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Observation of significant Doppler shift in deuterium-deuterium neutron energy caused by neutral beam injection in the large helical device

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Abstract

The compact neutron emission spectrometer (CNES) having a tangential sightline was installed to observe a significant Doppler shift of the neutron energy due to the high-energy tangential neutral beam (NB) injections in the Large Helical Device (LHD) for understanding of the energy distribution of fast-ion. The CNES is based on a 1-inch diameter and 1-inch height EJ301 liquid scintillator coupled with a conventional 1-inch photomultiplier tube. The histogram of the integrated pulse signal (Q_{total}) during different NBs heating phases measured by the CNES shows that the edge of Q_{total} changes depending on NB directions. Using the simple derivative unfolding technique, the neutron energy spectra were unfolded from the measured Q_{total} histogram. Peaks of the neutron energy shift to 2.0 MeV, 2.42 MeV, and 3.0 MeV according to the injection direction of NBs. The obtained neutron energy is almost consistent with the virgin deuterium-deuterium neutron energy evaluated by the simple two-body kinematics considering the sightline of CNES, NB injection angle, and NB injection energy.

Keywords: Doppler effect, Compact neutron emission spectrometer, Large helical device, Liquid scintillator, Neutral beam heating

1 Introduction

Understanding fast-ion confinement is one of the issues for obtaining high-performance plasmas because plasmas are auxiliary heated by fast-ions created by neutral beam (NB) injection and/or ion cyclotron heating. Predominantly, fast-ion transport due to fast-ion driven magnetohydrodynamic (MHD) instability is one of the key topics for fast-ion confinement study [1]. In the Large Helical Device (LHD), a study of fast-ion transport due to fast-ion-driven MHD instability has been performed using intensive NBs [2]. In

hydrogen experiments, beam ion transport/loss due to toroidal Alfvén eigenmode has been studied using a neutral particle analyzer [3] and a fast-ion loss detector [4]. Although the transport and loss process due to toroidal Alfvén eigenmode was revealed by comparing experimental results and numerical simulations [5, 6], information of fast-ion confinement was limited in real and phase spaces. By starting the deuterium experiment in LHD in March 2017, global information of confined fast-ions can be obtained using a comprehensive neutron diagnostic [7–10] because neutrons are mainly created by the fusion reaction between fast-ion and bulk plasma [11]. Time evolution of neutron emission profile obtained in energetic-ion-driven resistive interchange mode discharge in the experiment and numerical simulation revealed the substantial radial

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transport of beam ions [12, 13]. For a deeper understanding of the excitation of fast-ion-driven MHD instability and resonance between fast-ion and fast-ion-driven MHD instability, the energy distribution of fast-ion is necessary. In particular, high-acceleration energy NBs are installed in LHD. Therefore, beam ion distribution can be observed as the significant Doppler shift of the neutron energy due to the high-energy NBs. A tangential line-of-sight compact neutron emission spectrometer based on an EJ301 liquid scintillation detector (the so-called CNES) is newly implemented in LHD to obtain the energy distribution of beam ions created by tangential NBs. In this work, neutron spectroscopy during different NB heating is reported.

This paper is organized in the following manner. The description of the experimental setup of the CNES in LHD is shown in Section 2. The neutron energy spectra measurement results during NBs heated deuterium plasma in LHD are presented in Section 3. Finally, in Section 4, the summary is given.

2 Experimental setups

LHD is equipped with three tangential negative-ion-source-based NBs (NB#1, NB#2, and NB#3) and two perpendicular positive-ion-source-based NBs (NB#4 and NB#5), as shown in Fig. 1. Note that the tangency radius of NB#1, NB#2, and NB#3 injections are 3.75 m, 3.75 m, and 3.70 m, respectively. The CNES is newly installed at the tangential LHD port (the so-called 6T port) with tangential sightlines with a tangency radius of approximately 3.5 m. NB#2 injects beam ions that move away from the CNES, whereas NB#3 injects beam ions that move toward the CNES, and NB#5 injects beam ions in a perpendicular direction. By installing the CNES, the measurement of neutron energy spectra, reflecting the fast-ion distribution function, becomes newly possible. The advantage of the CNES is its compactness compared with the time-of-flight-type neutron emission spectrometer under commissioning on LHD [14] occupying the space of a cube 2 m on a side.

The CNES is installed at a distance of approximately 100 cm from the 6T port. The detector is enclosed in the

Fig. 1 A schematic top view of the LHD, NBs, and CNES installed at LHD 6T port. The black arrow indicates the direction of the CNES line-of-sight

shielding box. Figure 2a right shows the cut view schematic of the shielding box. To prevent the stray magnetic field effect on the photomultiplier tube (PMT), the detector is placed in the magnetic shielding made of SS400 with 1 cm thick. The outer layers are equipped with the γ -ray shielding made of 5 cm thick lead and neutron shielding made of 10% doped borated polyethylene with

30 cm width, 60 cm length, and 40 cm height. The collimator with an inner diameter of 3 cm is placed in front of the detector in order to enhance the directivity (Fig. 2b).

The EJ301 liquid scintillator [15], 1-inch in diameter and 1-inch in height, is directly coupled to a conventional 1-inch PMT (H10580-100-01, Hamamatsu Photonics K.K [16].) and is used as a fast-neutron detector (Fig. 2a

a) EJ301 scintillation detector and the top view schematic of shielding

b) Front view of CNES

c) Electronics schematic of CNES

Fig. 2 **a** Left: the EJ301 scintillation detector. Right: a cut view of the shielding box of CNES. **b** The front view of the shielding box. EJ301 detector is placed inside the upper hole with the height of 16 cm above the plasma midplane. Note that the CLYC7 detector is beyond the scope of this paper. **c** Electronics schematic of CNES

left). The detector is biased with a high voltage of -1000 V with an externally controllable quad high voltage power supply (RPH-033, HAYASHI-REPIC Corp [17]). The anode signal of the detector is directly fed into the fast digital data acquisition system (APV8102-14MWP-SAGb, Techno AP Corp [18]). Then, the data is transferred to the LHD experiment database via 1 Gbps ethernet. Figure 2c shows the block diagram of the CNES. Figure 3a shows the typical waveform of the neutron and γ -ray induced pulse signals obtained by the CNES in LHD deuterium plasma discharge #162340. Pulse shape discrimination PSD = $\frac{Q_{\text{total}} - Q_{\text{fast}}}{Q_{\text{total}}}$, where Q_{total} is an integrated signal in t_{total} of 34 ns and Q_{fast} is an integrated signal in t_{fast} of 10 ns, is used for discriminating neutron and γ -ray. The acceptable pulse counting rate is decided to be 3.6×10^5 cps, where the pulse pileup ratio is less than 1.5% in order to obtain reliable pulse height spectra. Figure 3b shows an example of a two-dimensional PSD plot obtained in #162340. Neutrons and γ -rays induced signals are discriminated by setting appropriate t_{fast} . In the following analysis, PSD from 0.27 to 0.44 is recognized as a neutron signal. Note that the ratio of neutron signal and γ -ray signal is 5:1.

3 Measurement of neutron energy in NB heated LHD plasma

Measurement of the Doppler shift of neutron energy using CNES during NB injection was performed at deuterium plasma discharges from #162325 to #162358. The typical time evolution of plasma discharge is shown in Fig. 4. In the experiments, the magnetic axis position in vacuum $R_{\text{ax, vac}}$ is set to be 3.6 m and toroidal magnetic field strength B_T is set to be 1 T with counterclockwise

(CCW) directions viewed from the top. Here, NB#2, NB#3, and NB#5 are injected separately. During the NB#3 heating phase, NB#1 injects a hydrogen beam. Although the neutron emission from beam ions injected by NB#1 is negligibly small compared with NB#3 components, NB#1 might affect the fast-ion distribution function through the nonlinear collision [19]. The experiments were performed in a relatively low-electron temperature condition in order to maintain the low total neutron emission rate (S_n) so to avoid the counting loss of the CNES. The neutron counting rate obtained by CNES in each NB phase is compared to S_n obtained by a neutron flux monitor (NFM) [7, 20], as shown in Fig. 5a). The ratios of the neutron counting rate of the CNES to S_n are $\sim 4.56 \times 10^{-9}$, $\sim 4.03 \times 10^{-9}$, and $\sim 2.26 \times 10^{-9}$ for NB#3, NB#2, and NB#5 phases, respectively (see Fig. 5b). Here, the viewing angle is calculated based on the sight-line of CNES and the NB injection angle. The relation of the neutron counting rate obtained by CNES and S_n is different in each phase because of the anisotropy of the deuterium-deuterium fusion neutron emission. In a previous study, the anisotropy effect of the deuterium-deuterium neutron was observed using the neutron activation system installed on the outboard side of LHD [21]. In contrast, the effect is negligibly small for the neutron flux monitor installed on the top [22]. The anisotropy of deuterium-deuterium neutron emission obtained using CNES is consistent with the neutron activation system measurement. The operational range in CNES pulse counting rate is up to 3.6×10^5 cps which corresponds to the neutron counting rate of 3.0×10^5 cps because the ratio of neutron signal and γ -ray is 5:1. As shown in Fig. 5, the linearity of the neutron counting rate is limited

at the neutron pulse counting rate of 3×10^5 cps corresponding to $S_n \sim 6 \times 10^{13}$ n/s for the NB#3 injection case. The histogram of Q_{total} is measured by the CNES during different NB phases and is shown in Fig. 6. Time intervals from 4.20 s to 4.30 s, 5.60 s to 6.10 s, and 7.20 s to 7.30 s are selected for NB#3, NB#5, and NB#2 phases, respectively. The edge position in Q_{total} is relatively high in the NB#3 case, whereas the Q_{total} edge position is relatively low in the NB#5 case. The edge position of Q_{total} in the NB#5 case is located between the NB#3 and the NB#2 cases.

To unfold the neutron energy spectra from the Q_{total} histogram, the simple derivative unfolding technique [23, 24] is used because the Q_{total} corresponds to the recoiled proton energy deposited in the scintillator. Q_{total} is changed to electron equivalent energy E_e [MeVee] using the Compton edge measured from ^{137}Cs and ^{60}Co γ -ray calibration sources. The relation of $Q_{\text{total}} = 13.96 \times E_e$ [MeVee] is obtained. Further, using the through the light output L as a function of recoil particle energy [25] shown in Fig. 7a, recoil proton energy (E_p) as a function of E_e is obtained. The unfolded neutron energy spectra was obtained with the calculation of differential neutron flux ($\phi(E)$) that can be expressed as [22]: $\phi(E) = \frac{-E_p}{TnV\sigma(E_p)} \left[y'(x) \{gL'(E_p)\}^2 + y(x)gL''(E_p) \right]$ where T is the time duration [s], n is the density of hydrogen

atom [cm^{-3}], V is the sensitivity volume [cm^3], σ is the neutron-proton elastic scattering cross section [cm^2], $y(x)$ is Q_{total} histogram, and the PMT gain g is set to be 6.6×10^5 . Note that the detection efficiency is not taken into account in this calculation. Here, ' and '' represent the first and the second derivatives, respectively. Unfolded neutron energy spectra shown in Fig. 7b indicates that the peaks of neutron energies located above 2 MeV, which corresponds to the virgin deuterium-deuterium neutron in NB#2, NB#5, and NB#3 phases are 2.0 MeV, 2.42 MeV, and 3.0 MeV, respectively. The peaks in neutron energy below 1.5 MeV may be due to the scattered neutron. The virgin deuterium-deuterium neutron energy to be observed by CNES is compared with the simple calculation based on the two-body kinematics. Here, the fusion reaction of a cold deuteron and a beam deuteron having the NB injection energy occurred at the magnetic axis position with the finite beta (3.86 m) is considered. The viewing angle is estimated from the CNES sightline and the NB injection angle shown in Fig. 5b. The virgin deuterium-deuterium neutron energies are calculated to be 2.11 MeV, 2.45 MeV, and 2.93 MeV during NB#2, NB#5, and NB#3 heating phases, respectively. The experimentally obtained neutron energies are almost consistent with the neutron energies expected from the simple two-body kinematics. The detailed analysis of the fast-ion energy distribution,

Fig. 6 Histogram of Q_{total} obtained during different NB heating phases. The edge position of Q_{total} changes according to NBs direction

Fig. 7 a Light output L as a function of the recoil particle energy [25]. b The unfolded neutron energy spectrum

including the effect of the hydrogen NB#1 injection, using calculation based on the drift kinetic code such as GNET [26] will be our future work.

4 Summary

The neutron spectroscopy is performed in NB heated LHD plasma by the newly installed CNES having the tangential sightlines. The CNES consists of an EJ301 liquid scintillator, PMT, the externally controllable high voltage power supply, and the novel fast data acquisition system. The neutron energy spectra were measured in deuterium discharges with various NB injection conditions. The anisotropy of the deuterium-deuterium fusion neutron emission measured by the CNES is consistent with the result obtained by the neutron activation system. The histograms of Q_{total} during different NB heating phases are measured. Q_{total} becomes lower and higher during the NB#2 and the NB#3 injections, respectively. In this work, the derivative unfolding technique is used in order to unfold the neutron energy spectra from the Q_{total} histograms. The neutron energies measured by CNES are consistent with the neutron energies expected from the simple two-body kinematics calculation. The results show that the neutron energies become higher during NB#3 and lower during NB#2 due to the Doppler effect when the beam ions move toward and move away from the CNES.

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Authors' contributions

S. Sangaroon, K. Ogawa, and M. Isobe equally contributed to all aspects of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

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Not applicable

Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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