Experimental Check of Deceleration of Neutral Beam-Injected Energetic Ions in the HL-2A Tokamak*)

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Short pulses of a deuterium neutral beam (NB) with a duration of less than ~ 5 ms were co-injected into magnetohydrodynamic (MHD)-quiescent ohmic deuterium plasmas of the HL-2A tokamak to study the variation of the slowing-down time in two different electron temperature environments. Analyses were made for the decay rate of D-D neutrons produced by beam-plasma interaction following NB turn-off, i.e., experimentally observed neutron decay rates were compared with those predicted by a classical slowing-down model. The results suggest the beam ions decelerate without significant loss in the HL-2A tokamak in round terms. When the critical energy for beam ions is higher than the beam injection energy, it seems that a small fraction of the beam ions is lost.

Keywords: HL-2A, NBI, deuterium, energetic ion, neutron, beam blip

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1. Introduction

The physics issue related to energetic ions is of great concern in magnetically confined fusion plasmas, since charged energetic fusion products will play a role as primary heating source and sustain a self-ignited condition in future burning plasmas. For this reason, numerous efforts have been made in existing fusion devices to reveal issues related to energetic ions such as ripple-induced diffusion and/or loss, and rapid transport due to magnetohydrodynamic (MHD) instabilities, as reviewed in Refs. [1, 2].

In the HL-2A tokamak, high-energy deuterium neutral beam (NB) injection was begun in October 2008. While the NB injection can efficiently heat target plasmas, energetic beam ions act as a free energy source to destabilize energetic-ion-driven MHD instabilities such as Alfvén eigenmodes and the fishbone (FB) mode. Beam-ion-driven FB modes have already been observed during NB injection in the HL-2A tokamak [3]. In this work, we examined the more fundamental issue of a steady-going step. We injected a deuterium NB of which the pulse duration was much less than the slowing-down time for beam ions into MHD-quiescent ohmic deuterium plasmas and measured the neutron decay rate following the NB turn-off. This method is often called "beam blip" and has been widely used in magnetically confined plasma experiments, i.e. DIII-D, TFTR, JT-60U and CHS [4–7]. Because in the HL-2A condition the total neutron yield is dominated by neutrons produced by the beam-plasma reaction, the neutron decay rate after beam blip provides information about deceleration and/or dilution of beam ions. The first beam blip experiment in the HL-2A was carried out in plasmas with low B_t/I_p (= 1.3 T/130 kA) [8]. In 2010, we performed beam blip injection in higher B_t/I_p (= 2.4 T/325 kA), in other words, in a longer slowing-down time regime through a higher electron temperature.

In Sec. 2, energetic ions, e.g., arrangement of the neutral beam injector (NBI) and typical beam ion orbit in the HL-2A are described. In Sec. 3, the beam blip experiment and analyses of the neutron decay rate following the beam blip are reported. Finally, this work is briefly summarized in Sec. 4

2. Experimental Setup

2.1 Energetic ions in HL-2A

Experiments were performed on the HL-2A tokamak (R_{ax} = 1.65 m, a = 0.4 m) with lower single-null divertor configuration. The toroidal magnetic field, B_t, is directed to be clockwise (CW), whereas the plasma current, I_p, is oriented to be counter-clockwise (CCW) in the standard operation as seen from the top. An NBI equipped with four positive ion sources is installed on the HL-2A [9]. The typical acceleration voltage and the port-through power are about 30 kV and 0.8 MW, respectively. Arrangement of the NBI on the HL-2A is depicted in Fig. 1 a). The NB is tangentially co-injected with a tangency radius, R_{tan} of 1.4 m. The initial beam ion velocities are therefore not perfectly parallel to the magnetic axis.

The Lorentz orbit code was developed to check the class of initial beam-ion orbit right after ionization. Full gyromotion following orbits are tracked in the cylindrical

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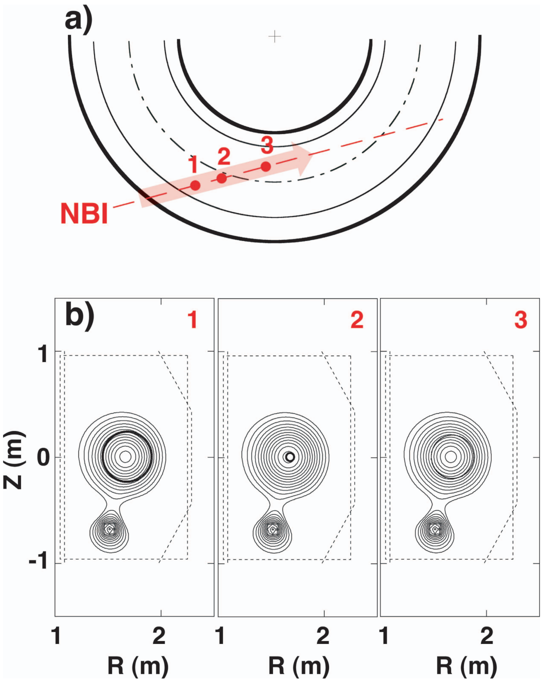

Fig. 1 a) Arrangement of the NBI on the HL-2A. B_t and I_p are oriented to be CW and CCW, respectively, as seen from the top. b) Initial collisionless orbits of beam ions with E of 30 keV on the center of the beam line at plasma of B_t = 2.4 T/I_p = 305 kA and q_{95} of ~ 3.8.

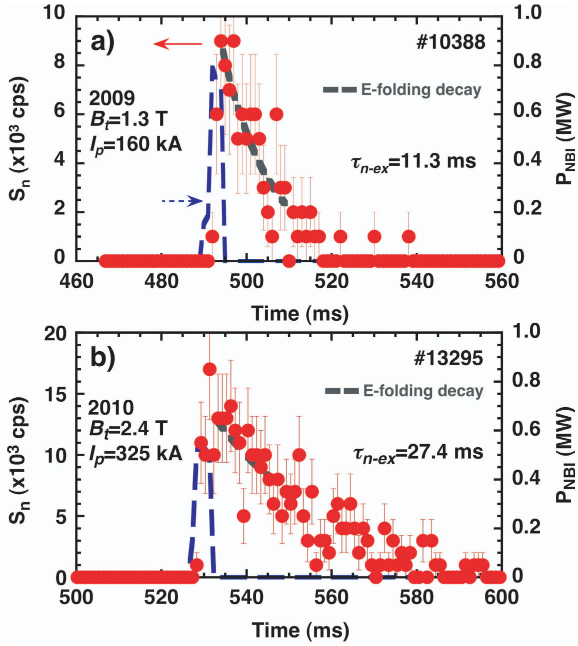

Fig. 2 a) Time evolution of the neutron emission rate S_n, when the deuterium beam blip is injected into the MHD quiescent ohmic plasma in B_t/I_p of 1.3 T/160 kA. b) The neutron emission rate due to the beam blip in B_t/I_p of 2.4 T/325 kA. The line-averaged electron density (~ 1×10^{19} m^{-3}) and q_{95} (~ 3.8) are kept for both plasmas.

coordinate system (R, Z, ϕ). This code uses equilibrium data, i.e., the poloidal flux function $\Psi(R, Z)$ calculated by the EFIT code to produce the axisymmetric poloidal field components B_R (= $-(d\Psi/dZ)/R$) and B_Z (= $(d\Psi/dR)/R$). Currently, toroidal field ripple due to the finite number of toroidal coils is not considered. Fig. 2 b) shows three typical collisionless orbits of beam ions (E = 30 keV) ionized at different places on the center of the beam line. It can be seen that the initial orbits of beam ions are classified as passing orbits in the HL-2A.

2.2 Neutron rate measurement

A ^{235}U fission chamber (FC) with uranium oxide of 3 g [10] was employed to measure the total neutron emission rate. The FC was covered by a polyethylene moderator of about 5 cm in thickness to increase its sensitivity to thermal neutrons. In 2009, the FC was placed about 5 m away from the diagnostic port at the equatorial plane of the outboard side of the tokamak. To enhance neutron counts, the FC was moved and in 2010 was placed about 1.5 m away from the machine. Note that currently the FC system is operated in the pulse counting mode.

3. Experimental Results

Fig. 2 a) shows a typical time evolution of the D-D neutron rate when a deuterium beam blip with a pulse duration of ~ 4 ms was injected into an MHD quiescent ohmic plasma in B_t/I_p of 1.3 T/160 kA. The safety factor at the plasma edge, q_{95}, was ~ 3.9. The line-averaged electron density, n_e, and central electron temperature, $T_e(0)$, were ~ 1×10^{19} m^{-3} and ~ 0.8 keV, respectively, in this shot. D-D neutrons due to the beam-plasma interaction suddenly appear right after the NB turn-on. As can be seen in Fig. 2 a), the neutron emission rate starts to decay exponentially following the NB turn-off. The observed neutron decay rate is associated with $<\sigma v>_b$ becoming smaller in time as the beam ions of 30 keV decelerate through Coulomb collisions with the background plasma of the HL-2A. Here, $<\sigma v>_b$ represents the d-d reactivity of the neutron branch (D(d,n)^{3}He) for a high-energy deuterium injection into a deuterium Maxwellian plasma at finite-ion temperature. Note that the neutron decay time is much longer than the pulse duration of the NB. The e-folding neutron decay time is evaluated to be ~ 11 ms in this low B_t and I_p shot. The neutron decay rate should be sensitive to the electron temperature, T_e, because it is expressed as a function of the slowing-down time of beam ions [11]. Next, to verify the above-mentioned scenario, we injected the beam blip into a higher B_t and I_p plasma while keeping the values of n_e and q_{95}. In such a plasma, it can be expected that the slowing-down time for beam ions is longer because of the higher T_e.

Fig. 2 b) shows a time evolution of the neutron emission rate due to beam blip in B_t/I_p of 2.4 T/325 kA. The line-averaged n_e was intentionally kept at ~ 1×10^{19} m^{-3} and $T_e(0)$ was over 2 keV. It can be seen that the neutron decay rate in this discharge is much longer than that seen in Fig. 2 a), as expected. This is due to the longer slowing-down time on electrons ($\tau_{se} \propto T_e^{1.5}/n_e$) for beam ions though higher T_e. The e-holding neutron decay time is evaluated to be 27 ~ 28 ms for the higher B_t and I_p discharge.

4. Discussion

For the two discharges shown in Fig. 2, we analyzed the neutron decay rate following the beam blip injection to determine whether co-injected beam ions slow down classically without significant loss. The neutron emission rate from the beam-plasma reaction can be scaled as $S_n \propto n_i n_b <\sigma v>_b$. Here, n_i and n_b are the background plasma ion density and beam ion density, respectively. Assuming that $<\sigma v>_b$ decreases exponentially as beam ions slow down classically without loss and n_i is constant after the NB turn-off, S_n is predicted as $S_n(t) \propto <\sigma(v(t))v(t)>_b \approx \exp(-t/\tau_{n\text{-th}})$. Here, $\tau_{n\text{-th}}$ is the e-folding decay time of the neutron rate predicted by the model written above. According to the paper by Strachan [11], $\tau_{n\text{-th}}$ based on the classical slowing-down model can be expressed as follows:

$$\tau_{n\text{-th}} = -\int_{E_n}^{E_b} \frac{dE}{\{dE/dt\}_{th}} \cong \frac{\tau_{se}}{3} \ln \frac{E_b^{3/2} + E_c^{3/2}}{E_n^{3/2} + E_c^{3/2}}, \quad (1)$$

where E_n is the energy at which $<\sigma v>_b$ is reduced by $1/e$ from the value at E_b, E_c is the critical energy of beam ions at which the bulk electron Coulomb friction equals the bulk ion Coulomb friction and τ_{se} is the Spitzer's slowing-down time on electrons. Radial profiles of measured n_e, T_e and $\tau_{n\text{-th}}$ predicted from Eq. (1) for the discharge of B_t/I_p of 1.3 T/160 kA are shown in Fig. 3 and those for the discharge of B_t/I_p of 2.4 T/325 kA are shown in Fig. 4. The line of $\tau_{n\text{-ex}}$ is also drawn for each discharge. As seen in both Figs. 3 and 4, $\tau_{n\text{-th}}$ became shorter toward the peripheral region since τ_{se}, which is a key parameter in determining $\tau_{n\text{-th}}$, becomes shorter toward the peripheral region. E_c becomes smaller as T_e becomes smaller, and E_n becomes slightly larger toward the edge. Note that E_n is a function of $<\sigma v>_b$ through the value of T_i. $\tau_{n\text{-ex}}$ is roughly in agreement with $\tau_{n\text{-th}}$ in the core region ($r/a < 0.4$) for both discharges. This suggests that tangentially co-injected beam ions have a peaked profile, decelerating classically without significant loss in the HL-2A. It also tells us that the observed D-D neutrons were primarily produced from beam-target reactions in the core region. Note that a slight difference between $\tau_{n\text{-ex}}$ and $\tau_{n\text{-th}}$ in the higher T_e discharge with B_t/I_p of 2.4 T/325 kA is recognized while $\tau_{n\text{-ex}}$ agrees well with $\tau_{n\text{-th}}$ in the lower T_e discharge with B_t/I_p of 1.3 T/160 kA. There are two possible reasons for this difference. In the discharge at B_t/I_p of 2.4 T/325 kA, E_{crit} at the plasma center is about 38 keV and is higher than E_b, while E_{crit} for the discharge at B_t/I_p of 1.3 T/160 kA is about 16 keV and is lower than E_b. Therefore, pitch-angle scattering is probably enhanced in the higher T_e discharge, leading to toroidal field ripple trapping and consequent losses of beam ions. Another possibility is energetic-ion transport by plasma turbulence, which is being discussed intensively at present. This topic has been highlighted lately by experimental results with NB injection in ASDEX-Upgrade [12] and DIII-D [13]. Evidence for cross-field diffusion of energetic ions by micro-turbulence has been experimentally shown in a setting with low characteristics values of the ratio of fast-ion energy E to plasma temperature T. Note that energetic-ion transport by micro/turbulence above E_c is negligible. In the higher B_t and I_p discharge of the HL-2A, E_b is certainly below E_c, and this situation may lead to anomalous transport of beam ions by plasma turbulence. To clarify this, more beam blip shots together with superior turbulence diagnostics are required.

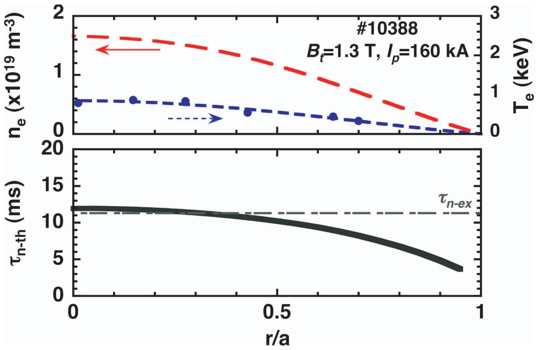

Fig. 3 Radial profiles of the electron density, n_e, and the temperature, T_e (top) in the discharge at B_t/I_p of 1.3 T and 160 kA and the D-D neutron decay time, $\tau_{n\text{-th}}$, predicted by the classical slowing-down model. The experimentally evaluated neutron decay time, $\tau_{n\text{-ex}}$, is also drawn.

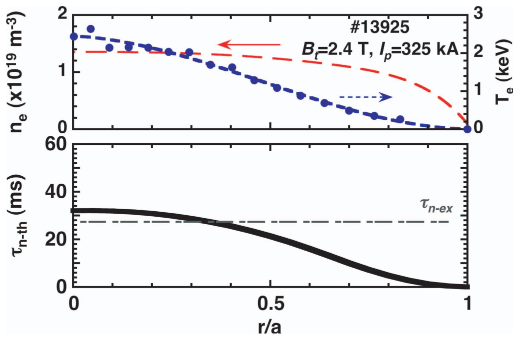

Fig. 4 Radial profiles of the electron density, n_e, and the temperature, T_e (top) in the discharge at B_t/I_p of 2.4 T and 325 kA and the D-D neutron decay time, $\tau_{n\text{-th}}$, predicted by the classical slowing-down model. The experimentally evaluated neutron decay time, $\tau_{n\text{-ex}}$, is also drawn.

5. Summary

The deceleration property of tangentially co-injected beam ions was experimentally studied in two different B_t/I_p discharges, 2.4 T/325 kA and 1.3 T/160 kA of the

HL-2A tokamak by injecting a short pulse high-energy deuterium beam. In the higher B_t and I_p plasma, the rate of decay of the D-D neutrons due to the beam-plasma interaction following the beam blip was much longer than that observed in the lower B_t and I_p plasma, as expected, because the slowing-down time in the former, higher T_e discharge is longer than that in the latter, lower T_e discharge. Analyses on the neutron decay rates after NB turn-off for both discharges suggest that in broad terms, co-injected beam ions decelerate without significant losses of beam ions in the core domain. This tells us that tangentially co-injected beam ions have a peaked profile and observed D-D neutrons are primarily produced from beam-target reactions in the core region. We note in particular that the experimentally observed neutron decay rate in the discharge with B_t/I_p of 1.3 T/160 kA agrees well with the decay rate predicted by the classical slowing-down model. On the other hand, although beam ion orbits are expected to be better in B_t/I_p of 2.4 T/325 kA, the slight difference between experimental and predicted neutron decay rates in the core domain is recognized. This small discrepancy may be due to enhanced pitch angle scattering through a higher T_e environment or the anomalous transport of beam ions associated with plasma turbulence in the condition of $E_c > E$.

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