Fast Ion Confinement Study by Neutron Emission Rate Measurement after Short Pulse NB Injection in the Large Helical Device*)

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The confinement of neutral beam (NB)-injected fast ions has been investigated by the neutron intensity decay time (τ_n) after the short pulse NB injection called "NB-blip." The Large Helical Device (LHD) has five NB injectors. NBI#1, #2, and #3 are tangential direction injectors with typical energy of 180 keV. NBI#4 and #5 are perpendicular direction injectors with typical energies of 60 keV and of 80 keV, respectively. In this experiment, NBI#1, #2, #3, and #4 each with the pulse width of 40 ms are injected into different configuration plasmas with various electron densities. The τ_n is analyzed with a 0-dimensional fast ion slowing down model. The loss of the fast ion increases significantly with decrease in the electron density. From the comparison of calculated and measured τ_n for different plasma configurations, the fast ion confinement is worst on the outward shifted plasma of R_{ax} = 3.90 m. On the other hand, it seems that the fast ion confinement is best on the plasma of R_{ax} = 3.74 m.

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1. Introduction

The first deuterium plasma experiment was conducted in March-July, 2017, in the Large Helical Device (LHD). In LHD, neutrons are mainly produced by reactions between beam ions and bulk plasma ions. The beam-bulk plasma reactivity is the strong function of the beam ion energy. Therefore, the neutron emission rate measurement is an effective tool for studying the NB-injected fast ion confinement. In particular, 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, because an NB-blip provides insignificant impact on major plasma parameters, such as the electron density and temperature. This experiment is widely carried on many magnetic confinement devices [1–6]. However, it has not been applied for the large stellarator with the deuterium plasma operation. LHD has various NB injectors with different energy and different injection angles. Also, a neutron flux monitor with a wide dynamic range and the fast time resolution are equipped on LHD. Here, we investigated the confinement of NB-injected fast ions with the τ_n measurement on the various plasma configurations.

2. Experimental Setup

LHD has five NB injectors as shown in Fig. 1 [7]. 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 counterclockwise 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.

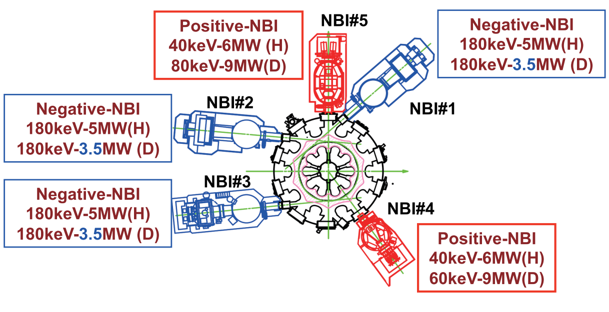

Fig. 1 Arrangement of the NB injectors on LHD.

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Table 1 List of plasma configurations.

#	R_{ax} (m)	B_t (T)
1	3.6	2.75
2	3.75	2.64
3	3.9	2.538
4	3.6	1.375

R_{ax}: Major radius of the plasma axis; B_t: Toroidal field

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 NFM are positioned at three locations outside the cryostat: on the top of the center axis and near two large outside ports called the 4-O port and the 10-O port. The NFM has a wide dynamic range up to 5×10^9 cps and the temporal resolution of 2 ms [8].

NBI#1, #2, #3 and #4 with the pulse width of 40 ms were injected to the various configuration plasmas (see Table 1) with various electron density. The response of the neutron emission rate for NB injection is measured with NFM. The plasma was sustained with the ECH of 2.5 MW.

3. Experimental Results

Figure 2 shows the typical waveforms of the NB-blip experiment. The neutron emission rate (*Sn*) decays exponentially after each NB-blip. The neutron intensity decay time (τ_n) is evaluated by the e-folding decay time of *Sn*.

It is found that the NB-blips do not affect plasma parameters such as electron density and electron temperature. Therefore, the bulk plasma can be regarded to be constant during the NB-blip and the succeeding neutron emission rate decay phase.

Figure 3 shows the time histories of the neutron emission rate in the NB blip experiments with different electron density. It is clearly seen that τ_n becomes faster with the electron density.

Figure 4 shows measured τ_n as a function of line-averaged electron density for the plasma with R_{ax} = 3.6 m and B_T = 2.75 T. The τ_n decreases exponentially with the electron density. The τ_n for the NBI#4 is approximately 1/3 of those for NBI#1, #2, and #3. It seems that the τ_n for the NBI#2 is slightly shorter than those for NBI#1 and #3. However, we could not conclude that the difference is due to the effect of co- and counter injection of the beam, because the beam energy of NBI#2 is 20 - 30 keV lower than that of NBI#1 and NBI#3 in this experiment.

Measured τ_n as a function of line-averaged electron density for different plasma configurations is shown in Figs. 5 (a) and 5 (b). There is no significant difference between τ_n for R_{ax} = 3.6 m (B_t = 2.75 T) and R_{ax} = 3.75 m (B_t = 2.64 T). The τ_n for R_{ax} = 3.9 m (B_t = 2.538 T) is clearly shorter than those for R_{ax} = 3.6 m (B_t = 2.75 T) and R_{ax} = 3.75 m (B_t = 2.64 T) at the same electron density. Also, the τ_n for R_{ax} = 3.6 m (B_t = 1.375 T) is approximately one-half

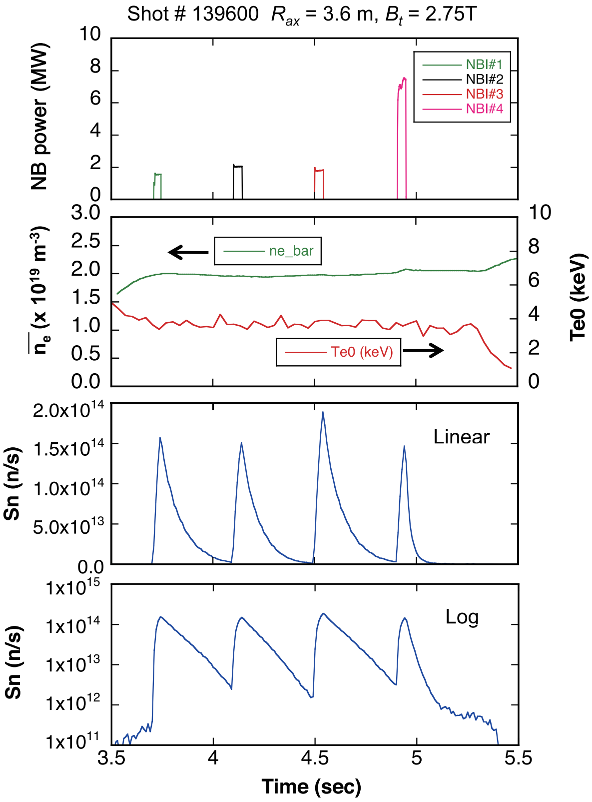

Fig. 2 Typical waveforms of the NB-blip experiment.

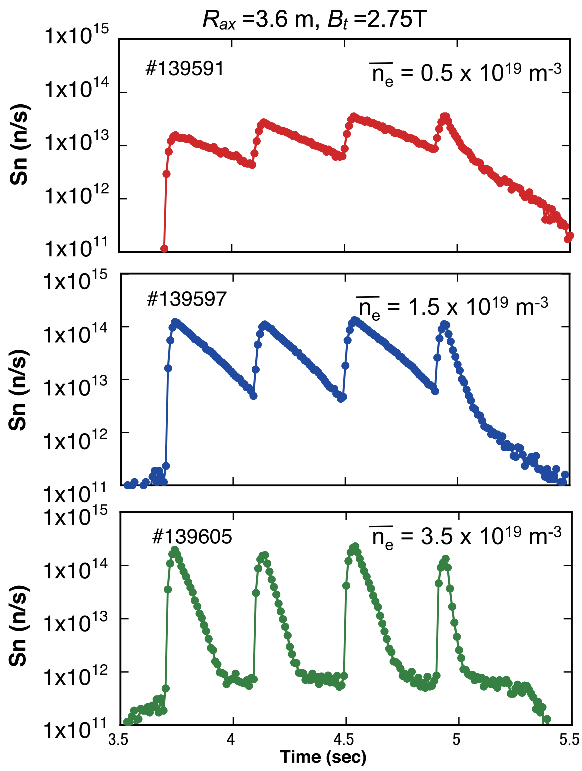

Fig. 3 Time histories of the neutron emission rate at the NB blip experiments with different electron density.

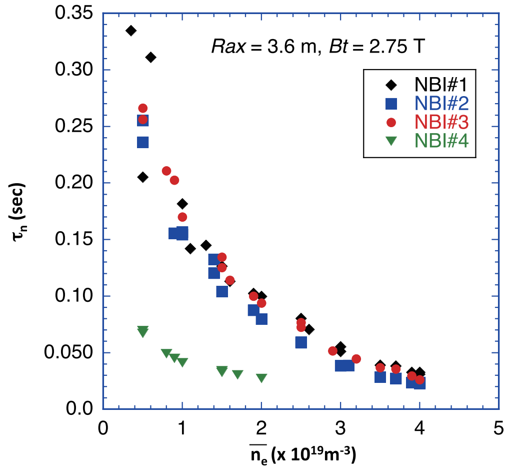

Fig. 4 Measured τ_n as a function of line-averaged electron density for the plasma with R_{ax} = 3.6 m and B_t = 2.75 T.

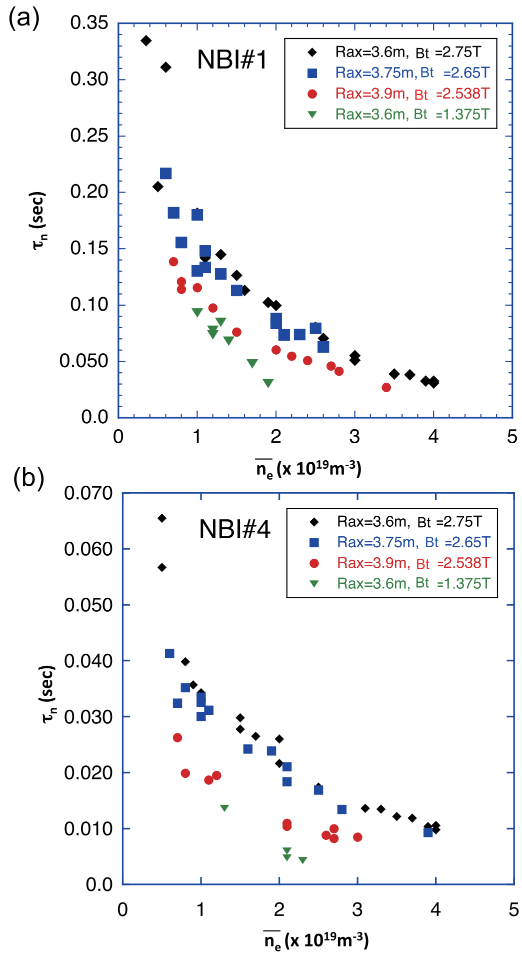

Fig. 5 Measured τ_n as a function of line-averaged electron density for different plasma configurations. (a) is for NBI#1, #2, and #3, and (b) is for NBI#4.

of that for R_{ax} = 3.6 m (B_t = 2.75 T), which suggests that the fast ion confinement degrades with the decrease in the toroidal magnetic field.

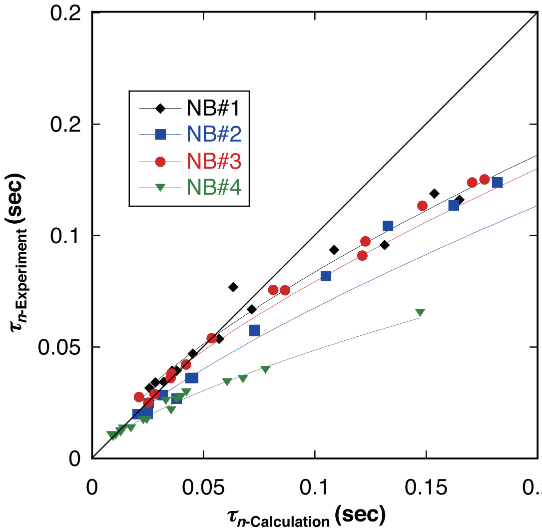

Fig. 6 Comparison of calculated and measured τ_n for the plasma with R_{ax} = 3.6 m and B_t = 2.75 T.

4. Analyses

The e-folding time of the neutron emission rate after the NB-blip is analyzed by a simple slowing down model. The τ_n, is represented by the following equation [9],

$$\tau_n = \frac{\tau_{se}}{3} \ln \frac{E_b^{3/2} + E_c^{3/2}}{E_n^{3/2} + E_c^{3/2}}, \tag{1}$$

where τ_{se} is the Spitzer slowing-down time of the fast ion on electrons as,

$$\tau_{se} = \frac{1.3 \times 10^9 T_e\,[\mathrm{eV}]^{3/2}}{n_e \ln \Lambda_{ie}}, \tag{2}$$

E_b is the beam energy, E_c is the critical energy, and E_n is the energy where the beam-thermal reactivity is reduced to 1/e, and Λ_{ie} is the Coulomb logarithm for electron-ion collisions. Here, τ_{se} is evaluated from the line-averaged electron density and the electron temperature at ρ/2. Those parameters are assumed to be constant during the NB-blip and the neutron emission rate decay period. E_n is a weak function of the ion temperature and a strong function of the beam energy. We calculated E_n for each NB-blip assuming the ion temperature to be 1 keV, because measured ion temperature is around 1 keV in this experiment.

Figure 6 shows the comparison of calculated and measured τ_n for the plasma with R_{ax} = 3.6 m and B_t = 2.75 T. In the region of calculated τ_n shorter than 0.05 sec, which is the higher electron density region, the measured τ_n has good agreement with the calculated τ_n for NBI#1, #2, and #3. The measured τ_n is shorter than the calculated τ_n in the region of calculated τ_n shorter than 0.05 sec. The deviation of measured and calculated τ_n increases with the calculated τ_n, which indicates that the loss of fast ions increases in lower electron density. The measured τ_n for NBI#2 is slightly shorter than the measured τ_n for NBI#1 and #3, which is probably because that NBI#2 is counter injection.

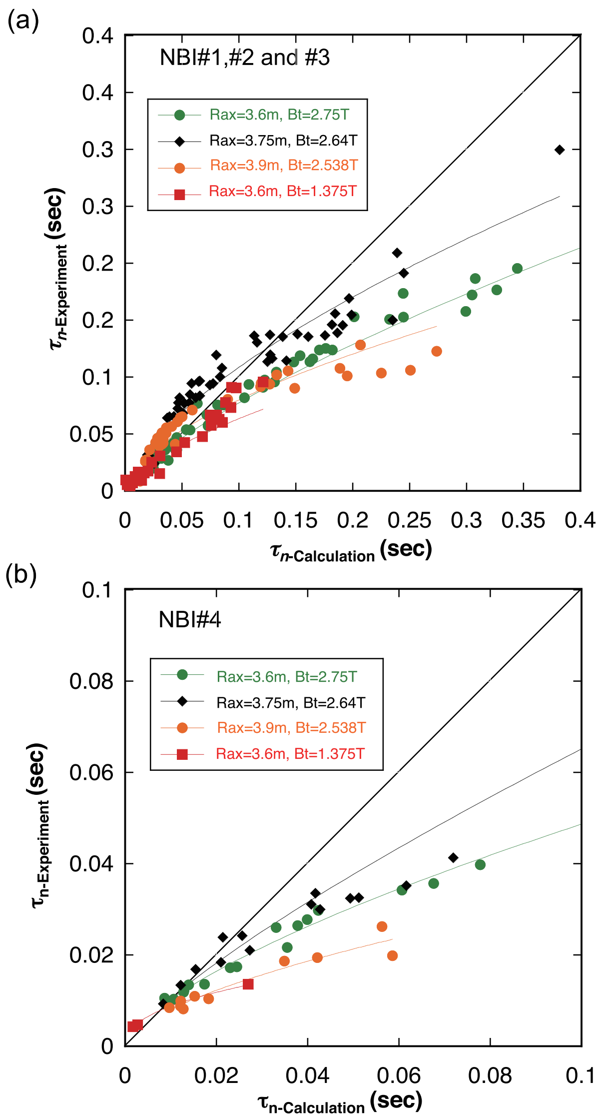

Fig. 7 Comparison of calculated and measured τ_n for different plasma configurations. (a) is for NBI#1, #2, and #3, and (b) is for NBI#4.

The measured τ_n for NBI#4 is approximately 1/2 of the calculated τ_n, which indicates that the confinement of perpendicular injected fast ions is worse than the confinement of tangentially injected fast ions in LHD.

The comparison of calculated and measured τ_n for different plasma configurations is shown in Figs. 7 (a) and 7 (b). It seems that the loss of fast ions is the lowest in the configuration with R_{ax} = 3.74 m (B_t = 2.64 T) for tangential injections. The reason for this loss is under discussion. Also the loss of fast ions is largest in the configuration with R_{ax} = 3.6 m (B_t = 1.375 T), which indicates that the fast loss increases with the decrease in the toroidal magnetic field at the same magnetic axis.

5. Summary and Discussion

The confinement of the NB-injected fast ion has been investigated by the neutron emission rate decay time, t_n, after the short pulse NB injection. The τ_n is analyzed with a simple fast ion slowing down model. The loss of the fast ion increases significantly with decrease in the electron density. From the comparison of calculated and measured τ_n for different plasma configurations, the fast ion confinement is the worst on the outward shifted plasma of R_{ax} = 3.90 m. On the other hand, it seems that the fast ion confinement is the best on the plasma of R_{ax} = 3.74 m (B_t = 2.64 T). Also, the fast loss increases with the decrease in the toroidal magnetic field at the same magnetic axis of the plasma.

This simple analysis does not take into account the beam deposition profile, which is affected by the electron density. More precise analyses taking account of the beam deposition profile should be performed in the near future.

Acknowledgments

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