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Orbit Effects of Energetic Particles on the Reachable β–Value and the Radial Electric Field in NBI and ECR Heated Heliotron Plasmas

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ORBIT EFFECTS OF ENERGETIC PARTICLES ON THE REACHABLE β-VALUE AND THE RADIAL ELECTRIC FIELD IN NBI AND ECR HEATED HELIOTRON PLASMAS

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Keywords : energetic particle, high beta, radial electric field, NBI heating, ECR heating, heliotron, power deposition, Monte Carlo simulation

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ORBIT EFFECTS OF ENERGETIC PARTICLES ON THE REACHABLE β-VALUE AND THE RADIAL ELECTRIC FIELD IN NBI AND ECR HEATED HELIOTRON PLASMAS

ABSTRACT

Effects of energetic particles on the plasma heating process and the radial electric field are studied in NBI and ECR heated heliotrons. The NBI heating efficiency is reduced as the magnetic field becomes weak even for tangential injection due to large orbit deviation, which is changed significantly by finite β effects. It is found that this reduction of the heating efficiency due to beam orbit loss plays an important role to determine the reachable β-value in the high β experiments on the Compact Helical System (CHS). It is also found that the radial flux due to tangentially injected NBI beams can enhance the strong negative radial electric field near the plasma periphery in the CHS and the enhancement of radial electric field is larger for high density case which is consistent with experimental results. Effects of energetic electrons on the heating process and the radial electric field in ECR heating are also studied using newly developed Monte Carlo simulation code. The large radial broadening of power deposition profile and radial flux due to the energetic electrons are obtained. This radial flux can enhance the positive radial electric field with significant heating power, which can explain the transition phenomena of radial electric field in the CHS experiments.

1. INTRODUCTION

In heliotrons behaviours of energetic particles created by various heating methods are considerably complicated because of three dimensional magnetic configurations. Further, both changes of the configuration due to the large Shafranov shift (finite-β effects) and generated radial electric field significantly affect characteristics of the energetic particle orbits, i.e., the drift motions across the magnetic flux surfaces. At the same time, the large drift motions of the energetic particles have an influence on both the plasma heating process, through the deposition profile, and the generation of the radial electric field owing to the enhanced radial flux of energetic particles. Therefore the self-consistent consideration of magnetic configuration, radial electric field, and complex particle motions are necessary to clarify the physics of energetic particles in heliotrons.

In this paper, we examine self-consistent relations between the large drift orbits of energetic particles created by NBI or ECR heating and both heating process and generation of the radial electric field. The role of the large drift orbits in the Compact

Helical System[1] (CHS: l = 2 and m = 8 heliotron) is studied and compared with the experimental results. Predictions for the Large Helical Device[2] (LHD: l = 2 and m = 10 heliotron) is also done.

2. BEAM ORBIT EFFECTS ON REACHABLE β-VALUE

The high β experiments in CHS[3,4] (with reduced magnetic field strength) show that the obtained β-values saturate at $B \sim 0.6$T and those values are lower than the one expected by equilibrium and stability β limit. This fact suggests that there exist other mechanisms to limit the plasma-β depending on the magnetic field strength. The deviation of drift orbits of tangentially injected NBI particles from magnetic surfaces becomes non negligible in the weak magnetic field. Effects of beam particle orbits on the NBI heated high-β plasma are studied in the CHS including the configuration change due to the Shafranov shift in a self-consistent way. We evaluate the energetic particle loss based on the orbital deviation and the birth profile of tangentially injected beams[5], and the orbital aspects of the heating efficiency and the reachable β-value are examined.

Figure 1-(a) shows the heating efficiency (= $1 - N_{loss}/N_{total}$; N_{total} and N_{loss} are the total deposit particle number and the number of lost particle by orbit loss, respectively.) as a function of the magnetic field strength for co injection NBI heating in the CHS. It is found that the heating efficiency is reduced in a weak magnetic field and that the changes of the configuration due to the finite β effect (Shafranov shift) alter the NBI heating efficiency largely. The Shafranov shift changes the magnetic configuration from magnetic hill to well in heliotron, which is important for the MHD stabilities. This magnetic well or hill condition is also an important factor to determine the heating efficiency in a weak magnetic field.

The achievable plasma-β is then evaluated by means of β-value scaling based on an empirically obtained energy confinement scaling law[6] (LHD scaling; τ_E^{LHD}),

$$\beta = \frac{2}{3}\frac{P_h \tau_E^{LHD}}{\int \frac{1}{2\mu_0}B^2 \mathrm{d}V} = 0.0144 R^{-0.25} a^2 n^{0.69} B^{-1.16} P_h^{0.42}. \qquad (1)$$

The heating efficiency and the reachable β-value are nonlinear functions of β, and we calculate the configuration change and particle orbits consistently to obtain a reachable β. The comparison of numerical results (solid line) with experimental results in the CHS[4] at $\bar{n} = 5.0 \times 10^{19}\mathrm{m}^{-3}$ (closed circles) is shown in Fig. 1-(b). Although the experimental results are slightly lower than the numerical ones, we can see a good agreement. The saturation of the β-value is observed at $B \sim 0.6$T and the rapid fall is seen at $B < 0.5$T. This is attributed to the fact that beam orbit losses are significantly enhanced for the weak magnetic field less than 0.5T. Thus, beam particle orbits play an important role to determine the achievable β-value in the CHS high β experiments in the weak magnetic field.

Next we calculate the reachable β-value for the LHD. We, here, introduce the LHD configuration called the 'standard configuration' which satisfies the requirements for high plasma performance, i.e. a good bulk particle confinement, a high plasma beta ($\beta_c \geq 5\%$) and creating a divertor configuration. Beam energy of 180keV and heating power of 20MW are assumed. Predictions for the LHD plasma show that $\beta = 5\%$ could be achieved at $B = 0.5$T by assuming a density $1.4 \times 10^{20}\mathrm{m}^{-3}$ in average.

3. BEAM ORBIT EFFECTS ON THE RADIAL ELECTRIC FIELD

A strong radial electric field is expected not only to reduce the anomalous transport but also to reduce the neoclassical diffusion in heliotrons. Recently a strong negative radial electric field near the plasma periphery has been measured in the CHS[7]. However, the origin of this negative electric field has been an unsolved problem. In the previous section we have shown that the beam loss becomes large even for tangential injection in a weak magnetic field. This loss flux could affect the radial electric field and enhance the negative radial electric field.

We study the effect of beam orbit flux on the radial electric field in heliotrons using the Monte Carlo simulations. First, the birth profile of neutral beams is calculated by NBI deposition code and beam particle orbits are followed taking into account Coulomb collisions with background plasma particle until beam particles are slowed down to thermal energy. Then, the radial flux due to beam orbit loss is evaluated using obtained distribution function of beam particles. Finally the radial electric field is determined to satisfy the ambipolar condition,

$$\Gamma_{beam} + \Gamma_i^{NC} + \Gamma_e^{NC} = 0 \tag{2}$$

where Γ_{beam} is the radial flux of the beam particles, and Γ_i^{NC} and Γ_e^{NC} are radial fluxes of background ions and electrons due to the neoclassical $1/\nu$ ripple diffusion.

Figure 2-(a) shows the radial flux due to the beam particles of counter injection NBI heating in the two different densities; n_0 = 2.0 and $6.0 \times 10^{19}\mathrm{m}^{-3}$. We can see the larger radial flux in high density case because of less shine through of neutral beam and the outward shifted deposition profile, which enhance more loss particle for counter injection. The enhanced radial electric field with two different densities are shown in Fig. 2-(b). It is found that strong negative radial electric field is obtained at the plasma periphery in higher density case but small enhancement is observed in lower density case. The density dependence of the enhanced radial electric field is consistent with the experimental observation. As a result it is found that the beam enhanced flux plays an important role in generating strong negative radial electric fields as observed in the CHS.

Using this enhancement of radial electric field due to beam component we can consider a radial electric field bifurcation scenario in the CHS related to the H-mode in heliotrons, by introducing the nonlinear viscosity term. Effects of anomalous and nonlinear viscosity are now under investigation.

4. ELECTRON ORBIT EFFECTS IN ECR HEATING

Although linear theory predicts a local absorption of ECR heating power, broader heating profiles are observed in electron cyclotron heating of low density plasma in both heliotrons and stellarators[8]. It is also observed that the radial electric field can suddenly changes when ECR waves are applied to NBI heated plasma[9]. Ripple trapped energetic particles are created and their drift motions across the magnetic surfaces can play an important role in these phenomena. However, this drift motion effect has not been analyzed due to the difficulty in solving the electron orbits and the radial electric field consistently.

We have developed a Monte Carlo simulation code based on a technique similar to the adjoint equation for dynamic linearized problems[10]. The linearized drift kinetic equation for the deviation from the Maxwellian background $f_1(\underline{x}, \underline{v})$,

$$\vec{v} \cdot \nabla f_1 + \vec{a} \cdot \nabla_v f_1 = C(f_1) + S_{ql}^0, \tag{3}$$

is evaluated as,

$$f_1(\underline{x}, \underline{v}) = \int_0^\infty dt \int d\underline{x}' \int d\underline{v}' S_{ql}^0(\underline{x}', \underline{v}') g(\underline{x}, \underline{v}, t | \underline{x}', \underline{v}'), \tag{4}$$

where $C(f_1)$ is the linear Coulomb collision operator and S_{ql}^0 is the wave induced flux in velocity space (quasi-linear diffusion term) which is assumed to be a given function. The time dependent Green function $g(\underline{x}, \underline{v}, t|\underline{x}', \underline{v}')$ is the solution of the drift kinetic equation

$$\frac{\partial g}{\partial t} + \vec{v} \cdot \nabla g + \vec{a} \cdot \nabla_v g = C(g), \tag{5}$$

with initial condition $g(\underline{x}, \underline{v}, t = 0|\underline{x}', \underline{v}') = \delta(\underline{x} - \underline{x}')\delta(\underline{v} - \underline{v}')$. The solution of Eq. (5) is obtained using the Monte Carlo simulation in which the complex magnetic field configuration, the finite-β effect, and the radial electric field can be included[11]. Using this code we investigate the broadening of the heating profile and the orbit effects on the radial electric field.

Figure 3-(a) shows the radial profile of the ECRH power deposition in the CHS (X-mode, 2nd-harmonic) for two different densities; $n_0 = 0.7$ and $1.0 \times 10^{19}\mathrm{m}^{-3}$. The temperatures are set to 400eV for electrons and 200eV for ions (ECR and NBI combined heating). The heating point is the bottom heating case in the CHS experiments[7] which is the bottom of the toroidal field and $r/a = 0.5$. The quasi-linear diffusion

term S^0_{ql} is estimated through an analytical model of ECR heating. We can see the broadening of the power deposition profile due to the large orbit of energetic electrons and the broadness is larger in lower density case. Figure 3-(b) shows the radial profile of the radial flux due to the electrons enhanced by the ECR heating. The obtained radial flux is comparable or larger than the neoclassical flux and it could affect the radial electric field and the density profile.

Next we study the effect of enhanced radial flux due to energetic electrons on the radial electric field. Figure 4 shows the radial electric field due to the enhanced radial electron flux ($n_0 = 1.0 \times 10^{19} m^{-3}$) with changing the ECR heating power solving the ambipolar condition [See Eq. (2)]. It is found that, for significant heating power, the large enhanced radial flux due to ECR heating changes the radial electric field profile. In order to determined the radial electric field self-consistently, the ambipolar condition and the Monte Carlo code are iteratively solved.

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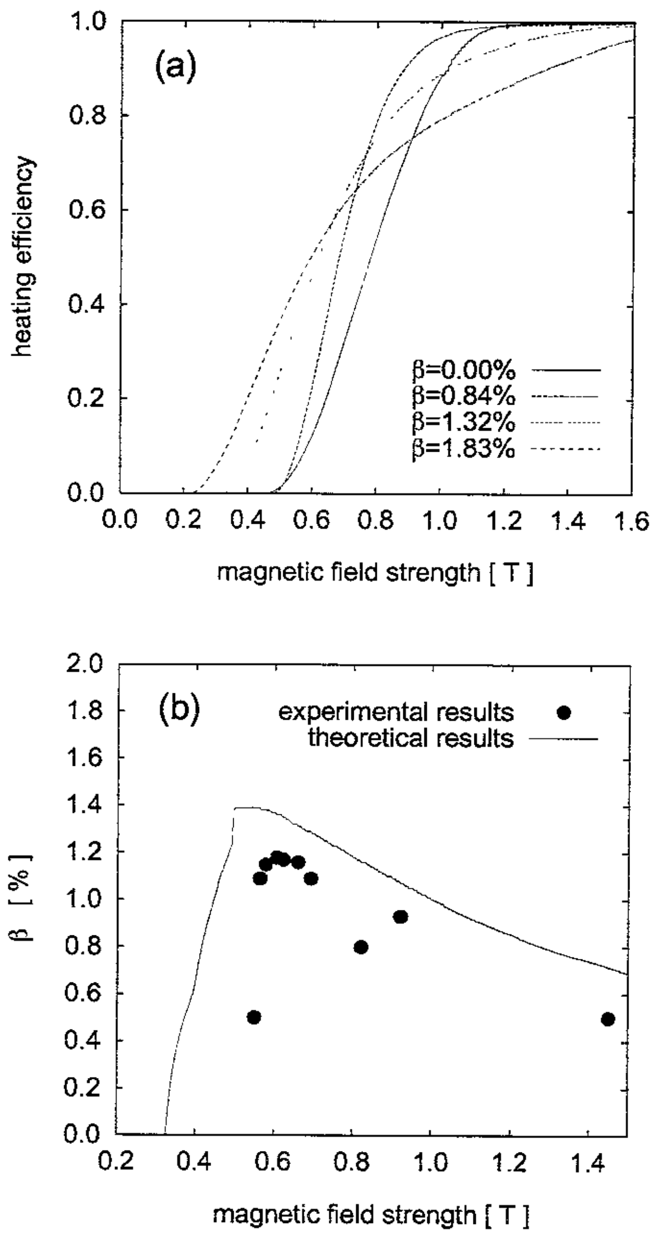

Fig. 1 : (a) Heating efficiencies of co injection NBI heating as a function of the magnetic field strength with four different β magnetic configurations and (b) comparison of the B-dependence of consistently calculated achievable β with experimental ones[4] in the CHS.

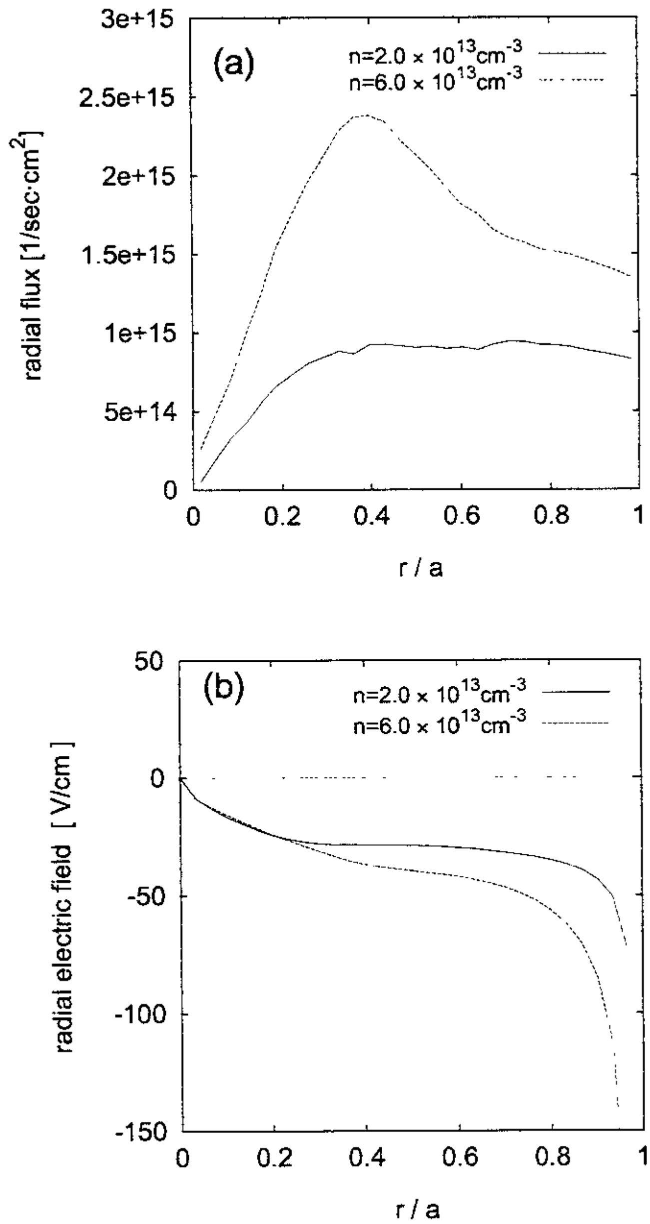

Fig. 2 : (a) Radial flux due to energetic beam particles [$n_0 = 2.0$ and $6.0 \times 10^{19} m^{-3}$] and (b) build up of radial electric field due to beam radial flux in the CHS.

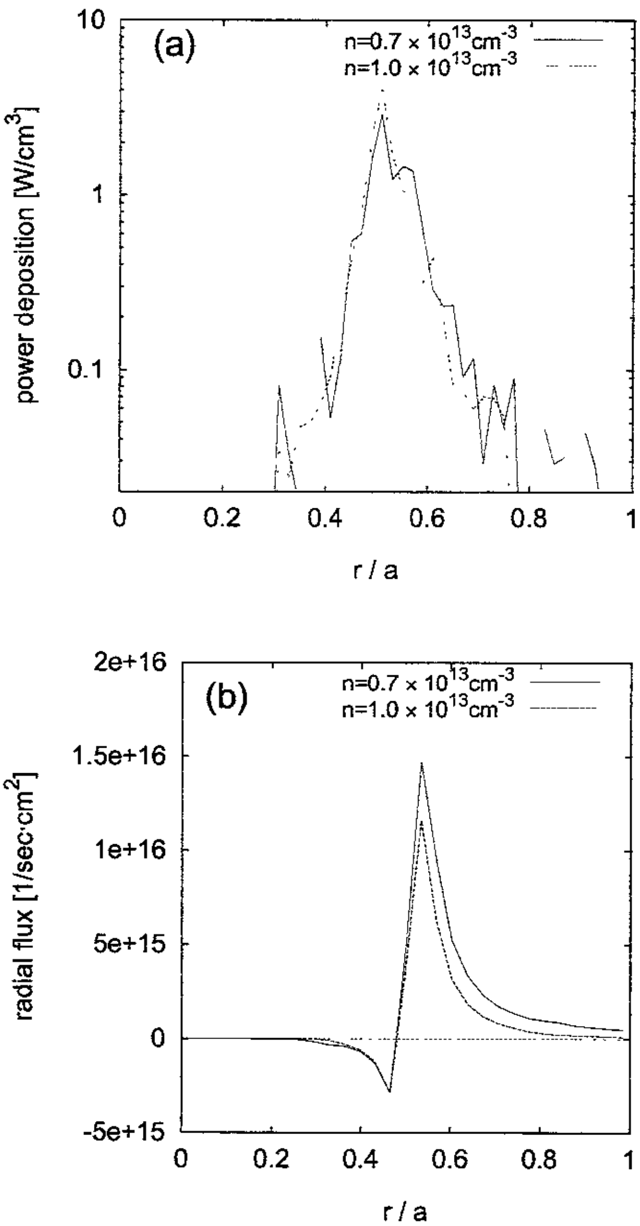

Fig. 3 : (a) Radial profile of the power deposition and (b) the enhanced radial flux due to energetic electrons in the CHS (X-mode, 2nd-harmonic).

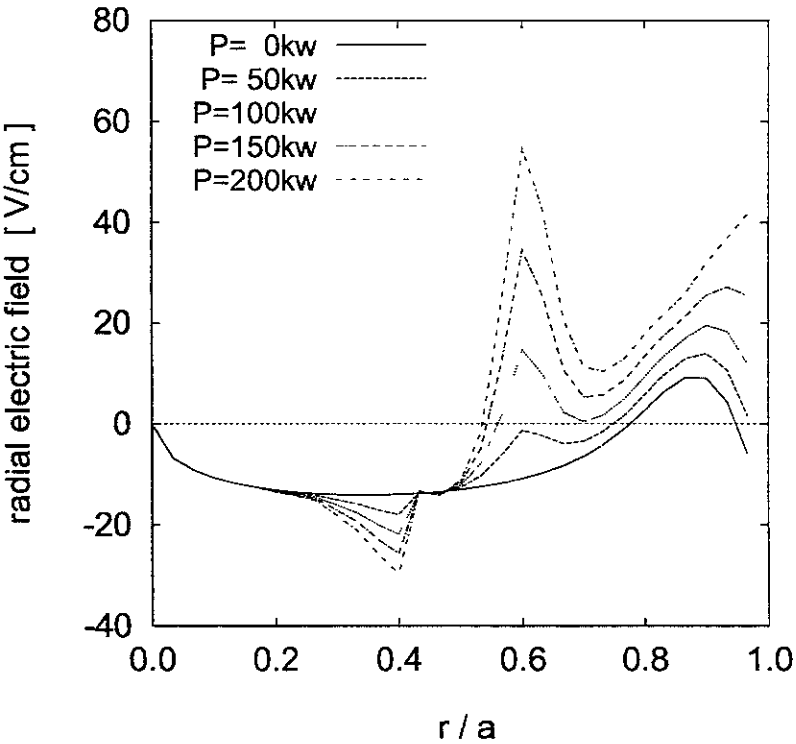

Fig. 4 : Build up of radial electric field due to energetic electrons in the CHS

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