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Simulational study on losses of neutral beam-injected energetic ions via collisional ripple transport in the low aspect ratio helical system CHS

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Abstract. Confinement and loss properties of tangentially co-injected beam ions have been studied for a standard configuration of the Compact Helical System ($R_{\rm ax}/B_{\rm t} = 0.921$ m/1.9 T) by use of the global particle simulation code DELTA5D. Both ripple transport and collisions with a background plasma are taken into account. It has appeared that partially thermalized, pitch-angle scattered beam ions are dominantly lost at the small major radius side. It has also been shown that the negative potential can enhance beam ions losses.

1. Introduction

The Compact Helical System (CHS) is a medium size helical device having poloidal periods $l = 2$ and toroidal periods m of 8 [1]. One of the key issues in CHS is a confinement property of fast ions because of the symmetry breaking of the system caused by the mixing of toroidal and helical magnetic fields and enhanced toroidicity due to its low aspect ratio ($R/a \sim 5$). Currently, high-energy neutral beam (NB) injection is performed in CHS as a primary plasma heating method. In order to study behavior of NB ions experimentally, a scintillator-based lost fast ion probe (LIP) [2] and a neutral particle analyzer (NPA) are employed in CHS. However, generally speaking, information obtained from these diagnostics is limited because LIP detects only lost fast ions reaching the probe and NPA provides line-integrated energy distribution of confined fast ions at a particular range of pitch angle ($v_\parallel/v$). It can be said that experimental observations depend on a synergy between the effects of both collisions with the background plasma and ripple transport. In order to see the global behavior of beam ions and enhance the understanding of experimental observation, some help with global simulation on beam ions involving collisional ripple transport is therefore required. In this work, we numerically analyze the confinement and/or loss properties of beam ions in the tangential co-injection which is a standard operation mode of the NB in CHS.

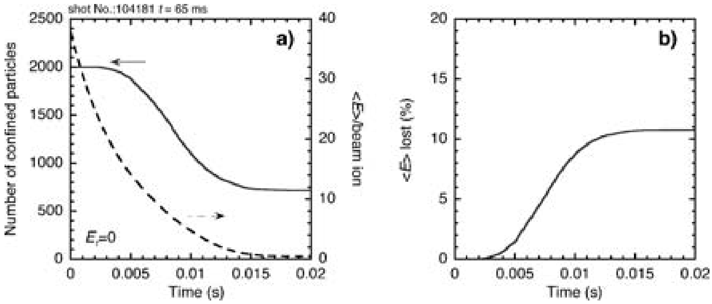

Figure 1. Time evolutions of (a) number of confined beam ions and $\langle E\rangle$/beam ion and, (b) $\langle E\rangle$ lost in $B_t/R_{ax} = 1.9$ T/0.921 m.

2. On the simulation scheme

The scheme on simulation for NB ions is briefly described. First, the equilibrium magnetic field is obtained from the three-dimentional (3D) magnetohydrodynamic (MHD) equilibrium calculation code VMEC [3] which is then transferred to Boozer coordinates. Next, in order to obtain the birth deposition profile of energetic NB ions, we use the HFREYA code [4] which can model a realistic NB injector and also can consider the 3D shape of CHS plasma. The electron temperature T_e and density n_e measured with the Thomson scattering diagnostic are given as background plasma parameters. The confinement and/or loss properties of NB ions in CHS are analyzed by use of the particle simulation code DELTA5D [5]. Beam ions are initially distributed in space according to a birth profile calculated by the HFREYA. In DELTA5D, guiding center orbits of energetic ions are tracked in the equilibrium magnetic field on Boozer coordinates. The background plasma parameters used here are the same as used in the HFREYA. Collisions, i.e. slowing-down and pitch angle scattering processes with a background plasma, are taken into account. A variety of information of the escaping fast ions such as the particle's life time, energy, pitch angle and location where fast ions are lost are preserved to help in understanding the loss mechanisms. Owing to the use of VMEC equilibrium, once beam ions intersect the last closed flux surface (LCFS), they are recognized to be lost in this model.

3. Simulation results

3.1. Characteristics of beam ion losses

Figure 1 shows time evolution of the percentage of energy lost ($\langle E\rangle$ lost) from the beam averaged over the ensemble of 2000 ions, the number of confined ions and averaged energy of ions in a magnetic field of strength $B_t = 1.9$ T and magnetic axis position R_{ax} of 0.921 m. The hydrogen NB is tangentially co-injected in the tangency radius R_{tan} of 0.87 m and its injection energy E_b is 38 keV. The profiles of background plasma (shot No. 104181, $t = 65$ ms) are $T_e(\rho)(\text{keV}) = 0.4986+0.04816\cdot\rho-1.437\cdot\rho^2+0.8938\cdot\rho^3, T_i = T_e, n_e(\rho)(\times10^{19}\ \text{m}^{-3}) = 3.210-0.9977\cdot\rho+0.3557\cdot\rho^2-2.506\cdot\rho^3$, and effective ionic charge $Z_{eff} = 3.0$ assuming fully ionized carbon. Here ρ represents the normalized minor radius. The electric potential ϕ is set to be zero and charge exchange loss is not considered. In DELTA5D, the beam ions slowed down to $(3/2)\cdot T_i$ are counted as part of the background thermal ions. The final percentage of $\langle E\rangle$ lost is determined when it reaches a saturated plateau in its time evolution. This plateau is associated with the average beam ion decelerating down

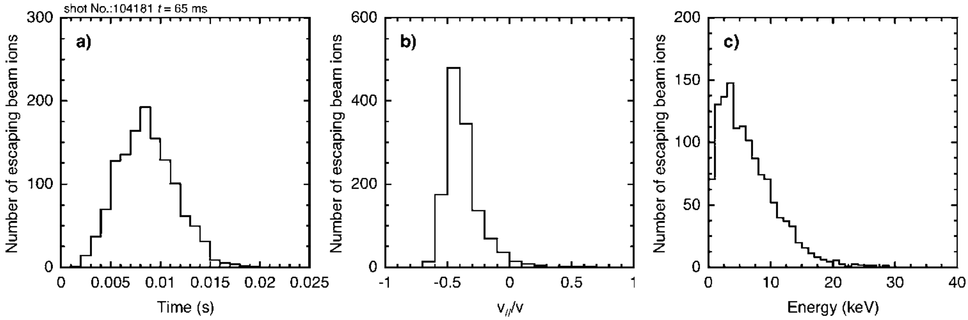

Figure 2. (a) Time evolution of number of escaping beam ions, (b) pitch-angle spectrum and (c) energy spectrum of escaping beam ions.

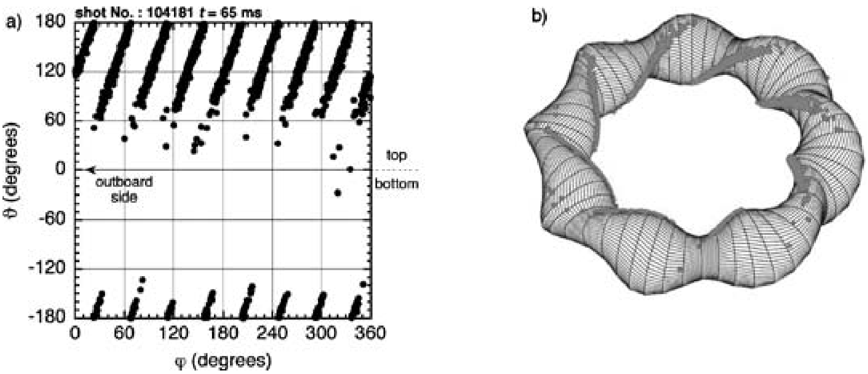

Figure 3. (a) Spatial distribution of beam ion losses in Cartesian coordinates. (b) 3D plot of beam ion losses on the last closed flux surface of CHS in $B_{\mathrm{t}}/R_{\mathrm{ax}} = 1.9$ T/0.921m.

to the thermal energy level of $(3/2) \cdot T_{\mathrm{i}}$. $\langle E \rangle$ lost is evaluated to be about 11% in this case. Time evolution, pitch angle and energy spectra of the escaping beam ions from the CHS plasma are shown in Fig. 2. The pitch-angle distribution is peaked in $v_{\parallel}/v$ of -0.4 to -0.5 (see Fig. 2(b)), although initial $v_{\parallel}/v$ mostly ranges from $+0.82$ to $+1.0$ because of tangential co-injection. Here '+' and '−' in $v_{\parallel}/v$ mean co-going and counter-going, respectively. Judging from Fig. 2(b), primary losses are supposed to be due to helically trapped ions because once trapped, they move in the counter-direction as they rotate poloidally. Beam ion losses begin after beam ions slow down to about 30 keV (Fig. 2(c)). From this view point, one may say that partially thermalized, pitch-angle scattered beam ions are dominantly lost in this case. Figures 3(a) and (b) show spatial distribution in a toroidal angle φ-poloidal angle ϑ plane in Cartesian coordinates transformed from Boozer coodinates and a 3D plot for the location where partially thermalized beam ions intersect the LCFS. It is seen that beam ion losses occur along the valley of two helical winding coils where particles are helically trapped. This is because mod-B_{min} contours which are basically equivalent to drift surfaces of helically trapped ions are not well aligned with the flux surfaces in CHS and deviate toward the small major radius R side [6].

3.2. Effect of the radial electric field on the confinement of beam ions

We have studied the influence of the radial electric field on beam ion confinement. It has been theoretically predicted that the radial electric field E_{r} plays an important

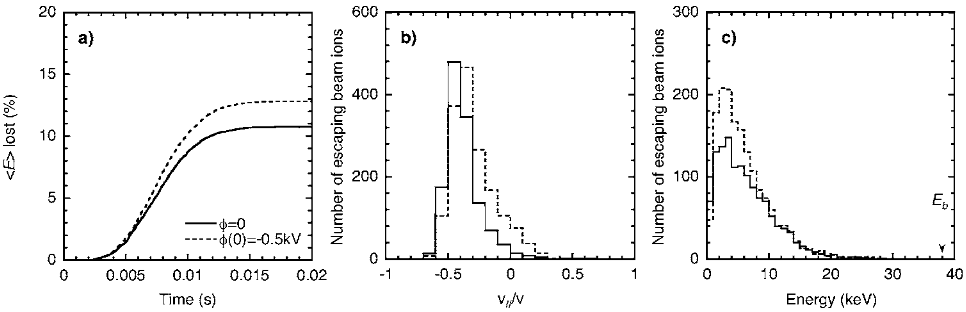

Figure 4. Comparisons on beam ion losses with and without ϕ: (a) time evolution of number of lost beam ions; (b) pitch-angle; and (c) energy spectra of lost beam ions.

role especially in the confinement of helically trapped ions in a non-axisymmetric system such as CHS. Here, because the object of this analysis is a NB-heated plasma, the negative electric potential ϕ ($\phi(\rho) = 0.8 \cdot \exp(-(\rho^2 - 1.2)^2/1.2^2)$) is considered. Here, $\phi(0)$ is about 0.5 kV ($\approx T(0)$) when $\phi(1) = 0$. This value is chosen so as to be consistent with experimental observation by a heavy ion beam probe. Figure 4 shows simulational results on beam ion losses with and without ϕ. The $\langle E \rangle$ lost increases by about 19% compared with the $\phi = 0$ condition. Pitch-angle spectrum also shifts to a more perpendicular range. The enhancement of beam ion losses due to negative ϕ assumed from measurement is explained by cancellation of the poloidal motions of helically trapped beam ions due to $E \times B$ drifts.

4. Summary

Confinement and characteristics of beam ion losses have been analyzed for the CHS plasma at the highest B_t of 1.9 T and the standard R_ax position by using the global particle simulation code DELTA5D. Energy loss for tangentially co-injected beam ions is evaluated to be about 11% in the $\phi = 0$ condition. The analysis indicates that dominant loss mechanism is associated with helically trapped orbits and they intersect the LCFS at the inboard side. It is shown that negative ϕ where $\phi(0) = T(0)(\approx 0.5\ \mathrm{keV})$ enhances the energy loss of beam ions by about 19% compared with the $\phi = 0$ case.

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