Fast ion confinement study by NB blips in the LHD deuterium plasma

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Introduction

The measurement of the neutron intensity decay time (τ_n) after the short pulse NB injection called "NB-blip" is a very convenient tool for the study of the NB-injected fast ion confinement. This is because an NB-blip provides insignificant impact on major plasma parameters, such as the electron density and the temperature. This experiment is widely carried on many magnetic confinement devices[1-6]. Also, the NB-blip experiment was performed in the first deuterium plasma campaign of the Large Helical Device (LHD) in March-July, 2017 [7].

Generally, neutron intensity decay time after the NB blip is analyzed by a 0-dimensional fast ion slowing down model, where differences in the beam deposition profile for each shot are not taken into account, which may cause large ambiguity of the calculated value of τ_n. We have developed a neutron emission rate calculation code FBURN [8,9] based on the classical slowing down model, which takes into account of not only the beam deposition profile but also other plasma parameter profiles such as the electron density and the electron temperature, and time evolutions of those parameters. Here not only τ_n but also absolute neutron emission rate during the NB-blip have been analyzed with the FBURN code for the various plasma configurations.

Experimental setup and plasma operation scenario

LHD has five NB injectors. NBI#1, #2, and #3 are tangential direction injectors with negative-ion sources whose typical energy is 180 keV. NBI#4 and #5 are perpendicular direction injectors with positive-ion sources whose typical energies are 60 keV and 80 keV, respectively. In this experiment, the direction of the toroidal field is counter clockwise viewed from above. Therefore, NBI#1 and #3 are co-direction injections to the toroidal magnetic field, and NBI#2 is a counter-direction injection.

The absolute neutron emission rate has been measured with the Neutron Flux Monitor (NFM), which consists of ^{235}U fission chambers and additional highly sensitive neutron detectors of a ^{10}B proportional counter or a ^{3}He proportional counter. The NFMs are positioned at three locations outside the cryostat: on the top of the center axis and near two large outside ports. The NFM has a wide dynamic range up to 5×10^9 cps and the temporal resolution of 2 ms [10], which are absolutely calibrated by ^{252}Cf neutron source rotating inside the LHD vacuum vessel [11].

Figure 1 shows the typical waveforms of the NB-blip experiment. NBI#1, #2, #3 and #4 with the pulse width of 40 ms were injected into the plasma with 0.7 s duration time. The line averaged electron density was controlled to remain constant at 2×10^{19}m^3. Also, it is confirmed that the electron temperature was kept almost constant from 3.7 sec to 5.3 sec. The plasma was sustained with the ECH of 2.5 MW. It is clearly seen that neutron emission rate (S_n) measured with NFM decays exponentially after each NB-blip.

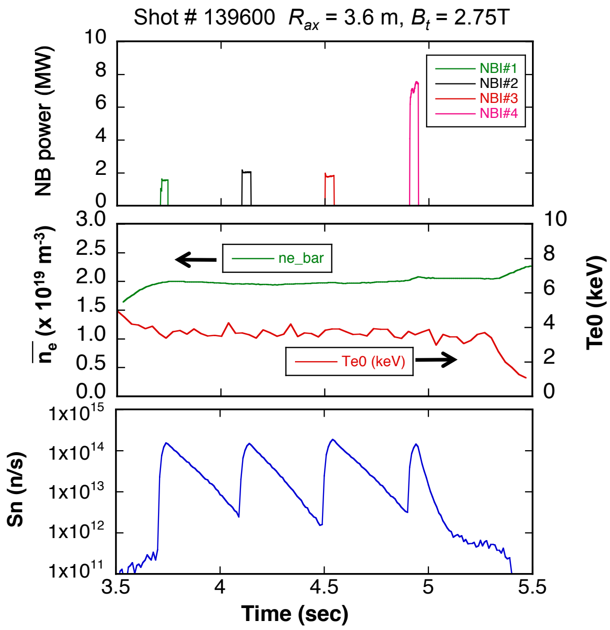

Figure 1: *Typical waveforms of the NB-blip experiment at LHD.*

In this experiment, NB-blips were injected to plasmas with the magnetic axis R_{ax} of 3.6, 3.75, and 3.9 m in the range of the line-averaged electron density of 0.5×10^{19} m^3- 4×10^{19} m^3.

FBURN code

The FBURN code has been developed for the time dependence analyses for D-D and secondary D-T reactivity in NB heated plasmas using experimental data. Here we use the D-D neutron yield estimation function of the FBURN code, where only beam-thermal reaction is considered. The plasma is divided into 100 nested shells. The volume of each shell is given according to the equilibrium reconstructed by the VMEC2000 code [12] based on experimentally obtained plasma parameters such as the temperature and the density profiles. The deposition profile of beam ions is calculated by the FHREYA code [13]. NB-injected ions are assumed to be frozen in each shell and to be slowed down according to the classical energy loss theory using the following equation [14] in the shell, which is similar to BURNIT code [15] and TBURN code [16].

$$\left(\frac{dE}{dt}\right)_{classical} = -\frac{\alpha}{\sqrt{E}} - \beta E \qquad (1)$$

$$\alpha = 1.81\times10^{-13}\ln\Lambda_{ii}A^{1/2}Z^2\sum_j\frac{n_jZ_j}{A_j} \quad , \quad \beta = 3.18\times10^{-15}\ln\Lambda_{ei}\frac{Z^2}{A}\frac{n_e}{T_e^{1.5}}$$

where E is the deuteron energy and T_e is the electron temperature, both in eV, n_e is the electron density in m^{-3} and $ln\Lambda$ is the Coulomb logarithm. A and Z are the deuteron mass and charge number: n_j, A_j, and Z_j are the deuterium and impurity density in m^{-3}, which are the mass and charge numbers, respectively. The typical time step in the slowing down calculation is 2 ms. The local emissivity of DD neutrons is calculated from the reaction between Maxwellian and the fast ions during the slowing down process. Neutrons from thermal-thermal and fast-fast DD reactions are not calculated because the contribution of those reactions is negligibly small in this experiment.

Fast ion confinement analyses

Figure 2 shows the time evolution of the neutro n emission rate calculated by the FBURN code compared with the measured neutron emission rate. Here, we evaluate the fast ion confinement by two different methods.

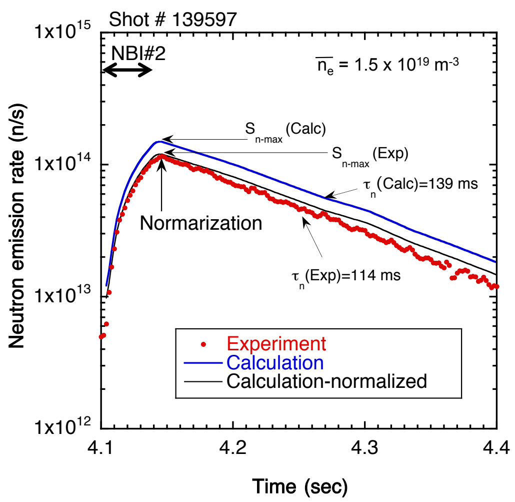

Figure 2: *Time evolution of the neutron emission rate calculated by the FBURN code compared with the measured neutron emission rate.*

One method is from the ratio of measured and calculated neutron emission rate at the NB-blip termination, which are represented by $S_{n\text{-}max}$ *(Exp)* and $S_{n\text{-}max}$ *(Calc)*, respectively. $S_{n\text{-}max}$ *(Calc)* is calculated assuming no fast ion losses. Therefore, the confinement time of fast ions τ_c is evaluated by $\Delta t/ln\{S_{n\text{-}max}(Exp)/S_{n\text{-}max}(Calc)\}$, where Δt is the time width of the NB blip. The diffusivity of a fast ion D is derived from the relation $\tau_c = a_p^2/5.8\,D$, where a_p is averaged plasma minor radius. The other method is the evaluation of τ_c from the decay time constant of the measured and calculated neutron emission rates after the NB-blip termination, which are represented by τ_n and τ_{calc}, respectively, using the relation $1/\tau_n = 1/\tau_c + 1/\tau_{calc}$. In this experiment, τ_n and τ_{calc} are evaluated by the exponential fitting of the neutron emission rate decay from $S_{n\text{-}max}$ to $S_{n\text{-}max}/10$.

It is considered that the ion losses are caused by prompt loss, collision-less diffusion and collisional diffusion. The τ_c derived from the first method is reflected by the collisional diffusion primarily and that from the second method is reflected by the collision-less diffusion and prompt loss primarily.

Results

Figure 3(a) shows the diffusivity of a fast ion derived from $S_{n\text{-}max}$ plotted against the major radius of the magnetic axis R_{ax}, where line-averaged electron density is in the range of 0.5 × 10^{19} m^3- 4 × 10^{19} m^3. For perpendicular injections, the fast ion diffusivity is 2-5 m^2/s and increases with R_{ax}. For tangential injections, the fast ion diffusivity is smaller than 1.2 m^2/s at R_{ax} of 3.6 m, and 0.2-1.8 m^2/s at R_{ax} of 3.75 m and 3.9 m. There is not significant difference between the diffusivities at R_{ax} of 3.75 m and 3.9 m. The diffusivity of a fast ion derived from τ_n is much smaller than that from $S_{n\text{-}max}$ as shown in Figure 3(b), which indicates that prompt loss and collision-less diffusion are larger than collisional diffusion for the NB injected fast ions at LHD. In Figure 3(b), the diffusivities at R_{ax} of 3.9 m are larger than those at R_{ax} of 3.6 m and 3.75 m. However, difference between the diffusivities at R_{ax} of 3.6 m and 3.75 m is not clear.

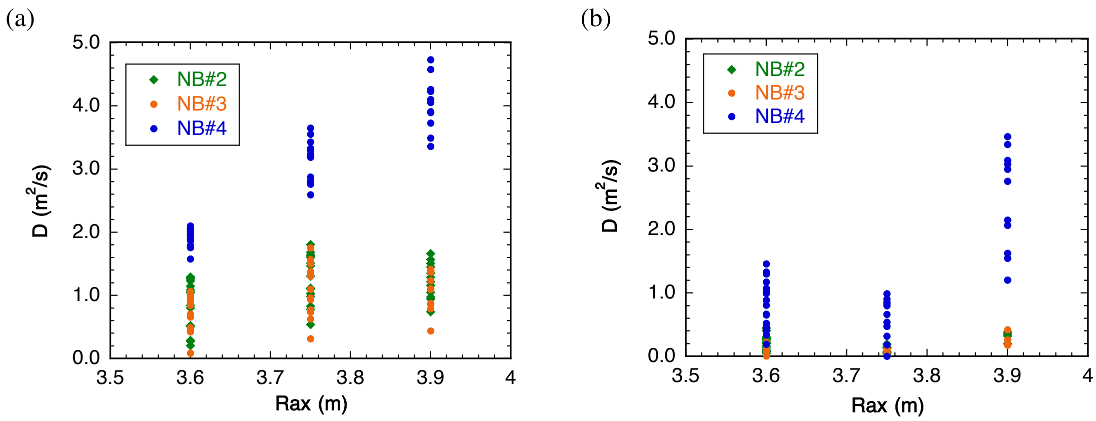

Figure 3: *Diffusivity of a fast ion derived from (a) maximum neutron emission rate for NB blip and (b) decay time constant of the neutron emission rate after NB blip.*

References

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