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ABSTRACT

Time-resolved triton burnup studies have been carried out to estimate the behavior of alpha particles in DD fusion experimental devices. In those studies, 14 MeV neutrons emitted through DT reactions in DD plasmas should be measured selectively in the backgrounds of DD neutrons and gamma rays. For this purpose, a scintillating-fiber (Sci-Fi) based fast-neutron detector has been adapted because of its advantages such as fast response, design flexibility in detection efficiency by changing the number of Sci-Fi, and discrimination property against 2.4 MeV neutrons produced through DD reactions and gamma rays. However, its length had conventionally been set to around 10 cm without an optimization study of its design parameters to meet the requirements as 14 MeV neutron detector. In the present study, we tested three types of Sci-Fi detectors with three different lengths and compared with the simulated results of energy deposition, through which we tried to understand the phenomena in the detection process of fast neutrons. From the results, it has been shown that, due to the self-shielding of neutrons by Sci-Fi and the attenuation of scintillation photons during the transmission process to the photomultiplier tube, the optimal length of Sci-Fi is concluded to be about 6 cm.

I. INTRODUCTION

In deuterium operation of fusion experimental devices, to assess energetic-alpha-particle confinement performance, the behavior of 1 MeV tritons produced by d(d, p)t reactions has been studied. It is because the kinetic parameters of alpha particles produced by DT reactions such as Larmor radius and precession frequency are similar to those of tritons.[1] In addition, it has been shown that the initial velocity distribution of tritons is isotropic, as is the case of alpha particles. Time-resolved triton burnup studies have been performed by measuring secondary DT neutrons created by t(d, n)α using scintillating-fiber (Sci-Fi) detectors in large tokamaks[2–5] and helical systems[6–9] because of their properties such as fast response, high counting efficiency, gamma suppression ability, and directional response to incident neutrons. However, in these studies, the parameters of Sci-Fi detectors have been similar, namely, the length of Sci-Fi was set to around 10 cm. Considering the demands for Sci-Fi detectors in various fusion experimental devices such as LHD and KSTAR,[6–9] it is required to optimize the design parameters depending on the radiation fields for each experimental device. In a previous study, the authors compared the simulated and measured responses of the Sci-Fi detector under neutron and gamma irradiation to understand the behavior of the detector.[10] In the present study, after preparing the detectors with low transmission loss of scintillation photons, the physical phenomena occurring in Sci-Fi detectors upon fast neutron measurements as energy production of recoil protons, energy deposition by protons, production of scintillation photons, and propagation of photons including loss have been studied through simulations and experiments by using fast-neutron sources. From the results, the optimum length of Sci-Fi was revealed to be 6 cm.

II. Sci-Fi DETECTOR

A Sci-Fi detector was developed in the 1990s to measure 14 MeV neutrons from the secondary DT reactions in the fusion experimental devices such as TFTR and JT-60U.[2–5] From the measured results with 10 cm-long Sci-Fi detectors, it was shown that 14 MeV neutrons could be selectively measured near the fusion devices being operated by DD discharge. In the experiments at JT-60U, 14 MeV neutrons generated in the central and the peripheral region were measured with the Sci-Fi detectors. The results demonstrated the feasibility of this detector to measure the time resolved triton burnup in each region, which provided valuable knowledge such as toroidal Alfvén eigenmodes principally affected fast tritons in the plasma periphery.

As shown in Fig. 1, the Sci-Fi detector is composed of scintillating optical fibers set in each hole made through a metal material such as aluminum alloy. A photomultiplier tube (PMT) is set to one end, and the other end is also covered with an aluminum alloy with the reflective surface. When a fast neutron enters a Sci-Fi, a recoil proton is generated which deposits energy inside the Sci-Fi core and scintillation photons are generated. The photons transmit to the ends of the Sci-Fi to reach the PMT set at one end of the Sci-Fi head. If the Sci-Fi is long enough, transmitting photons are limited to those which are generated for the directional angle larger than the critical angle of Sci-Fi. However, as the Sci-Fi detector length is less than 10 cm, scintillation photons emitted to smaller angle can transmit to the PMT after being reflected at the inner surface of the hole in which the Sci-Fi is set. If the hole surface is rough, the number of scintillation photons which can reach the PMT depends largely on the position of generation. When a proton is recoiled to the direction nearly parallel to the Sci-Fi, it can deposit large energy inside its core, however, if it is generated to the direction with larger angle to the Sci-Fi, its energy deposition becomes small. In addition, the recoil proton is generated with larger probability to the direction close to the neutron incident direction. Therefore, by setting an appropriate discrimination level to the measured pulse height by the PMT, it can realize a directional property to the neutron. The authors have been trying to understand the physical phenomena occurring during the measurement process,[10] and, in this study, after improving the condition of the Sci-Fi detector such as polishing the hole surfaces where the Sci-Fi is set, carried out the optimization of the detector configuration.

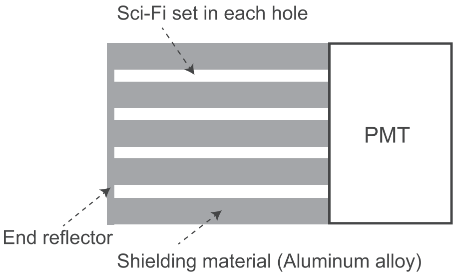

FIG. 1. Structure of the Sci-Fi detector.

III. EXPERIMENT AND SIMULATION

In the present study, Sci-Fi detectors were fabricated with the scintillating optical fibers: SCSF-78M (Kuraray), which were connected to the PMTs: H11934-100MOD (Hamamatsu). The pulses from the PMTs were converted to digital signals with the fast DAQ (Data Acquisition System): DT5751 (CAEN), where the sampling was carried out at 1 GHz and the sampled values were integrated for each pulse. To understand the physical phenomena, we carried out the experiments with the accelerator neutron sources, OKTAVIAN[11] at Osaka University and Fast Neutron Laboratory (FNL)[12] at Tohoku University, and a ^{252}Cf spontaneous fission neutron source. To see the position dependencies of detection efficiency, the gamma ray sources of ^{137}Cs and ^{60}Co were also used. In the experiments, Sci-Fi detectors with lengths of 3 cm, 6 cm, and 9 cm are used, where the number and the diameter of the Sci-Fi were set to be 144 and 1 mm, respectively. As the 3 cm-long Sci-Fi detectors, we used two types, namely, one which is capped with an aluminum reflector at the different end of the PMT and the other without it. With the latter type, we studied the effect of reflection of scintillation photons by the end cap by changing the material to put at the end. In addition, the measurement was carried out with two PMTs set at both ends of one 3 cm-long detector head to examine the possibility of efficient measurement of scintillation photons.

IV. RESULTS AND DISCUSSION

A. Optimization of Sci-Fi length through evaluation of measuring efficiency

A recoil proton is generated by a fast neutron, and it deposits energy inside a Sci-Fi. Scintillation photons propagate to the PMT which generates a voltage pulse. In our experimental setup, each pulse was sampled at every 1 ns with the resolution of 10 bits for the reference voltage of 1 V. After summing the converted values over the total pulse shape, the sum was divided by 10 to set the maximum to be 1023. In Fig. 2, the measured pulse height distributions are shown for the three types of detectors, namely, 9 cm-, 6 cm-, and 3 cm-long detectors, where 14 MeV neutrons were irradiated on them at OKTAVIAN. The detectors were set at the distance of 40 cm from the Tritium target with the angle of 90° from the beamline. The value on the horizontal axis denotes the integrated value of the sampled values for each pulse, which are proportional to the total charges in the measured pulse. It also corresponds to the pulse height in the conventional measurements. The data have been normalized by the neutron flux at the detector position estimated with the measured results by using the ^{3}He proportional detector and the activation foils.

In the highest region over 1200 ch of the pulse height distribution shown in Fig. 2, the number of counts for the three detectors was almost the same, besides the tail in the result with the 9 cm-length detector is shorter than those with the 6 cm- and 3 cm-long detectors. The reason for this difference is unclear, but it may be caused

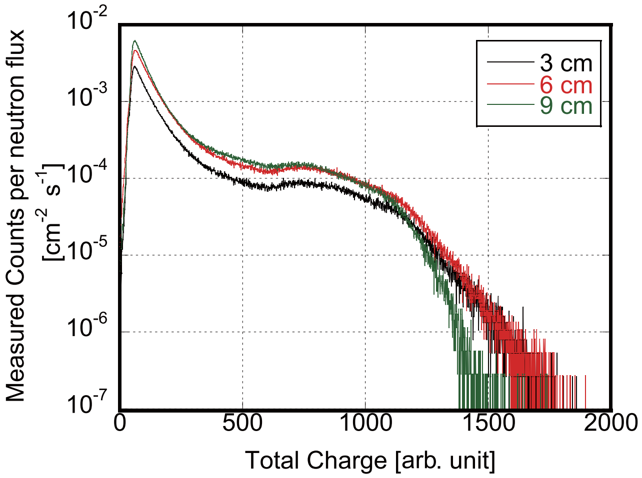

FIG. 2. Measured pulse height distributions with the three types of Sci-Fi detectors, namely, with the lengths of 9 cm, 6 cm, and 3 cm.

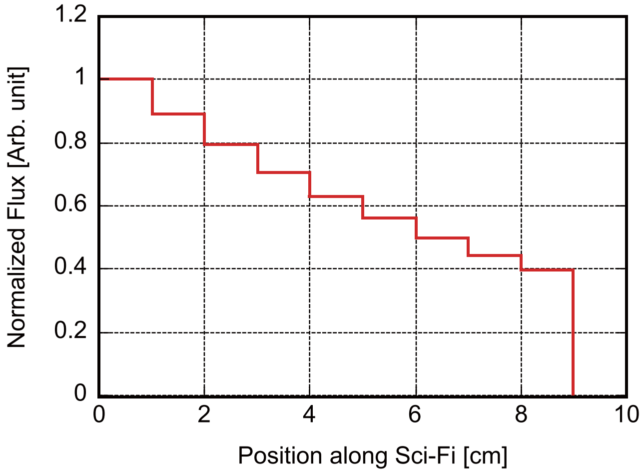

FIG. 4. Calculated dependence of the normalized recoil proton flux on the distance from the input end of the scintillating fiber.

by the difference of reflection condition near the PMT. Although the holes in which Sci-Fi were set have been made by drilling carefully, their surface conditions may be different between each detector. However, the counts over 1200 ch are less than several percentage of those over 500 ch, and once the detector is chosen which is to be used in fusion experimental devices, its property will be constant. We believe that the influence of the difference in the pulse height spectra over 1200 ch can be ignored.

In the region over 800 ch, the measured counts with the 9 cm- and 6 cm-directors are almost comparable. This should be caused by self-shielding of the neutrons by the Sci-Fi itself. Figures 3 and 4 show the calculated distribution of recoil protons near a 9 cm-long detector by the simulation code the "Particle and Heavy Ion Transportation code System" (PHITS),[13] where 14 MeV neutrons are irradiated parallel to the Sci-Fi detector. PHITS is the abbreviation of Particle and Heavy Ion Transport code System which has been developed under collaboration between Japan Atomic Energy Agency, Research Organization for Information Science and Technology and High Energy Accelerator Organization. It can deal with the transportation of all particles over wide energy ranges, using several nuclear reaction models and nuclear data libraries. We can observe a gradual decrease of the recoiled proton flux with increasing distance from the input end which results in the comparable counts of 9 cm- and 6 cm-detectors in the highest pulse height region.

Figure 5 shows the pulse height distributions measured at FNL with changing the neutron energy generated through DD reactions, where the counts have been normalized by the measured counts with the ^{3}He proportional detector. We can conclude that, by setting the threshold level at around 500 ch, we can measure DT neutrons selectively in a high background of DD neutrons around fusion experimental devices. In Fig. 6, the results measured for ^{60}Co gamma rays are shown. Considering the difference of the production efficiencies of scintillation photons by protons and gamma rays, the pulse height for the gamma rays with energy of over 1 MeV corresponds to that for the protons with energy of over 2 MeV. On the other hand, from the previous study on the radiation field around LHD, it is concluded that the average energy of gamma rays is 1.4 MeV,[14] which means that, by setting the threshold as mentioned above, gamma ray pulses can also be discriminated. From the comparison of the measured results with 9 cm- and 6 cm-long detectors shown in Fig. 3, even if we use a Sci-Fi detector longer than 6 cm, the counts should be almost the same as those measured by a 6 cm-long detector. From the results, it can be concluded that the optimal length of the Sci-Fi detector is around 6 cm for the radiation condition around LHD.

The threshold for the Sci-Fi detector is determined considering the gamma ray energy at the detector position. If its energy is lower than that assumed in the present estimation, the threshold can be set to the lower value, where 9 cm-long Sci-Fi becomes more advantageous than the 6 cm-long Sci-Fi as more counts are observed in the lower pulse height region for 9 cm-long Sci-Fi in Fig. 2. On the other hand, if the gamma ray energy is higher than the present case, as the threshold should be set higher, the optimum Sci-Fi length can become shorter. Specifically, 6 cm is the optimum length for the experimental devices such as LHD at which the peak gamma ray energy is about 1–2 MeV.

As for the difference of 14 MeV neutron flux, the number of Sci-Fi and their diameter can be the other optimizing parameters. When

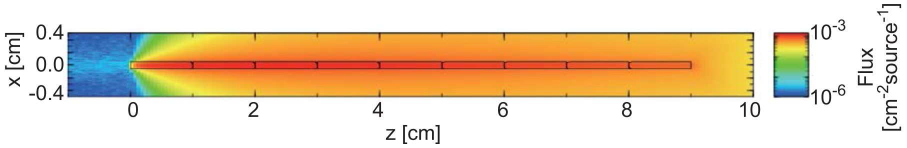

FIG. 3. Calculated recoil proton distribution when the 14 MeV neutron is input parallel to one 9 cm-long Sci-Fi, where the intensity is shown as a heat map.

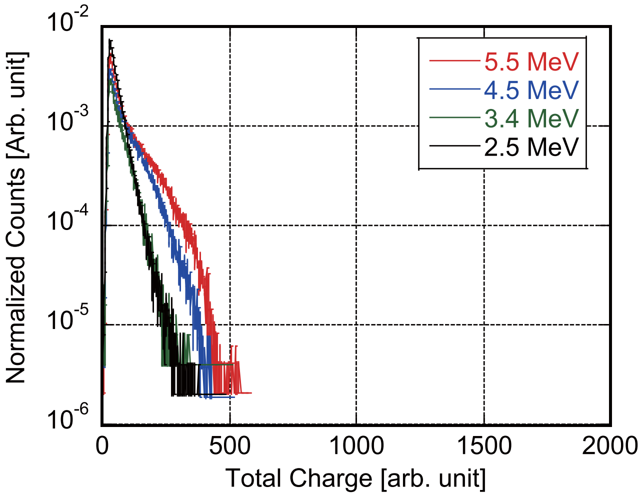

FIG. 5. Pulse height distributions measured at FNL with changing the neutron energy generated through DD reactions where the counts have been normalized by the measured counts with the ^{3}He proportional detector.

the 14 MeV neutron flux is low, we can enhance the efficiency by increasing the number of Sci-Fi. If we choose to increase the diameter to enhance the efficiency, the pulse height of the gamma ray signal should also become higher, which means that we should set the threshold higher and the optimum length may become shorter than 6 cm.

B. Attenuation of scintillation photons through their transmission

The scintillation photons can be scattered and absorbed in the transmission process inside the detector. If the Sci-Fi is long enough and act as a usual optical fiber, only the scintillation photons emitted to the direction over its critical angle can transmit to the PMT. However, as the Sci-Fi is short, the photons generated to all directions are reflected at the surface of Sci-Fi halls made through the aluminum alloy and can transmit to the PMT. Through the transmission process, scattering and absorption at the interface between Sci-Fi and aluminum can affect the photon numbers to reach the PMT. To see the effect, we irradiated the gamma rays from a ^{137}Cs gamma source with the configuration shown in Fig. 7, where gamma rays are collimated with a lead brick and irradiated perpendicularly to the detector with changing the irradiation position. The change of measured pulse height distributions is shown in Fig. 8 for the incident position of 0.25 cm, 1.25 cm, and 2.25 cm from the PMT, where two types of end reflectors were used, namely, highly reflective type or matte black coating type. In Fig. 9, the counts over 100 ch are shown for the 3 incident positions. Each measured count with

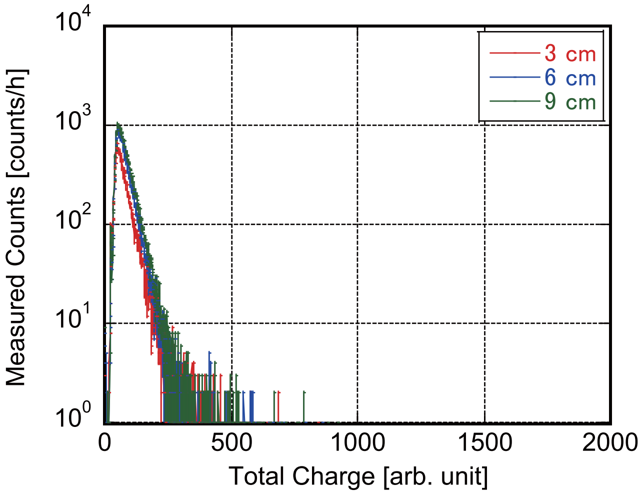

FIG. 6. Pulse height distributions measured under irradiation of gamma rays from a ^{60}Co gamma ray source. The gamma rays were irradiated parallel to the axis of Sci-Fi.

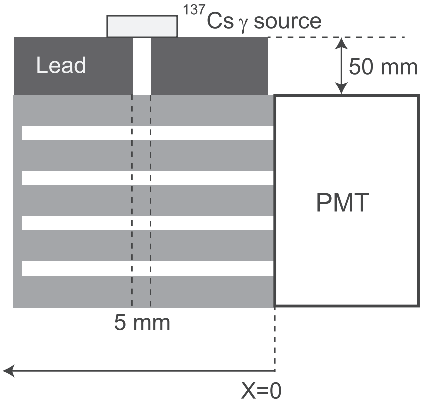

FIG. 7. Experimental setup to estimate the effect of interaction position on the pulse height distribution. The incident position of ^{137}Cs gamma rays was changed.

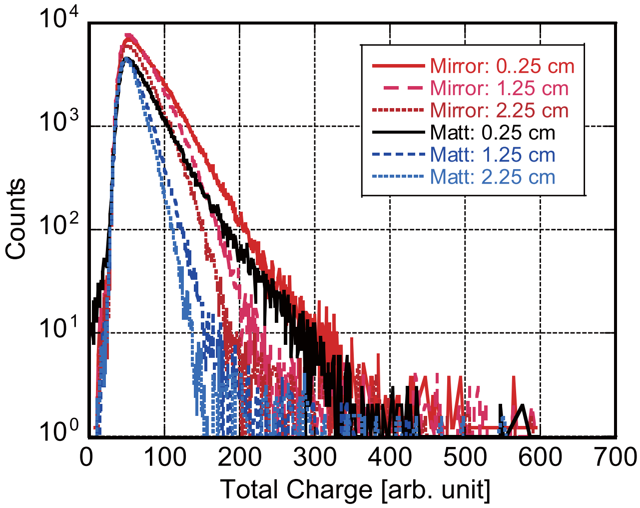

FIG. 8. Comparison of the pulse height distributions where the gamma ray incident positions were set to 0.25 cm, 0.75 cm, and 2.25 cm from the PMT. The two types of end reflectors were used, namely, highly reflective type and matte black coating type.

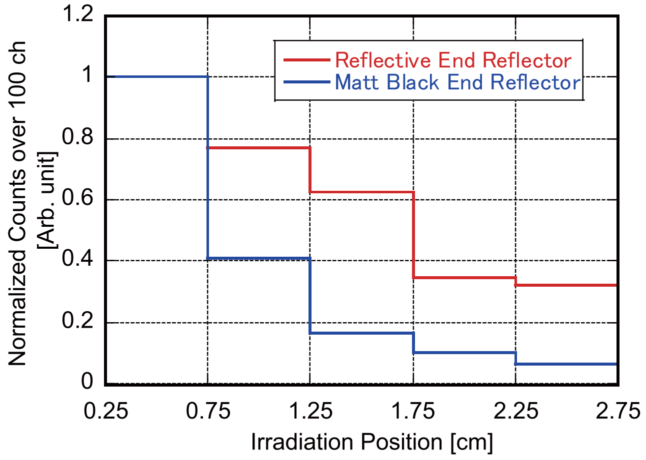

FIG. 9. Relation between the incident position of ^{137}Cs gamma rays and the measured counts over the threshold of 100 ch in Fig. 8.

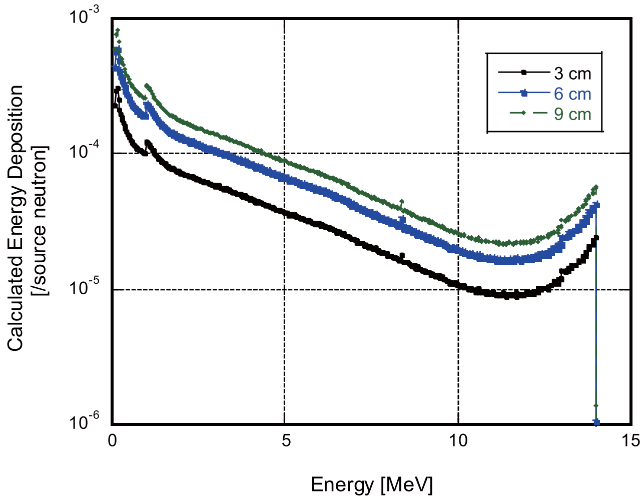

FIG. 10. Simulated energy deposition in each Sci-Fi detector with 3 lengths. The simulation was carried out by using the PHITS code.

the ^{137}Cs gamma ray source at each position was normalized by the energy depositions simulated by using PHITS with the same configuration. From Fig. 8, the difference between the distributions of 0.25 cm and 1.25 cm or 1.75 cm is larger with a matte reflector compared to the case with the mirror reflector. From the results, we can conclude that the number of scintillation photons to reach the PMT is affected also by the interaction position of neutrons and the Sci-Fi. Especially when the end reflector is coated with the matte material, the difference is large. This should be the cause of broadening of pulse height distribution. However, the detection efficiency changed gradually with the incident position, it seems that we should not necessarily pay excessive attention onto the large signals from the nearest interaction which occurs in the nearest region of the PMT.

From the results shown above, we can conclude that there are two factors affecting the pulse height distribution measured by the Sci-Fi detector, namely, (a) self-shielding of 14 MeV neutrons by Sci-Fi itself and (b) attenuation of scintillation photons during their propagation to the PMT. By the self-shielding effect, the production of recoil protons near the PMT becomes fewer for the 9 cm-long Sci-Fi than for the 6 cm-long one. On the other hand, because of the difference of their length, more recoil protons are generated in the 9 cm-long Sci-Fi at the positions far from the PMT. However, the photons generated at the positions far from the PMT decrease before arriving the PMT, the resulting pulse height for that signal becomes lower and is counted in the pulse height region lower than the threshold. These effects totally result in the comparable counts for the 9 cm and 6 cm Sci-Fi.

C. Comparison of measured and simulated detector responses

To understand the phenomena occurring in the Sci-fi detector, energy deposition in the detectors was calculated with PHITS. In Fig. 10, the results are shown. As the Sci-Fi is very thin in diameter, once the incident neutron is scattered, it will go outside of the Sci-Fi. Hence, as the probability of secondary scattering is low, the shape of the pulse height distribution becomes independent of its length and shows just a vertical shift for different lengths. In addition, we can observe the steep edge at the highest energy region for the detectors with three lengths. In the measured results, however, "knee" like distributions are observed at that region. To reproduce the measured distribution by simulation, we considered the two phenomena such as (a) production efficiency of scintillation photons through interaction with protons compared with electrons and (b) probabilistic distribution of measured scintillation photon numbers for each energy deposition. For (a), we calculated the light output from the Sci-Fi by using Eq. (1) shown below which has been obtained by least square fitting of the data measured for a plastic scintillator (Saint-Gobain, BC-408)[15]

$$\mathrm{L[MeVee]} = 0.211\mathrm{E}_{\mathrm{proton}}^{1.342}. \tag{1}$$

Considering the response of the scintillation detector, namely, the phenomenon (b), we assumed the Gaussian distribution for the statistical distribution of the measured counts. In this assumption, the standard deviation (σ) is proportional to the square root of measured counts (N). If we assume that N is proportional to the electron equivalent energy deposition (E), σ can be written as follows:

$$\sigma = \mathrm{K}\sqrt{\mathrm{N}} = \mathrm{A}\sqrt{\mathrm{E}}. \tag{2}$$

Based on the above relationship, we accounted the energy resolution in the simulated energy deposition and compared with the measured values. Figure 11 shows the results by assuming the proportional constant (A) as 0, 0.05, 0.1, 0.15, and 0.2. From the results, if we assume A to be 0.15, the simulated distribution shows a similar tendency with the measured one in the energy range of above 5 MeV. However, in the lower energy region, the tendency is not the same. The measured pulse height is lowered by the two phenomena such as (a) low energy deposition because the proton was scattered to the direction with large angle to the Sci-Fi axis and (b) loss of scintillation photons during their transmission process to the PMT. As, in the current simulation, the phenomenon (b) is not considered, the simulated result does not show the same tendency with the measured one. To estimate the response of the Sci-Fi based system

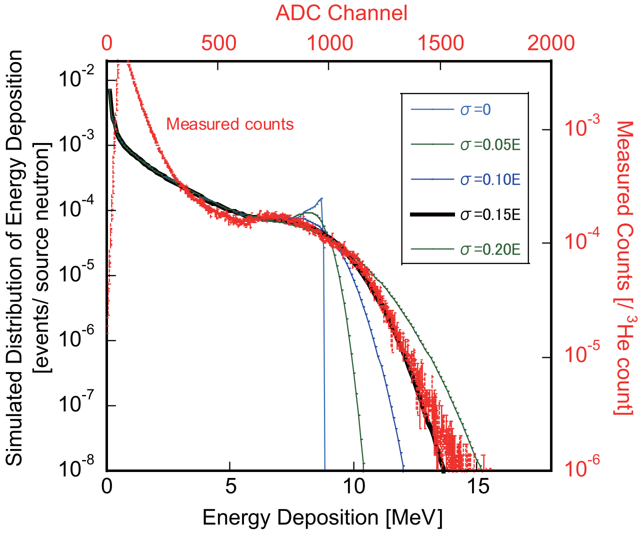

FIG. 11. Comparison of measured pulse height distribution and simulated electron equivalent energy deposition by PHITS for the 6 cm-long detector.

precisely, the transmission process of the scintillation photons should be considered in the simulation.

V. SUMMARY

To understand and enhance the properties of the Sci-Fi detector for triton burnup experiments, fundamental experiments and simulations have been carried out. From the results, it has been shown that the reflection condition at the hole surface where the Sci-Fi are set is important. In addition, it can be concluded that it is not necessary to make Sci-Fi detectors longer than 6 cm, as the 14 MeV neutrons are shielded by the Sci-Fi itself and the energy deposition at far positions from the PMT results in low pulse height due to scattering and absorption of scintillation photons in the transmission process to the PMT. The information will be beneficial to design Sci-Fi detectors to be used at the fusion experimental devices.

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