Development of a Nitrogen-gas Filled Neutron Beam Monitor

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On behalf of KENS members

Outline

- Introduction

J-PARC, Materials and Life Science Experimental Facility (MLF), High Intensity Total Diffractometer (NOVA), Neutron Detection

- Neutron Beam Monitor

Neutron Beam Monitor (NBM), N_2 Gas-Filled Neutron Beam Monitor (N_2-NBM), Geant4 Simulation, Geant4 Simulation Results

- Commissioning

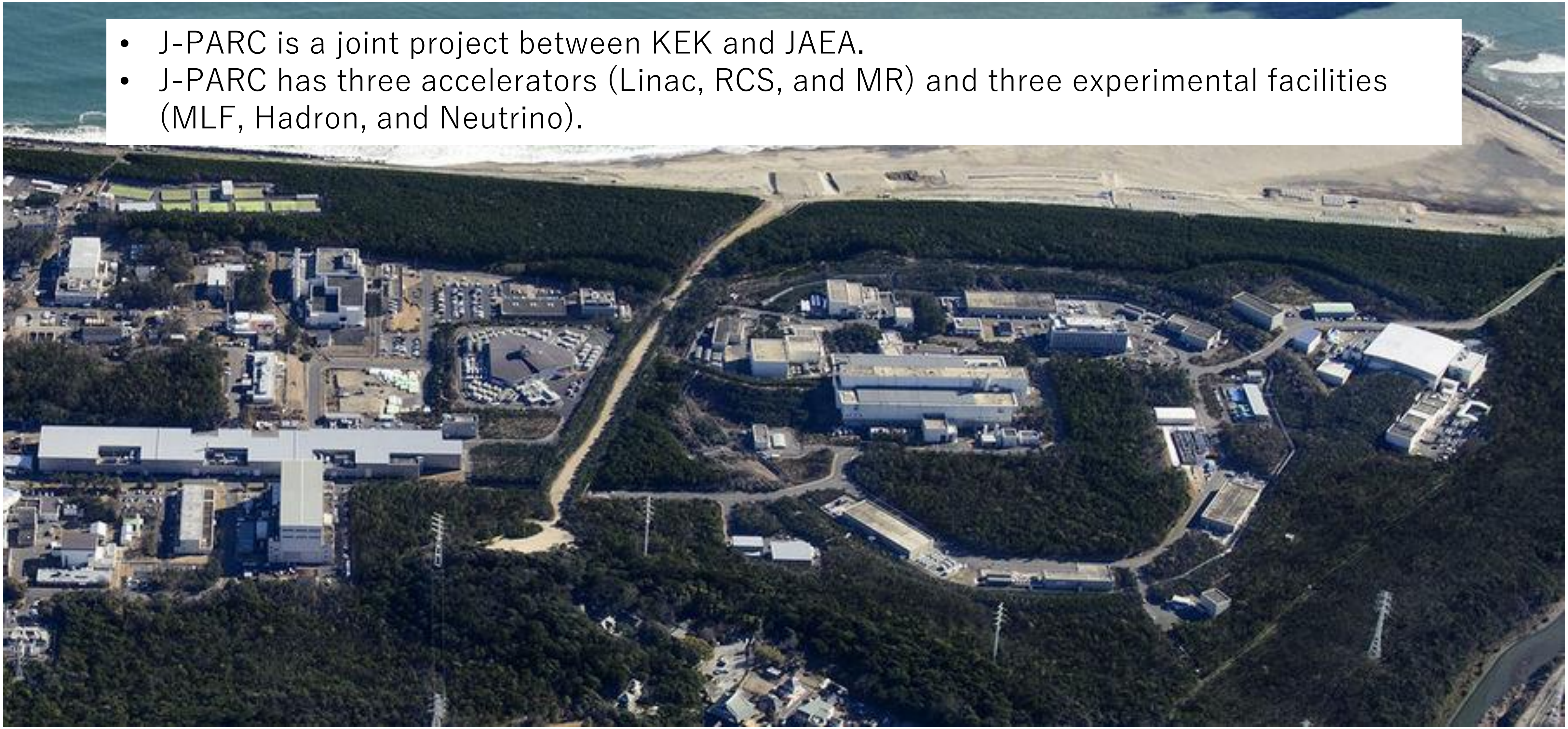
Experimental Setup, Neutron Transmittance, Output Charge Distribution, Contribution of Neutrons, Separation of Neutron Components, Measurement-based Neutron Intensity $I(E)$, Simulation-based Neutron Intensity $I_{cal}(E)$, Comparison of $I(E)$ and $I_{cal}(E)$, Robustness of $I(E)$ Measurement

- Summary

To realize the absolute neutron measurement, we simply divide the counting data by the detector efficiency. However, because the NBM has poor nγ discrimination, we cannot determine the correct neutron efficiency. In this study, we adopt a unique method for separating neutron events.

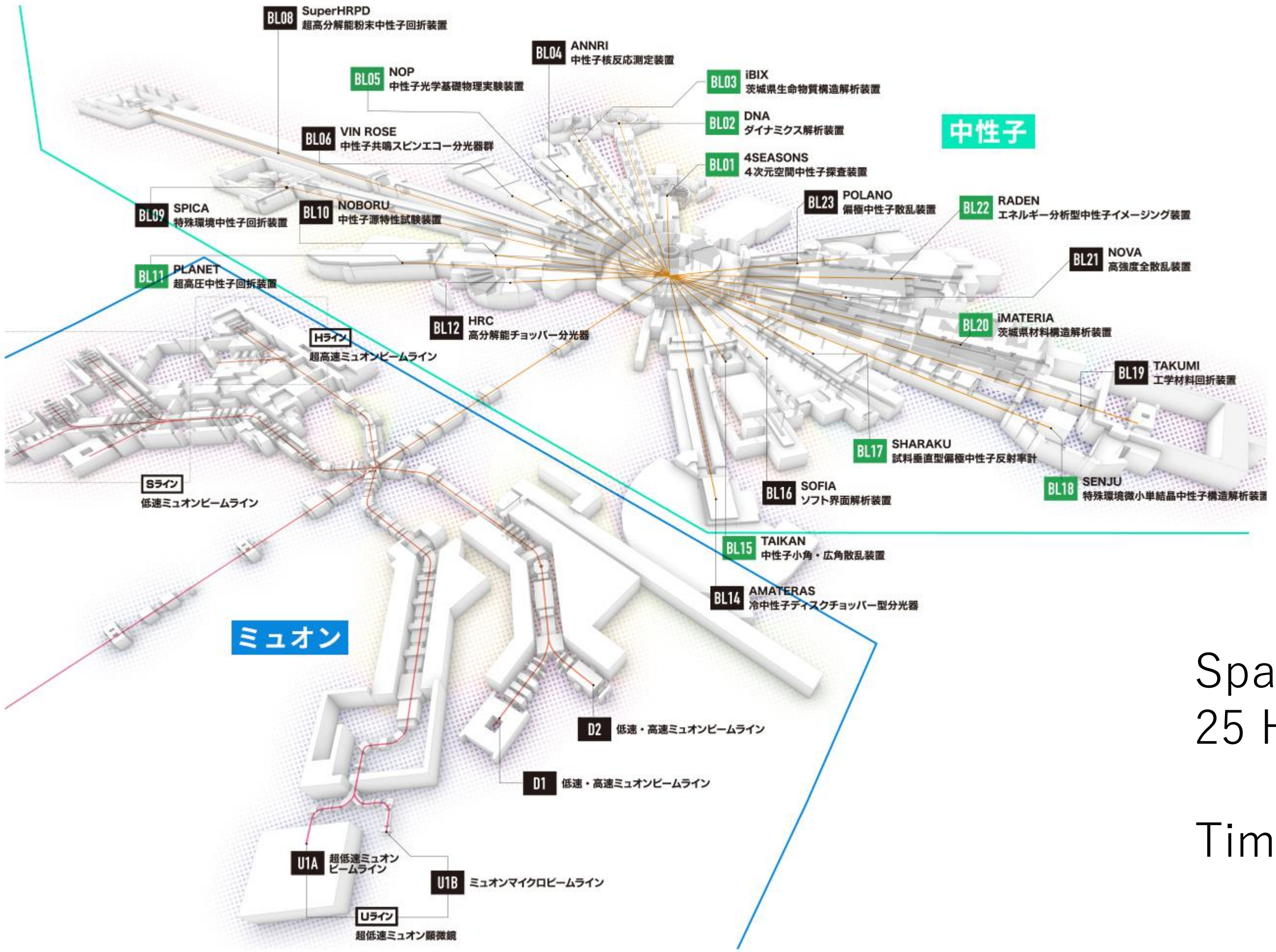
J-PARC

- J-PARC is a joint project between KEK and JAEA.
- J-PARC has three accelerators (Linac, RCS, and MR) and three experimental facilities (MLF, Hadron, and Neutrino).



Materials and Life Science Experimental Facility (MLF)

- MLF is the most intense pulsed muon and neutron source.
- We research for materials and life science, elementary physics, and industrial used.

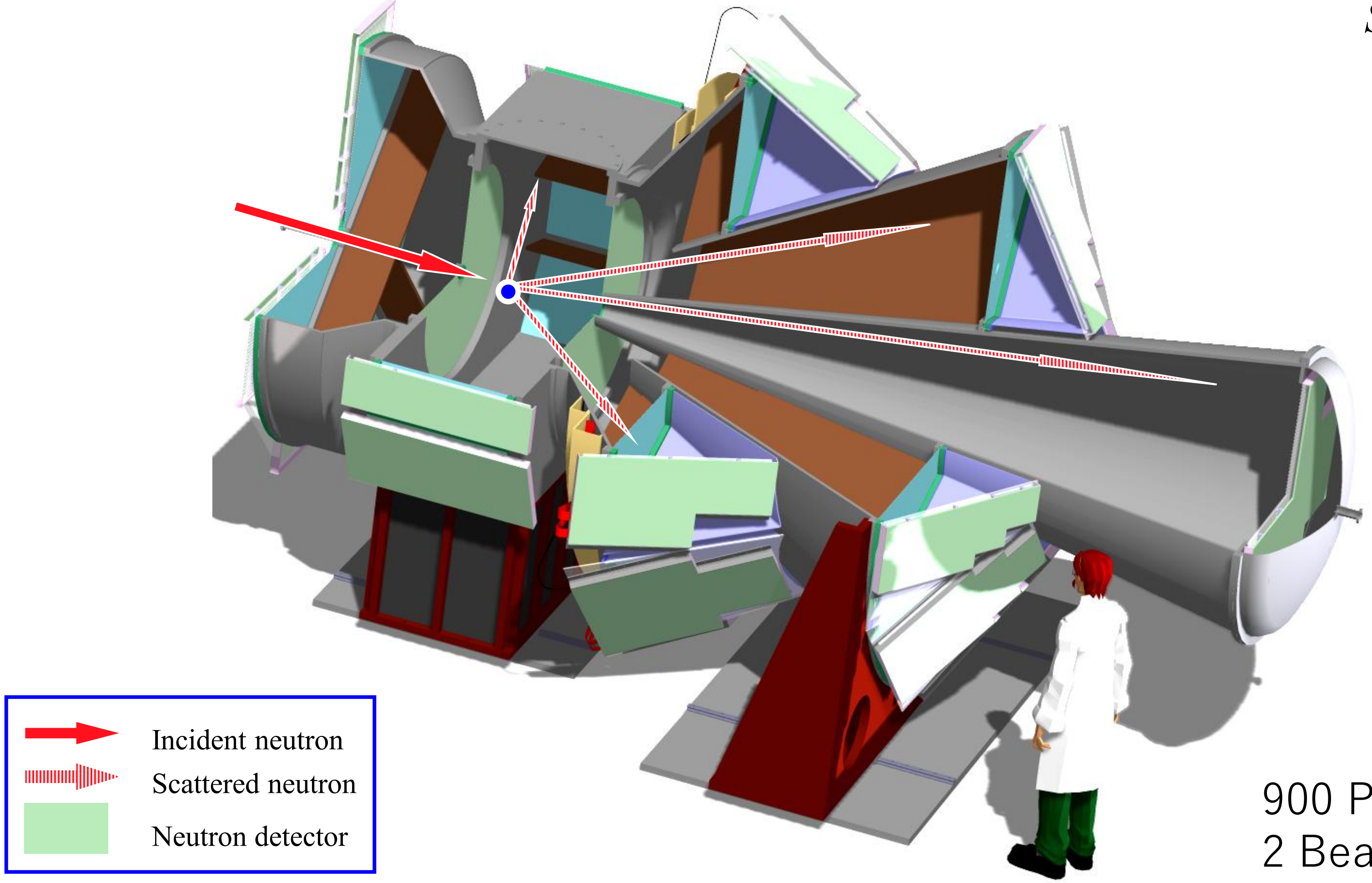


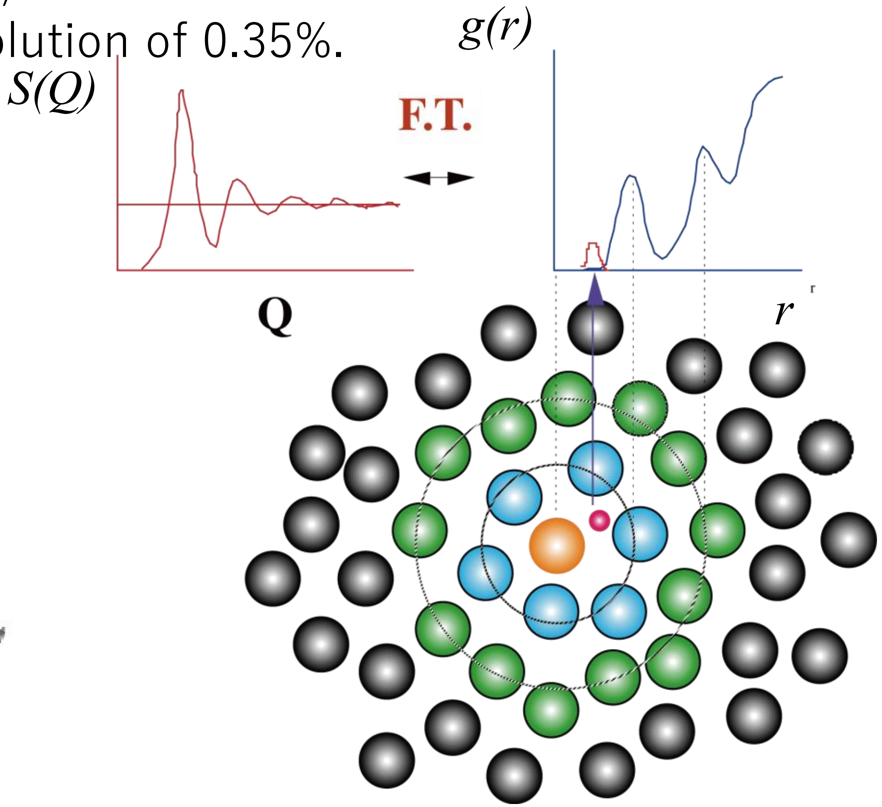
Spallation reaction,
25 Hz, 1 MW

Time Of Flight

High Intensity Total Diffractometer (NOVA)

- NOVA is capable of measuring the static structure factor *S(Q)*.
- By Fourier transforming *S(Q)*, the pair distribution function, *g(r)*, can be derived.
- NOVA is also a high-intensity powder diffractometer with a resolution of 0.35%.





900 Position Sensitive Neutron Detectors,
2 Beam monitors

Neutron Detection

- Neutron detection is done by detecting the charged particles emitted from the neutron reaction.
- Such materials are called neutron convertor.

Reaction	*Q*-value	Particle	Energy	Particle	Energy
$^{3}He(n,p)^{3}H$	0.77 MeV	p	0.57 MeV	^{3}H	0.19 MeV
$^{6}Li(n,\alpha)^{3}H$	4.79 MeV	α	2.05 MeV	^{3}H	2.74 MeV
$^{10}B(n,\alpha)^{7}Li+\gamma$ (0.48 MeV) 93% $^{10}B(n,\alpha)^{7}Li$ 7%	2.3 MeV 2.79 MeV	α α	1.47 MeV 1.77 MeV	^{7}Li ^{7}Li	0.83 MeV 1.01 MeV
$^{14}N(n,p)^{14}C$	0.62 MeV	p	0.58 MeV	^{14}C	0.04 MeV
$^{157}Gd(n,\gamma)^{158}Gd+e^{-}$	≤0.182 MeV	Conversion electron 0.07~0.182 MeV			
$^{235}U(n,Lfr)Hfr$	~100 MeV	Light fragment (Lfr)	≤80 MeV	Heavy fragment (Hfr)	≤60 MeV

with little modification from A. Oed, Nucl. Instr. and Meth. A **525** (2004) 62.

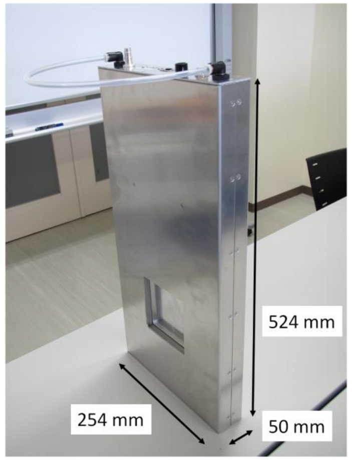
Neutron Beam Monitor (NBM)

- The role of NBMs is to observe the incident neutrons and to provide normalization parameters for the neutron experimental data.
- The current status is that there are no adequately working NBMs available at MLF.

Conventional products:
3-helium gas-filled NBM (^{3}He-NBM), NBM using Gas Electron Multiplier (nGEM)

【^{3}He-NBM】
Detector type: Proportional counter
Detection reaction: ^{3}He(n,p)^{3}H
Thermal neutron efficiency: 10^{-5}~10^{-3}

Memo:
Low counting rate capability,
unpurchasable



【nGEM】
Detector type: Foil detector
Detection reaction: ^{10}B(n,α)^{7}Li
Thermal neutron efficiency: 10^{-4}～10^{-2}

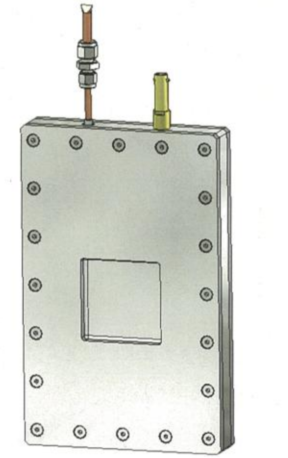
Memo:
Too high counting rate,
Radiation damage, unpurchasable

Moderate counting rate capability, purchasable, …

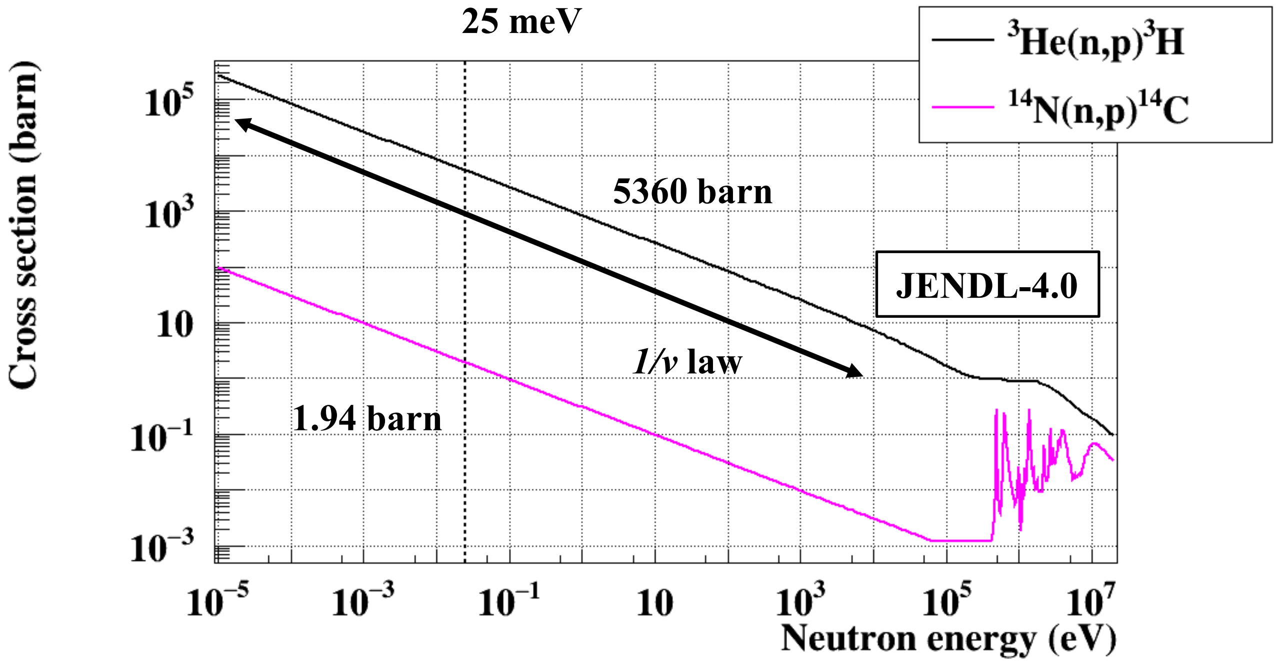
[^{3}He-NBM] T. Ino, *et al.*, J. Phys. Conf. Ser. **528** (2014) 012039, [nGEM] H. Ohshita, *et al.*, JPS Conf. Proc. **8** (2015) 036019.

N_2 Gas-Filled Neutron Beam Monitor (N_2-NBM)

- The N_2-NBM was developed as a new NBM and operates stably in a high-intensity neutron environment such as MLF.
- Since the neutron reaction cross-section is very low, the neutron efficiency can be precisely adjusted.



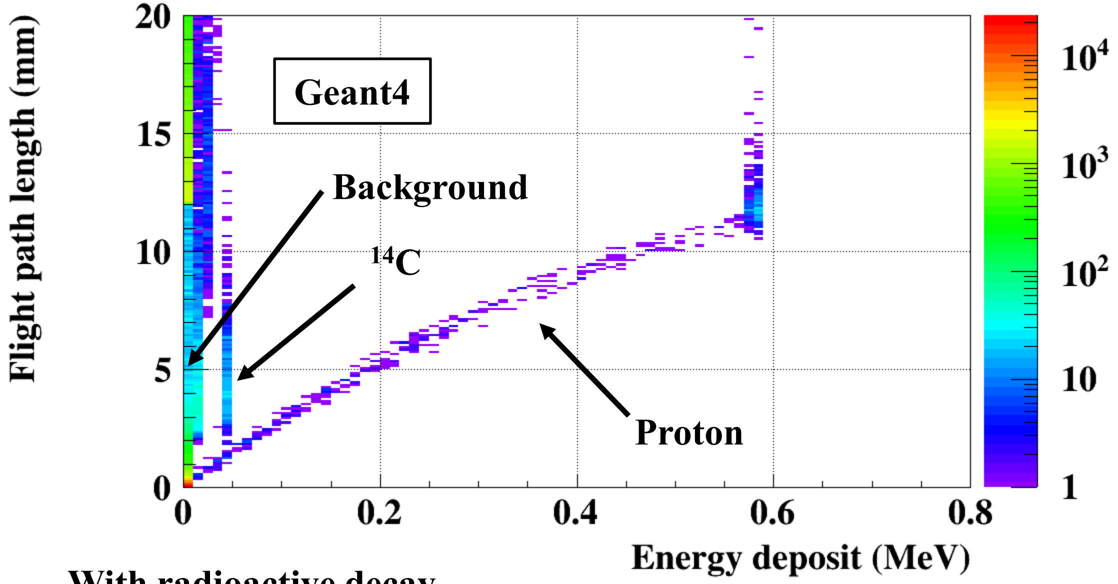
CANON E68953	
Neutron detection reaction	$^{14}N(n,p)^{14}C$
Q-value	0.62 MeV
Chamber gas	Ar/N_2 (786 Torr/50 Torr)
Active area, its thickness	65 mm × 65 mm, 12 mm*t*
Detector structure	Multi Wire Proportional Chamber
Outer size	250 mm × 160 mm × 32 mm
Position detection	×
Thermal neutron efficiency	6.73×10^{-6}
Operation voltage	1400 V

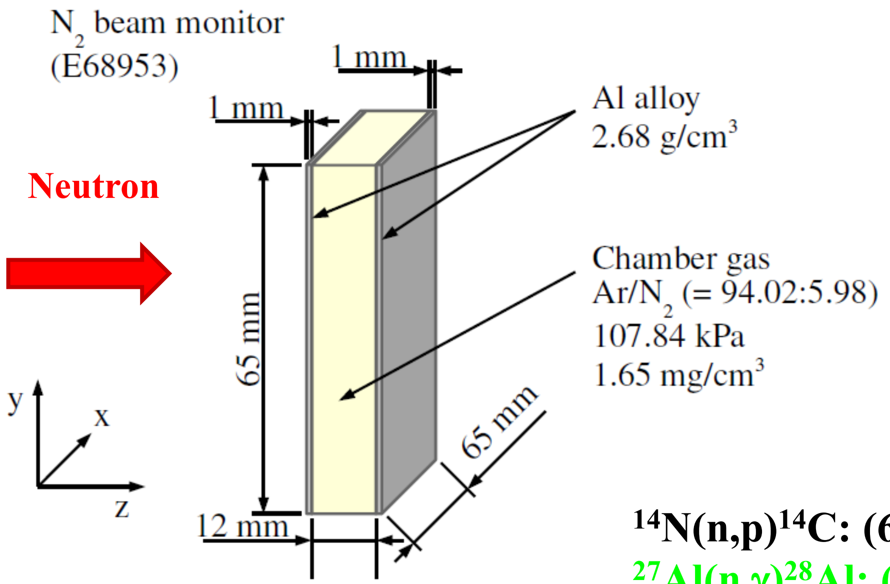


[JENDL-4.0] K. Shibata, *et al.*, J. Nucl. Sci. Technol. **48(1)** (2011) 1, [CANON ELECTRON TUBES & DEVICES] https://etd.canon/en/index.html.

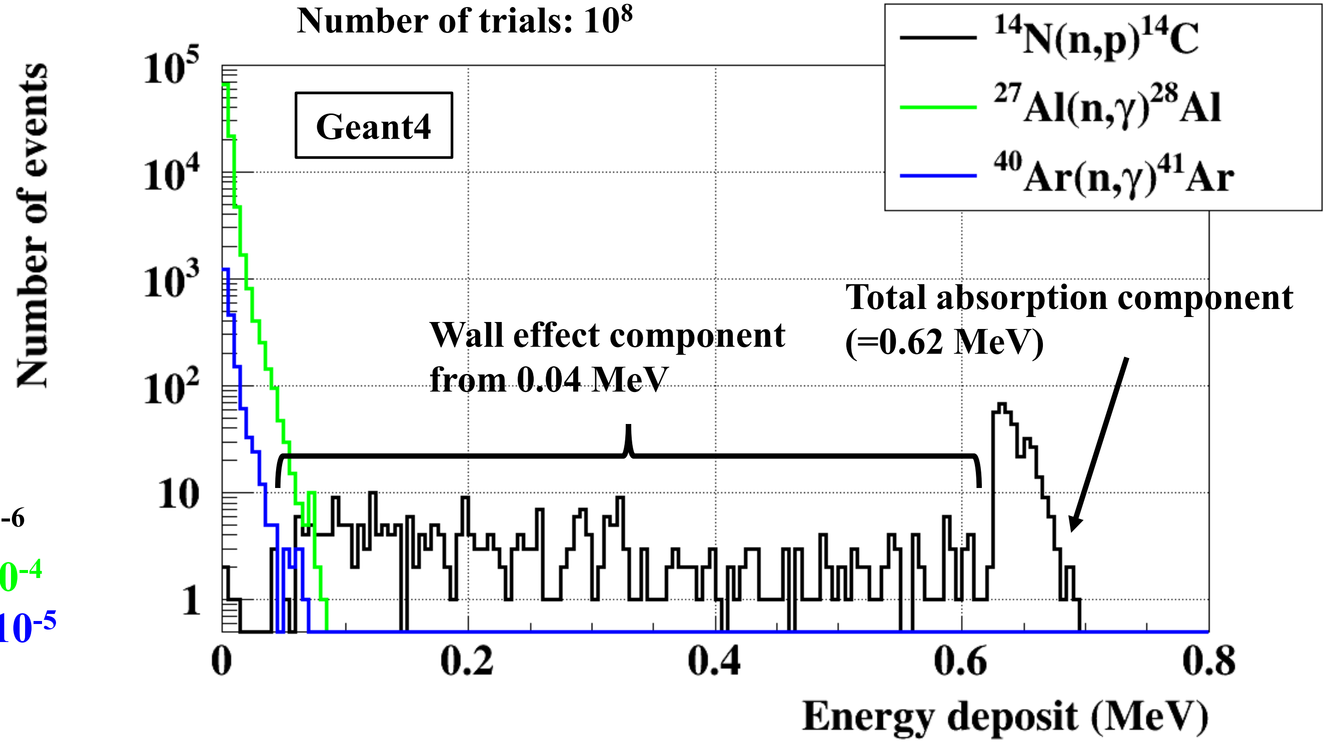
Geant4 Simulation

- Geant4 is a toolkit for simulating the interaction of particles with matter.
- The user defines the geometry and selects the physics model.
- It’s possible to evaluate the detector performance, such as the output charge distribution, transmittance, and detector efficiency.





With radioactive decay
Number of trials: 10^8

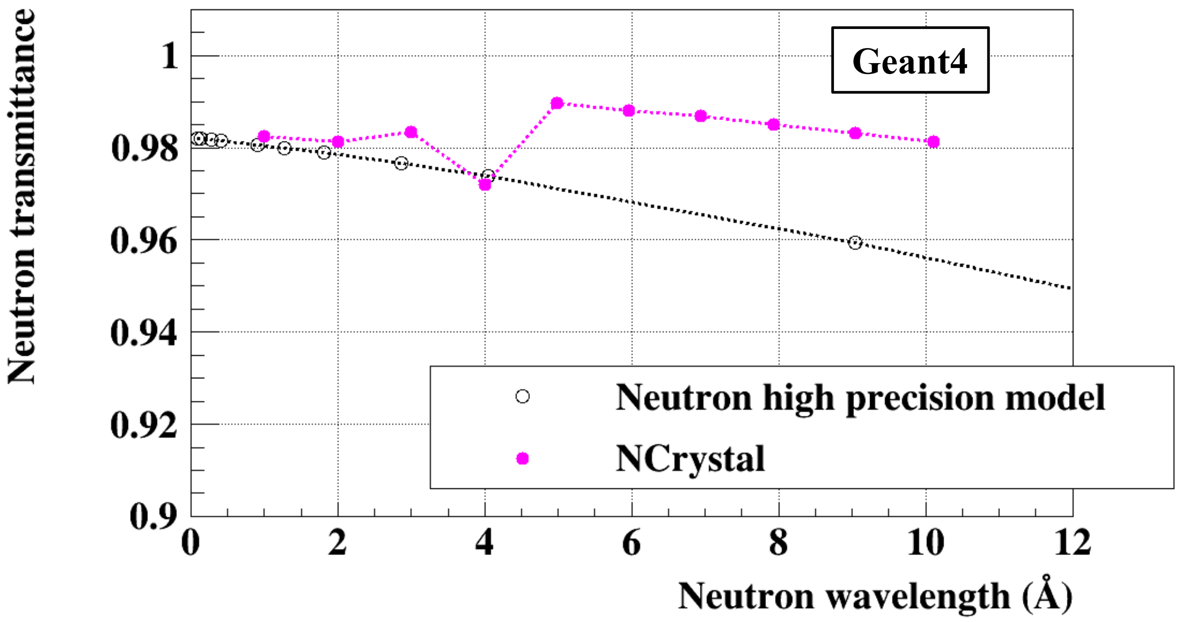


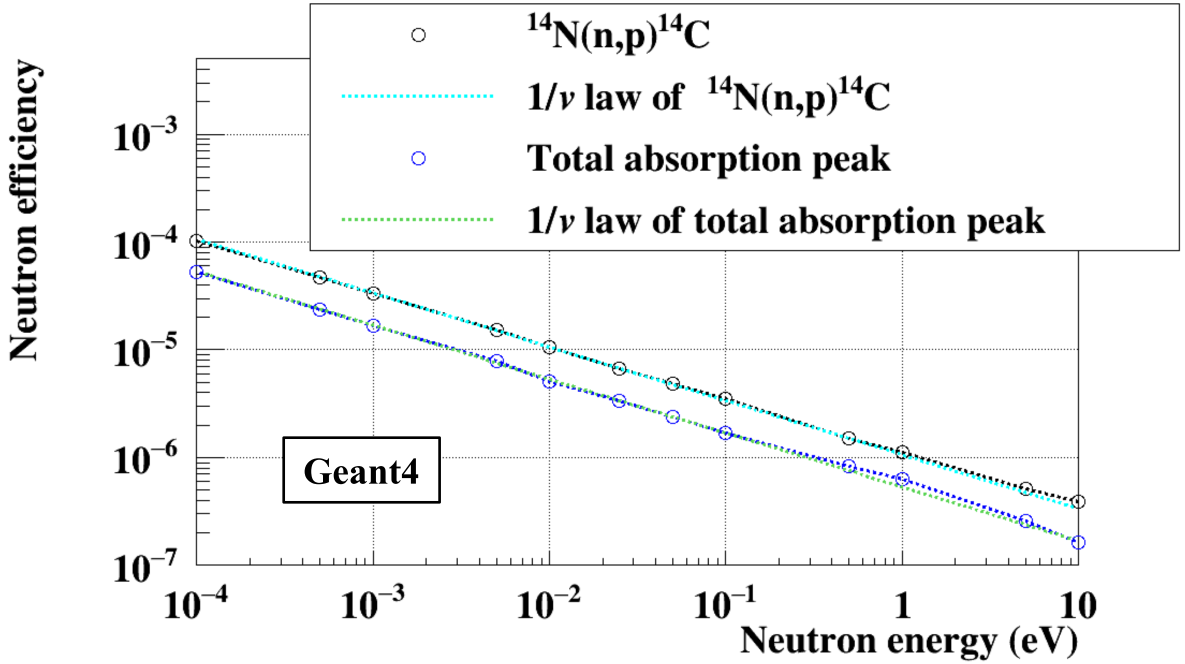
$^{14}N(n,p)^{14}C$: $(6.73 \pm 0.26) \times 10^{-6}$
$^{27}Al(n,\gamma)^{28}Al$: $(9.80 \pm 0.03) \times 10^{-4}$
$^{40}Ar(n,\gamma)^{41}Ar$: $(1.97 \pm 0.04) \times 10^{-5}$

[Geant4] S. Agostinelli, *et al.*, Nucl. Instr. and Meth. A **506** (2003) 250.

Geant4 Simulation Results

- The Neutron high precision (HP) model is a standard physics model that reproduces neutron reactions below 20 MeV, but it cannot reproduce coherent scattering which represents the material structure.
- In addition to the neutron efficiency derived from the total number of neutron reactions, it is possible to derive the neutron efficiency from the total absorption component.
- Since these efficiencies are sufficiently low, they obey the $1/v$ law.

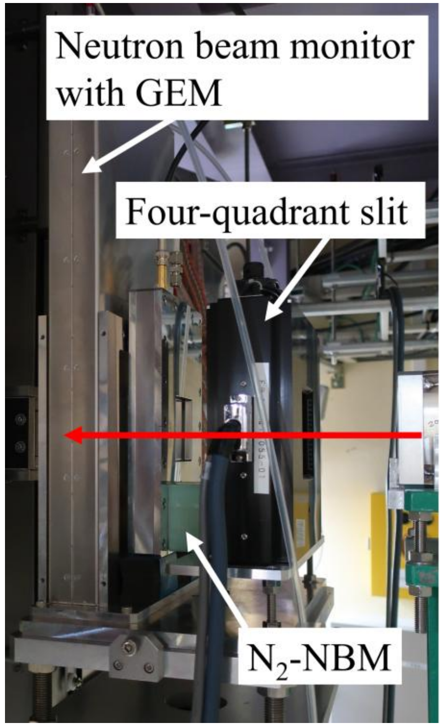


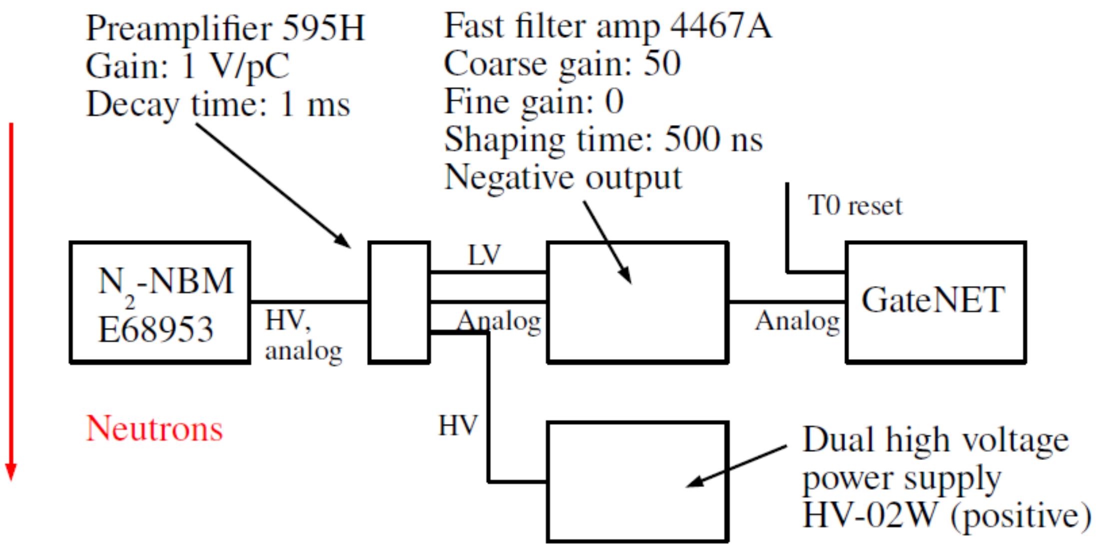


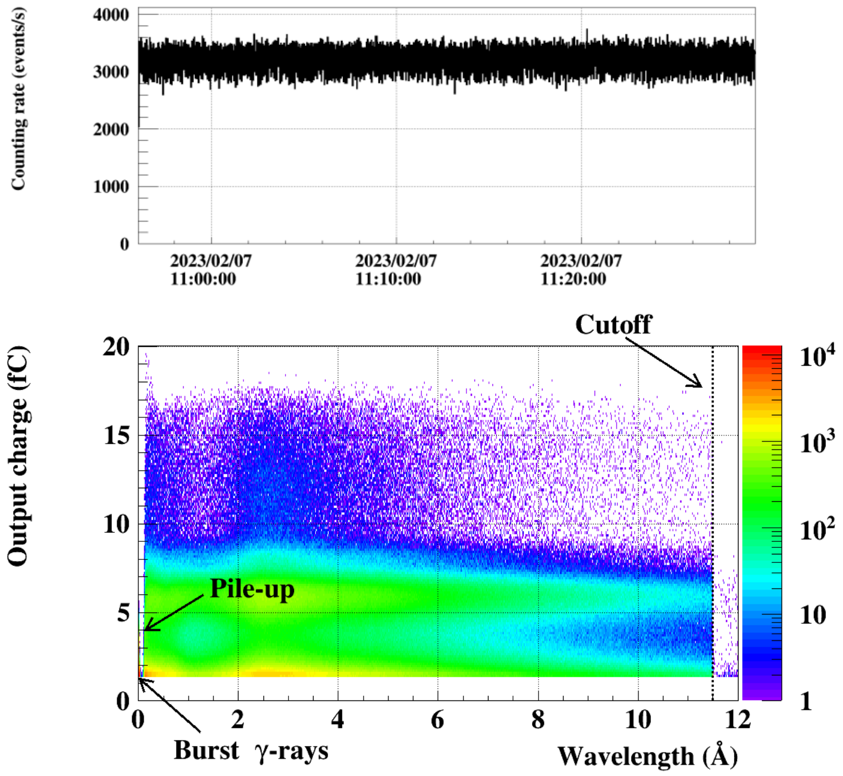
[NCrystal] X. -X. Cai, and T. Kittelmann, Comput. Phys. Commun. **246** (2020) 106851.

Experimental Setup

- The N_2-NBM was installed upstream of the NOVA vacuum chamber, between the slit and the nGEM.
- The nGEM was used to measure the neutron transmittance of the N_2-NBM.
- The TOF and output charge were measured using the standard DAQ system of MLF.



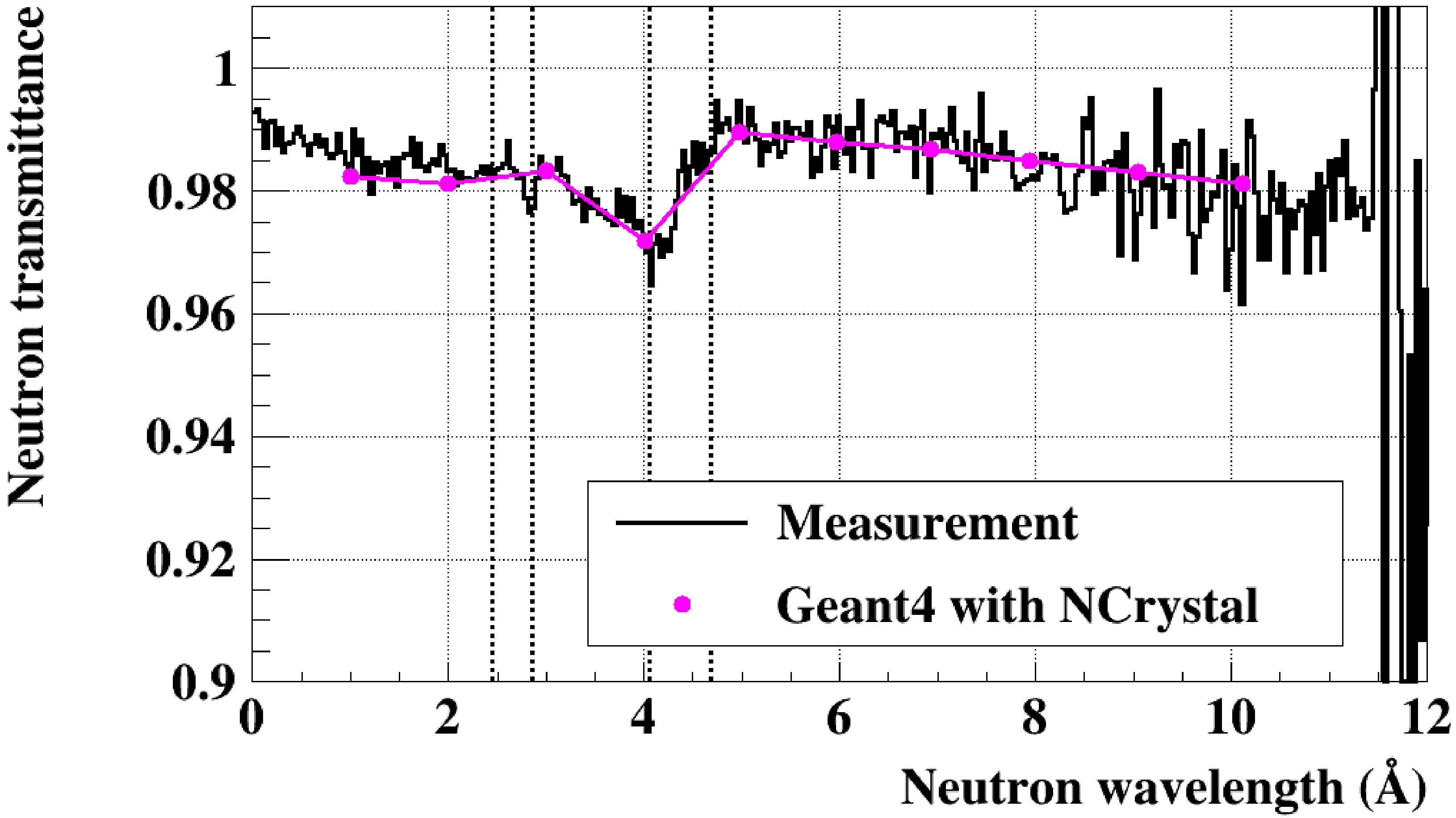




Beam power: 793 kW、T0 chopper: 25 Hz mode、L_1: 13.76 m、Beam size@nGEM: 3.44×3.44 cm^2

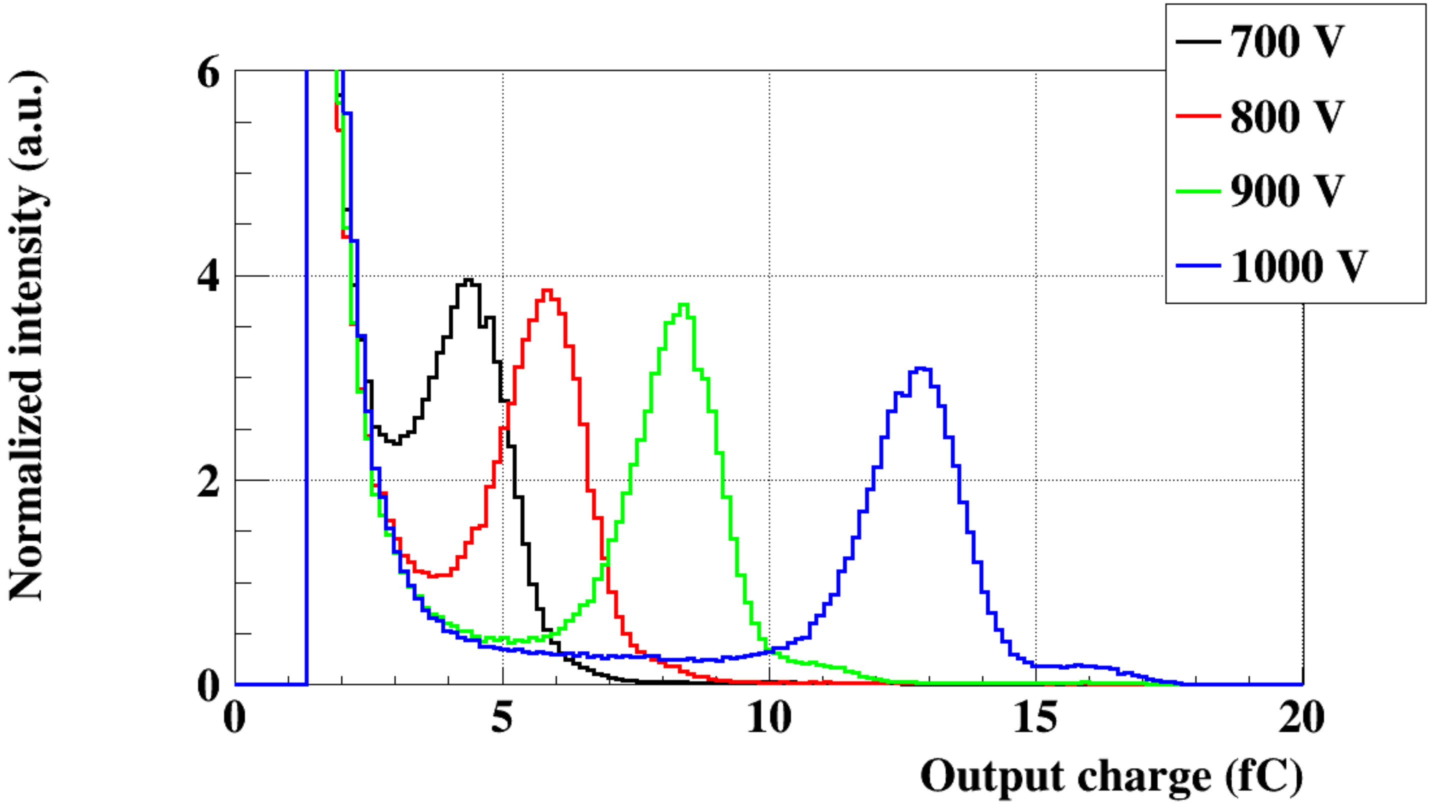
Neutron Transmittance

- The neutron transmittance of N_2-NBM was well reproduced using NCrystal, which is a plugin for Geant4.
- Since NCrystal can reproduce scattering for specific materials (in this case, aluminum), the Bragg edges of aluminum are reproduced.



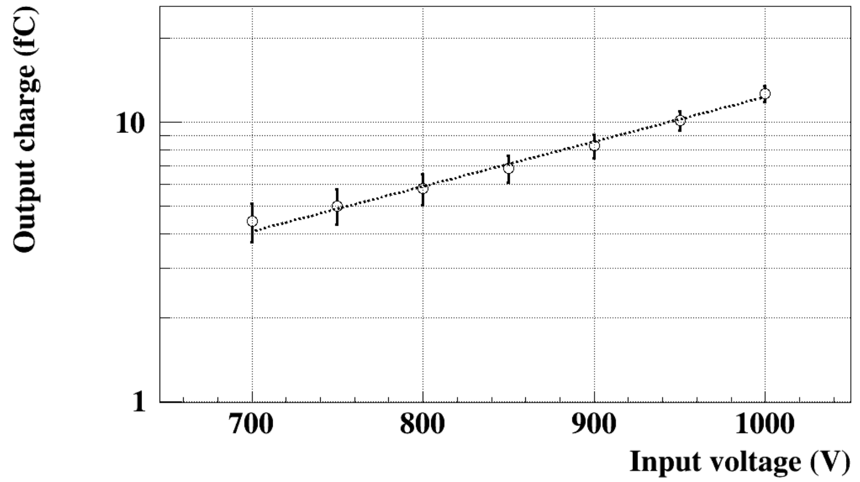
Output Charge Distribution

- The output charge distribution of the N_2-NBM includes multiple components, such as an exponential component and a peak component.
- The N_2-NBM operates in the proportional mode of the gaseous detector.
- The operating voltage was set at 800 V to reduce the consumption of the chamber gas, in consideration of the detector lifetime.



$$f_c = \exp(-1.151967 + 0.003651V)$$

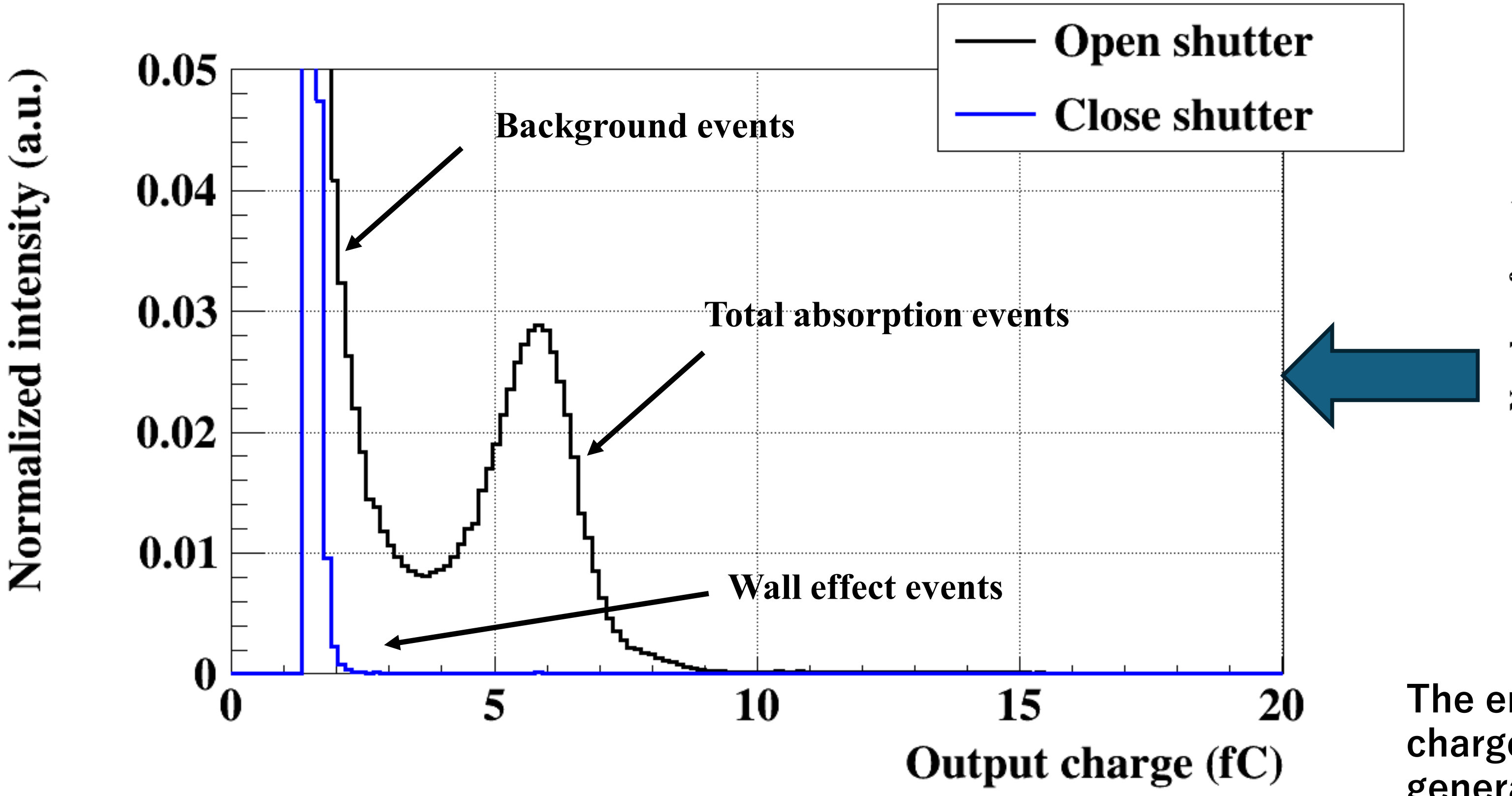
52.5 fC@1400 V, 5.9 fC@800 V

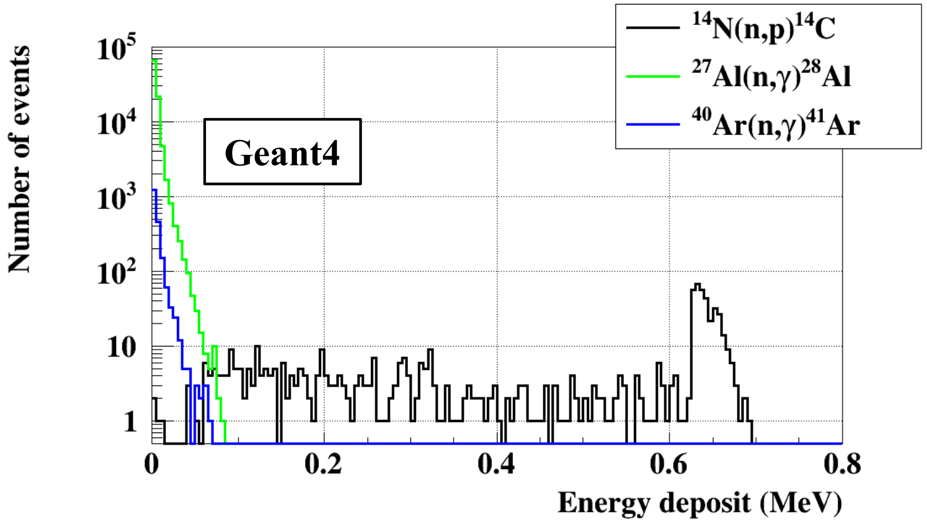


$$G = \frac{(\text{Output charge})}{\frac{(\text{Deposited energy})}{W} \times 1.602 \times 10^{-19}} = \frac{5.9 \times 10^{-15}}{\frac{620000}{30} \times 1.602 \times 10^{-19}} \sim 1.8$$

Contribution of Neutrons

- To confirm the neutron contribution in the output charge distribution, a measurement was carried out with the beam shutter closed.
- Although the difference between the two histograms represents the contribution of neutron events, it is difficult to count the total number of neutron reactions due to the poor nγ discrimination.

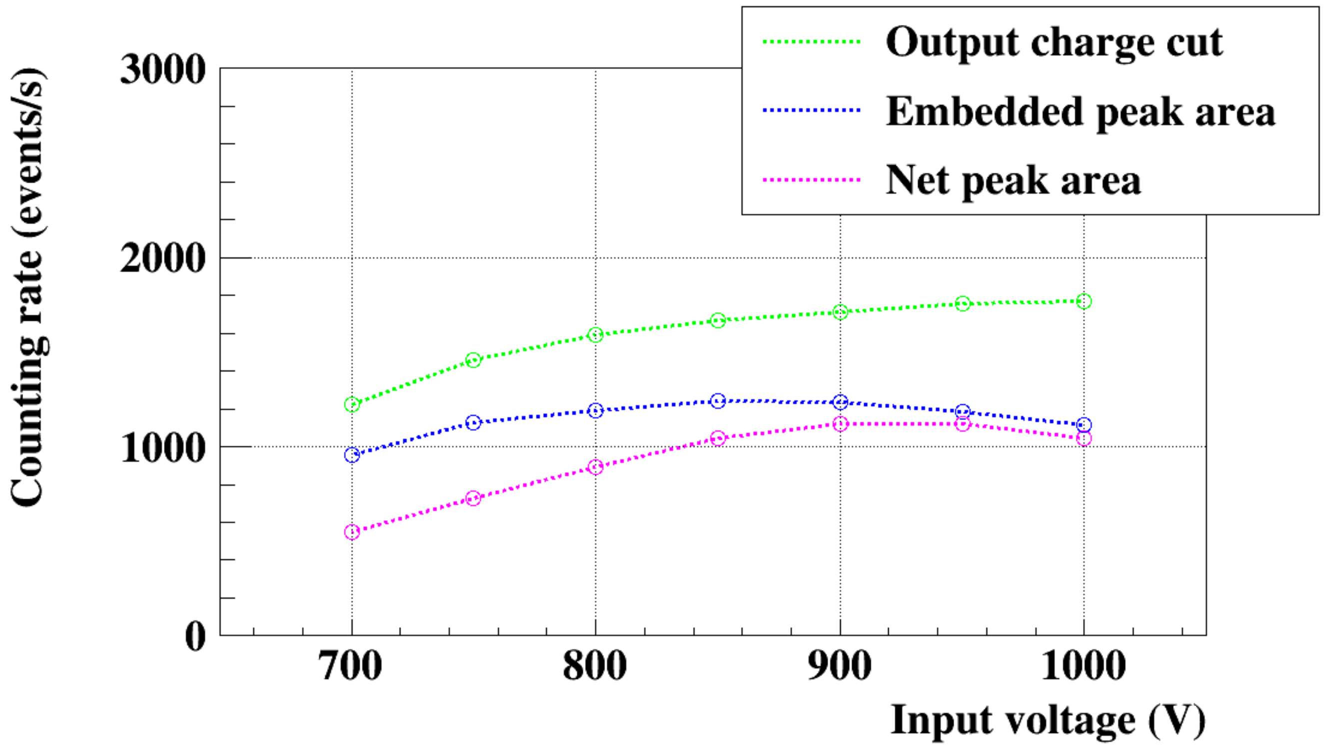




The energy deposit distribution becomes the output charge distribution after convolution with the signal generation process.

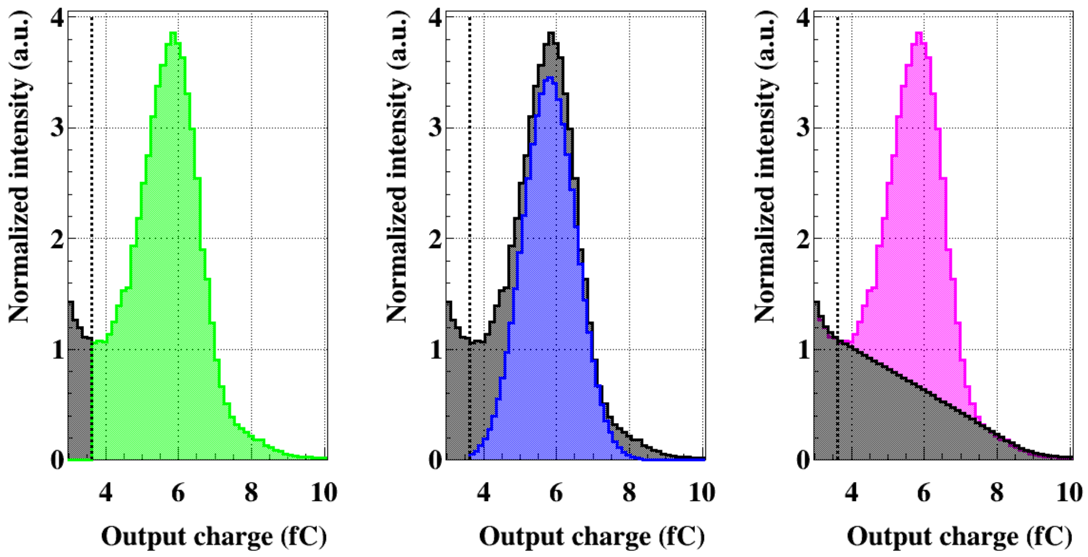
Separation of Neutron Components

- An algorithm was investigated to extract the total absorption component of the $^{14}N(n,p)^{14}C$ reaction from the peak component of the output charge distribution.
- The "Embedded peak area" is the least affected by changes in the distribution shape.



Counting rate of the "Embedded peak area":
1194.29 ± 45.43 events/s@800 ~ 1000 V

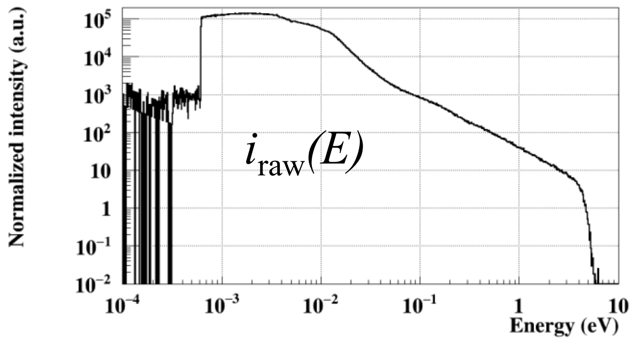
Output charge cut: The number of events over the threshold level
Embedded peak area: The Gaussian component obtained by fitting with a combined function of an exponential and a Gaussian distribution.
Net peak area: The number of events after subtracting the baseline determined by the spline curve.

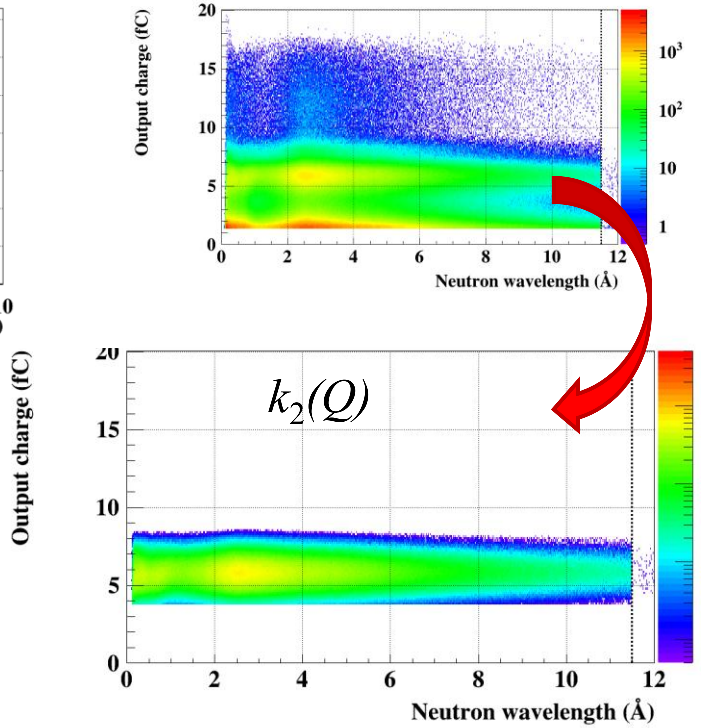


Measurement-based Neutron Intensity *I(E)*

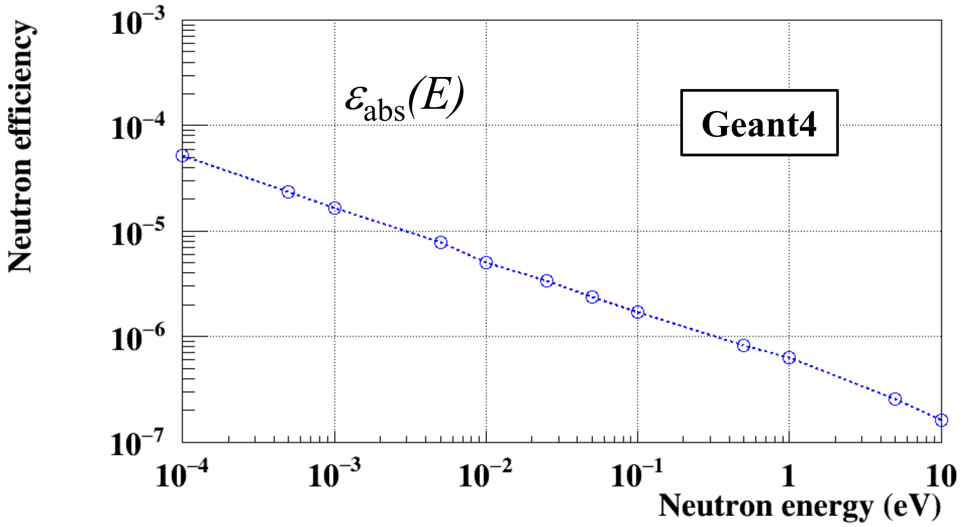
$$I(E) = \frac{i_{\mathrm{raw}}(E) k_1 k_2(Q)}{\varepsilon_{\mathrm{abs}}(E)}$$

$i_{raw}(E)$:The incident neutron energy distribution derived from the measurement data of the N_2-NBM
$\varepsilon_{abs}(E)$:The total absorption component of the N_2-NBM's neutron efficiency obtained by Geant4
k_1 :The correction term for the J-PARC accelerator beam power (1 MW/793 kW=1.26)
$k_2(Q)$:A weighting function for extracting the total absorption component of the $^{14}N(n,p)^{14}C$ reaction





Thermal neutron efficiency：3.38×10⁻⁶

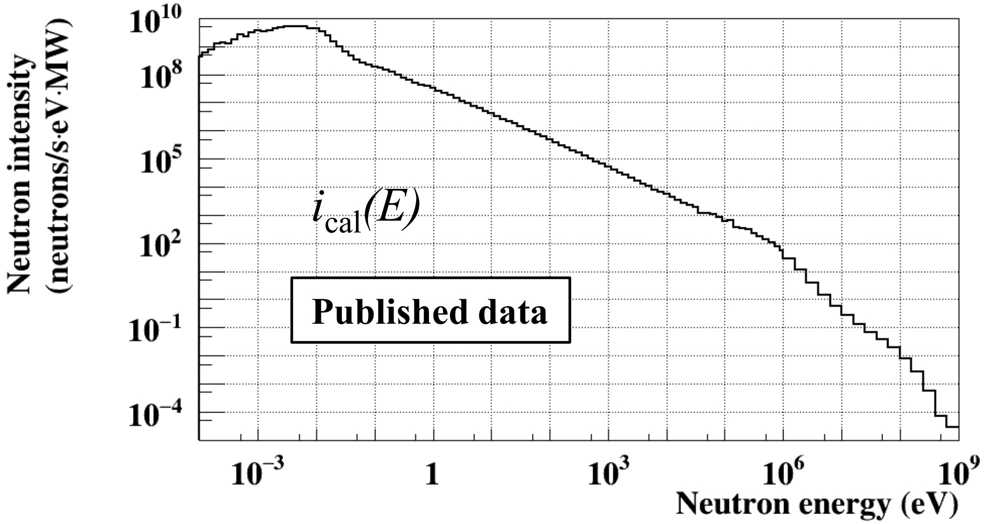


Simulation-based Neutron Intensity $I_{\text{cal}}(E)$

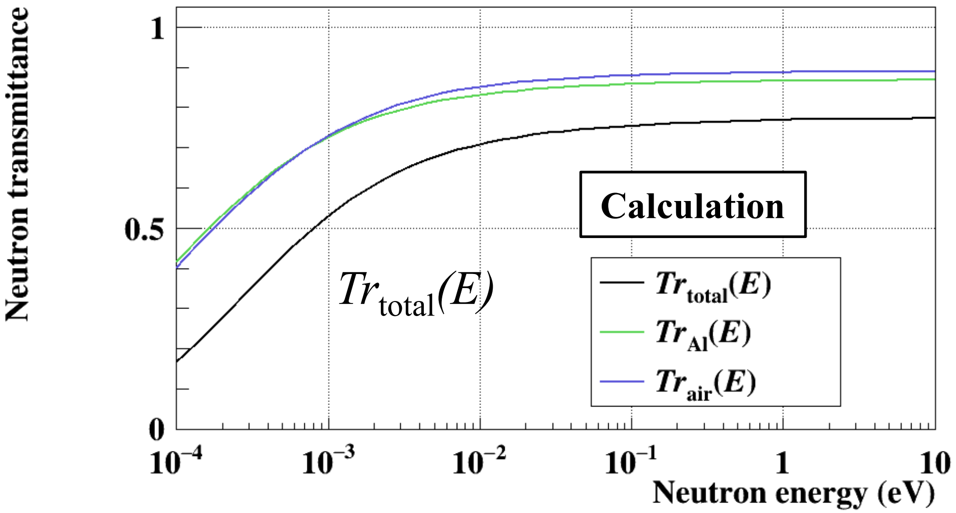
$$I_{\text{cal}}(E) = i_{\text{cal}}(E) Tr_{\text{total}}(E) p_1 p_2$$

$i_{\text{cal}}(E)$:The neutron intensity based on the data published by the MLF facility
$Tr_{\text{total}}(E)$:The neutron transmittance due to the NOVA beamline structures
p_1 :The correction term due to the effect of the neutron moderator using light water (=0.82)
p_2 :The correction term for proton beam loss in the muon target (=0.94)

The published data include a PHITS simulation of the spallation reaction caused by injecting a proton beam into the neutron target.



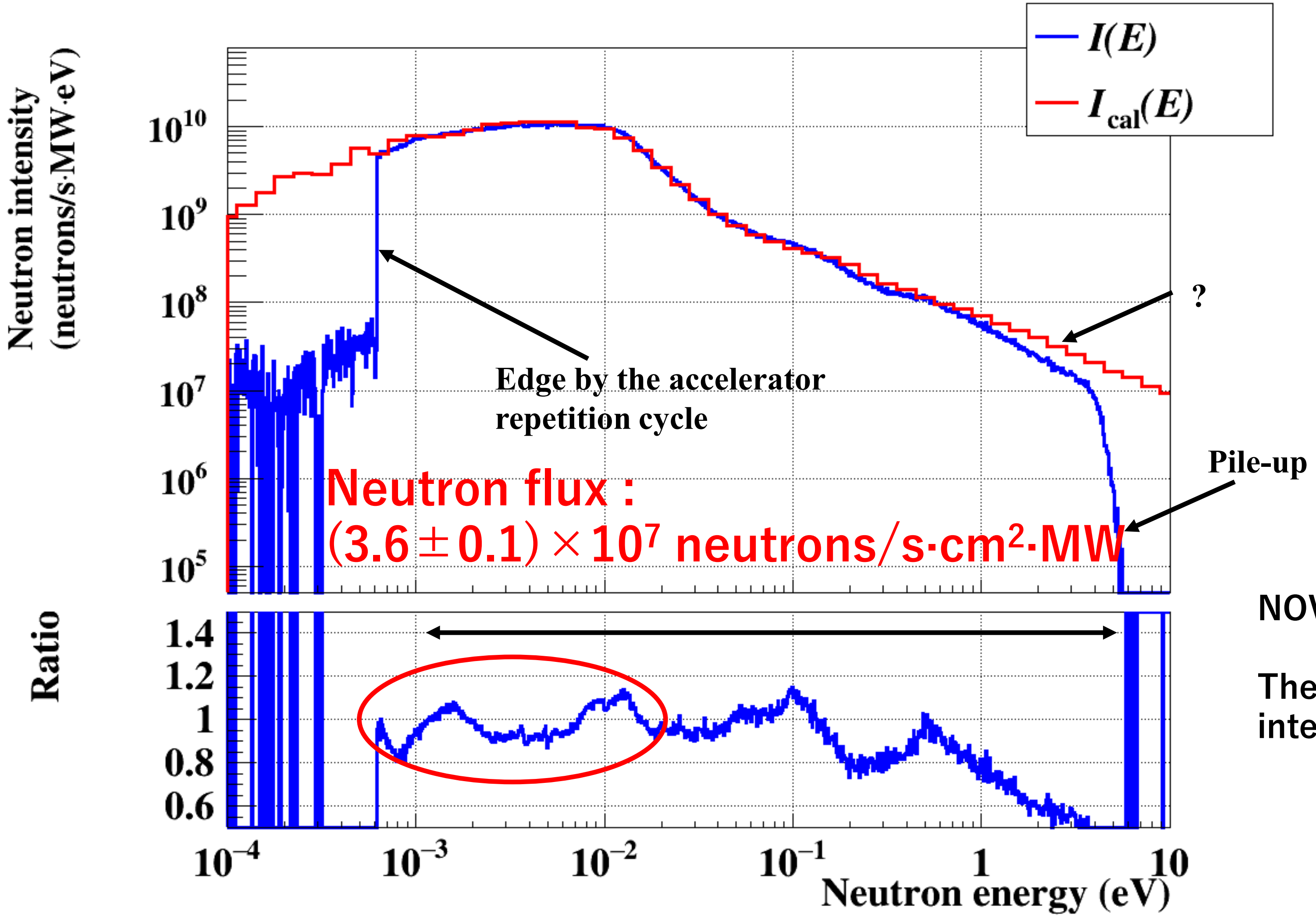
Aluminum alloy layer :16.5 mm
Air layer :2715 mm

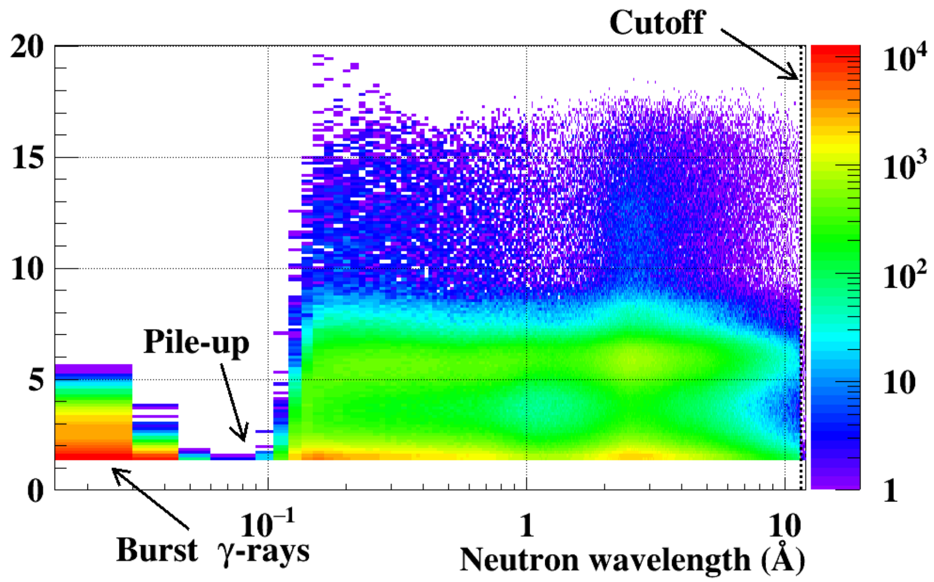


[Published data] Web page of the MLF beamline specifications, https://j-parc.jp/researcher/MatLife/en/instrumentation/ns3.html.
[PHITS] T. Sato, *et al.*, J. Nucl. Sci. Technol. **61** (2024) 127.

Comparison of $I(E)$ and $I_{cal}(E)$

- $I(E)$ and $I_{cal}(E)$ show good agreement, which indicates that the assumption that the peak comp. of the output charge distribution corresponds to the total absorption comp. of the $^{14}N(n,p)^{14}C$ reaction is correct.
- The neutron flux also agrees with previous our studies.



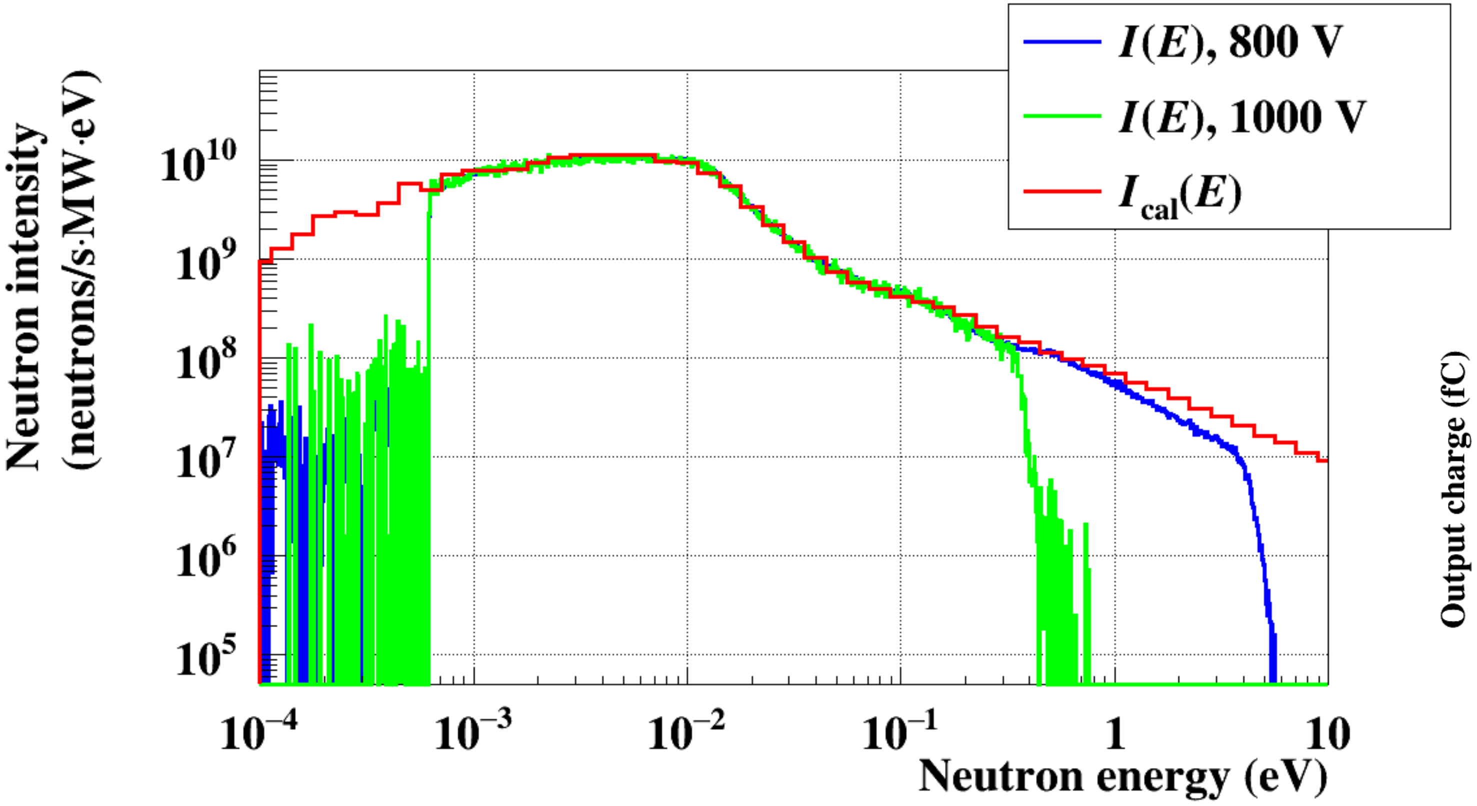


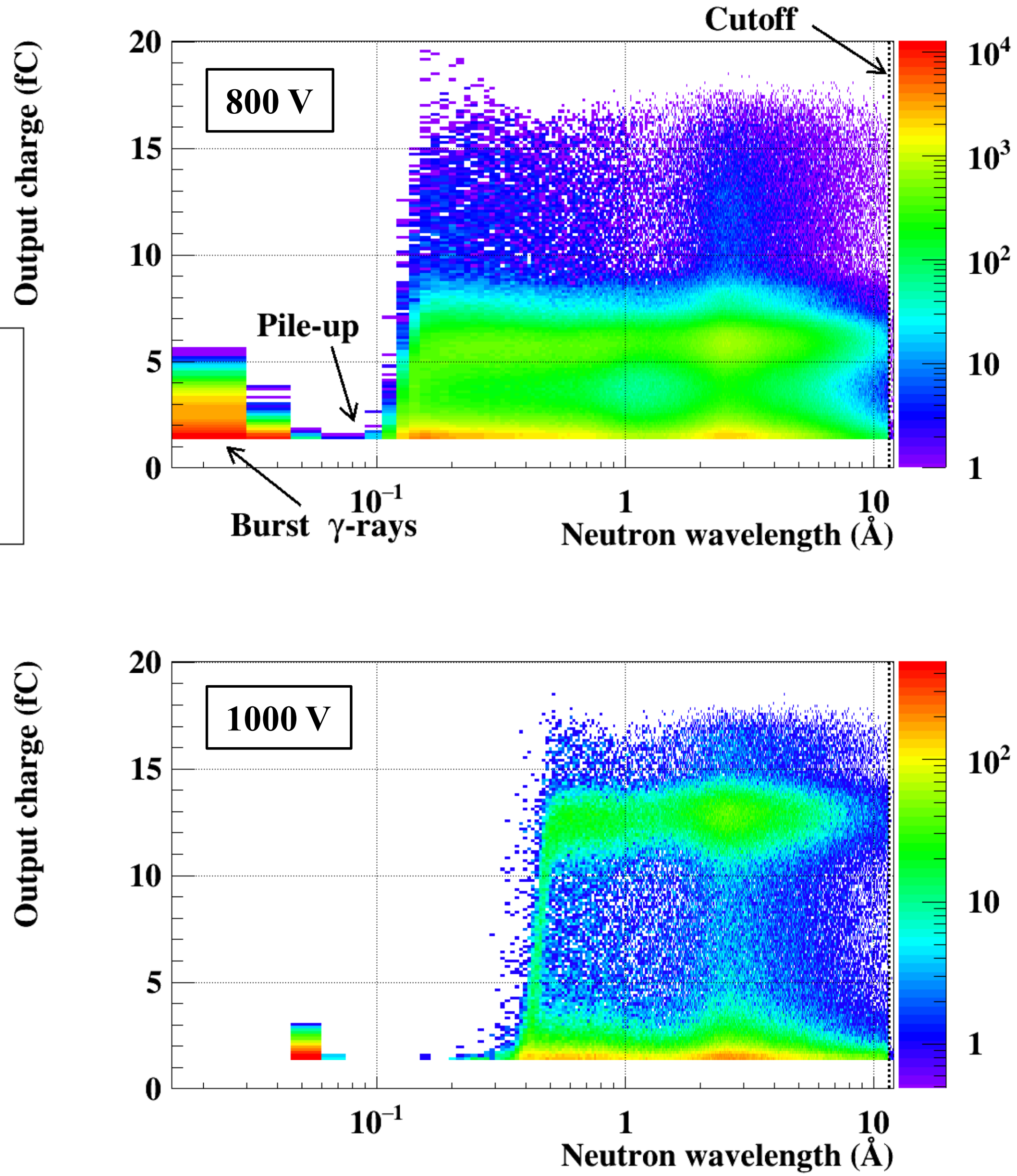
NOVA analysis range :0.0012～5.68 eV

The difference of $I(E)$ and $I_{cal}(E)$ in the high neutron intensity range (0.6 meV~2 eV) :-20～14%

Robustness of *I(E)* measurement (1)

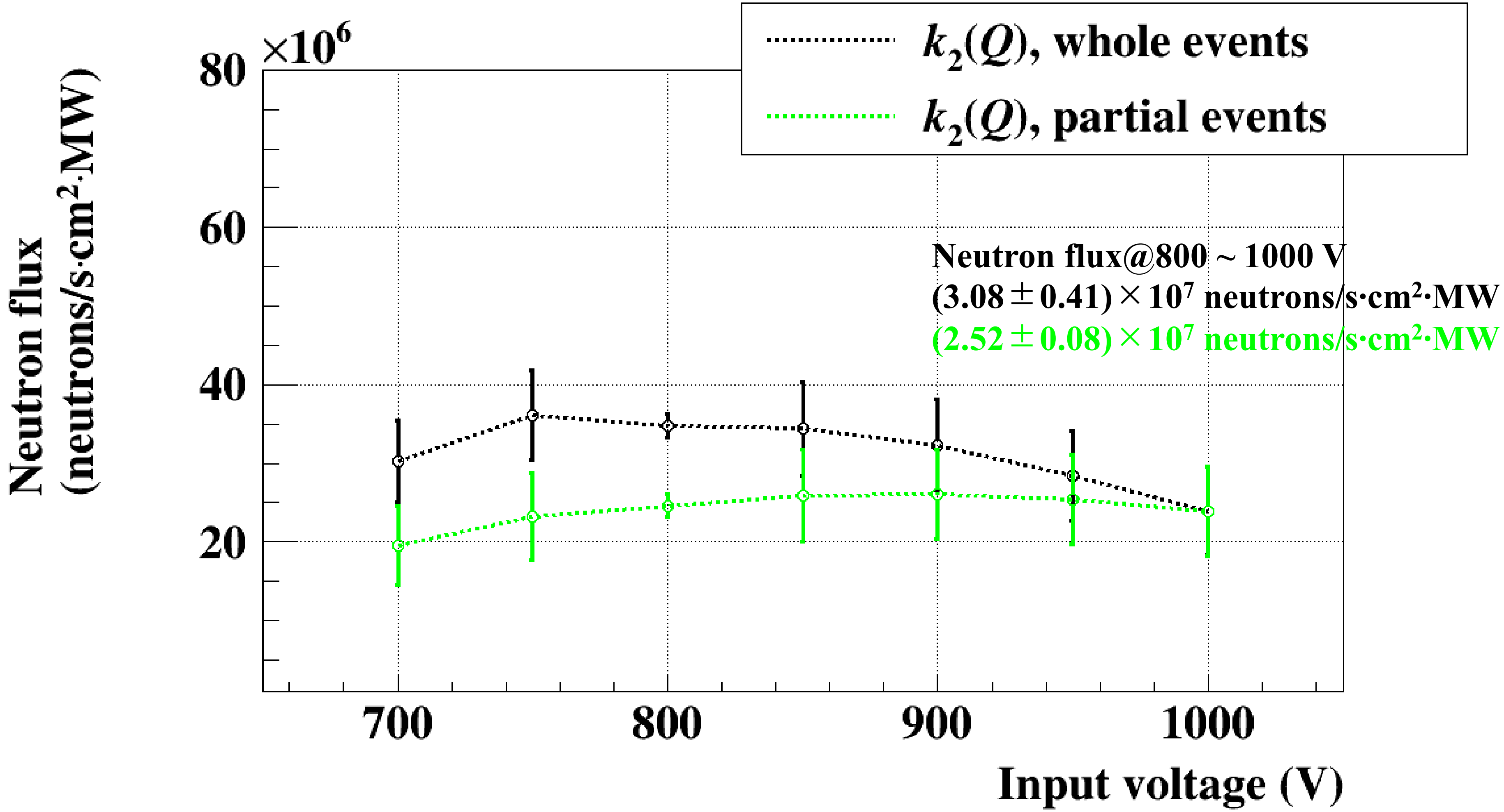
- Although the pile-up effect becomes stronger as the input voltage is increased, the neutron intensity does not change across a wide neutron energy range. This demonstrates robustness against variations in the output charge.





Robustness of *I(E)* measurement (2)

- By removing the pile-up effect within the range of 0.0006 to 0.4 eV (or 0.45 to 11.68 Å), the flatness of the neutron flux dependence on the input voltage is improved.



Summary

Commissioning of N_2-NBM was carried out at MLF BL21.

To evaluate the absolute neutron intensity,

- the results of the Geant4 simulation were considered
- Not the total events of the $^{14}N(n,p)^{14}C$ reaction,

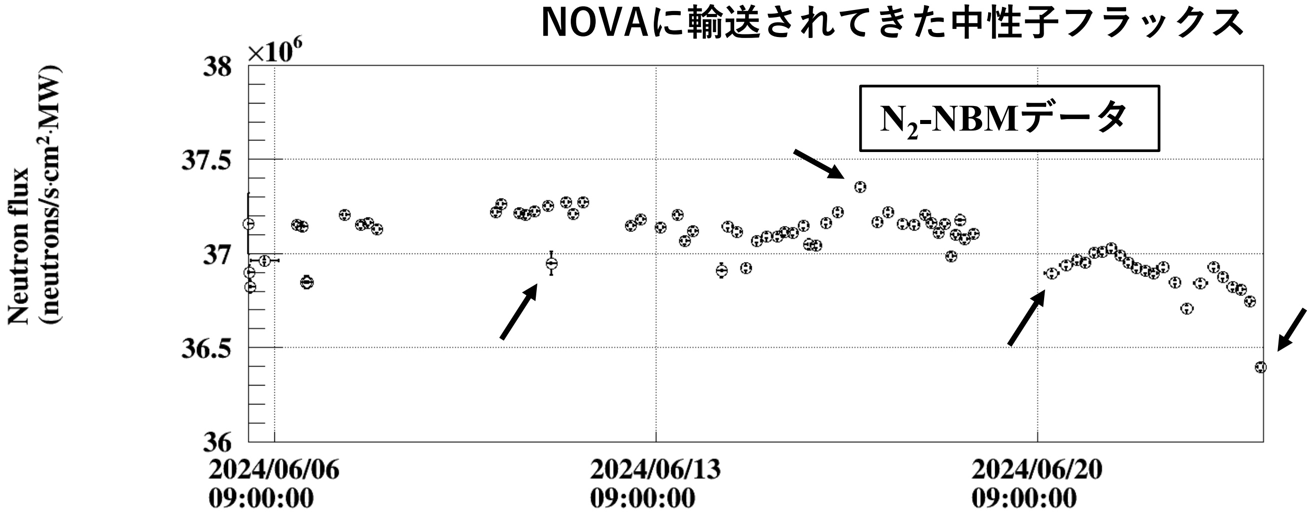
but the total absorption component was counted

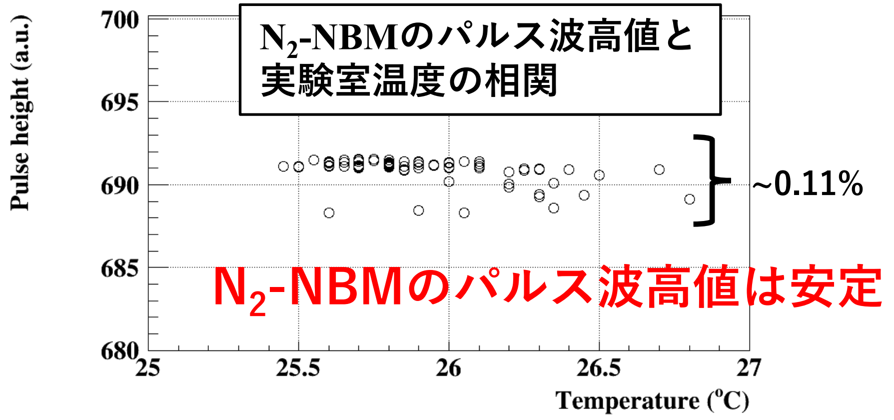
These steps demonstrated the validity of $I(E)$ and $I_{cal}(E)$.

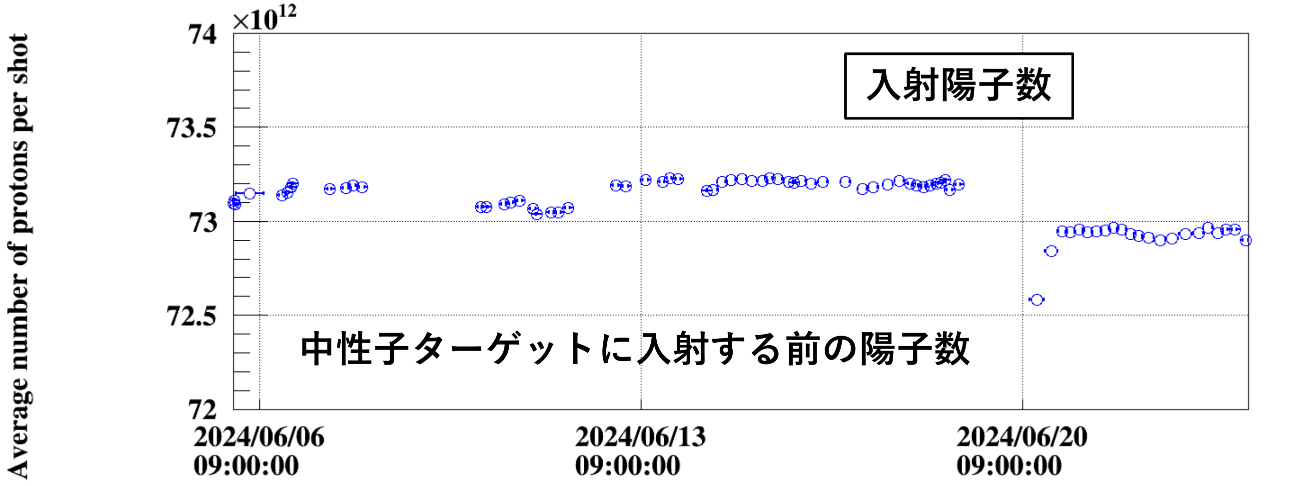
This research was conducted with the support of JSPS KAKENHI Grant Number JP20H04461.
In addition, the neutron irradiation test at MLF BL21 was conducted by the Neutron Scattering Program Advisory Committee of IMSS, KEK (Proposal No. 2019S06).

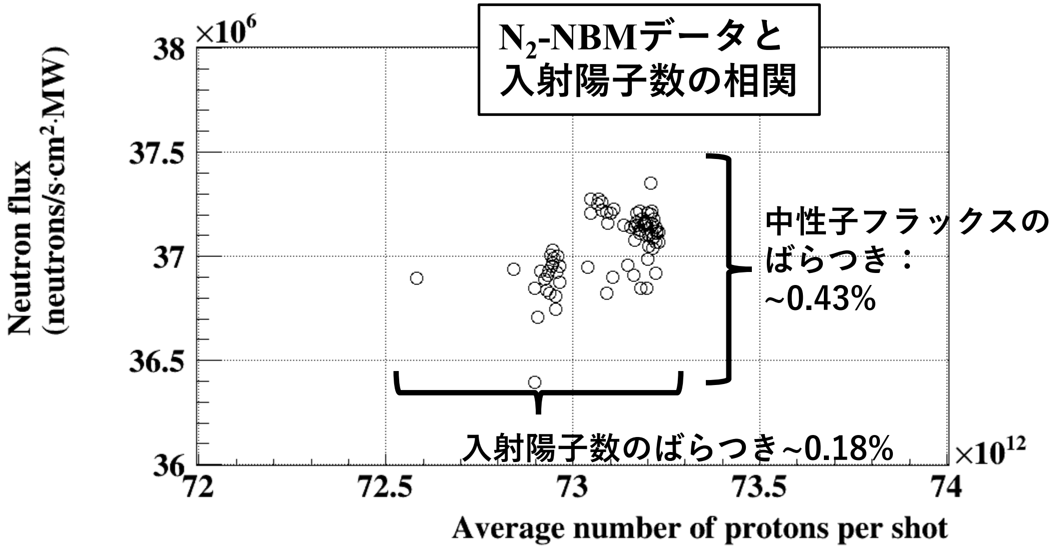
Thank you for your attention!
ご清聴ありがとうございました。

実際の中性子実験への適用









規格化パラメータとして、N$_2$-NBMデータと入射陽子数は安定している
今後、さらに長期運用において評価を継続する