On-line evaluation of spatial dose-distribution by using a 15m-long plastic scintillation-fiber detector

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***Abstract*–A 15m-long plastic scintillation fiber (PSF) detector has been applied to the on-line evaluation of spatial dose-distribution inside radiation facilities. The aim of this study is to realize the real-time measurement system which is not only simple but also reliable for monitoring use. Determination of radiation-incident points was made by the measurement of time difference that two directional signals of the scintillation light reach both ends of the PSF [so called "time-of-flight (TOF) method"]. The PSF used had practically enough sensitivity to detect both fast neutrons and gamma-rays.**

I. Introduction

The long position-sensitive detector using a plastic-scintillation fiber (PSF) is an attractive device for the distributed radiation-sensing. Because the position determination is based on a simple principle, the application is generally easy to construct and moreover reliable. From this view, some developmental studies have been carried out in the past. Soramoto et al. used a 2.52 m PSF for the detection of neutrons from the fast neutron source reactor "YAYOI" in University of Tokyo[1]. They also verified that it was possible to apply this method to a radiation sensing for the longer distance with connection of normal optical fibers and the PSF. Emoto et al. applied a similar system to the measurement of spatial dose distribution at a radiation field in a nuclear facility[2]. The obtained count-rate distribution along a 5 m PSF was nearly identical to that of gamma dose-rate measured by a survey meter at several points.

The use of long PSF detectors is practically limited by the significant reduction of pulse height during the propagation of light signals inside the scintillation fiber, which is accompanied with the notable degradation of position resolution as well as counting losses. In the present work, a 15 m-long plastic-scintillation fiber has applied to the on-line evaluation of spatial dose distribution in a neutron-gamma mixed field.

II. Experimental

Determination of radiation-incident position is achieved by the measurement of time difference that two directional signals of the scintillation light reach both ends of the PSF [so called "time-of-flight (TOF) method"]. The electronic schematic is drawn in Fig. 1. The electronic signals from the fast PMTs, after passing through two corresponding PM amplifiers and constant-fraction discriminators (CFD), are sent to the start channel of the time-to-amplitude converter (TAC) or to the stop channel of that with a proper delay time. The output pulse height is proportional to the time difference between the start input and the stop input, which is recorded by a PC-based multi-channel analyzer (MCA). Ten 15m-PSFs were bundled in order to enhance the detection efficiency of radiations.

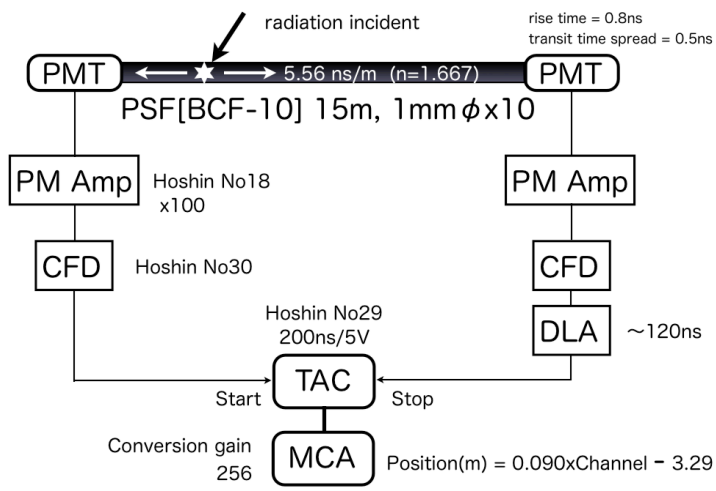

Fig. 1. Schematic drawing of data acquisition system for the PSF system.

The basic characteristics of position sensing were examined by using RI checking sources, a ^{252}Cf source (spontaneous-fission neutrons, ~ 3 MBq) and a ^{137}Cs source (662 keV gamma-rays, ~ 0.7 MBq). We evaluated the position resolution and the linearity between source position and peak channel. Pulse-height distributions of the PMT output were also measured for different source positions. Some long-time (2 ~ 3 days) measurements were done for the check of detection uniformity and stability by using only background radiations with no particular checking sources. An NE-213 detector was used to investigate the intrinsic efficiencies to neutrons and gamma-rays.

A performance test was carried out in the room of a research nuclear reactor "UTR-KINKI" at Kinki University. Count-rate distributions obtained at the neutron-gamma mixed field were compared with the direct readings of two survey meters (an air ionization-chamber and a neutron rem-counter) at several points.

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III. Results and Discussions

A. Position Resolution and Linearity

Position (TAC output) spectra for ^{137}Cs gamma-rays are shown in Fig. 2. The dimension of effective source region of ^{137}Cs is less than 5 mm. The source was placed at the different positions on the surface of the PSF and no collimation was made. Fig. 3 is the linearity between source position and peak channel obtained by the same measurement of Fig. 2.

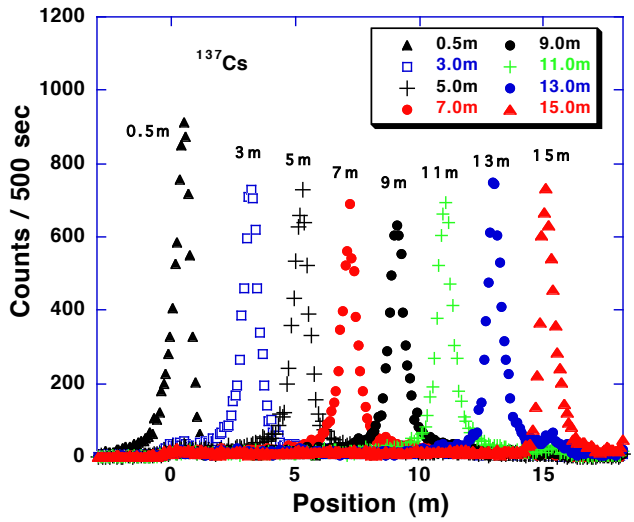

Fig. 2. Position (TAC output) spectra for ^{137}Cs gamma-rays.

From Fig. 2, the position resolution is estimated to be about 60 cm (at the center part of PSF) and about 75 cm (near the both edges of PSF) in FWHM. Throughout the whole length of 15 m, a good linearity is maintained between source position and peak channel as clearly shown in Fig. 3.

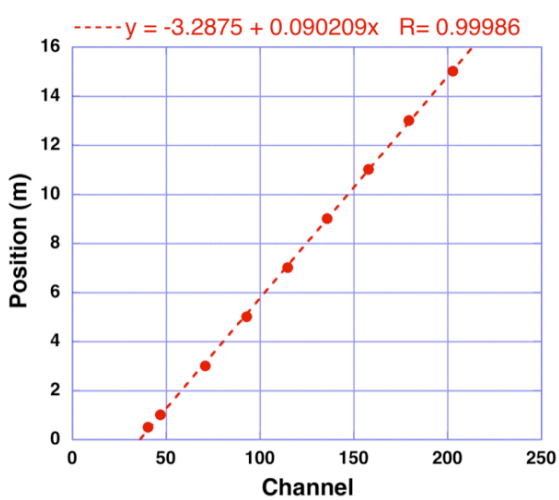

Fig. 3. Linearity between source position and peak channel for ^{137}Cs gamma-rays.

B. Pulse Height Reduction along the PSF

Pulse height spectra of one-side PMT output signals were measured for different irradiation positions by a ^{252}Cf source. As shown in Fig. 4, a steep reduction of pulse height was observed when the source was moved from 0.2 m to 15 m; the integral counts of each spectra decreased to ~ 1/100.

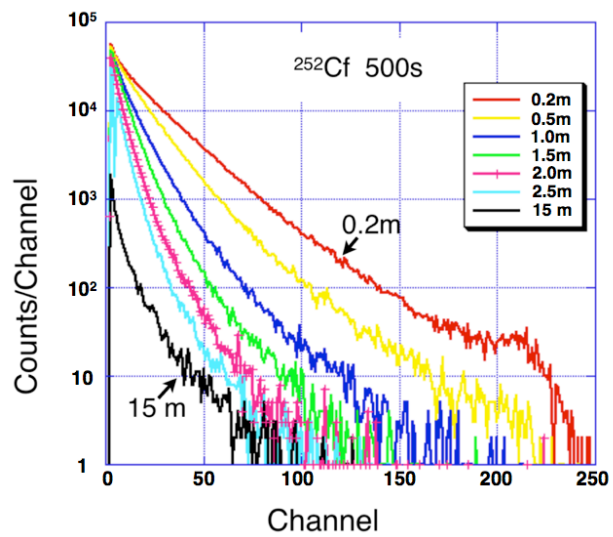

Fig. 4. Pulse height spectra of one-side PMT output signals for a ^{252}Cf source. The length indicated in unit of [m] is distance from the irradiation position to the PMT used.

C. Detection Uniformity

In order to examine the detection uniformity along the PSF, background radiations were utilized. Two ~ three days data accumulation was repeated several times for different settings. The results are shown in Fig. 5. Apparent inclination was noticed when the discrimination levels of both CFDs were equivalent (200 mV). After the start-side discrimination level was adjusted to 150 mV, rather reasonable uniformity was achieved. Some unremovable complicated-structures on the spectra, e.g. 50 ~ 60 channel, may be due to inherent defects of bundled PSF.

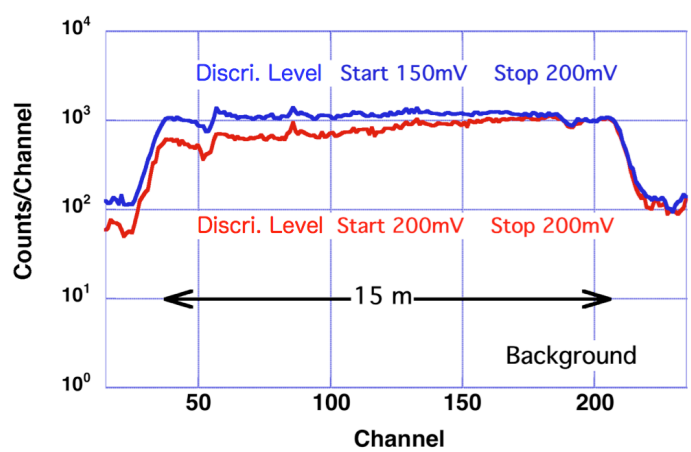

Fig. 5. Background spectra for the examination of PSF detection uniformity.

D. Intrinsic Efficiency Ratio for Neutrons and Gamma-rays

Almost comparable results of the position spectrum by ^{137}Cs (Fig. 2) were obtained for ^{252}Cf as shown in Fig. 6. In this case, neutrons and gamma-rays are irradiated to the PSF detector. The ratio of PSF intrinsic efficiencies for neutrons and gamma-rays has been roughly evaluated by the following procedure with this ^{252}Cf checking source [A_1 MBq]. Through the spontaneous fission disintegration, ^{252}Cf emits 0.116 neutrons per second per Bq and almost all them emerge from the source [3]. On the other hand, gamma-ray emerging probability significantly depends on the each source structure and is usually unknown because the isotope is generally encapsulated in a sufficiently thick container. In order to investigate the actual emission rate (y), an NE-213 liquid scintillator was arranged near the ^{252}Cf source. The count rates of neutrons and gamma-rays ($N_n^{\text{NE-213}}$ and $N_\gamma^{\text{NE-213}}$) were separately obtained on the basis of pulse shape discrimination technique for a certain geometrical configuration (Fig. 7 [a]) as shown in Fig. 8. When intrinsic efficiencies of neutrons and gamma-rays are expressed as ε_n and ε_γ respectively,

$$(A_1 \times 10^6) \times 0.116 \times \frac{\Omega_1}{4\pi} \times \varepsilon_n = N_n^{\text{NE-213}} \qquad (1),$$

$$(A_1 \times 10^6) \times y \times \frac{\Omega_1}{4\pi} \times \varepsilon_\gamma = N_\gamma^{\text{NE-213}} \qquad (2),$$

where y is actual emission rate of gamma-rays and Ω_1 is the solid angle subtended by the NE-213 detector at the source position.

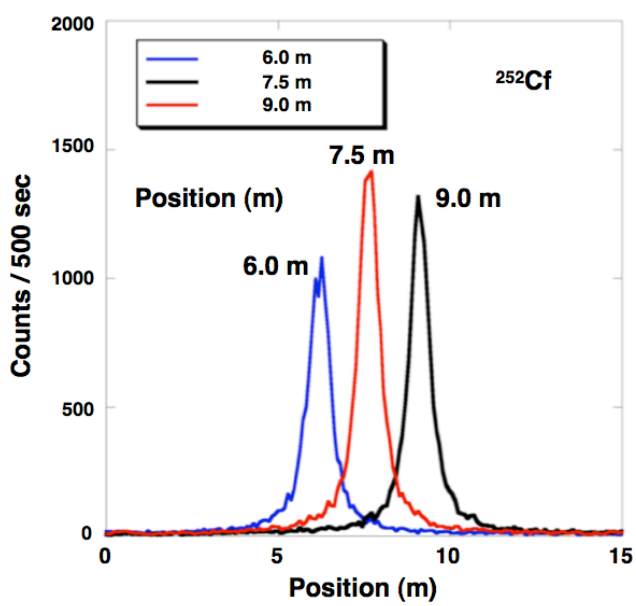

Fig. 6. Position (TAC output) spectra for a ^{252}Cf source.

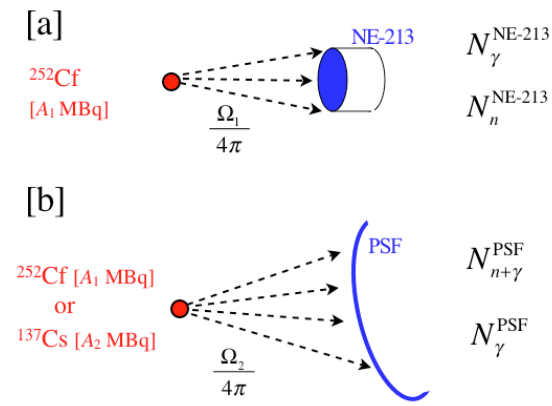

Fig. 7. Configurations of irradiation to [a] NE-213 detector and [b] PSF detector by checking sources.

Next the same ^{252}Cf source was measured by the PSF detector (Fig. 7 [b]). Because both NE-213 and PSF are organic scintillators basically consisting of hydrogen and carbon, if we assume that ε_n and ε_γ for the PSF are almost equivalent to those for NE-213,

$$(A_1 \times 10^6) \times \left[0.116\varepsilon_n + y\varepsilon_\gamma\right] \times \frac{\Omega_2}{4\pi} = N_{n+\gamma}^{\text{PSF}} \qquad (3),$$

where $N_{n+\gamma}^{\text{PSF}}$ is the total count rate of neutrons and gamma-rays by the PSF detector and Ω_2 is the solid angle subtended by the PSF detector at the source position. In addition to the above measurements, a ^{137}Cs checking source [A_2 MBq] was used in the same geometrical configuration for ^{252}Cf to examine the response of PSF to sole gamma-rays (count rate N_γ^{PSF}). The 662 keV gamma-ray yield is 0.95. Therfore,

$$(A_2 \times 10^6) \times 0.95 \times \frac{\Omega_2}{4\pi} \times \varepsilon_\gamma = N_\gamma^{\text{PSF}} \qquad (4).$$

By solving equations (1) ~ (4) with measured values of $N_n^{\text{NE-213}}$, $N_\gamma^{\text{NE-213}}$, $N_{n+\gamma}^{\text{PSF}}$ and N_γ^{PSF}, we obtain

$$\frac{\varepsilon_n}{\varepsilon_\gamma} \approx 1.5 \quad \textit{and} \quad y \approx 0.3 \qquad (5).$$

This rough evaluation given above indicates that the intrinsic efficiencies of the PSF detector for neutrons and gamma-rays are almost comparable or that for neutrons is even higher than that for gamma-rays.

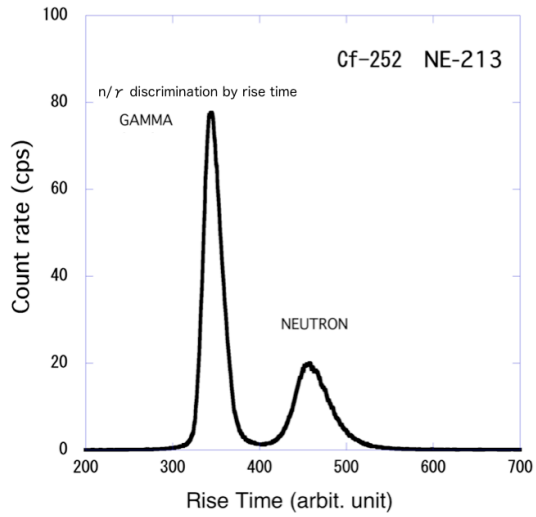

Fig. 8. Rise time spectrum for a ^{252}Cf source measured by an NE-213 detector

E. Dependence of Position Resolution to the Length of PSF

The position resolutios appeared in Fig. 2 and Fig. 6 are compared with the previously-reported values[1,2] in Fig.9 for different length PSFs. In the figure, the best resolution of each PSF, which was commonly obtained by the center part irradiation, is plotted as a function of the PSF length. As shown in the figure, the FWHM becomes larger with the increase of PSF length. It is obvious that the degradation is originated from the significant reduction of pulse height during the propagation of light signals inside the scintillation fiber. The position resolution of the present application is effectively limited by the pulse timing properties of photomultiplier tube (PMT) used, especially "transit time spread (TTS)" [3].

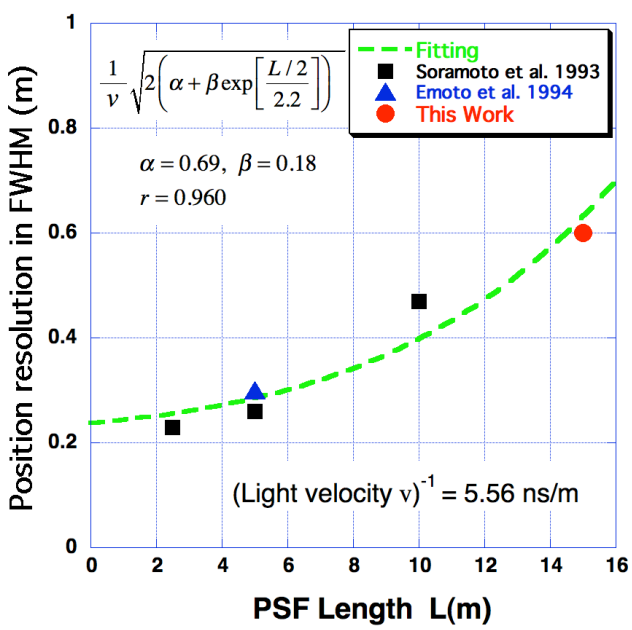

Fig. 9. Position resolution for different length PSFs.

The dependence of position resolution to the length of PSF used may be described as follows. The transit time spread (TTS) of the signal generated by a photomultiplier mainly consists of the following three components:

[A] Distribution of initial velocities of photoelectrons formed at the surface of photocathode $\sim T_A$

[B] Path difference from the photocathode to the first dynode of PMT $\sim T_B$

[C] Number of photoelectrons created at the photocathode per pulse $\sim T_C$

Among above three components, only [C] is related to the number of photoelectrons which becomes less when the incident position of radiation moves farther from the read-out PMT due to the attenuation of the scinitllation light during the propagation. The number of scintillating photons reaching the PMT, N, can be simply expressed as

$$N = N_0 \exp\left[-\frac{x}{\lambda}\right] \qquad (6)$$

where N_0 is the number of photons at the radiation incident position, x is the distance from the radiation incident position to the PMT and λ is the attenuation length of the PSF used (λ = 2.2 m in the present case). Here x was chosen to be the half of PSF full length L, i.e. $L/2$ = 7.5 m, in order to evaluate the average value of N at the practical situations. Because the relative spread in transit time should vary with the square root of the number of photoelectrons generated per pulse [3],

$$T_C \propto \frac{1}{\sqrt{N}} = \frac{1}{\sqrt{N_0 \exp\left[-\frac{L/2}{\lambda}\right]}} \qquad (7).$$

So, for the single side reading by a PMT,

$$TTS_{\text{single}} = \sqrt{T_A^2 + T_B^2 + T_C^2} = \sqrt{\alpha + \frac{\beta}{\exp\left[-\frac{L/2}{\lambda}\right]}} \qquad (8),$$

and for the both side reading by two PMTs,

$$TTS_{\text{double}} = \sqrt{2 \times TTS_{\text{single}}^2} = \sqrt{2\left(\alpha + \beta \exp\left[\frac{L/2}{\lambda}\right]\right)} \qquad (9).$$

where α and β are constants.

Finally, the position resolution of the present measurement may obey the expression of

$$\text{Position Resolution} \propto \frac{TTS_{\text{double}}}{\text{Light Propagaion Velocity } v} = \frac{1}{v}\sqrt{2\left(\alpha + \beta \exp\left[\frac{L/2}{\lambda}\right]\right)} \quad (10),$$

where v is the light propagation velocity inside the PSF ($1/v = 5.56$ [ns/m] in this case). A result of the least-square fitting of measured data by Equation (10) is also expressed in Fig. 9 with a dashed line.

F. Performance Test at a Research Nuclear Reactor

A performance test of the developed system was carried out in the room of a research nuclear reactor "UTR-KINKI" at Kinki University [4]; the maximum thermal output is 1 W. The PSF detector was arranged around the reactor core as photographed in Fig. 10. Count-rate distribution measurements were performed for 0.2 mW, 0.1 W and 1 W reactor operations. Each measurement time was chosen to be 600 sec except for the background measurement (about 1 night). As shown in Fig. 11, the count rate was almost proportional to the reactor power. Moreover, the relative count-rate distributions along the PSF were approximately identical to that of total dose rates measured by the survey meters at several points. This means the newly-developed detector system is available for quick check of the dose-distribution change during the reactor operation instead of conventional survey meters, such as air ionization-chambers or neutron rem-counters.

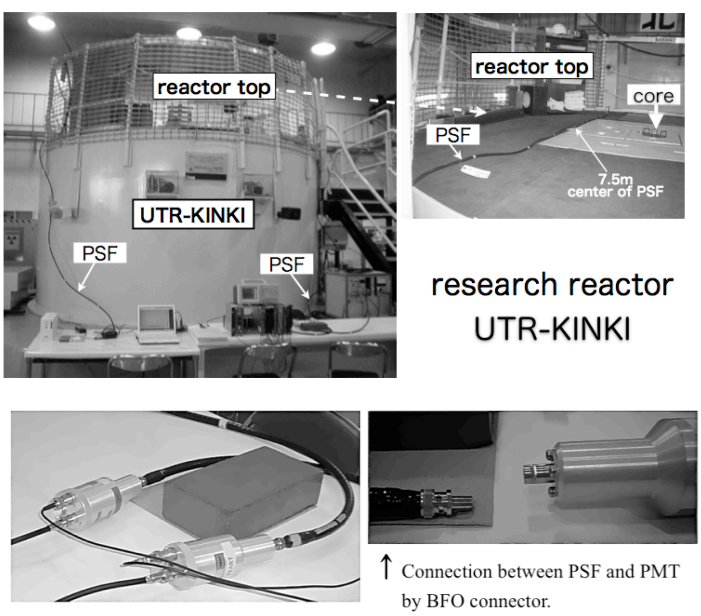

Fig. 10. Arrangement of PSF detector around the reactor core of UTR-KINKI.

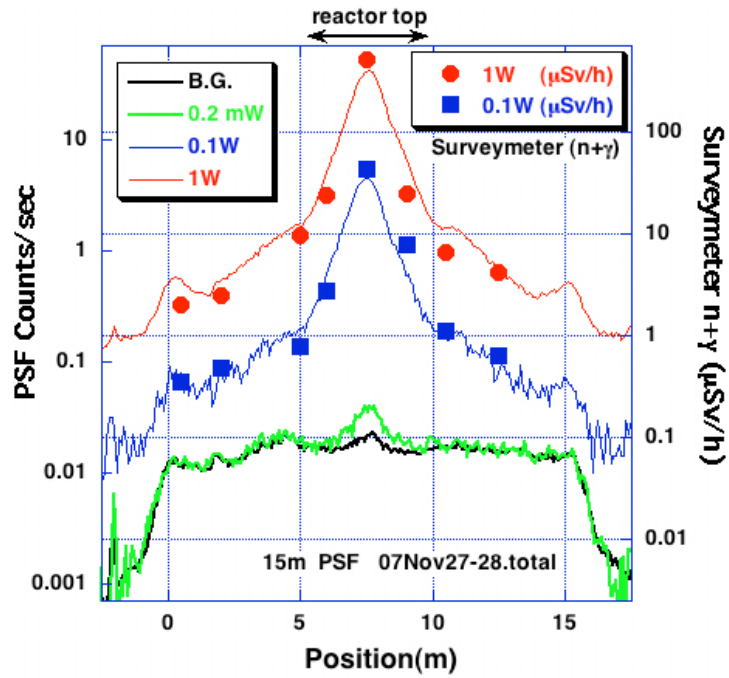

Fig. 11. Count-rate distributions in the reactor room of UTR-KINKI measured by the PSF detector.

IV. Summary

A 15m-long plastic scintillation fiber (PSF) detector has been developed and applied to the on-line evaluation of spatial dose-distribution inside the room of a low power research-reactor. It was found that the present PSF detector has enough performance as the real-time measurement system which is not only quick and simple but also reliable for monitoring use in a neutron-gamma mixed field. For more precise dosimetry, neutron-gamma discrimination must be accomplished by some means.

Such application may be also useful at the medical fields which routinely use radio isotopes for diagnosis purposes such as PET facilities; a rather straightforward interpretation from the count rate to the dose rate will be possible for the 511keV gamma-ray dominant situations inside a PET examination room.

From the present observation, it seems that the practically-acceptable maximum limit of PSF length is at most 15 m. More than this, the severe signal reduction brings unavoidable difficulties for the following signal processing. The employment of PMTs using multi-channel plates may bring a notable improvement of position resolution owing to the excellent timing characteristics.

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[4] Kinki University, Atomic Energy Research Institute http://kuaeri.ned.kindai.ac.jp/