Neutron beam monitor for the high-intensity neutron total diffractometer NOVA

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- Collaborator

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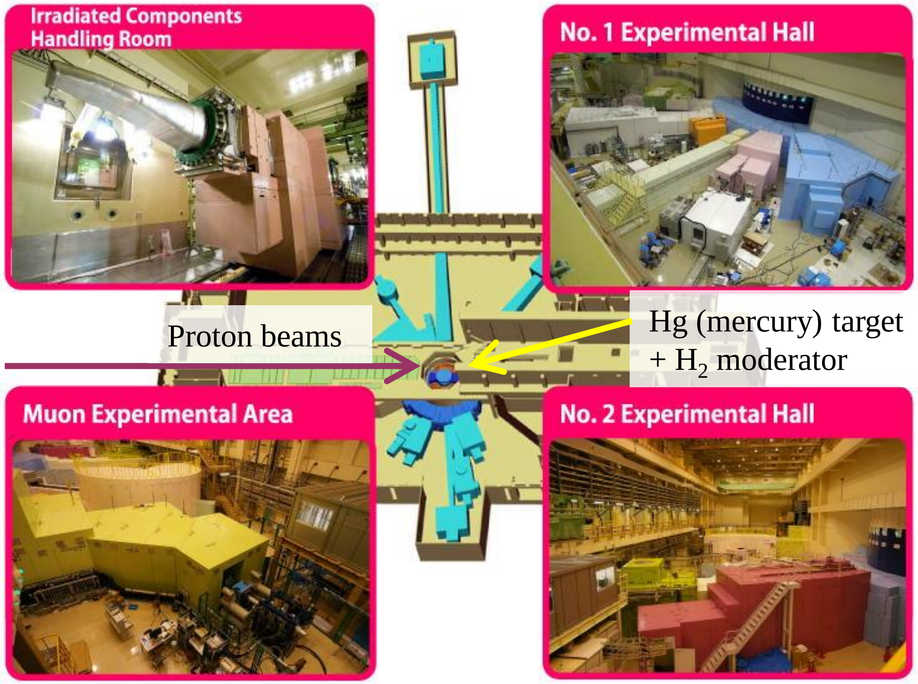
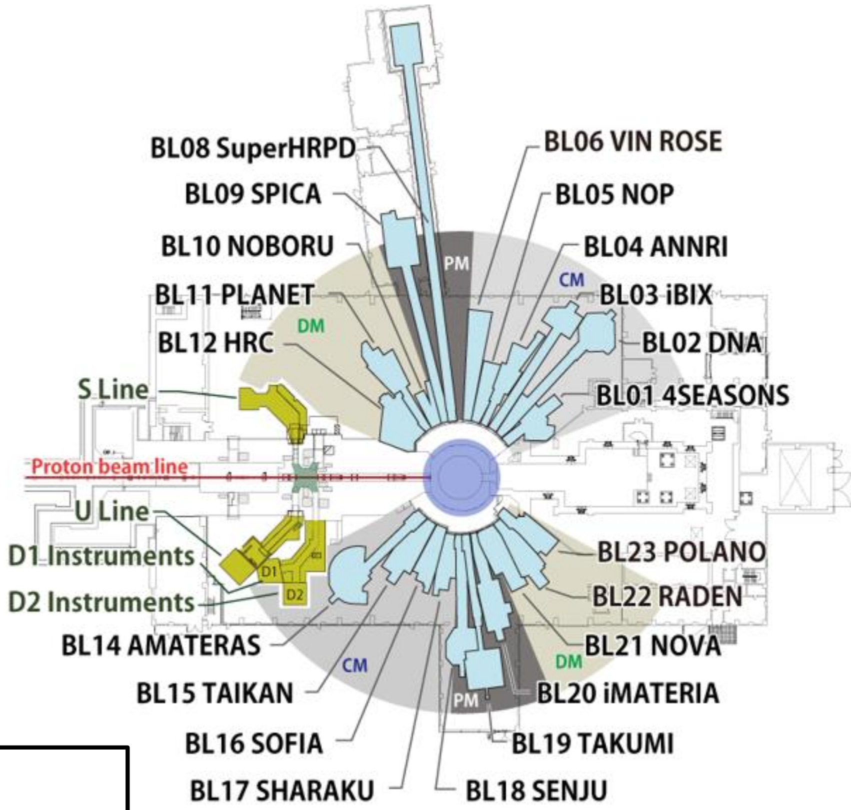
Materials and Life Science Experimental Facility, MLF

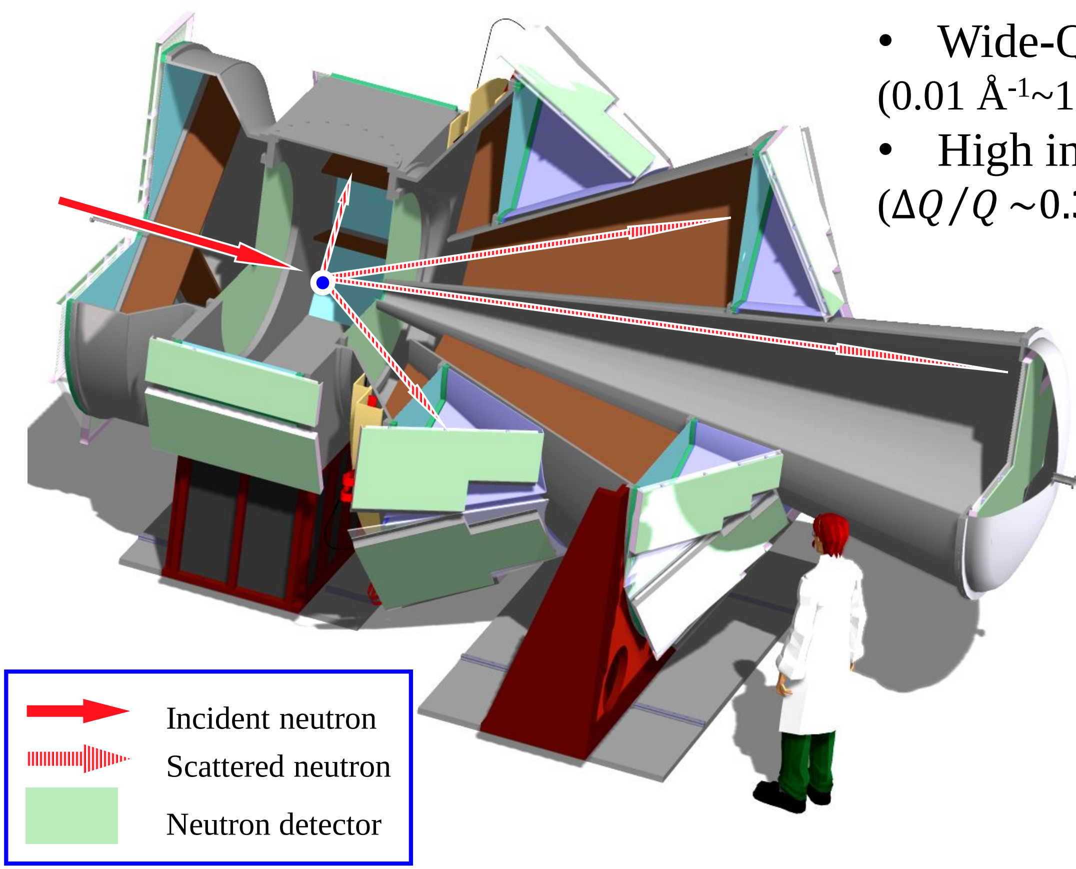
- The most intense pulsed neutron source in the world
- Research center for material structure science, life science and elementary physics





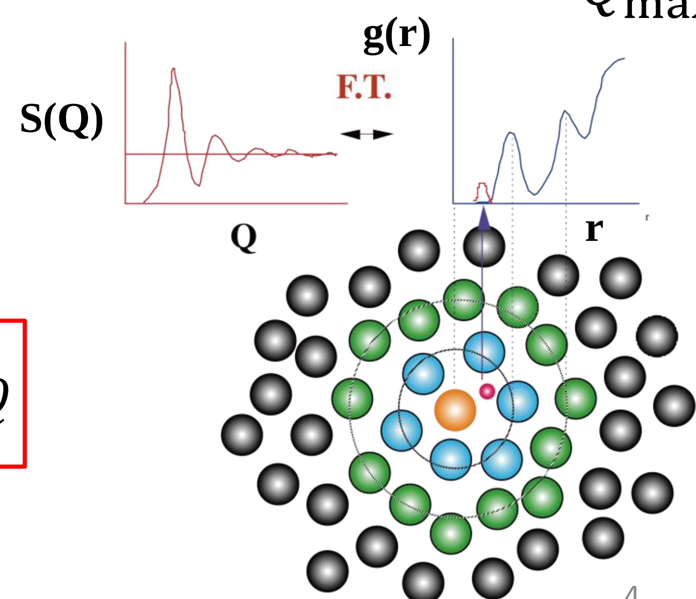
- Beam power: 1 MW
- Beam repetition rate: 25 Hz
- Neutron source: Mercury (Hg) target
- Neutron moderator: Supercritical hydrogen
- 3 kinds of moderator structure: coupled, decoupled, poisoned

High-intensity neutron total diffractometer, NOVA



- Constructed in MLF BL21 at J-PARC
- Wide-Q measurement including small scattering ($0.01\ Å^{-1}$~$100\ Å^{-1}$)
- High intensity Powder Diffractometer ($\Delta Q/Q$ ~0.35%, ~10^8 neutrons/cm^2·sec)

$$\Delta r \approx \frac{\pi}{Q_{\max}}$$



$$g(r) = 1 + \frac{1}{2\pi^2 \rho_0 r} \int_0^{Q_{\max}} Q[S(Q) - 1] \sin(Qr) dQ$$

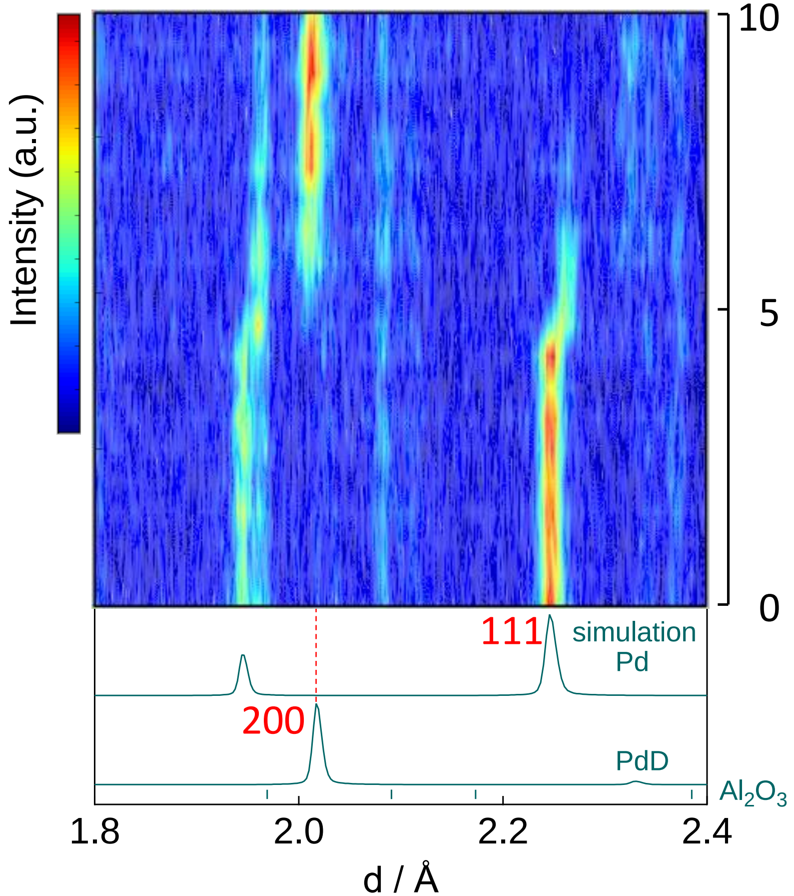
Total scattering method is a powerful method
to analyze the complex structure of disordered materials:
liquids, glasses, amorphous materials and disordered crystals.

Motivation

- To normalize the data under a huge amount of neutrons
- In an in-situ measurement, required a high-counting detector

Performance requirements of neutron beam monitor for NOVA

- Neutron efficiency: ~0.1%
- Data transfer rate: ~1 MHz (special)
- Position resolution: ~1 mm (FWHM)
- Wavelength separation capability
- Active area: 50 mm × 50 mm

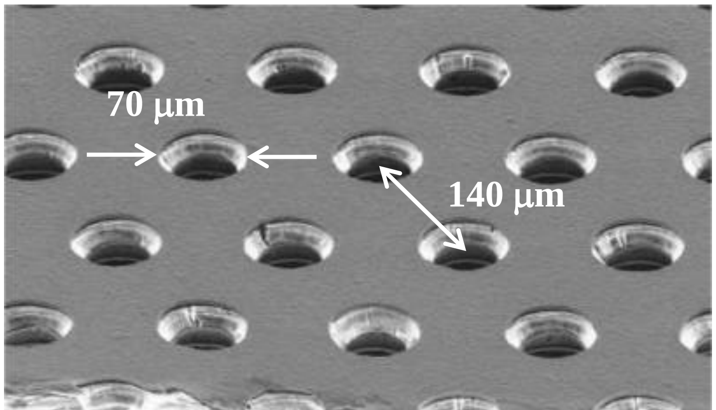


A Gas Electron Multiplier is one of the few detectors which satisfies all the requirements.

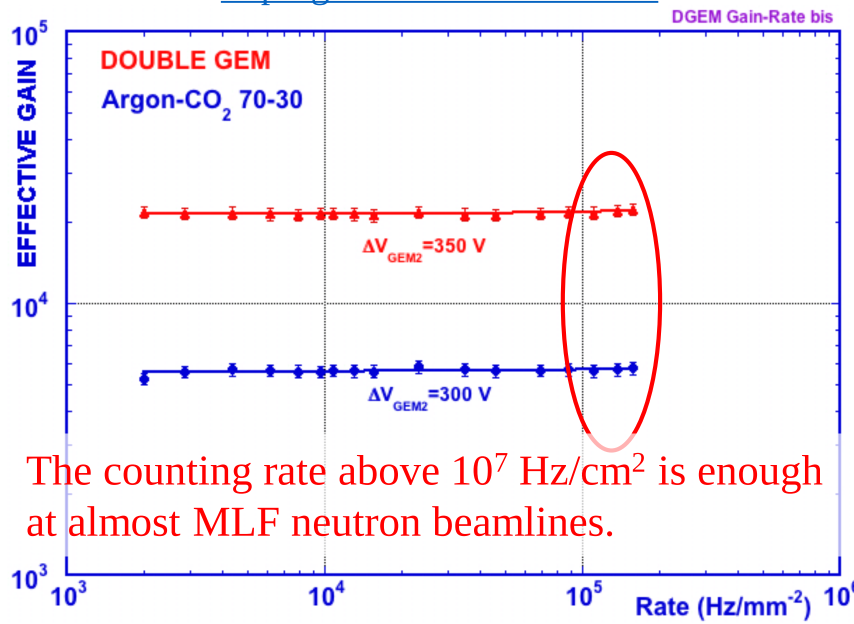
Gas Electron Multiplier, GEM

- One of Micro Pattern Gas Detectors (MPGDs), developed by F. Sauli
- Good high counting rate capability, stable operation under the intense radiation environment

F. Sauli, Nucl. Instr. and Meth. A **386** (1997) 531.
http://gdd.web.cern.ch/GDD/



50 μm*t* polyimide film with Cu-clad



The counting rate above 10^7 Hz/cm^2 is enough at almost MLF neutron beamlines.

The main characteristics and performances of GEM detectors are:

- **Operation in most gas filling, including pure noble gases**
- **Proportional gains above 10^5**
- **Energy resolution 18% FWHM at 5.9 keV X-rays**
- **Space localization accuracy 60 μm rms or better**
- **Rate capability above 10^5 counts/mm^2·sec**
- **Active areas up to 1000 cm^2**
- **Flexible detector shape and readout patterns**
- **Robust, Low cost**

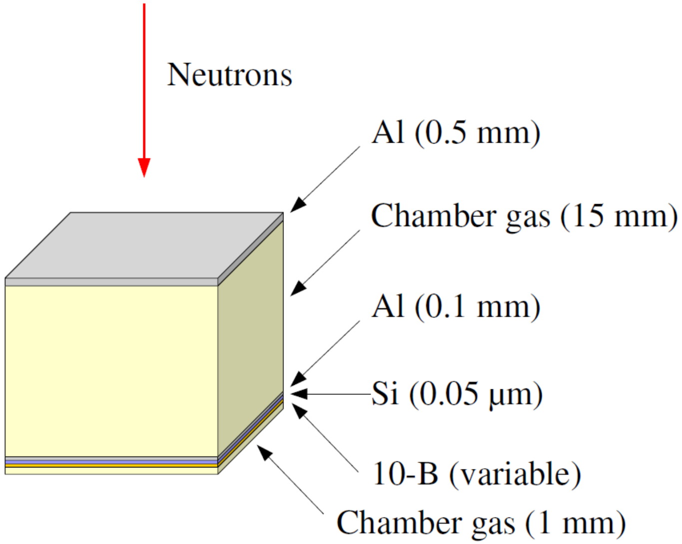
Principle of neutron detection

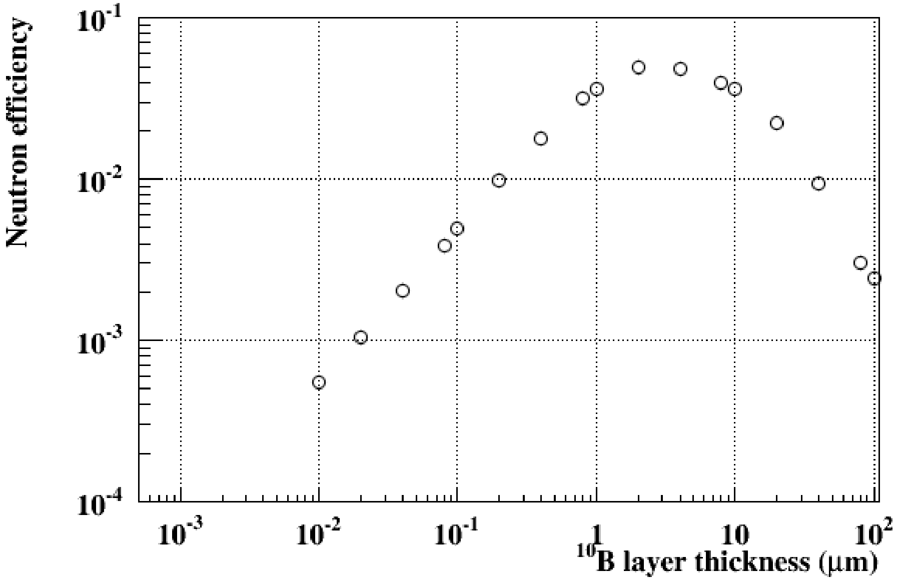
- To detect charged particles from the following neutron nuclear reactions

$^{10}B + n \rightarrow {}^{7}Li + \alpha + 2.79$ MeV (6%)
$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha + 2.31$ MeV (94%)
$^{7}Li^{*} \rightarrow {}^{7}Li + 0.48$ MeV (prompt γ)

$^{3}He + n \rightarrow {}^{3}H + p + 0.765$ MeV (5330 barn)
$^{6}Li + n \rightarrow {}^{3}H + \alpha + 4.78$ MeV (940 barn)

Geant4-based simulation





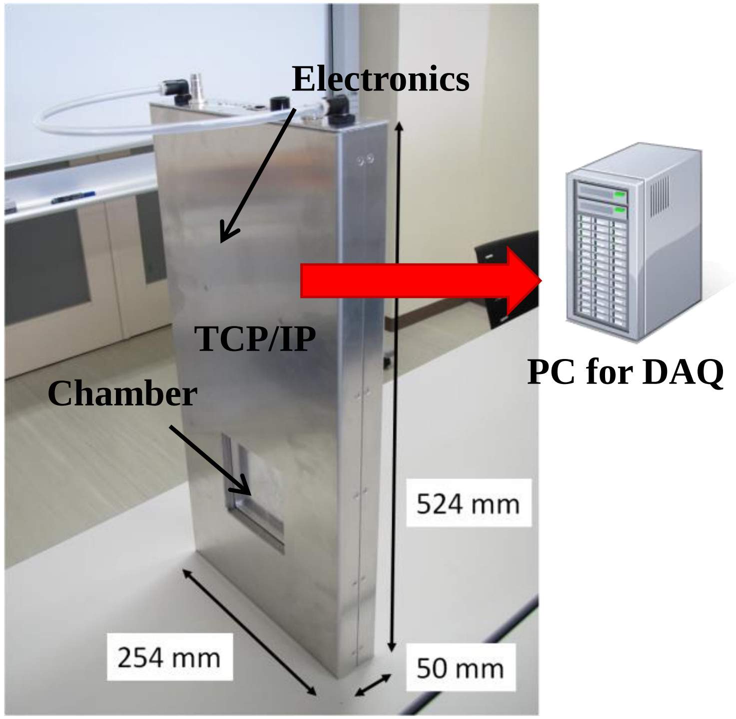
The Geant4-based simulation conditions are:
- Version 9.6
- Used with high precision neutron model (G4NDL 4.2)
- Reconstructed as ^{10}B lined gaseous detector

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

Neutron beam monitor nGEM

- Two-dimensional neutron detector for J-PARC MLF
- Supported by the technologies of the KEK detector technology project such as SiTCP, ASIC-FE2007, DAQ-MW

Web site of the KEK detector technology project, http://rd.kek.jp.
T. Uchida, et al., IEEE Trans. Nucl. Sci. **NS-55** (2008) 2698.
Y. Fujita, et al., presented at the IEEE NSS 2007.
K. Nakayoshi, et al., Nucl. Instr. and Meth. A **600** (2009) 173.



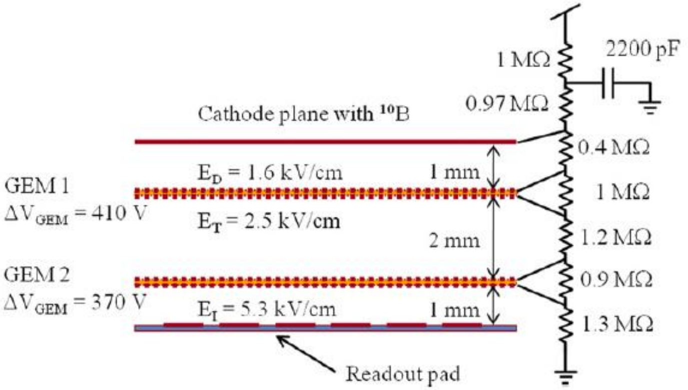
The main characteristics and performances of nGEM are:

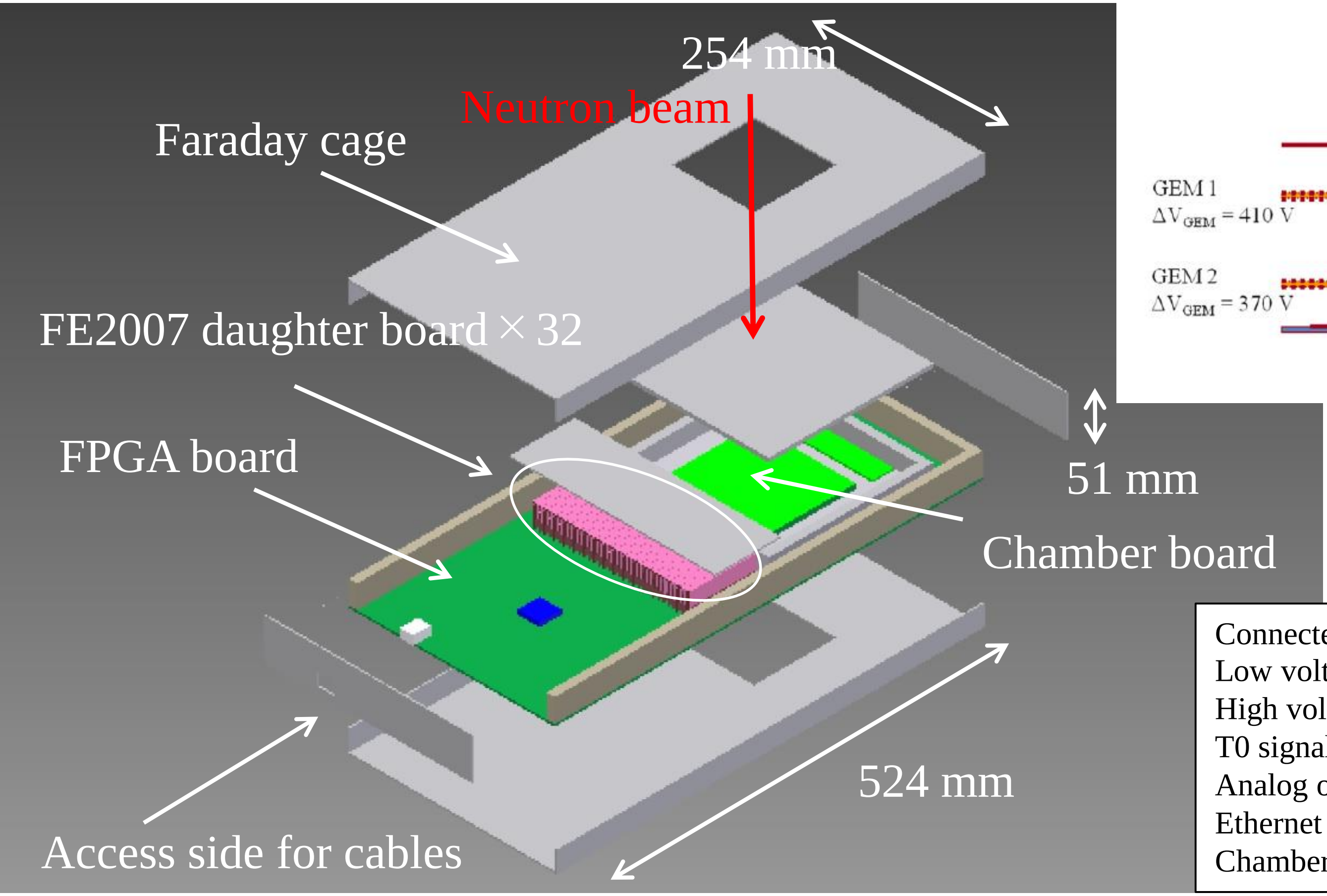
- **Gas flow radiation detector that can measure charged particles from a n(^{10}B, α)^{7}Li nuclear reaction**
- **Thermal neutron efficiency between 0.01% and 5% (depending on ^{10}B layer thickness)**
- **Data taking rate over 1 MHz (limited by Gigabit Ethernet) Available for list-mode, not histogram-mode**
- **Minimum time step of 5 ns**
- **Position resolution approximately 0.85 mm (FWHM)**
- **Operation voltage near 2700 V (negative)**
- **Ar/CO_2 (7:3) gas mixture**
- **Active area of 100 mm ×100 mm**
- **128 ch ×128 ch readout channels with 0.8 mm pitch**

Overview of nGEM

nGEM is a built-in system having a gas chamber and an electronics.
All signal lines from the readout pad are wired inside the printed circuit board.
FE2007 daughter board is able to exchange.
We can stack some 100 mm × 100 mm GEMs in the chamber stand
(The height of the chamber: ~20 mm, Gas flow system only).

Detector configuration



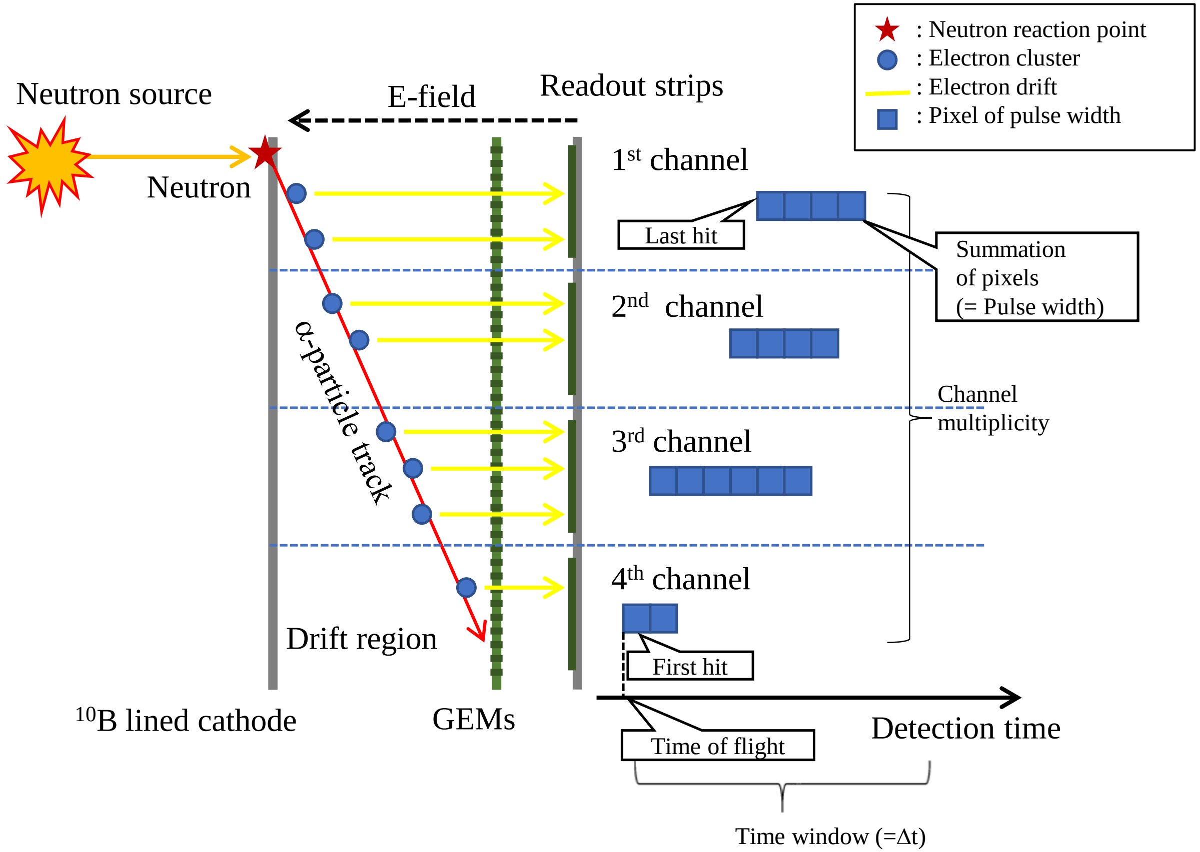


Connected cables and tubes are:
Low voltage (±5 V) × 1
High voltage × 1
T0 signal × 1
Analog output × 1
Ethernet × 1
Chamber gas (input and output) × 2

Event selection algorithm

M. Shoji, et al., JINST **7** (2012) C05003.

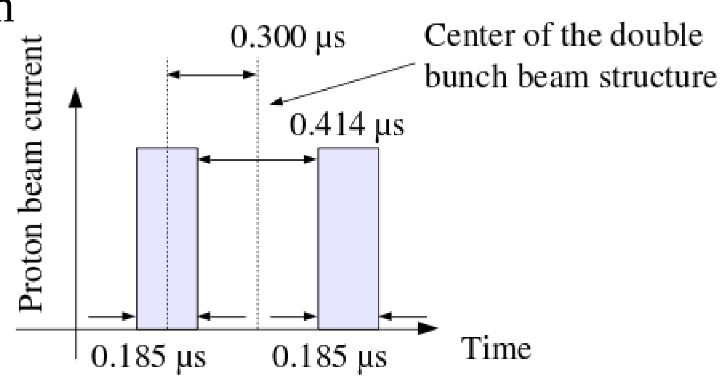
- Based on the behavior of primary electron clusters
- Installed to the Field Programmable Gate Array (FPGA) chip for the online processing



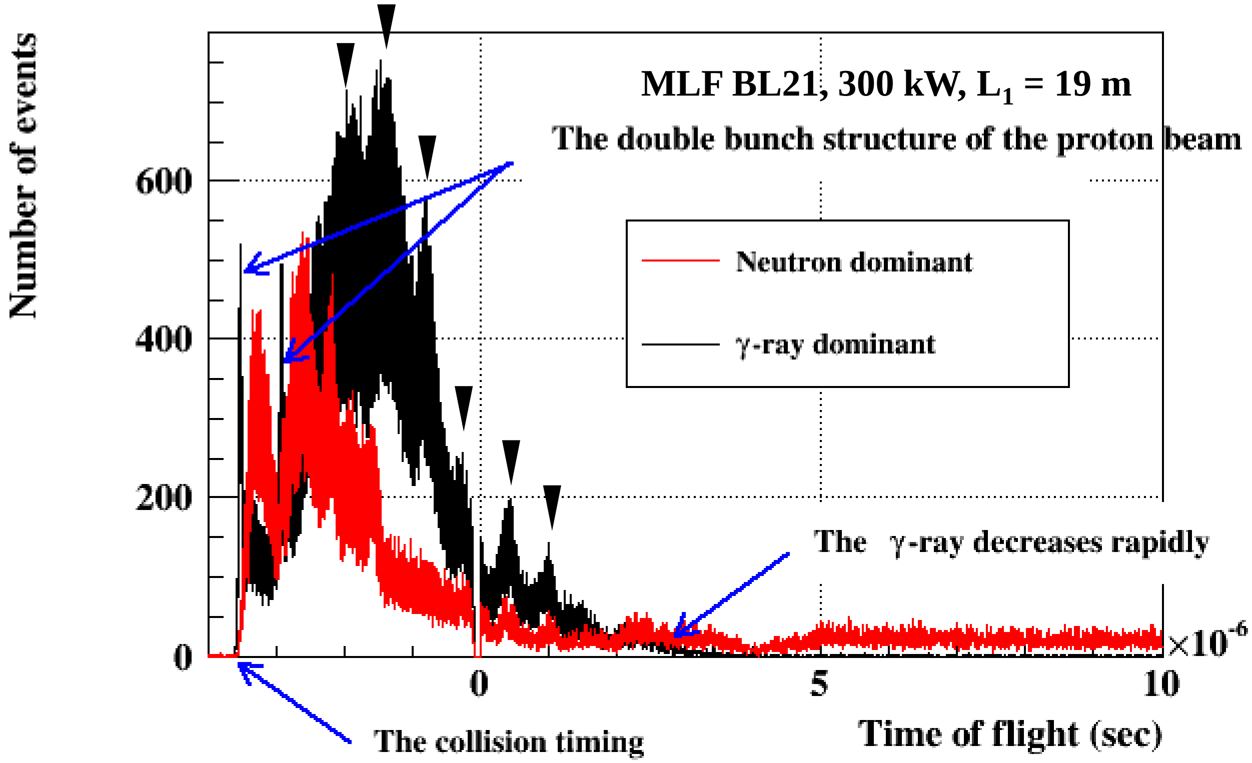
1. Primary electron clusters make along the track of an α particle, and then drift toward the anode electrode.
2. The latest arrival produces near the reaction point of the n(^{10}B, α)^{7}Li reaction.
3. The pulse width is proportional to the amount of collected electron clusters.

Example of n-γ separation

- Observation of the collision timing for the proton beam
  Double bunch structure, strange oscillation (?)



Lower pulse width events are regarded as a γ-ray component, higher pulse width events are regarded as a neutron component.



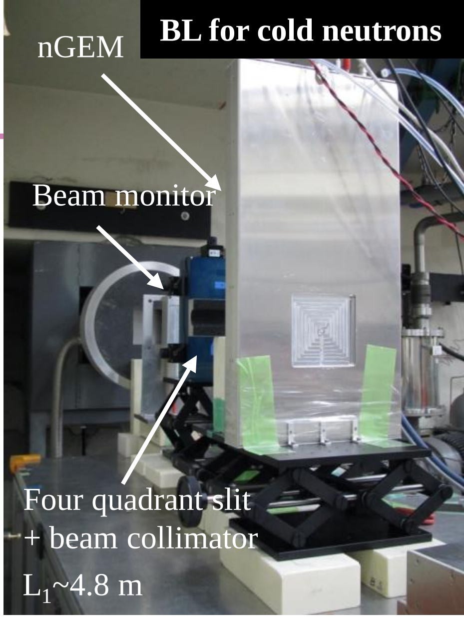
Neutron efficiency and uniformity

- Evaluated at Hokkaido Univ. 45 MeV electron LINAC
- Good agreement with the Geant4-based simulation

$$\text{Neutron efficiency } \varepsilon(E) = \frac{\text{Number of counts for nGEM}}{\text{Neutron flux}}$$

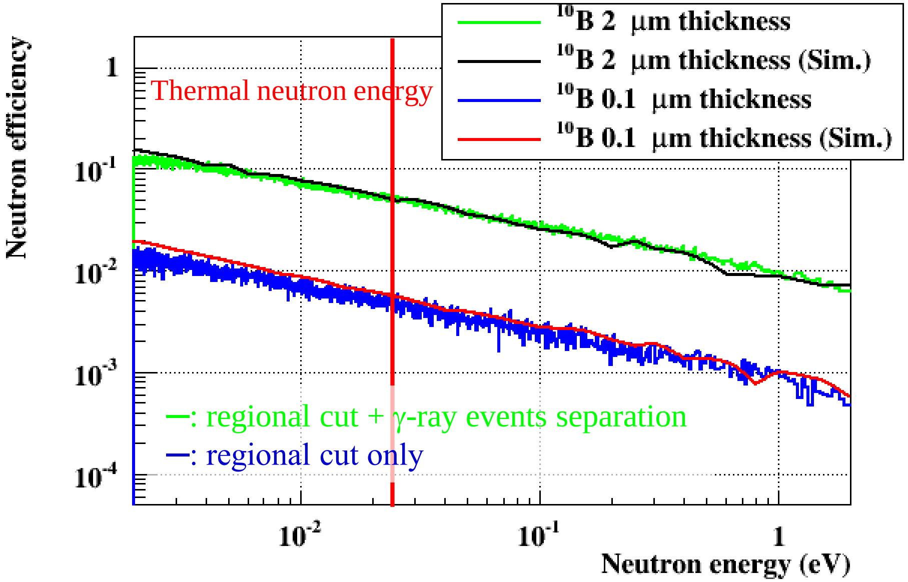
$$\text{Neutron flux } I_n(E) = \frac{N_{3He}(E) \times 50}{\varepsilon_{3He}(E)}$$

N_{3He} : Counting rate for 3-helium detector, ε_{3He} : Neutron efficiency for 3-helium detector

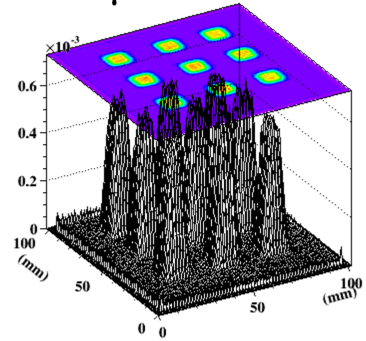


The neutron flux was measured by a 3-helium proportional counter (1-inch diameter, 3-helium partial pressure: 10 atm)

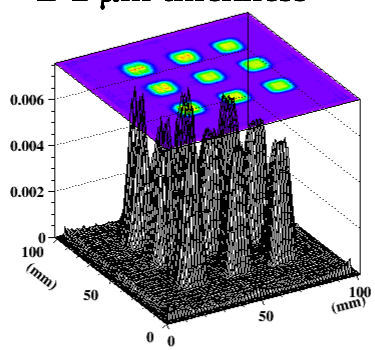
2.5×10^4 neutrons/cm^2·sec (10^{-3} eV～0.5 eV, L=4.64 m)



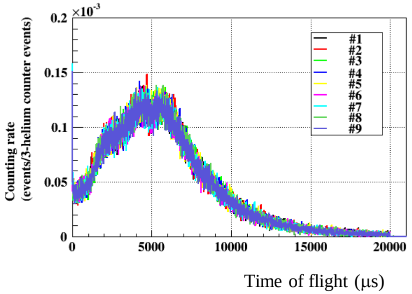
^{10}B 0.1 μm thickness



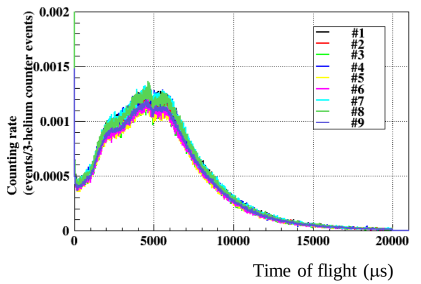
^{10}B 2 μm thickness



Beam power: ~30 μA, 50 Hz
Collimated beam size: 1 cm × 1 cm



The standard deviation of total events: 0.8%



The standard deviation of total events: 4.3%

Neutron intensity and beam profile at NOVA

- Evaluated at the NOVA sample position
- Good agreement with the Monte Carlo (MC) simulation and the calculation

- The MC simulation with simple considerations of the geometry of the NOVA beam line, no physics reaction
- The neutron intensity at the sample position:

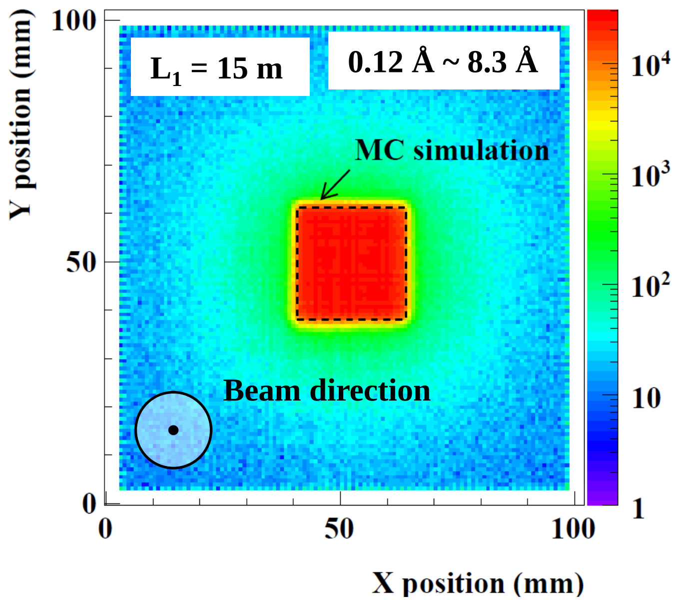
$$I(E) = i_{raw}(E)/\varepsilon(E),$$

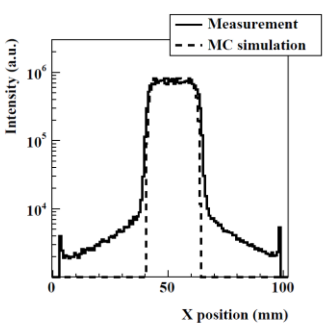
where $i_{raw}(E)$: the raw distribution, $\varepsilon(E)$: the neutron efficiency obtained from the Geant4-based simulation

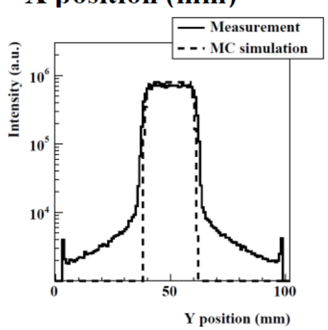
- The calculated neutron intensity:

$$I_{cal}(E) = i_{cal}(E) \times T_{r\ total}(E) \times k,$$

where $i_{cal}(E)$: the calculation of the neutron intensity obtained from the JSNS group's study, $T_{r\ total}(E)$: the total transmission of the NOVA beam line, k: other factors such as the type of cooling water and the existence of the muon target

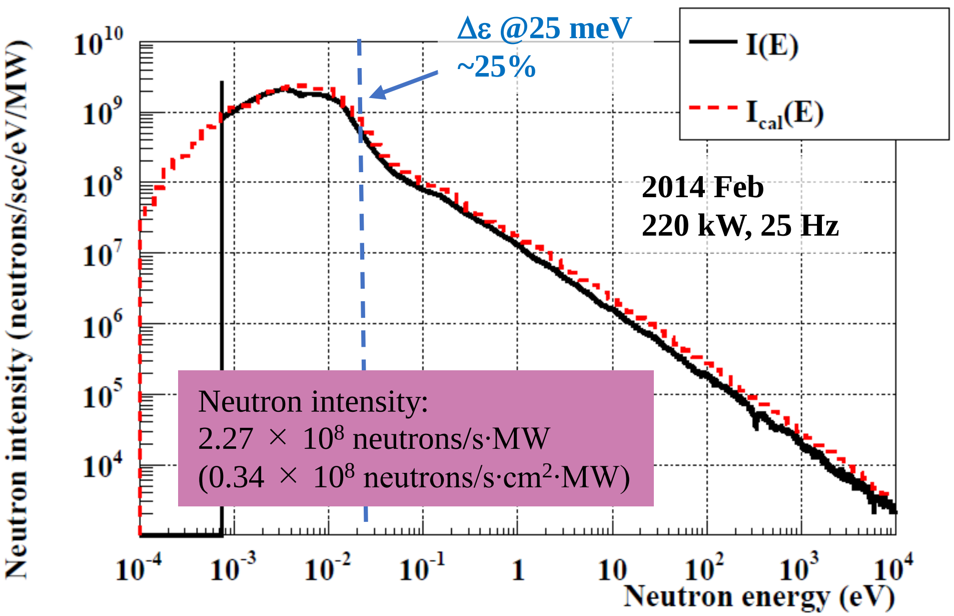






Measurement: 25.6 mm × 26.4 mm
MC simulation: 23.2 mm × 23.2 mm

H. Ohshita, et al., JPS Conf. Proc. **8** (2015) 036019.

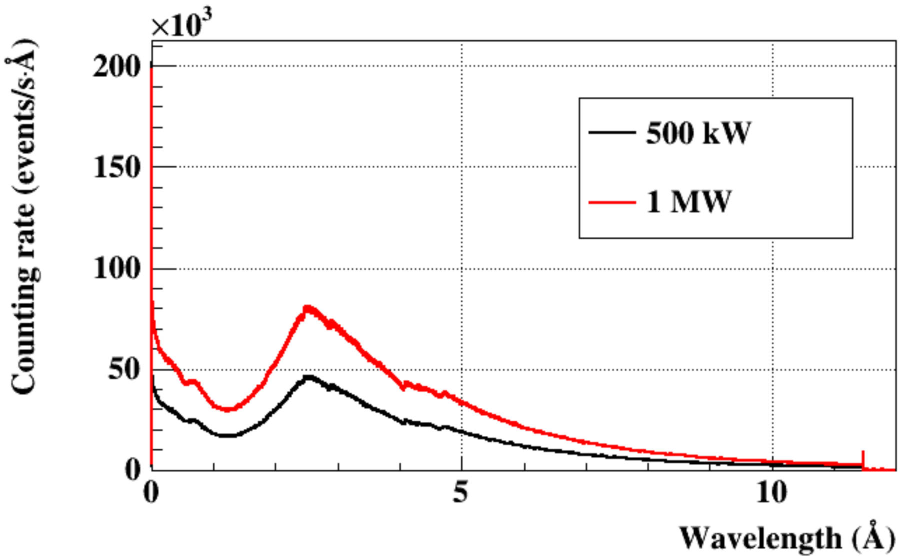


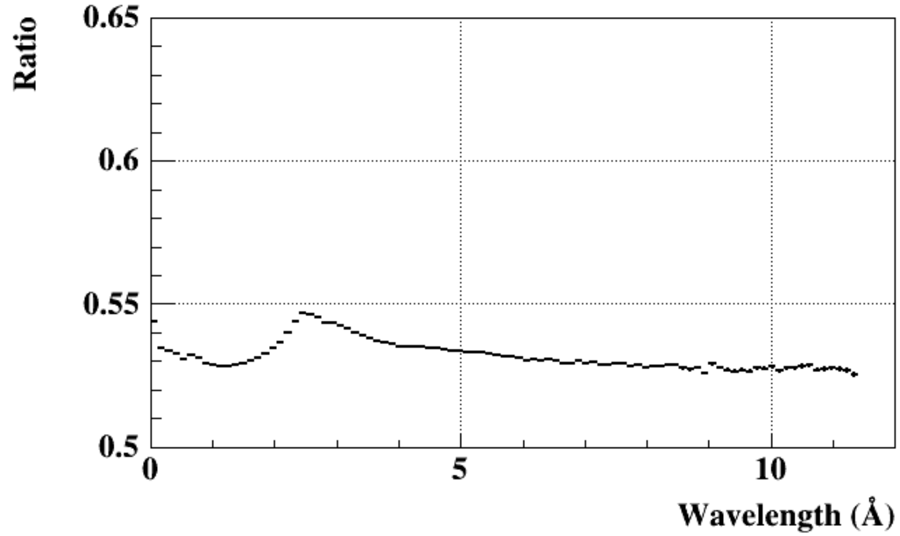
Neutron irradiation test (1)

- Observation of the counting loss in the previous test
- To realize a no-counting loss monitor

The nGEM with 0.01% neutron efficiency is prepared

Analysis workflow
(1) Decision of the ROI
(2) Decision of the operation high voltage
(3) Evaluation of the analog outputs
(pulse width, channel multiplicity)
between 500 kW and 1 MW beam power
(4) Evaluation of the ratio of TOF distributions
between 500 kW and 1 MW beam power

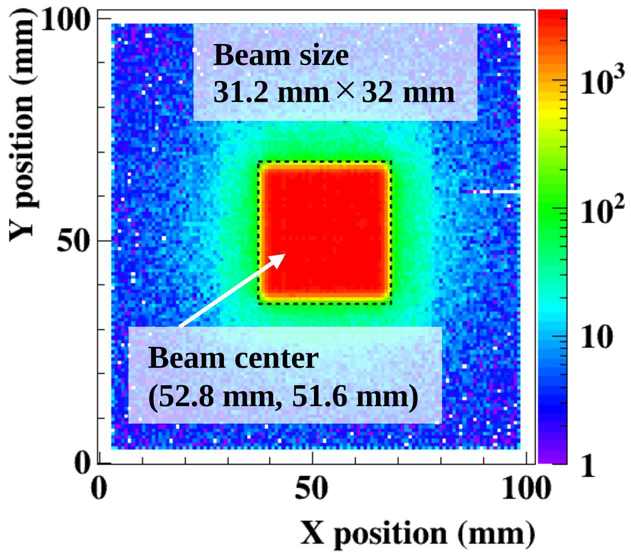


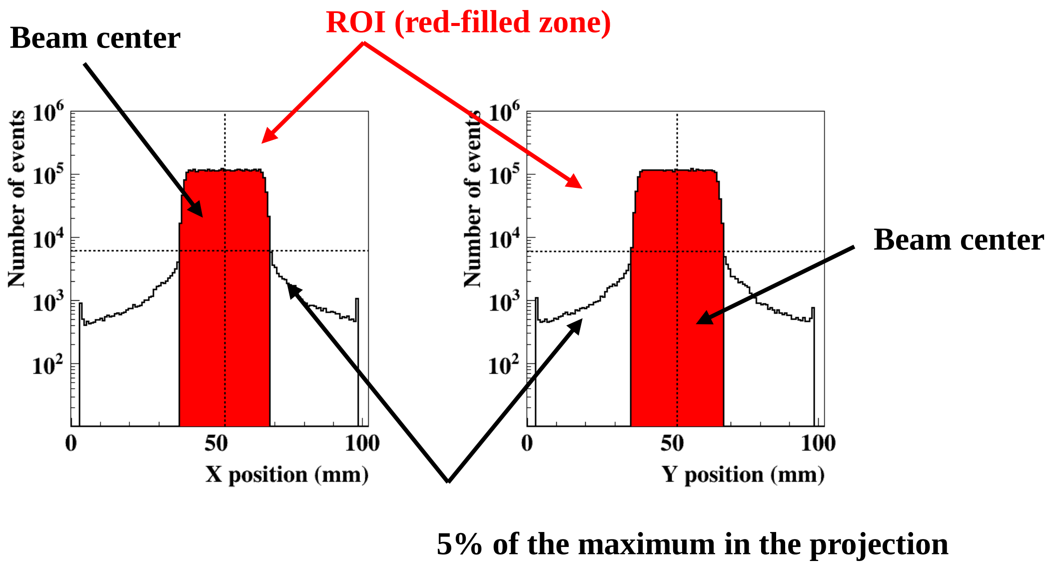


Neutron irradiation test (2)

- Beam profile

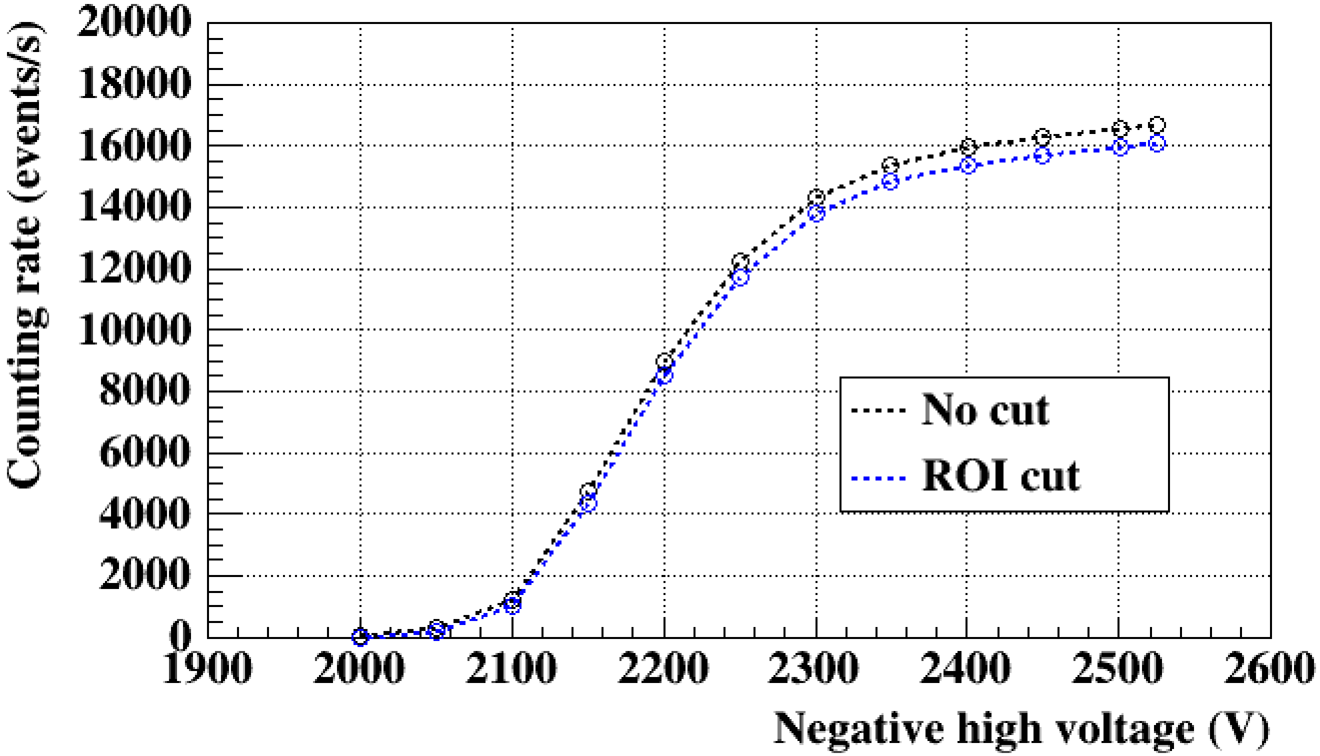
-2450 V, 500 kW





Neutron irradiation test (3)

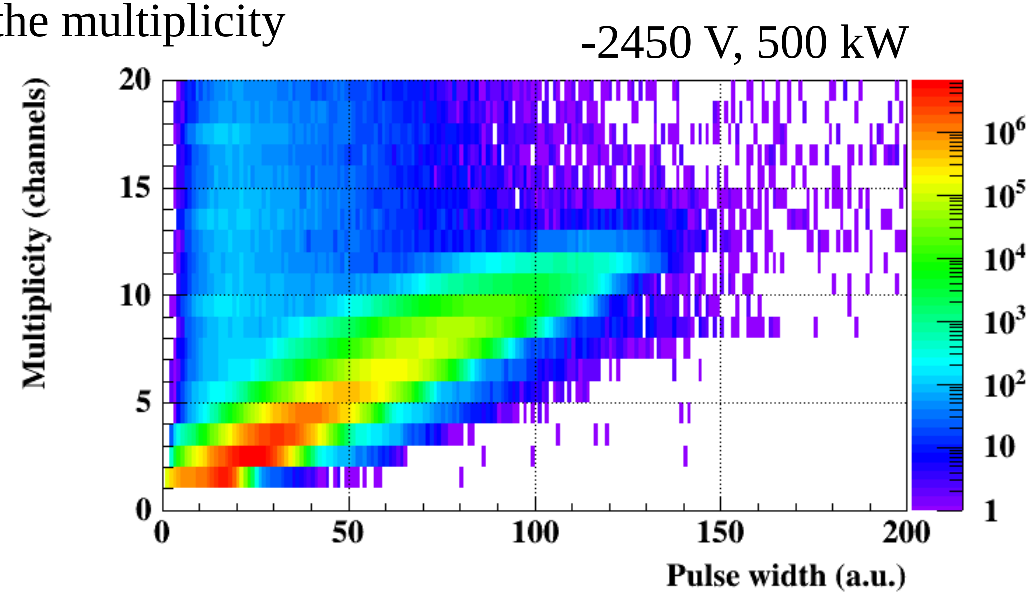
- Plateau curves with the different cut conditions



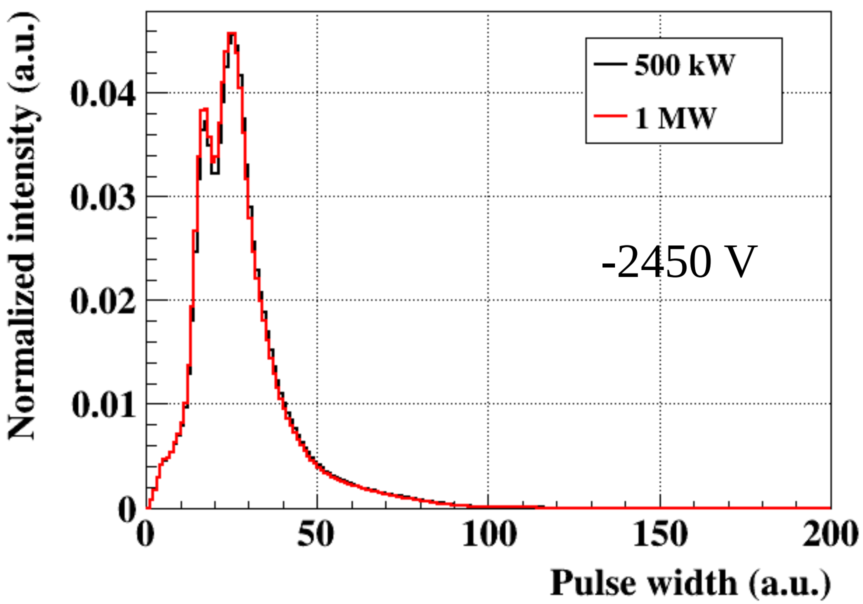
The plateau region: -2350 V~ -2525 V
The operating high voltage: -2450 V

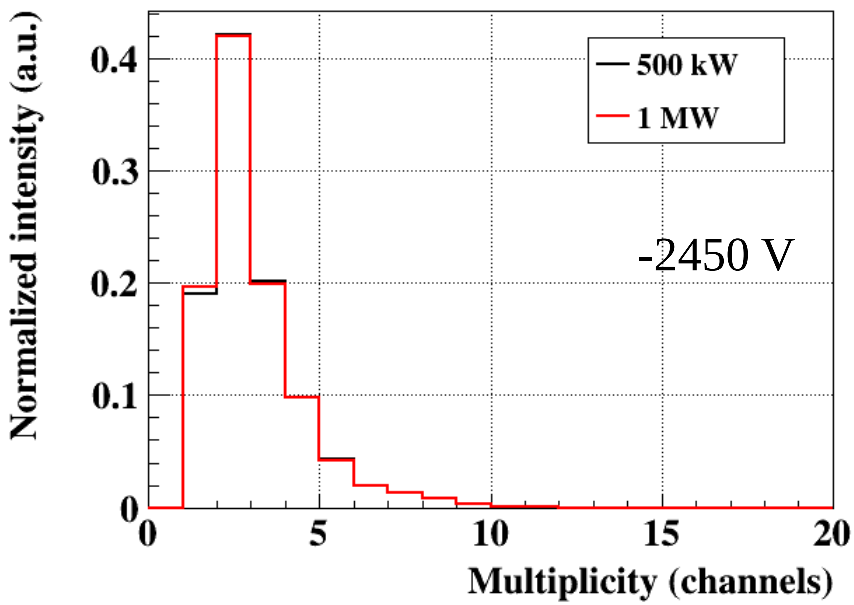
Neutron irradiation test (4)

- Correlation with the pulse width and the multiplicity
- Comparison with the distributions of the different beam power



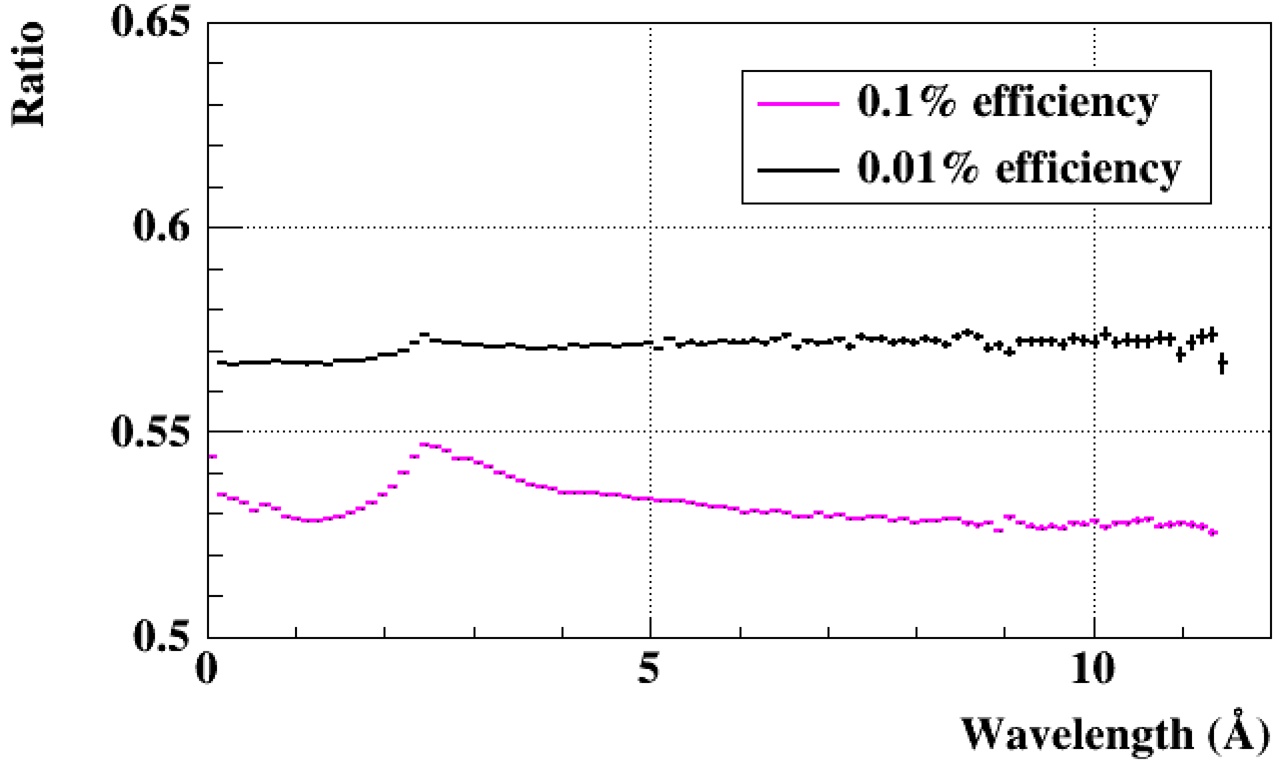
The distributions are almost same between 500 kW and 1 MW beam power.





Neutron irradiation test (5)

- Ratio of the TOF distributions
between 500 kW and 1 MW beam power



Summary

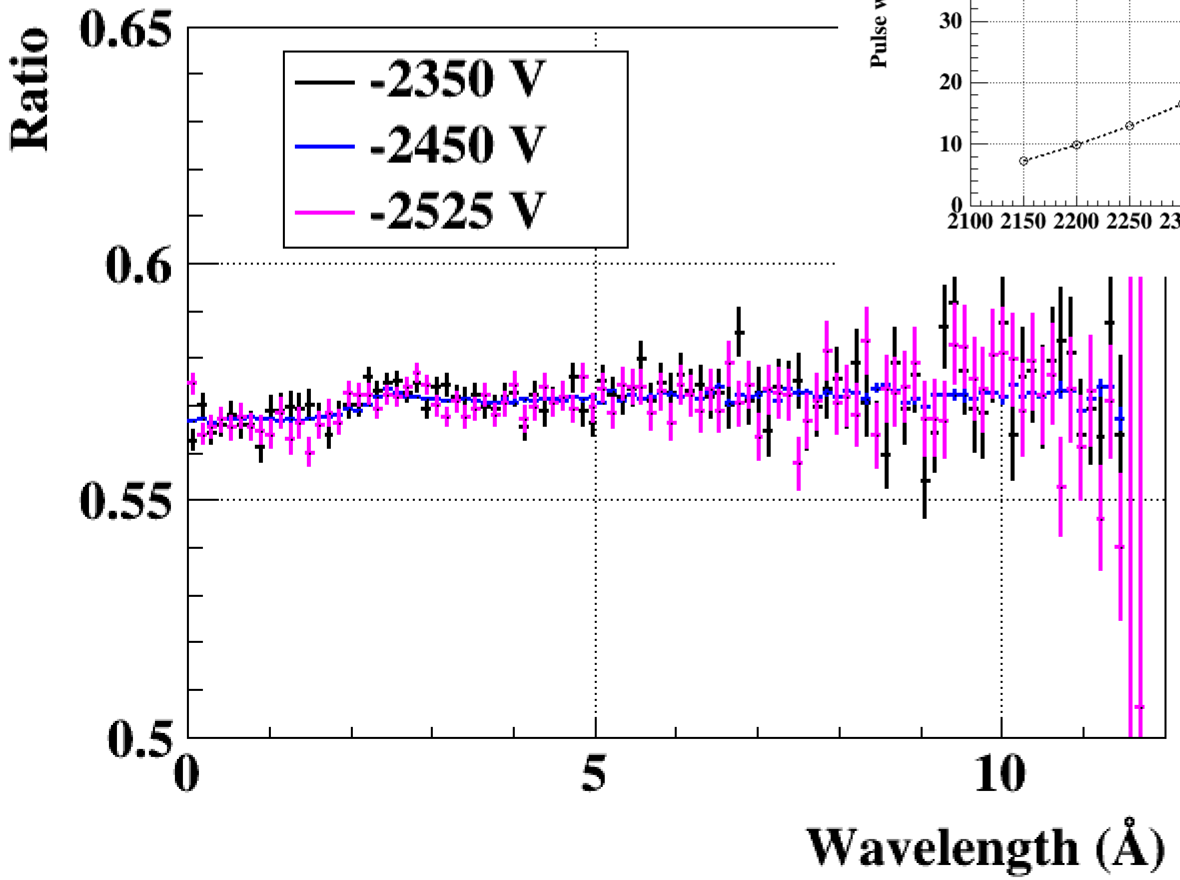
- We have been developing a new neutron beam monitor nGEM.
- The performances such as the neutron efficiency and the uniformity have already evaluated.
- The neutron intensity and the beam profile for NOVA have evaluated by using nGEM

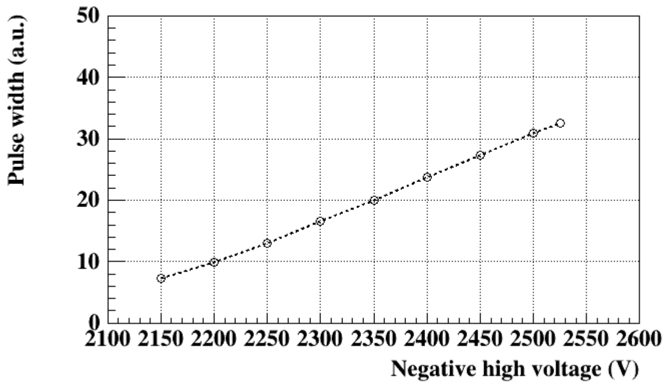
- But in our previous work, there is some counting loss under the 1 MW proton beam power.
- To realize a no-counting loss monitor, we try testing the nGEM with 0.01% neutron efficiency.

- There is no gain loss for both analog outputs (pulse width distributions and multiplicity distributions).
- There is some improvement for the counting loss, but the structure remains a little.

Neutron irradiation test (6)

- Ratio of the TOF distributions between 500 kW and 1 MW beam power





Thanks for your attention !