Energetic-ion Confinement Studies by Using Comprehensive Neutron Diagnostics in the Large Helical Device

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Study of energetic particle (EP) transport in the Large Helical Device (LHD) has been performed by means of escaping EP diagnostics. By starting deuterium operation of the LHD, confinement study of EPs has remarkably progressed by using newly developed comprehensive neutron diagnostics providing the information of EPs confined in the core region. The total neutron emission rate ($S_n$) increases with the inward shift of the magnetic axis. $S_n$ has the peak around the electron density of $2 \times 10^{19}$ m$^{-3}$ to $3 \times 10^{19}$ m$^{-3}$, as predicted by the Fokker-Planck code. The equivalent $Q_{ep}$ achieved 0.11 in negative ion based neutral beam (NB) heated plasma. Time evolution of $S_n$ following the short pulse NB injection is reproduced by drift kinetic simulation, indicating that beam ion transport can be described with neoclassical models in magnetohydrodynamic quiet low-beta plasmas. The vertical neutron camera (VNC) works successfully, demonstrating that neutron emission profile shifts according to magnetic axis position ($R_a$). The shift of the neutron emission profile is reproduced by orbit-following models MORH code. Time-resolved triton burnup study is performed for the first time in stellarator/heliotron so as to understand the alpha particle confinement. It is found that the triton burnup ratio, which largely increases at inward shifted configurations is similar to that measured in tokamak having a similar minor radius with the LHD. We demonstrate the confinement capability of EPs toward a helical reactor and expansion of the energetic-ion physics study in toroidal fusion plasmas.

1. INTRODUCTION

One of the issues for realizing a fusion reactor is how to sustain the high performance plasma by self-heating using fusion born alpha particles [1]. In order to predict/understand the alpha particle confinement in a fusion reactor, much attention has been given to studying the energetic ion physics study in existing fusion plasma devices using energetic particles produced by neutral beam injections and/or ion cyclotron heating, especially in middle and large tokamaks [2]. Although the plasma performance of the stellarator and helical systems do not exceed the performance achieved in tokamaks, stellarators and helical systems have the advantage of steady-state operation because of the absence of disruption. Recently, the performance of stellarator and helical devices increased dramatically, e.g., achievement of 10 keV ion temperature in LHD [3] and the stored plasma energy exceeds $6 \times 10^{26}$ Celsius m$^{-3}$s in Wendelstein 7-X [4]. In stellarators and helical systems, the energetic particle confinement study has been led by the Large Helical Device (LHD) using intensive neutral beam (NB) injection. In hydrogen experiments, the study of energetic ion confinement is mainly performed by the measurement of energetic particle that escaped from the plasma confinement region using a neutral particle analyzer and fast ion loss detector [5].

Recently, comprehensive neutron diagnostics are installed for the deuterium operation of the LHD initiated in March 2017. The neutron diagnostics work well, as planned. The neutrons emitted from the NB heated plasma are mainly due to the beam-thermal reactions, therefore the confinement property of the energetic ions can be obtained using neutron diagnostics. The deuterium operation of the LHD provides us the opportunity to extend the study of the energetic particle physics based on confined energetic particle measurement.

2. NEUTRON DIAGNOSTICS IN THE LARGE HELICAL DEVICE

The comprehensive neutron diagnostics have been installed and are working in the first LHD deuterium campaign. The neutron flux monitor, the neutron activation system, the vertical neutron camera, and scintillating fiber detectors are used for obtaining total neutron emission rate ($S_n$), total DD and secondary DT neutron emission amount, neutron emission profile, and time evolution of the DT neutron emission rate, respectively. The time evolution of $S_n$ is obtained by the absolutely calibrated neutron flux monitor consisting of fission chambers and $^3$He/$^6$B proportional counters [6]. The digital signal processing unit developed for the fission chamber equipped with the field programmable logic circuit realizing the wide dynamic range up to $5 \times 10^9$ cps and finer temporal resolution of 2 ns. The study of global confinement of beam ions will be enhanced by means of the neutron flux monitor. The vertical neutron camera consists of the multichannel collimator, fast-neutron scintillation detectors, and the fast analog to digital converter equipped with field programmable logic controller gives the radial neutron emission profile [7]. The multichannel collimator is made of 7 tons of heavy concrete having the weight density of 3.5 g/cc. There are eleven fast-neutron detectors. Each detector consists of a stilbene scintillator whose diameter/thickness is 20 mm/10 mm and the photomultiplier having the high gain stability even at $10^6$ cps. The newly developed data acquisition system enables us the online and offline pulse shape analysis simultaneously even in the $10^6$ cps region. The radial profile of the beam ion density can be obtained by the vertical neutron...
camera. The shot-integrated neutron emission amount is obtained by the neutron activation system consisting of two pneumatic capsule station and two high-purity germanium semiconductor detectors [8]. By means of silicon and indium foils, the ratio of secondary DT neutron emission amount and primary DD neutron emission amount are obtained. The time resolved DT neutron emission rate is obtained by means of scintillating fiber detectors [9, 10]. The scintillation fiber detectors consist of 10 cm long fibers embedded into the Al substrate and the magnetic resistant photomultiplier tube. The triton burnup ratio evaluated by the scintillating fiber detector absolutely calibrated by neutron activation system is studied in order to understand the 1 MeV triton confinement as a demonstration of 3.5 MeV alpha particle confinement.

3. TOTAL NEUTRON EMISSION RATE STUDY

The study of $S_n$ on the NB heated deuterium plasma is performed in various magnetic configurations. In these experiments, three negative-ion-based neutral beams (N-NBs), and two positive-ion-based neutral beams (P-NBs) are injected with the power of 6 MW and 24 MW, respectively. The line averaged electron density ($n_{e\text{avg}}$) is changed from $1 \times 10^{19}$ m$^{-3}$ to $5 \times 10^{19}$ m$^{-3}$. The maximum $S_n$ in one shot as a function of $n_{e\text{avg}}$ in four different magnetic configurations are plotted in Fig. 2. The total neutron emission rate has a peak at $n_{e\text{avg}}$ of $2 \times 10^{18}$m$^{-3}$ to $3 \times 10^{18}$m$^{-3}$, as predicted by Fokker-Planck models [11]. Here, the increase of $S_n$ in the relatively low density range is due to the improvement of beam deposition, whereas the decrease of $S_n$ in the relatively high density range is due to the decrease of the slowing down time induced by the lower electron temperature. The total neutron emission rate becomes lower with the outward shift of the magnetic axis position ($R_{ax}$) in the same density. The maximum value of $S_n$ in the inward shifted configuration is approximately $3 \times 10^{15}$ n/s, whereas in the outward shifted configuration $S_n$ is approximately $3 \times 10^{14}$ n/s; there is almost one order of difference. There are two possible reasons for this. One is due to the plasma performance. In the LHD plasma, the plasma temperature tends to be higher in the inward shifted configuration compared with the outward shifted configuration with the same heating power and the plasma density. The higher electron temperature provides the longer slowing time at the same density. The other is due to the drift orbit of beam ions. In the inward shifted configuration, the guiding center orbit of helically trapped ions matched the flux surface. Therefore, confinement of helically trapped ions is predicted to be better in the inward shifted configuration compared with the outward shifted configuration. In addition, the deviation of the passing ion orbit from the flux surface becomes smaller in the inward shifted configuration compared with the outward shifted configuration. In order to see the effect of the plasma parameter on $S_n$, the neutron calculation with considering the fast-ion-orbit effect in the short time period is performed using FIT3D-DD code [12]. Here, the orbit following time is set to be 0.1 ms and the effective ion charge is set to be 1.

FIG. 1. The schematic drawing of the Large Helical Device, the neutron flux monitor, the neutron activation system, the vertical neutron camera, and the scintillating fiber detector.
Although the absolute value of \( S_n \) is almost two times higher in the FIT3D-DD code, \( S_n \) has a peak at \( n_{e_{\text{avg}}} \) of around \( 2 \times 10^{19} \) to \( 3 \times 10^{19} \) m\(^{-3} \) and \( S_n \) becomes lower as the outward shift of \( S_n \), as observed in the experiments.

**FIG. 2.** The dependence of the maximum total neutron emission rate in one shot on the line averaged density. The total neutron has the peak at around the density of \( 2 \times 10^{19} \) m\(^{-3} \) to \( 3 \times 10^{19} \) m\(^{-3} \).

The fusion gain of the LHD deuterium plasma is surveyed with N-NB heated plasmas. The fusion gain of deuterium plasma is defined as \( Q_{\text{DD}} = (S_n \times 7.25 \text{ MeV})/(P_{\text{N-NB dep}}) \). The dependence of \( Q_{\text{DD}} \) on the deposition power is surveyed in the normal \( B_t \) (2.75 T) case and half \( B_t \) (1.375 T) case in the magnetic axis position of 3.6 m. The higher \( Q_{\text{DD}} \) is obtained in the normal \( B_t \) case compared with the half \( B_t \) case, as expected. The fusion gain increases as \( P_{\text{N-NB dep}} \) until 3 MW, and then the fusion gain becomes relatively flat in both cases. The equivalent \( Q_{\text{DT}} \) is evaluated using the FBURN code which is based on the classical beam ion confinement assumption [13]. In the case of deuterium beam injection to triton plasma, \( Q_{\text{DT}}/Q_{\text{DD}} \) is 249, whereas \( Q_{\text{DT}}/Q_{\text{DD}} \) is 164 in the case of triton beam injection to deuterium plasma. Note that the reason for higher \( Q_{\text{DT}}/Q_{\text{DD}} \) in deuterium beam injection to triton plasma compared with triton beam injection to deuterium plasma is that the relative velocity is higher in the case of deuterium beam injection. The value of \( Q_{\text{DT}}/Q_{\text{DD}} \) is almost the same as \( Q_{\text{DT}}/Q_{\text{DD}} \) obtained in TFTR [14]. The maximum equivalent \( Q_{\text{DT}} \) in the first campaign of the LHD deuterium experiment is 0.11 which is almost the same value obtained in large tokamaks with 5 MW NB injections [14-16]. The dependence of \( Q_{\text{DD}} \) on the plasma parameters is surveyed. It is found that that the \( Q_{\text{DD}} \) linearly increases with \( T_{e_{01.5}} \) (Fig.4 (b)). In the NB-heated LHD plasmas, neutrons are mainly created by a beam-plasma reaction. Therefore, the fusion gain can be approximately expressed as \( Q_{\text{DD}} \sim S_n/P_{\text{NB}} \sim n_i P_{\text{NB}} \times \tau_{s}/P_{\text{NB}} \sim n_i \times T_{e_{01.5}}/n_e \sim T_{e_{01.5}} \). Figure 4 (b) insists that neutrons are mainly created by a beam-thermal reactions, as expected.

**FIG. 4.** (a) \( Q_{\text{DD}} \) as a function of absorbed power of N-NB injection measured in the experiment. Equivalent \( Q_{\text{DT}} \) is evaluated by FBURN code. Higher \( Q_{\text{DD}} \) can be obtained in higher magnetic field strength configuration, as expected. (b) \( Q_{\text{DD}} \) as a function of \( T_{e_{01.5}} \). \( Q_{\text{DD}} \) proportionate to \( T_{e_{01.5}} \) showing that neutrons are mainly created by beam-thermal reactions.
We performed NB blip experiments with P-NB injection having the acceleration voltage of 55 kV into the ECH plasma in order to study the beam ion confinement. In this experiment, $n_{\text{e,avg}}$ is approximately $1.5 \times 10^{19}$ m$^{-3}$ and the central electron temperature is 3 keV. The injection power of electron cyclotron heating (ECH), and NB is 0.8 MW and 7 MW, respectively. The time evolution of $S_n$ measured in experiment shows that the decay time of $S_n$ is 216 ms. Time evolution of $S_n$ obtained with the experiment is compared with the numerical simulation using the five-dimensional drift kinetic equation solver based on the Boozer coordinates, the Global NEoclassical Transport (GNET) code [17] using the experimental data. It is found that not only the decay time of $S_n$, but also the absolute value of $S_n$ matched with that obtained in the experiments.

![FIG. 5. Time evolution of total neutron emission rate in NB blip experiment. The time trace of total neutron emission rate successfully reproduced by GNET calculation.](image)

4. NEUTRON PROFILE STUDY

The neutron emission profile measurement in N-NB heated deuterium plasma using the vertical neutron camera is performed in three different magnetic axis configurations. In this experiment, an N-NB (NB#3) is injected into the ECH plasma. The central electron temperature and $n_{\text{e,avg}}$ are 4 keV and $1.2 \times 10^{19}$ m$^{-3}$, respectively. The line-integrated neutron emission profile shown in Fig. 6 indicates that the neutron counts decreased as the outward shift of $R_{\text{ax}}$. The behavior of neutron counts is consistent with the dependence of $S_n$ in different $R_{\text{ax}}$ configurations shown in Fig. 2. The peak of the neutron counts changed according to $R_{\text{ax}}$. Note that in the calculation, the line-integrated neutron emission profile is narrower compared with experiments. The spread of the VNC sightline could be one reason for the narrow profile and will be included.

![FIG. 6. (a) Line-integrated neutron emission profile measured by the vertical neutron camera. The neutron count increases with the inward shift of the magnetic axis. The peak of neutron counts changes according to the magnetic axis, as expected. (b) Line-integrated neutron emission profile calculated by the MORH code. The absolute neutron count is the same order as the count in the experiment. The shift of the neutron counts peak according to the magnetic axis is reproduced.](image)
5. TRITON BURNUP STUDY

The triton burnup study is performed for the first time in stellarator and helical devices. The triton burnup ratio is defined as \( S_{n_{DT}} / S_{n_{DD}} \), where \( S_{n_{DT}} \) and \( S_{n_{DD}} \) represent total DT neutron emission rate and total DD neutron emission rate, respectively. The triton burnup experiments are performed in \( R_{ax} \) from 3.55 m to 3.90 m by the scintillating fiber detector calibrated by the neutron activation system. The triton burnup ratio as a function of \( R_{ax} \) shown in Fig. 7 indicates that the triton burnup ratio substantially increases with the inward shift of \( R_{ax} \). Here, the different triton burnup ratio obtained in each \( R_{ax} \) condition is due to the different density. The maximum triton burnup ratio achieved in the first deuterium campaign in the LHD is 0.45 \%, which is a similar value to that obtained in middle-sized tokamaks whose minor radius is comparable to the LHD [18, 19]. The triton burnup ratio is evaluated using the GNET code in \( R_{ax} \) of 3.5 m, 3.6 m, and 3.75 m. The calculation result shows that the triton burnup ratio increases with the inward shift of \( R_{ax} \) as obtained in experiments. However, the absolute value of the triton burnup ratio is lower than the value obtained in experiments. The mismatch of the absolute value might be due to the finite Larmor radius and re-entering effects because the guiding center orbit of triton is followed in the Boozer coordinates in GNET code.

![Fig. 7. Triton burnup ratio as a function of the magnetic axis position. An increase of triton burnup ratio with the inward shift of magnetic axis is reproduced by the GNET calculation.](image)

6. SUMMARY

The research on the energetic particle confinement has progressed by means of comprehensive neutron diagnostics installed for the deuterium operation of the LHD plasma. The total neutron emission rate dependence on electron density shows that \( S_n \) has a peak around \( n_{e_{avg}} \) of \( 2 \times 10^{19} - 3 \times 10^{19} \) m\(^{-3} \) as predicted by Fokker-Planck code and FIT3D-DD code. The fusion gain of the N-NB heated deuterium plasma is evaluated to be \( 4.0 \times 10^{-4} \) which is comparable with the value obtained in the large tokamak with similar heating power. The equivalent \( Q_{DT} \) of 0.11 is calculated by FBURN code using the experimental data. The NB blip experiments are performed in electron cyclotron heated plasma with P-NB injection. Not only the decay time of \( S_n \) but also the absolute value of \( S_n \) matched with the GNET code. The result indicates that beam ion transport can be described with the neoclassical model in magnetohydrodynamic quiet low-beta plasmas. Neutron emission profile from stellarators and helical devices is obtained for the first time. The line-integrated neutron emission profile shows that the peak of the profile shifted outward as expected. The shift of the neutron emission profile as well as absolute neutron counts are reproduced by MORH code. The triton burnup experiment is performed in various magnetic field configurations. This is the first triton burnup experiment in stellarators and helical devices. It is found that the triton burnup ratio increases considerably with the inward shift of the magnetic axis in both experiment and numerical simulation.

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