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High detection efficiency scintillating fiber detector for time-resolved measurement of triton burnup 14 MeV neutron in deuterium plasma experiment

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The behavior of the 1 MeV triton has been studied in order to understand the alpha particle confinement property in the deuterium operation of toroidal fusion devices. To obtain time evolution of the deuterium-tritium (D-T) neutron emission rate where the secondary DT neutron emission rate is approximately 10^{12} n/s, we designed two high detection efficiency scintillating fiber (Sci-Fi) detectors: a 1 mm-diameter scintillation fiber-based detector Sci-Fi1 and a 2 mm-diameter scintillation fiber-based detector Sci-Fi2. The test in an accelerator-based neutron generator was performed. The result shows that the directionality of each detector is 15° and 25°, respectively. It is found that detection efficiency for DT neutrons is around 0.23 counts/n cm^2 for the Sci-Fi1 detector and is around 1.0 counts/ n cm^2 for the Sci-Fi2 detector. *Published by AIP Publishing.* https://doi.org/10.1063/1.5032118

I. INTRODUCTION

In deuterium operation of toroidal fusion devices, the behavior of the 1 MeV triton created by the d(d,p)t reaction has been studied in order to understand the alpha particle confinement property because kinetic parameters of the 1 MeV triton such as Larmor radius and precession frequency are similar to those of DT born alpha particles.[1] In addition, unlike fast ions created by neutral beam injection and ion cyclotron resonance heating, the velocity distribution of the triton is isotropic, as is the case of alpha particles. A time-resolved triton burnup study has been performed by measuring secondary DT neutrons created by t(d,n)α using a scintillating fiber (Sci-Fi) detector in large tokamaks[2–4] and helical systems[5] with the typical deuterium-deuterium (DD) neutron emission rate (S_n) of 10^{15} n/s–10^{16} n/s. In these experiments, the triton burnup ratio in these machines is up to 1%, therefore, the 14 MeV neutron emission rate (S_{nDT}) is around 10^{13} n/s–10^{14} n/s. In medium size tokamaks, the time-integrated triton burnup ratio was successfully measured by the activation foil technique[6,7] and it is reported that S_{nDT} is 10^{11}–10^{12} n/s in KSTAR.[6] To obtain time evolution of the DT neutron emission rate under S_{nDT} of 10^{12} n/s order, we designed the high detection efficiency Sci-Fi detector having a diameter of 160 mm. The paper reports the design and the characteristics of the high detection efficiency Sci-Fi detector for measuring the time evolution of the DT neutron rate in deuterium plasma experiments.

II. DESIGN OF HIGH DETECTION EFFICIENCY SCINTILLATING FIBER DETECTOR

The high detection efficiency Sci-Fi detector shown in Fig. 1 is composed of a detector head, a light guide, and a photomultiplier (PMT). The diameter of the detector head is 160 mm, which is much larger than the diameter of the Sci-Fi detector head used in TFTR and JT-60U (35 mm).[2–4] The scintillating fibers (BCT-10) of 50 mm length are embedded into the aluminum substrate. We designed two detectors called Sci-Fi1 and Sci-Fi2 detectors equipped with different fiber diameters. In the Sci-Fi1 detector head, 5156 fibers a diameter of 1 mm are embedded, whereas 2248 fibers a diameter of 2 mm are embedded in the Sci-Fi2 detector head. The fibers are multi-stacked in a trefoil shape, and the minimum distance between the centers of the two fibers is 2 mm for the Sci-Fi1 detector and 3 mm for the Sci-Fi2 detector so that the minimum thickness of the aluminum substrate between the fibers is 1 mm in order to absorb unwanted recoiled protons and electrons. A tapered light guide made of Acryl (ACRYLITE-L #001) surrounded by a thin aluminum plate is used in order to focus the scintillation light to the 2-in. diameter PMT. Magnetic-resistant PMT having fine-mesh structure (H6614-70, Hamamatsu Photonics KK.) is chosen as the light detector to minimize the magnetic shield in order to be installed near the fusion device. The typical gain of the PMT is 10^7. The rise time and the

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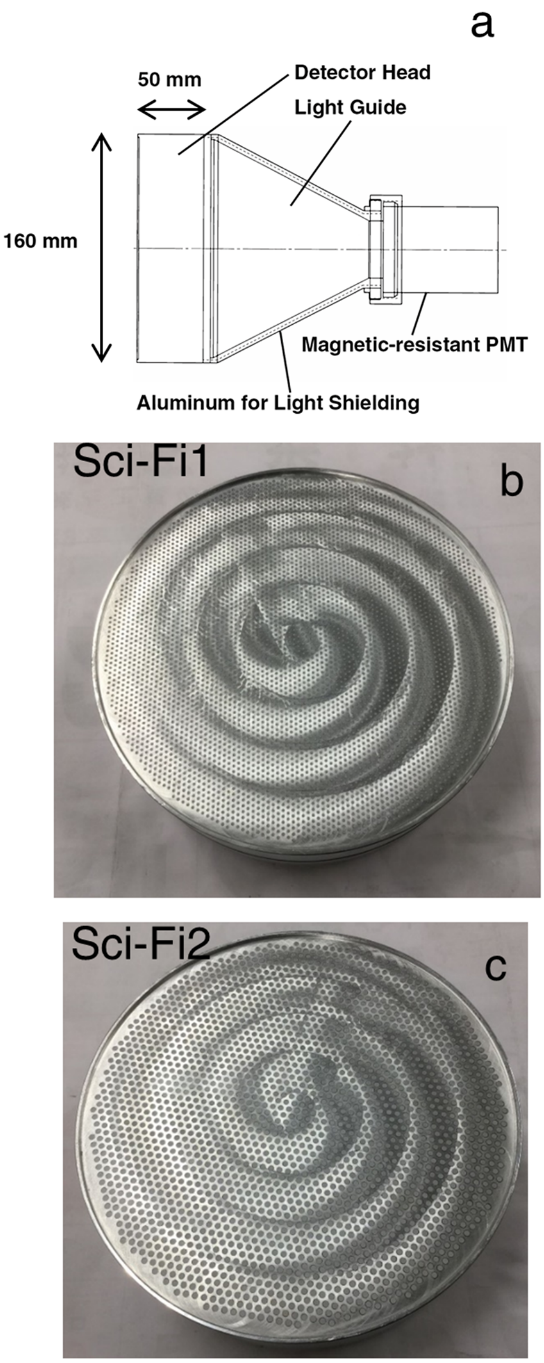

FIG. 1. (a) High detection efficiency scintillating fiber detector. (b) Detector head of the 1 mm-diameter scintillation fiber based Sci-Fi (Sci-Fi1) detector. (c) Detector head of the 2 mm-diameter scintillation fiber based Sci-Fi (Sci-Fi2) detector.

fall time of the PMT is 2.5 ns and 9.5 ns, respectively. The anode signal of the PMT is directly fed into the data acquisition system (APV8104-14MW, Techno AP Corp.) which is equivalent to the data acquisition system used for the vertical neutron camera in the Large Helical Device,[8] but it only has the function of offline analysis. The peak to peak voltage and bit resolution of the data acquisition system are 2 V and 14 bits, respectively, in this test. We acquired 64 points per pulse signal with the 1 GHz sampling rate and stored to the dynamic random access memory installed on the data acquisition board. After the measurement, all the data are transferred to the personal computer. The pulse height of each pulse is analyzed using the stored data offline. Note that the length of the signal cable is 30 m. A high voltage system (556, Ortec) is used to apply high voltage to the PMT.

III. TEST IN ACCELERATOR-BASED NEUTRON GENERATOR

The neutron measurements are performed in an accelerator-based neutron generator in the fast neutron laboratory (FNL)[9] in Tohoku University and the Intense 14 MeV Neutron Source Facility (OKTAVIAN)[10] in Osaka University. In FNL, measurements of DD neutrons are conducted, whereas measurements of DT neutrons are performed in OKTAVIAN. In both cases, accelerated deuteron beams are irradiated on the deuterium or tritium occlusion titanium target. In these experiments, the acceleration voltage of the deuteron beam and the typical neutron emission rate from the target are 1.5 MeV and 2.5×10^6 n/s for DD experiments and 250 keV and 10^8 n/s for DT experiments, respectively. Therefore, peak energies of DD and DT neutrons are around 3 MeV and 14 MeV, respectively. Note that the distance between the target and the detector is 220 mm for DD experiments and 850 mm for DT experiments. Here, a time trend of the neutron emission rate is measured by using a ^{3}He proportional counter with a 10 cm neutron moderator made of polyethylene calibrated by a ^{252}Cf source.

The dependence of PMT gain on the pulse height spectra is obtained in DT neutron measurements. We changed high voltage from 1100 V to 1450 V. We see the pulse when the applied voltage exceeds 1100 V. Note that the maximum applied voltage of the PMT is 2000 V. In this experiment, the angle formed between a beam line and normal vector of the detector surface was 15° and the Sci-Fi detectors are placed so that the center of the target is placed on the central axis of the detector. Pulse height spectra shown in Fig. 2 obtained in different high voltages are similar in shape, and maximum pulse height becomes greater along with the high voltage, as expected. The pulse height spectra have a characteristic shape at the height of 0.05–0.1 V. These are the typical pulse height spectra of Sci-Fi detectors. The appropriate high voltage can be chosen in order to change the sensitivity (pulse count per DT neutron flux) slightly according to this result. The angular dependence of pulse height spectra is obtained in DT neutron measurements. In this experiment, the angle of detectors is changed by means of the rotation stage from 0 to 90°. Here, the angle is defined by two lines. One is the straight line passing through the target center and the center of the detector head, and the other is the central axis of the detector. Note that the applied voltage to the PMT is 1300 V. Figures 3(a) and 3(b) show the typical pulse height spectra obtained with Sci-Fi1 and Sci-Fi2 detectors, respectively. The pulse height spectra have a characteristic shape at the height of 0.05–0.1 V when the angle is less than 60°. The characteristic shape disappears when the angle is greater than 60°. Figure 3(c) shows the normalized pulse counts as a function of the angle in each discrimination level. Here, pulse counts are normalized by the pulse counts obtained in the case of the angle of 0°. The directivity is better in the Sci-Fi1 detector compared with

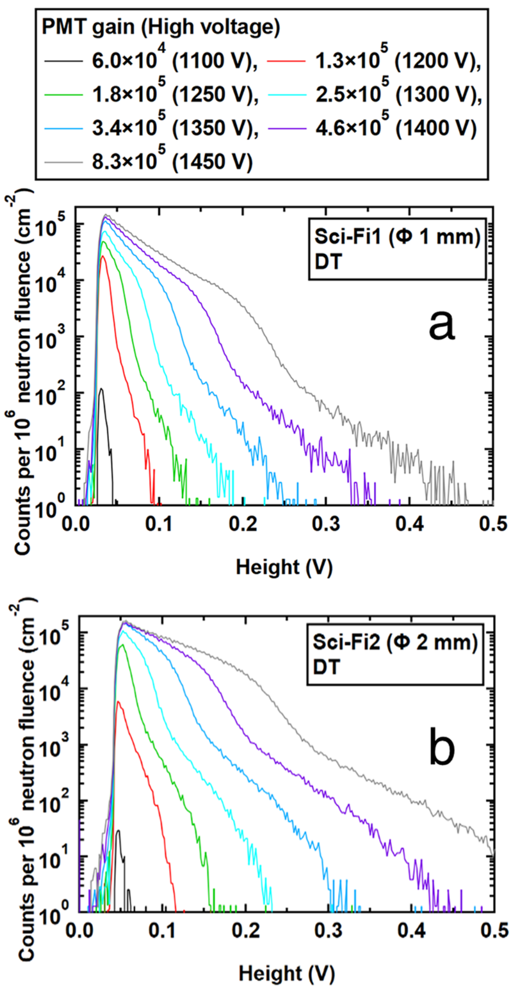

FIG. 2. Typical pulse height spectra obtained with different gain in the DT experiment performed in OKTAVIAN for (a) Sci-Fi1 and (b) Sci-Fi2 detectors. Here, applied high voltages are 1100 V, 1200 V, 1250 V, 1300 V, 1350 V, 1400 V, and 1450 V.

the Sci-Fi2 detector as expected by the diameter of scintillating fiber. Both Sci-Fi detectors have almost no directivity when the discrimination voltage is 0.05 V; however, the Sci-Fi detectors have directivity when the discrimination voltage is 0.10 V and 0.15 V. The half width at half maximum of directivity in the Sci-Fi1 detector and Sci-Fi2 detector is around 15° and 25°, respectively.

DD and DT neutron measurements are performed using Sci-Fi1 and Sci-Fi2 detectors with an angle of 0° and a high voltage of 1300 V. Figure 4(a) shows the typical waveform obtained by using the Sci-Fi1 detector. The typical pulse width is around 20 ns and the pulse height in the DT experiment is higher than that of the DD experiment, as expected. Figures 4(b) and 4(c) show the pulse height spectra obtained in these experiments with Sci-Fi1 and Sci-Fi2 detectors. Here, the applied voltage to the detector is 1400 V. Note that two components appear in the DD neutron measurement. The first component having the smaller pulse height corresponds to the signal induced by DD neutrons, and the second component corresponds to the signal induced by DT neutrons. DT neutrons are from the D beam and T existing in the titanium target created by the DD reaction. The larger number of pulses in the

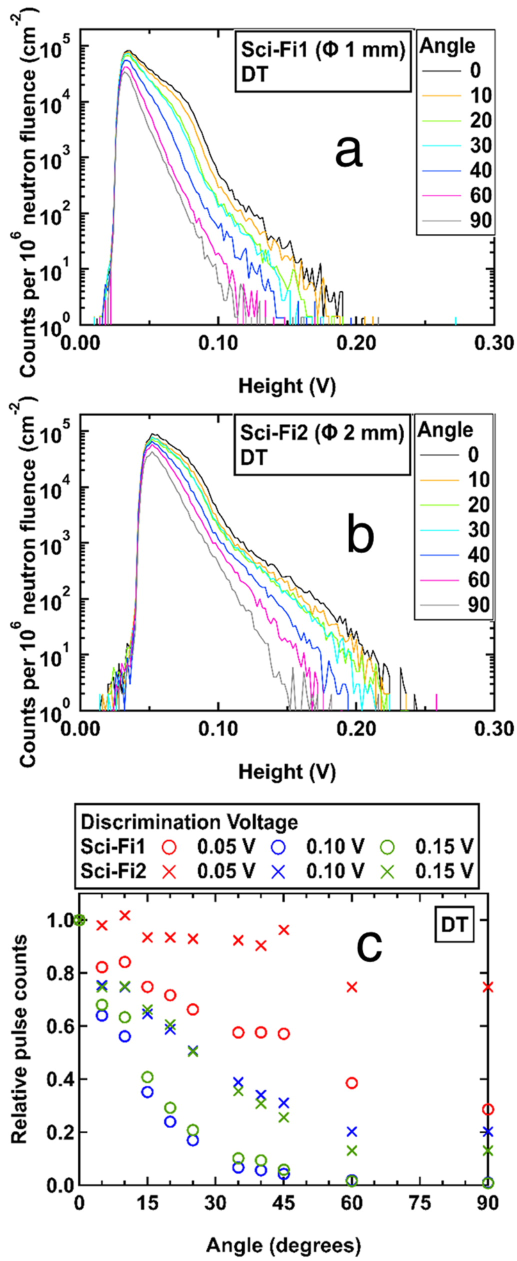

FIG. 3. Typical angle dependence of pulse height spectra of the (a) Sci-Fi1 detector and (b) Sci-Fi2 detector for DT neutrons. The applied voltages are 1300 V. The knee that appeared at around the height of 0.08 V becomes smaller as the angle increases. (c) Directionality of Sci-Fi detectors in different discrimination voltages for DT neutrons. The half width at half maximum of directivity is around 15° for the Sci-Fi1 detector and is 25° for the Sci-Fi2 detector when the discrimination level of 0.10 V or 0.15 V.

Sci-Fi2 detector shows that the Sci-Fi2 detector is more sensitive to neutrons and gamma-ray compared with the Sci-Fi1 detector. Note that the minimum pulse heights obtained with the Sci-Fi1 detector are smaller than those obtained with the Sci-Fi2 detector in the DT experiment. It supposed to be that minimum pulse would be created when recoiled proton moves perpendicular to the fiber. Therefore the minimum pulse height decreases with a fiber diameter. In the case of DD neutrons, the maximum pulse height was around 150 mV, whereas the maximum pulse height becomes 400 mV in the case of DT neutrons. Figure 4(d) shows the number of neutron counts per

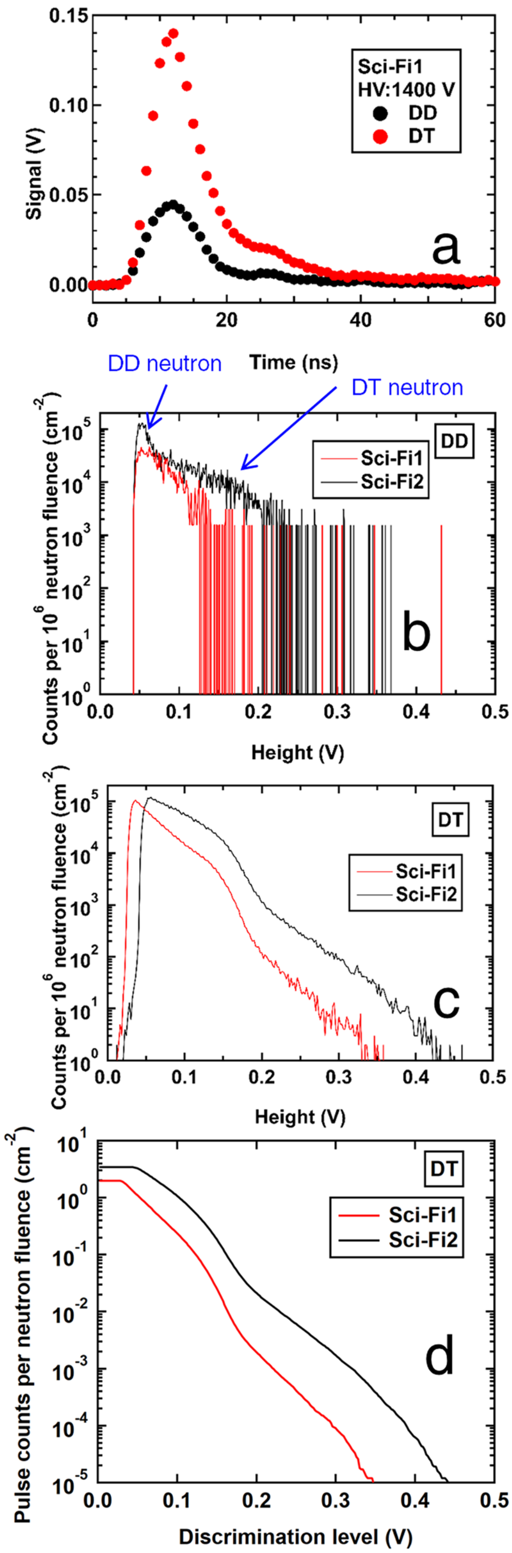

FIG. 4. (a) Typical waveform of a pulse obtained with the Sci-Fi1 detector. Pulse height spectra of Sci-Fi detectors (b) in the DD experiment performed in FNL and (c) in the DT experiment performed in OKTAVIAN. (d) Detection efficiency for DT neutrons as a function of the discrimination level.

DT neutron flux as a function of discrimination voltage. The detection efficiency of the Sci-Fi2 detector is around 4 times higher than that of the Sci-Fi1 detector when the discrimination voltage is set to be 0.1 V. Note that Sci-Fi1 will be favorable in a relatively high gamma-ray environment in order to reduce the gamma-ray effect, whereas in a relatively low gamma-ray environment, Sci-Fi2 will be favorable in order to obtain a higher DT neutron counting rate. The expected pulse counting rate of Sci-Fi1 and Sci-Fi2 detectors placed in the KSTAR torus hall is evaluated to be 2.8×10^4 cps and 1.2×10^5 cps, respectively, because the typical DT neutron flux in the torus hall is around 1.2×10^5 n s^{-1} cm^{-2} when S_{nDT} is 10^{12} n/s.[7]

IV. SUMMARY

To obtain the time evolution of the secondary DT neutron emission rate where the DT neutron emission rate is around 10^{12} n/s, we designed high detection efficiency scintillating fiber detectors embedded in the aluminum substrate. DD and DT neutron measurements are performed by using accelerator-based neutron generators in FNL and OKTAVIAN. For the pulse counting with a discrimination level of 0.1 V in the DT measurement, the directionality of the Sci-Fi1 detector and Sci-Fi2 detector is evaluated to be 15° and 25°, respectively. We found that typical detection efficiency against DT neutrons is 0.23 counts/n cm^2 for the Sci-Fi1 detector and 1.0 counts/n cm^2 for the Sci-Fi2 detector. This system will be installed to measure the time evolution of the 14 MeV neutron in a fusion device where the order DT neutron rate is around 10^{12} n/s.

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