Neutron Flux Measurement Using a Fast-Neutron Scintillation Detector with High Temporal Resolution on the Large Helical Device[*)]

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To obtain rapid change of the neutron emission rate caused by magnetohydrodynamic (MHD) instabilities, measurements of the neutron flux with the high temporal resolution are made on the Large Helical Device (LHD) with a fast-neutron scintillation detector called neutron fluctuation (NF) operated in current modes. The time response of this detector is up to 5 microseconds. We checked the unwanted signal level caused by neutrons/gamma-rays inside the PMT. The intensity of the unwanted signal was negligibly small compared with the intensity of the scintillation signal as expected. The signal of NF has linear dependence with total neutron emission rate measured by neutron flux monitor in MHD quiet discharges. Rapid decreases of the neutron flux associated with bursting MHD modes excited in a neutral-beam-heated LHD plasma are observed with NF. We found that the neutron flux rapidly decreases within 2 ms.

Keywords: neutron flux measurement, fast neutron detector, the Large Helical Device, deuterium discharge

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1. Introduction

Research on energetic ion physics has been intensively performed in the Large Helical Device (LHD) [1]. In the hydrogen experiment in LHD, the study was performed mainly with the neutral particle analyzer and the scintillator-based lost-fast ion probe [2–4]. It is reported that energetic-ion-driven magnetohydrodynamic (MHD) modes such as toroidal Alfvén eigenmodes or energetic particle modes, and pressure driven MHD mode such as resistive interchange modes cause energetic ion loss within sub-millisecond order [5]. However, it is difficult to obtain the information of the energetic ion confinement directly in the core region of plasmas because the neutral particle analyzer and the scintillator-based lost-fast ion probe only can measure energetic particles escaping from the plasma. Deuterium experiment in the LHD was initiated in 2017 [6]. In neutral-beam-heated deuterium LHD plasmas, neutrons are mainly created by beam-plasma reactions. Therefore, expanding the energetic ion physics is expected by means of neutron measurements. For example, total neutron emission rate ($S_{\rm n}$) reflects the global confinement of energetic ions, a neutron emission profile has information of the radial profile and the radial transport of energetic ions, and neutron energy spectra have the information of a distribution function of energetic ion in the velocity space [7]. This paper shows the installation of the scintillation-detector-based neutron flux diagnostics characterized by the high temporal resolution compared with the neutron flux monitor to measure time evolution of neutron flux for studying global energetic ion transports due to MHD events occurred in sub-millisecond order.

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2. Experimental Setup

The LHD is one of the largest helical devices in the world with the average minor and major radii of 0.60 m and 3.90 m, respectively [8]. Three tangentially injected relatively high energy (up to 180 keV) neutral beams (NNBs) and two perpendicularly injected relatively low energy (up to 80 keV) neutral beams (PNBs) are available on the LHD. Those high power neutral beam injections (NBs) generate energetic ions in LHD plasmas. The absolutely calibrated neutron flux monitor (NFM) is utilized to measure $S_{\rm n}$ [9, 10]. Note that because the NFM calculates $S_{\rm n}$ with 0.5 ms time bin and eight ensemble averages, the time response of the NFM is similar to that of analogue circuits having time response of 2 ms. Electron temperature in the plasma core ($T_{\rm e0}$) is provided by the Thomson scattering diagnostics [11]. The line-averaged density ($n_{\rm e\_av}$) is measured with a multichannel far-infrared laser interferometer [12]. The magnetic fluctuation amplitude is measured by the Mirnov coil placed on the vacuum vessel [13].

A fast-neutron scintillation detector with high tempo-

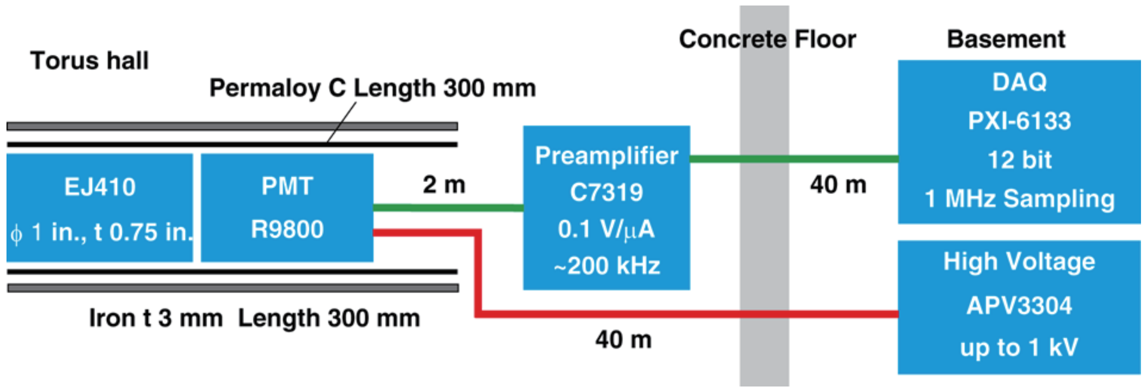

Fig. 1 Block diagram for fast-neutron scintillation diagnostics.

ral resolution (NF) is installed on the LHD. Figure 1 shows the block diagram of NF systems. The system consists of the fast-neutron scintillator (EJ410, Eljen Technology), the 1 inch diameter photomultiplier (R9800, Hamamatsu Photonics K.K.), the current amplifier (C7319, Hamamatsu Photonics K.K.) and the data acquisition system (PXI-6133, National Instruments). The high voltage for PMT is supplied by high voltage power supply (APV3304, Techno-AP Co. Ltd.) which is characterized by external controllability through the local area network. The size of the scintillator is 1 inch diameter and 0.75 inch thickness. The advantage of this scintillator is that it is almost insensitive to gamma-ray and low energy (< 1 MeV) neutron. The scintillator is directly coupled with the PMT. The length of magnetic shield consisting of iron and Permaloy C is 300 mm so as to avoid the effect on the relatively strong magnetic field on the PMT. Note that the magnetic field strength at the detector position is around 100 mT. Here, the lengths of the signal cable (3D-FB) between the PMT and the current amplifier is 2 m in order to reduce the electromagnetic noise and that between current amplifier and data acquisition system is 40 m to avoid the irradiation effect on the data acquisition system. The gain and frequency responses of current amplifier are 0.1 V/μA and 200 kHz, respectively. The bit resolution, peak-to-peak voltage, and the sampling frequency of the data acquisition system is 12 bits, 10 V, and 1 MHz, respectively.

It is reported that the neutron and gamma-ray irradiation makes the significant signal by the secondary electron generated inside the PMT in middle sized tokamaks [14] where neutron emission rate is almost one or two order smaller than that of the LHD. Therefore, the unwanted signal level caused by neutrons/gamma-ray inside the PMT is checked because NF placed near the LHD vacuum vessel which is the high radiation (neutron and gamma-ray) flux areas. Note that expected maximum neutron flux at the detector position is 10^9 n/cm^2 [15]. A NF without EJ410 scintillator called bare PMT is installed next to the NF and the signals from the NF and the bare PMT are compared. Note that the gains of two PMTs are adjusted by controlling the high voltage. Figure 2 shows the time evolutions of S_n, the NF signal, and the bare PMT signal. The signal from the bare PMT is almost three orders smaller than that of the NF signal. Hence, the intensity of the signal caused by neutrons and gamma-ray inside the PMT is negligibly small compared with that of the scintillation signal.

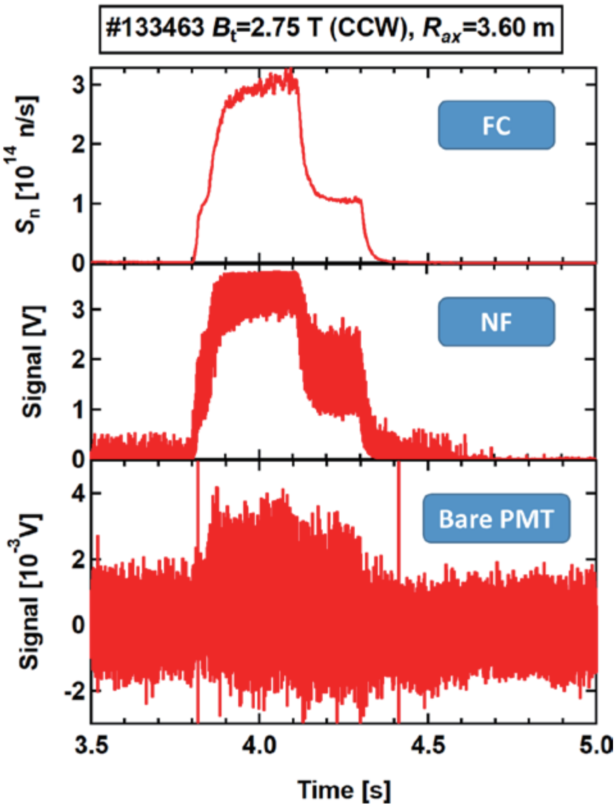

Fig. 2 Time evolutions of S_n, NF signal, and bare PMT signal. The signal caused in PMT by neutron/gamma-ray is three orders smaller than that of the scintillation signal.

3. Experimental Results

Measurement of the neutron flux by means of the NF were performed in relatively high S_n and MHD quiet dis-

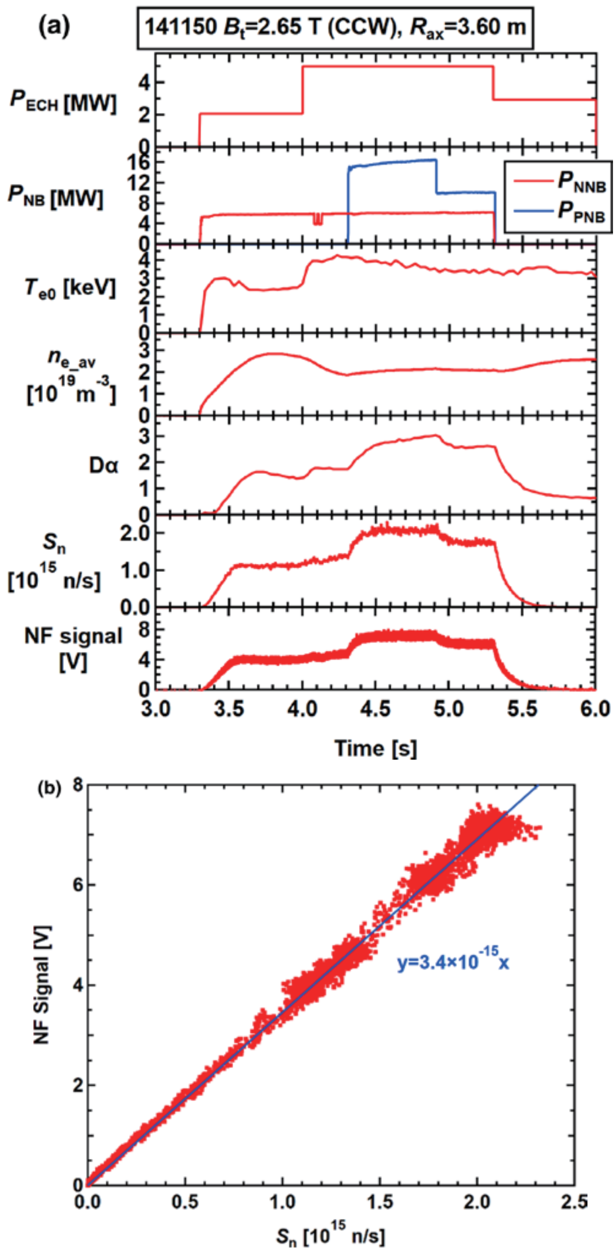

Fig. 3 (a) Time evolution of injection powers of ECH and NBI, T_{e0}, n_{e_av}, Dα, S_n, and NF signal on the MHD quiet discharge. (b) Relation between S_n and NF signal. NF signal linearly increases with S_n.

charges in a magnetic configuration with toroidal magnetic field strength (B_t) of 2.65 T (direction of toroidal field is counterclockwise from the top) and a preset magnetic axis position (R_{ax}) of 3.60 m. Figure 3 (a) shows time evolutions of the injected powers of ECH (P_{ECH}) and NB (P_{NB}), T_{e0}, n_{e_av}, Dα signal, S_n, and NF signal. During this discharge, S_n of 2.2×10^{15} n/s is achieved with intensive ECHs and NBs heating. Here all NBs injects deuterium beams. NF signal increases from t of around 4.3 s along with S_n due to the PNB injection. Figure 3 (b) shows the relation between NF signal and S_n. The NF signal has a linear dependence with S_n as expected. Note that the conversion factor of NF signal to S_n can be evaluated with the inverse of the gradient of linear fitting of 2.9×10^{14} n/s/V in this discharge.

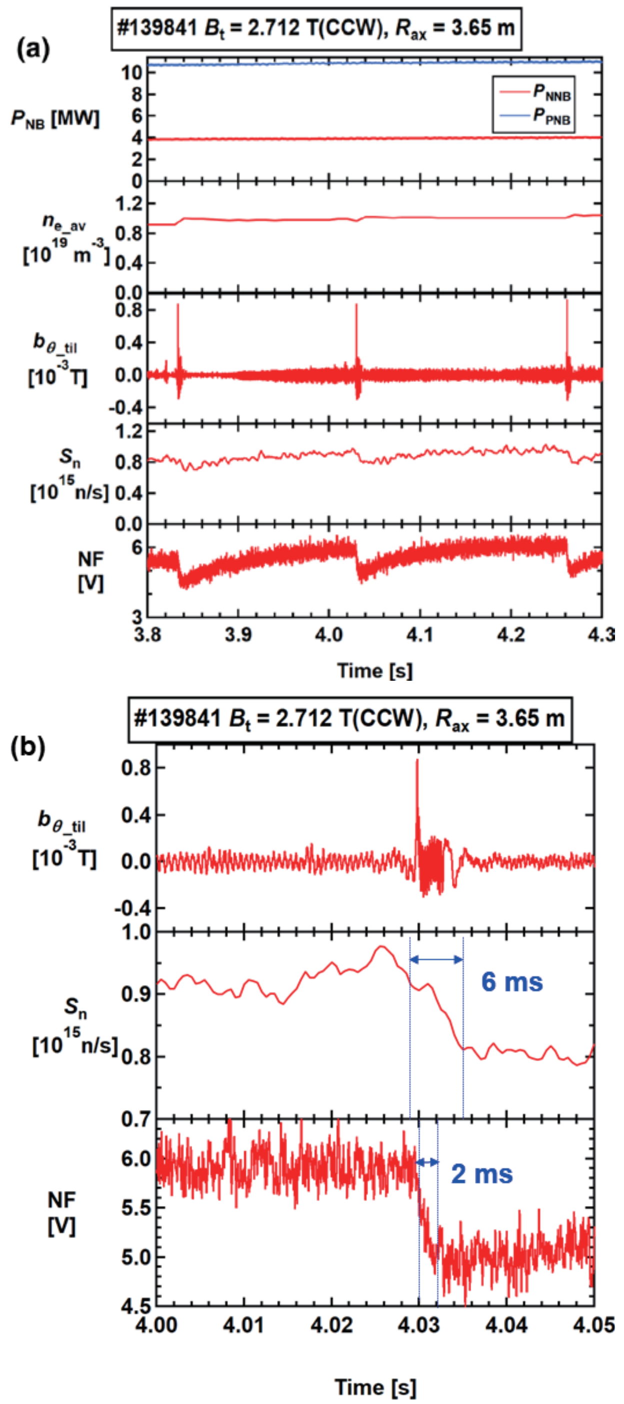

Fig. 4 (a) Time evolutions injection powers of NBIs, n_{e_av}, magnetic fluctuation amplitude, S_n and NF signal on the discharge with strong MHD bursts. (b) Enlarged figure of (a) Rapid changes of NF signal due to intermittent MHD bursts are observed.

The typical time evolutions of P_{NB}, n_{e_av}, magnetic fluctuation amplitude, S_n and NF signal on the discharge with strong MHD bursts are shown in Fig. 4. Here, B_t and R_{ax} are 2.712 T (direction of toroidal field is counterclockwise from the top) and 3.65 m, respectively. In this discharge, intermittent MHD bursts having large amplitudes are clearly seen on magnetic fluctuation amplitude. Here, frequency range of magnetic fluctuation is 0.3 kHz to 100 kHz so as to cover MHD burst frequency. The signals of NF and S_{n} decrease by almost 20 % synchronized with MHD bursts (Fig. 4 (b)). Here, the decay of S_{n} observed within around 6 ms is resulting in time response of NFM. The decreases of NF signal and S_{n} show degradation of global confinement of energetic ion. The NF signal clearly shows that the drop of neutron flux occurs within 2 ms due to MHD burst.

4. Summary

The fast-neutron scintillation detector characterized by high temporal-resolution is installed in LHD for measuring rapid changes of neutron flux due to MHD modes. The level of neutron and/or gamma-ray induced signal caused in a PMT is negligibly small compared with that caused in a scintillation material. The neutron flux measured by NF has a linear dependence with total neutron emission rate measured by the neutron flux monitor in MHD quiet discharges as expected. Measurement of neutron flux by NF clearly shows that neutron flux decreases by around 20 % within 2 ms due to MHD modes.

Acknowledgments

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