Development of the Scintillation-fiber Detector for the Neutron-Beam Profile Measurement

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Contents

1. Motivation

1) High LET (linear energy transfer) radiations:

   - Fast neutrons, protons, heavy-ions…
   - significantly large energy deposit in tissue per unit length

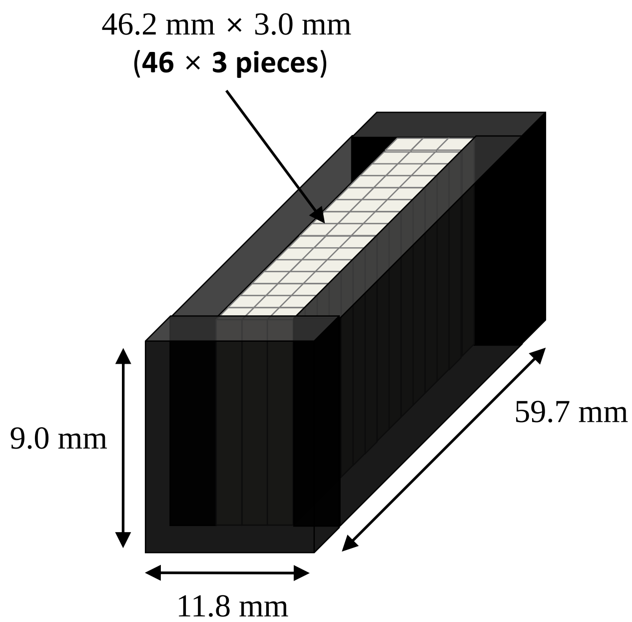
2) Fast-neutron radiotherapy:

   Very effective treatment for soft-tissue cancer

3) Necessity of precise neutron beam-profile measurement device

4) We designed, built, and tested scintillation fiber detector based on a current-mode electronics.

2. Detector characteristics - a. Scintillation fiber



Saint-Gobain Crystals
Plastic Scintillating Fibers
Specific Properties of Standard Formulations

Fiber	Emission Color	Emission Peak, nm	Decay Time, ns	1/e Length m*	# of Photons per MeV**	Characteristics/ Applications
BCF-10	blue	432	2.7	2.2	~8000	General purpose; optimized for diameters>250μm
BCF-12	blue	435	3.2	2.7	~8000	Improved trans-mission for use in long lengths
BCF-20	green	492	2.7	>3.5	~8000	Fast green scintillator
BCF-60	green	530	7	>3.5	~7100	3HF formulation for increased hardness
BCF-91A	green	494	12	>3.5	n/a	Shifts blue to green
BCF-92	green	492	2.7	>3.5	n/a	Fast blue to green shifter
BCF-98	n/a	n/a	n/a	n/a	n/a	Clear waveguide

* For 1mm diameter fiber; measured with a bialkali cathode PMT
** For Minimum Ionizing Particle (MIP), corrected for PMT sensitivity

1) Line scan detector with 46 × 3 pixels
2) Single-clad scintillation fiber (Bicron BCF-60)
3) 9 mm fiber length:
   - Compromised between neutron sensitivity enhancement & multiple scattering probability suppression
4) Three-layer structure for maximized light yield produced by the scattered protons

2. Detector characteristics - b. Si-photodiode array and Electronics

Electronics board

46 channel Si-photodiode array
(Hamamatsu S4111-46Q)

1) 46 channel Si-photodiode (Hamamatsu S4111-46Q)
   - Dark current: ~ 10 pA
2) Current-integration-mode electronics
   - Designed for high-intensity fast neutron-beams
   (neutron beams for typical radiotherapies, $10^8 \sim 10^{10}$ Hz/cm^2)

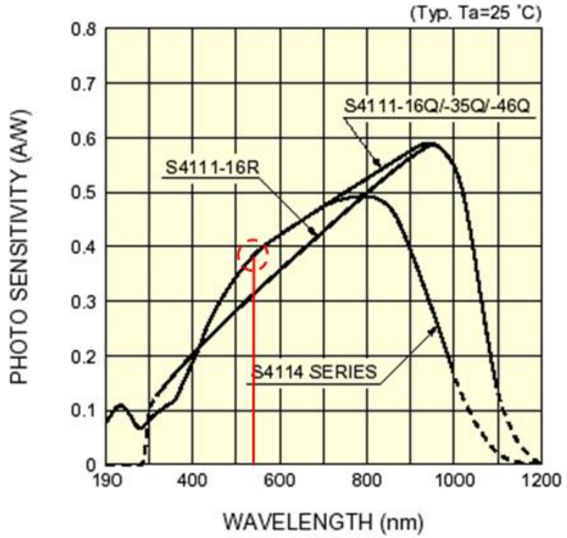
2. Detector characteristics - b. Si-photodiode array and Electronics

Specifications

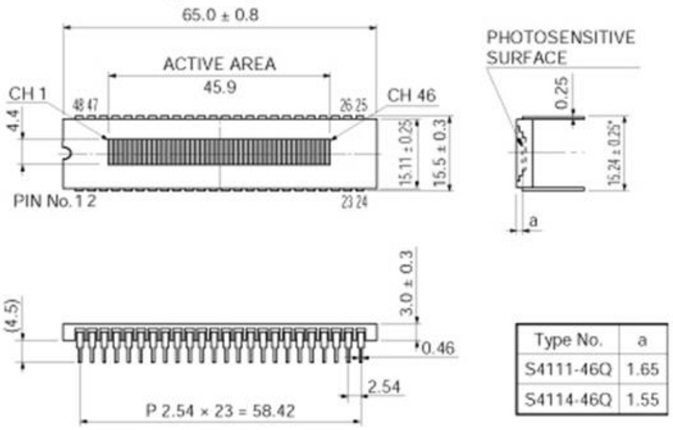
Package	Ceramic
Active Area	45.9 x 4.4 mm
Number of Elements	46
Spectral Response Range	190 to1100 nm
Peak Wavelength	960 nm
Photo Sensitivity at peak	0.58 A/W
Dark Current Max.	0.01 nA
Rise Time	1.2 us
Terminal Capacitance	550 pF
Note	
Measurement Condition	Typ. Ta=25 deg. C, unless otherwise noted

Dimensional/Characteristic Chart

Spectral Response



Dimensional Outline (Unit: mm)



Type No.	a
S4111-46Q	1.65
S4114-46Q	1.55

2. Detector characteristics - b. Si-photodiode array and Electronics

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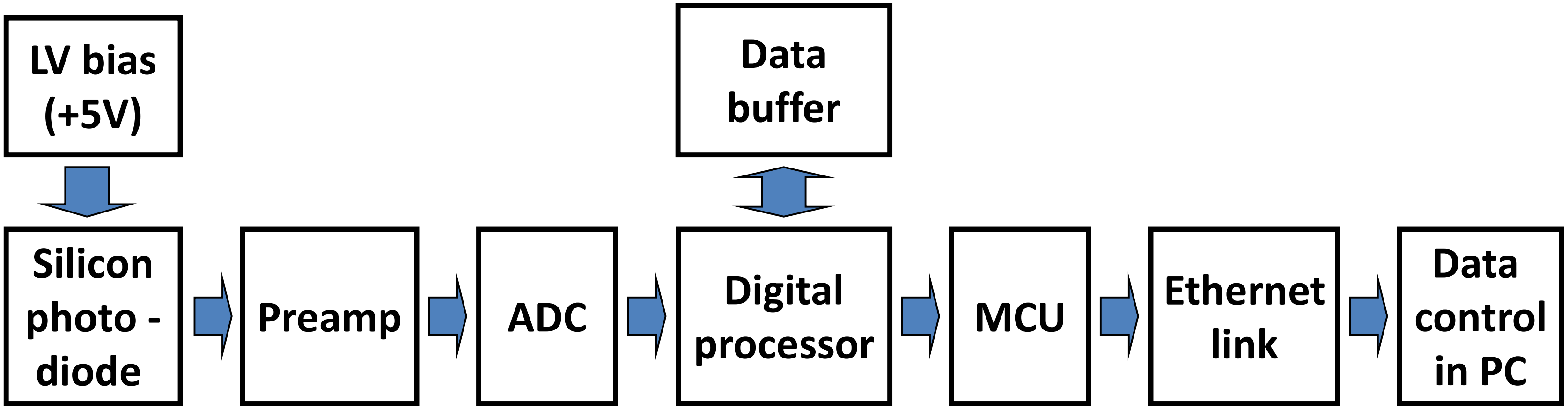
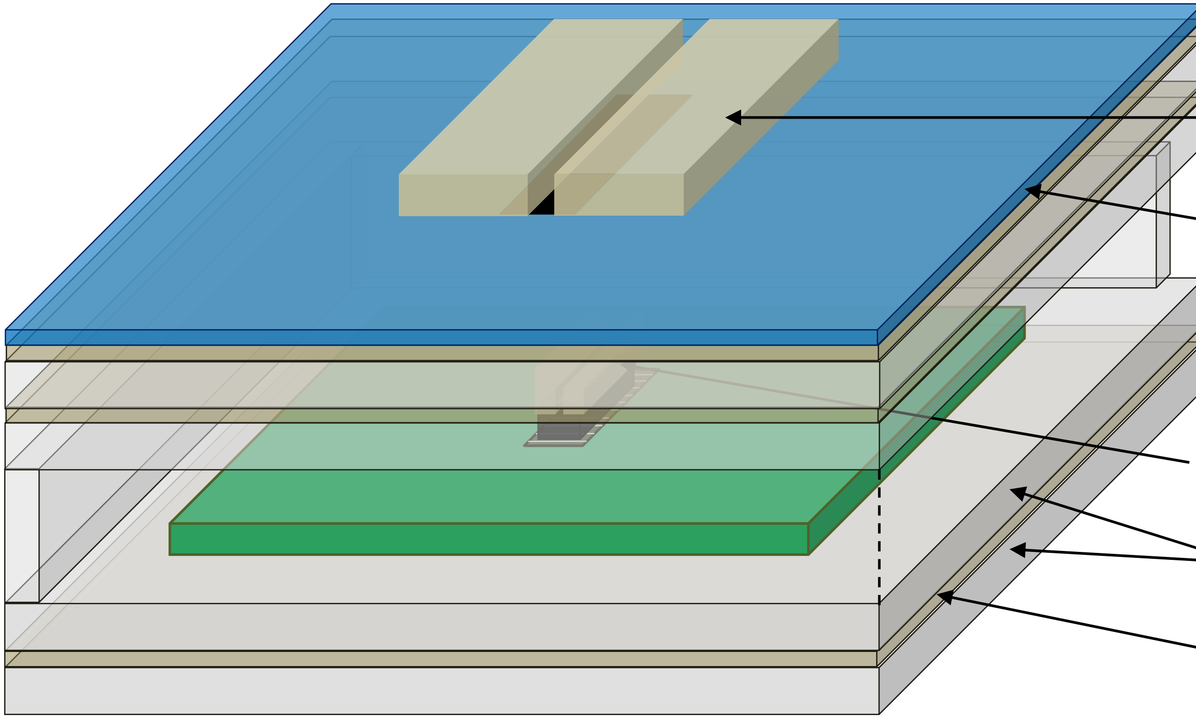


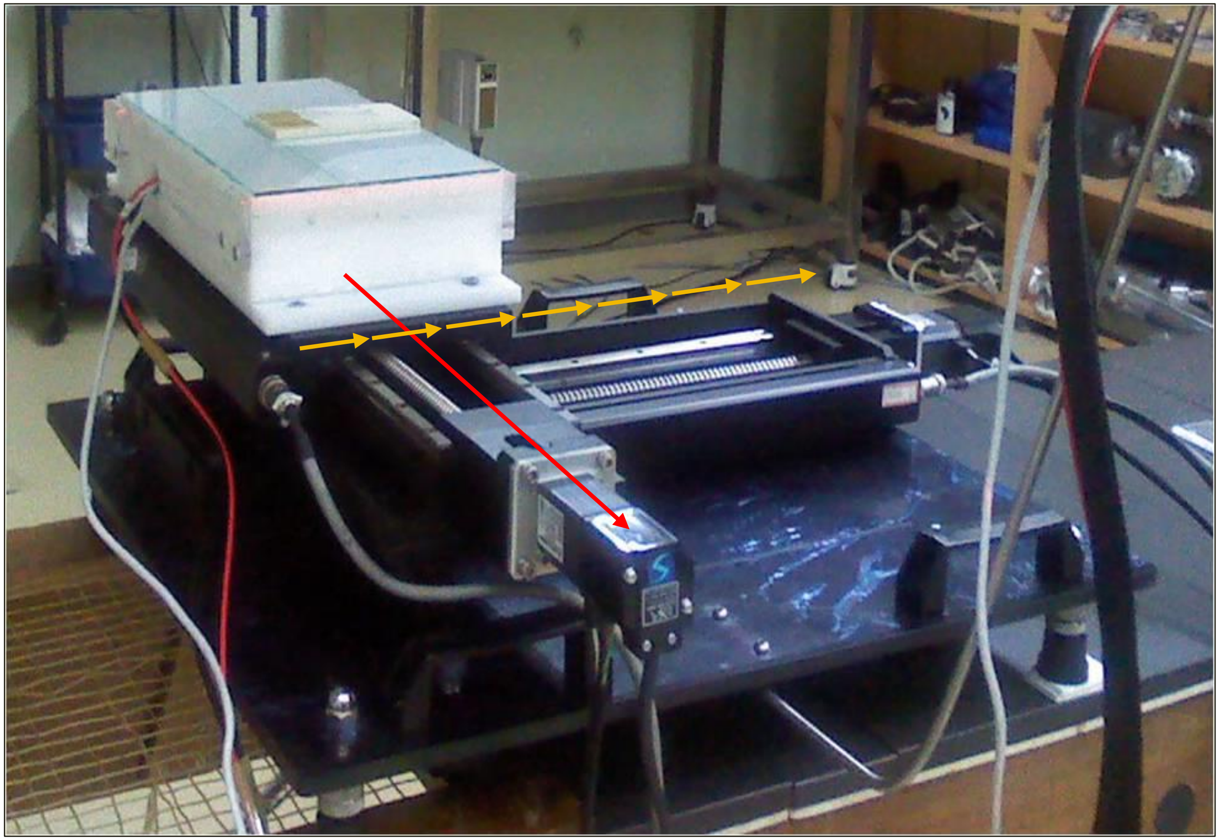
1) Output pulses fed into preamp (preamp sensitivity: $10^{-10} \sim 10^{-2}$ A)
2) Preamp converts output pulses to voltage-sensitive pulses
3) Preamp outputs are multiplexed to four ADCs
4) ADCs convert the voltage-sensitive analog inputs into 12-bit digital signals (in every 7.8 μs) and feed them to a digital processor
5) Input signals transferred from the ADCs are summed over 1 ms and fed into a data buffer area
6) Data from digital processor are transferred to PC by MCU via Ethernet link

2. Detector characteristics - c. Protection system



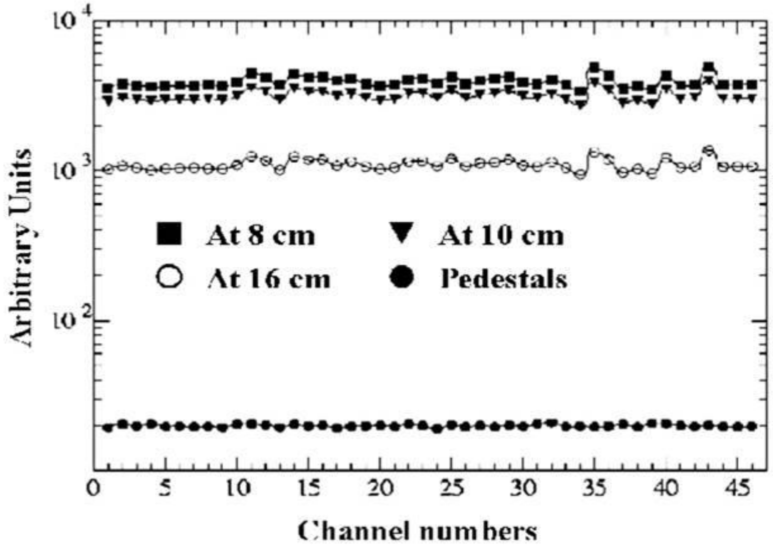
1) Two-step collimation for the fast neutrons
   - Collimators made of natural Gd_2O_3 powder and epoxy
   - Slit width of V-shape collimator: 1 mm
2) Gd layers for fast/thermal neutron shielding

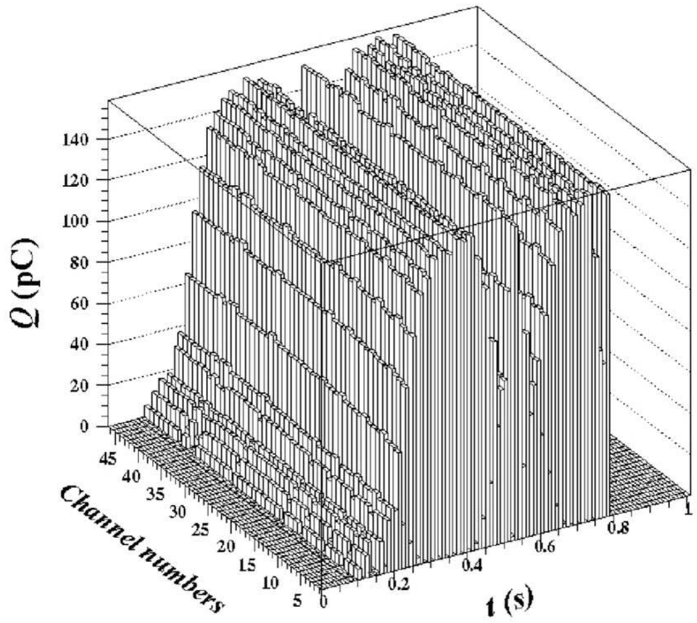
2. Detector characteristics - d. Control device for scan operations



1) Transverse movement (red line):
   - continuous with adjustable speed (1~5 cm/s)
2) Vertical movement (yellow line): 46 mm per step
3) Total possible scan area: 30 × 32 cm^2

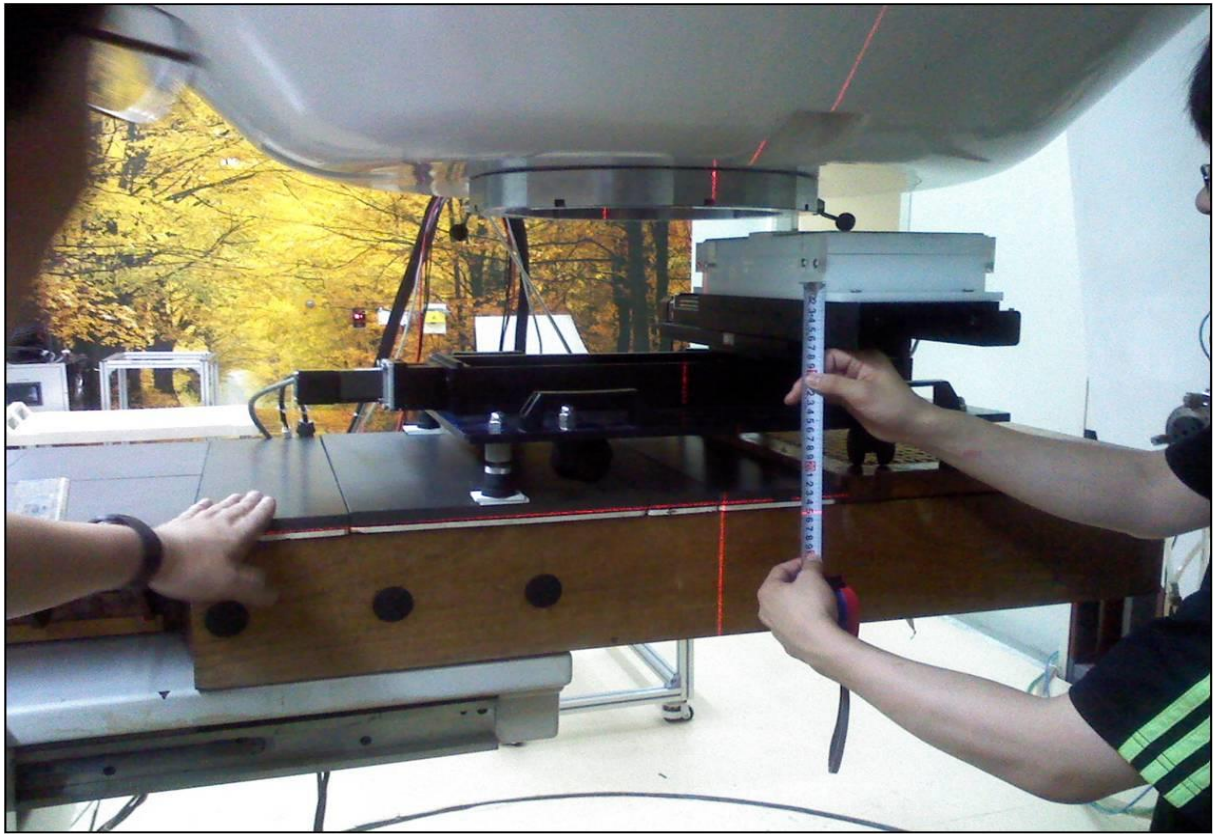
3. Test - a. Calibration by X-ray





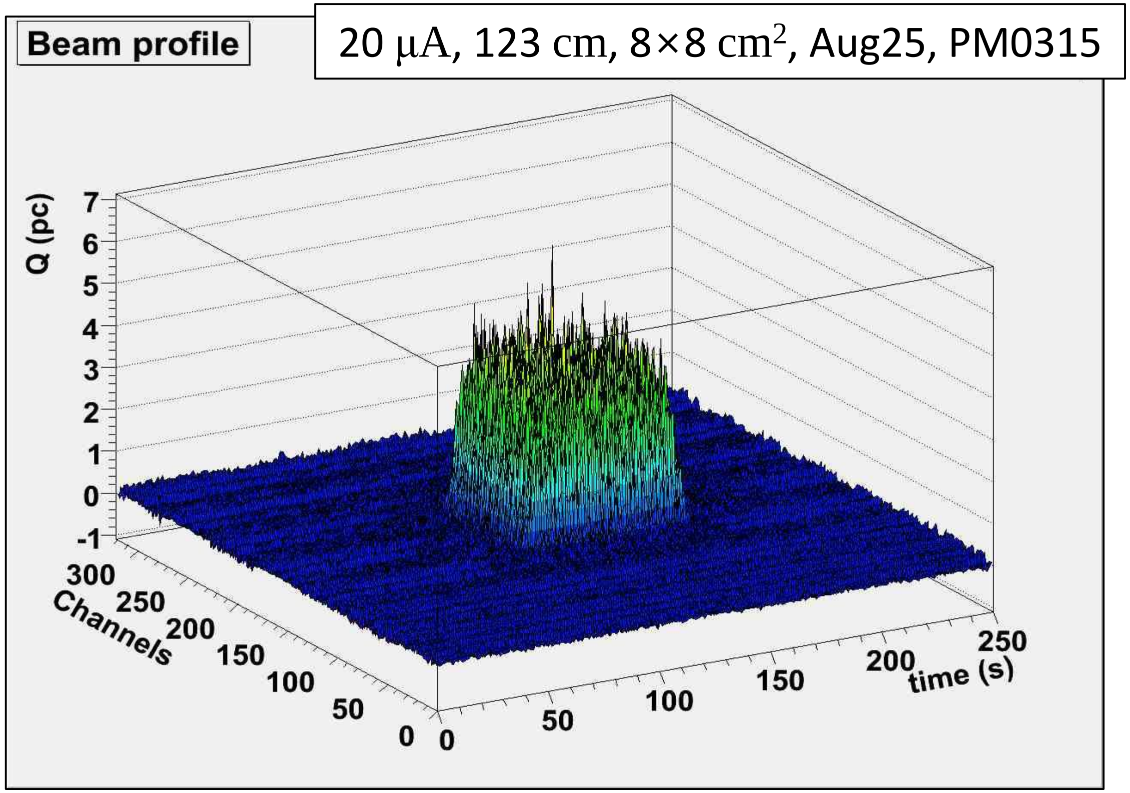
1) Calibration test for the sensitivity of each channel
2) Test was performed by the X-ray generator (8 mA, 70 kV)
   - The portable X-ray gun was placed at three different distances (8, 10, and 16 cm) from the detector
3) Results:
   - Sensitivity varies at the level of a few %
   - Channel responses were measured precisely.
   - Calibration factors were obtained for the channel responses.

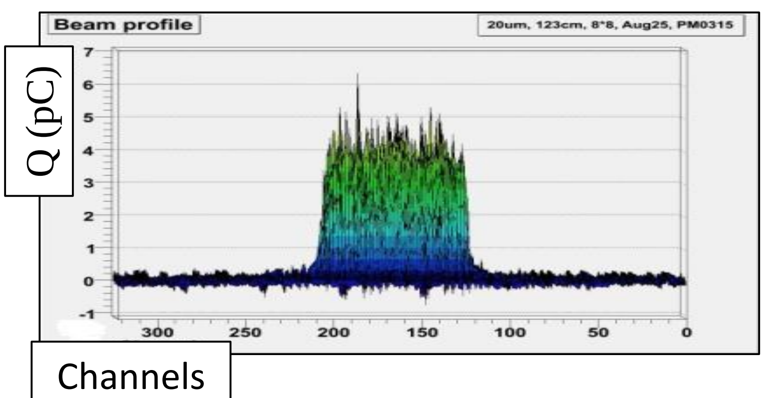
3. Test - b. Neutron-beam profile measurement at KIRAMS

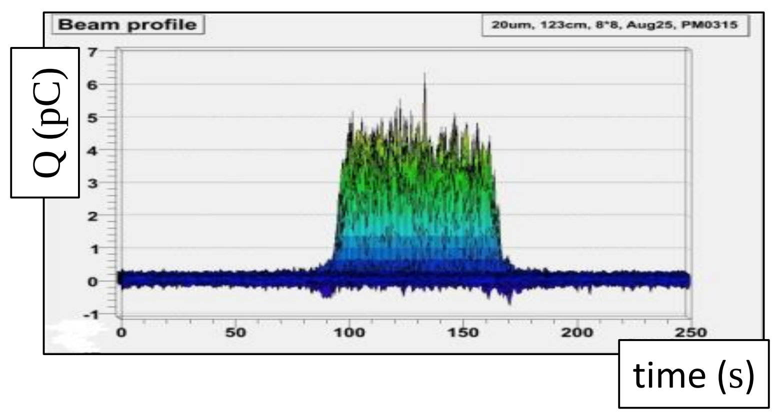


1) Fast-neutron beam was provided by MC50 cyclotron at KIRAMS
2) Distance from Be target to the scan detector: 123 cm
3) Incident proton energy: 45 MeV
4) Be target thickness: 10.5 mm
5) Test was performed with two beam currents: 10 μA and 20 μA

3. Test - b. Neutron-beam profile measurement at KIRAMS







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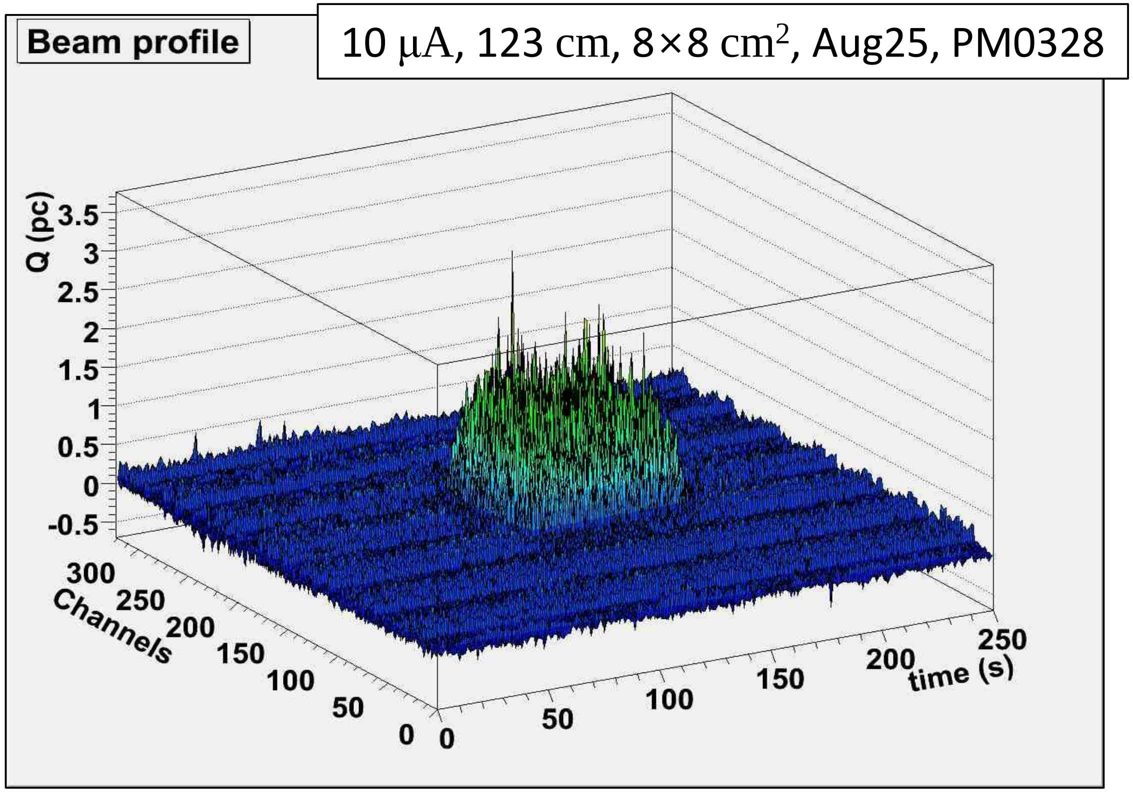

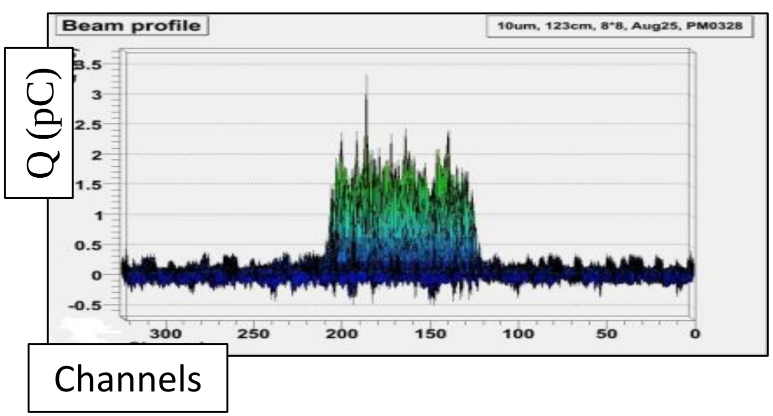

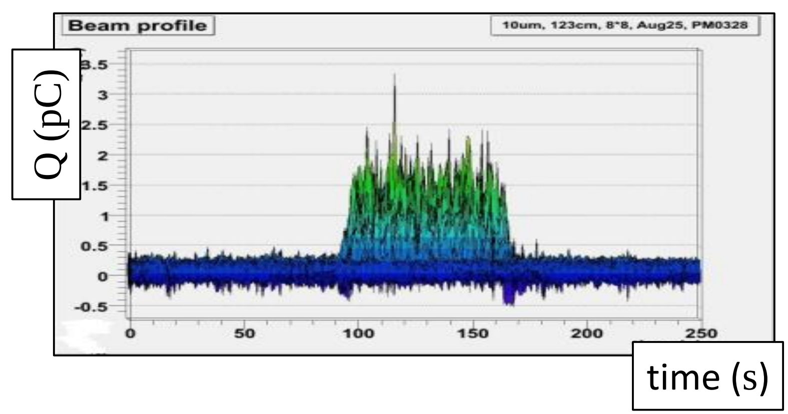

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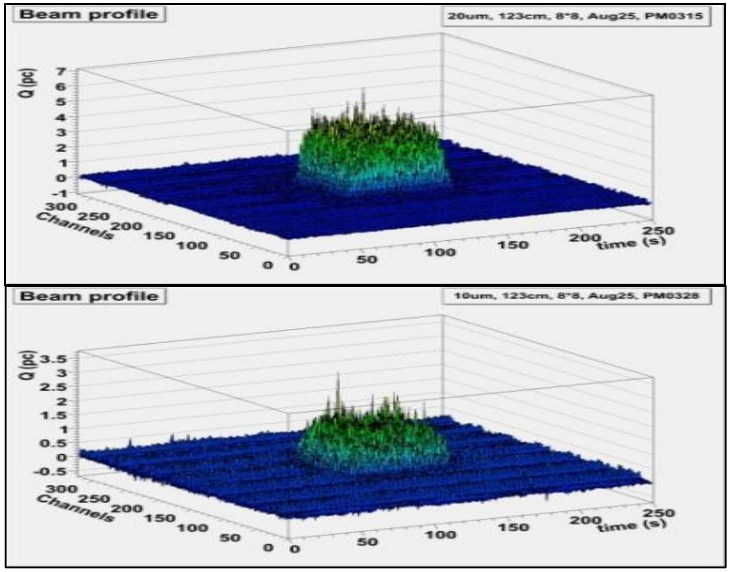

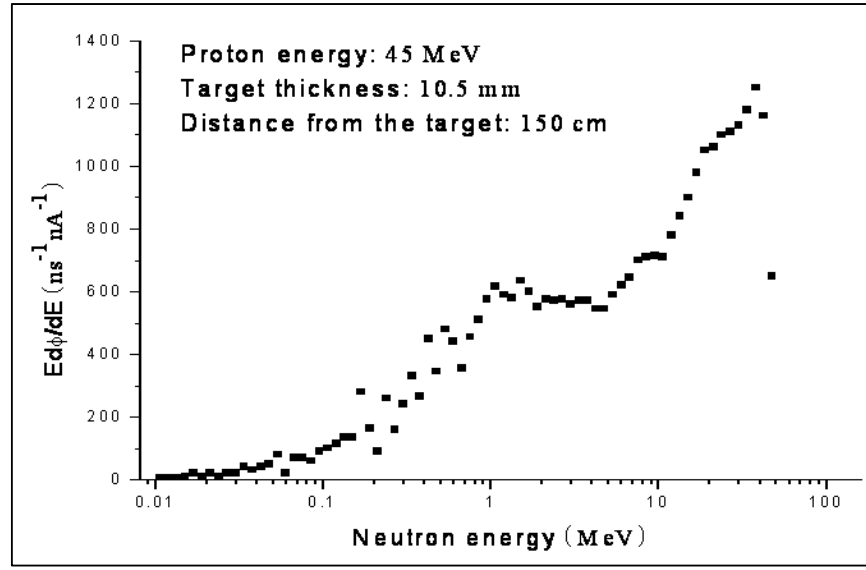

Measured beam profiles at KIRAMS (left) and Unfolded neutron flounce spectrum (lethargy spectrum) measured by Boner sphere system *(KAERI/RR-2442/2003)* (right)

Beam-profile measurement conditions:

- Corresponding mean charge value to neutron beam intensities:

  ~ 4.0 pC ↔ ~ 4.8 × 10^7 Hz/cm^2 (20 μA beam current)

  ~ 1.8 pC ↔ ~ 2.4 × 10^7 Hz/cm^2 (10 μA beam current)

- Test performed under the beam intensities lower than operational intensity (10^8 ~ 10^{10} Hz/cm^2)

4. Beam-profile images in absorbed dose rates

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1) Beam-profile image (charge distribution)
- Detector signal is roughly proportional to the deposited energy in the detector
- Beam-profile images ≈ distribution of expose dose rate induced in the detector

2) Conversion by using Geant4 simulations

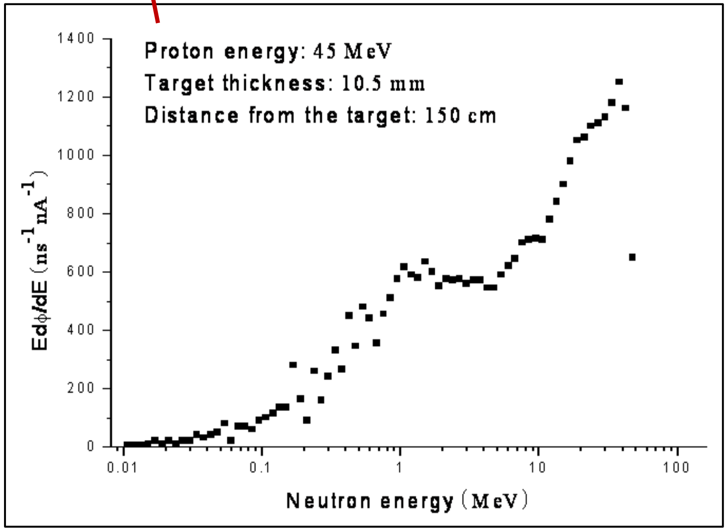
$$\left(\frac{dD}{dt}\right)_{avg} = \frac{A_p}{m}\frac{dE_{dep}}{dtdA} = \frac{A_p}{m} \times i_p \times 1.602 \times 10^{-13} \sum \epsilon_i(\delta E_i)\left(E_i \frac{\Delta \Phi_i}{\Delta E_i}\right)\Delta(\log E_i) \quad (\mathrm{Gy\ s^{-1}})$$

Where,
A_p : area of each image pixel (cm^2)
i_p : proton beam current (nA)
E_i : neutron energy (MeV)
$E_i\, \Delta\Phi_i / \Delta E_i$: differential neutron flux (n/s/nA)
δE_i : energy deposited in the detector (GEANT4)
ϵ_i : interaction sensitivity (GEANT4)
Q_m : mean charge induced in the beam area

→ The conversion factor $C_f = \dfrac{\left(\frac{dD}{dt}\right)_{avg}}{Q_m}$ (Gy h^{-1} C^{-1})

∴ Distribution of the beam profile in Gy :

$$\frac{dD(x,y)}{dt} = C_f \times q(x,y) \quad (\mathrm{Gy\ h^{-1}})$$

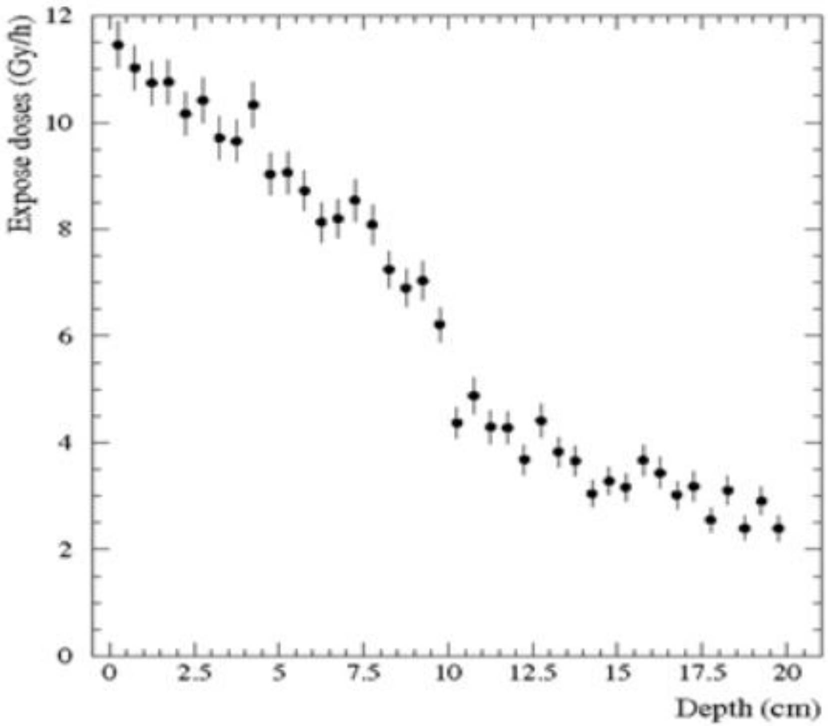


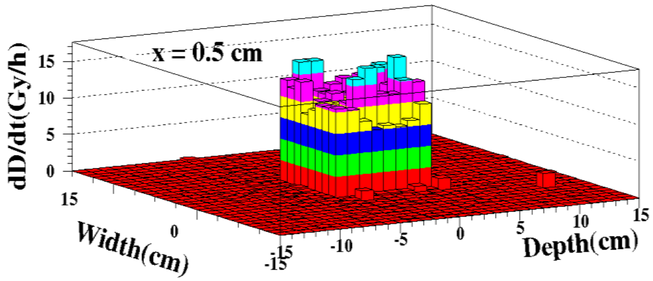
Neutron spectrum measured at 1.5 m (n/s/nA) *(KAERI/RR-2442/2003)*

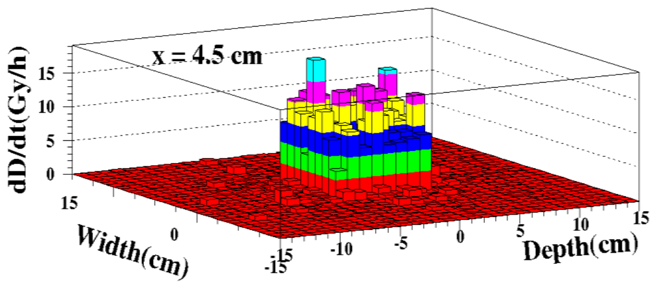
4. Beam-profile images in absorbed dose rates

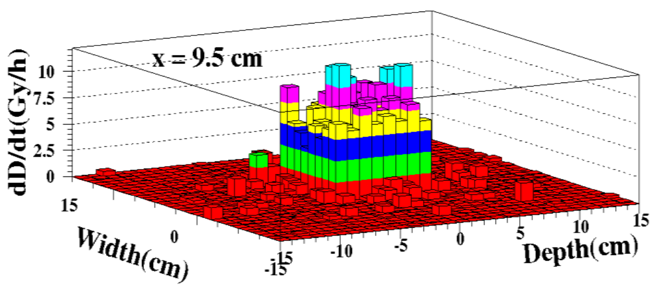
3) Applying to human-body:

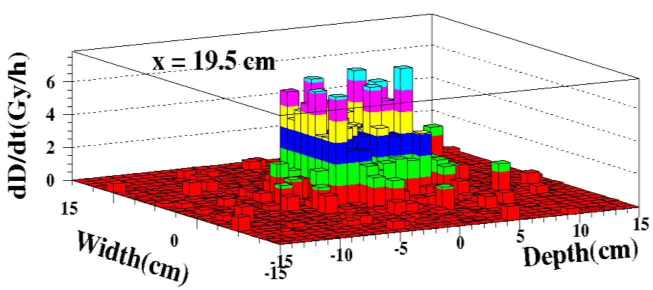
- Proton beam status: 45 MeV, 20 μA
- Be target thickness: 10.5 mm
- Distance: 123 cm
- Beam area : 8 × 8 cm^2
- Human body phantom : 30 × 30 × 20 (depth) cm^3
- Size of a voxel : 1 cm^3











4. Beam-profile images in absorbed dose rates

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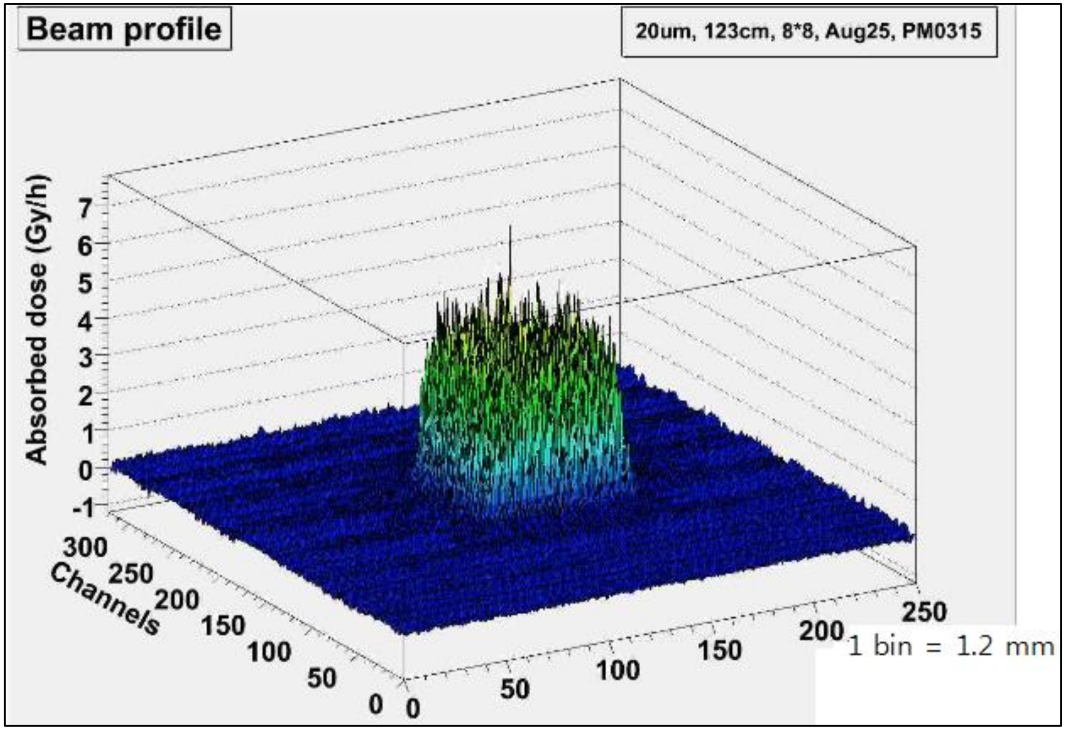
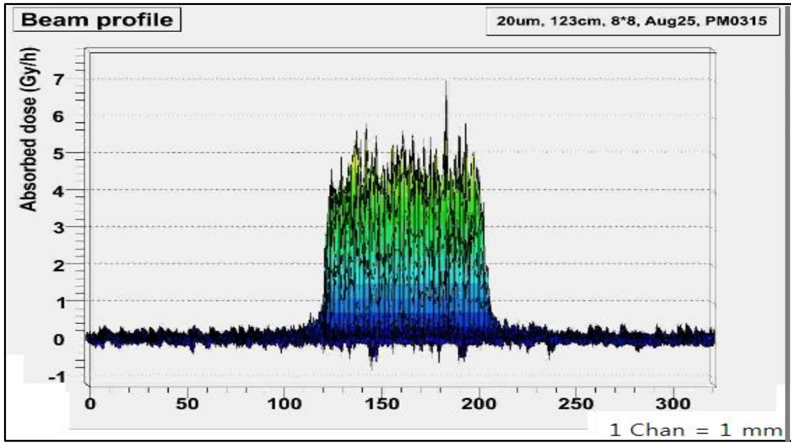
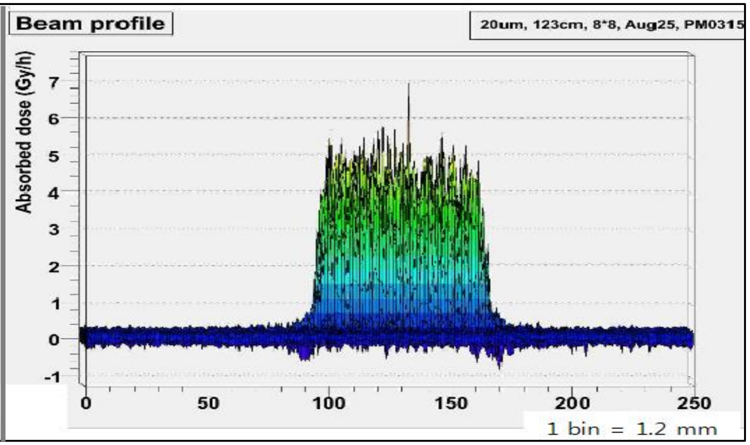
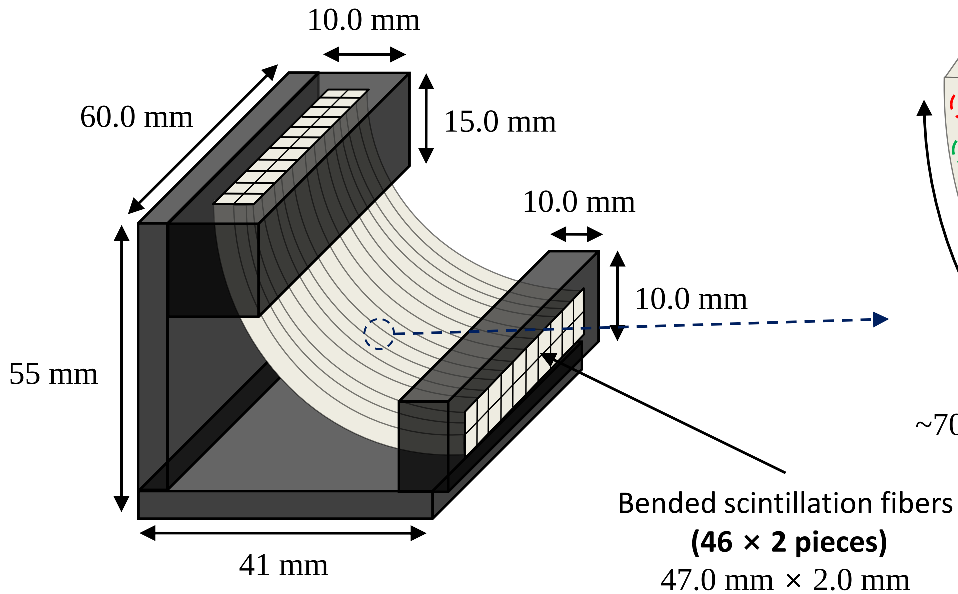
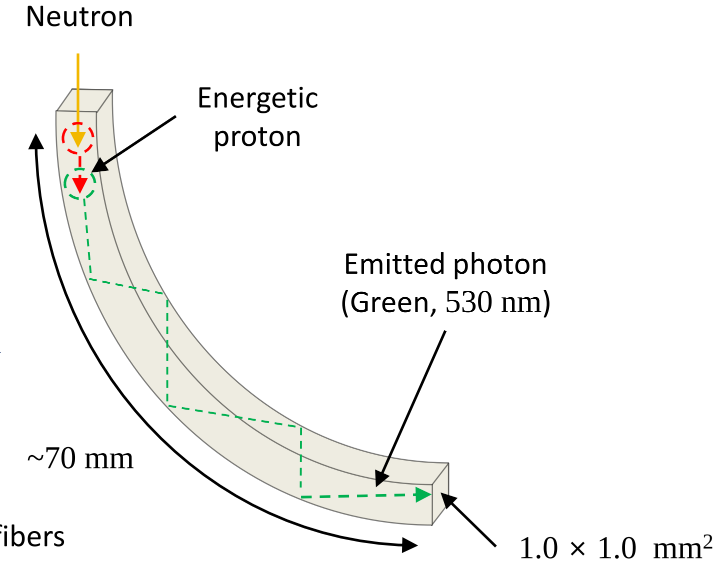






5. Detector modification





1) Bended structure to avoid direct beam-exposure

2) Improvement in statistics: {($10^8 \rightarrow 10^7$) ~ 10^{10}} (Hz/cm^2)
   - Increased fiber length (9 mm → ~ 20 mm)
   - Collimator slit removed (open width: 1 mm → 2 mm)
   - * movement speed will also be adjusted

5. Detector modification

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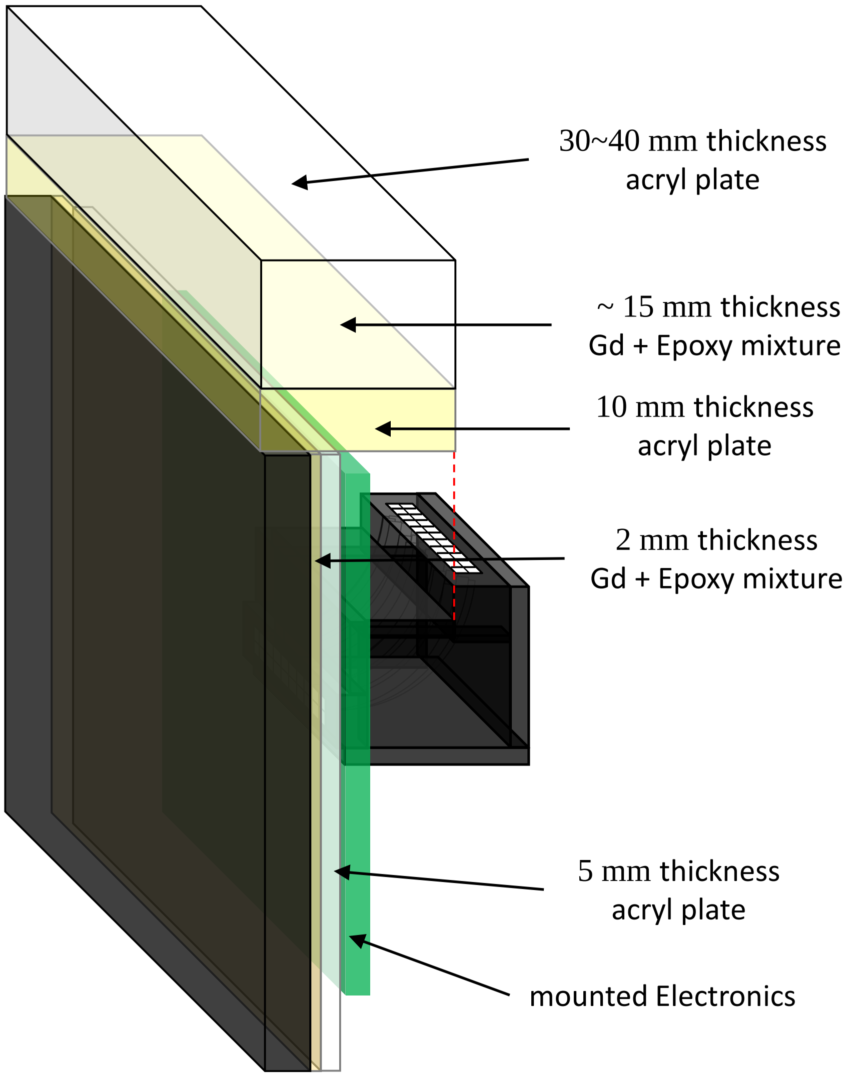


6. Conclusions and Prospects

Conclusions

1) Fast-neutron beam profile was successfully measured.
2) The detector composed of scintillation fiber and current-integration mode electronics was proved as a reliable instrument for the beam-profile measurement.
3) High-precision data measurement:
   not only beam area but also beam-halo were observed.
4) Stable beam-profile measurement is possible
5) Direct result (charge distribution) can be converted to absorbed dose rates by Geant4 simulation

6. Conclusions and Prospects

Prospects

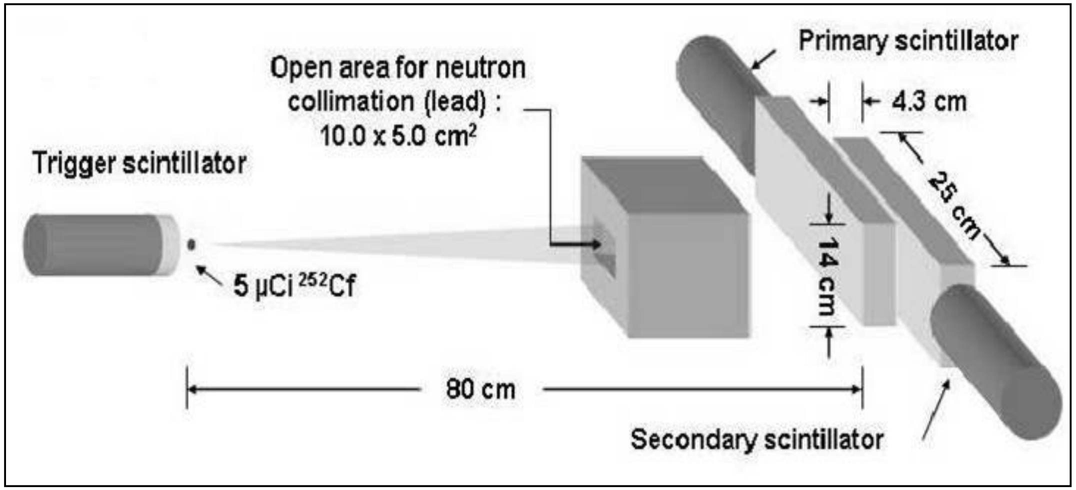
1) Second neutron-beam test arranged at KIRAMS: March 16
2) Further, and deeper simulations by Geant4 are required for precise absorbed/equivalent dose rates calculation

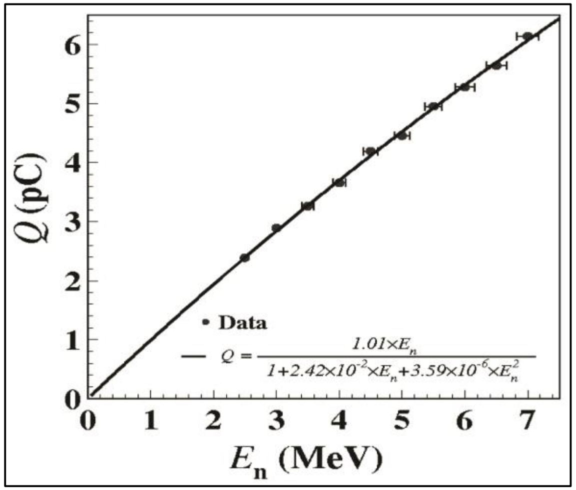
Thank you!

Backup Slides - Signal produce

1) Elastic scatterings
   I. n-p elastic scattering: deposited energy by recoiled proton (dominant)
   II. n-^{12}C elastic scattering: deposited energy by recoiled ^{12}C
   III. Neutron signal is proportional to deposited energy
   IV. The beam-profile images directly reflects the distribution of absorbed doses

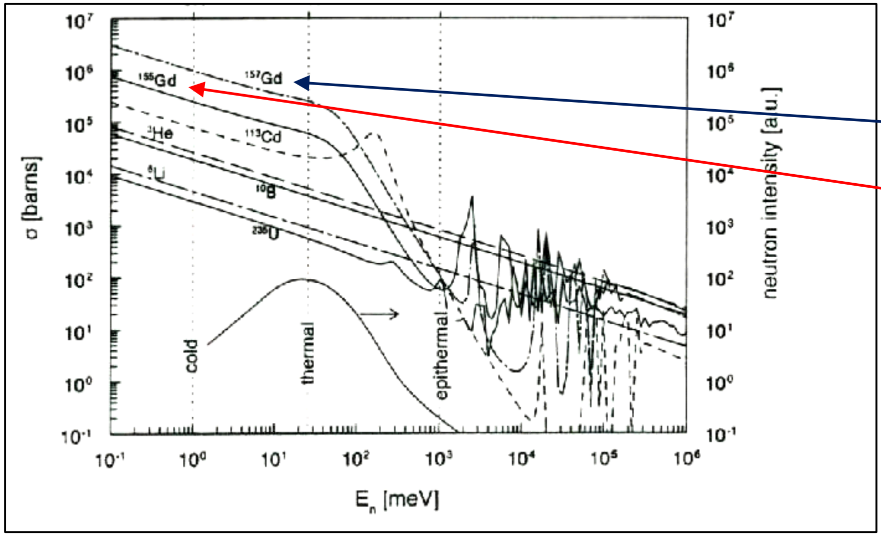
2) Inelastic scatterings
   I. p(n , γ)d $\longrightarrow$ signals by secondary deuteron
   II. n + $^{12}C \longrightarrow$ 3 α's





Backup Slides - Gadolinium

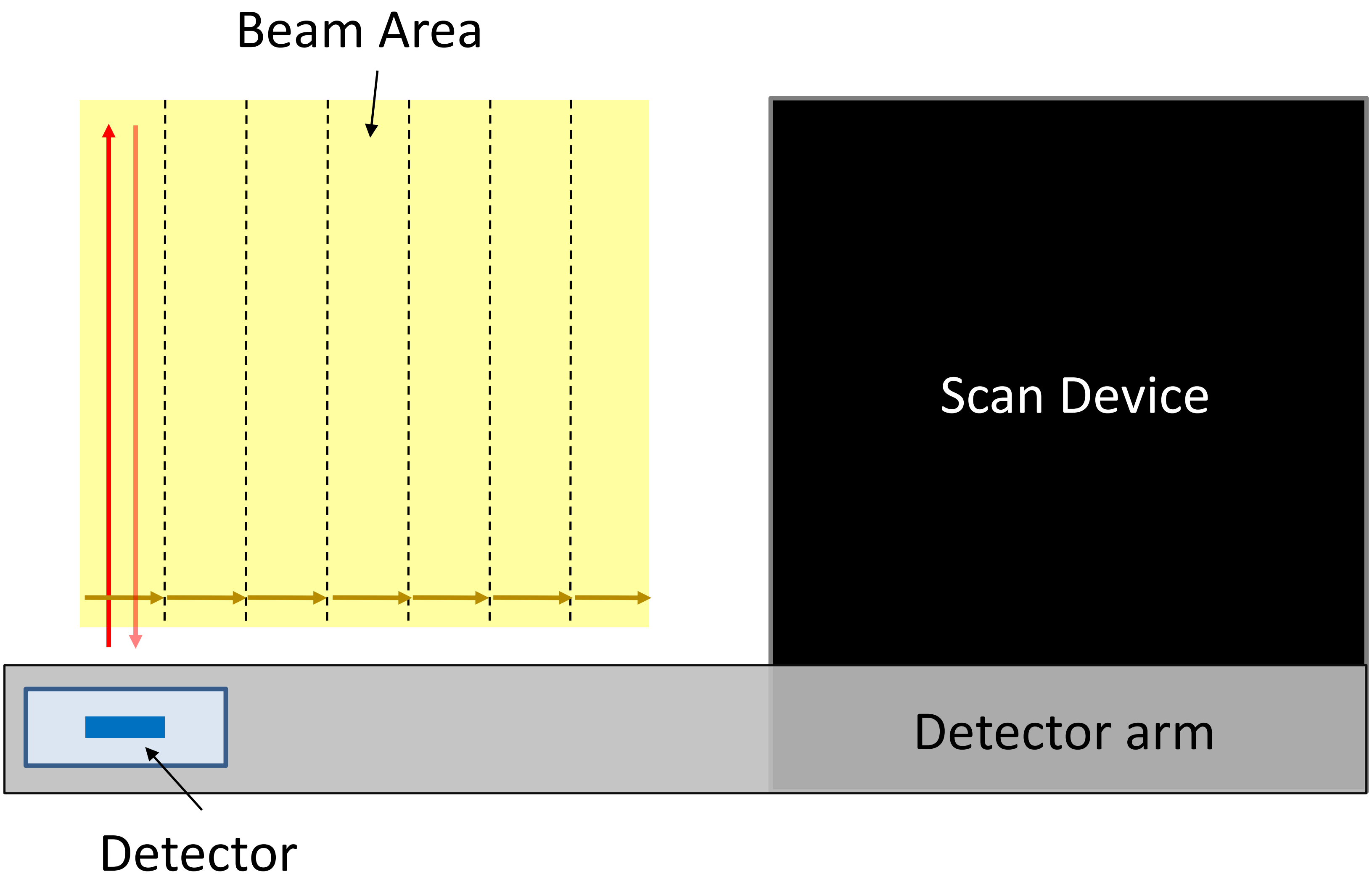
동위원소 질량비		내부전환에 의해 발생하는 전자의 에너지	
질량수	존재비 (%)	Energy (KeV)	내부전환 확률 (%)
152	0.2	29	9.82
154	2.2	39	4.19
155	**14.8**	**71**	**26.80**
156	20.5	78	6.17
157	**15.7**	81	4.97
158	24.8	88	1.16
160	21.8	131	3.41
여백		150 이상	~2



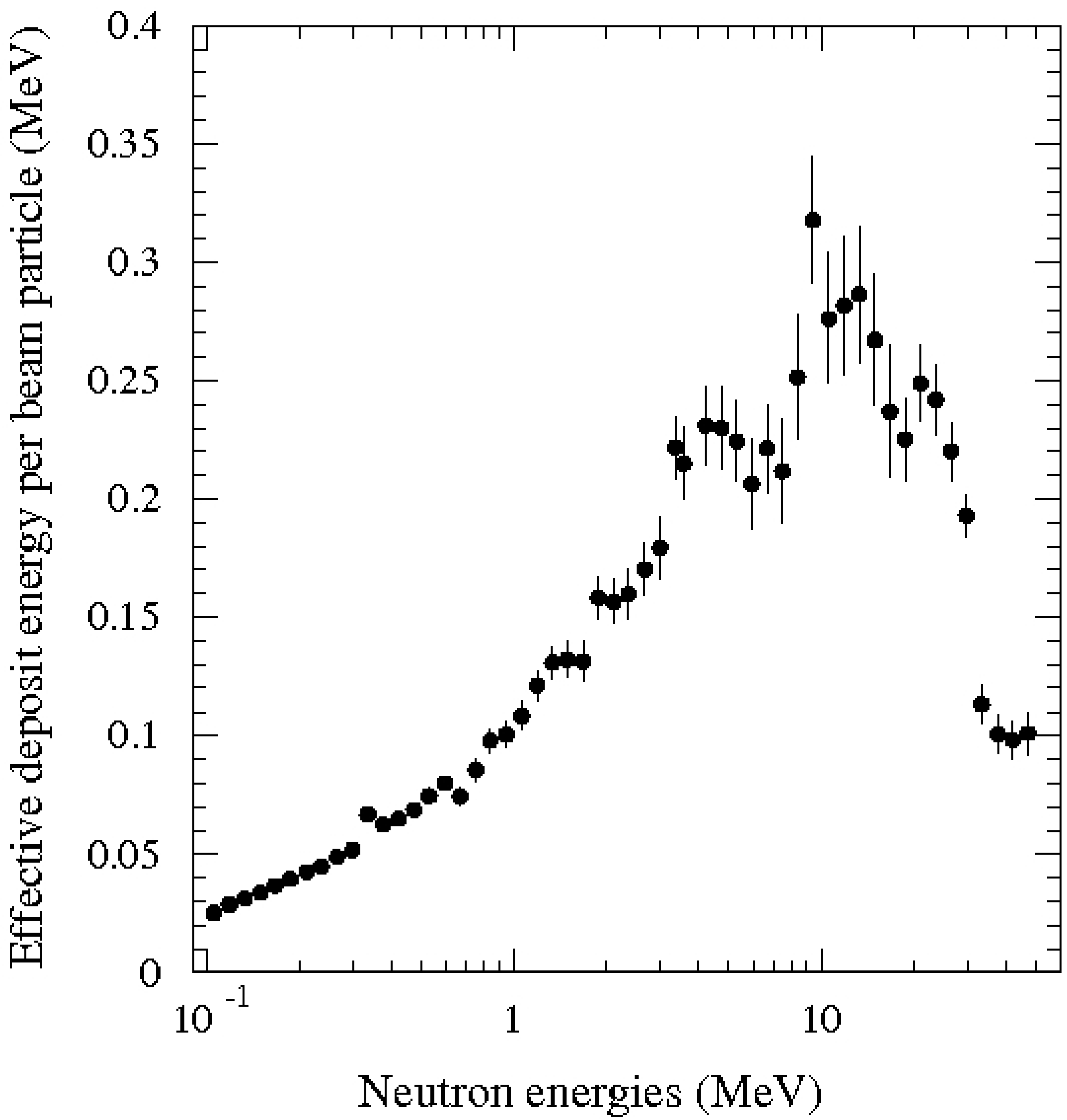
^{157}Gd: 6.3×10^{6} barn

^{155}Gd: 3.6×10^{5} barn

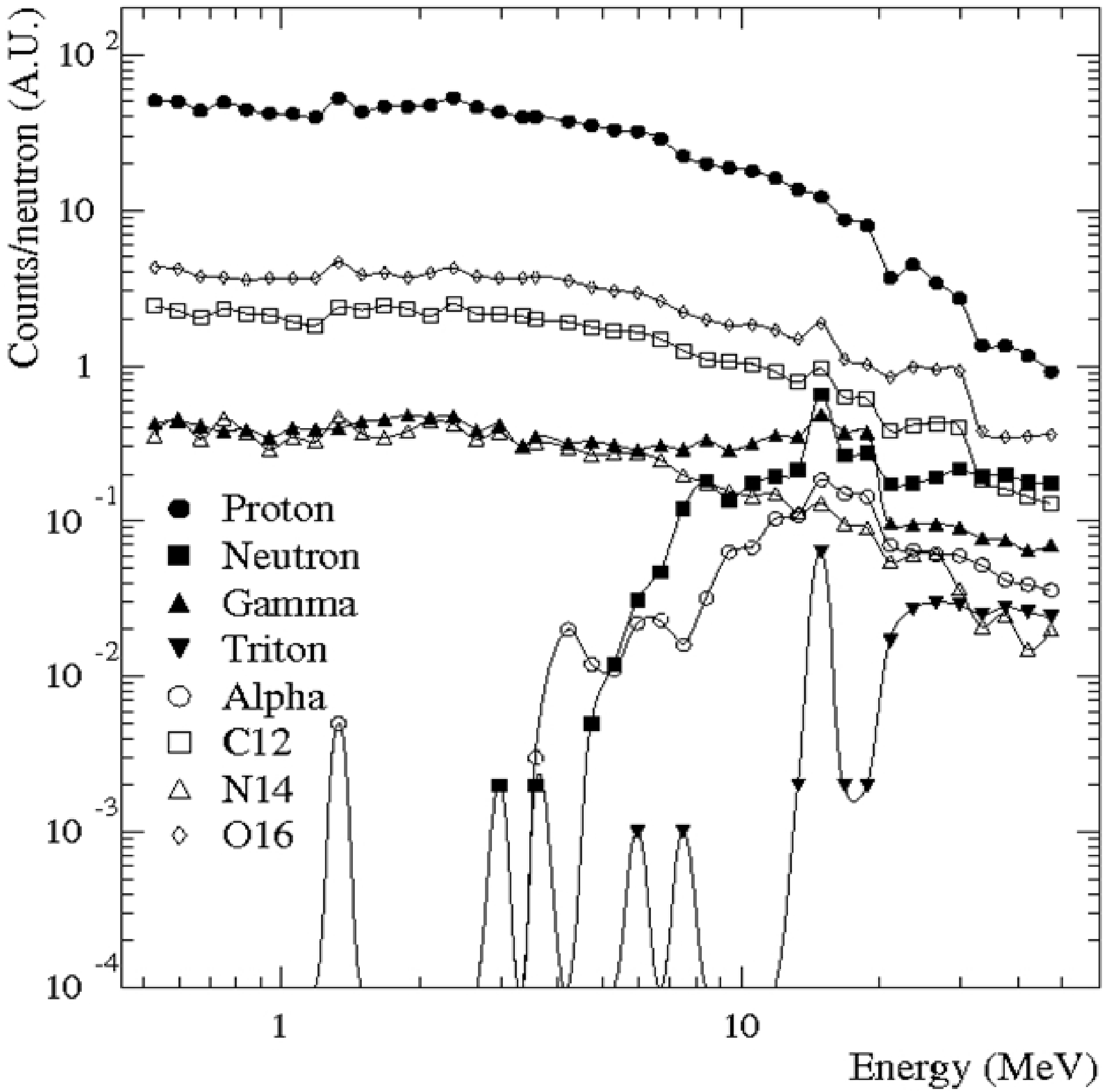
Backup Slides – Detector arm



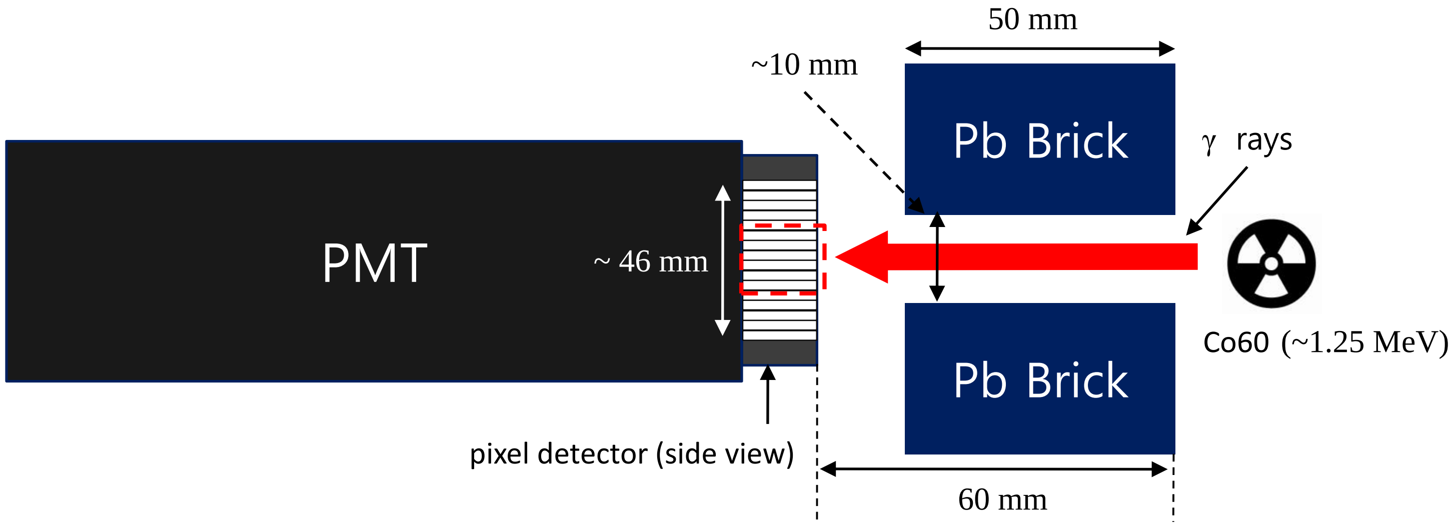
Backup Slides – (tagging efficiency × deposited energy) / neutron



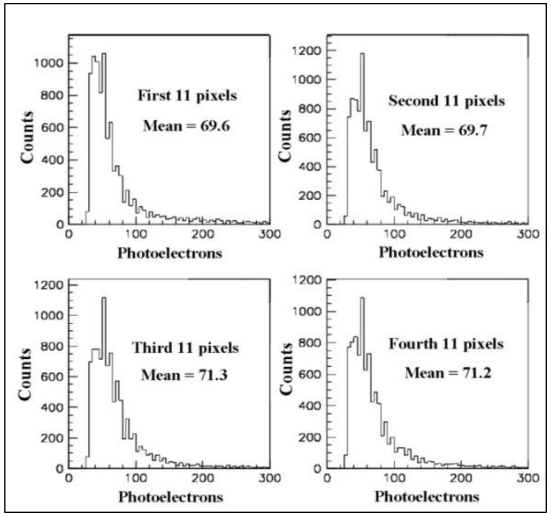
Backup Slides – Counts of secondary particles / neutron



Backup Slides - Position sensitivity test

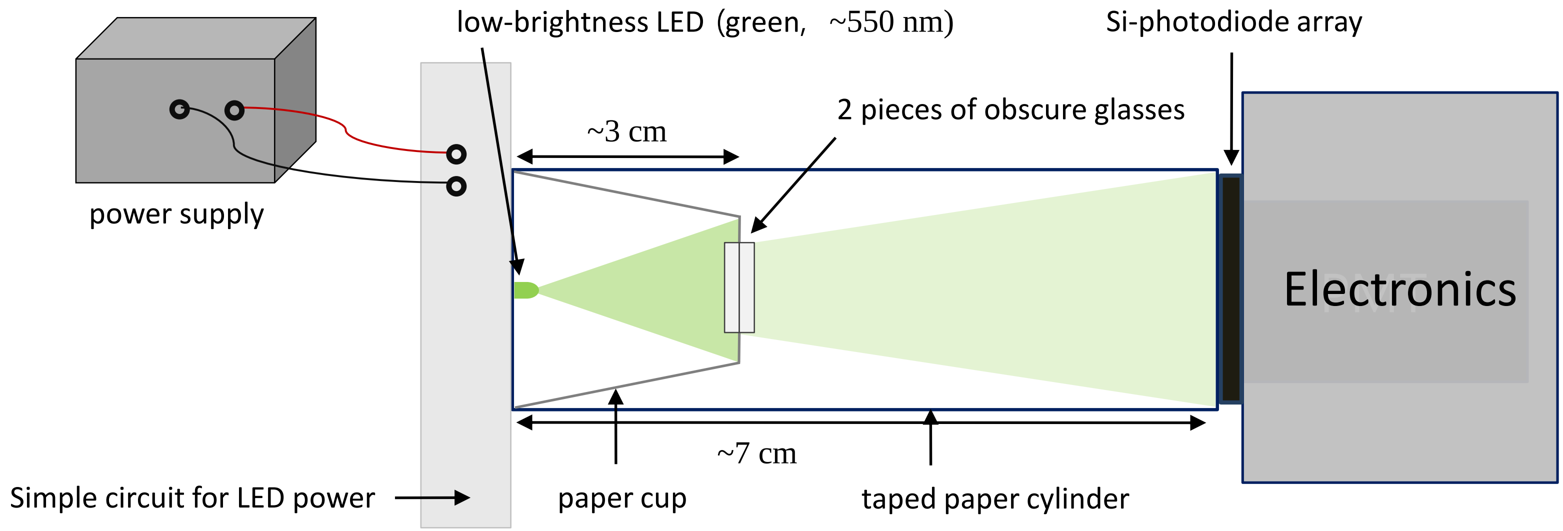


Schematic diagram of position sensitivity test. The width of γ-ray pass (open space between lead bricks) adjusted to overcome low irradiation rate of γ-source.

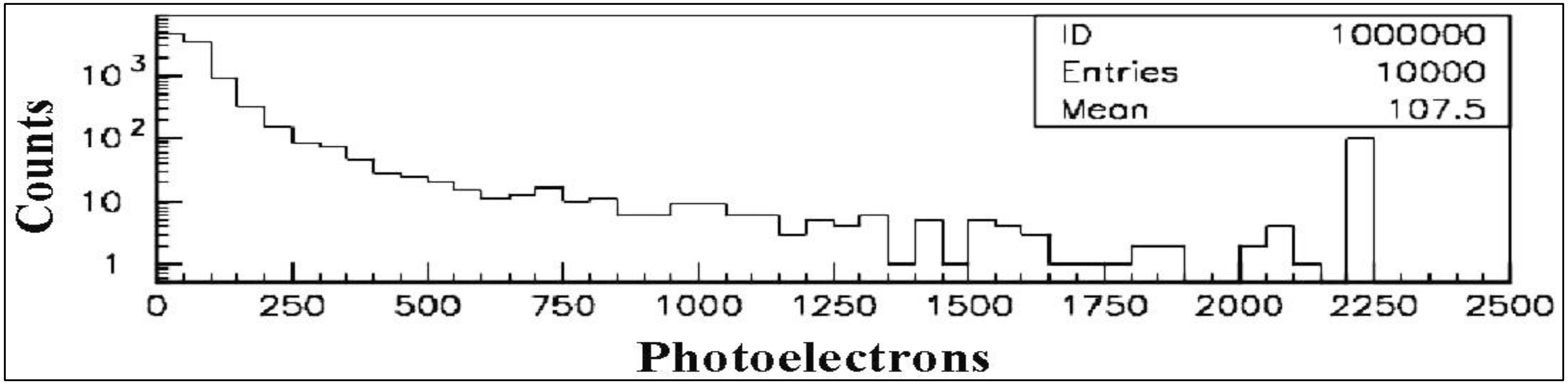


- 4 points (by 1 cm interval) of detector checked to examine position-sensitivity of detector.
- γ-ray distribution of each points were all uniform.

Backup Slides - LED Test



Schematic diagram of LED test



- Amounts of photon correspondent to LED power measured by PMT
- Same experiment repeated by designed electronics