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メタデータ	言語: eng
	出版者:
	公開日: 2021-07-13
	キーワード (Ja):
	キーワード (En):
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URL	http://hdl.handle.net/10655/00012567

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Time-resolved triton burnup measurement using the scintillating fiber detector in the Large Helical Device

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Abstract
Time-resolved measurement of triton burnup is performed with a scintillating fiber detector system in the deuterium operation of the Large Helical Device. The scintillating fiber detector system is composed of the detector head consisting of 109 scintillating fibers having a diameter of 1 mm and a length of 100 mm embedded in the aluminum substrate, the magnetic registrant photomultiplier tube, and the data acquisition system equipped with 1 GHz sampling rate analogies to digital converter and the field programmable gate array. The discrimination level of 150 mV was set to extract the pulse signal induced by 14 MeV neutrons according to the pulse height spectra obtained in the experiment. The decay time of 14 MeV neutron emission rate after neutral beam is turned off measured by the scintillating fiber detector. The decay time is consistent with the decay time of total neutron emission rate corresponding to the 14 MeV neutrons measured by the neutron flux monitor as expected. Evaluation of the diffusion coefficient is conducted using a simple classical slowing-down model FBURN code. It is found that the diffusion coefficient of triton is evaluated to be less than 0.2 m^2/s.

Introduction
Studies on energetic ion confinement have been intensively performed in magnetic confinement fusion devices to understand the confinement of fusion-born alpha particles [1]. Understanding of the behavior of 1 MeV tritons created by d(d,p)t reaction in deuterium plasmas provides a way to obtain better confinement of alpha particles because kinetic parameters of tritons such as Larmor radius and precession frequency are the same as those of alpha particles [2]. In addition, the distribution of tritons on the velocity space is isotropic as is the case of alpha particles. Triton confinement studied by means of

d(t,n)^{4}He reaction has been performed in tokamaks [3-10]. Sufficient number of 14 MeV neutrons can be measured if the energy of 1 MeV triton decreases due to slowing down around the peak of the cross section of d(t,n)^{4}He reactions that is at around 100 keV. Time-resolved triton burnup study has been conducted in large tokamaks by means of silicon diodes and scintillating fiber detectors [3, 4, and 9]. They found that the diffusion coefficient of tritons evaluated by comparing the experimental results and the simple code is around 0.1 m^2/s. In stellarators and helical devices, deuterium experiment was initiated in the Large Helical Device (LHD) in 2017. The expected neutron emission rate reaches an order of 10^{16} n/s which is the same order as deuterium experiments in large tokamaks [11]. The numerical simulation performed in advance by the five-dimensional drift kinetic equation code (GNET) shows the possibility of triton burn up study in LHD [12]. In this paper, the time-resolved triton burnup measurement by means of the scintillating fiber detector in the LHD is reported.

Experimental setup

An experiment was performed in LHD having a major radius/minor radius of 3.9 m/~0.6 m. The LHD is equipped with the high-power electron cyclotron heating system (ECH) whose injection powers up to 5 MW and three negative-ion-based tangentially-injected neutral beams (NNB) having an acceleration voltage of around 180 keV and total injection power of up to 15 MWs. The absolutely calibrated primary fission chamber (FC) which is the part of the neutron flux monitor [13] installed on the central axis of the LHD is utilized to measure the total neutron emission rate (S_n). The radial profiles of electron temperature and electron density are determined by Thomson scattering diagnostics [14], the millimeter wave interferometer is used to measure line-averaged density [15], and the stored energy of plasma is measured by diamagnetic loop [16]. Figure 1 shows the scintillating fiber detector system installed on the LHD. The detector is composed of the detector head, an acryl plate, and a photomultiplier tube (PMT). The 109 fibers having diameter ϕ of 1 mm and a length of 100 mm (SCSF-78M, Kuraray Co. Ltd.) are embedded in the aluminum substrate of the detector head. The neutron arriving on the fiber axis can make the largest pulse height. The pulse height discrimination technique is used to extract pulses induced by 14 MeV neutrons incoming along the fiber. The function of the aluminum substrate is to avoid the escaping recoil protons produced by fast neutrons and Compton electrons created by gamma-rays going into other fibers. Acryl plate having 10 mm thickness is for applying the high voltage to the PMT. The magnetic registrant PMT (H6152-70, Hamamatsu Photonics K.K.) is chosen so as to reduce the weight of the magnetic shielding consisting of Iron having a thickness of 3 mm and a length of 200 mm.

Note that the magnetic field strength on the detector position is around 100 mT. The anode signal of PMT is directly fed into the data acquisition system (DAQ) whose input impedance is 50 ohms (APV8102-14MWPSAGb, Techno AP Co. Ltd.). The DAQ consists of 1 GHz sampling analog-to-digital converter (ADC) and the field programmable gate array is developed for the vertical neutron camera in the LHD [17]. The DAQ stores the trigger time, 1 GHz sampled data within 64 ns, and shaping parameter of each pulse. In this experiment, the 1 GHz sampled pulse data is used for the pulse height discrimination. The high voltage to the PMT is applied by the externally-controllable high-voltage-system through the Ethernet (APV3304, Techno AP Co. Ltd.). Note that the cable length from the detector to the data acquisition system or the high voltage system is 30 m in order to avoid the irradiation effect on DAQ and the high-voltage-system [18].

Experimental results

Time-resolved measurement of triton burnup is performed in the ECH and NNB heated deuterium plasma (Fig.2). The plasma is initiated and sustained with ECH and NNB is injected to produce sufficient tritons inside the deuterium plasma. Note that NNBs are turned off at t of 5.3 s in order to see the decay of 14 MeV neutrons clearly. The central electron temperature (T_{e0}) is around 4 keV, n_{e_av} is around 1×10^{19} m^{-3}, and plasma stored energy is around 100 kJ. Figure 3 shows the pulse height spectra measured with the scintillating fiber detector in this discharge. There are two components on the pulse height spectra. The first component mainly corresponds to the pulse signal induced by gamma-ray or relatively low-energy neutron whereas the other component corresponds to the pulse induced by 14 MeV neutrons. We decide the discrimination level of 150 mV to extract 14 MeV neutrons-induced pulses counting rate ($C_{n\mathrm{DT}}$). The time evolution of FC signal shows that S_n decays with two components. The first component is due to slowing down of energetic deuteron and the second component is due to the slowing down of triton (Fig.4 a). Note that the decay time of S_n and C_{nDT} almost matched as expected. Time evolution of C_{nDT} is compared with the second decay of S_n in order to obtain the detection efficiency of the scintillating fiber detector to convert from C_{nDT} to total neutron emission rate of 14 MeV neutrons (S_{nDT}). We obtained the detection efficiency of 3.5×10^{10} n/counts. Figure 4 b shows the time evolution of injection power of NNB, S_n, and S_{nDT}. The figure shows that S_{nDT} increases and decreases slowly compared with S_n, which can be explained by the difference between DD and DT cross section.

Evaluation of Triton diffusivity

To understand triton diffusivity, the time evolution of 14 MeV neuron emissivity is simulated by FBURN code (Fig. 5) which is upgraded version of the TBURN code [9]. The code mainly calculates the 14 MeV neutron emissivity by a simple classical slowing-down model. Energetic ions are assumed to be slowed down in each shell according to the classical energy loss theory [19]. In this calculation, the plasma is divided into 120 circular shells and each volume is given according to the equilibrium reconstruction by VMEC2000 code [20]. Here, the equilibrium is reconstructed every 50 ms and slowing down and the nuclear reaction are calculated every 2 ms. Note that reactivity between Maxwellian and the mono energetic fast ion is given from Ref. [21]. Z_{eff} is assumed to be 2 and hydrogen to deuterium ratio and hydrogen to helium ratio are specified from Hα, Dα, and He line ratio [22]. To obtain the triton birth profile, the radial profile of the beam-plasma reactivity is calculated because tritons are mainly created by beam-plasma reactions in NNB-heated LHD plasma. Here, beam deposition profile is calculated using the HFREYA code [23]. By means of calculated radial profile of triton birth, triton slowing down and DT reaction rate are calculated. Here, radial diffusion of tritons is considered. Diffusion coefficient is assumed to be constant in radius and unchanged in time. The time bin of the triton diffusion calculation is 10 microseconds to avoid the divergence of the diffusion calculation. Figure 6 shows the experimentally obtained time evolution of S_{nDT} and S_{nDT} calculated by FBURN with diffusion coefficients (D^*) of 0.0 m^2/s, 0.1 m^2/s, and 0.2 m^2/s, respectively. Here, calculated S_{nDT} is normalized at t of 5.3 s when NNB is turned off. Note that the rise time of S_{nDT} becomes longer with the decrease of D^* because 1 MeV triton reaches the peak of DT cross section more slowly in the case of small D^*. Delay of S_{nDT} peak according to D^* decrease also supports that longer slowing time of triton in the case of small D^* compared with large D^*. It is found that the time trend of the DT neutron emission rate with D^* of less than 0.2 m^2/s gives good agreement with the experimental results, which is the same order as obtained in large tokamaks [8, 9].

Summary

Time-resolved measurement of triton burnup is performed in the LHD. A scintillating fiber detector equipped with the high-speed DAQ is utilized to measure time trend of S_{nDT}. Measurement of time evolution of S_{nDT} is performed in ECH plasma with NNB injections. The discrimination level to extract pulses induced by DT neutron is set to be 150 mV according to the pulse height spectra. The detection efficiency of the scintillating fiber detector is obtained by comparing C_{nDT} and the second decay of S_n measured by NFM corresponding to the DT neutron emission rate. D^* of triton is evaluated by means of a simple classical slowing down model. It is found that D^* of triton is evaluated to be less than 0.2 m^2/s.

Acknowledgments
This work is supported partly by LHD project budgets (ULHH003 and ULHH034).

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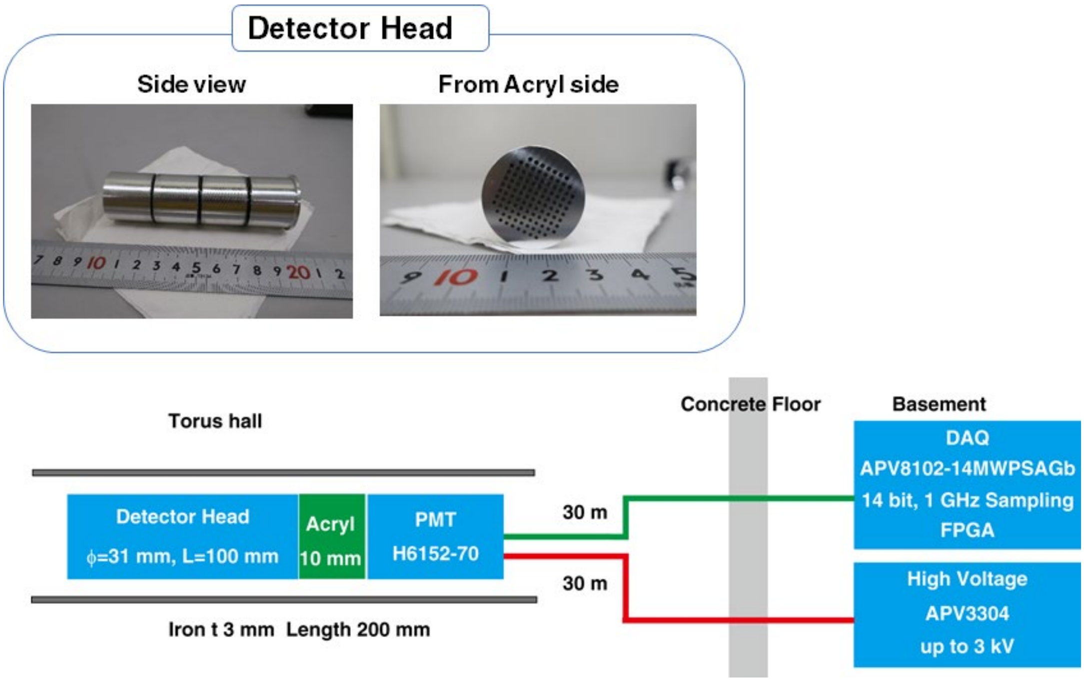

Fig1. Scintillating fiber detector system installed in LHD. The detector head consists of 109 fibers having diameter ϕ of 1 mm and a length of 100 mm embedded into aluminum substrate.

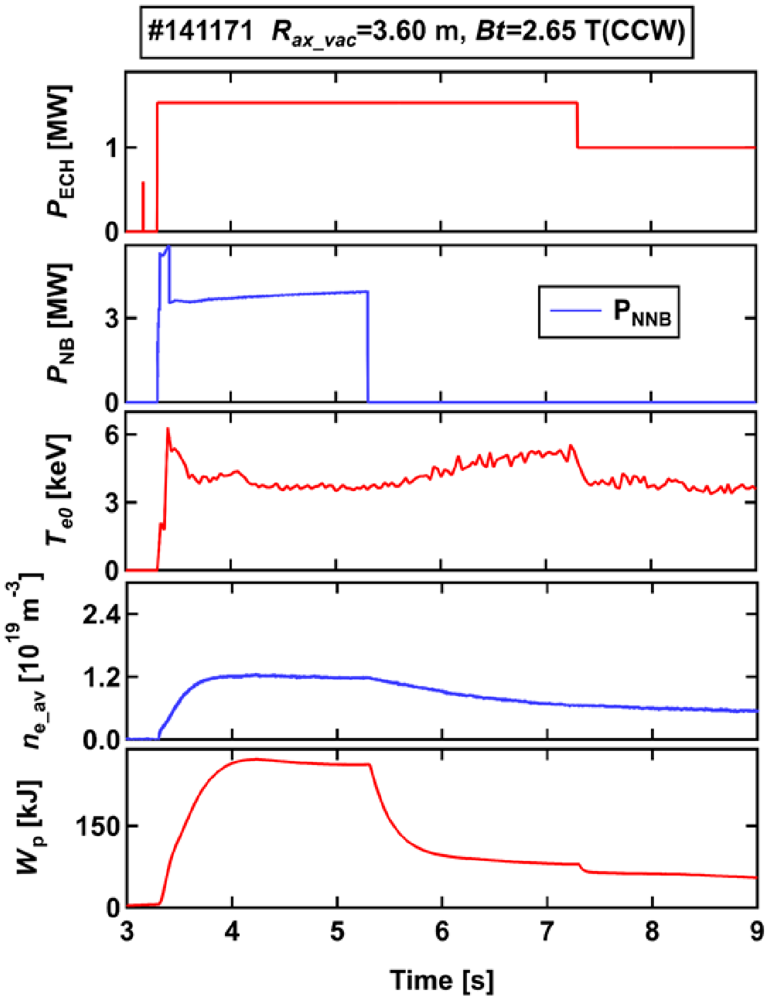

Fig.2 Time evolution of ECH power, NB power, central electron temperature, line-averaged density, and stored energy of the discharge where time resolved measurement of triton burnup is performed.

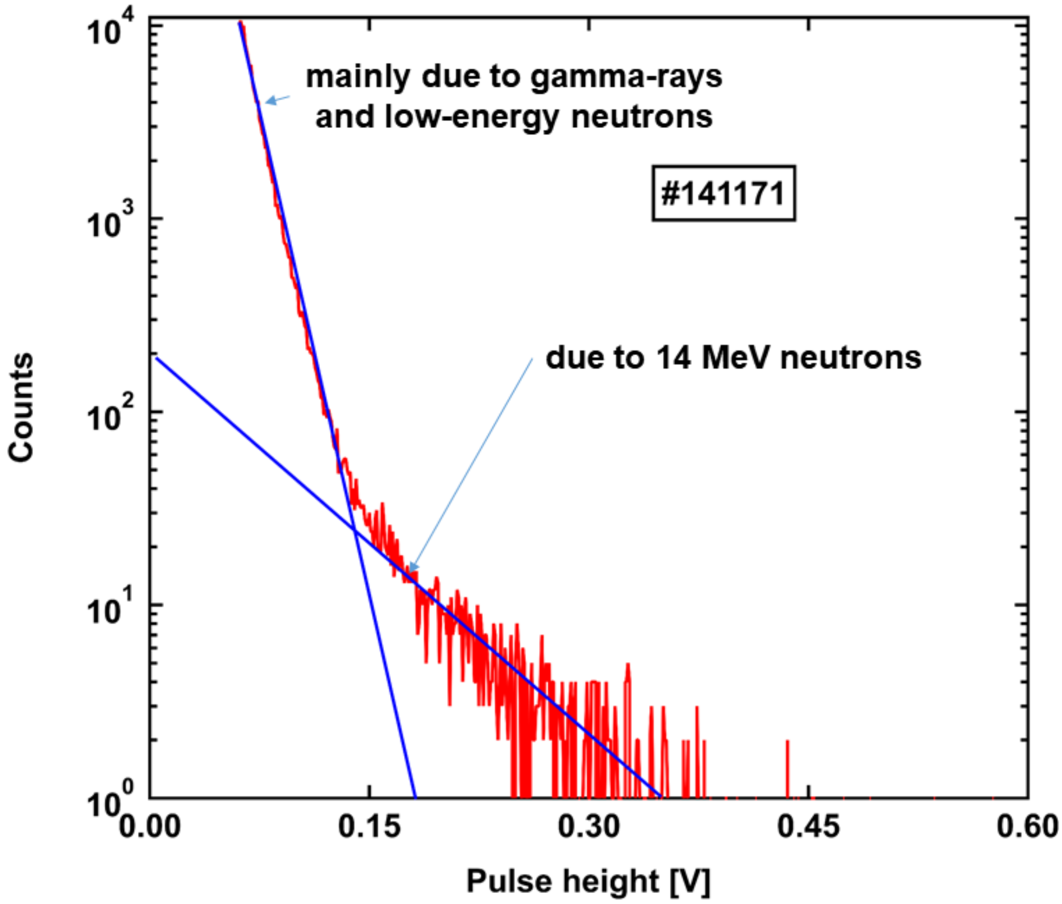

Fig.3 Pulse height spectra of scintillating fiber detector signal on shot number of 141171. A second component corresponding to pulses created by 14 MeV neutrons.

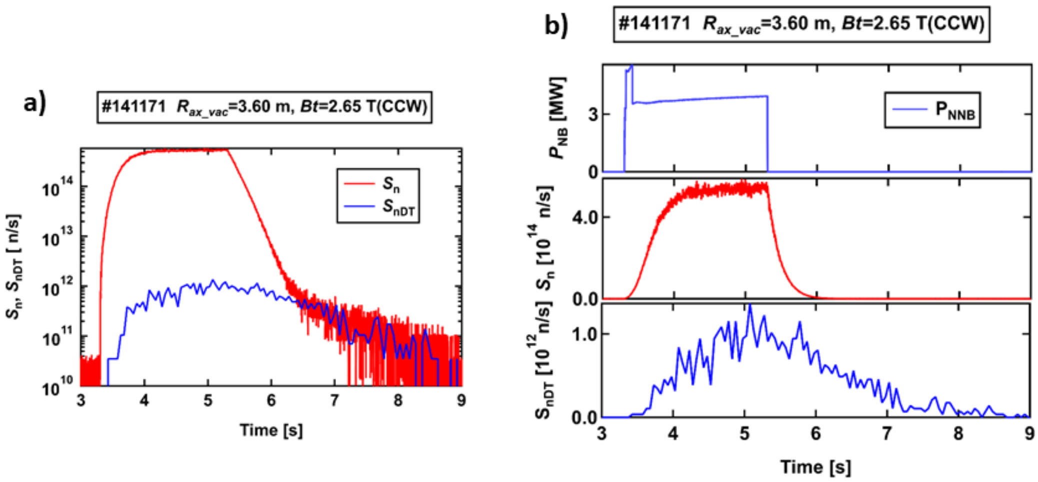

Fig.4 (a) Time evolution of S_n measured by NFM and S_{nDT} measured by the scintillating fiber detector. The absolute value of S_{nDT} is evaluated by comparing the scintillating fiber signal and the second decay component of NFM. (b) Time evolutions of P_{NB}, S_n, and S_{nDT}. Rise and slowing times of S_{nDT} are longer than that of S_n, which comes from the difference of a cross section of DD and DT cross section.

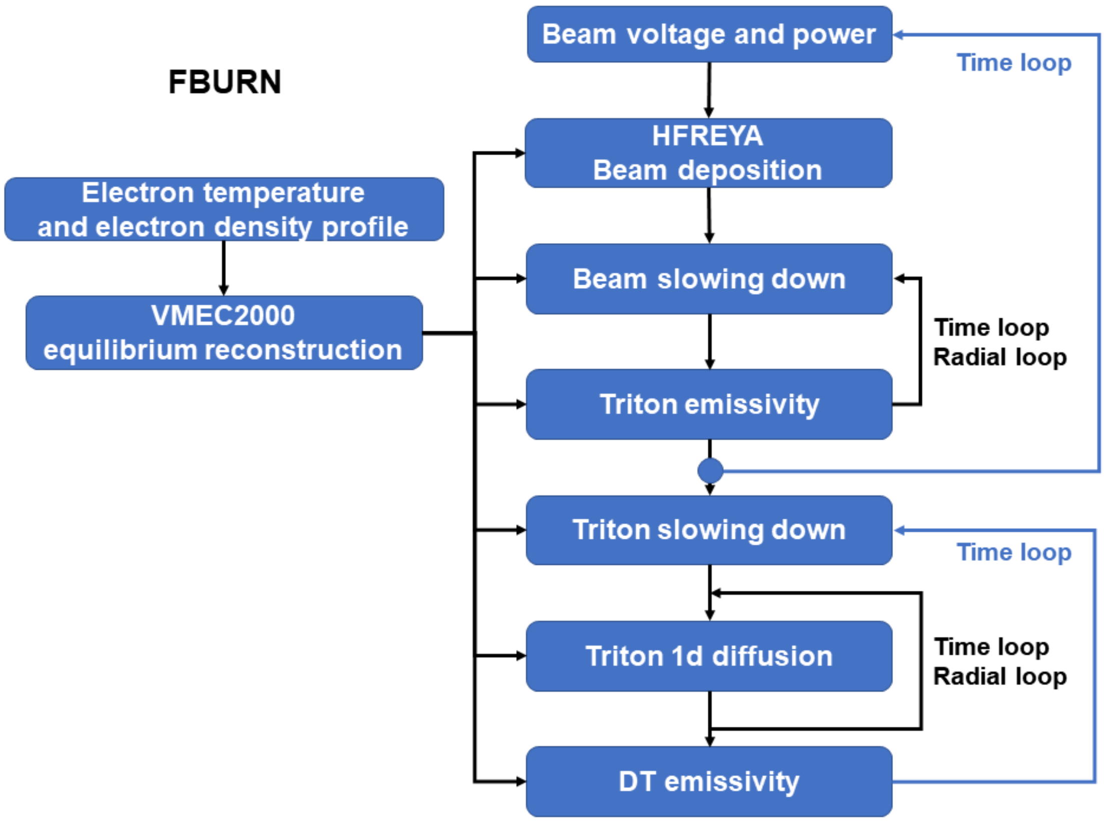

Fig.5 Block diagram of FBURN code.

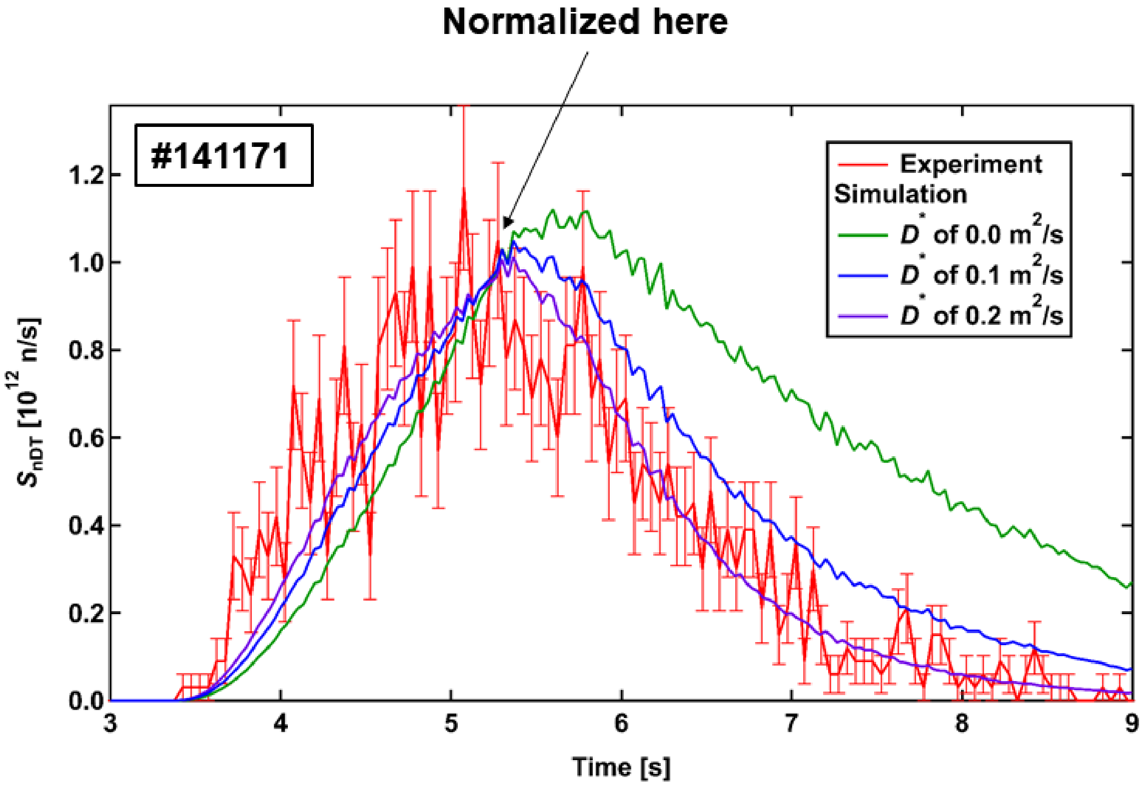

Fig. 6 Experimentally obtained S_{nDT} and S_{nDT} calculated by FBURN code with different diffusion coefficient (D^* of 0.0 m^2/s, 0.1 m^2/s, and 0.2 m^2/s). Here, calculated S_{nDT} is normalized at t of 5.3 s where NNBs are turned off. It is found that D^* of triton is less than 0.2 m^2/s in this discharge.