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Scintillating fiber detectors for time evolution measurement of the triton burnup on the Large Helical Device

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Two scintillating fiber (Sci-Fi) detectors have been operated in the first deuterium plasma campaign of the Large Helical Device in order to investigate the time evolution of the triton burnup through secondary 14 MeV neutron measurement. Two detectors use scintillating fibers of 1 mm diameter embedded in an aluminum matrix with a length of 10 cm connected to the magnetic field resistant photomultiplier. A detector with 91 fibers was developed in the Los Alamos National Laboratory and has been employed on JT-60U. Another detector with 109 fibers has been developed in the National Institute for Fusion Science. The signals are fed into a discriminator of 300 MHz bandwidth with a pulse counter module for online measurement and a digitizer of 1 GHz sampling with 14 bits to acquire pulse shape information for offline data analysis. The triton burnup ratio has been evaluated shot-by-shot by the 14 MeV neutron measurement of Sci-Fi detectors which are calibrated by using the neutron activation system and the total neutron measurement of the neutron flux monitor using ^{235}U fission chambers. *Published by AIP Publishing.* https://doi.org/10.1063/1.5035290

I. INTRODUCTION

The Large Helical Device (LHD) is a large superconducting heliotron device in Japan, having a major radius of 3.9 m and an averaged plasma minor radius of ~0.6 m.[1] In the LHD, the deuterium plasma operation started in March 2017 to explore high-performance deuterium plasmas of LHD. There are two reactions D(d, n)^{3}He and D(d, p)T to produce 2.45 MeV neutrons and 1 MeV tritons in deuterium plasmas. The production rates of 2.45 MeV neutrons and 1 MeV tritons are almost the same. Energetic tritons will undergo secondary D-T reaction with background deuterons, while those tritons slow down. Kinematic properties such as the Larmor radius and the precessional drift frequency of 1 MeV tritons are almost the same as those of 3.5 MeV alphas in D-T plasmas. Therefore, the triton burnup study is useful to estimate the behavior of D-T born alphas in deuterium plasmas. To evaluate the absolute neutron yield from LHD deuterium plasmas, a wide dynamic range neutron flux monitor (NFM)[2] and a neutron activation system (NAS)[3] are employed in LHD.[4] The NFM on LHD consists of three ^{235}U fission chambers and three high-sensitivity thermal neutron detectors. The NFM plays a primary role in the evaluation of the total neutron yield. Although NAS does not provide the time evolution of the neutron emission rate, it is absolutely insensitive to gamma-rays and is of a great value for performing cross-check of the neutron yield evaluated by using NFM.[5,6] In the tokamaks such as TFTR,[7] JET,[8] ASDEX-U,[9] JT-60U,[10] DIII-D,[11] FT,[12] PLT,[13] and KSTAR,[14] neutron activation techniques have been applied to measure the shot integral primary 2.45 MeV neutron yields and secondary 14 MeV neutron yields in the deuterium plasmas. The scintillating fiber (Sci-Fi) detector has been developed by the Los Alamos National Laboratory (LANL) and was utilized for the time-resolved 14 MeV neutron measurement on TFTR[15] and JT-60U.[16] The Sci-Fi detector has a high counting rate capability (higher than 10^7 counts/s) and good discrimination characteristic for 2.45 MeV neutrons and gamma-rays; consequently, it is suitable for the time-resolved triton burnup measurement.

In the first deuterium campaign of LHD, two Sci-Fi detectors work for the time evolution of 14 MeV neutron measurement. Two detectors use scintillating fibers of 1 mm diameter embedded in an aluminum (Al) matrix with a length of 10 cm, which are connected to the magnetic field resistant photomultiplier tube (PMT) for signal output. A detector with 91 fibers was developed in LANL, which is named LANL Sci-Fi detector. Another detector with 109 fibers has been developed in the National Institute for Fusion Science (NIFS), which is named NIFS Sci-Fi detector. A new compact NIFS Sci-Fi detector and a Digital Pulse Processor (DPP) are described in Sec. II. Pulse height character and threshold effect on time evolution measurement are shown in Sec. III. Calibration of two Sci-Fi detectors by NAS measurement is given in Sec. IV. Finally, the operation of Sci-Fi detectors in this campaign is summarized in Sec. V.

II. EXPERIMENTAL SETUP

Figures 1(a) and 1(b) show the picture of the LANL Sci-Fi detector and the NIFS Sci-Fi detector. The NIFS Sci-Fi detector is a newly developed compact detector consisting of 109 fibers with a diameter of 1 mm and a length of 10 cm. The fibers were embedded into an aluminum matrix for stopping

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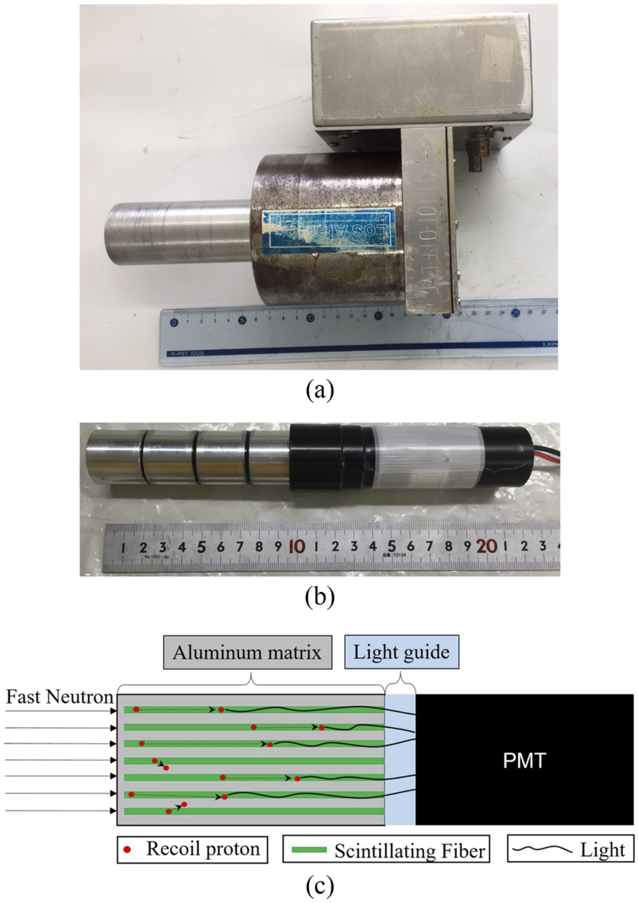

FIG. 1. (a) Overview of the LANL Sci-Fi detector with 91 fibers of 1 mm diameter and a length of 10 cm, (b) overview of the NIFS Sci-Fi detector with 109 fibers of 1 mm diameter and a length of 10 cm, (c) the principle of the Sci-Fi detector: the signal is induced by the energy of protons or electrons deposited on fibers; in other words, the signal cannot be produced when the protons or electrons induced by the incoming neutrons or gamma-rays run away from the fiber and are absorbed by the Al matrix. Note that the light guide is not used for the LANL Sci-Fi detector. The plastic plate was applied to connect the Al head of the LANL Sci-Fi detector and the PMT window.

recoil protons and electrons induced by 2.45 MeV neutrons and gamma-rays passing into the adjacent fiber to reduce the contribution from low-energy neutrons and gamma-rays, as shown in Fig. 1(c). The acryl plastic plate of 10 mm thickness is a light guide for the fiber and is an insulation layer for an aluminum matrix and a PMT window. The light output of the plastic plate induced by 2.45 MeV neutrons and gamma-rays is negligible which is confirmed by experiment using a 14 MeV neutron generator.[17] A magnetic resistant PMT assembly H6152-70 with a maximum divider current of 0.41 mA is used for signal output. H6152-70 consists of a magnetic resistant PMT R5505-70 and RC divider base. The gain of PMT R5505-70 is constant (5×10^5) at magnetic field of 0-0.25 T in the high voltage (HV) of 2000 V. In the LHD experiment, a soft iron collar with 5 mm thickness is around the PMT and a permalloy collar is placed inside the PMT assembly of the NIFS Sci-Fi detector to improve magnetic resistance. The total length of the detector is less than 22 cm. This compact Sci-Fi detector will be helpful for the development of a 14 MeV neutron camera.

The setup of detectors is shown in Fig. 2(a). The LANL Sci-Fi detector is located on the outside of the 8-O port, and the NIFS Sci-Fi detector is located on the outside of the 2.5-L port. The distance from the two detectors to the plasma center is around 4 m. The block diagram of electronics and DPP is also shown in Fig. 2(a). In the LHD experiment, the ORTEC 556 was used as a high voltage direct current power supply for Sci-Fi detectors. The anode signals of PMT are divided into two channels, which are directly fed into the DPP and the nuclear instrument module (NIM) in the basement by coaxial cables of 10 m and 20 m with an input impedance of 50 Ω for each detector, as shown in Fig. 2(a). The NIM module is employed for online measurement with a fixed threshold, which consists of a FAN-IN/FAN-OUT module, a discriminator of 300 MHz bandwidth, and a pulse counter. The DPP (model no. APV8102-14MWPSAGb) with 1 Mcps data throughput consists of two channel digitizers which include two analog-/time-to-digital converters (ADC/TDC) of 1 GHz sampling with 14 bit resolution and two constant fraction discriminators (CFD), a flash memory RAM of 1 GB (512 MB for each channel) for data storage, and the field programmable gate array (FPGA)

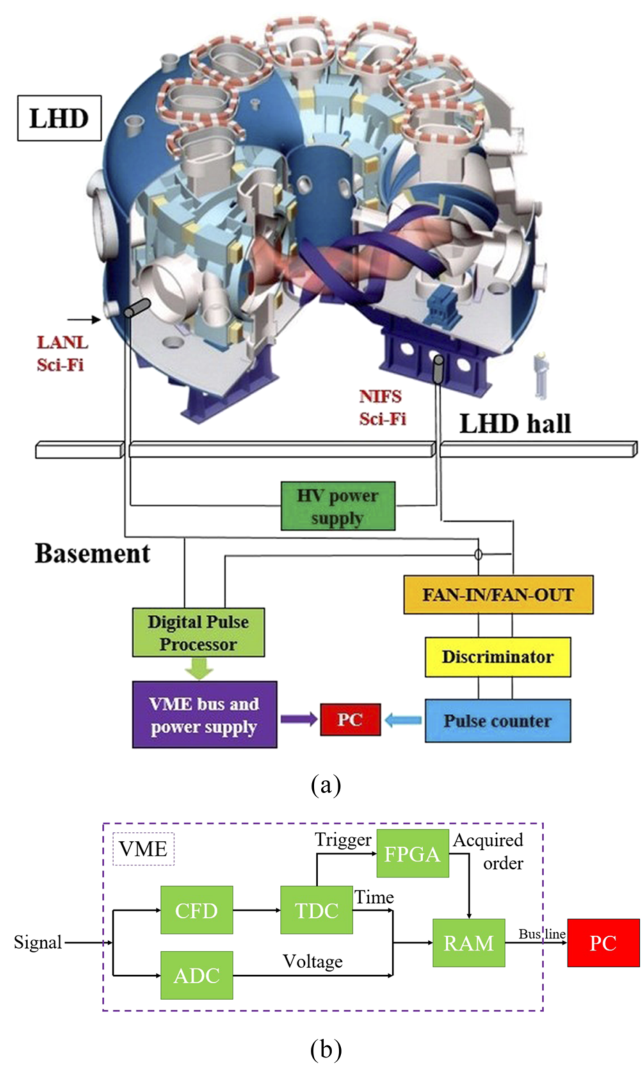

FIG. 2. (a) Experimental setup of Sci-Fi detectors and the block diagram of electronics and the data acquisition system and (b) the logic diagram of the DPP.

module for signal processing. The raw data (the shaping information of each pulse) have been used for offline analysis. The pulse height spectrum and time evolution of integral counts can be obtained.

Full pulse shape information for each pulse is recorded by the DPP, as shown in Fig. 2(b). A low level threshold was set in the digitizer to discriminate lower pulse height signals and noise. A pulse higher than this low threshold comes into the digitizer, and FPGA receives a trigger to start to record this pulse in 64 sampling points with 1 ns time bin, where 10 sampling points are before the trigger and 54 sampling points are after the trigger. Also the time stump of the trigger time is recorded. Here, the pulse width of the anode signal from the Sci-Fi detectors is 10–20 ns. The maximum voltage value of the pulse is picked up for pulse amplitude analysis, and pulse counts integrated in 1 ms where the pulse height is larger than the specific threshold can be picked for the time-resolved measurement.

III. PULSE HEIGHT CHARACTER AND THRESHOLD EFFECT ON TIME EVOLUTION MEASUREMENT

The pulse height spectra of the two Sci-Fi detectors have shown the same characteristic (two decay) in a high neutron yield shot, as shown in Fig. 3. In shot no. 141170, the neutron emission rate reaches 1.15×10^{15} n/s, where the line-averaged electron density is 1.5×10^{19} m^{-3}, and the central electron temperature is about 3 keV. The first decay of both spectra in the low pulse height region corresponds to the detector signal induced by 2.45 MeV neutrons and gamma-rays. The second decay in the higher pulse height region corresponds to the signal induced by 14 MeV neutrons.

Figure 4 shows the plasma parameter of shot no. 141170 and the comparison of the 14 MeV neutron emission rate measured by using the two Sci-Fi detectors with different thresholds. The two Sci-Fi detectors have shown the same time evolution of 14 MeV neutrons with the high threshold levels and the same influence by 2.45 MeV neutrons and gamma-rays

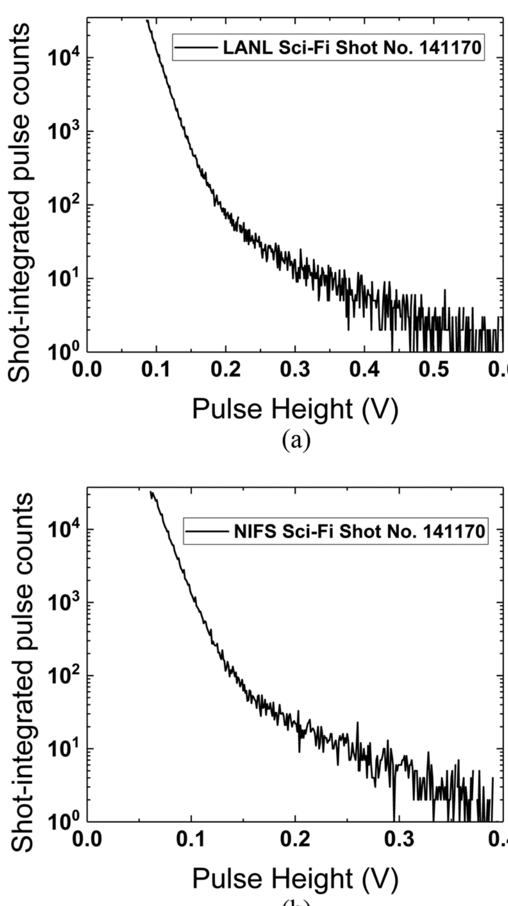

FIG. 3. (a) The pulse height spectra of the LANL Sci-Fi detector at PMT HV of −1700 V and (b) the pulse height spectra of the NIFS Sci-Fi detector at PMT HV of 2000 V.

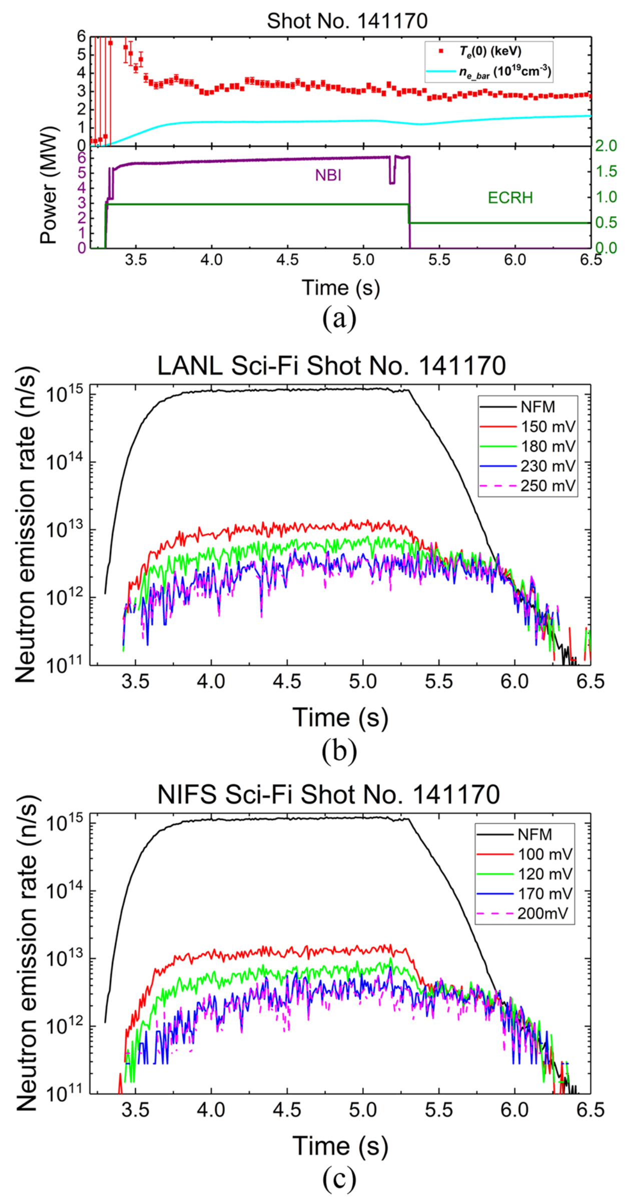

FIG. 4. (a) Plasma parameter of shot no. 141170, (b) comparison of the 14 MeV neutron emission rate measured by using the LANL Sci-Fi detector with different thresholds at PMT HV of −1700 V and the total neutron emission rate measured by using NFM, (c) comparison of the 14 MeV neutron emission rate measured by using the NIFS Sci-Fi detector with different thresholds at PMT HV of 2000 V and the total neutron emission rate measured by using NFM.

with the low threshold levels in the same shot. In addition to this, time evolution measurements of 14 MeV neutrons have shown the same tendency in two different high-threshold cases of each Sci-Fi detector, which means that the measurement of Sci-Fi detectors is not affected by 2.45 MeV neutrons and gamma-rays in the high-threshold case.

IV. CALIBRATION OF Sci-Fi DETECTORS BY NAS MEASUREMENT

Shot-integrated 14 MeV neutrons measured by using Sci-Fi detectors have been calibrated by the absolute 14 MeV neutron measurement of NAS, as shown in Fig. 5. The two Sci-Fi detectors show good linearity with thresholds of 250 mV and 170 mV. The absolute detection efficiencies for 14 MeV neutrons in the LHD experiment are evaluated to be 6.3×10^{-10} for the LANL Sci-Fi detector at PMT HV of −1700 V and 3.9×10^{-10} for the NIFS Sci-Fi detector at PMT HV of 2000 V. The triton burnup ratio can be evaluated shot-by-shot by the shot-integrated 14 MeV neutron yield measurement of Sci-Fi detectors calibrated by the absolute 14 MeV neutron measurement of NAS and the total neutron measurement of NFM.

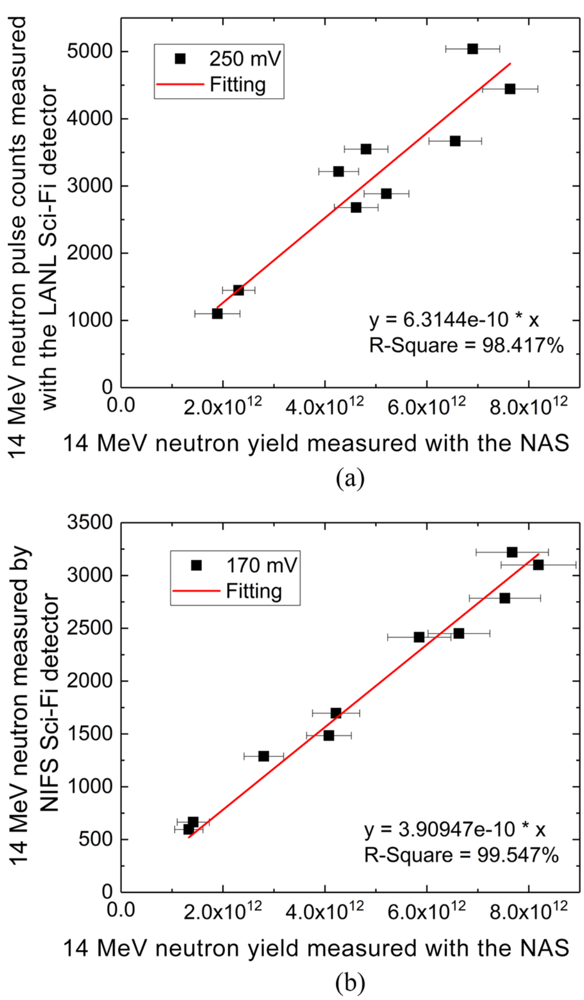

FIG. 5. (a) Shot-integrated 14 MeV neutron pulse counts measured with the LANL Sci-Fi detector at PMT HV of −1700 V as a function of 14 MeV neutron yield measured with calibrated NAS and (b) shot-integrated 14 MeV neutron pulse counts measured with the NIFS Sci-Fi detector at PMT HV of 2000 V as a function of 14 MeV neutron yield measured with calibrated NAS.

V. SUMMARY

In the first deuterium campaign of LHD, two Sci-Fi detectors successfully worked to measure the time evolution of the 14 MeV neutron emission rate for the triton burnup study. By using fast digitizers, the shaping information of each pulse was obtained for the offline analysis on the pulse height spectrum and the time evolution of 14 MeV neutrons. By using the digitizer data, the threshold for the time evolution of 14 MeV neutrons can be easily chosen, which is not achieved by using traditional NIM discriminators. By the calibration of shot-integrated 14 MeV neutron yield measured by using Sci-Fi detectors with the absolute 14 MeV neutron measurement of NAS, the triton burnup ratio has been evaluated shot-by-shot. In addition to this, the compact design for the NIFS Sci-Fi detector will be helpful for the development of a 14 MeV neutron camera in the future.

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[1] A. Iiyoshi, A. Komori, A. Ejiri, M. Emoto, H. Funaba, M. Goto, K. Ida, H. Idei, S. Inagaki, S. Kado, O. Kaneko, K. Kawahata, T. Kobuchi, S. Kubo, R. Kumazawa, S. Masuzaki, T. Minami, J. Miyazawa, T. Morisaki, S. Morita, S. Murakami, S. Muto, T. Mutoh, Y. Nagayama, Y. Nakamura, H. Nakanishi, K. Narihara, K. Nishimura, N. Noda, S. Ohdachi, N. Ohyabu, Y. Oka, M. Osakabe, T. Ozaki, B. J. Peterson, A. Sagara, S. Sakakibara, R. Sakamoto, H. Sasao, M. Sasao, K. Sato, M. Sato, T. Seki, T. Shimozuma, M. Shoji, H. Suzuki, Y. Takeiri, K. Tanaka, K. Toi, T. Tokuzawa, K. Tsumori, K. Tsuzuki, K. Y. Watanabe, T. Watari, H. Yamada, I. Yamada, S. Yamaguchi, M. Yokoyama, R. Akiyama, H. Chikaraishi, K. Haba, S. Hamaguchi, M. Iima, S. Imagawa, N. Inoue, K. Iwamoto, S. Kitagawa, J. Kodaira, Y. Kubota, R. Maekawa, T. Mito, T. Nagasaka, A. Nishimura, C. Takahashi, K. Takahata, Y. Takita, H. Tamura, T. Tsuzuki, S. Yamada, K. Yamauchi, N. Yanagi, H. Yonezu, Y. Hamada, K. Matsuoka, K. Murai, K. Ohkubo, I. Ohtake, M. Okamoto, S. Satoh, T. Satow, S. Sudo, S. Tanahashi, K. Yamazaki, M. Fujiwara, and O. Motojima, "Overview of the Large Helical Device project," Nucl. Fusion **39**, 1245 (1999).

[2] M. Isobe, K. Ogawa, H. Miyake, H. Hayashi, T. Kobuchi, Y. Nakano, K. Watanabe, A. Uritani, T. Misawa, T. Nishitani, M. Tomitaka, T. Kumagai, Y. Mashiyama, D. Ito, S. Kono, M. Yamauchi, and Y. Takeiri, "Wide dynamic range neutron flux monitor having fast time response for the Large Helical Device," Rev. Sci. Instrum. **85**, 11E114 (2014).

[3] N. Pu, T. Nishitani, M. Isobe, K. Ogawa, H. Kawase, T. Tanaka, S. Y. Li, S. Yoshihashi, and A. Uritani, "*In situ* calibration of neutron activation system on the large helical device," Rev. Sci. Instrum. **88**, 113302 (2017).

[4] M. Isobe, H. Yamanishi, M. Osakabe, H. Miyake, H. Tomita, K. Watanabe, H. Iwai, Y. Nomura, N. Nishio, K. Ishii, J. H. Kaneko, J. Kawarabayashi, E. Takada, A. Uritani, M. Sasao, T. Iguchi, Y. Takeiri, and H. Yamada, "Fusion product diagnostics planned for large helical device deuterium experiment," Rev. Sci. Instrum. **81**, 10D310 (2010).

[5] L. C. Johnson, C. W. Barnes, H. H. Duong, W. W. Heidbrink, D. L. Jassby, M. J. Loughlin, A. L. Roquemore, E. Ruskov, and J. D. Strachan, "Cross calibration of neutron detectors for deuterium-tritium operation in TFTR," Rev. Sci. Instrum. **66**, 894 (1995).

[6] C. W. Barnes, E. B. Nieschmidt, A. G. A. Huibers, L. P. Ku, R. W. Motley, and T. Saito, "Operation and cross calibration of the activation foil system on TFTR," Rev. Sci. Instrum. **61**, 3190 (1990).

[7] C. W. Barnes, H. S. Bosch, H. W. Hendel, A. G. A. Huibers, D. L. Jassby, R. W. Motley, E. B. Nieschmidt, T. Saito, J. D. Strachan, M. Bitter,

R. V. Budny, K. W. Hill, D. K. Mansfield, D. C. Mccune, R. Nazikian, H. K. Park, A. T. Ramsey, S. D. Scott, G. Taylor, and M. C. Zarnstorff, "Triton burnup measurements and calculations on TFTR," Nucl. Fusion **38**, 597 (1998).

[8]J. Källne, P. Batistoni, G. Gorini, G. B. Huxtable, M. Pillon, S. Podda, and M. Rapisarda, "Triton burnup measurements in JET using a neutron activation technique," Nucl. Fusion **28**, 1291 (1988).

[9]M. Hoek, H. S. Bosch, and W. Ullrich, "Triton burnup measurements at ASDEX upgrade by neutron foil activation," IPP-Report IPP-1/320, 1999.

[10]M. Hoek, T. Nishitani, M. Carlsson, and T. Carlsson, "Triton burnup measurements by neutron activation at JT-60U," Nucl. Instrum. Methods Phys. Res., Sect. A **368**, 804 (1996).

[11]H. H. Duong and W. W. Heidbrink, "Confinement of fusion produced MeV Ions in the DIII-D tokamak," Nucl. Fusion **33**, 211 (1993).

[12]P. Batistoni, M. Martone, M. Pillon, S. Podda, and M. Rapisarda, "Measurements of triton burnup in low q discharges in the FT tokamak," Nucl. Fusion **27**, 1040 (1987).

[13]W. W. Heidbrink, R. E. Chrien, and J. D. Strachan, "Burn-up of fusion-produced tritons and ^{3}He ions in PLT and PDX," Nucl. Fusion **23**, 917 (1983).

[14]J. Jo, M. Cheon, J. Kim, T. Rhee, J. Kim, Y. Shi, M. Isobe, K. Ogawa, K. Chung, and Y. Hwang, "Triton burnup measurements in KSTAR using a neutron activation system," Rev. Sci. Instrum. **87**, 11D828 (2016).

[15]G. A. Wurden, R. E. Chrien, C. W. Barnes, W. C. Sailor, A. L. Roquemore, M. J. Lavelle, P. M. O'Gara, and R. J. Jordan, "Scintillating-fiber 14 MeV neutron detector on TFTR during DT operation," Rev. Sci. Instrum. **66**(1), 901 (1995).

[16]T. Nishitani, M. Hoek, H. Harano, M. Isobe, K. Tobita, Y. Kusama, G. A. Wurden, and R. E. Chrien, "Triton burn-up study in JT-60U," Plasma Phys. Controlled Fusion **38**, 355 (1996).

[17]K. Ogawa, M. Isobe, T. Nishitani, E. Takada, H. Kawase, T. Amitani, N. Pu, J. Jo, M. Cheon, J. Kim, M. Miwa, S. Matsuyama, and I. Murata, "High detection efficiency scintillating fiber detector for time-resolved measurement of triton burnup 14 MeV neutron in deuterium plasma experiment," Rev. Sci. Instrum. **89**, 10I101 (2018).