Fusion neutron production with deuterium neutral beam injection and enhancement of energetic-particle physics study in the large helical device

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Abstract

The deuterium operation of the large helical device (LHD) heliotron started in March 7, 2017, after long-term preparation and commissioning works necessary to execute the deuterium experiment. A comprehensive set of neutron diagnostics was implemented to accelerate energetic-particle physics research in the LHD. The calibrated ex-vessel neutron flux monitor indicated that the total neutron emission rate in the first deuterium campaign reached $3.3 \times 10^{15}$ n s$^{-1}$ in inward shifted magnetic field configuration where confinement of helically trapped energetic ions is predicted to be better. Density dependence of measured total neutron emission rate was consistent with that predicted by the calculation. The neutron decay rate analysis following perpendicular deuterium beam blips injection suggested that the confinement of helically trapped beam ions can be understood by the classical slowing down model in relatively high-electron density plasmas at inward shifted magnetic field configuration. On the other hand, loss of helically-trapped beam ions was recognized even in the inward shifted configuration in the case of low density. Performance of the vertical neutron camera was verified by changing the plasma position and/or magnetic field strength. Drastic change of neutron emission profile was observed when the resistive interchange mode driven by helically-trapped beam ions appears. It was successfully demonstrated that the vertical neutron camera can play an important role in revealing radial transport and/or loss of beam ions. Triton burnup study was also conducted. In the first deuterium campaign, the maximum triton burnup ratio of 0.45% was obtained in inward shifted configuration. The burnup ratio decreased as a plasma was shifted outwardly as expected.

Keywords: deuterium plasma, neutron, energetic ion, triton, the large helical device

(Some figures may appear in colour only in the online journal)
1. Introduction

In high-temperature deuterium and/or deuterium–tritium plasmas, fusion neutrons are generated due to d–d and/or d–t fusion reaction. Fusion neutron has been one of the attractive objects for diagnosing the plasma performance in the history of nuclear fusion development. In the early days of fusion study, the measurement of the fusion neutrons was recognized as a fuel-ion temperature diagnostic. Around 1970, neutron spectroscopy was proposed to evaluate fuel-ion temperature through the measurement of Doppler broadening of neutron energy [1, 2]. In the mid-1970s, the fuel-ion temperature was evaluated from the total neutron emission rate (Sn) measurements in small-sized tokamaks [3, 4] and was also assessed through neutron spectroscopy in the mid-1980s [5, 6]. In parallel with the fuel-ion temperature measurements, as the deuterium neutral injection experiment progressed, the role of the neutron measurement shifted from being a fuel-ion temperature diagnostic to being an energetic-ion diagnostic in addition to fusion gain assessment because generated neutrons in deuterium neutral beam (NB)–heated deuterium plasmas are dominated by neutrons resulting from beam-plasma reactions [7, 8]. Deceleration of beam ions following NB turn-off was checked for the first time by measuring Sn in the Princeton Large Torus [9]. Subsequently, a beam blip injection method was developed to enhance accuracy of analysis on slowing-down property on beam ions in tokamaks [10–12]. After that, a rapid drop of Sn due to fishbone mode destabilized by perpendicularly-injected beam ions was found in the Poloidal Divertor Experiment [13]. It has been increasingly recognized that fusion neutron diagnostic can provide beneficial information of global behavior of energetic ions in tokamaks utilizing deuterium NB injections [14, 15]. Based on this background, diagnostics based upon nuclear technology have been steadily enhanced, in particular, in large tokamaks such as the Joint European Torus (JET) [16–18]. In the near future, neutron and gamma-ray diagnostics will play the leading role in assessing fusion output and/or energetic-ion confinement property in the International Thermonuclear Experiment Reactor [19–21].

Turning one’s eyes to helical/stellarator devices, fusion neutron measurement was performed in Wendelstein 7-A for the first time in helical/stellarator devices. Then, the decay time of Sn following NB turn-off was analyzed to check whether beam ions were decelerated classically without loss or not [22]. Subsequently, neutron emission rate and/or yield measurements were conducted in the Heliotron-E [23, 24], the Advanced Toroidal Facility [25], the Compact Helical System [26, 27], and the Wendelstein 7-AS [28, 29]. Because those devices were small- and/or medium-sized and their heating systems were not as intense, Sn were very low, by about $10^7$–$10^{10} \text{n s}^{-1}$. In such a case, the usage of neutron diagnostic was limited and was not very effective in studying confinement property of energetic ions. The helical plasma research entered a new stage on March 7, 2017. The deuterium operation began in the large helical device (LHD), which is the world’s largest-class helical device [30] in order to explore a higher-confinement plasma regime. One of the primary purposes of the LHD deuterium project is to demonstrate that confinement capability of energetic ions is relevant to the future burning plasma in helical systems. Note that energetic-ion physics studies such as ripple transport of beam ions [31–33], effect of toroidicity-induced Alfvén eigenmodes [34–36], energetic-particle continuum modes [37], resistive interchange modes [38] on beam ion loss, and effects of resonant magnetic perturbation field on beam ion loss [39] have been intensively conducted by using various energetic-particle diagnostics such as scintillator-based escaping energetic-ion diagnostic and charge-exchanged neutral particle analyzers [40] in the hydrogen operation phase in the LHD. Because these diagnostics do not provide directly information of energetic ions at core domain, we have concentrated on phenomenological and qualitative arguments regarding energetic ion’s behavior. Since fusion neutron signals are newly available, the deuterium plasma experiment can provide an important opportunity to enhance energetic-particle physics study in the LHD. The LHD is capable of producing fusion neutrons over $1 \times 10^{16} \text{n s}^{-1}$, which is much higher than that observed in the small and medium class helical/stellarator devices. To extend energetic-particle physics study in the LHD, a comprehensive set of neutron diagnostics was prepared before the start of deuterium operation consisting of the neutron flux monitor (NFM), the neutron activation system (NAS), the vertical neutron camera (VNC), the neutron fluctuation diagnostic, and scintillating-fiber detectors for triton burnup. In this paper, hardware on neutron diagnostics prepared for the LHD deuterium operation is described. Also, representative measurement results obtained in the first deuterium campaign of the LHD are presented.

2. Neutron generation in the LHD deuterium plasma

LHD is the world largest-class helical device equipped with intense NB heating facility of the 30 MW class. The first
plasma was initiated in March 1998 with hydrogen gas and high $\beta$, high temperature, and steady-state operation capabilities have been demonstrated to date [41]. To explore achievable maximum performance of the LHD plasma, the deuterium operation began in March 2017. In a deuterium plasma, the following nuclear fusion reactions primarily occur

$$d + d \rightarrow n(2.45\,\text{MeV}) + ^3\text{He}(0.82\,\text{MeV})Q = 3.27\,\text{MeV}$$
$$d + d \rightarrow p(3.02\,\text{MeV}) + t(1.01\,\text{MeV})Q = 4.03\,\text{MeV}.$$  

Both $d-d$ reactions take place almost equally. In addition to these two reactions, triton generated by $d-d$ reaction will undergo secondary t-d reaction producing $^3\text{He}$ (3.56 MeV) and neutron (14.03 MeV) with background thermal deuterons. Tritons produced by $d(d,p)t$ reaction are isotropic in the velocity space. Also, kinematic parameters of 1 MeV triton such as Larmor radius and precessional drift frequency are almost the same as those of d-t born alpha particles. Therefore, triton born in deuterium plasma has been often used in place of alpha particle.

The LHD is equipped with three negative-ion-source-based neutral beam (N-NB) injectors and two positive-ion-source-based neutral beam (P-NB) injectors as shown in figure 1. Energetic beam ion with injection energy $E_b$ of about 180 keV is delivered by the three tangential N-NB injectors (1, 2, and 3). The N-NB injection power in the first deuterium campaign was ~2 MW for each. Beam ions provided by the P-NB injectors are perpendicularly injected and the total injection power was 9 MW with $E_b$ of 60 keV–80 keV. Beam ions delivered by those NB injectors play an essential role in generating fusion neutron in the LHD. Prior to the start of deuterium operation, expected $S_n$ in the LHD was calculated with velocity distribution function expressed by a steady-state Fokker–Planck equation. The calculation suggests that $S_n$ will exceed $1 \times 10^{19} \text{ n s}^{-1}$ when full power NB heating is performed [30]. The maximum $S_n$ expected in the LHD deuterium plasma is almost comparable with that recorded in the deuterium operation of large tokamaks, e.g. the Tokamak fusion test reactor (TFTR) [42] and the JAERI Tomakak-60U (JT-60U) [43].

### Table 1. A comprehensive set of neutron diagnostics prepared for the first deuterium campaign of the LHD.

| System | Diagnostic | Detector | Manufacturer (model, spec.) or originator | Channel |
|--------|------------|----------|------------------------------------------|---------|
| NFM    | Fusion output | $^{235}\text{U}$ fission chamber | TETD* (KSA-01, 0.1 cps/nv) | 3 |
|        | Time resolved total neutron emission rate | $^{10}\text{B}$ counter | TETD* (E6863-558, 6.5 cps/nv) | 1 |
|        |            | $^{3}\text{He}$ counter | TETD* (E6862-500, 30 cps/nv) | 2 |
| NAS    | Shot-integrated DD neutron yield | Indium disk | G-TECH (10 mm $\phi \times 1\text{ mm}$ t, purity 99.999%) | 2 |
|        | Shot-integrated secondary DT neutron yield | Aluminum disk | | |
|        |            | Silicon disk | | |
| VNC    | Time-resolved DD neutron profile | Stilbene scintillator | G-TECH (20 mm $\phi \times 10\text{ mm}$ t) | 11 |
| NFD    | DD neutron fluctuation | $\text{ZnS:Ag}$ phosphor embedded in a hydrogenous polymer matrix | G-TECH (EJ-410, 25 mm $\phi \times 19\text{ mm}$ t) | 2 |
| Sci.-Fi.| Time resolved secondary DT neutron flux | Scintillating fiber | Los Alamos National Laboratory | |
|        |            | | National Institute for Fusion Science | |
|        |            | | National Institute of Technology, Toyama College | 3 |

*TETD: Toshiba Electron Tube Device Co. Ltd.

3. **Neutron diagnostics prepared for the LHD deuterium operation**

To extend energetic-particle physics studies in the LHD, a comprehensive neutron diagnostic system was developed. The neutron diagnostics prepared for the first deuterium campaign of the LHD are listed in table 1. The NFM is essential in the LHD operation in addition to physics purposes since annual neutron budget permitted by the Nuclear Regulation Authority of Japan is set to be $2.1 \times 10^{13}$. Therefore, the LHD cannot be operated without the NFM. Conceptual design of the LHD neutron diagnostics was performed before the initial operation of LHD [44]. Component technology test and/or development was initiated in around 2000 and a more concrete system was proposed subsequently [45]. As for the system development, we initiated development of a wide dynamic range NFM based on leading-edge digital technologies at the outset [46]. The NFM on LHD consists of three sets of two detectors as schematically depicted in figure 2(a). Each set has a $^{235}\text{U}$ fission chamber (FC), and a $^{10}\text{B}$ counter or a $^{3}\text{He}$ counter. The FC line can provide very wide dynamic range and fast-time response capabilities, and is designed so as to realize neutron pulse counting rate up to $5 \times 10^{9}$ cps. The FC line is responsible for middle- to high-neutron yield shots when NBs are injected. Other neutron counters can work for low-neutron yield shot such as electron cyclotron resonance heating (ECRH) shot without NB injection. Parallel to the hardware development, numerous efforts by using the Monte Carlo N-particle transport code (MCNP) have been made on characterizations of neutron field near the LHD, neutron detector response, estimation of necessary time for in situ calibration of the NFM, etc [47–51]. Note that the wide dynamic NFM had been employed in the TFTR [52] and the JT-60U [53], consisting of both functions of pulse counting and Campelling modes jointly. However, these systems are based on traditional analogue technology and are no longer commercially available at the present time. Therefore, we needed to develop a new system based on new technologies. Prior to the deuterium operation of the LHD, in situ calibration of the NFM was carried out from November.
Neutron emission profile was measured with nuclear emulsion methods in the PLT for the first time in tori [57]. In the era of large tokamaks, neutron profile diagnostic has been regularly employed in the TFTR [58–60], the JET [61, 62], and the JT-60U [63], providing valuable information on beam ion profile and/or radiation transport of beam ions due to magnetohydrodynamic (MHD) instabilities [64–66].

In the LHD, high-performance VNC of eleven channels was installed. The overview of the LHD-VNC is schematically drawn in figure 2(b). This is the first neutron camera in helical/stellarator devices in the world. The stilbene scintillation detector was chosen as a fast-neutron detector in terms of brightness and good neutron (n)-gamma (γ)-ray discrimination capability through various detector tests at accelerator-type fusion neutron facilities. The LHD-VNC system is characterized by MHz range operation capability with automated neutron and gamma-ray discrimination function based on a leading-edge field-programmable gate array technology [67] and negligibly small cross talk fraction [51, 68]. The neutron collimator is made of heavy concrete and is embedded in a hole in the concrete floor (2.0 m thick) of the torus hall. Radially aligned eleven stainless steel pipes (1.5 m long × 3 cm φ) are embedded in a heavy concrete as a path for birth neutrons.

Detailed information of the LHD-VNC hardware are available in [68, 69].

Triton burnup study is one of the primary physics subjects in the LHD deuterium project to demonstrate that confinement capability of energetic ion, in particular, MeV ion, is relevant to a fusion reactor plasma. The triton burnup ratio, which is defined as the ratio of secondary d–t neutron yield to primary d–d neutron yield, $Y_{DT}/Y_{DD}$ has been examined in tokamaks, e.g. the Frascati Tokamak [70, 71], the JET [72, 73], the TFTR [74], the Doublet III-D [75], the JT-60U [76, 77], and the Korea superconducting Tokamak advanced research (KSTAR) [78]. In this work, initial study on triton behavior was performed by measuring 14 MeV neutrons generated by...
secondary d–t reaction in a deuterium plasma with a neutron activation technique [79] and scintillating-fiber (Sci.-Fi.) detector [76, 80, 81]. In addition to these, neutron fluctuation detector (NFD) with a fast-neutron sensor consisting of ZnS:Ag phosphor embedded in a hydrogenous polymer matrix is installed to measure fast-neutron fluctuation with high time resolution [82]. The LHD deuterium operation has begun with a comprehensive set of neutron diagnostics listed in table 1.

4. Experimental results

4.1. Neutron emission rate and yield

Neutrons resulting from d–d fusion reactions have been observed in LHD deuterium plasmas. The first deuterium plasma was successfully initiated by ECRH without NB injection in March 7, 2017. The discharge waveform of the first deuterium plasma is shown in figure 4. In this shot, neutrons were generated by thermonuclear reactions due to finite fuel ion temperature since energetic ion was not present because of ECRH plasmas, and $S_n$ was evaluated to be about $1 \times 10^{11} \text{n s}^{-1}$. As can be seen, the $^3\text{He}$ counter provides neutron pulse counting rate with good statistics because the sensitivity of $^3\text{He}$ counter to neutron is the highest among the three detectors whereas the FC signal is the weakest and is not effective for evaluating $S_n$ precisely. As for ECRH plasmas, a central fuel deuteron temperature was derived from $S_n$ measured with in situ calibrated NFM [83]. The analysis indicated that central fuel deuteron temperature ranged from 1 keV to 1.5 keV and was consistent with impurity ion temperature measured with spectroscopy.

The maximum $S_n$ shot was explored by injecting all five NBs with scanning electron density ($n_e$) and magnetic...
configuration. The maximum $S_0$ shot was achieved in an inward shifted configuration ($R/a/B_t$ of 3.55 m/2.87 T) that provides the longest energy confinement time and good confinement property of helically trapped energetic ions. The discharge waveforms are displayed in figure 5. In this particular shot, $S_0$ reached $3.3 \times 10^{15}$ n s$^{-1}$ with the help of fueling deuterium pellet injection which was the record value of $S_0$ in the first deuterium campaign of the LHD.

Next, $S_0$ was systematically examined to understand the parameter dependence of $S_0$ and to make a comparison with that predicted by simulations. Experimentally observed $S_0$ as a function of line-averaged $n_e$ is shown in figure 6. $S_0$ plotted in figure 6 is the peak value for each discharge and line-averaged $n_e$ is of the value when the maximum $S_0$ is recorded. As can be seen, $S_0$ increases as line-averaged $n_e$ increases in the low-$n_e$ region ($n_e < 2 \times 10^{19}$ m$^{-3}$). This is due to increase of beam deposition, and then $S_0$ reaches the peak in around $n_e$ of $(2-3) \times 10^{19}$ m$^{-3}$. $S_0$ starts to decrease as $n_e$ increases further because Spitzer slowing down time $\tau_s$ becomes shorter, and as a result, accumulation of beam ions is reduced in a plasma. This tendency agrees well with dependence of $S_0$ on $n_e$ predicted by the model based on velocity distribution function for beam ions described by the steady-state Fokker–Planck equation [30].

To confirm whether beam ions slow down classically without loss or not, deuterium beam blips were injected into ECRH plasmas. The beam blip method has been widely employed in an early phase of deuterium operation of several tokamaks and the Compact Helical System [10–12, 26, 27]. In this case, we injected beam ions perpendicularly by using P-NB #4 since confinement characteristic of helically trapped energetic ions have been a great concern in helical devices. The plasma density was gradually varied in time in this shot to change $\tau_s$ for beam ions. As can be seen in figure 7, $S_0$ increases immediately right after NB turn-on, and starts to decrease after NB turn-off with a finite decay time. Our interest is in whether perpendicularly injected beam ions decelerate classically without loss or not. Next, time evolution of $S_0$ is calculated with the simple classical slowing-down model FBURN [84]. In this code, beam ions are assumed to be slowed down in each shell according to the classical energy loss theory based on Stix’s formula [85]. The domain of plasma is divided into 120 circular shells and each volume is given according to the equilibrium reconstructed every 50 ms by VMEC2000 code [86]. Here, beam deposition profile is calculated using the HFREYA code [87]. Note that d–d fusion reactivity between a plasma and a beam ion is given in [88]. As can be seen in figure 7, the neutron decay rate following NB turn-off evaluated by the FBURN code agrees relatively well with experimentally measured neutron decay rate in line-averaged $n_e$ around $2 \times 10^{19}$ m$^{-3}$. It tells us that perpendicularly injected beam ions decelerate classically without significant loss in this $n_e$ region. Note that there is a discrepancy between measured and calculated decays in lower $n_e$ ($n_e \sim 1 \times 10^{19}$ m$^{-3}$) discharges characterized by a longer $\tau_s$ for beam ions, suggesting significant loss of perpendicularly injected beam ions in the low-$n_e$ regime.

4.2. Neutron emission profile

A radial profile of neutron emission rate is of inherent interest in nuclear fusion experiments. In the LHD, the line-integrated neutron emission profile has been successfully measured in the first deuterium campaign by using the VNC. At the beginning of commissioning phase, we performed $R_{ax}$ scanning experiments in the high field operation and verified the response of line-integrated neutron emission profile. The neutron emission profile was reasonably varied, i.e. the neutron profile shifted outwardly as the plasma column was shifted outwardly, and vice versa according to the $R_{ax}$ position.

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**Figure 6.** Maximum total neutron emission rate as a function of line-averaged electron density in $R/a/B_t$ of 3.55 m/2.89 T. $P_{P,NB}$ and $P_{P,NB}$ were about 6 MW and 18 MW, respectively.

**Figure 7.** Time evolutions of discharge when perpendicular beam blip is injected by using P-NB #4 ($P_{P,NB}$ ~ 7 MW) into ECRH ($P_{ERH}$ ~ 2.5 MW)-sustained plasma. Line-averaged $n_e$ is gradually increased from line-averaged $n_e$ of $1.5 \times 10^{19}$ m$^{-3}$ at $t = 4.4$ s to line-averaged $n_e$ of $2.7 \times 10^{19}$ m$^{-3}$ at $t = 5.4$ s.
Next, we measured neutron emission profiles in two different $B_t$ values, i.e., 1.375 T and 2.75 T at $R_{ax}$ of 3.6 m when two NBs, i.e., N-NB#1 and #3 are tangentially co-injected into the plasma of line-averaged $n_e = 2 \times 10^{19} \text{ m}^{-3}$.

Figure 8. Two radial profiles of line-integrated neutron pulse counting rates in the two different $B_t$, i.e. 1.375 T and 2.75 T at $R_{ax}$ of 3.6 m when two NBs, i.e. N-NB#1 and #3 are tangentially co-injected into the plasma of line-averaged $n_e = 2 \times 10^{19} \text{ m}^{-3}$.

Figure 9. Radial profiles of line-integrated neutron pulse counting rate. (a) Profile when N-NB#3 ($P_{\text{NB}} = 1.8 \text{ MW}$) is tangentially injected in $R_{ax}/B_t$ of 3.55 m/2.78 T, (b) profile when P-NB#4 ($P_{\text{NB}} = 4.3 \text{ MW}$) and P-NB#5 ($P_{\text{NB}} = 6.7 \text{ MW}$) are perpendicularly injected in $R_{ax}/B_t$ of 3.6 m/2.75 T. Line-averaged $n_e$ is set to be $\sim 2 \times 10^{19} \text{ m}^{-3}$ for both discharges.

[69]. Next, we measured neutron emission profiles in two different $B_t$ at the same $R_{ax}$ position. In this shot, N-NB#1 and N-NB#3 were tangentially co-injected with total $P_{\text{NB}}$ of 4 MW. Two radial profiles of line-integrated neutron pulse counting rate at the outboard side in $B_t$ of 1.375 T and 2.75 T at $R_{ax}$ of 3.6 m are shown in figure 8. The neutron pulse counting rate is centrally peaked in the case of $B_t$ of 2.75 T whereas the neutron profile is relatively flat in the case of $B_t$ of 1.375 T. This is because drift surfaces of co-going beam ions largely deviate from magnetic flux surfaces to the outboard side of the plasma in $B_t$ of 1.375 T compared with the deviation of co-going beam ions in $B_t$ of 2.75 T.

Two radial profiles of line-integrated neutron pulse counting rate with different injection angles of NB are shown in figure 9. One is the profile when the N-NB#3 of which $E_b$ and $P_{\text{NB}}$ are 164 keV and 1.8 MW, respectively, is tangentially co-injected. The other is the profile when the P-NB#4 of which $E_b$ and $P_{\text{NB}}$ are 45 keV and 4.3 MW, and the P-NB#5 of which $E_b$ and $P_{\text{NB}}$ are 69 keV and 6.7 MW, respectively, is perpendicularly injected. In both discharges, $n_e$ is set to be $\sim 2 \times 10^{19} \text{ m}^{-3}$. As can be seen in figure 9, clear difference between the two neutron emission profiles can be recognized.

In the case of tangential beam injection, the line-integrated neutron pulse counting rate is centrally peaked and decreases monotonically towards the peripheral domain. On the other hand, steep cliff can be recognized in the neutron emission profile in the case of perpendicular beam injection. This difference can be reasonably understood in the difference of orbit topologies in the Cartesian coordinates between co-going transit beam ions created by tangential NB injection and helically trapped beam ions generated by perpendicular NB injection [89].

Resistive interchange mode destabilized by helically trapped energetic ions often appear while two P-NBs are perpendicularly injected into relatively low-$n_e$ inward shifted plasma at high $B_t$. This mode occurs recurrently and is accompanied by a rapid frequency downshift. The mode is classified into energetic-particle continuum mode in the broad sense and is called energetic-ion-driven-interchange (EIC) mode [90, 91]. Note that in the hydrogen experiment phase, observations related to radial transport and/or expulsion of beam ions were fairly limited. Only indirect observation such as rapid change of potential to negative, and increase of charge-exchanged fast neutrals was observed in the hydrogen phase. After the deuterium operation began, neutron signal became newly available, giving more direct information of global behavior of energetic ions while the EICs are excited. The NFM have indicated that effect of the EIC burst on $S_n$ is significant and $S_n$ largely drops due to the EIC burst, by about 50% occasionally [92]. Figure 10 shows change of neutron emission

Figure 10. Significant change of neutron emission profile while MHD instabilities driven by helically trapped energetic beam ions are delivered by perpendicular P-NB#4 and #5 in $R_{ax}/B_t$ of 3.6 m/2.75 T. Line-averaged $n_e$ was $1.2 \times 10^{19} \text{ m}^{-3}$ in this shot. Here, black solid line represents time evolution of amplitude of MHD bursts in arbitrary unit.
Figure 11. Time evolutions of total neutron emission rates measured with the NFM and secondary d-t neutron emission rate evaluated with the Sci.-Fi. detector calibrated by the NAS. Total $P_{SNB}$ is 5.8 MW, and line-averaged $n_e$ is about $1 \times 10^{19}$ m$^{-3}$ in this shot.

Figure 12. Dependence of triton burnup ratio on magnetic field configuration in the LHD. Line-averaged $n_e$ ranges from $1 \times 10^{19}$ m$^{-3}$ to $4 \times 10^{19}$ m$^{-3}$. Full power NB heating is performed in these shots.

4.3. Triton burnup

The triton burnup experiment has been positioned as alpha particle simulation experiment in tokamaks. In deuterium plasmas of the LHD, secondary d-t neutron fluxes have been successfully measured by using the NAS and the Sci.-Fi. detector for the first time in helical/stellarator devices. Two time evolutions of $S_n$ measured with the NFM and secondary d-t neutron emission rate resulting from triton burnup evaluated with the Sci.-Fi. detector are shown in figure 11. The Sci.-Fi. detector is calibrated through the NAS measurement. In this shot, three N-NBs are injected simultaneously into the plasma with $n_e$ of $1.2 \times 10^{19}$ m$^{-3}$. As can be seen, drop of line-integrated neutron pulse counting rate measured at the core channel is drastic whereas change of neutron emission rate is not visible in the peripheral chord. This observation tells us that helically-trapped beam ions are expelled due to the EICs since helically-trapped beam ions are localized in a valley of two helical winding coils and confinement domain is just above the vicinity of central chord.

is predicted to be poor in an outward shifted configuration [94]. Therefore, we performed $R_{ax}$ scanning experiment for triton burnup to verify the theoretical prediction. Experimentally evaluated $Y_{DT}/Y_{DD}$ as a function of $R_{ax}$ is shown in figure 12. Data points taken in $n_e$ range from $1 \times 10^{19}$ m$^{-3}$ to $5 \times 10^{19}$ m$^{-3}$ are plotted. The inward shifted configuration at $R_{ax}/B_t$ of 3.55 m/2.89 T gives the highest $Y_{DT}/Y_{DD}$ of ~0.45% and $Y_{DT}/Y_{DD}$ decreases as a plasma column is shifted outwardly as expected in [94]. The highest value of $Y_{DT}/Y_{DD}$ recorded in the first deuterium campaign of the LHD is almost the same as that obtained in tokamak having a minor radius similar to that of the LHD. In the case of half $B_t$, $Y_{DT}/Y_{DD}$ is significantly reduced as seen in figure 12. This is probably due to effects of larger Larmour radii of energetic tritons and significant deviation of triton’s orbit from magnetic flux surfaces. Prior to the deuterium experiment, confinement property of 1 MeV tritons was investigated by using the Global Neoclassical Transport (GNET) code. The GNET code suggests that particle and/or energy loss fraction in the inward shifted configuration is lower than that in the outward shifted configuration [95]. The tendency of measured $Y_{DT}/Y_{DD}$ on $R_{ax}$ position is consistent with that predicted by the GNET code in terms of the particle and/or energy loss fraction. Further detailed calculation on the triton burnup is being performed by using the GNET code to predict the magnetic configuration and plasma parameters that can potentially provide the highest $Y_{DT}/Y_{DD}$ in LHD deuterium plasmas.

5. Summary

The LHD project has stepped into a new stage. The first deuterium plasma was obtained in March 7, 2017, after long-term preparation to execute the deuterium operation. A comprehensive set of neutron diagnostics has been installed onto the LHD to extend energetic-particle physics studies in the LHD plasma characterized by 3D magnetic configuration. The NFM on the
LHD is based on leading-edge digital technologies, providing the maximum neutron pulse counting rate up to $5 \times 10^7$ cps. Prior to the deuterium operation, in situ calibration of the NFM was performed by using an intense $^{252}$Cf of ~800 MBq. In the first deuterium campaign, $S_n$ reached $3 \times 10^{13}$ n s$^{-1}$ in the inwardly shifted configuration at $R_{ax}$ of 3.55 m. The dependence of $S_n$ on $R_{ax}$ is consistent with that predicted by the simple model calculation. Perpendicular beam blip experiments suggest that confinement of helically trapped beam ions can be explained by the classical slowing down model in high $n_d (>2 \times 10^{19}$ m$^{-3}$) range, whereas loss of helically-trapped beam ions is visible in low $n_d$ ($1 \times 10^{19}$ m$^{-3}$) range. The radial profile of DD neutron emission rate has been measured with the wide dynamic range VNC equipped with online $n$-$\gamma$ discrimination capability for the first time in helical/stellarator devices. The line-integrated neutron emission rate has been measured with the wide dynamic range VNC with online $n$-$\gamma$ discrimination capability for the first time in helical/stellarator devices. The line-integrated neutron emission rate has been measured with the wide dynamic range VNC equipped with online $n$-$\gamma$ discrimination capability for the first time in helical/stellarator devices.

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