



CANS at BNL

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K. Takahashi (Nagaoka Tech), G. Ceccio (NPI of Czech)

UCANS11 Feb. 25, 2025



History of Cans at Brookhaven

1951 The first clinical trial of BNCT using Graphite Research Reactor at BNL

1995 NIFTI and DISCOS, conceptual design of targets

1996 LDRD (internal fund) proposal, The development and demonstration of accelerator based BNCT capability

1998 Accelerator Based Neutron Source (ABNS) for BNCT, Preliminary Proposal

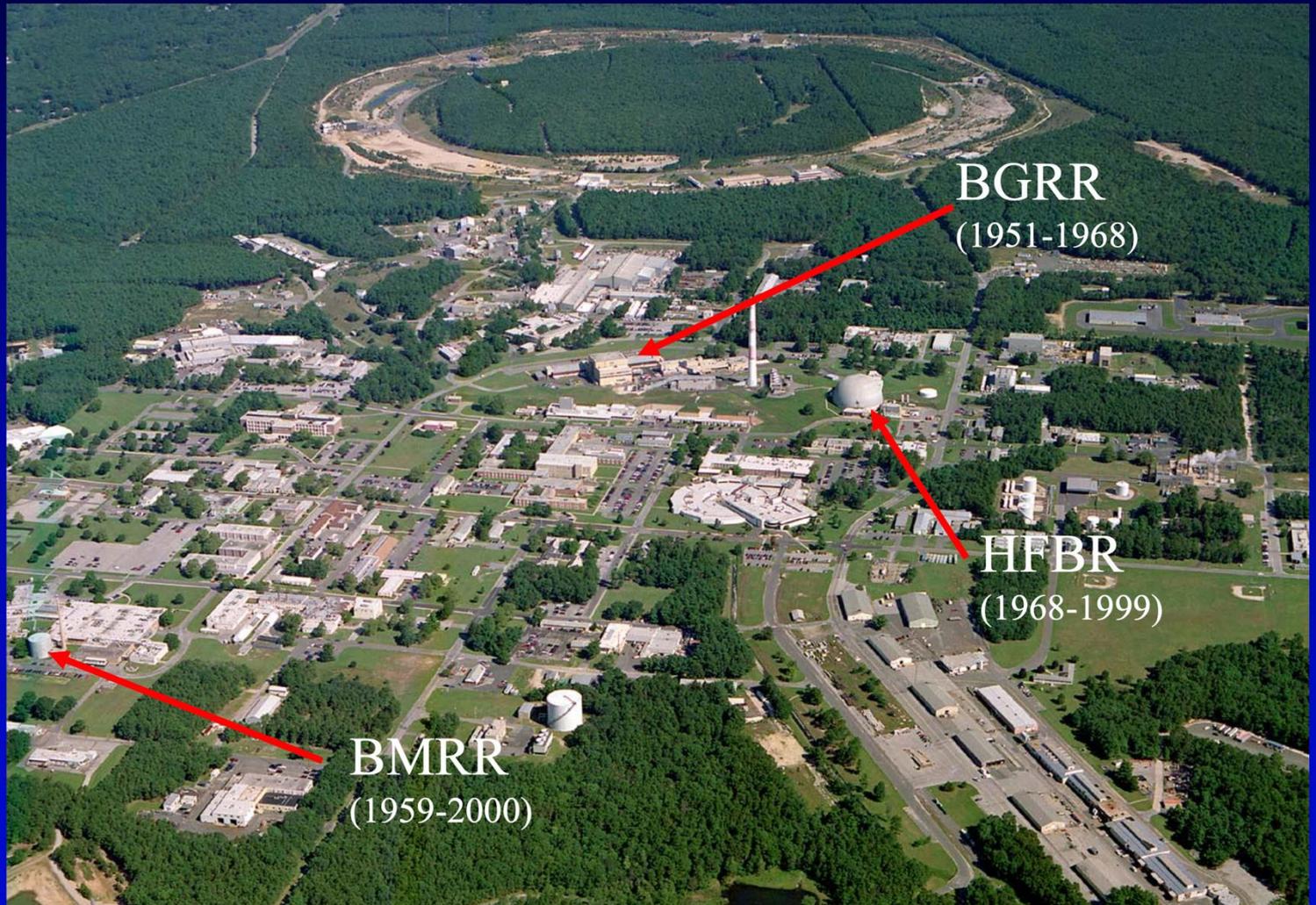
1999 Experimental and theoretical evaluation of accelerator based epithermal neutron yields for BNCT, AIP Conference Proceedings 475, 1033 (1999)

1999 A New Accelerator based Cancer Treatment (BNCT) Test & Demonstration Facility, Proposal by BNL and AES

FY 2022 High repetition rate Lithium Laser Ion Source for neutron beam production
(\$0.37M)

FY 2024 Development of a lithium beam driver for Boron Neutron Capture Therapy
(\$1.15M)

Brookhaven National Laboratory

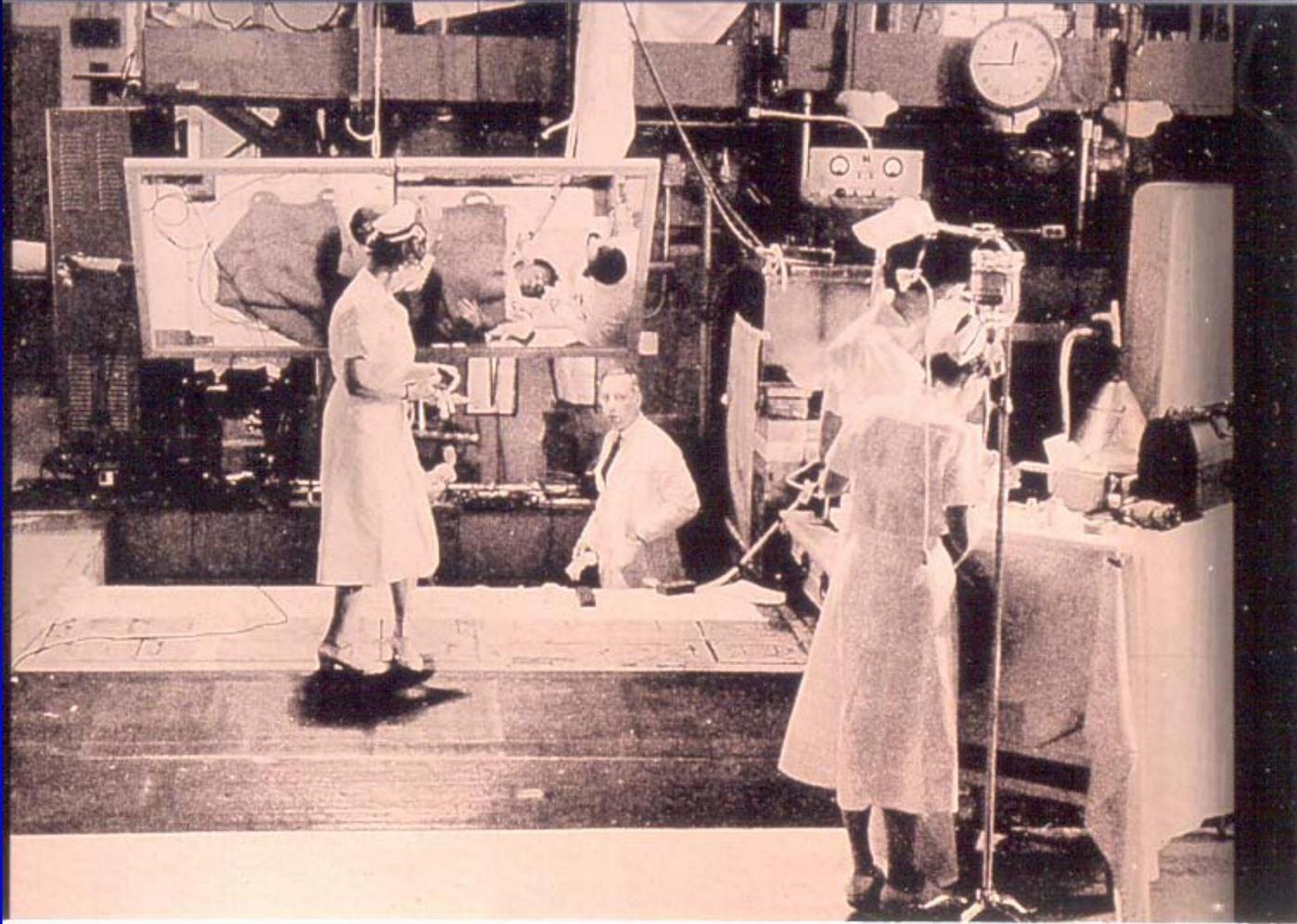


BGRR
(1951-1968)

HFBR
(1968-1999)

BMRR
(1959-2000)

BNCT Clinical Trial: ~1953



BGRR Clinical Trial: 1951-1959



BNCT Clinical Trial: 1959-1961



Brookhaven Medical Research Reactor



Beam shutter

BNL - 63865

NIFTI And DISCOS:

**New Concepts For A Compact Accelerator Neutron Source
For Boron Neutron Capture Therapy Applications**

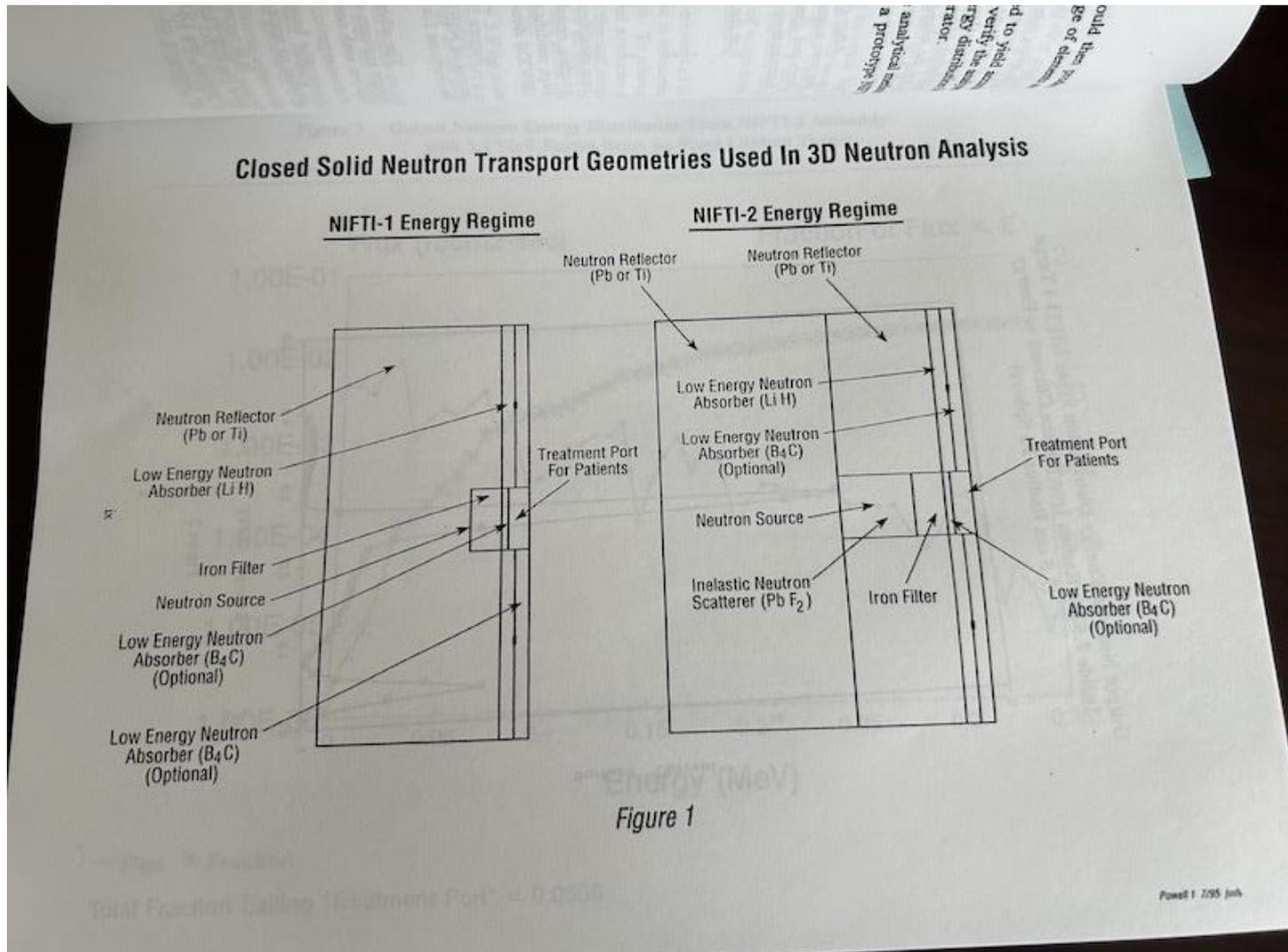
by

J. Powell, H. Ludewig, M. Todosow, and M. Reich
Department of Advanced Technology
Brookhaven National Laboratory
Upton, N.Y.

June 1995

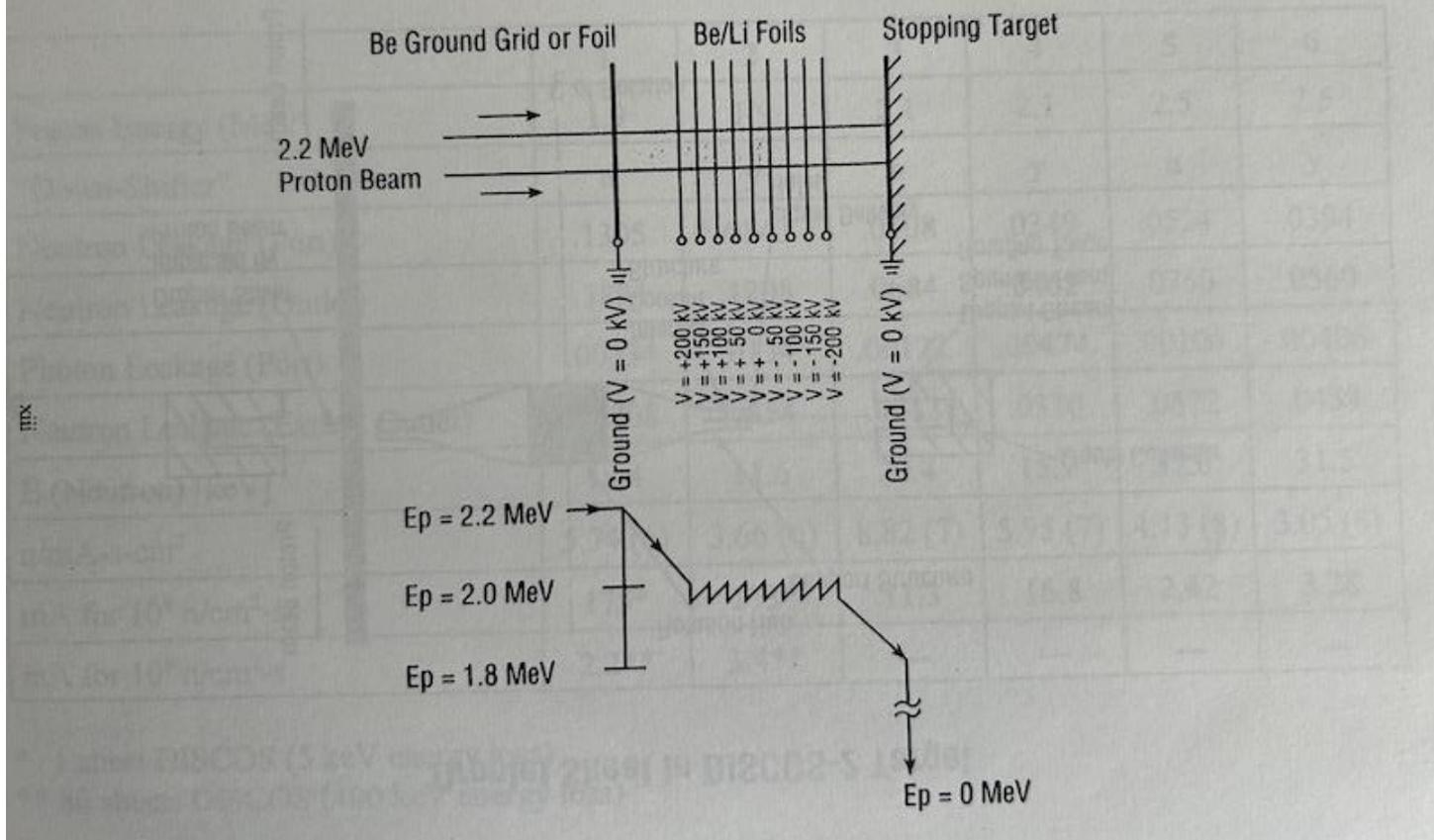
This work was performed under the auspices of
the U.S. Department of Energy under
contract #DE-AC02-76-CH00016.

NIFTI, Neutron Intensification by Filtered Transmission through Iron

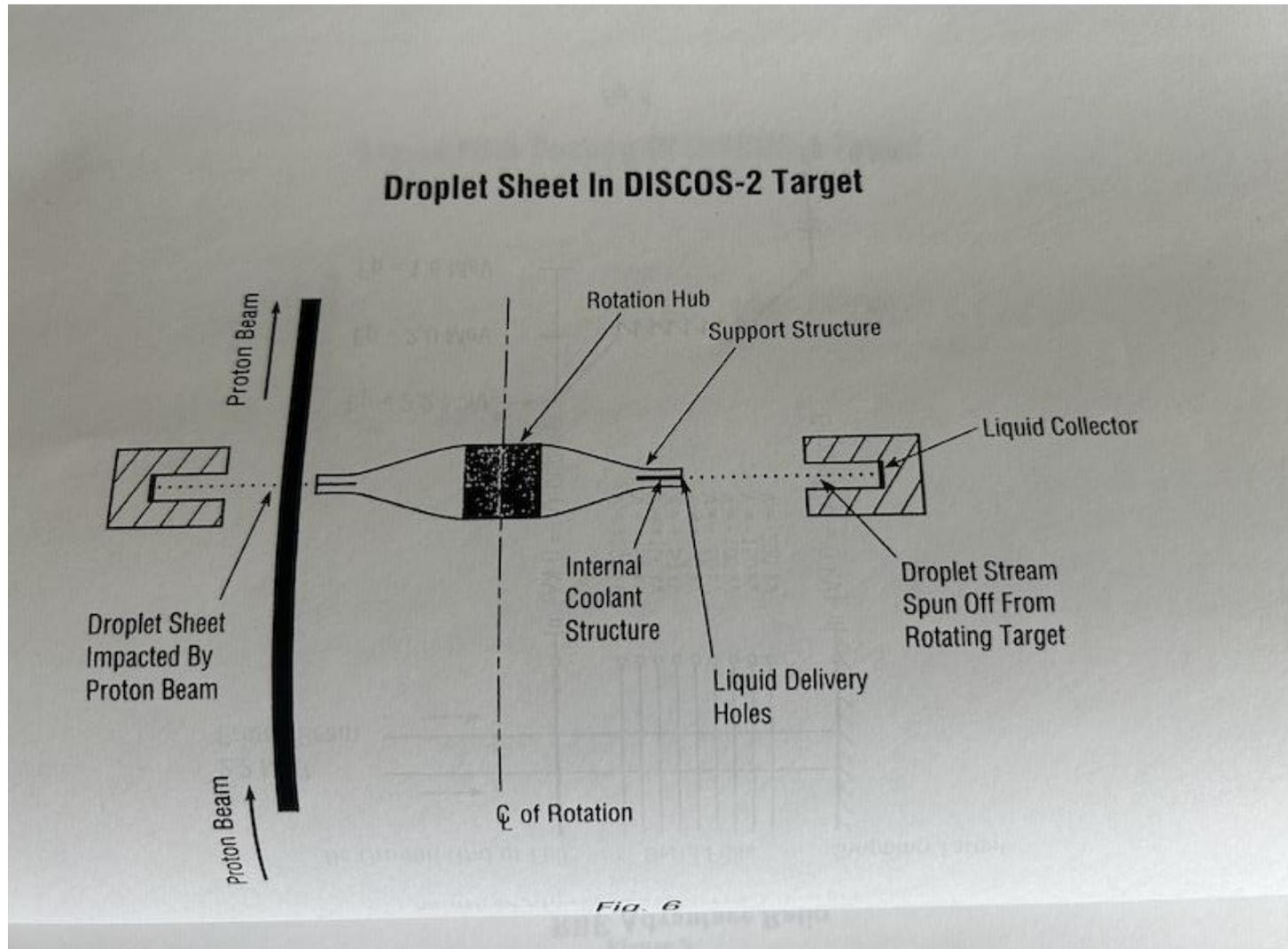


Neutrons with energies above 25 keV are strongly impeded from transmission through a thick iron layer, but readily pass through once their energy drops below 25keV. Fluorine compound to inelastically degraded high energy neutrons.

Re-Acceleration of Proton Beam By DC Field Between Multiple Sheets in DISCOS-1 Target



DISCOS, Discs Incorporating Sector Configured Orbiting Sources



**BROOKHAVEN NATIONAL LABORATORY
PROPOSAL INFORMATION QUESTIONNAIRE
LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROGRAM**

PRINCIPAL INVESTIGATOR Deepak Raparia PHONE 344-4849

DEPARTMENT/DIVISION AGS Department DATE April 22, 1996

OTHER INVESTIGATORS See Attachment 1

TITLE OF PROPOSAL The Development and Demonstration of Accelerator Based BNCT
Capability

PROPOSAL TERM From (month/year) May 1, 1996 To (month/year) March 31, 1998

SUMMARY OF PROPOSAL (Provide an abstract of the proposed project which highlights the central idea of the project scope, its purpose and what it hopes to accomplish. Also indicate how it meets the general characteristics of the LDRD Program. This should be no more than one half to three quarters of a page. Attach an extended proposal if desired.)

This proposal is to study the feasibility of producing neutrons for Boron Neutron Capture Therapy, BNCT, with an accelerator rather than with a reactor. If a small proton accelerator to produce neutrons is found to be acceptable, then BNCT could become a readily available clinical procedure.

The proposal is to study the yield and energy spectrum of neutrons produced with a proton beam (<2,5 MeV) from a Radio Frequency Quadrupole (RFQ) Linac. The major emphasis is to study the feasibility of various production target designs to optimize the yield and energy spectrum. The RFQ will be provided by the Chemistry Department, and SSC prototype machine from Accsys Technology Inc. The Department of Advanced Technology will be responsible for the target design and construction aspects. The Medical Department will be responsible for the installation of the detector instrumentation. The AGS Department will be responsible for the management of the effort and for the installation and commissioning of the ion source, RFQ accelerator and proton beam transport line. Both the Physics Department and the Department of Applied Science in conjunction with the other departments will be involved in the experimental program.

With the successful completion of this effort, we would expect to continue with industry to develop a marketable medical accelerator for use in BNCT.

It propose to test using a second hand RFQ to verify required beam current level.

Phantoms with $^{10}\text{BF}_3$ detectors for boron neutron capture therapy applications

D. E. Alburger, D. Raparia, and M. S. Zucker
Brookhaven National Laboratory, Upton, New York 11973

(Received 30 September 1997; accepted for publication 1 July 1998)

Two acrylic cube phantoms have been constructed for BNCT applications that allow the depth distribution of neutrons to be measured with miniature $^{10}\text{BF}_3$ detectors in 0.5-cm steps beginning at 1-cm depth. Sizes and weights of the cubes are 14 cm, 3.230 kg, and 11 cm, 1.567 kg. Tests were made with the epithermal neutron beam from the patient treatment port of the Brookhaven Medical Research Reactor. Thermal neutron depth profiles were measured with a bare $^{10}\text{BF}_3$ detector at a reactor power of 50 W, and Cd-covered detector profiles were measured at a reactor power of 1 kW. The resulting plots of counting rate versus depth illustrate the dependence of neutron moderation on the size of the phantom. But more importantly the data can serve as benchmarks for testing the thermal and epithermal neutron profiles obtained with accelerator-based BNCT facilities. Such tests could be made with these phantoms at power levels about five orders of magnitude lower than that required for the treatment of patients with brain tumors. © 1998 American Association of Physicists in Medicine. [S0094-2405(98)01809-4]

Key words: BNCT, phantom, $^{10}\text{BF}_3$ detector, depth-dose distributions

Preparation for testing RFQ beam

INTRODUCTION

Boron neutron capture therapy (BNCT) using epithermal neutron beams is a current research procedure at the Brookhaven Medical Research Reactor (BMRR) for the treatment of patients with certain types of brain tumor (glioblastoma multiforme).¹⁻³ As an alternative to reactors, the possibility of using a small relatively simple to operate and inexpensive accelerator to supply epithermal neutrons of sufficient intensity and spectral quality is being pursued at a number of institutions⁴ including Brookhaven National Laboratory (BNL). Most of the designs would make the neutrons by the $^7\text{Li}(p,n)^7\text{Be}$ reaction at proton energies of 2.1–2.5 MeV, although in one case^{5,6} the proton energy of 1.91 MeV is just above the reaction threshold. Among several advantages, an accelerator-based BNCT facility would make this treatment more widely available, probably at less cost, and with greater flexibility in the treatment protocol. In connection with the BNL effort, which is based on the use of a small radio frequency quadrupole (RFQ) as the accelerator, the need arose for a phantom technique to compare the neutron energy spectra from the BMRR that were deemed appropriate for BNCT, to the neutron spectra from the RFQ.

Previous phantom designs have consisted of a container of water, a plastic cylinder or solid block, or some other arrangement of close to tissue-equivalent material. In all cases neutron, gamma, or other radiation detectors are then located at various points within the phantom. The Brookhaven Medical Department phantom³ consists of an acrylic 14-cm cube and depends on the neutron activation of gold foils. At the full 3-MW reactor power a typical exposure of bare Au foils within the phantom for 10 min gives sufficient activity from thermal neutron absorption for counting the 411-keV gamma rays, from the decay of ^{198}Au ,

by means of a well-type NaI(Tl) detector. For epithermal neutrons when the Au foils are wrapped with Cd foils, the exposure time is about 1 h.

An alternative to the foil activation method is to count the neutrons directly with a $^{10}\text{BF}_3$ detector. This has been done previously in water tank phantoms, as mentioned by Watkins *et al.*⁷ and by Wang *et al.*⁸ but few details were given. This type of detector uses the same $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction that destroys tumor cells in patient treatment, and due to the high thermal neutron cross section⁹ of 3837(9) b, one can expect good efficiency with small detectors. $\sigma_{n,\alpha}$ for ^{10}B follows¹⁰ a $1/v$ dependence from thermal energies up to about 300 keV with no resonances.

The main purposes of the present work were to design a phantom incorporating a $^{10}\text{BF}_3$ neutron detector, to obtain neutron depth distributions when this phantom was exposed to the epithermal beam at the BMRR, and to use those results as benchmarks to assist in the design and testing of accelerator-based BNCT facilities. An incidental purpose was to study the effect of phantom size on the thermal and epithermal neutron depth distributions by making measurements using two sizes of phantom.

PHANTOM DESIGN

One of our phantoms was designed so as to reproduce the Medical Department phantom both in size and type of material, i.e., an acrylic cube 14.0 cm on a side. The weight of this cube is 3.230 kg or ~2.3 times greater than the average human brain (~1.400 kg). As shown in the upper part of Fig. 1, a number of $\frac{1}{2}$ -in.-diam holes are drilled with centers at the indicated distances of 1 cm to 13 cm from one of the surfaces. The hole for the 6- and 8-cm depths is necessarily offset by 1.1 cm, but for those measurements the block can

Accelerator Based Neutron Source (ABNS) for BNCT

Preliminary Proposal

**Lucian Wielopolski
Jim Powell
Hans Ludewig
Deepak Raparia
James Alessi**

Brookhaven National Laboratory

Upton NY 11973

(February 5, 1998)

This is for proposing to build a real accelerator for BNCT.
The total cost was estimated at 5 M USD.

Experimental and Theoretical Evaluation of Accelerator Based Epithermal Neutron Yields For BNCT*

L. Wielopolski¹, H. Ludewig², J.R. Powell², D. Raparia³, J.G. Alessi³, D.E. Alburger⁴, M.S. Zucker², D. I. Lowenstein³

¹ Department of Applied Science, ² Department of Advanced Technology, ³ Alternating Gradient Synchrotron, ⁴ Department of Physics, Brookhaven National Laboratory, Bldg. 490, Upton NY 11973

At BNL, we have evaluated the beam current required to produce a clinical neutron beam for Boron Neutron Capture Therapy (BNCT) with an epithermal neutron flux of 10^{12} n/cm²/hr. Experiments were carried out on a Van de Graaff accelerator at the Radiological Research Accelerator Facility (RARAF) at Columbia University. A thick Li target was irradiated by protons with energies from 1.8 to 2.5 MeV. The neutron spectra resulting from the ⁷Li(p,n)⁷Be reaction, followed by various filter configurations, were determined by measuring pulse height distributions with a gas filled proton recoil spectrometer. These distributions were unfolded into neutron energy spectra using the PSNS code, from which the required beam currents were estimated to be about 5 mA. Results are in good agreement with calculations using the MCNP-4A transport code. In addition comparison was also made between the neutron flux obtained at the Brookhaven Medical Research Reactor (where clinical trials of BNCT are ongoing), and measurements at RARAF, using a ¹⁰BF₃ detector in a phantom. These results also support the requirement for about 5 mA beam current.

INTRODUCTION

Boron Neutron Capture Therapy (BNCT) is a promising binary treatment modality for high-grade primary brain tumors (glioblastoma multiforme, GM) and other cancers (1-3). BNCT employs a boron-10 containing compound that preferentially accumulates in the cancer cells in the brain. Upon neutron capture by ¹⁰B, energetic alpha particles and Li nuclei released at the absorption site kill the cancer cell. In order to gain penetration depth in the brain Fairchild proposed, for this purpose, the use of energetic epithermal neutrons at about 10 keV (4,5). Phase I/II clinical trials of BNCT for GM are underway at the Brookhaven Medical Research Reactor (BMRR) (6) and at the MIT Reactor, using these nuclear reactors as the source for epithermal neutrons.

In light of the objective limitations, such as cost, safety and licensing, of new reactor installations and limited capability for modulating the reactor based neutron beam energy spectra, alternative neutron sources are being contemplated for wider implementation of this modality in a hospital environment. For example, accelerator-based neutron sources offer the possibility of tailoring the neutron beams, in terms of improved depth-dose distributions, to the individual and offer, with relative ease, the capability of modifying the neutron beam energy and port size.

In previous work new concepts for compact accelerator/target configurations were published (7,8). In this work we have explored different materials for

filtering and reflecting neutron beams produced by the Li-7(p,n)Be-7 reaction, in the energy range 1.8 to 2.5 MeV. The MCNP-4A computer code was used for the initial design studies that were verified with benchmark experiments using a proton recoil spectroscopy detection system. Comparison was also made between in phantom ¹⁰BF₃ readings made at the BMRR and those made at the RARAF accelerator facility.

ANALYTICAL MODEL

The geometrical configuration of the target, filter and reflector assembly is shown in Fig. 1. This configuration was used for the Monte Carlo calculation and the experiments. In the second configuration the Be reflector was replaced with two Teflon and Fe disks, and in the third configuration both Mo and Be reflectors were replaced with two larger Teflon and Fe disks. In addition there was about 1 mm thick water layer for target cooling purposes. The model calculates the neutron energy spectrum at the beam port and is used to estimate the current required to deliver an epithermal neutron flux of 10^{12} n/cm²/s. The calculations were performed at several proton energies, although the main effort was directed to proton energies of 2.5 MeV. The MCNP code was run for 5 million histories and the results were normalized per one source neutron. To derive the beam current, a thick Li target neutron yield of 1.4×10^{-4} neutrons per proton at 2.5 MeV was used.

CP475, *Applications of Accelerators in Research and Industry*,
edited by J. L. Duggan and I. L. Morgan

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1033

A NEW ACCELERATOR BASED CANCER TREATMENT (BNCT) TEST & DEMONSTRATION FACILITY

Boron Neutron Capture Therapy (BNCT) is a novel form of targeted radiotherapy which uses low energy neutrons to activate a boron containing drug delivered to a tumor. Because of the boron containing compound which is preferentially absorbed by the tumor, this technique enhances the radiation dose delivered to cancer cells while minimizing any damage to nearby healthy cells. There are at present five treatment centers worldwide, all using nuclear reactors as the source of the neutron beam. In clinical trials at Brookhaven National Laboratory (BNL), promising results have been obtained for the treatment of glioblastoma multiforme (GBM), a type of brain tumor with a very poor prognosis. At Massachusetts Institute of Technology promising results have also been obtained in the treatment of metastatic malignant melanoma. Treatment of other tumor types with BNCT is presently being investigated. If BNCT is ever to become a practical treatment, another source of neutrons (other than a nuclear reactor) is needed, such as a proton particle accelerator using a neutron generating target. The main advantages to using an accelerator based system are the ease of siting at or near hospitals (already in limited use), low system cost, and flexibility for satisfying various clinical requirements. The quality of the neutron beam produced by an accelerator based system is also more effective in the treatment process. Furthermore, it is not likely that any new reactors will be constructed in the US within the foreseeable future.

BNL and Advanced Energy Systems Inc. (AES) propose to construct a prototype accelerator based BNCT demonstration facility located at BNL (Figure 1).

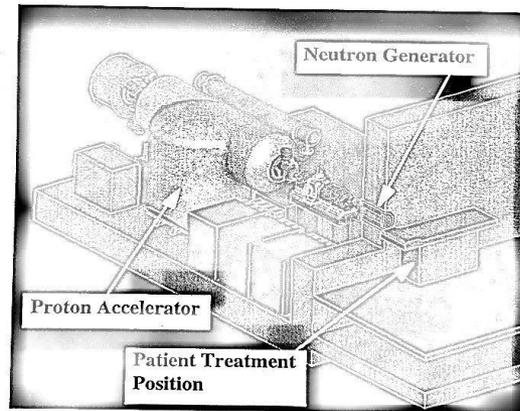


Figure 1: Proposed BNCT Test & Demonstration Facility

Jointly Prepared by
Brookhaven National Laboratory & Advanced Energy Systems, Inc.
January 29, 1999

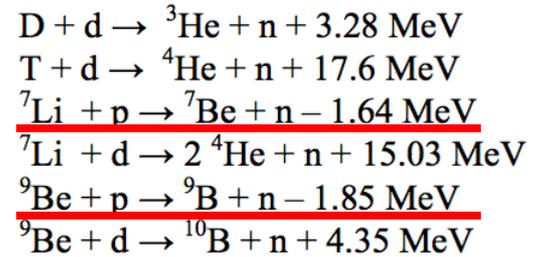
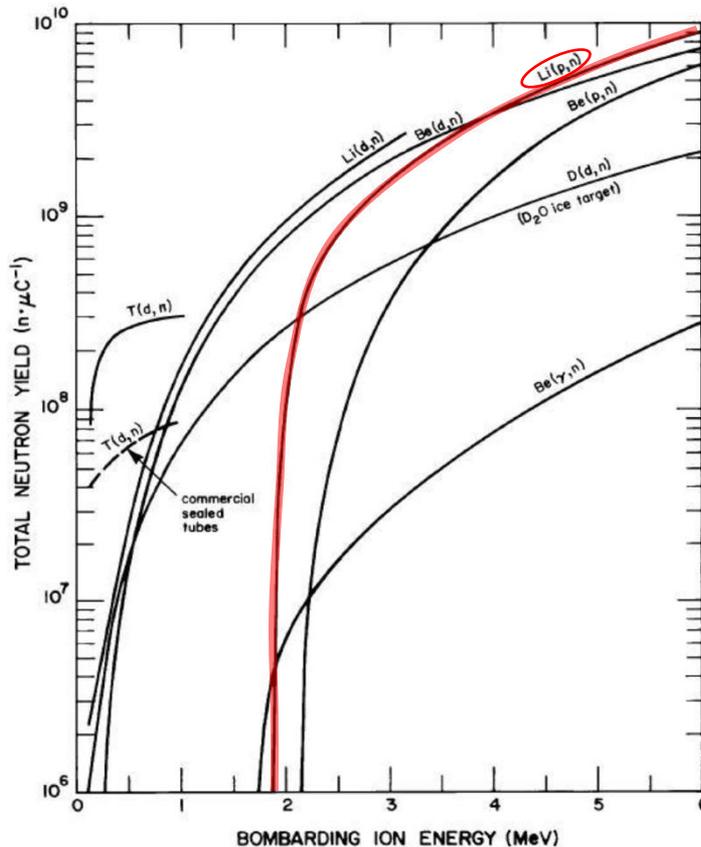
Another proposal teamed with a private company.
It uses an electrostatic accelerator, 1.9 – 2.3 MeV

Background

- Kinematic focusing of neutron is very effective for a compact generator.
 - use lithium beam instead of proton beam
- CAD/BNL has developed high current highly charged ion source.
 - direct plasma injection scheme (DPIS) ,
comparable peak current to proton accelerators
 - laser ion source has provided stable beams for more than 9 years
- By combining kinematic focusing and laser ion source,
a novel **compact neutron generator** can be realized.

Why lithium or beryllium?

Neutron yield and driver beam energy

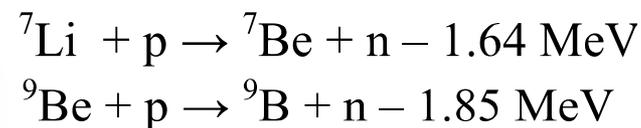
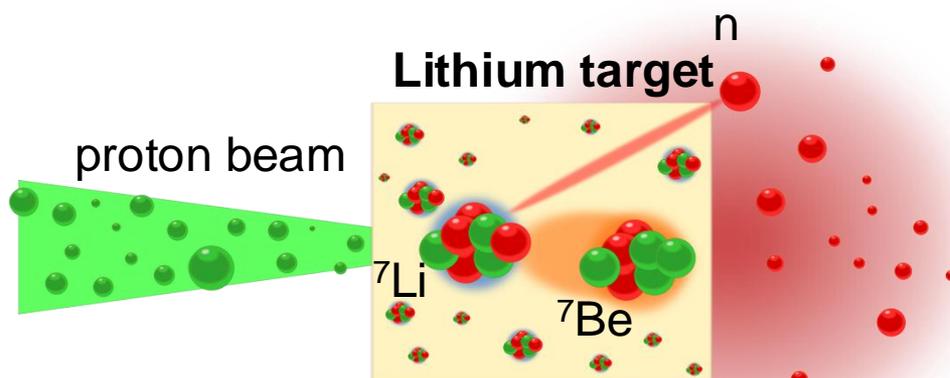


Endothermic reaction (negative energy emission)

Fig. 1. The thick target neutron yield as a function of bombarding ion energy for various low energy nuclear reactions [1].

Yubin Zuo et al. / Physics Procedia 60 (2014) 220 – 227

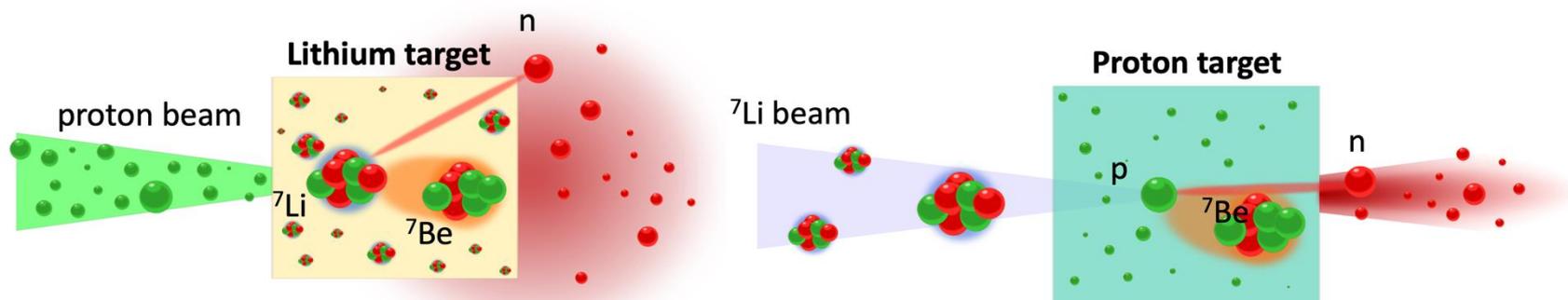
Neutron production with proton beam



Isotropic neutron production

- These reactions are endothermic and undesired radiations could be reduced if beam energy is near the thresholds.
- However, since the proton is lighter than target atoms, the neutrons are produced almost isotropically and only small fraction can be used.
- Therefore, higher beam energy is used to increase neutron flux. (causing undesired radiations)¹⁸

Neutron source with heavy ion driver



Isotropic neutron production

High directivity neutron

- When heavy ions are delivered, neutrons are directed to forward because of the high gravity center velocity.
- Neutron flux can be increased while beam energy is kept near the threshold.



Development of a kinematically focused neutron source with the $p(^7\text{Li},n)^7\text{Be}$ inverse reaction

M. Lebois ^{a,*}, J.N. Wilson ^a, P. Halipré ^a, B. Leniau ^a, I. Matea ^a, A. Oberstedt ^{c,d}, S. Oberstedt ^b, D. Verney ^a

^a Institut de Physique Nucléaire d'Orsay, 15 Rue G. Clémenceau, 91406 Orsay Cedex, France
^b Institute for Reference Materials and Measurements, Retieseweg 111, 2440 Geel, Belgium
^c CEA/DAM Ile-de-France, 91297 Arpajon Cedex, France
^d Fundamental Physics, Chalmers University of Technology, 41296 Göteborg, Sweden

• 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

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

3.1. Target heat evacuation

For conventional, isotropic neutron sources using the non-inverse reaction solid targets are usually thermally coupled to the beam stop and many tens of Watts of power must be evacuated. Target cooling with a flow of air or water is essential. However, in inverse kinematics the ^7Li beams have very much reduced power (factor of 100) so the amount of heat to be evacuated from the target is significantly decreased. Therefore, a thermal coupling between target and beam stop is no longer required. With a thermally decoupled target only a few tens of milliwatts will be deposited and thus radiative cooling will be sufficient without large rises in target temperature. For example, 100 nA of ^7Li on 4.4 μm of polypropylene or 1–3 μm of TiH_2 leads to a deposited power of 16 mW. The most pessimistic assumption is that the target undergoes a radiative cooling process only. In that case, the temperature depends only on the material emissivity and the temperature at thermal equilibrium can then be calculated. Considering an environment with an ambient temperature of 293 K, for both targets the equilibrium temperature is around 5 degrees higher at 298 K. This value is small compared to the melting point of the target and thus heat generation in the target is not a major problem and a cooling system is not required.

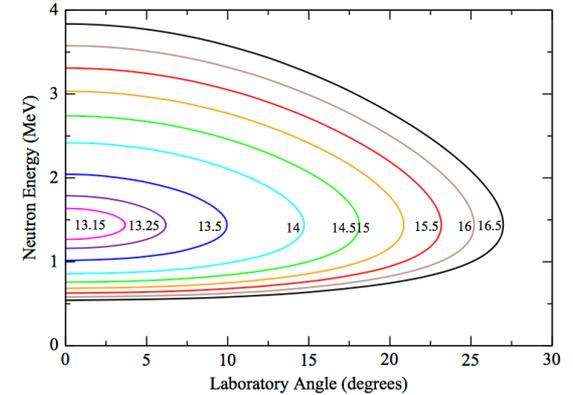


Fig. 1. Kinematic curves relating the angle of neutron emission to neutron energy in the laboratory frame for different ^7Li bombarding energies from 13.15 to 16.5 MeV, calculated using two-body relativistic kinematics.

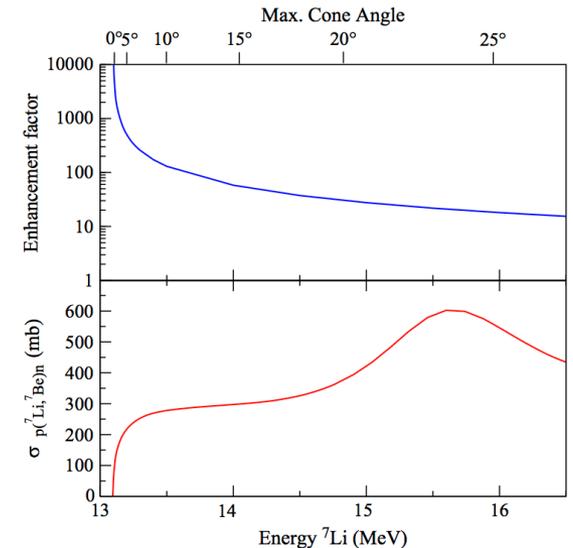
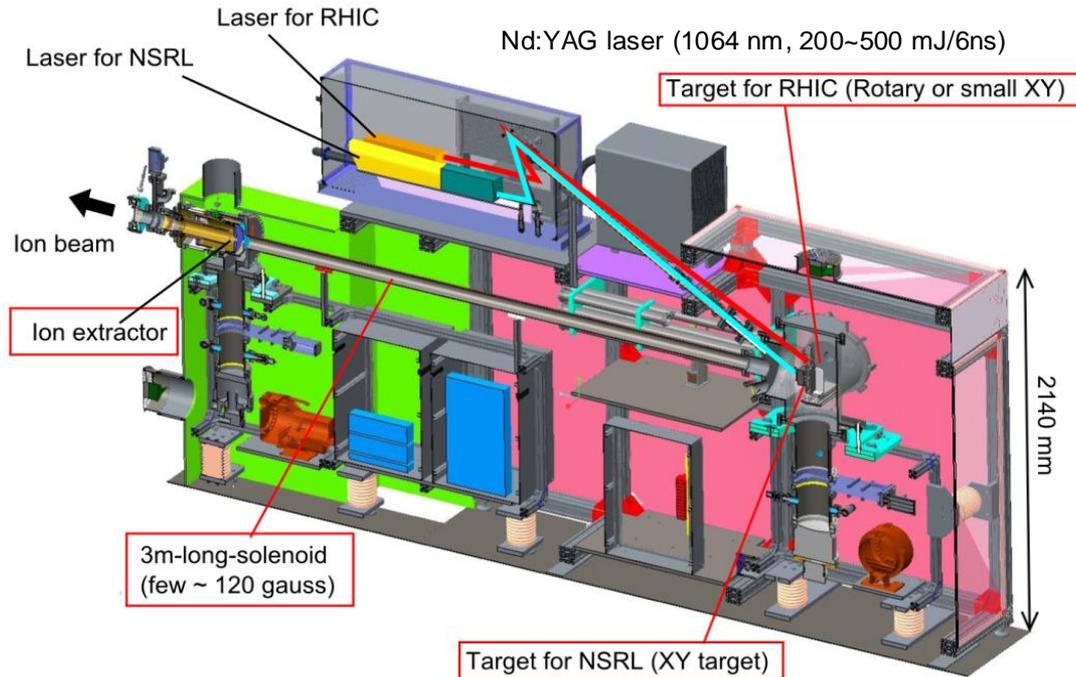


Fig. 2. The top panel shows the enhancement factor of the neutron flux between the inverse kinematic and the direct kinematic reaction as a function of ^7Li bombarding energy. The bottom panel shows the $p(^7\text{Li},^7\text{Be})n$ reaction cross-section over the same energy range.

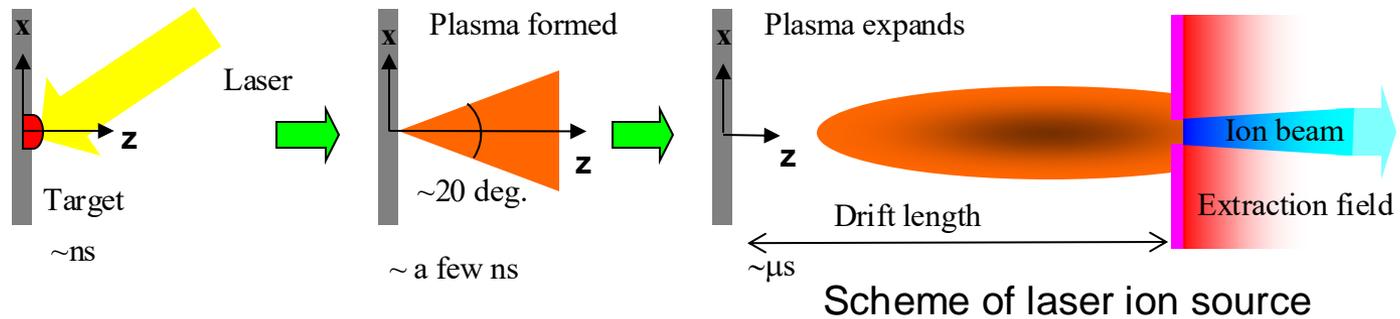
BNL has a long experience for providing stable beams from a laser ion source.

Laser Ion Source development at BNL



- The first beam in 2014 (since then no major maintenances on beam extractors)
- Pressure <math> < 10^{-4}</math> Pa
- Species switching within a few second, more than 20 species.
- No coupling between beam for RHIC and NSRL

Advantages of laser ion source (LIS)



- High density plasma created from a solid.
- Fast switching target materials.
- Low temperature after adiabatic expansion.
- Uniform density of beams.

Solenoid plasma guide plus DPIS

APPLIED PHYSICS LETTERS **105**, 193506 (2014)



Laser ion source with solenoid field

Takeshi Kanesue,^{1,a)} Yasuhiro Fuwa,^{2,3} Kotaro Kondo,⁴ and Masahiro Okamura¹

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²Graduate School of Science, Kyoto University, Kitashirakawa, Sakyo, Kyoto 606-7501, Japan

³RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

⁴Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8550, Japan

(Received 27 August 2014; accepted 27 October 2014; published online 12 November 2014)

Pulse length extension of highly charged ion beam generated from a laser ion source is experimentally demonstrated. The laser ion source (LIS) has been recognized as one of the most powerful heavy ion source. However, it was difficult to provide long pulse beams. By applying a solenoid field (90 mT, 1 m) at plasma drifting section, a pulse length of carbon ion beam reached 3.2 μ s which was 4.4 times longer than the width from a conventional LIS. The particle number of carbon ions accelerated by a radio frequency quadrupole linear accelerator was 1.2×10^{11} , which was provided by a single 1 J Nd-YAG laser shot. A laser ion source with solenoid field could be used in a next generation heavy ion accelerator. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4902021>]

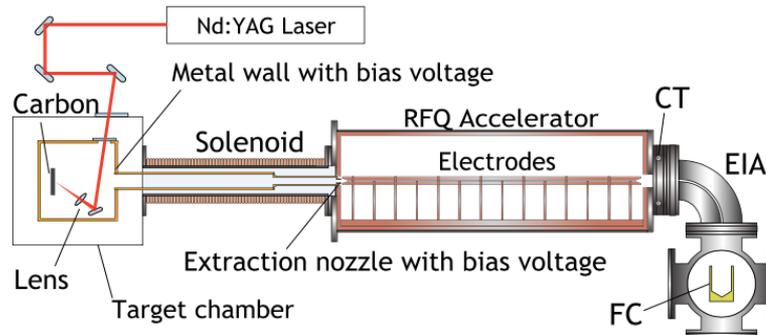


FIG. 3. Setup for ion acceleration by RFQ.

We have demonstrated that 1.2×10^{11} of C^{4+} can be provided by a single laser shot.

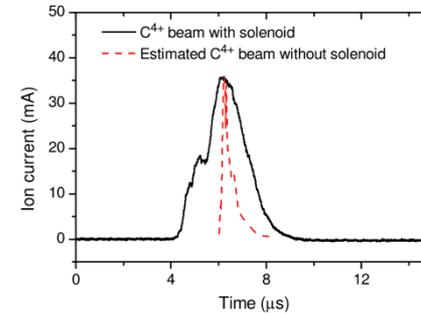


FIG. 5. C^{4+} beam with and without solenoid under the same laser irradiation condition. The wave form without solenoid is estimated based on the plasma measurement.

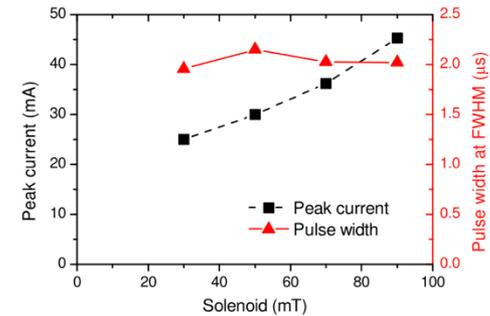


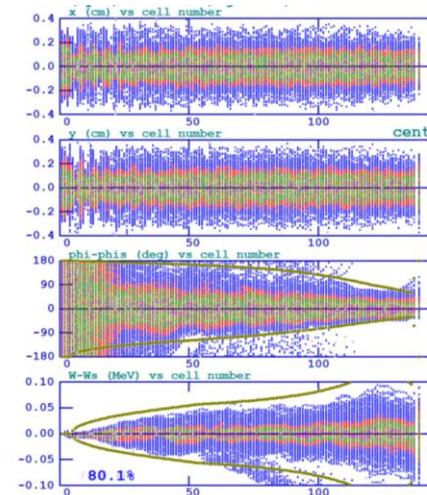
FIG. 6. CT peak current and pulse width at FWHM as a function of solenoid field.

Electrodes were designed for Li^{3+}

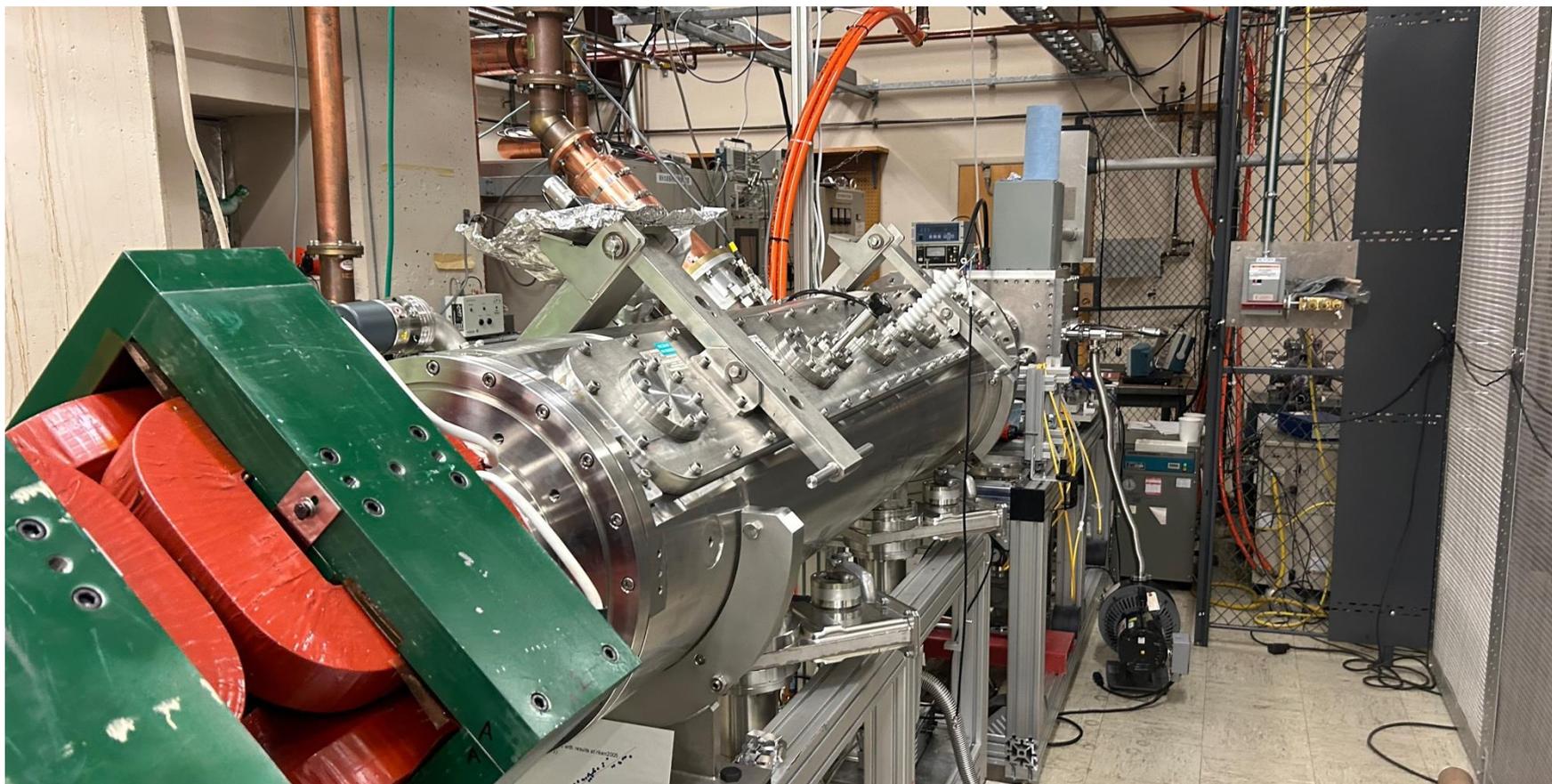
To demonstrate acceleration of high current lithium beam, we developed RFQ electrodes. It was predicted that the RFQ accelerates 40 mA of ${}^7\text{Li}^{3+}$ beam.

Basic parameters of RFQ

Parameter	Value
Structure	4 Rod
Frequency	100 MHz
Input energy	22 keV/n
Output energy	204 keV/n
Input beam current	50 mA
Transmission	80 %
RFQ length	1977 mm



Analyzing beam line with the RFQ



Lithium target exposed to the air

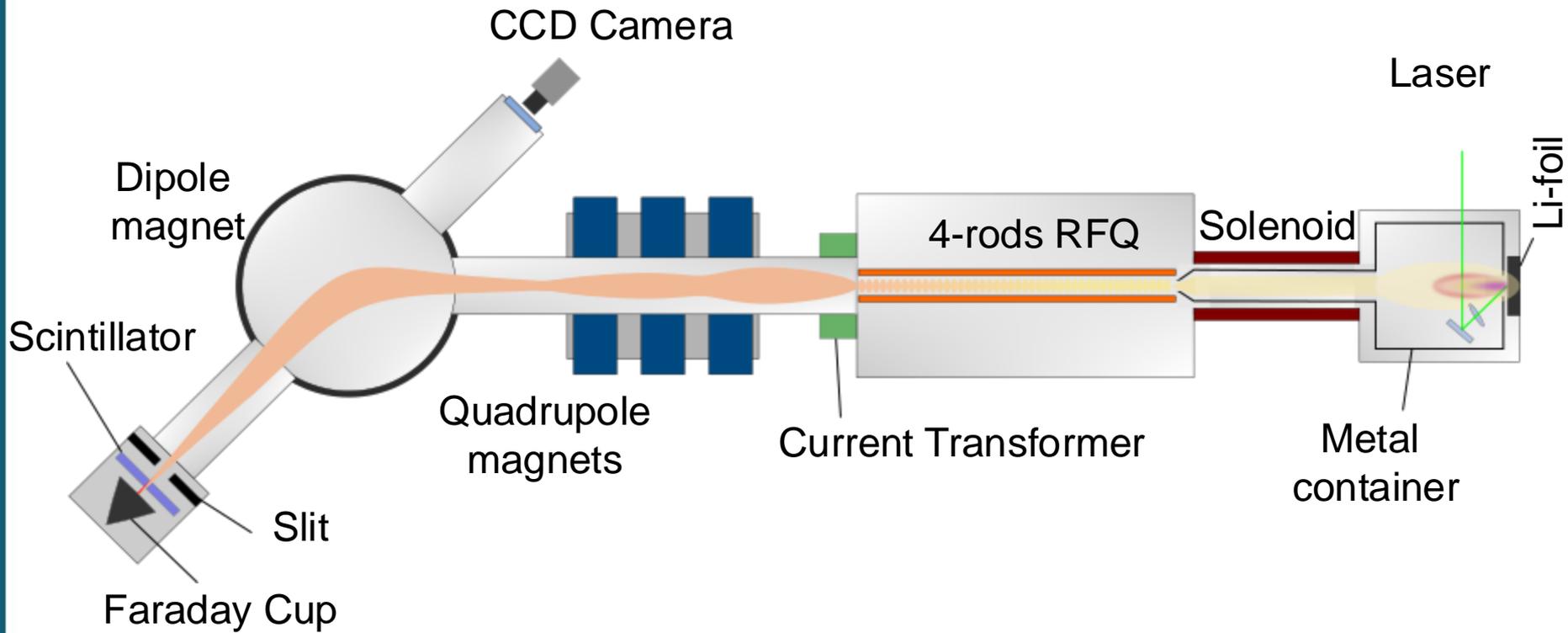
6 min



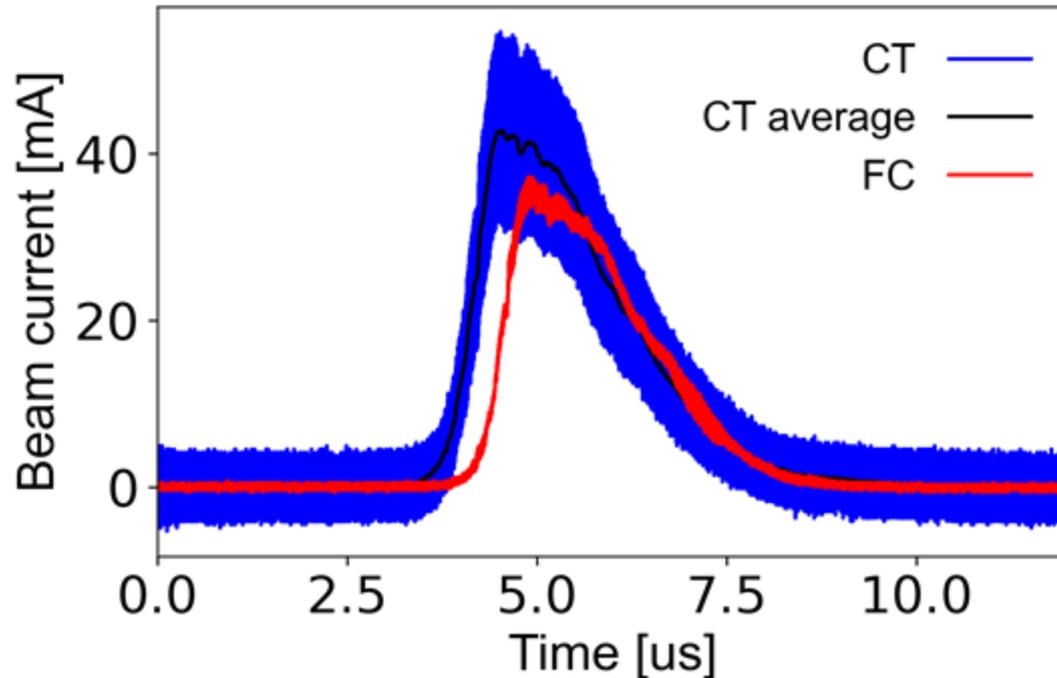
30 min



Acceleration test setup



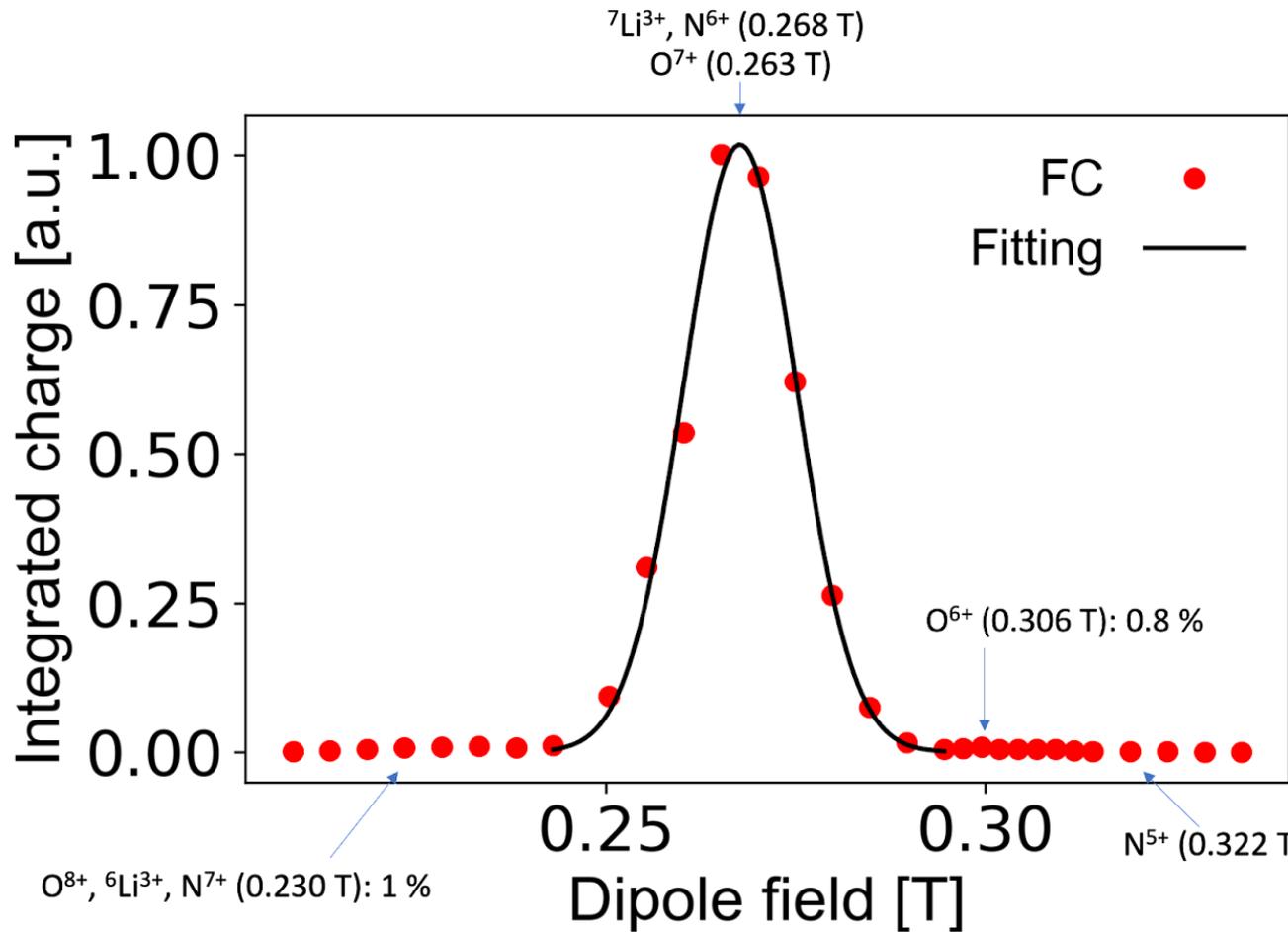
Accelerated 7Li^{3+} beam (parameters from target to FC were optimized for 7Li^{3+})



- Laser
 - Thales
 - QS220 us,
 - 1.6 J at laser exit (~ 0.8 J at target)
- Solenoid : 15 A (790 G)
- Extraction voltage : 52 kV
- RF power : ~ 100 kW
- Q1 : 8A
- Q2 : 13.2 A
- Q3 : 6.8 A
- Dipole : 110 A (2.7 kG)
- Ring bias : -400 V

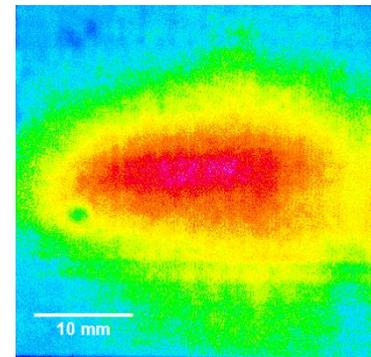
CT peak : 43 mA, 95 nC
FC peak : 35 mA, 74 nC
FWHM : 2.0 us

Analyzed beam

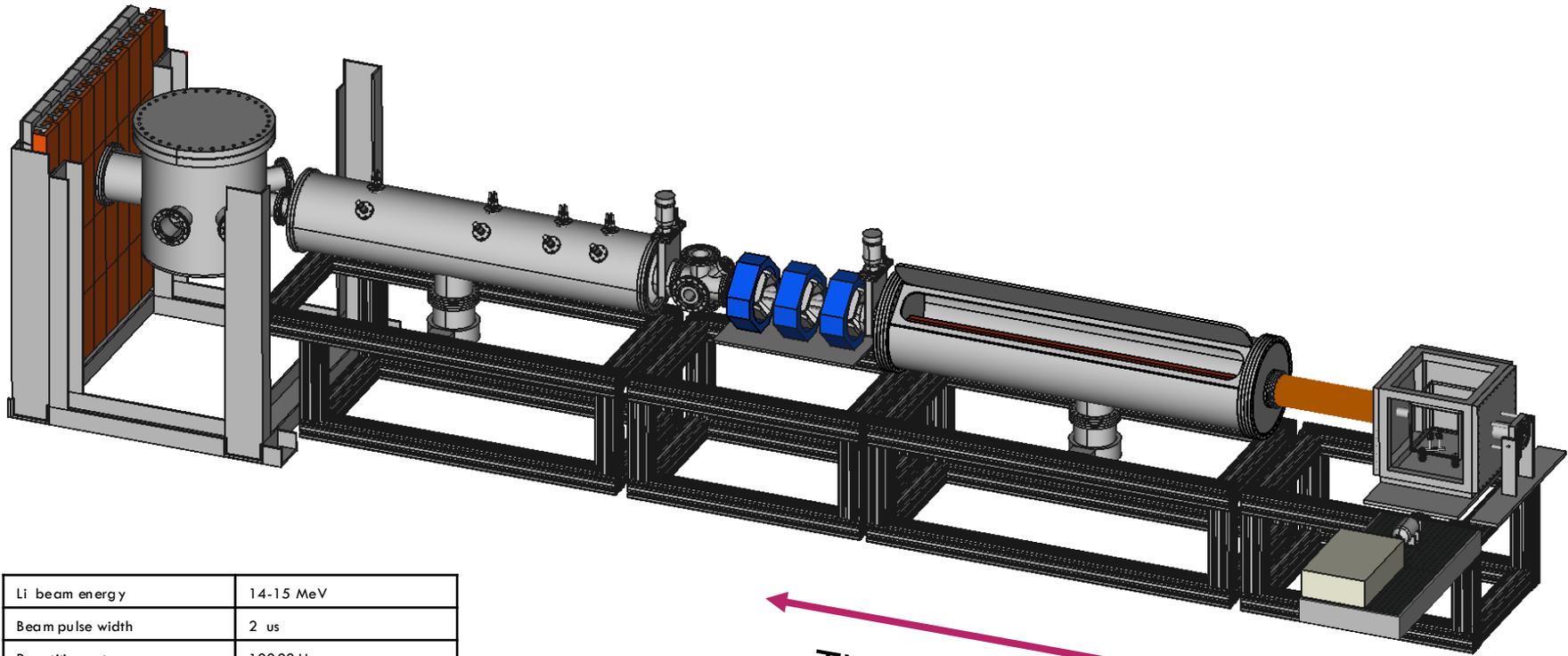


Ion	Q/A
O^{8+}	0.500
${}^6\text{Li}^{3+}$	0.500
N^{7+}	0.500
O^{7+}	0.438
${}^7\text{Li}^{3+}$	0.429
N^{6+}	0.429
O^{6+}	0.375
N^{5+}	0.357
${}^6\text{Li}^{2+}$	0.333
O^{5+}	0.313
${}^7\text{Li}^{2+}$	0.286
N^{4+}	0.286

➡ Contamination ~ 2 %



15 MeV lithium driver neutron generator



Li beam energy	14-15 MeV
Beam pulse width	2 μ s
Repetition rate	10000 Hz
Peak ion beam current	35 mA
Average ion beam current	70 μ A
Neutron energy	1 MeV -5 MeV
Average neutron flux	7×10^{10} n/s/sr

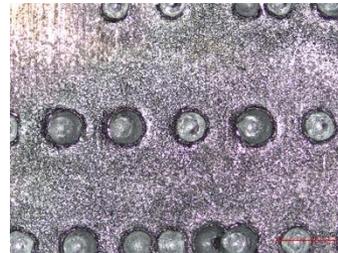
This part was completed

BNL-CANS project started 2022

Liquid target feasibility

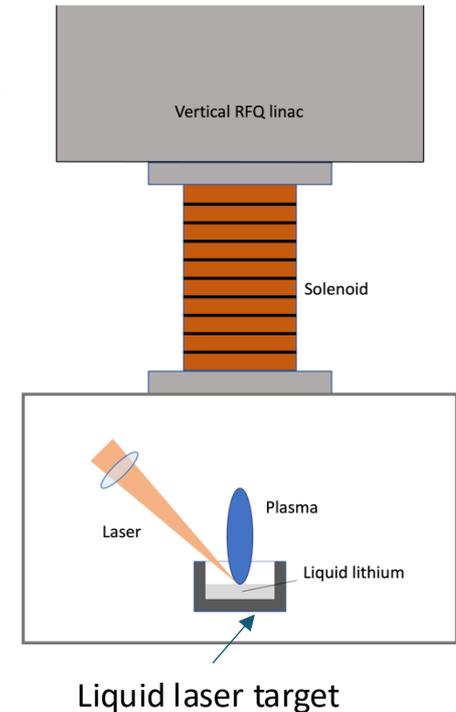
Limitation of rep. rate ~ 100 Hz with solid target,

- moving target every laser shot,
- Limitation of rep rate and lifetime,



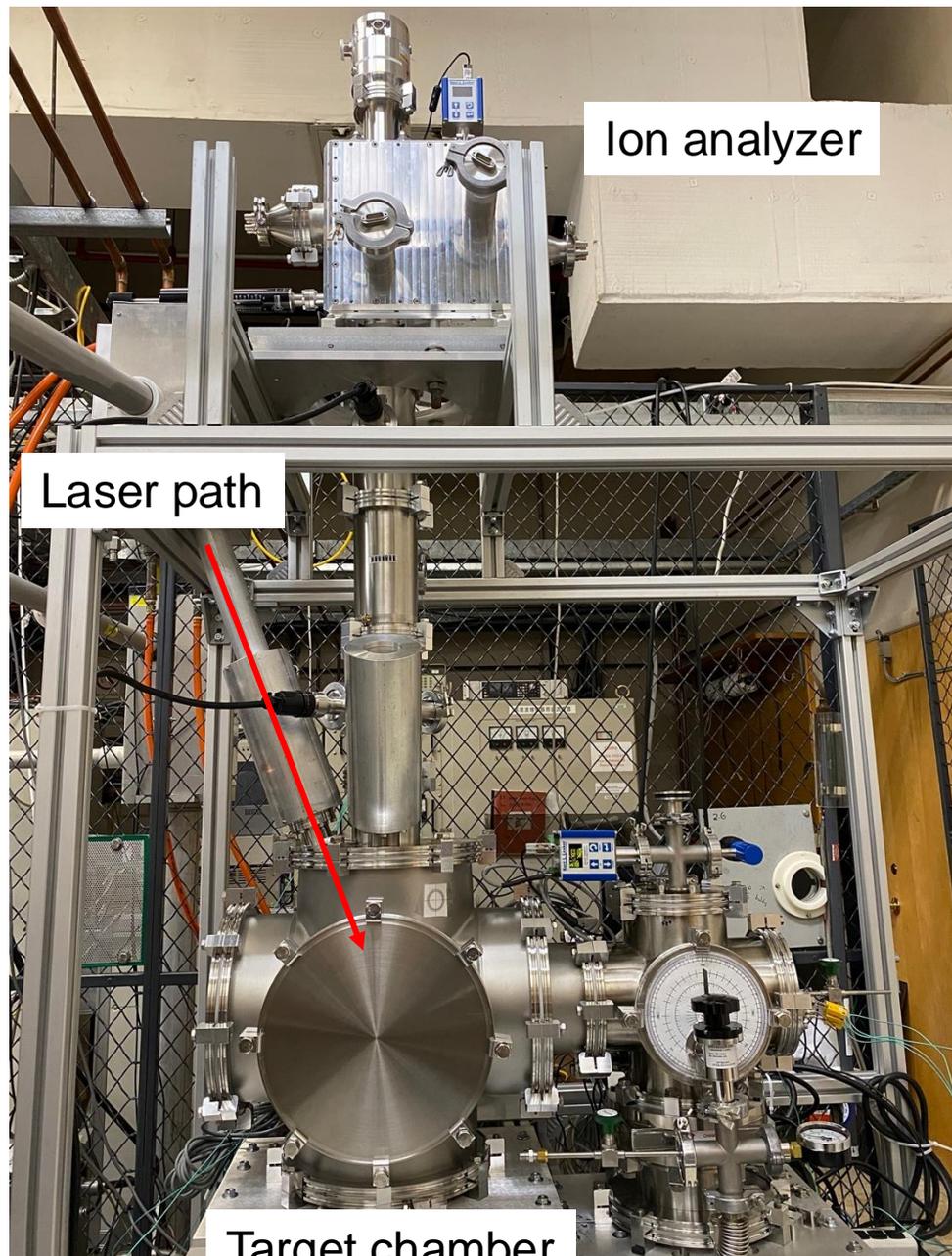
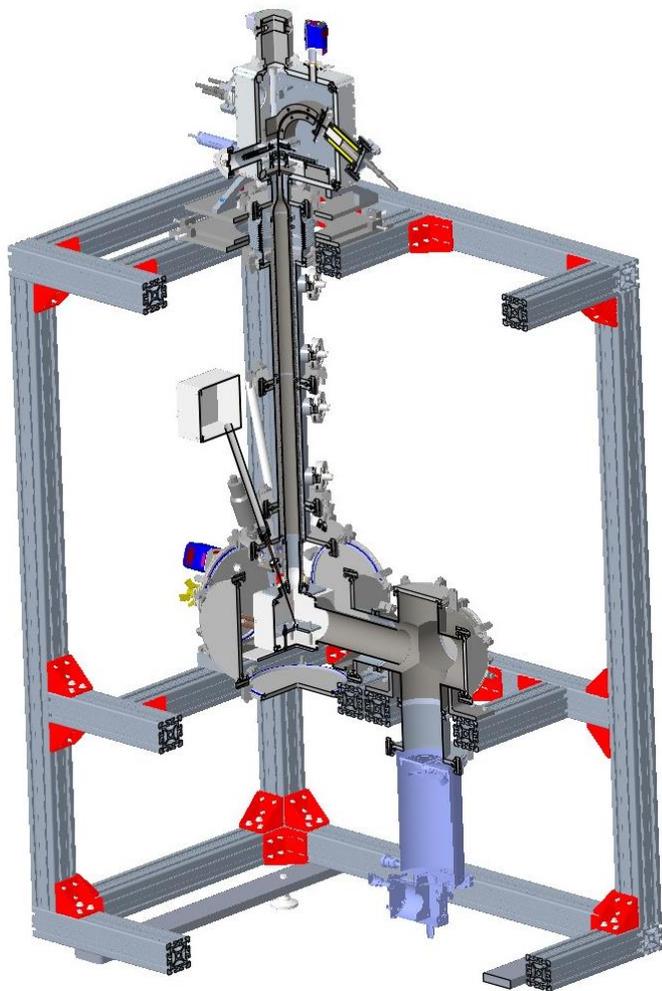
Liquid target to overcome limitation,

- Surface recovers itself,
- Same spot every shot.



Basic study on laser ablation with liquid target is being conducted.

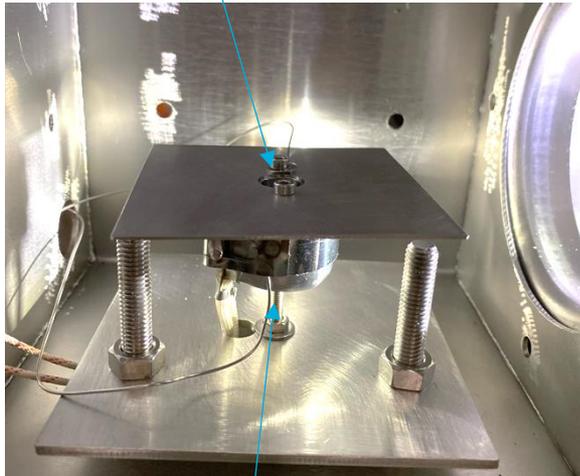
Experiment for basic study



Experiment for basic study

SS pipe + sheathed heater + copper cover

Crucible (Mo) in target chamber

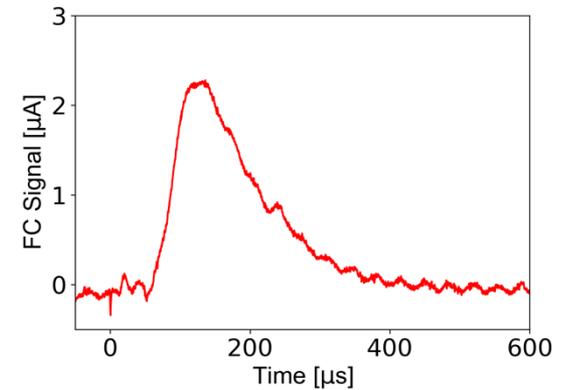
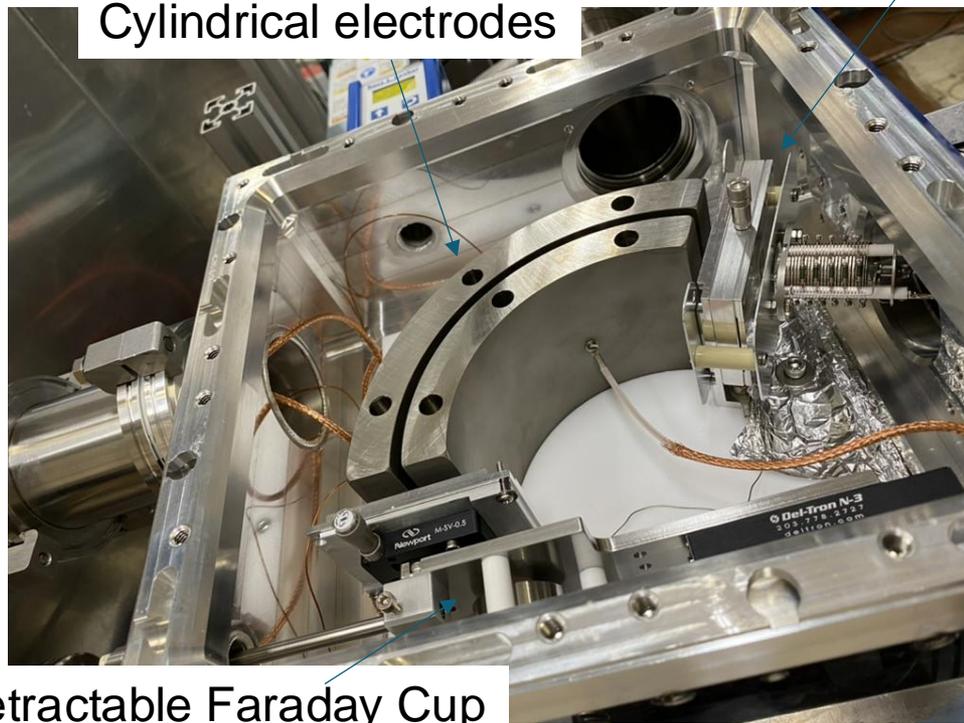


Band heater

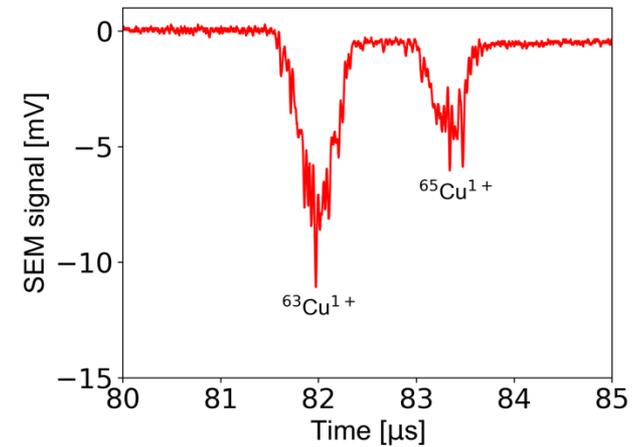
Heating crucible and vertical pipes to 200° C in sufficient vacuum was confirmed.



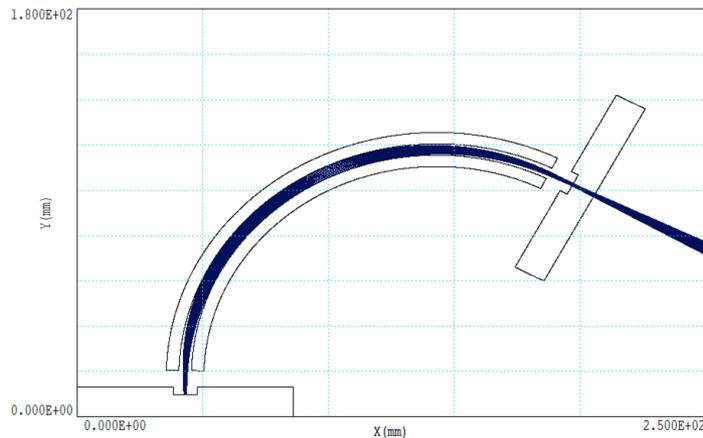
Electrostatic ion analyzer to measure contents of lithium plasma



Faraday cup signal

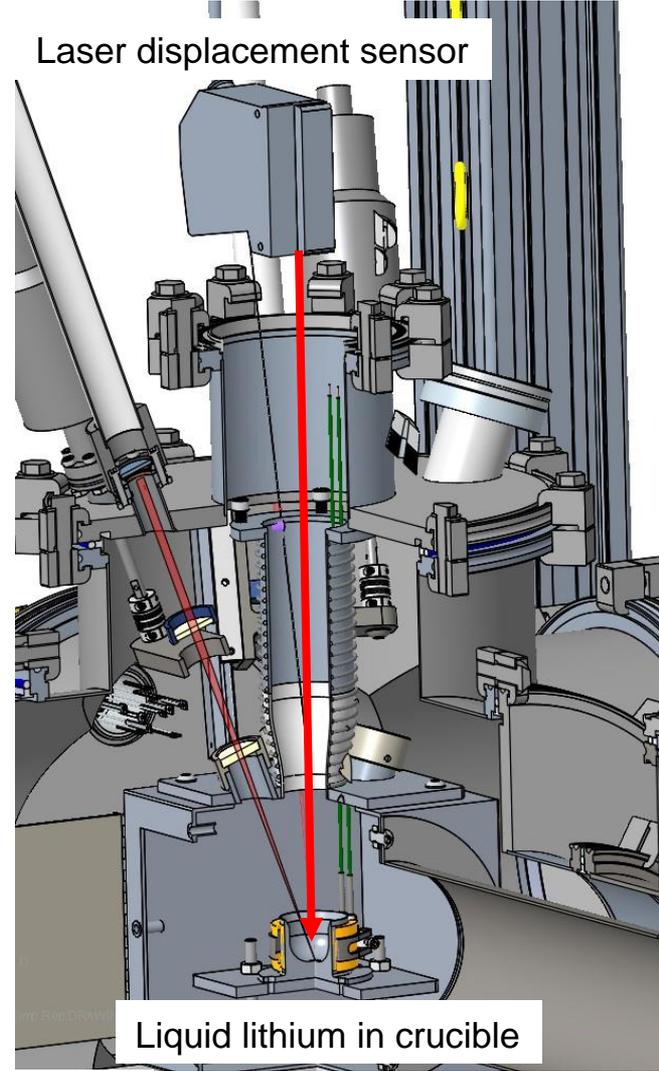
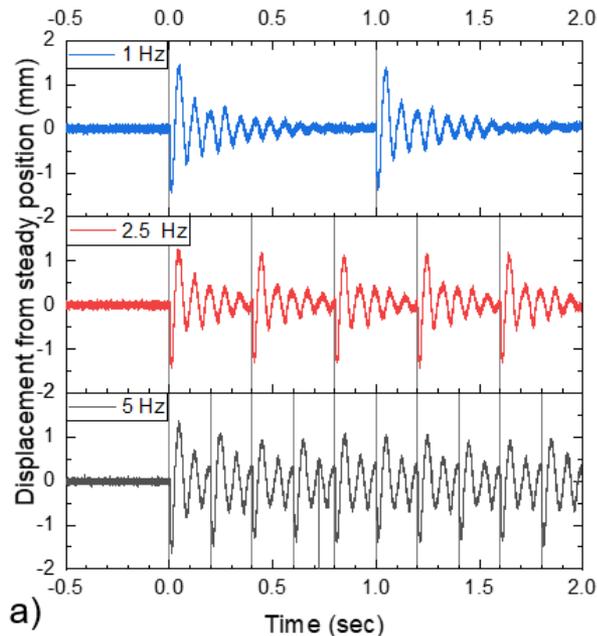


Separation of copper isotopes
= sufficient resolution for lithium plasma

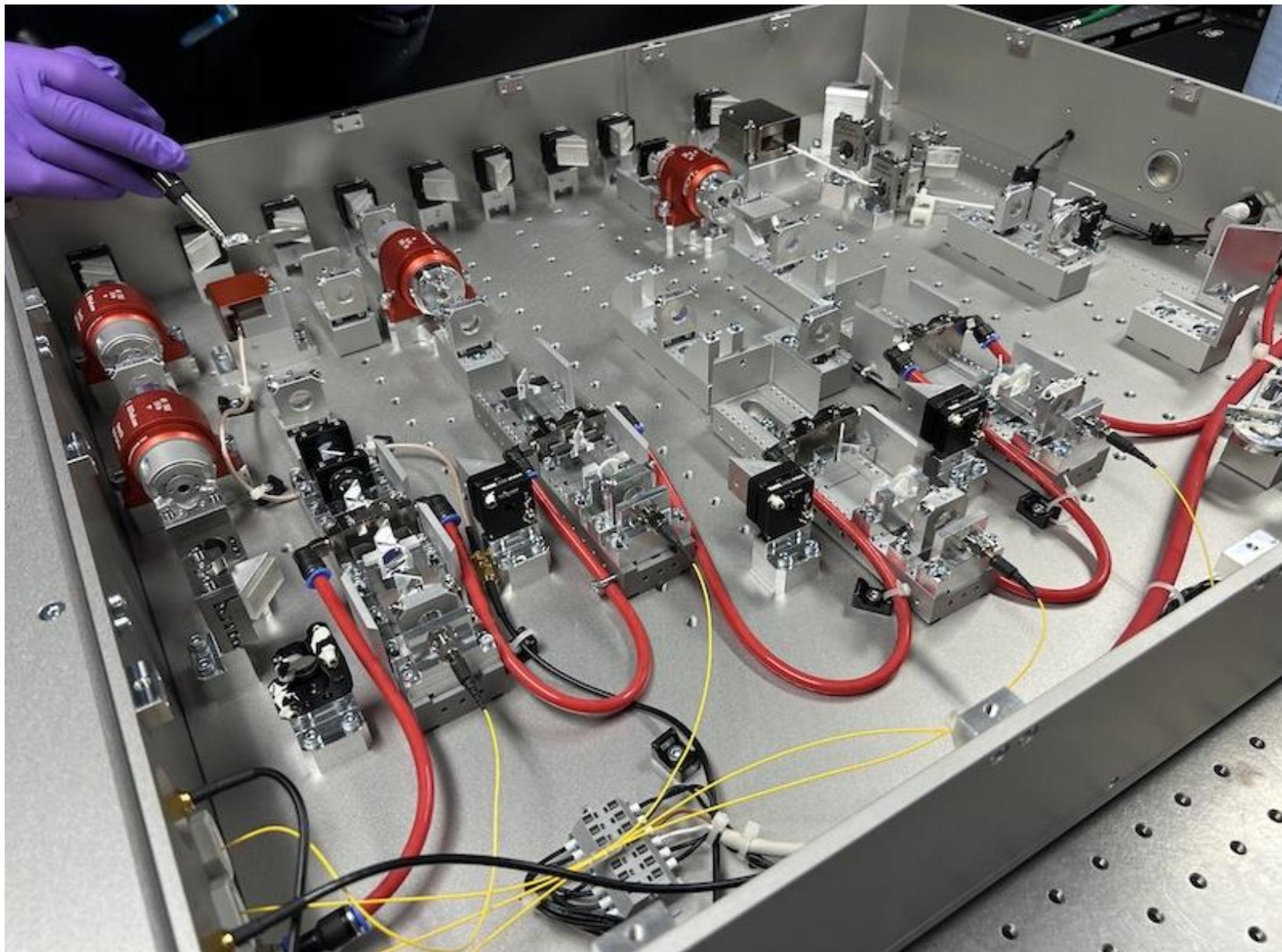


Surface oscillation measurement

- Surface oscillation excited by laser will be measured with a laser displacement sensor
- 0.1 mm accuracy, 0.3 mm spot, 1 kHz sampling



Measurement test result with liquid Ga.
Periodic structure is a good sign for reproducibility.



On going R&D 2

How high a beam current can we achieve?

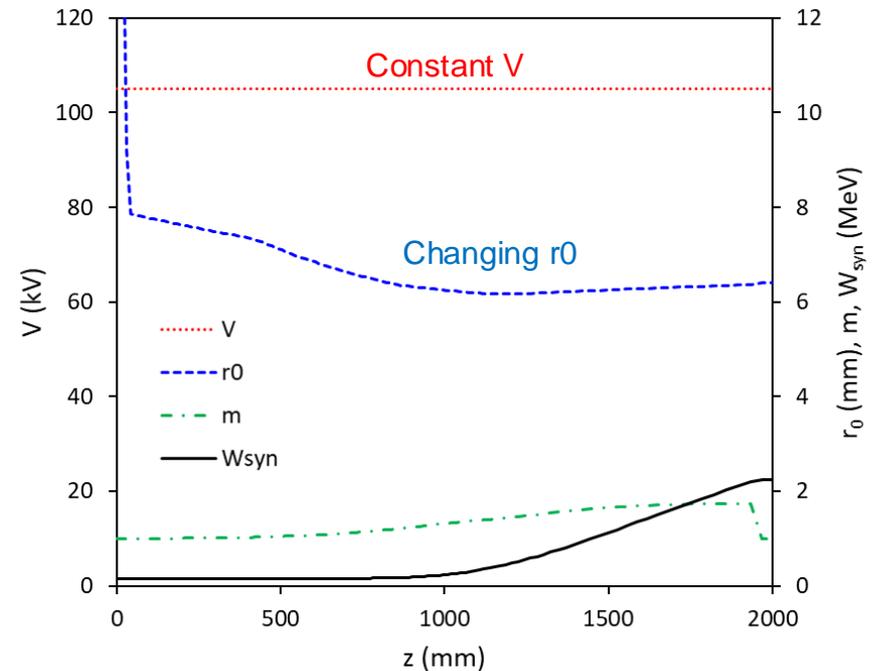
New RFQ electrode was designed and fabricated

Design criteria

- Max $m/q = 7/3$ (assuming ${}^7\text{Li}^{3+}$)
- Target output peak current > 100 emA
- Extraction voltage ~ 50 kV
- 100 MHz
- Transmission $\sim 75\%$ inter-vane voltage of 105 kV
- Kilpatrick factor less than 2
- 2 m long
- Output energy above 300 keV/n

Variable focusing force strategy

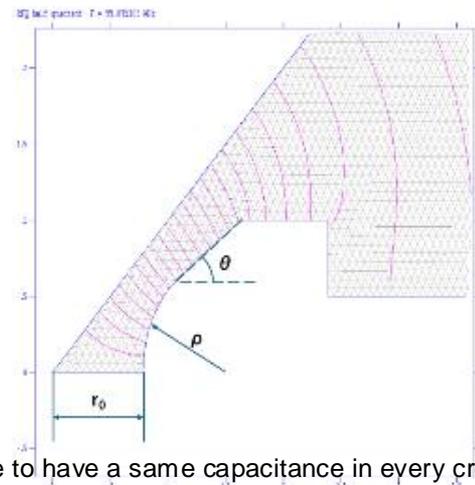
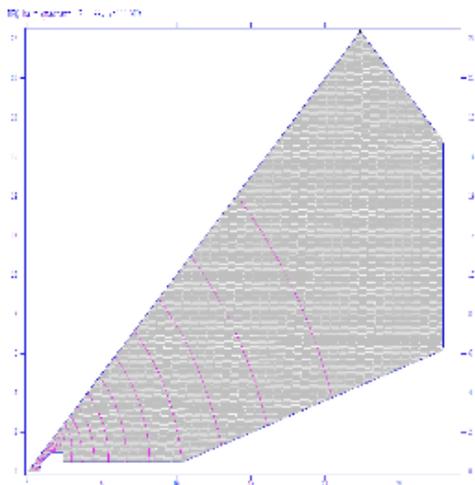
Resonant frequency	100 MHz
Accelerated particle	${}^7\text{Li}^{3+}$
Peak beam current	≥ 100 emA
Input energy	21.8 keV/u
Output energy	320 keV/u
Input normalized rms emittance	0.33 mmmrad
Number of cells	138
Rod length	1997.5 mm
V	105 kV
r_0 (without RMS)	6.2-7.8 mm
Transverse vane-tip curvature	Variable ($\leq 1.0r_0$)
E_{max} (Kilpatrick factor)	≤ 22.3 MV/m (1.96)



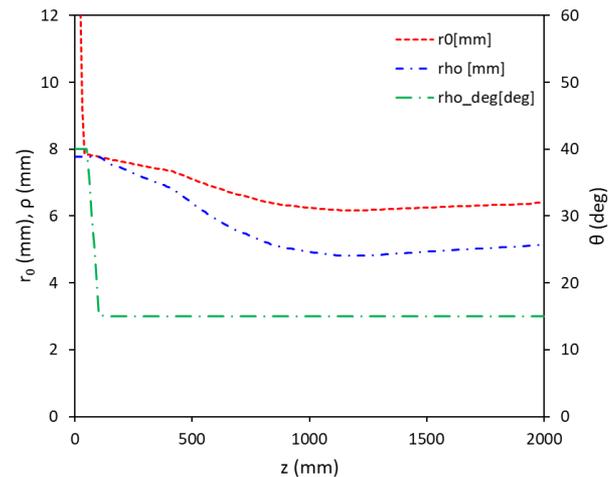
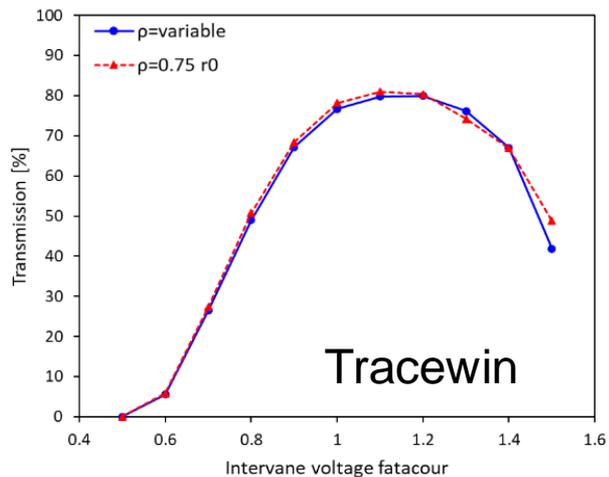
Vane voltage is always constant, but the beam aperture varies from place to place.

Total 138 cells

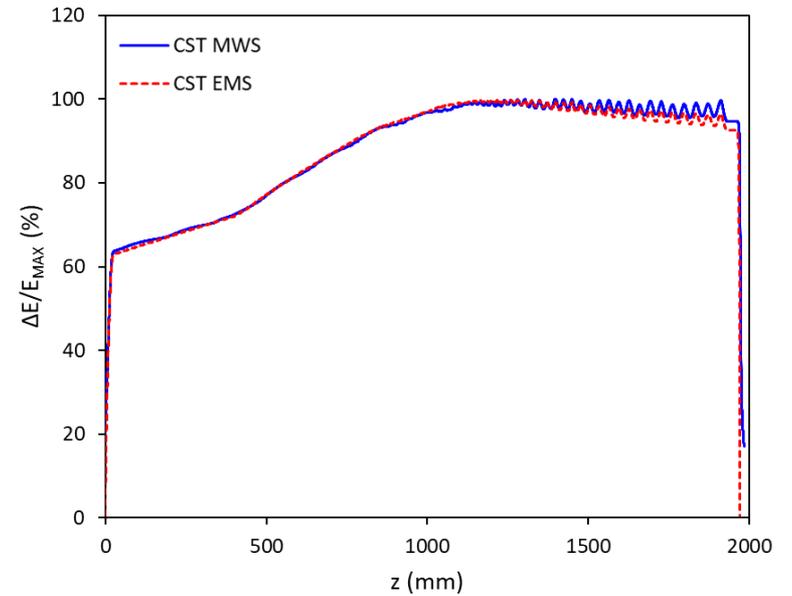
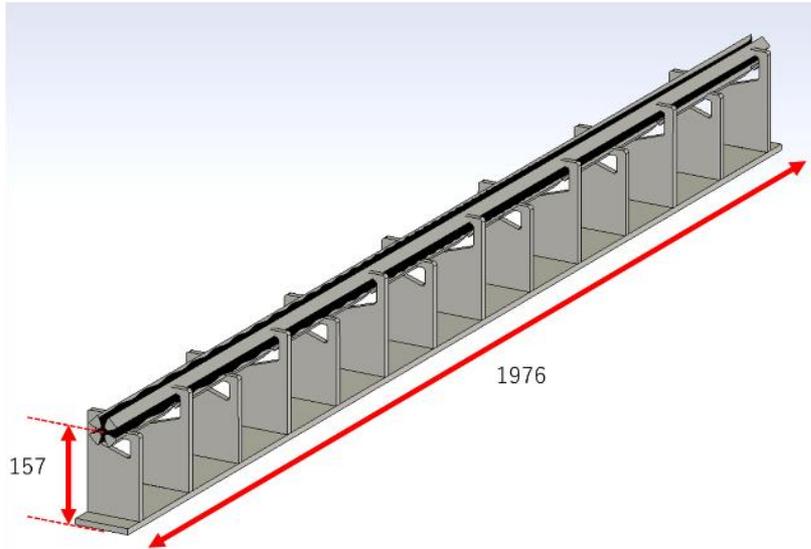
Vane tip geometry of each cell was optimized 2D simulation code assuming 4 vane structure.



Simulate to have a same capacitance in every cross-section.

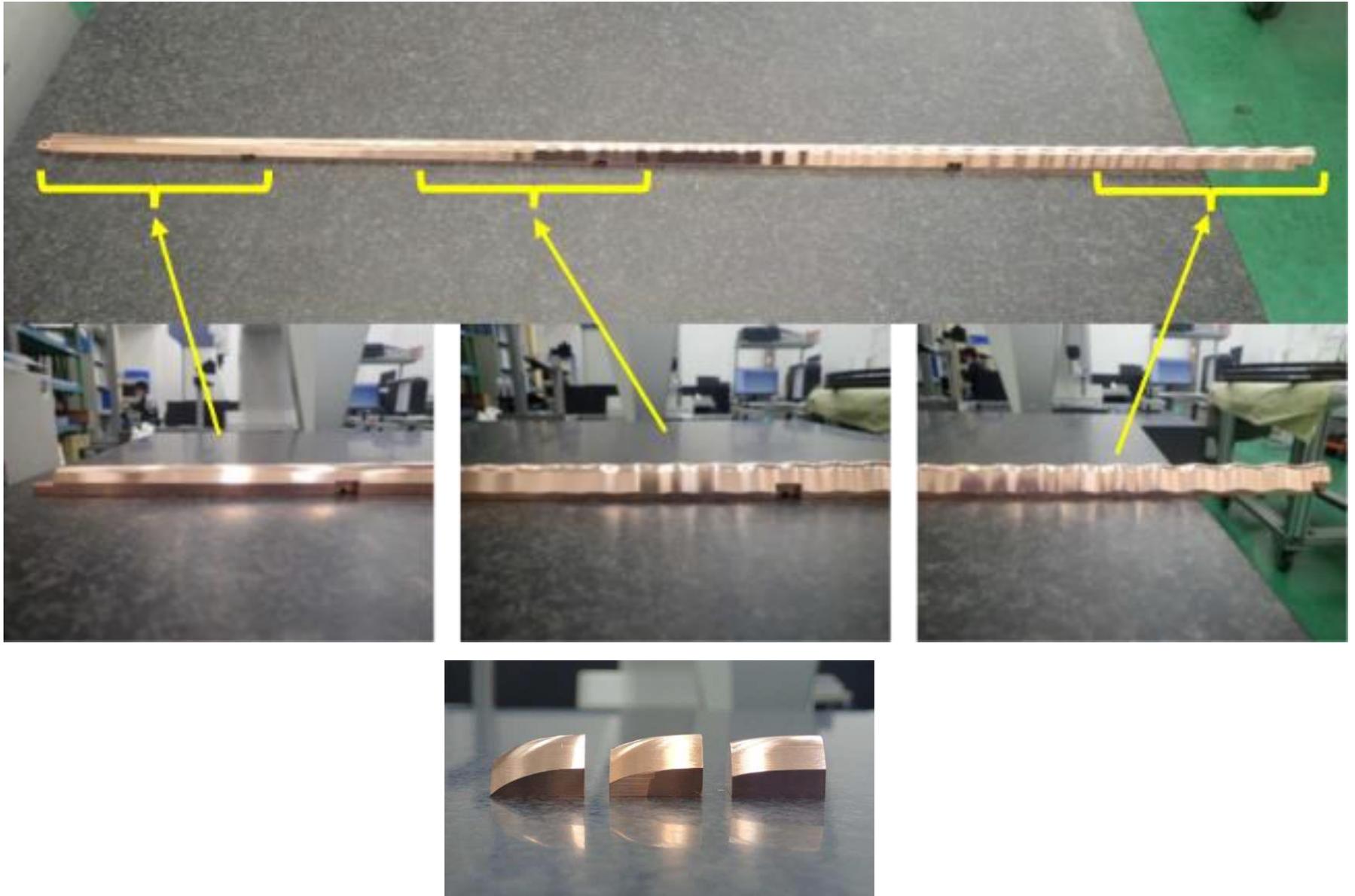


The cross-sectional shape of Vane varies with location.

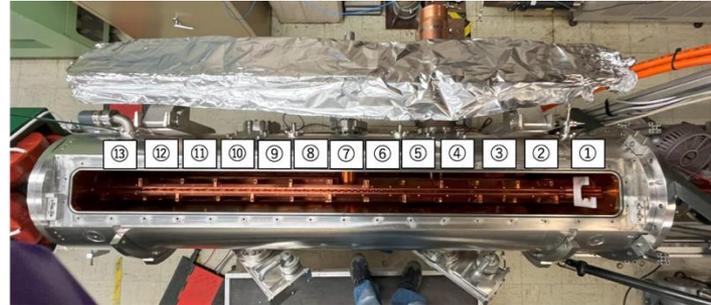


Full 3D calculation vs. forced constant voltage

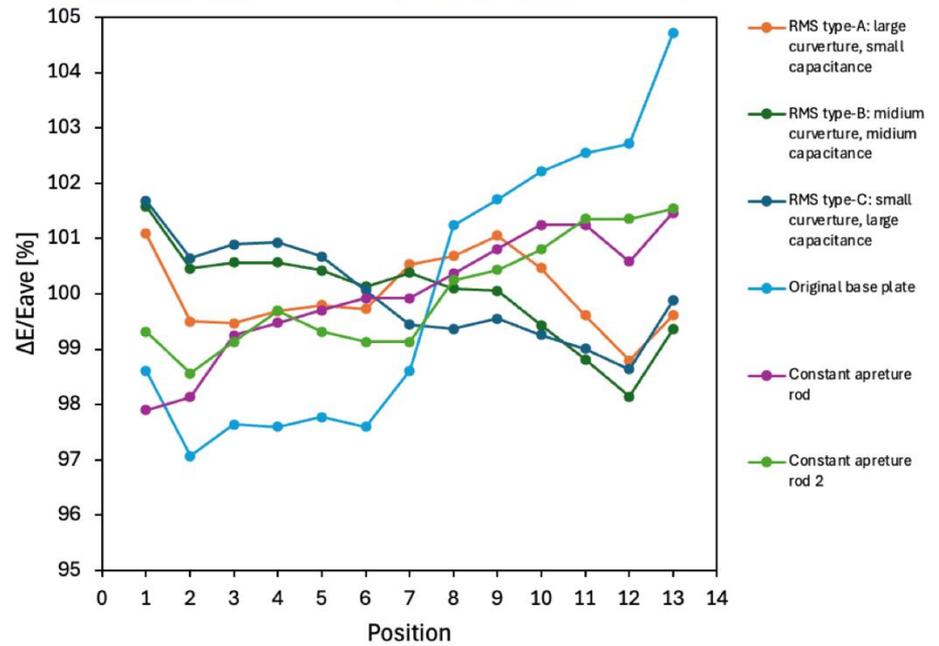
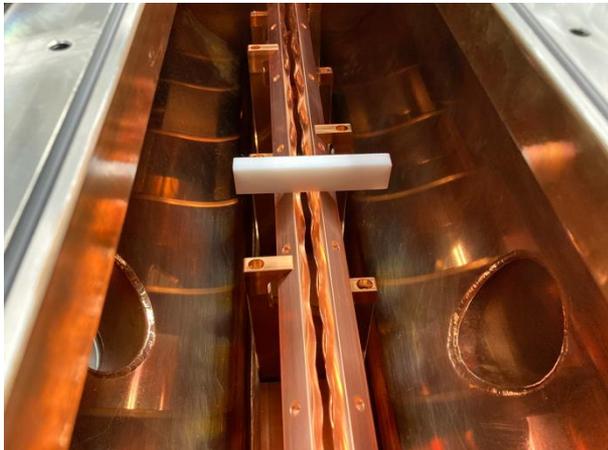
Resonant frequency	94.86 MHz (94.99 MHz)
Unloaded Q value	3324.3
E_{\max} (Kilpatrick factor)	≤ 24.8 MV/m (2.18 kilp)



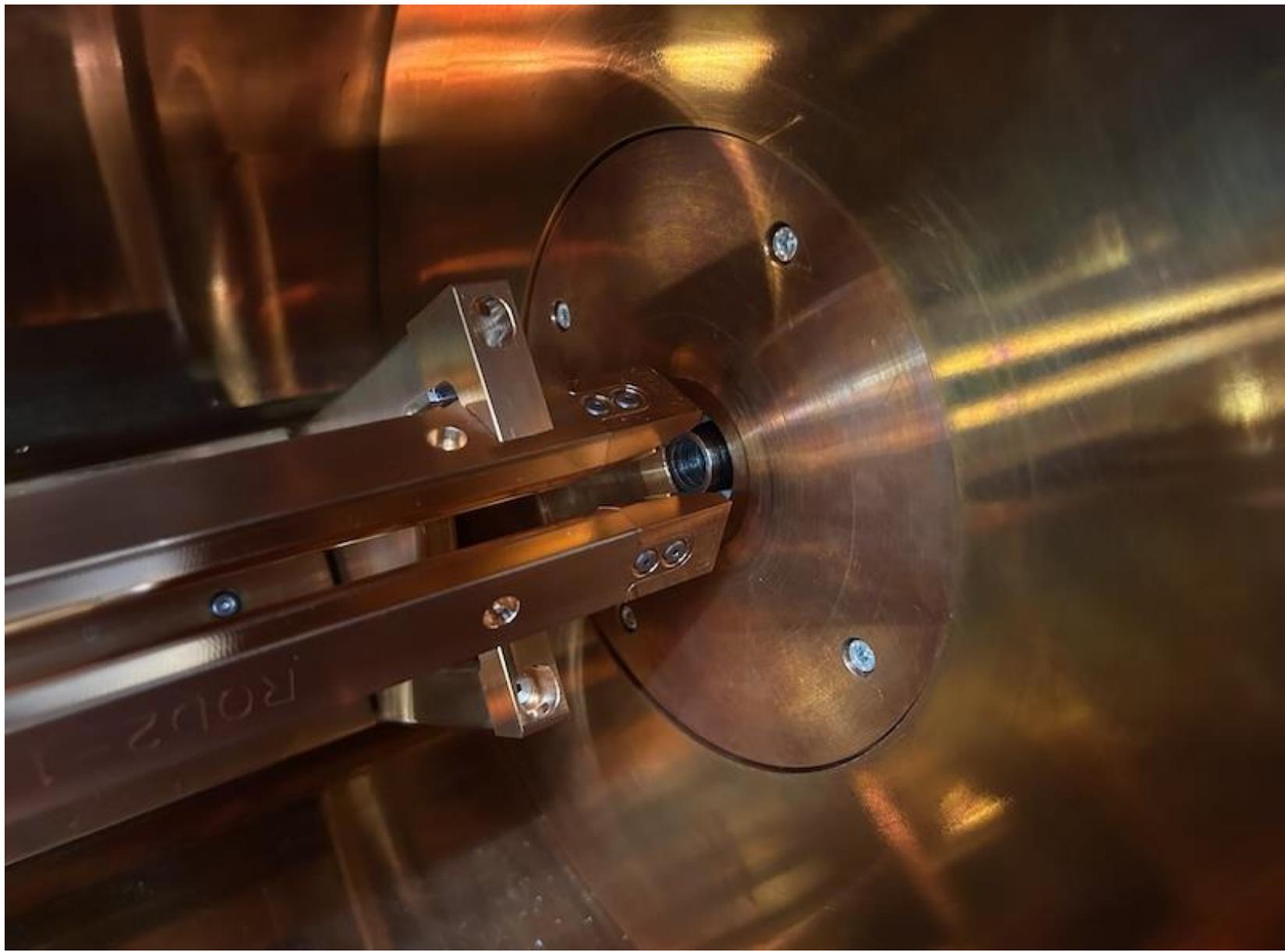
Electric field distribution adjustment

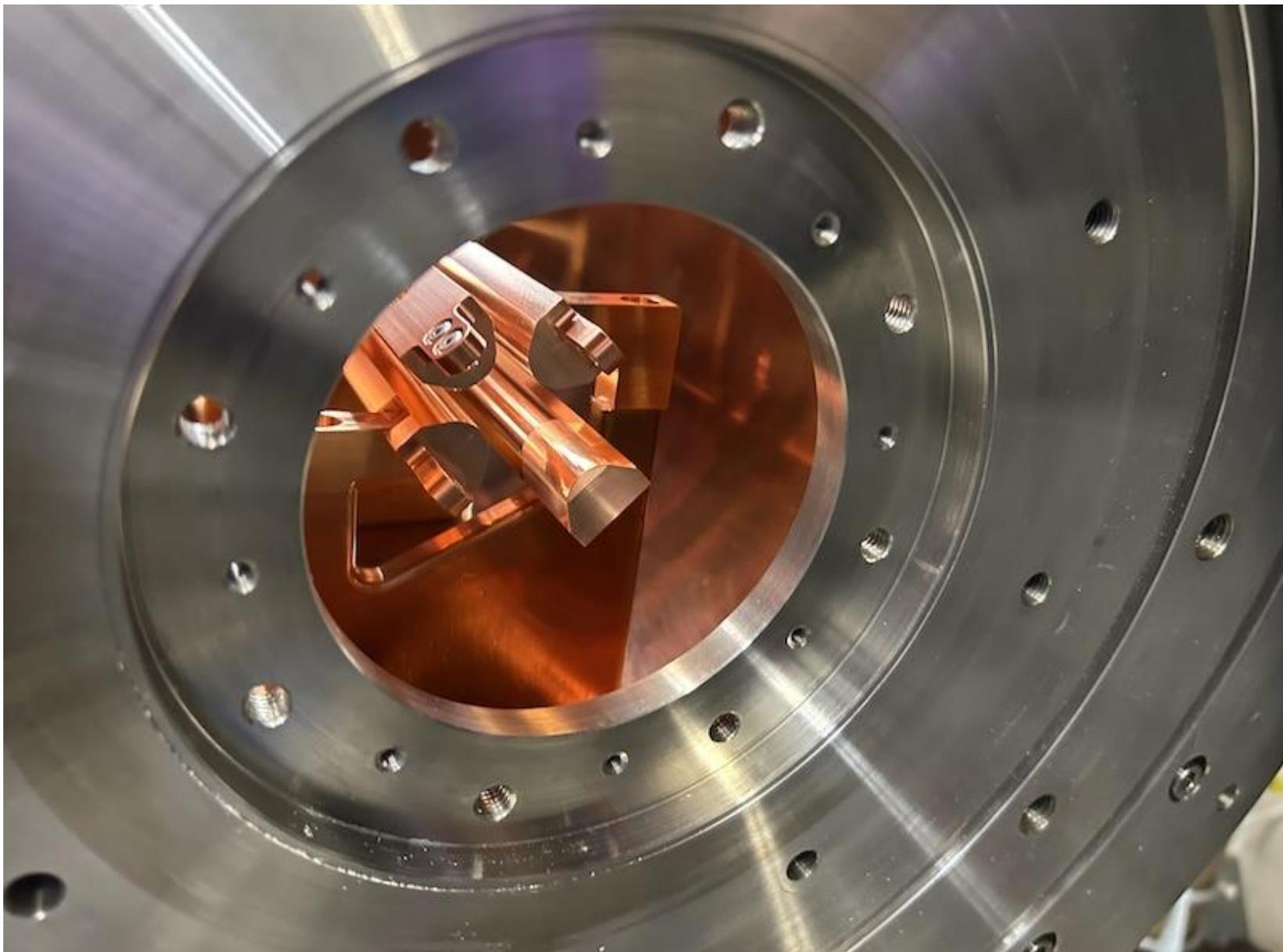


Perturbator

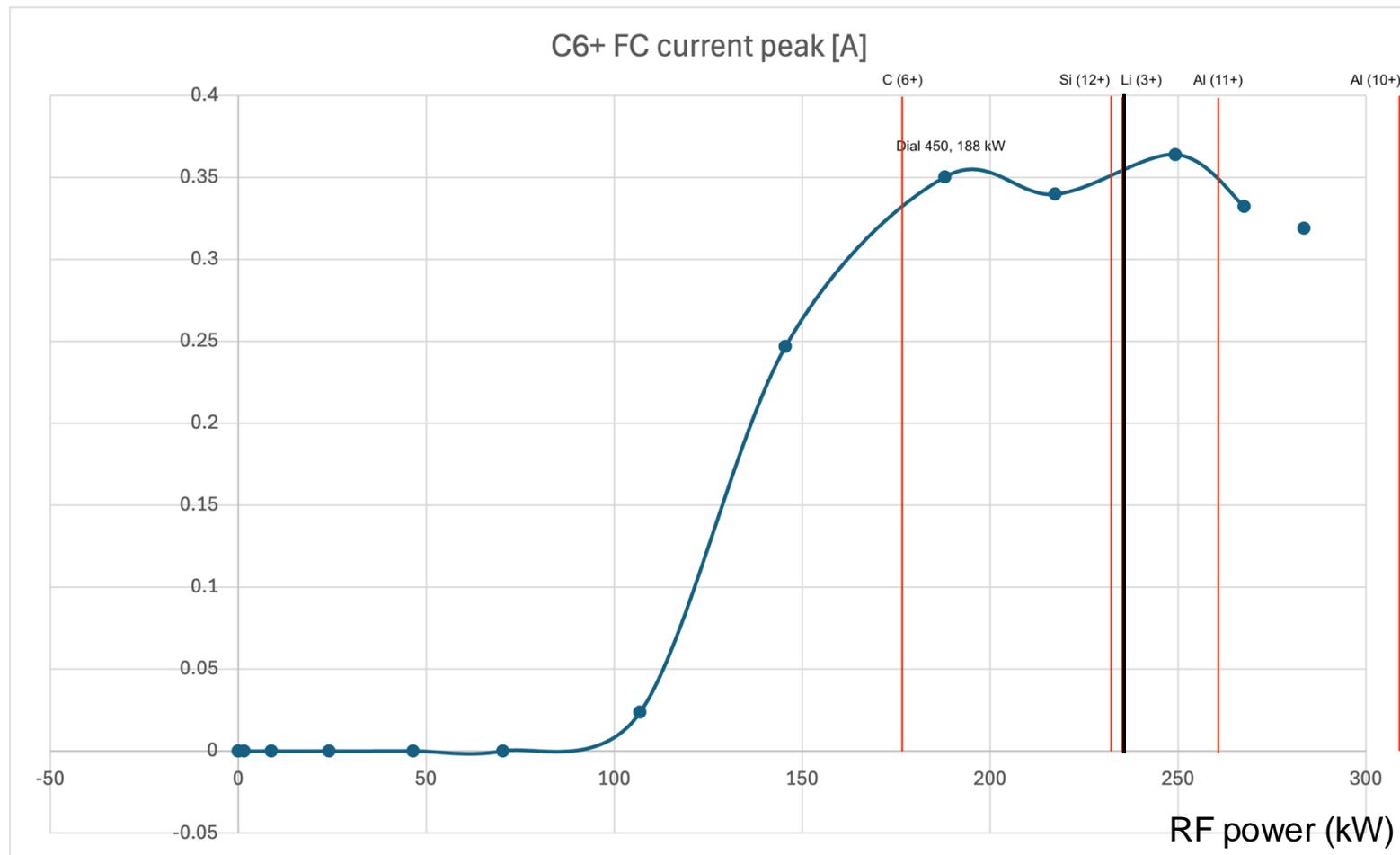






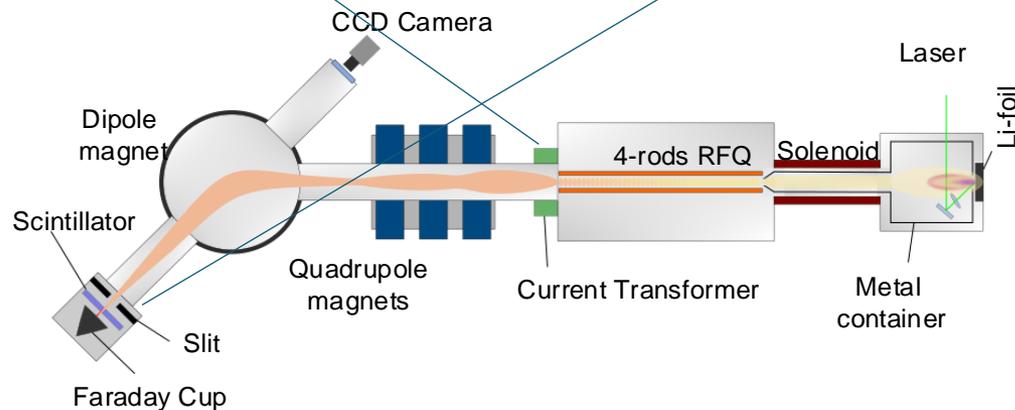
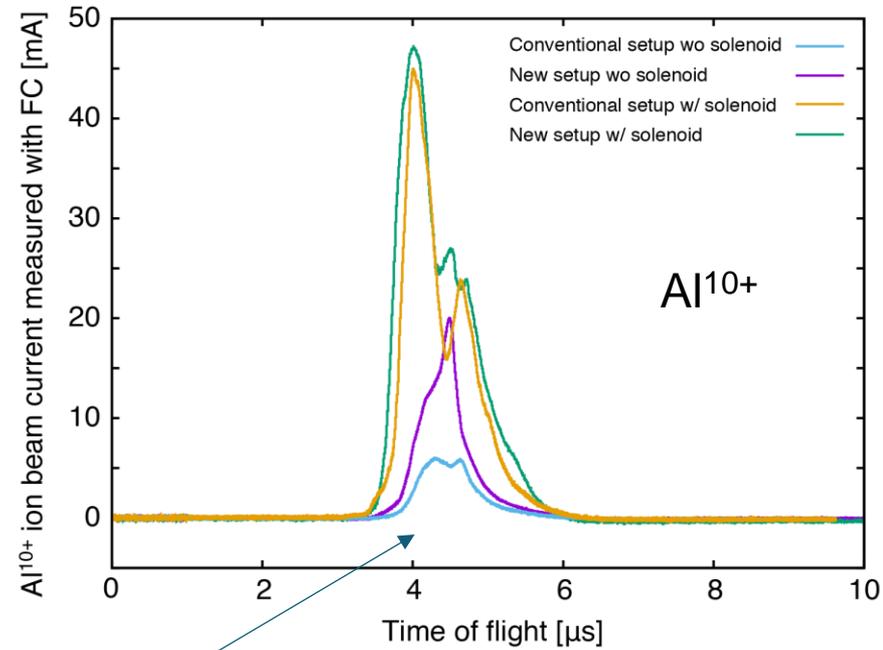
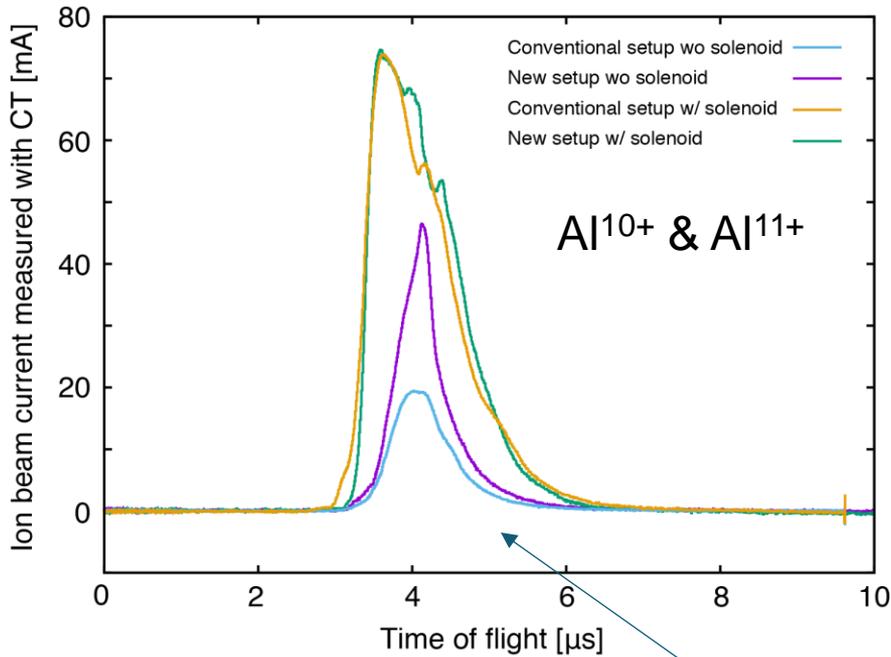


RF input test with C⁶⁺



Just commissioned two weeks ago!

CT and FC signals



Example of Proton Driver case

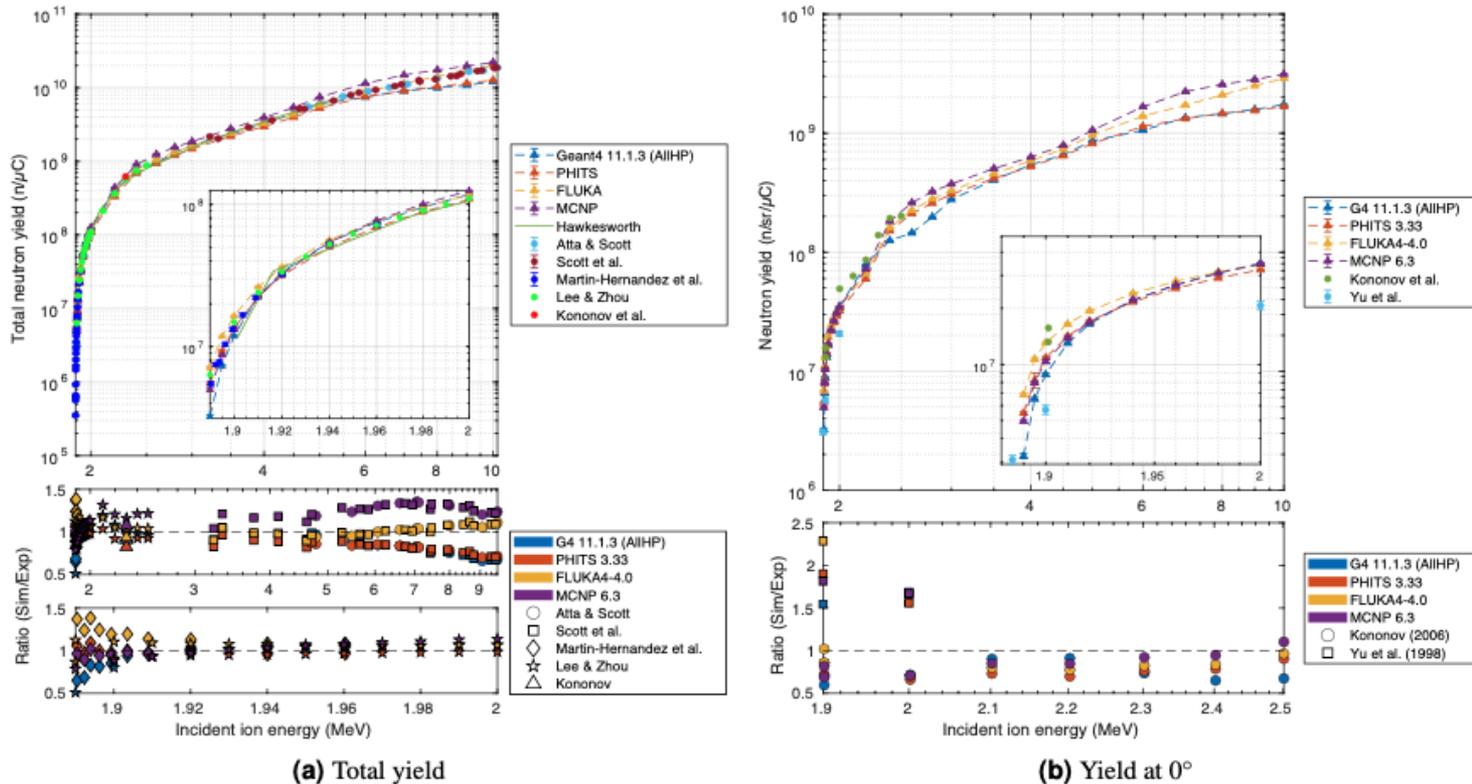


Figure 5. Neutron yield for the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction from incident proton energies of 1.89 MeV to 10 MeV. (a) Total neutron yield from each MC code compared to reference data from Hawkesworth [51], Atta and Scott [58], Scott [59], Martin-Hernandez et al. (2019) [60], Lee and Zhou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

Example of Lithium Driver case

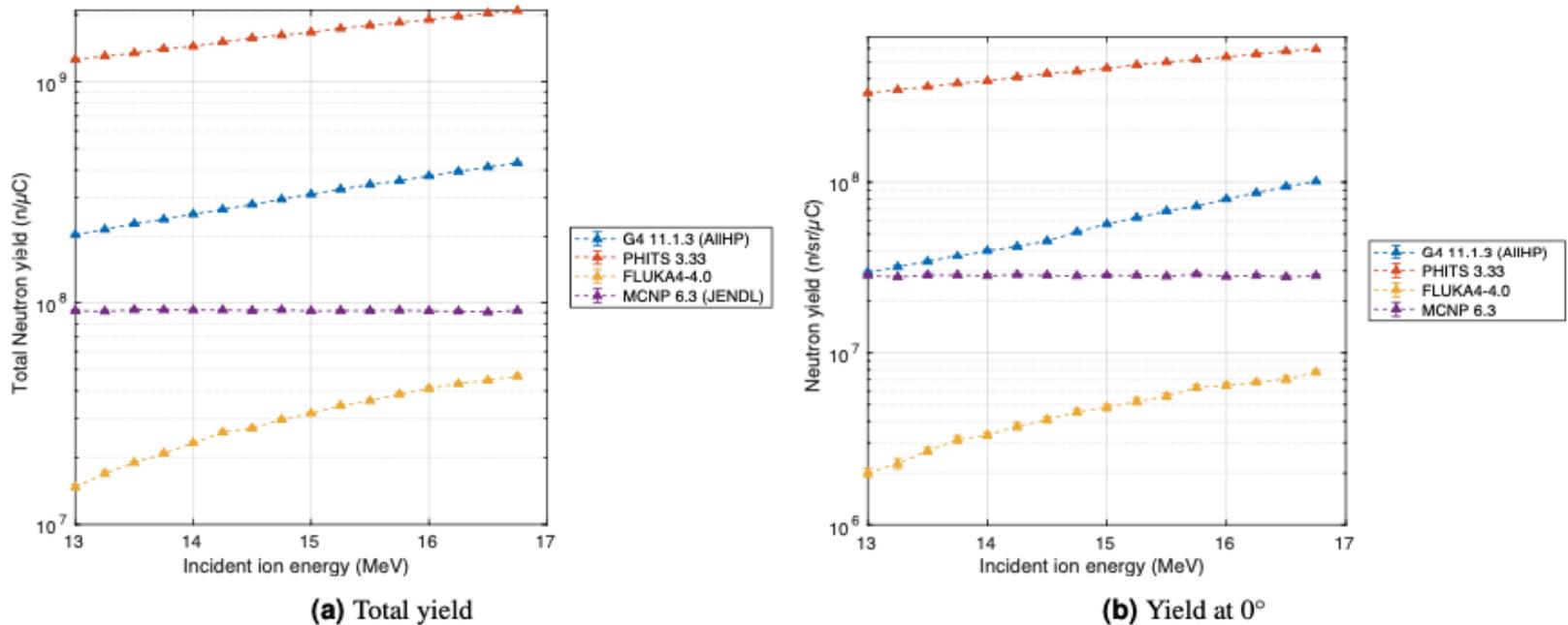


Figure 8. Neutron yield for the $p(^7\text{Li},n)^7\text{Be}$ reaction from incident lithium ions with energies ranging from 13 MeV to 16.5 MeV. Li ions of charge 3+ have been used to calculate yield, in accordance with the Li beam reported by Okamura et al. [19]. (a) Total neutron yield. (b) Neutron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

None of the software could simulate

<Frag data(Nuclear data format)>

The nuclear reaction models could NOT be used for the inverse kinematic reaction; $p(\text{Li}^7, n)\text{Be}^7$. 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; $p(7\text{Li}, n)7\text{Be}$.
 (Frag data is the cross-section data format for the PHITS code.)

Specification of new frag data

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

Table 1
 Main characteristics of the $p(^7\text{Li}, n)^7\text{Be}$ 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
$n_0 + ^7_4\text{Be}$	-1.644	13.098	1.44
$n_1 + ^7_4\text{Be}^*(0.429 \text{ MeV})$	-2.073	16.513	3.84
$n_2 + ^3_2\text{He} + ^4_2\text{He}$	-3.230	25.726	8.18
$n_3 + ^7_4\text{Be}^*(4.57 \text{ MeV})$	-6.214	49.489	18.79

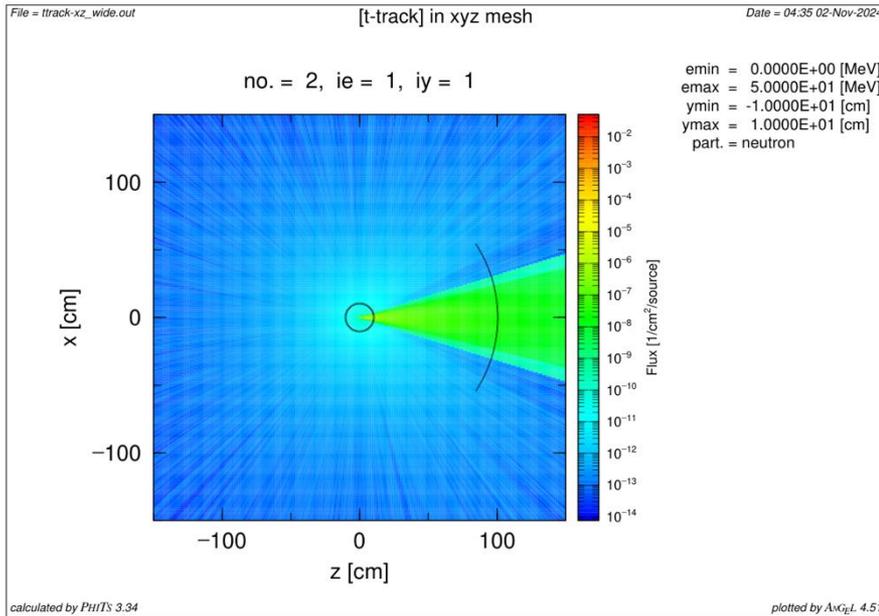
M. Lebois et al./Nuclear Instruments and Methods in Physics Research A 735 (2014) 145–151

Recent activity – Simulation study –

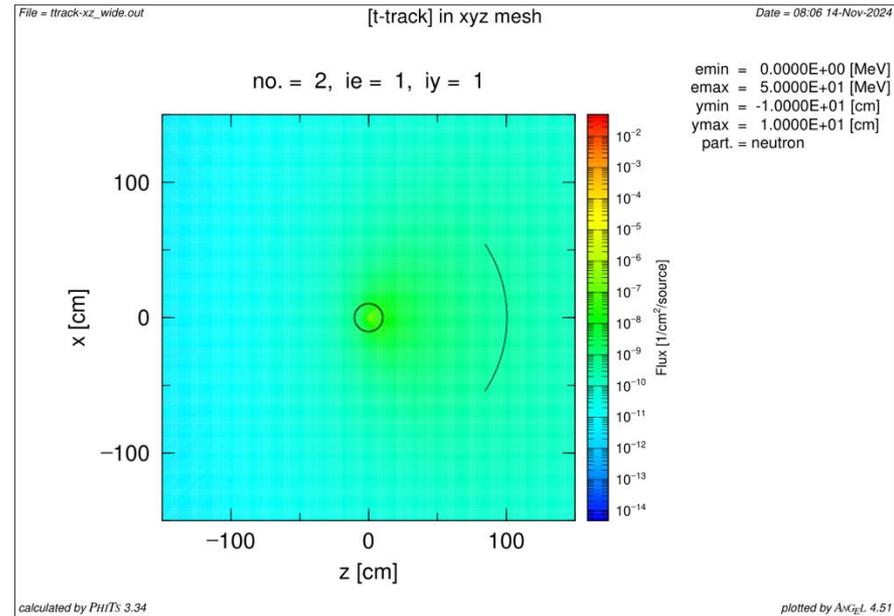
<Result>

Comparison with the proton-beam case

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

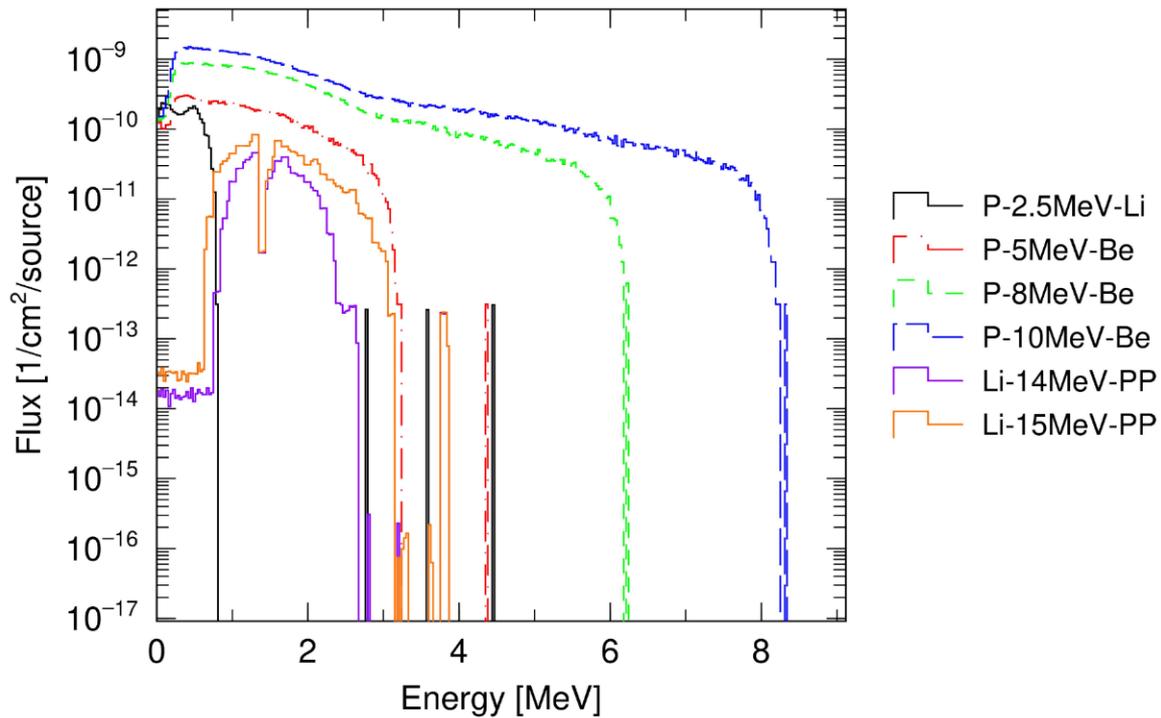


2 MeV/n of Proton-beam
(JENDL5, 12 μ m Lithium target)



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.

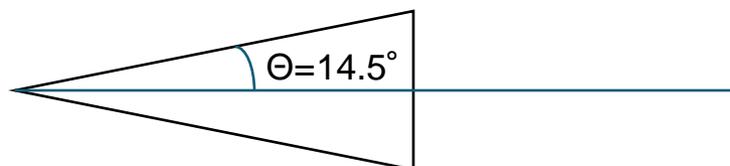
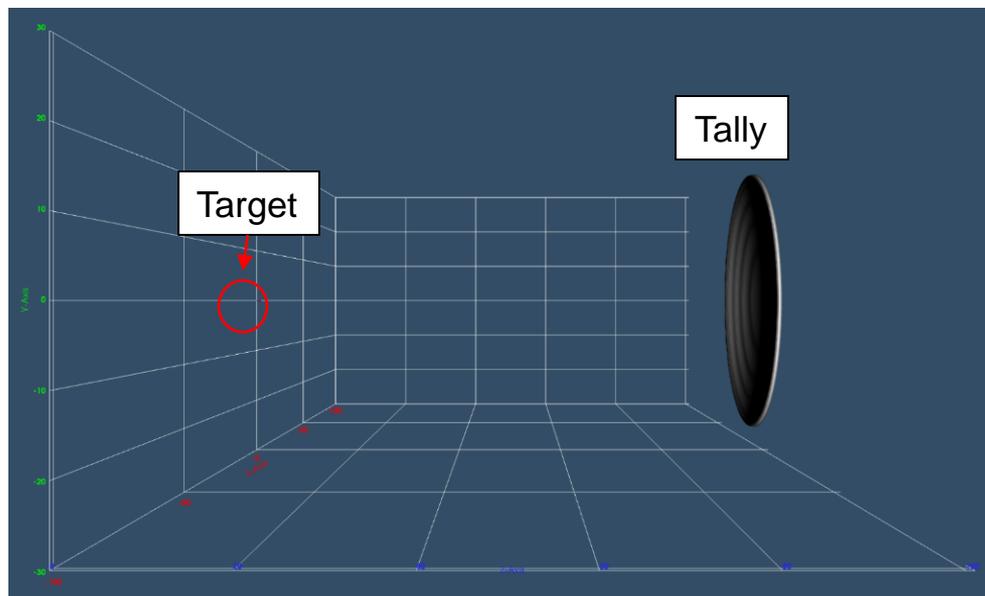
4 π directions (All directions)



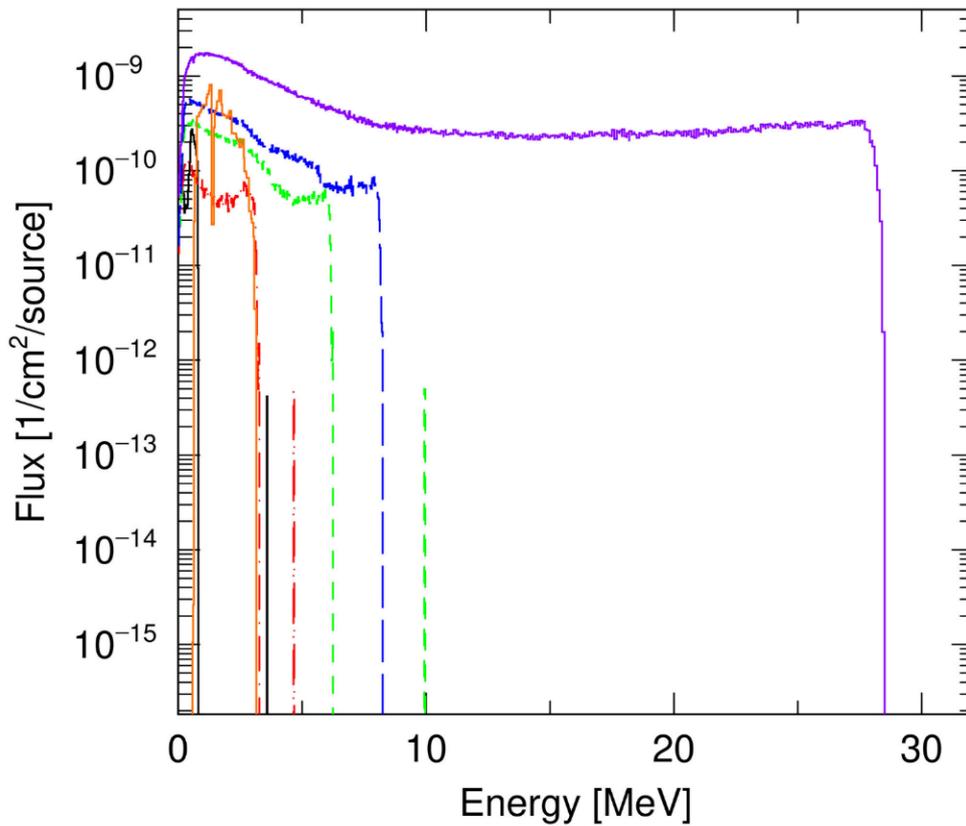
○-△△MeV-□□
 ○ : Incident particle
 (P means proton)
 △△ : Energy of incident particle
 □□ : Target material
 (PP means polypropylene)

Tally for 0.2 sr angle

Tally corresponding to 0.2 Sr was set in the geometry.
This tally was located in the forward position from the target.



Neutron spectra in the forward 0.2 sr cone



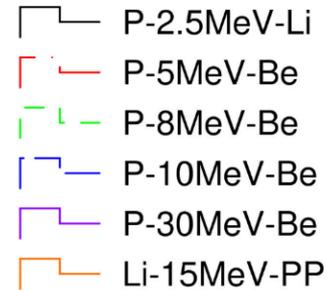
○-△△MeV-□□

○ : Incident particle
(P means proton)

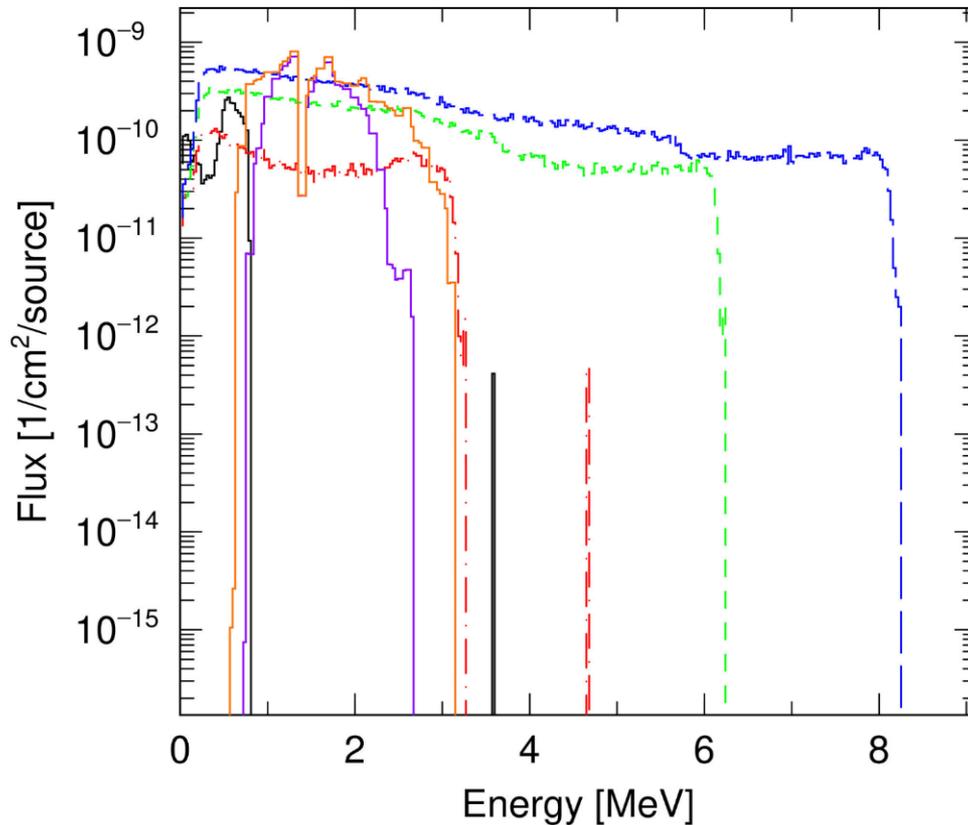
△△ : Energy of incident particle

□□ : Target material

(PP means polypropylene)



Neutron spectra in the forward 0.2 sr cone



○-△△MeV-□□
 ○ : Incident particle
 (P means proton)
 △△ : Energy of incident particle
 □□ : Target material
 (PP means polypropylene)

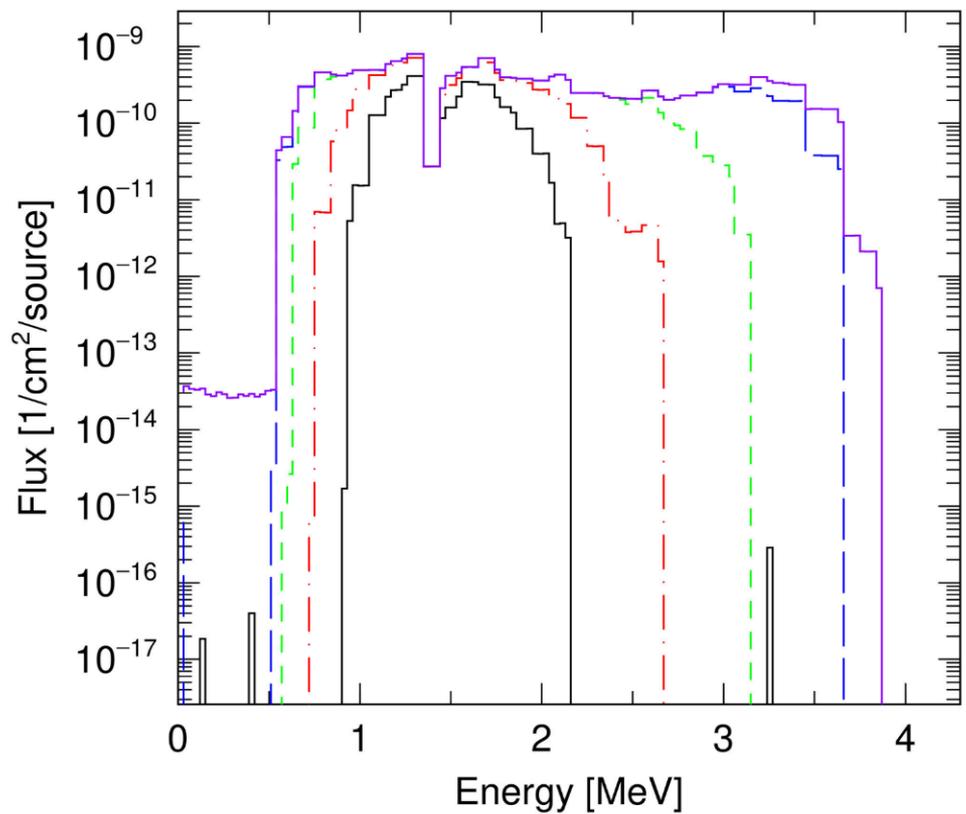
— P-2.5MeV-Li
 — P-5MeV-Be
 — P-8MeV-Be
 — P-10MeV-Be
 — Li-14MeV-PP
 — Li-15MeV-PP

Roughly, the energy spectra in the lithium beam case range between that in the Li target case and that in the Be target case.

Neutron spectra in the forward 0.2 sr cone (comparison between the lithium cases)



○-△△MeV-□□
 ○ : Incident particle
 (P means proton)
 △△ : Energy of incident particle
 □□ : Target material
 (PP means polypropylene)



- Li-13.5MeV-PP
- Li-14MeV-PP
- Li-15MeV-PP
- Li-16MeV-PP
- Li-16.5MeV-PP

The spectra in the case of 16.45 MeV covers the other spectra. This is because the neutron production reaction, $p(^7\text{Li}, n)^7\text{B}$, was induced continuously during the energy loss process of 16.45 MeV of lithium-ion to the threshold energy.

On going R&D 4

Neutron production experiment at Tandem van de Graaf in BNL

Basic information on the experiment

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



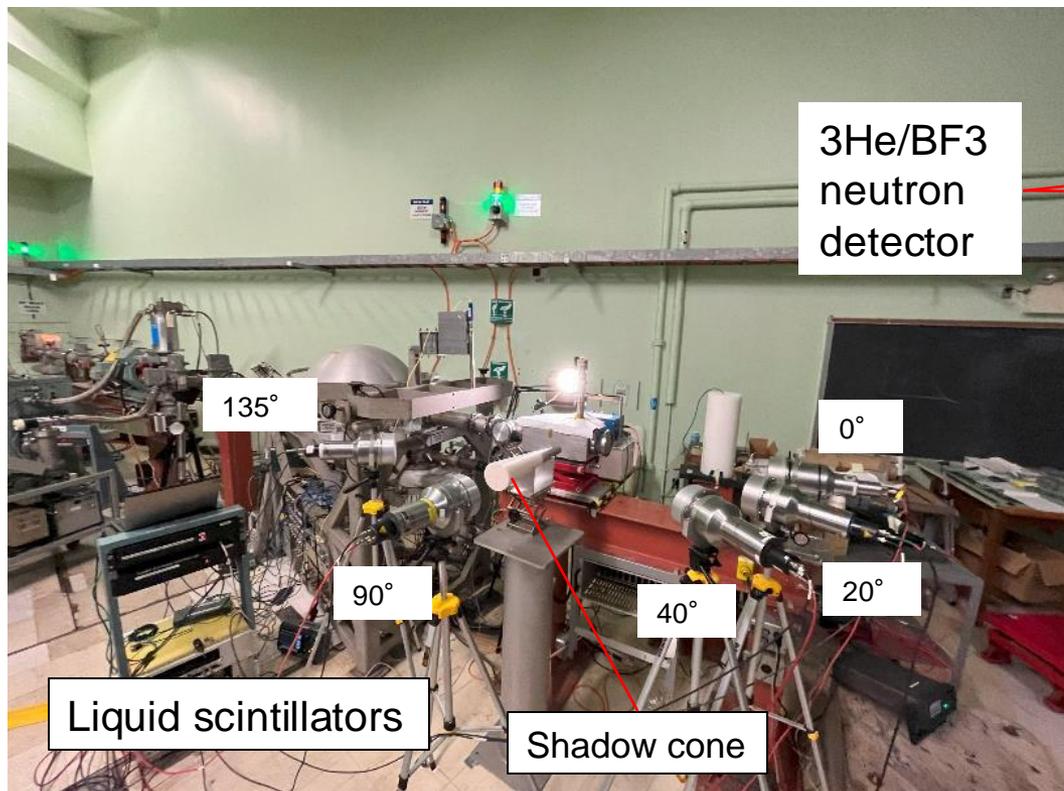
Tandem van de Graaf
accelerator at BNL

Recent activity – Experimental study –

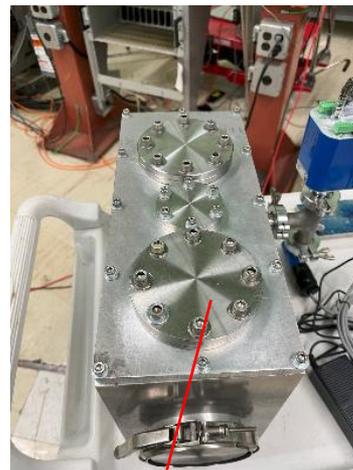
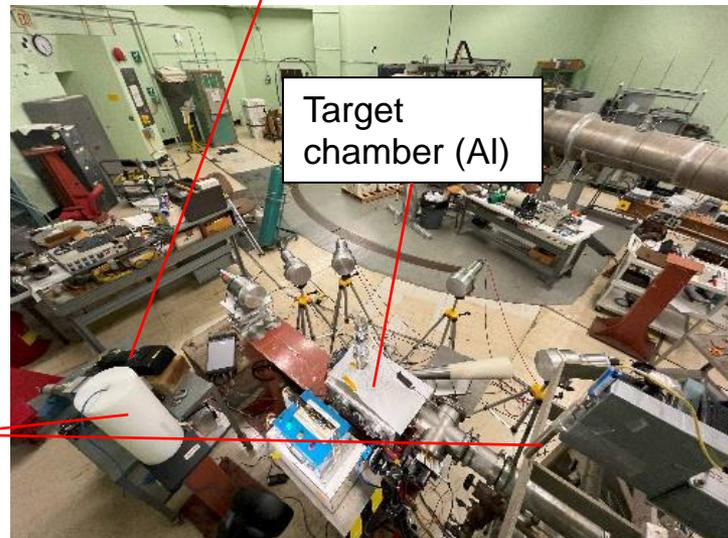
<Configuration>

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

The inverse kinematic reaction, $p(\text{Li}^7, n)\text{Be}^7$, was induced on the target.



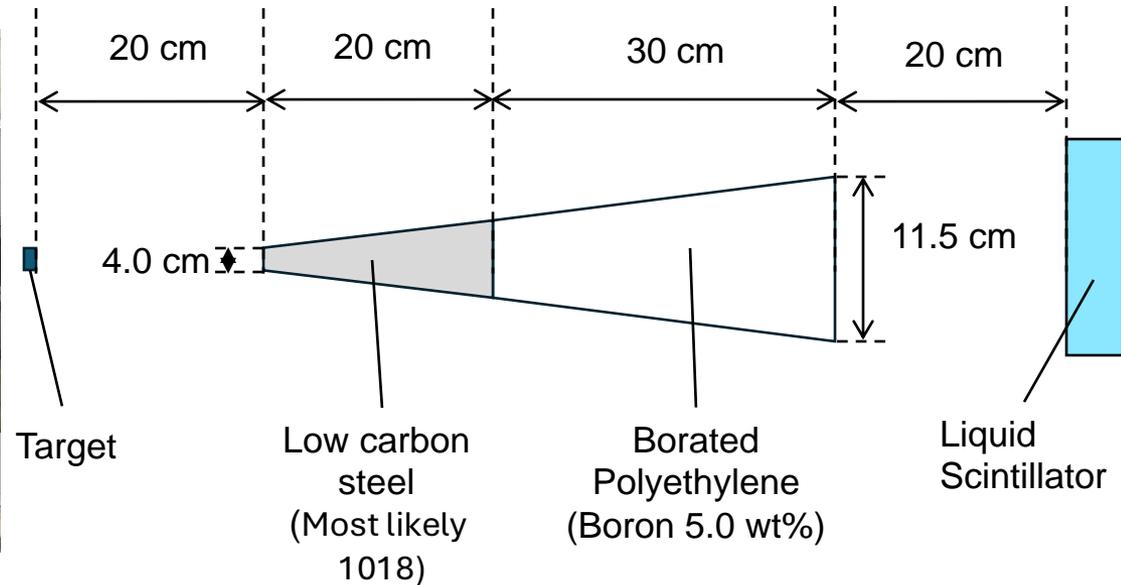
Nal scintillator



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.

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)

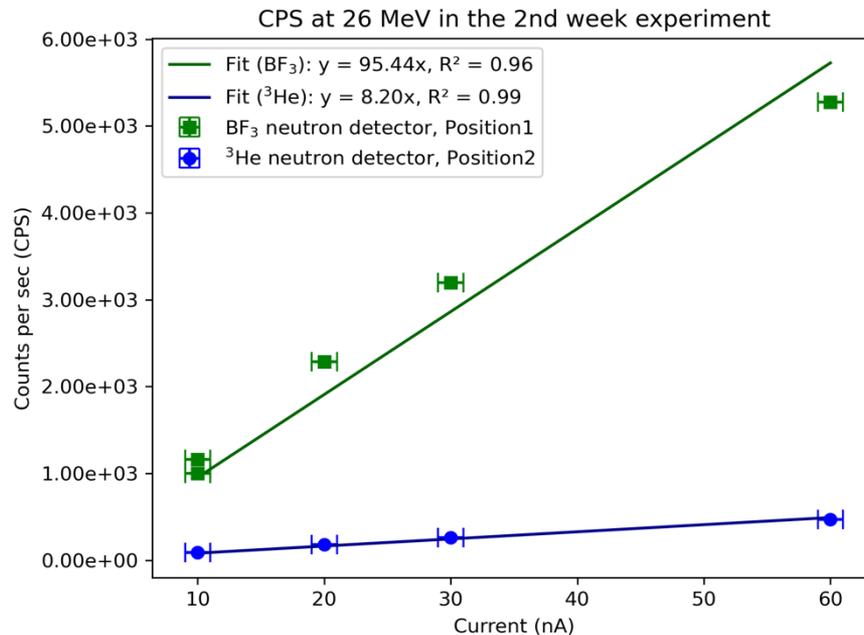


◆ Position1



◆ 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)

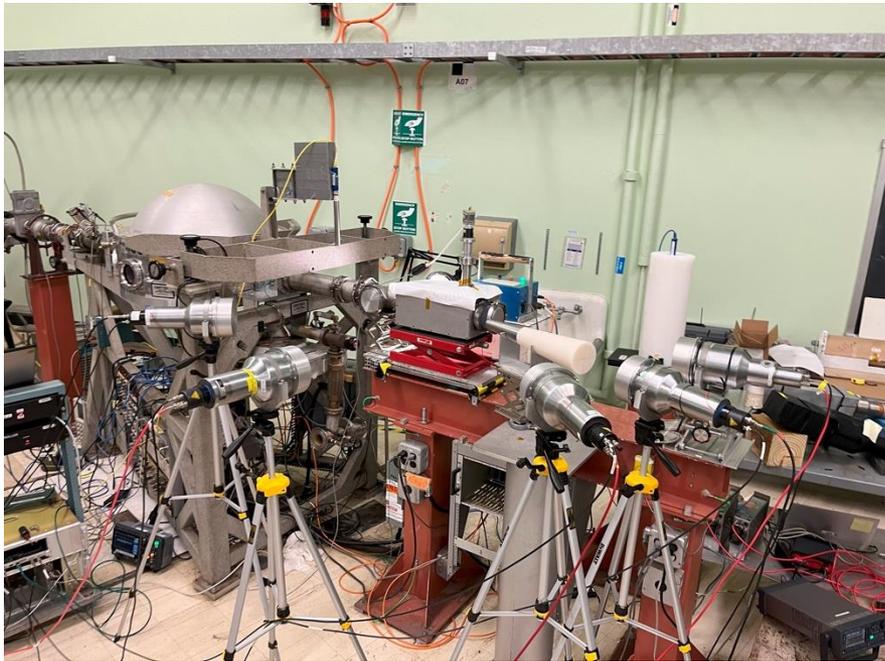
Recent activity – Experimental study –

<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.

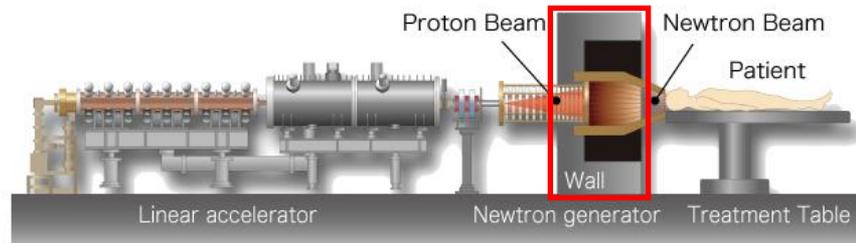


To analyze neutron flux quantitatively, the unfolding method will be applied to the liquid scintillator data.

Further analysis is required.

Neutron target has three functions:

1. Neutron converter
2. Beam dump
3. Moderator

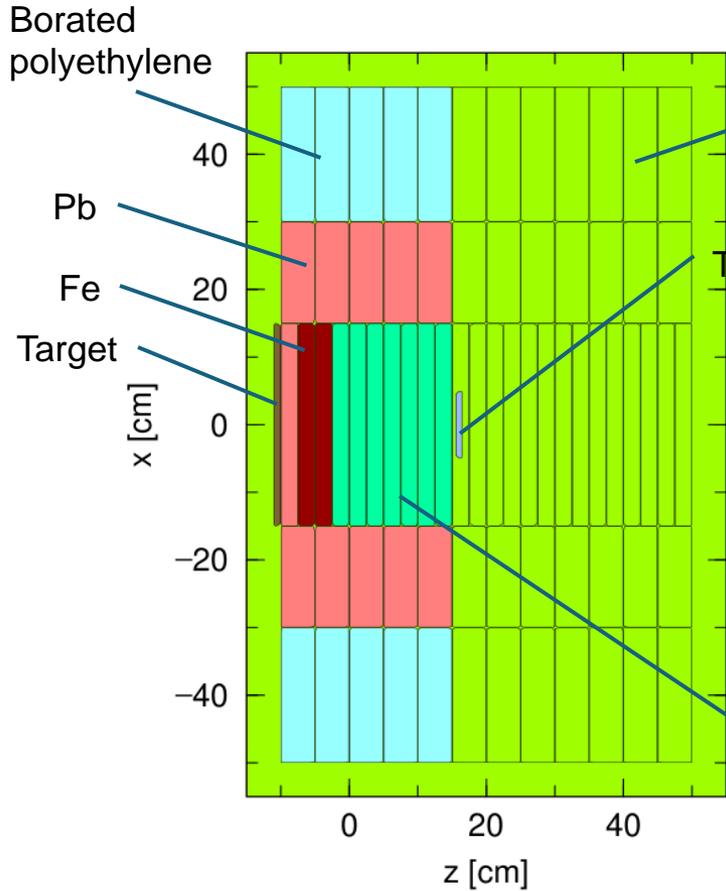


<https://bnct.kek.jp/eng/apparatus.html>

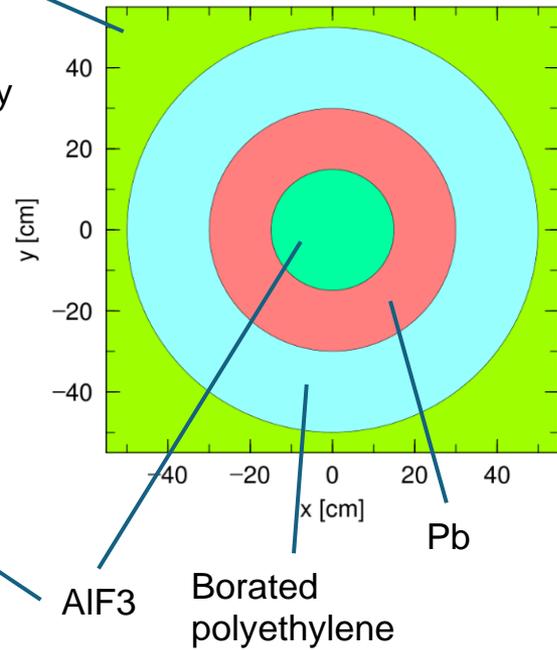
Geometry

Cylindrical structure is defined as the BSA.

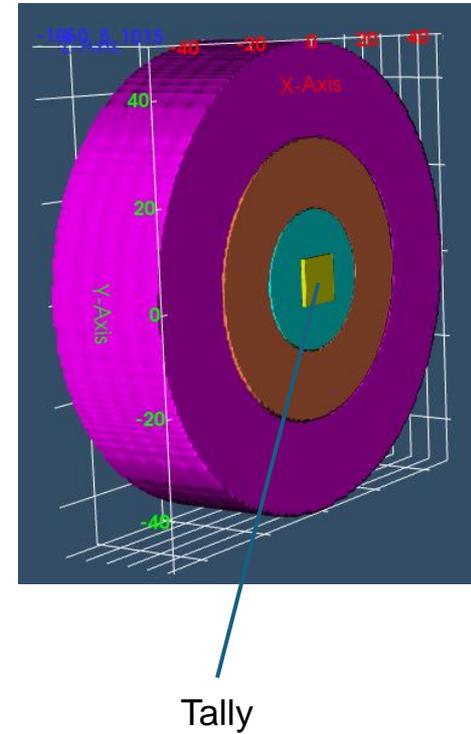
XZ plane at $y=0$



XY plane at $z=10(\text{cm})$



3D image

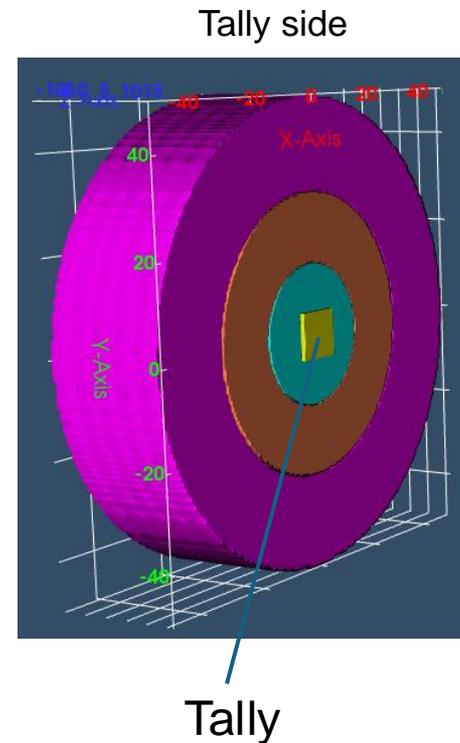
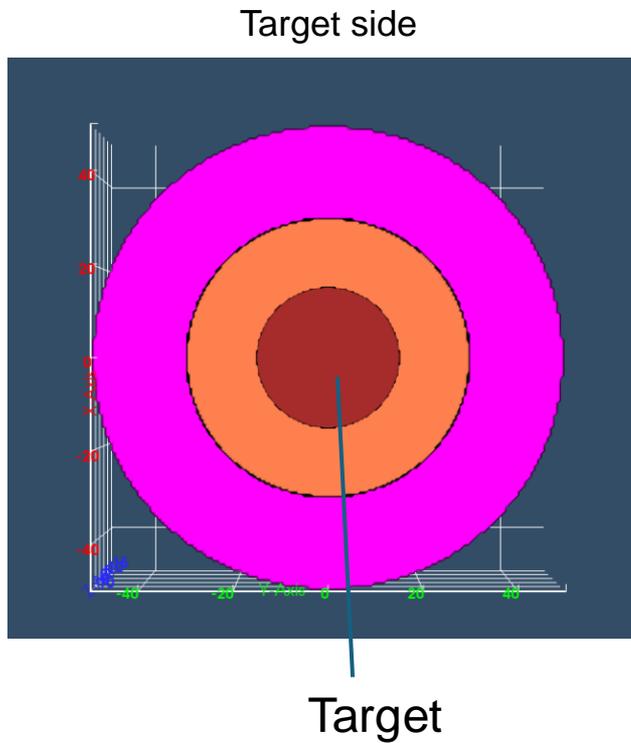


Geometry

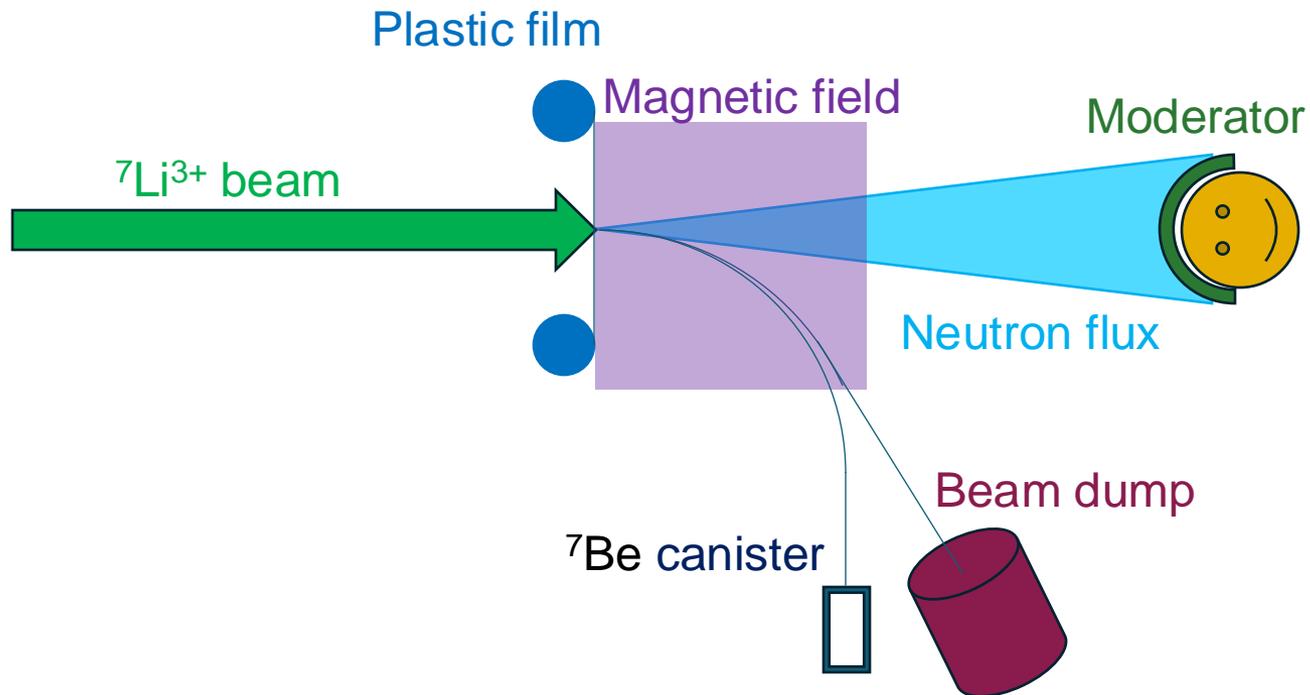
Cylindrical structure is defined as the BSA.

Beam hits the center of target.

(1) Proton beam and Li target case and (2) Li beam and polypropylene target case were simulated.



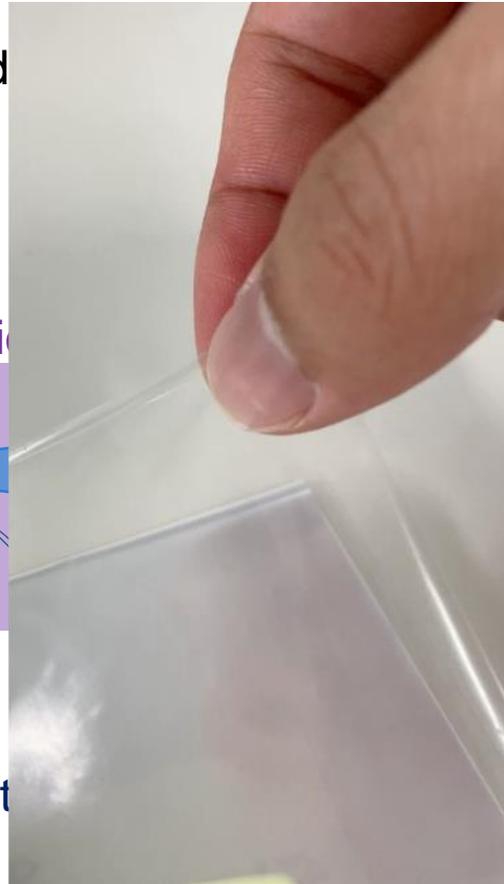
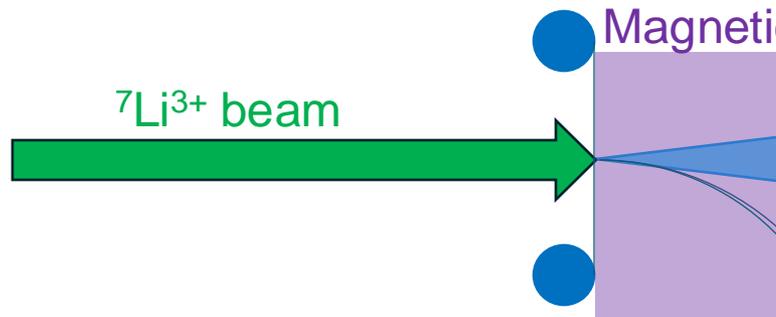
Target concept for Li driver neutron generator
Discrete functions.



Target concept for Li d

Discrete

Plastic film



${}^7\text{Be}$ canist

Target concept

D

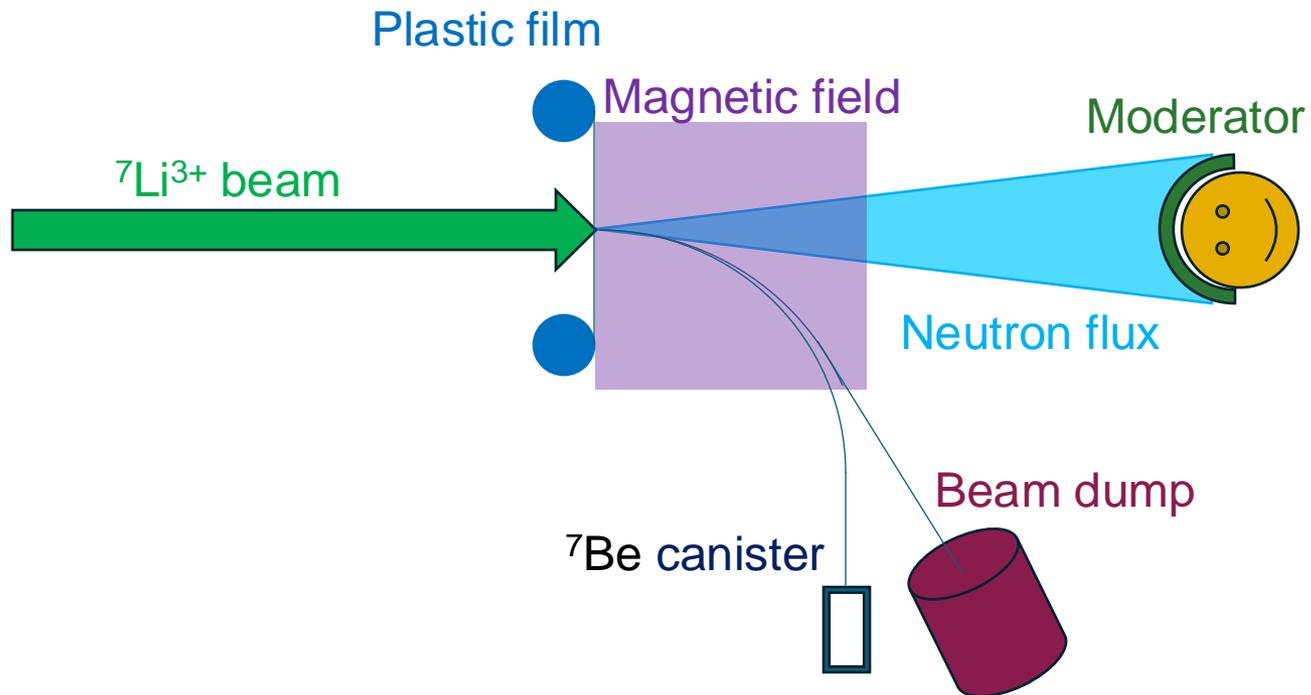
Plastic film



${}^7\text{Be}$

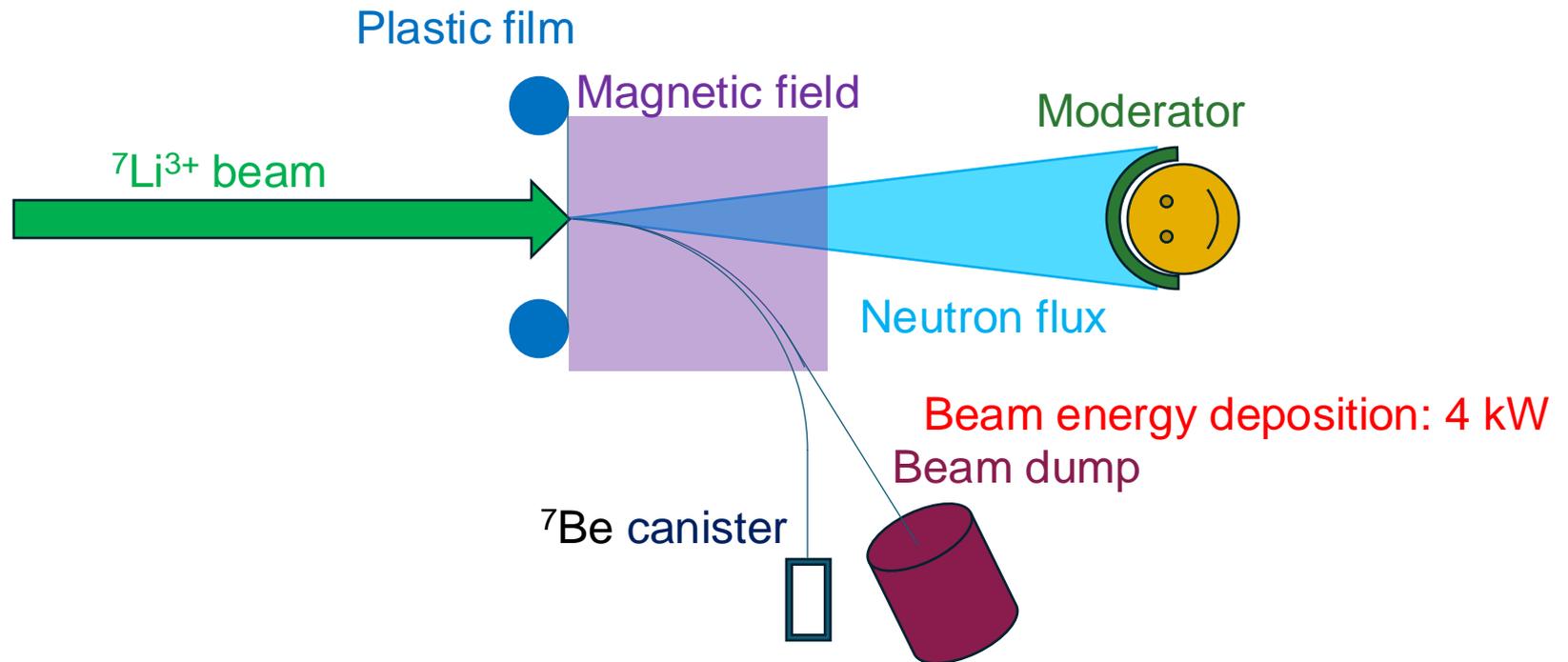


Target concept for Li driver neutron generator
Discrete functions.



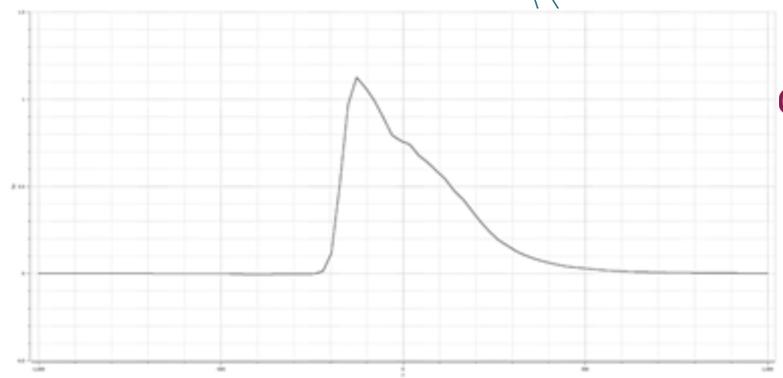
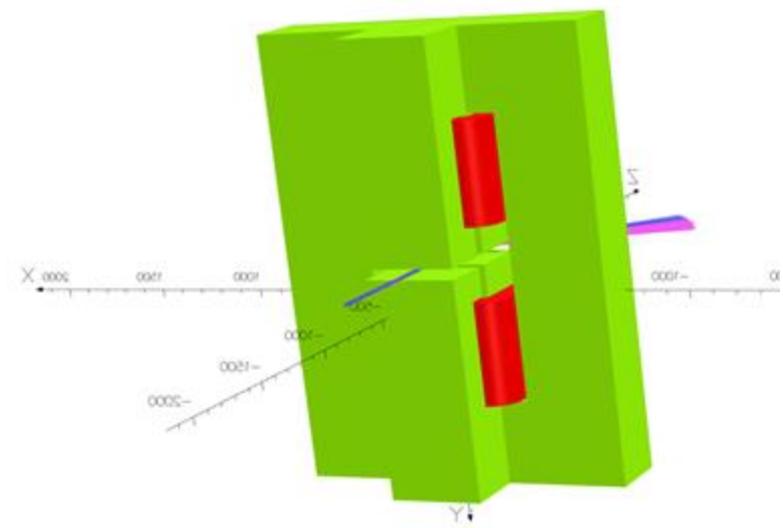
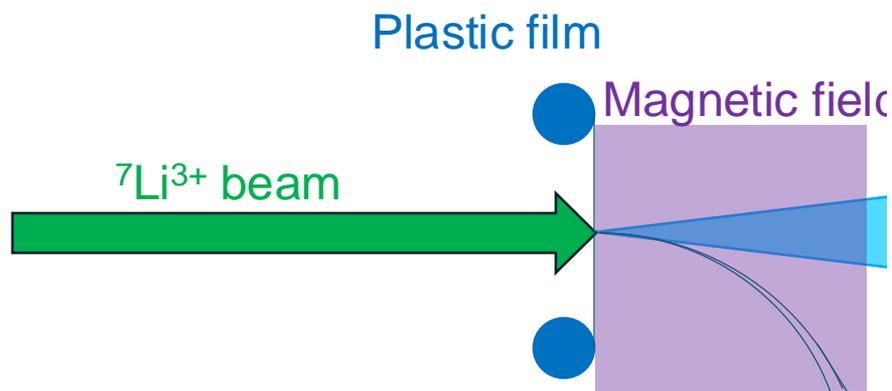
Target concept for Li driver neutron generator

Discrete functions.

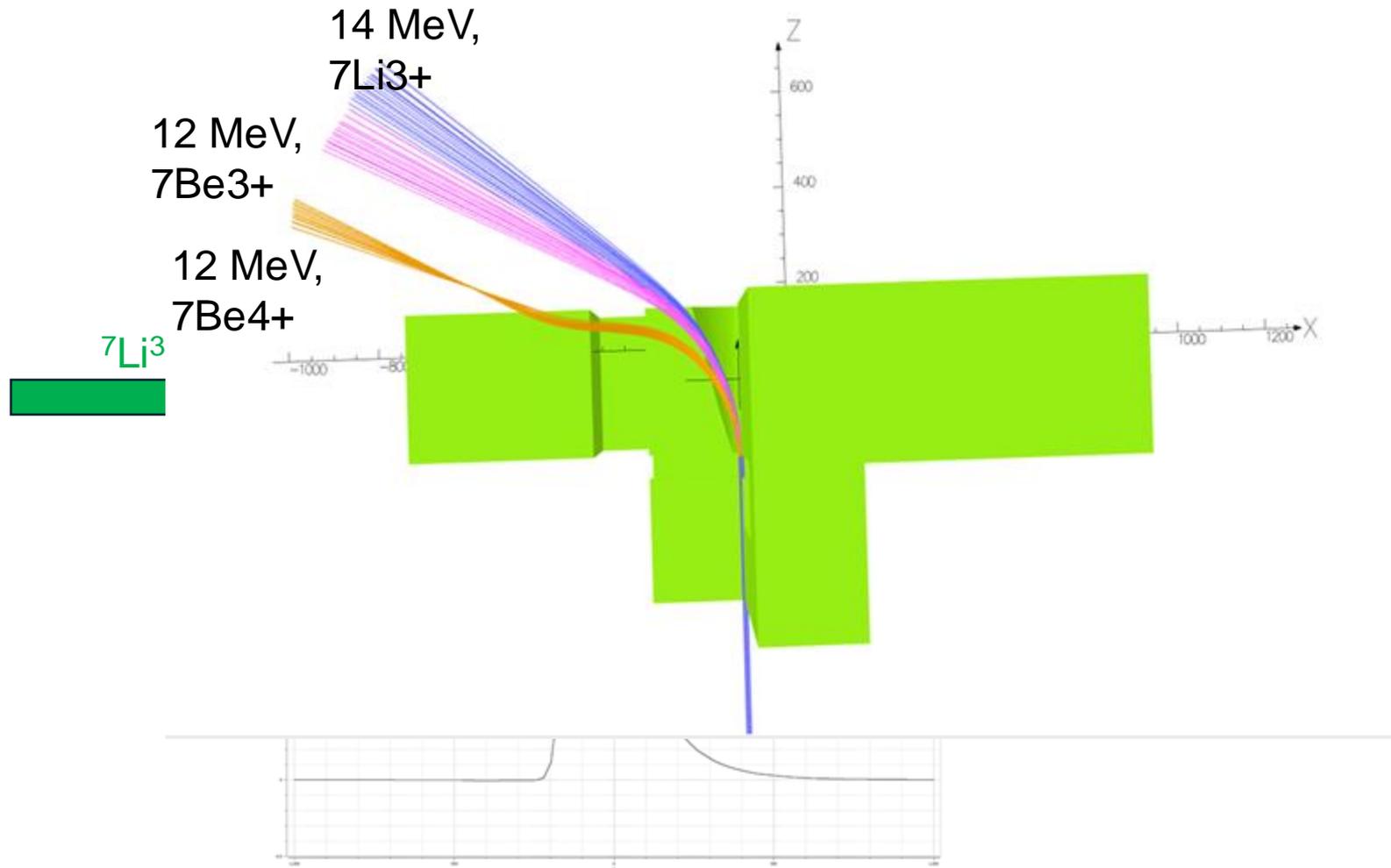


Target concept for Li driver

Discrete funct



dump



Summary

So far until now

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

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

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

Liquid laser target study was started

New RFQ was assembled for a higher beam current

Monte Carlo simulation started.

Neutron production experiments were tried and sharp directivity was confirmed.

(The data analysis is in progress.)

Future prospects

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

Neutron target design study will be finished in two years.

Detailed entire accelerator design will be completed.

**Thank you for your
attention**



GSI Helmholtzzentrum für Schwerionenforschung GmbH



@BrookhavenLab

Your participation is always welcome !