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Neutralization loss of high energy particles in the plasma boundary of LHD

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Abstract

The neutralization loss of high-energy particles is studied by investigating the density dependence of the energetic neutral flux from large helical device plasmas of hydrogen and helium discharges. Clear difference between the density dependence of energetic particles originated from neutral beams and those produced by ion cyclotron radio frequency (ICRF) is observed. One of the causes of this difference is the spatial profiles of energetic particles characteristic to each heating scheme. The spatial distributions of H^0, He^0, He^+ are calculated as a function of the neutral source temperature entering across the Last Closed Flux Surface (LCFS) including six charge exchange processes, assuming a cylindrical geometry (ACHEN-Code). While the observed density dependence of energetic neutral flux escaping from ICRF-heated helium plasmas is well reproduced by the calculation with the incoming neutral temperature of about 10 eV, that from NBI-heated helium plasmas shows more modest dependence than the calculation.

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1. Introduction

The confinement of energetic ions in the large helical device (LHD) has been intensively studied by measuring fast neutrals from ion cyclotron radio frequency (ICRF) sustained, or ICRF assisted NBI plasmas [1–5]. While the evidence that perpendicular particles, which are mostly deeply trapped in helical ripples, well-behave in LHD is observed, saturation in high-energy-tail temperature formed by ICRF and saturation in collisional decay time after the ICRF termination are observed in the low density region [3,6]. The latter phenomenon is directly indicating the existence of a loss of energetic trapped particles with a characteristic time of several hundreds ms. One of possible loss mechanisms is that governed by the combination of neutral particle (or ions not-fully ionized) density in a plasma boundary and energetic particle orbit. The latter is strongly related to the magnetic configuration, while the former is determined by the neutral temperature crossing LCFS. Goto and Morita measured Zeeman profiles of neutral helium He I 1728.1 and 1667.8 nm emission lines from the boundary of the LHD plasma and found that there is a high temperature component of 13–20 eV besides cold components [7]. Sasao et al. have recently developed a code to calculate H^0, He^0, He^+ distribution (ACHEN-Code) for a given neutral source temperature, and studied the electron density dependence of measured neutral flux of high energy particles measured by natural diamond detectors (NDD) from ICRF-heated plasmas [8,9]. The electron density dependence was well

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reproduced by the calculation with the incoming neutral temperature, T^0_{in}, of about 10 eV and the neutral density at LCFS of $0.4 \times 10^{-3} n_e$.

In this paper, it is attended the fact that the fast neutral particles measured are directly related to the neutralization loss, and the density dependence of energetic neutral flux escaping from NBI-heated hydrogen and helium plasmas is studied. The measured results are compared with the calculation to obtain the information on the neutralization effect on deflected energetic ions which are initially injected tangentially.

2. Experimental set-up and data analysis

The LHD is an $l = 2/m = 10$ heliotron-type device with superconducting helical and poloidal coils. The plasma is heated by ICRF and neutral beams, which are injected tangentially. In the present study, the fast neutral spectra measured by the central NDD chord of vertical line of sight during a NBI-sustained discharge is used [3,6,8]. This NDD views the longitudinally elongated plasma cross section with a vertical line of sight at $R = 3.65$ m covering the pitch angle range (χ) of 82–102°.

The relation of a measured neutral spectrum, $\Gamma_{meas}(E)$ to the local proton distribution function $F(E,z)$ can be expressed as

$$\Gamma_{meas}(E) = \int \eta_g(z) P(E,z) A(E,z) F(E,z) s(z)\, dz, \quad (1)$$

where z is the vertical coordinate, $P(E,z)$ the neutralization efficiency, $A(E,z)$ the attenuation factor [1], $\eta_g(z)$ the geometrical efficiency, and $s(z)\,dz$ the local observation volume. The fast neutrals are produced through charge exchange processes. Here H^0, He^0, and He^+, are particles responsible for the neutralization, but the contribution of the He^+ is most dominant for a helium plasma, and H^0 for a hydrogen plasma. The E-dependent factor can be approximately separated from the z-dependence factor if we assume the proton velocity distribution function is uniformly expressed by a simple parameter T_{eff}, and only one component (here, it is represented by He^+) contributes to the neutralization efficiency, $P(E,z) \approx n_{He^+}(z) g(E)$, as the following expression,

$$\Gamma_{meas}(E_z)\, dE \approx \eta_g s(0) g(E) f_p(E)\, dE \left\{ \int n_p(z) n_{He^+}(z)\, dz \right\},$$

$$\Gamma_{meas}(E_z)/g(E)\, dE \approx A v_\perp\, dv_\perp \lfloor (m/2\pi)^{1/2} (T_{eff})^{-1/2} \times \exp\{-(m v_\perp^2 / 2T_{eff})\} \rfloor \times \left\{ \int n_p(z) n_{He^+}(z)\, dz \right\},$$

$$E \approx m v_\perp^2 / 2 \quad [8]. \quad (2)$$

Here A is a geometrical constant. Then, the integration can be defined by an energetic neutral flux Φ as

$$\Phi = \int \Gamma_{meas}(E_z)/g(E)\, dE \approx \int n_p(z) n_{He^+}(z)\, dz. \quad (3)$$

The distributions of H^0, He^0, and He^+, $n_{He^+}(z)$, are calculated with ACHEN-Code, including six charge exchange processes, electron/ion impact ionization and recombination processes in plasma of cylindrical geometry assuming T^0_{in} of 10 eV, respecting the spectroscopic measurement [7]. Then, it is multiplied by the energetic particle profiles, $n_p(z)$ after the transformation of the coordinate z to ρ. For a ICRF plasma, the power deposition profile can be used as the energetic particle profiles for the first approximation, and a simple parabolic function for a NBI plasma. In Fig. 1 are compared the profiles of the product of energetic ion distribution and He^+ density, for three different density cases. As the density increases, the contribution from the center part becomes less. Note that the fast neutral particles

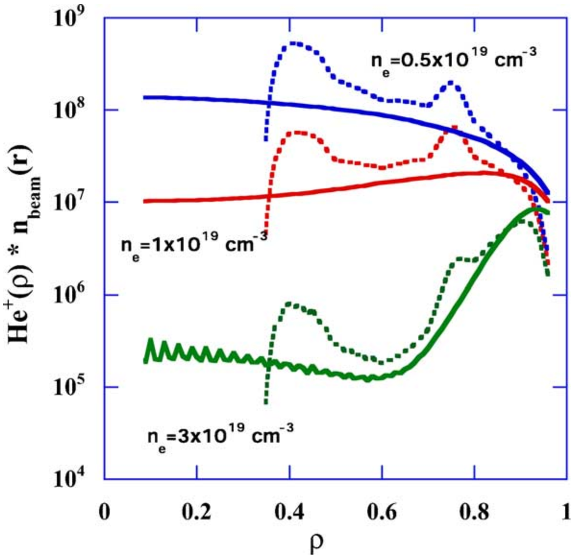

Fig. 1. Profiles of the product of energetic ion distribution and He^+ density, for three different density cases, 0.5×10^{19}, 1×10^{19}, $3 \times 10^{19}/cm^3$. The solid curves presents those for NBI, the dashed curves for ICRF distributions. The ICRF power deposition profile of type-5 [2] and a simple parabolic function for neutral beam particles are assumed as the first approximation.

[1] The attenuation effect is generally smaller in an He plasma by a factor of 4–10 than in a H/D plasma.

measured are directly related to the neutralization loss, and the main contribution of energetic particle loss moves toward the boundary region, and the loss flux decreases exponentially as the density increases.

3. Experimental results

In Fig. 2 are shown two examples, one hydrogen (left) and one helium (right), of time traces of plasma stored energy, the central electron density and beam current of two NBIs for discharges at $B_t = 2.75$ T, and $R_x = 3.6$ m, together with those of effective tail temperature, T_{eff}, and energetic neutral flux Φ (bottom). The tail temperature of helium discharges are higher than that of hydrogen. This fact can be interpreted by the Z_{eff} dependence of beam particle deflection time (Z_{eff}^{-2}) and the slowing-down time (Z_{eff}^{0}), because the beam particles are tangentially injected and measured perpendicularly. The ratio of T_{eff} (He) to T_{eff} (H) is roughly 0.6, similarly to that of the critical energy.

The electron density dependence of energetic neutral flux Φ is shown in Fig. 3 for hydrogen (a) and helium (b) discharges. The dependence for helium plasma is slightly steeper. Here the latter is also compared with density dependence of energetic neutral flux from ICRF-self-sustained plasma. The e-folding density for the ICRF plasma is about a half of the NBI plasma.

4. Discussions

The product of He^+ density and energetic particle profiles, $n_p(z)n_{He^+}(z)$, is integrated over the line of sight, and compared with the measured energetic neutral flux Φ as shown in Fig. 3 as a function of the density. The hatched areas indicate the ambiguity due to the beam particle profiles, $n_p(\rho) = (1 - (\rho/a)^2)^q$, with $2 \leqslant q \leqslant 4$. Similar dependence is obtained for ICRF (c) and for NBI (b) cases in the calculation, however the experimental e-folding density are much larger for NBI. One of possible reasons of this difference is the neutralization loss. Perpendicular energetic particles in a NBI-heated plasma are deflected particles which are originally injected in circulating orbits. Typical deflection time is larger than several hundreds ms when the density is lower than $0.5 \times 10^{19}/m^3$. There exist a region of unstable orbits, which easily excuse into the boundary region, between circulating and helically trapped region in a ρ–χ space.

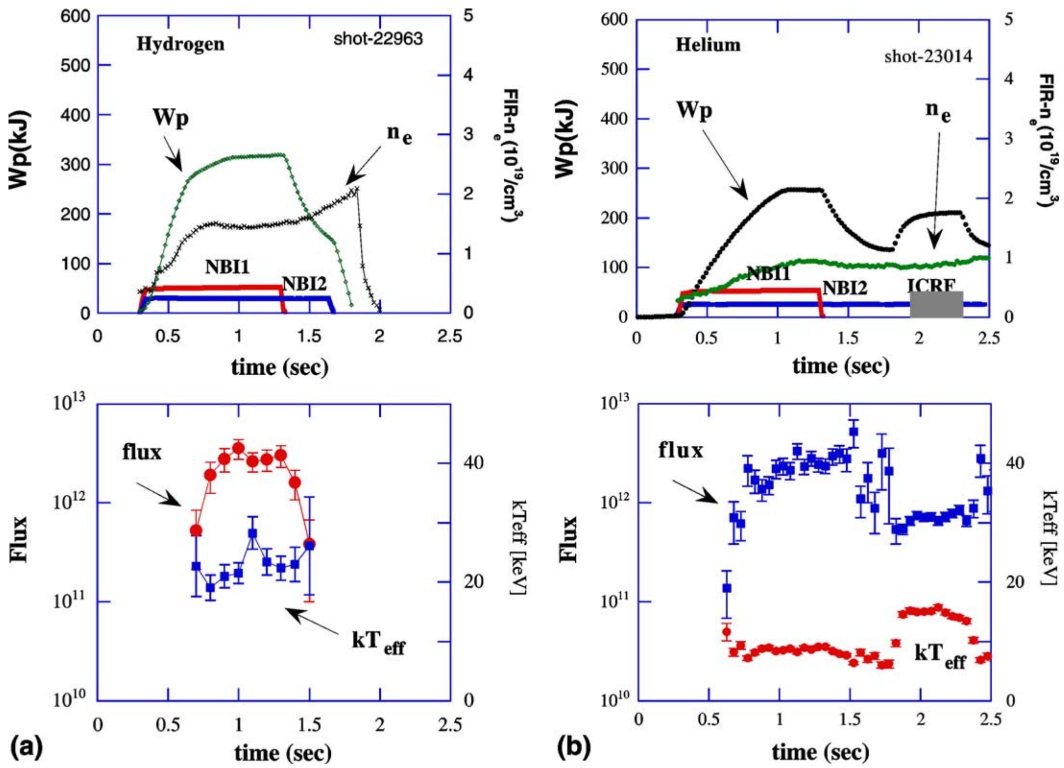

Fig. 2. Time traces of plasma stored energy, the central electron density and beam current of two injectors(up) for discharges at $B_t = 2.75$ T, and $R_x = 3.6$ m, together with those of effective tail temperature, T_{eff}, and energetic neutral flux Φ (bottom), perpendicularly measured by NDD at $R = 3.65$ m. The left is a discharge of a hydrogen, and the right is of helium.

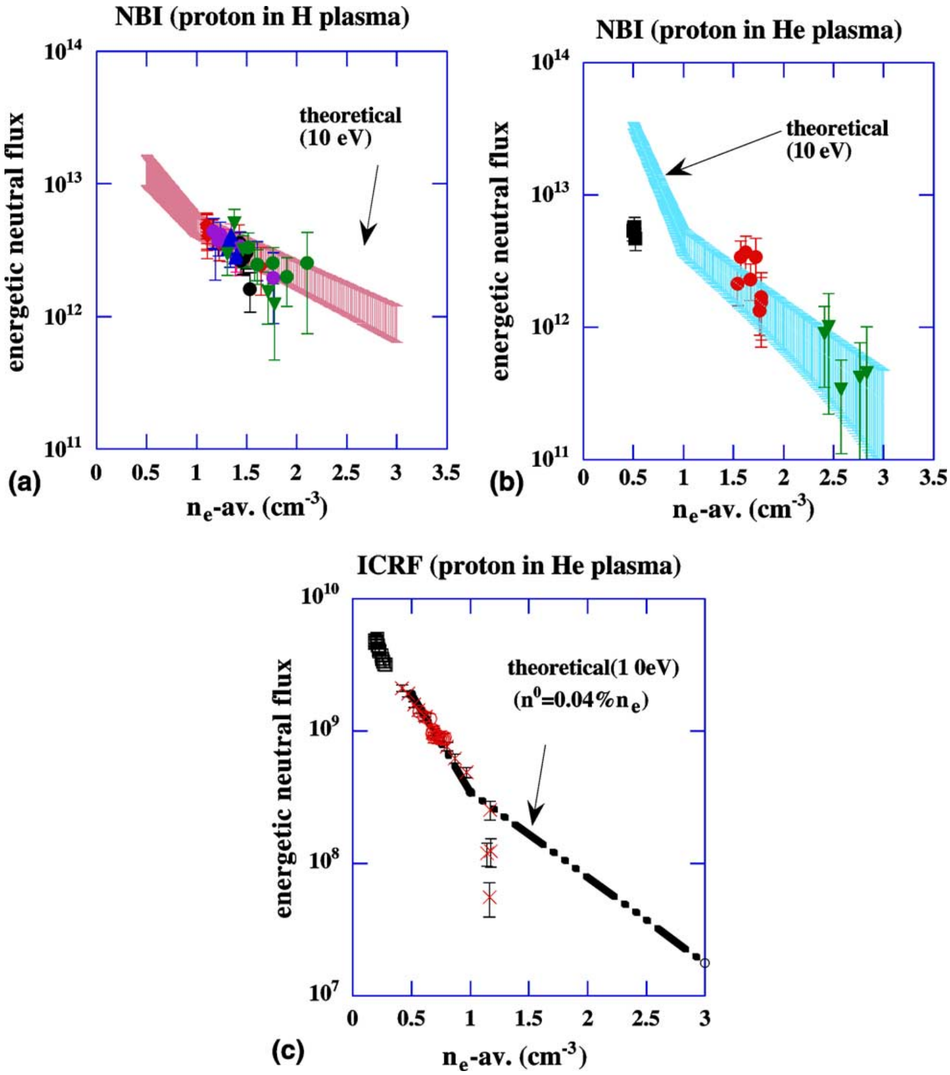

Fig. 3. The electron density dependence of energetic neutral flux Φ from hydrogen (a) and helium (b) NBI plasmas, and that from ICRF-assisted NBI plasma of hydrogen minority/helium majority scheme (c). Calculated density dependence of fast neutral flux estimated by line-integration of the product of He^+ density and energetic particle profiles are also shown. The hatched areas in (a) and (b) indicate the ambiguity due to the beam particle profiles, $n_p(\rho) = (1 - (\rho/a)^2)^q$, with $2 \leqslant q \leqslant 4$.

Similar estimation was done for hydrogen plasma assuming T_{in}^0 of 10 eV, and shown in Fig. 3(a) as well. The e-folding density is larger than that of helium plasma in the calculation. This fact comes from the difference of the density dependence of He^+ and H^0 profiles. The latter is also produced by charge exchange process in the core, hence the attenuation in the high density which is less than He^+. The difference of experimental e-folding time in NBI-heated helium and hydrogen plasmas is not obvious in present studies. An experiment of hydrogen discharges in the low density region was not carried out because the helium contamination from the wall and diverter tiles is not negligible. Careful reparation of the wall and diverter tiles is required to get conclusive results.

In order to estimate the neutralization loss time, more careful study on the energetic particle distribution and calibration of the detection efficiency of the measurement system are required. However, using parameters, T_{in}^0 and energetic neutral flux Φ, the neutralization loss is estimated for NBI plasmas. Preliminary numbers are similar to those for ICRF, and the characteristic time is smaller than several hundreds ms when the density is $0.5 \times 10^{19}/m^{-3}$. This is consistent with the saturation level of decaying time of tail temperature after the ICRF termination.

Obvious loss of beam particles injected tangentially is not seen in a NBI-heated helium plasma until detected in the perpendicular viewing chord, when the density is higher than $1.5 \times 10^{19}/\mathrm{m}^{-3}$ at $B_t = 2.75$ T, and $Rx = 3.6$ m.

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