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Electron Injection in the Inward Shift Configuration of LHD for the Control of the Electric Field in Plasma

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Abstract

High energy electron injection can be the way to control the electric field in plasma. Its effectiveness depends on many factors and one of them is the type of magnetic configuration, particularly the particle orbit properties, viscosity properties and others. Here the inward shift configuration of the Large Helical Device is studied in the relation with the transfer of the electrons from helically trapped particles at the point of the injection into the passing particles in the center of magnetic configuration under the effect of Coulomb scattering.

Keywords:

electron injection, particle orbits, Coulomb scattering, control of electric field in plasma, LHD

1. Introduction

One of the possible ways to affect the electric field profile in plasma is to inject the high energy electrons or ions [1,2]. In order the injected particles come to the center of the confinement volume it is possible to use the particles with the transit orbits. If such particles start in the core of plasma they can transfer from the passing (or blocked particles) into helically trapped and escape from the confinement volume. These particles are usually named as the particles that belong to the helical loss cone. However it is possible to use the particles with the transit orbits for the injection in plasma. The particles which belong to the loss cone can be injected as the helically trapped outside the confinement volume and then transfer into blocked (toroidally trapped) ones in the core of plasma. If these particles stay in the core of plasma during long time they can drive the additional fluxes which can lead to the bifurcation of the electric field in plasma. This effect was studied for LHD in our earlier paper [1] on the base of the Outward Shifted Configuration (R_{ax} = 3.9 m) and some advantages of the Outward Shifted Configuration of LHD were found.

Now the Inward Shift Configuration is under study. The viscosity in the Inward Shifted Configuration is smaller and hence it is favorable to introduce the bifurcation state in electric field E_r. In the Inward Shifted Configuration the size of loss cone is reduced compared to the Outward Shifted Configuration. However this feature is not unfavorable to inject the particle through the loss cone. In this paper it is shown that the energy of injected particles can be reduced (from 100–150 keV in Outward Shifted Configuration to 40 keV in the Inward Shifted Configuration) and the time of the particle staying in the center of the configuration is not smaller but larger (10 times) than in the case of Outward Shifted Configuration. If the energy of injected electrons is reduced the pitch-angle scattering can affect the particle penetration process. It is found that the deposition patterns of the injected

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particles are rather close to the center of the magnetic configuration.

2. Particle Orbits

Each particle is traced by solving the guiding center equations

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = V_\parallel \frac{\boldsymbol{B}}{B} + c\frac{[\boldsymbol{E}\times\boldsymbol{B}]}{B^2} + \frac{Mc(2V_\parallel^2+V_\perp^2)}{2eB^3}[\boldsymbol{B}\times\nabla B],$$
$$\frac{\mathrm{d}W}{\mathrm{d}t}=0,$$
$$\frac{\mathrm{d}\mu}{\mathrm{d}t}=0, \tag{1}$$

where W is the kinetic energy of the particles, $V_\parallel$ and $V_\perp$ are the parallel and the perpendicular velocities of the particles, M and e are the mass and charge of the particles respectively, $\boldsymbol{B}$ is the magnetic field and $\boldsymbol{E}$ is the electric field, μ is the magnetic moment of the particles ($\mu = MV_\perp^2/2\mathrm{B}$) and $\boldsymbol{r}$ is the particle guiding center radius-vector.

The magnetic field is modeled with the scalar potential ($\boldsymbol{B} = \nabla\Phi_B$)

$$\Phi_B = B_0 \left(R\varphi - \frac{R}{m}\sum_n \varepsilon_{n,m}\left(\frac{r}{a_h}\right)^n \sin(n\vartheta - m\varphi) + \varepsilon_{1,0}\, r\sin\vartheta\right), \tag{2}$$

where B_0 is the magnetic field at the circular axis of torus, R and a_h are the major and minor radii of the surface with the helical winding, m is the magnetic field number, r, ϑ, φ are the coordinates connected with the circular axis of the torus. Then $\boldsymbol{r}$ is the radial variable, ϑ and φ are the poloidal and toroidal angular variables along the minor and major circumferences of the torus respectively. The metric coefficients are the following: $h_r = 1$, $h_\vartheta = r$, $h_\varphi = R - r\cos\vartheta$. The index $n = l, l-1, l = 1, \ldots,$ where l is the helical winding pole number. For this study $l = 2$, $m = 10$, $R = 3.90$ m, $a_h = 0.975$ m, $B_0 = 3$ T are used. Numerical coefficients $\varepsilon_{n,m}$ representing the harmonics of the magnetic field are $\varepsilon_{2,10} = 0.76$, $\varepsilon_{3,10} = -0.032$, $\varepsilon_{1,10} = -0.056$, $\varepsilon_{1,0} = 0.05$. The configuration we study here is some different from the real Inward Shifted Configuration of LHD ($R_{ax} = 3.6$ m) because of the analytical approach for the description of the magnetic field. However some principal properties can be found with the use of the simplified analytical model. The most important characteristics of considered configuration is good confinement of trapped particles. It can be shown from the analysis of the loss cone losses [3].

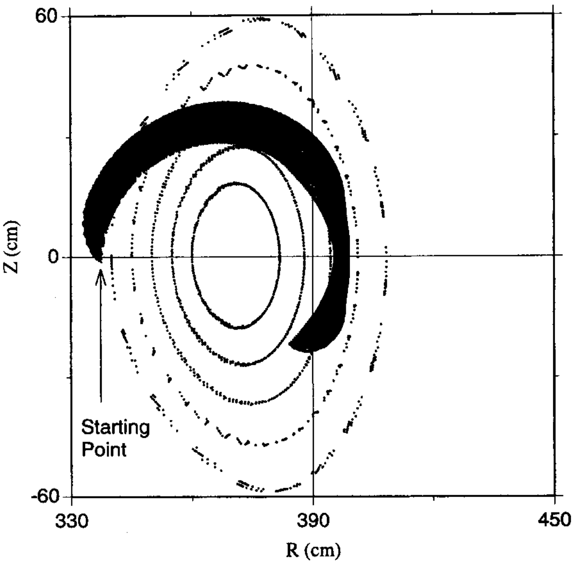

Fig. 1 Electron trajectory in the vertical plane.

It is assumed that there is the electric field in plasma and the electrical static potential is the function of the magnetic surface. The electric potential is taken as $e\Phi_0/W = 0.1$. The more detail of the magnetic field model and electric field model can be found in [1,4].

The typical trajectory of the injected electron with the moderate energy ($W = 40$ keV) is shown in Figure 1. The starting position of the electron has the following coordinates: $r_0 = 54.58$ cm, $\vartheta_0 = 6.29$ rad, $\varphi_0 = 2.14$ rad. The electron starts outside the last closed magnetic surface as the helically trapped particle, becomes the blocked particle and penetrates into the center of the confinement volume and stays there until the re-trapping occurs. The time of staying of such particle in the core of plasma is almost 10 times larger than in the Outward Shift Configuration. The staying time in the core region (in the state of blocked or passing particle) is evaluated as $\tau_{\mathrm{retrap}} - \tau_{\mathrm{detrap}}$, where τ_{retrap} and τ_{detrap} are the times of the re-trapping and de-trapping of the particles respectively. The staying time of the injected electrons with energy $W = 40$ keV is some less than 1 ms (Fig. 2).

3. Effect of Coulomb Scattering

Injected particles collide with the bulk plasma during the staying time and dispose in the some space inside the plasma.

3.1 Pitch-angle Scattering Model

Collisions are taken into account in the following

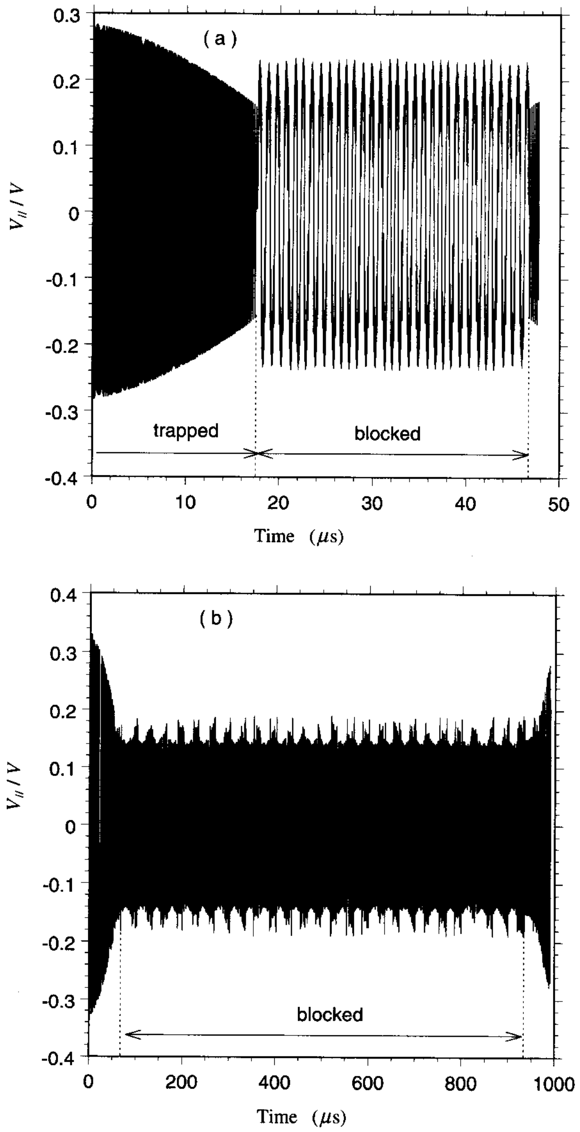

Fig. 2 Time evolution of the electron velocity in the Outward Shifted Configuration (a) and Inward Shifted Configuration (b).

way.

Test particle is scattered by the particles of the bulk plasma of the density $n^* = n^*(0)[1 - \Psi/\Psi(a_{\rm pl})]^k$. Parameters $n^*(0)$ and k can be varied; the function Ψ describes the cross-section of the magnetic surfaces, it is

$$\Psi = \left(\frac{r}{a_h}\right)^2 + 2\left(\frac{R}{a_h m}\right)^2 \sum_n n\varepsilon_{n,m}\left(\frac{r}{a_h}\right)^n \cos(n\vartheta - m\varphi) \quad (3)$$

$\Psi(a_{\rm pl})$ is the function that describes the cross-section of the magnetic surface which surrounds the plasma; $a_{\rm pl}$ is the plasma radius, in the case considered here $a_{\rm pl}$ = 43 cm; Under Coulomb scattering the moments of the test particle change in accordance with the following rule [5,6]:

$$\frac{dp_\parallel}{dt} = -\frac{4\pi e^2}{V^3} V_\parallel \sum_* \frac{Le^{*2}(M+m^*)}{Mm^*} n^* \Phi_1(b^* V)$$
$$\frac{dp_\perp^2}{dt} = \frac{8\pi e^2}{V} \sum_* Ln^{*2} e^{*2} \Phi(b^* V) \quad (4)$$

where $\Phi_1(x) = \Phi(x) - x\, d\Phi/dx$, $\Phi(x)$ is the *error integral*. Parameter $b^* = \sqrt{m^*/2T^*}$; L is *Coulomb logarithm*; e^*, m^*, T^* and n^* are charge, mass, temperature and density of the plasma particles; the following dependence of the temperature $T^* = T^*(0)[1 - \Psi/\Psi(a_{\rm pl})]$ is supposed. Index (*) denotes the sort of particles in (2); it means summation.

Time evolution of $V_\parallel$ and $V_\perp$ (4) let us evaluate the characteristic times $\tau_\parallel$ and $\tau_\perp$ which are roughly the time in which the test particle loses its ordered velocity in the initial direction of motion ($\tau_\parallel$) and the time in which the velocity vector of the test particle is turned through an angle 90^0 ($\tau_\perp$). These characteristic times are defined by the relations

$$\tau_\parallel = \frac{MV^3}{4\pi e^2 \sum_* \frac{Le^{*2}}{\mu} n^* \Phi_1(b^* V)} \quad (5)$$

$$\tau_\perp = \frac{M^2 V^3}{8\pi e^2 \sum_* Le^{*2} n^* \Phi(b^* V)} \quad (6)$$

3.2 Deposition of the Injected Particles

To study the effect of the scattering on the deposition of particles here some different procedure is considered. The pitch velocity $V_\parallel/V$ is changed trough the equal time intervals. The size of "jumps" ($\Delta V_\parallel/V$) is fixed. The sign of $\Delta V_\parallel/V$ is chosen randomly. Adiabatic invariant of the test particle remains constant between the collisions. The value $\Delta V_\parallel/V$ is taken as 0.2 that corresponds to the helical magnetic well value. The time interval between the jumps is near 1.45×10^{-5} s. It is much smaller compared the $\tau_\perp$ that is near 0.1 s under the density $n^* = 10^{13}$ cm^{-3}. One example of the particle trajectory with the consequences of the kicks is shown in Figure 3. Its trajectory is some different from the initial trajectory (Fig.1), the particle becomes the passing earlier than the particle without collisions.

The deposition of the passing particles can be seen on Figure 4. These are the footprints of the passing

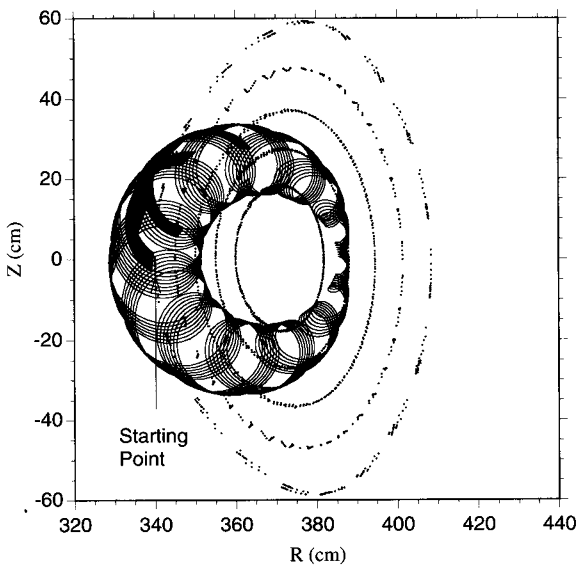

Fig. 3 Typical trajectory of the particle transforming from the helically trapped into passing due to pitch angle scattering.

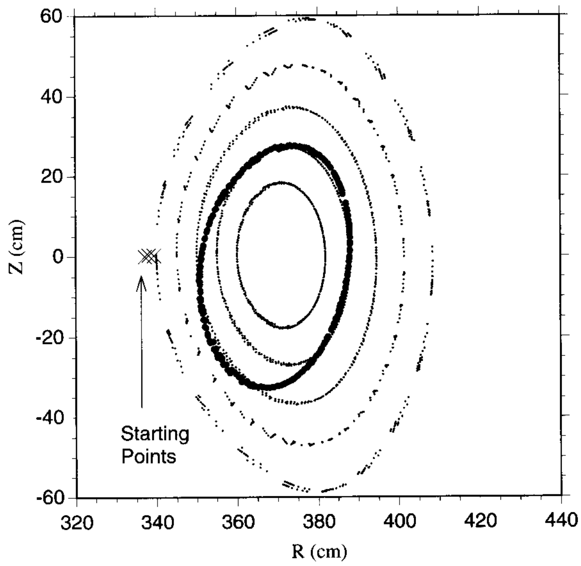

Fig. 4 Deposition of the passing particles in one vertical cross section.

particle trajectories in one cross-section of the torus on the background of the same cross-section of the magnetic surface.

4. Conclusions

4.1 In the LHD configuration with the inward shift of the magnetic axis all effects of the electric field control in plasma can take place as it was shown before for the configuration with the outward shift of the magnetic axis shift.

4.2 The energy of injected electrons can be reduced to the moderate values (40 keV) instead the high energy (100–150 keV). Such particles have the transit orbits and can penetrate in the core of plasma. The total power of the injection can be smaller 2.5 – 4 times in comparison with the case as it was considered earlier.

4.3 The deposition of the injected particles is obtained when the collisions are taken into account. The location of the deposition of injected particles is shifted relatively the position of the particles without collisions but not so strong. The penetration length of injected particles with collisions becomes shorter than one without collisions but not so strong.

4.4 For the study here we select electrons because in the experimental way it is more simple to arrange the electron guns instead of ion gun and the high energy particles can not be effected strongly by the collisions. In such way the idea to control of the electric field with the injection of high energy particles can be checked.

4.5 Calculating of the radial electric field generated by injected electrons is under the performance now.

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