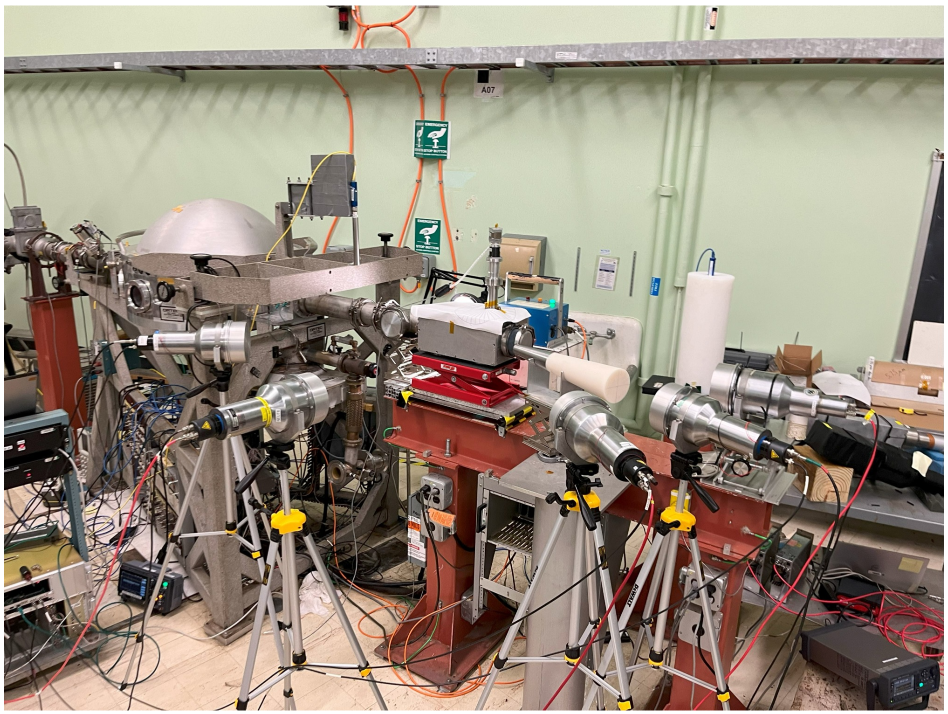
Recent activity – Experimental study –

<Result of the scintillators>

The results of the liquid scintillators and the NaI scintillator are still under analysis.

In summary, throughout the measurement by the liquid scintillators,

- Neutron concentration in 0-degree positions was observed.
- A large difference in signal amounts was observed between the cases with/without the shadow cone.



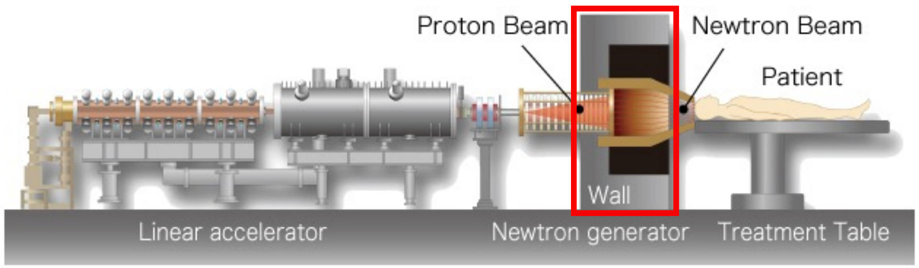
To analyze neutron flux quantitatively, the unfolding method will be applied to the liquid scintillator data.

Further analysis is required.

Neutron target for lithium driver beam

Neutron target has three functions:

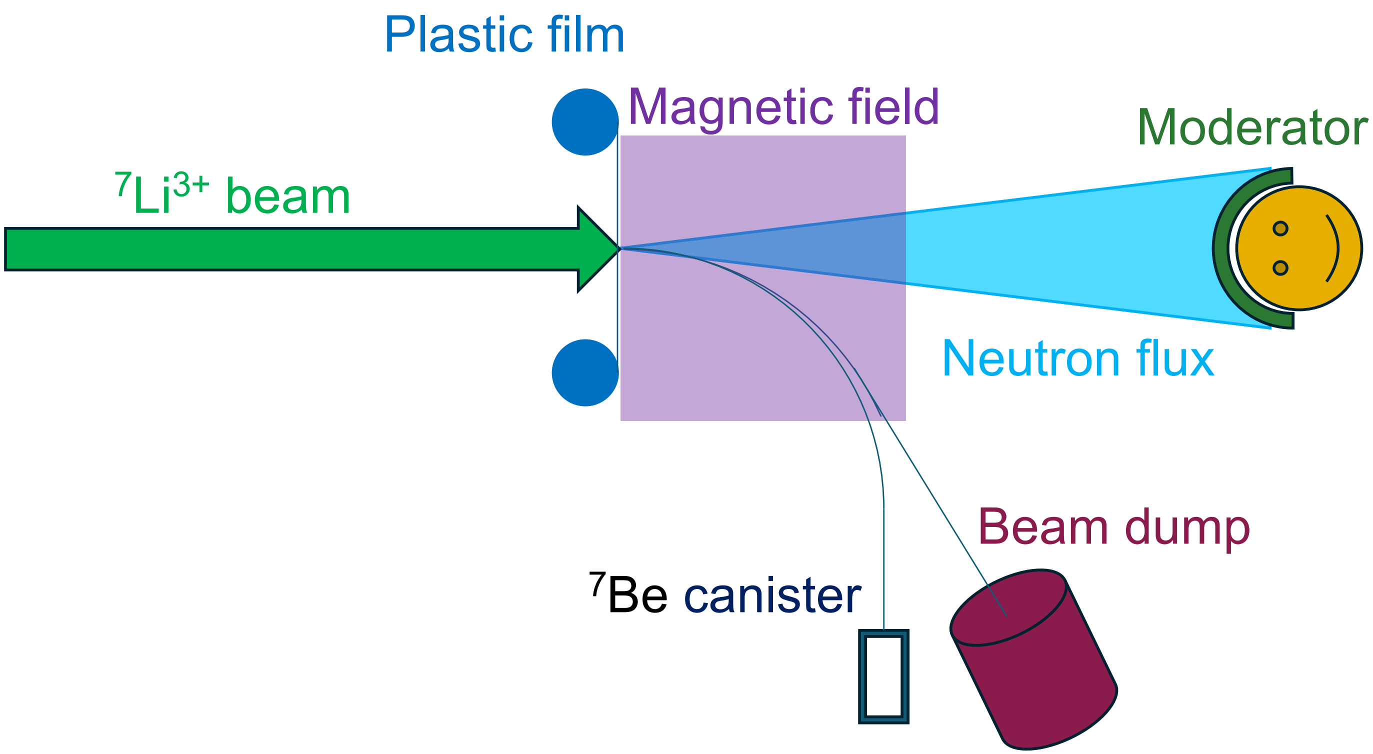
1. Neutron converter
2. Beam dump
3. Moderator



https://bnct.kek.jp/eng/apparatus.html

Target concept for Li driver neutron generator

Discrete functions.



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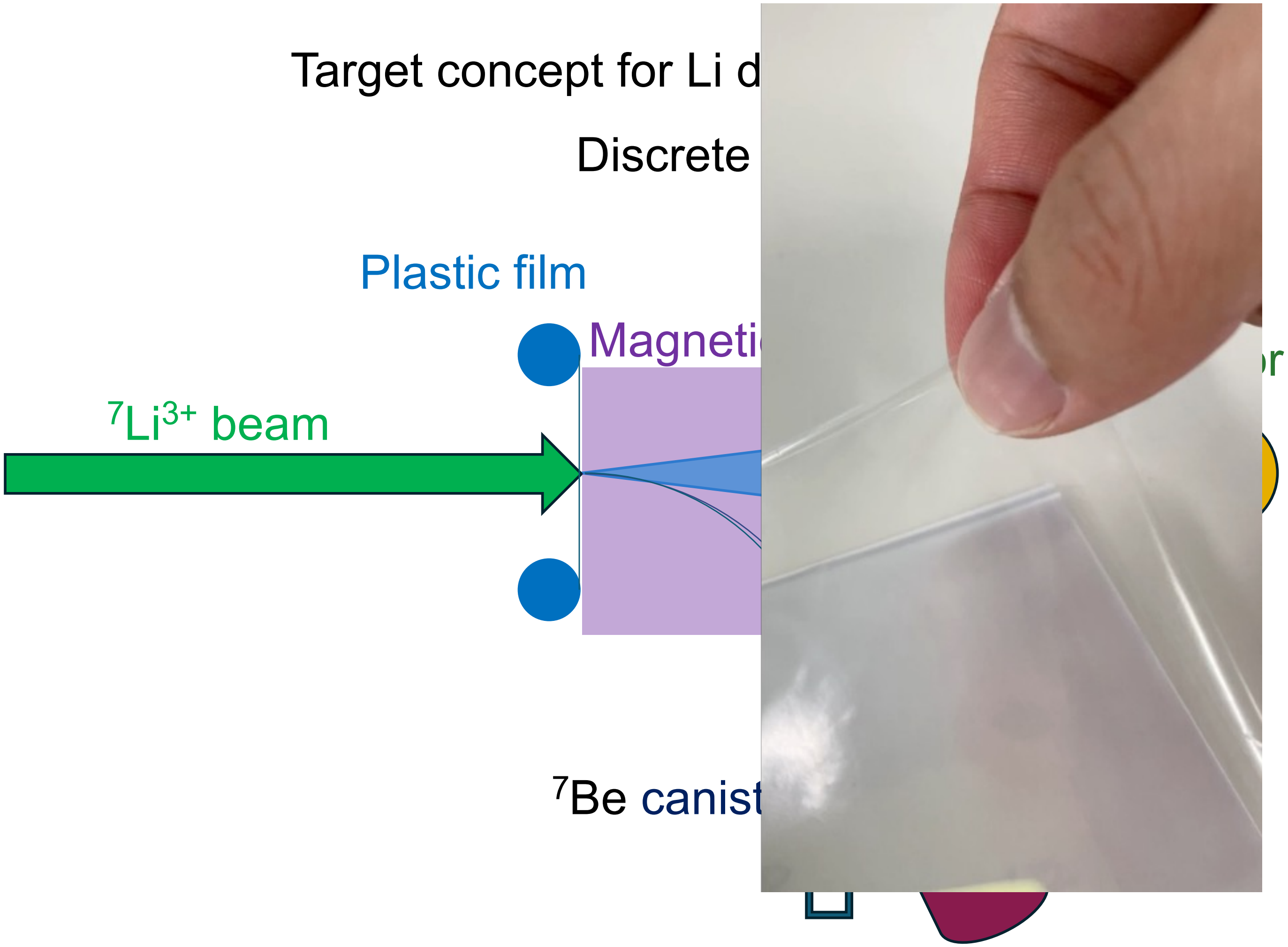
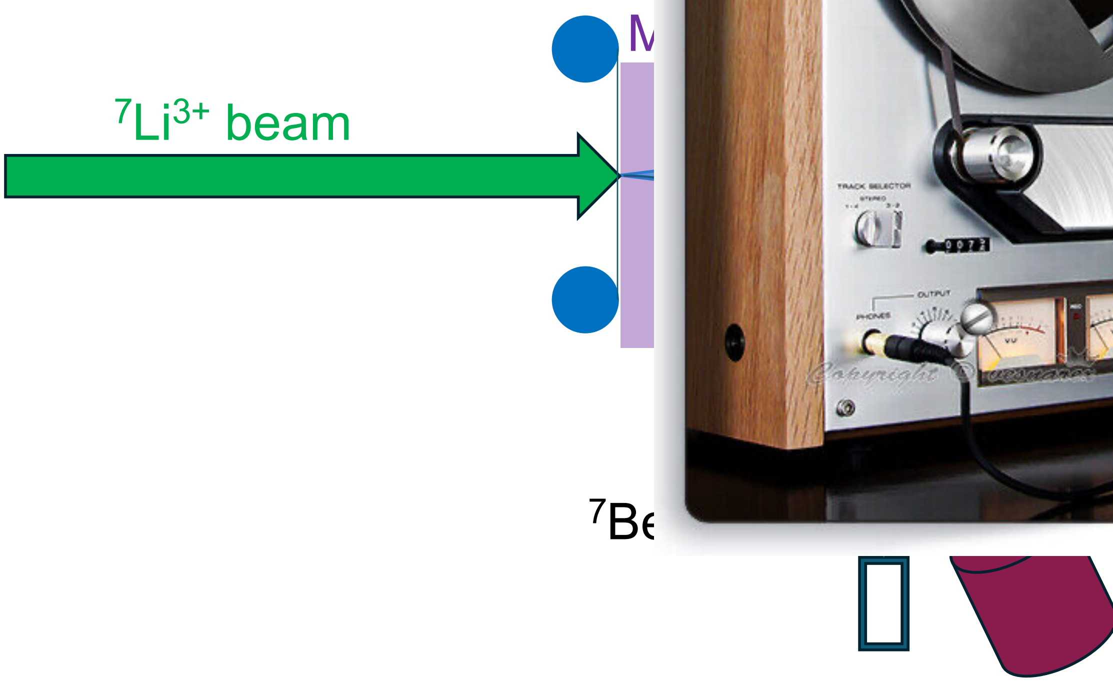
Target concept for Li d

Discrete

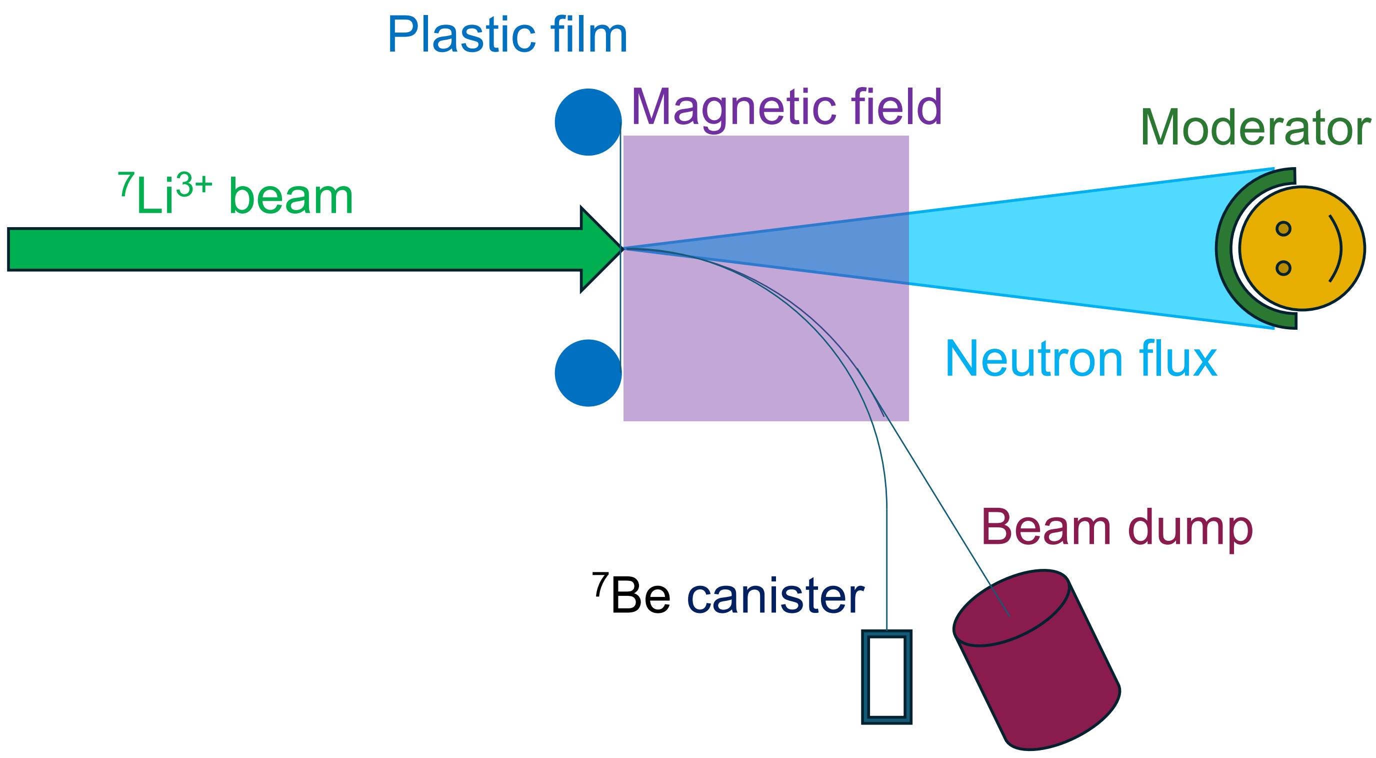


Target concept



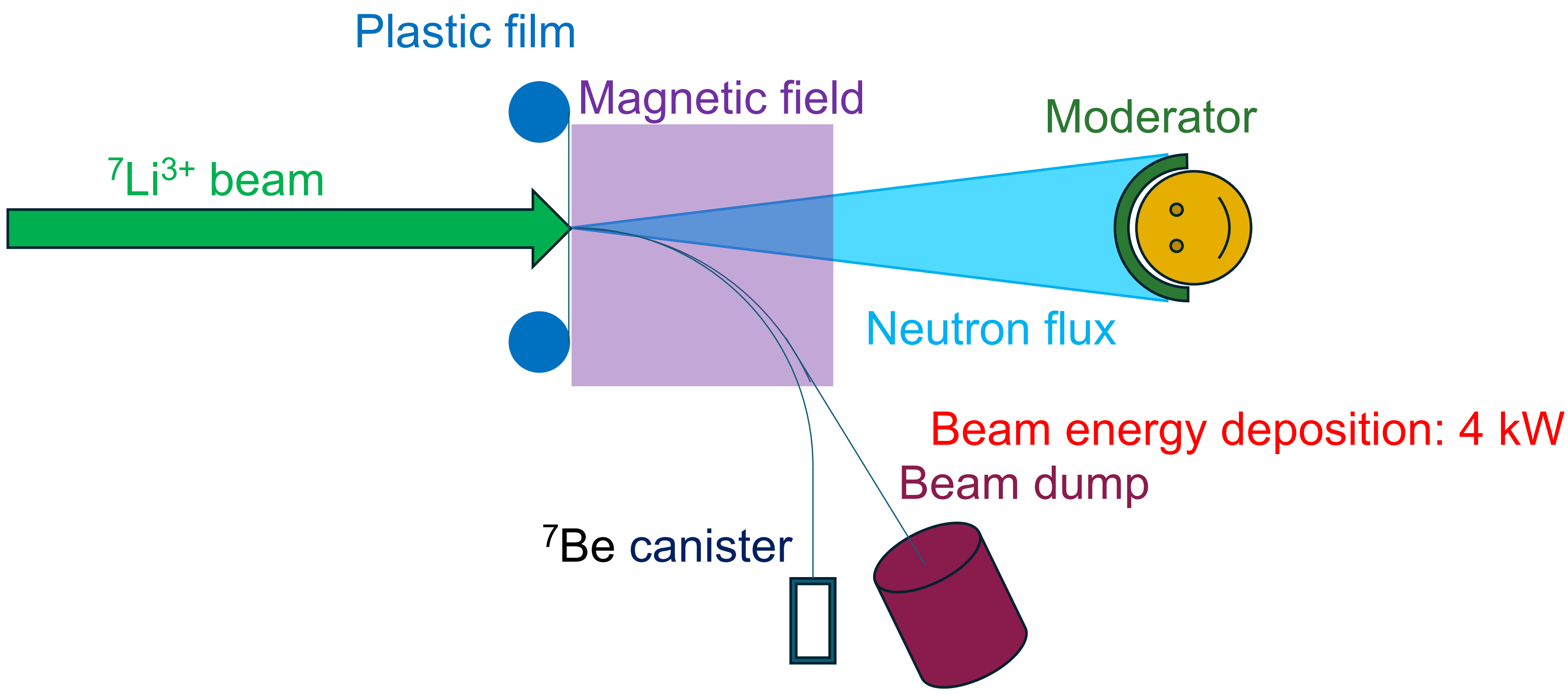
Target concept for Li driver neutron generator

Discrete functions.



Target concept for Li driver neutron generator

Discrete functions.



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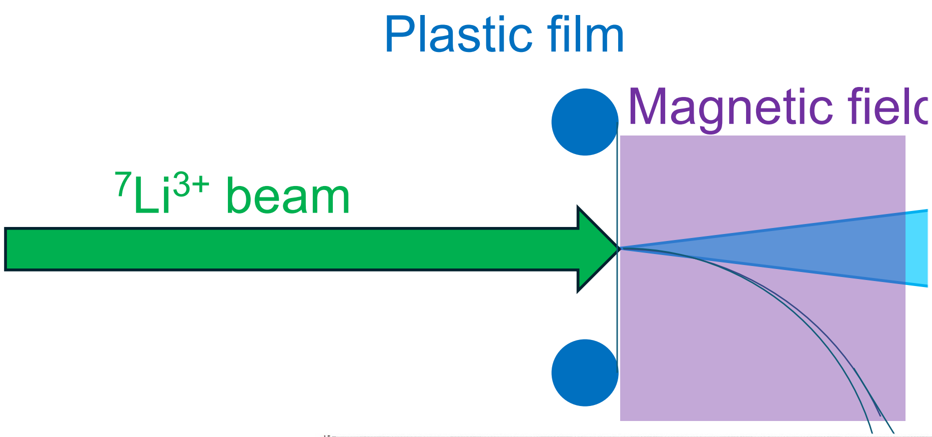
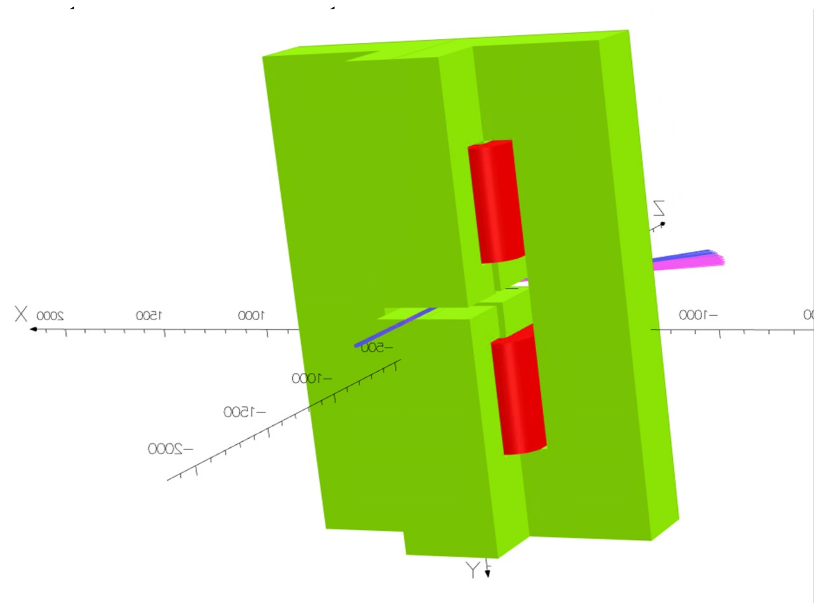
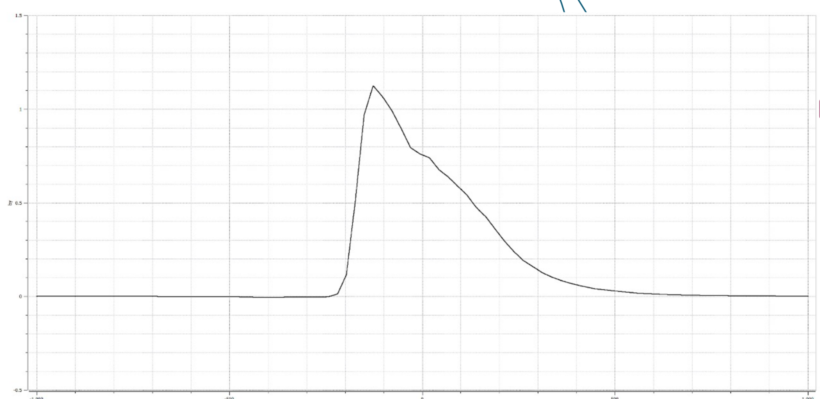
Target concept for Li driver

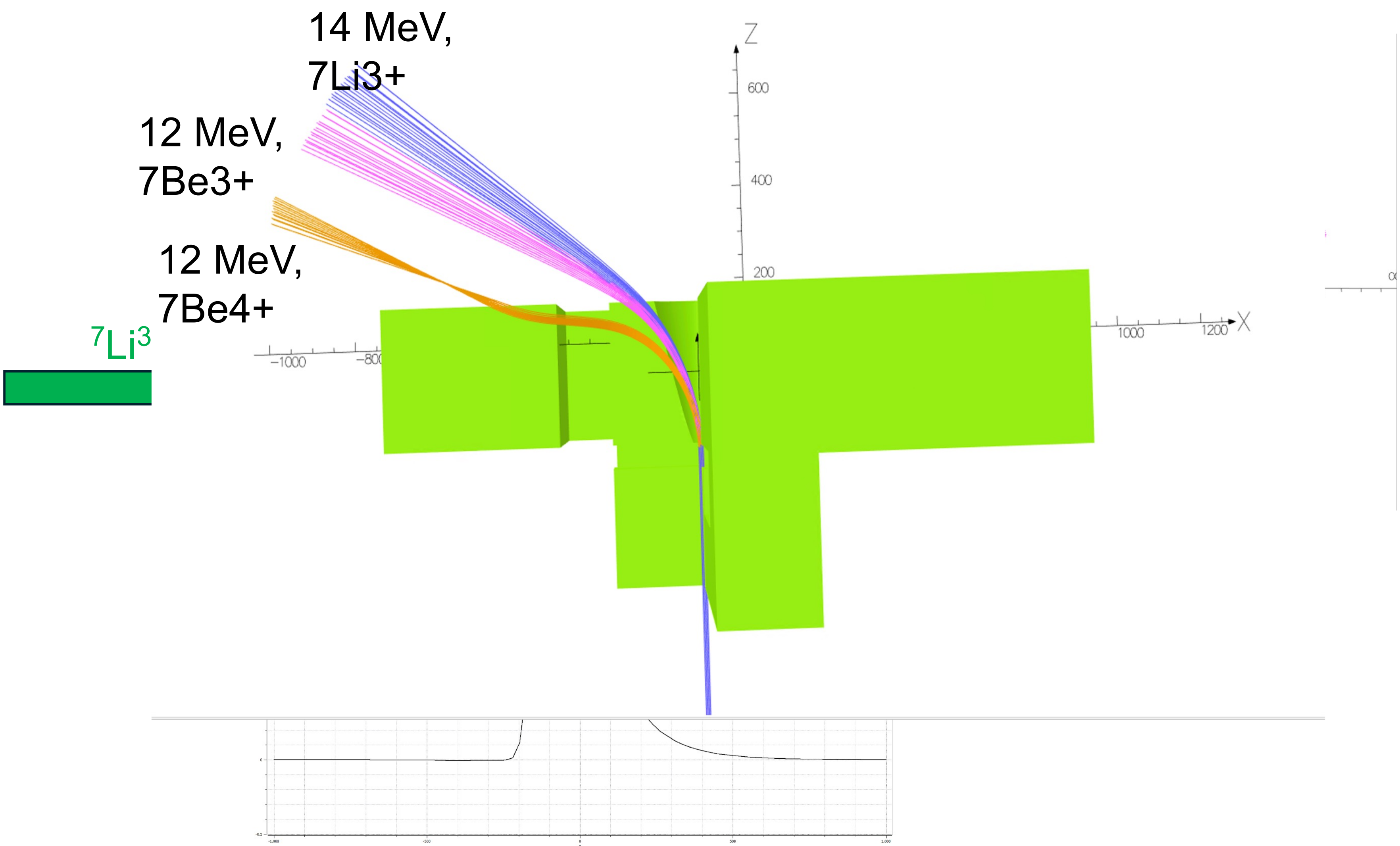
Discrete functi







dump


14 MeV,
7Li3+
12 MeV,
7Be3+
12 MeV,
7Be4+
$^{7}Li^{3}$
Z
600
400
200
X
1000
1200
−1000
−800

Summary

So far until now

Neutron generator based on intense lithium beam driver was proposed as a clean compact source

Lithium beam driver scheme will make the BNCT target system functionally separable.

(next generation moderator)

RFQ linac was designed and tested with Li^{3+} ions.

- 35 mA (peak) beam was demonstrated
- Almost no contamination

Monte Carlo simulation started. We need to create nuclear data.

Neutron production experiments were tried and sharp directivity was confirmed.

(The data analysis is in progress.)

Future prospects

Higher power RFQ electrode is being installed, and we plan to test it very soon.

More detailed experiments are being planned. BNL Tandem and Dresden Tandem.

Neutron target design study will be finished in two years.

Detailed accelerator design will be completed.

Thank you for your attention

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