J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 485–488

New Method of Ion Injection into Helical Device with the Use of the Helical Ripple Loss Cone

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(Received: 18 January 2000 / Accepted: 27 June 2000)

Abstract

New physical mechanism of the ion injection into the helical device is proposed in which the natural helical loss cone is used. We have shown that the ions with the energy $W = 5$ keV and small pitch-angle $V_{\|}/V = 0.3$ injected into the helical magnetic trap from outside of the confinement volume can penetrate in the core of plasma. The particles with the transit orbits can reach the center of the confinement volume. In addition we have clarified the possibility of generating the strong positive radial electric field in the bulk plasma within the framework of neoclassical theory.

Keywords:

Ion transportation, toroidal trap, helical ripple, loss cone, transit orbits, radial electric field

1. Introduction

It is commonly understood that radial electric field, E_r plays an important role in improving the confinement properties of helical type magnetic traps like the Large Helical Device (LHD) [1] especially in a low collisional regime under the physics picture of the neoclassical theory [2]. Moreover, some theories for turbulence predict that the anomalous transport caused by plasma fluctuations is influenced by the radial electric field through its shear [3]. Thus, it is important to generate an appropriate radial electric field. As one of possible ways to control the E_r a new idea is proposed to inject high energy ions into the plasma core. If ions are injected into the plasma the positive E_r will build up. The positive electric field is expected not only to improve the confinement of bulk plasma, but also to protect the plasma center against the penetration of the impurity ions from the periphery.

However, it is not easy to bring charged particles freely into the core region across a strong toroidal magnetic field. In the case of LHD, it is possible to utilize the existing loss cone orbit, which has a reversible characteristic. Usually, these loss cone orbits should be minimized during field design optimization to reduce direct particle loss and to increase the confinement capability. Therefore, we need to choose the appropriate particles, which will possibly reach the central core of the plasma. The candidate orbit for this scenario is the transit particle, which show transitions from helically trapped orbits to blocked ones [4]. Blocked particle means that it is no longer the helically trapped however it becomes toroidally trapped and its velocity is only modulated by the helical magnetic field.

The senario to control the radial electric field, which is demonstrated in this paper, is as follows: (i) The ions injected from a gun which is installed outside of the last closed magnetic surface trace loss cone orbit. (ii) These ions collide with thermal particles and are deposited in the bulk plasma, and thus the radial current

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is produced. (iii) The plasma compensates this radial current by changing in E_r.

2. Transit Particle

The size of the loss cone depends on the magnetic field spectrum in angular variables or, in other words, the type of the modulation of the strength of magnetic field along the magnetic force line. The LHD is a very flexible device and different types of magnetic configurations can be realized [5]. For our study, a special configuration is taken, in which the major radius of the magnetic axis (R_{ax}) is shifted outside (R_{ax} = 3.9 m) compared to the standard configuration (R_{ax} = 3.75 m). The loss cone boundary of transit particle in the outer shifted configuration is shown in Fig. 1. It was made clear that the outer shifted configuration is favorable for the transition of the particles from the helically trapped to the blocked, and even helps them to be a passing particle in the core of the plasma. The typical trajectory of transit deuterium ion with the energy W = 5 keV is calculated by using a model magnetic field and shown in Fig. 2. The ion is injected from outside of the last closed magnetic surface and then penetrates into the internal area, close to the center of plasma. At the launching point the ion is helically trapped and it becomes the blocked particle. The launching point coordinates are the following r_0 = 54.0 cm, ϑ_0 = 0.338, φ_0 = 2.27, and $V_{\|}/V$ = 0.356, where r_0, ϑ_0, φ_0 are the coordinates connected with the circular axis of torus. Then r, φ and ϑ are the radial variable, the toloidal angle and the poroidal angle, respectively.

The time necessary for the penetration of the ion into the core of plasma, τ_{penetr}, and the time of the staying as the blocked particle there, $\tau_{blocked}$, can be seen in Fig. 3. It is necessary for depositing the injected ions that they collide with thermal particles during the

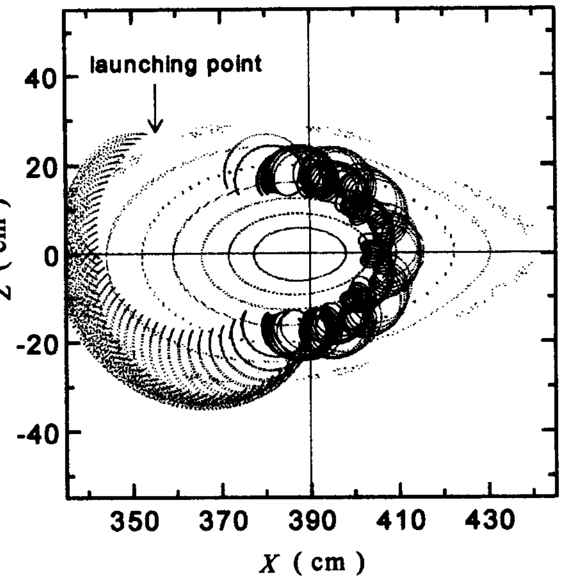

Fig. 2 Trajectory of the transit ion from "loss cone" in vertical cross-section.

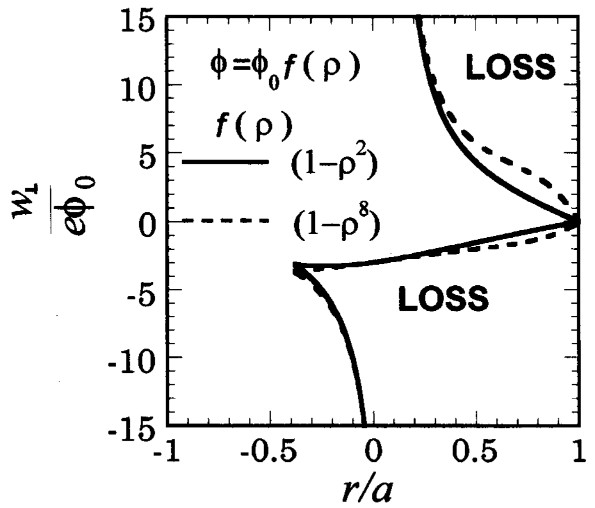

Fig. 1 Loss-cone boundary for ion. Here $W_\perp$ and ϕ_0 are the perpendicular energy and the central plasma potential, respectively.

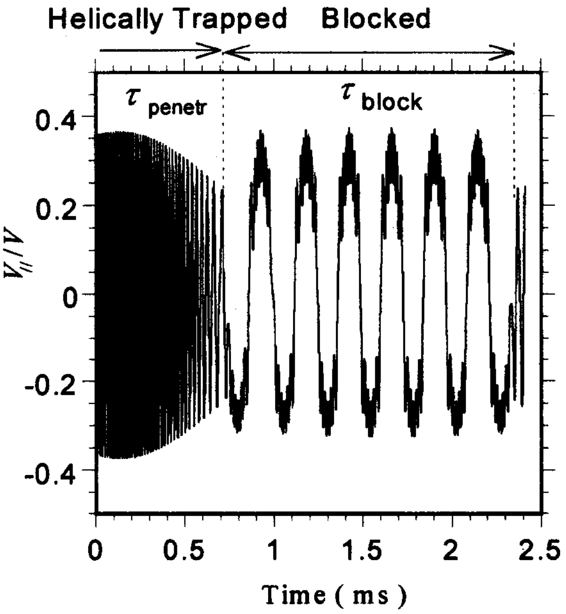

Fig. 3 Time dependence of velocity of transit ion

staying time in the blocked state. When the density is of the order of 10^{20} m^{-3} the effective collision time of injected ions are of the order of 1 ms and comparable to the staying time in the blocked state. Therefore it is expected that the injected ions are detrapped from the ripples (become passing state) and thermalized during the blocked state. If ions are injected into the plasma the radial electric field will build up positively.

3. The Behavior of the Radial Electric Field Ambipolar Condition

When the loss mechanisms, which are not intrinsically ambipolar, are present, the radial electric field is determined by the condition that the total particle flux is ambipolar in steady state. This condition can be written as

$$\Gamma_i(E_r)=\Gamma_e(E_r), \tag{1}$$

where Γ_i (Γ_e) is ion (electron) particle flux. This equation is equivalent to $J_r(E_r)$ = 0, where Jr is the radial current density. Each of these non-ambipolar fluxes, such as the orbit loss of ions [6], the diffusion flux introduced by helically trapped particles [7] and the flux due to the bulk ion viscosity [8] has a non-linear dependence on the radial electric field, and hence a drastic change of the radial electric field is expected when the additional non-ambipolar fluxes are introduced. If ions are injected into the plasma, the radial electric field is determined from the new ambipolar condition

$$\Gamma_i(E_r)-\Gamma_i^{\mathrm{beam}}(E_r)=\Gamma_e(E_r), \tag{2}$$

where Γ_i^{beam} is the injected ion flux. This equation is equivalent to

$$J_r(E_r)=J_r^{\mathrm{beam}}(E_r). \tag{3}$$

We consider the ion-root plasma [9] as a target because the high density plasma is favorable for the deposite of the ion beam. We are interested in the generation of strong positive E_r in the bulk plasma and thus the flux due to the bulk viscosity and the loss cone loss of the toroidally trapped particles are not important. The loss cone loss of the helically trapped particles are small compared to the diffusion flux introduced by helically trapped particles in this collisionality regime. We thus consider the diffusion flux induced by helically trapped particles only as the non-ambipolar flux. We choose the beam energy, the pitch angle and launching point so that the ion can penetrate the core region and assume the weak dependence of J_r^{beam} on E_r. The injected ion beam is influenced by collision, and thus reduced with the distance from launching point. For simplisity, we assume that all injected ions are deposited at $r_b/a_p \sim 1 + 0.5\varepsilon - (2\varepsilon)^{1/2}$. Here r_b is the loss cone boundary, $\varepsilon = \varepsilon_{ta}/\varepsilon_{ha}$ and ε_{ta} (ε_{ha}) is the toroidal (helical) ripple at the outer most magnetic surface, where we employ ε_{ta} = 0.148 and ε_{ha} = 0.192. The total current is conserved in the region of $r > r_b$, and thereby J_r^{beam} is writen as

$$J_r^{\mathrm{beam}}=I^{\mathrm{beam}}/4\pi^2 Rr, (r>r_b)$$
$$J_r^{\mathrm{beam}}=0\,(r<r_b) \tag{4}$$

where I^{beam} is the injected beam current.

The influences of ion injection on the radial electric field

The equilibrium of E_r is determined by plotting the left and right sides of Eq. (3) as a function of E_r. In the case of no beam injection, the E_r has only a small solution as shown in Fig. 4 (see an intersection of the solid curve and the broken curves). In low current injection case, a drastic change in E_r is not expected. When the beam current increases, E_r can have three solutions. In this situation, there is a possibility to introduce the bifurcation of E_r. If the bifurcation occurs and E_r becomes large enough, the neoclassical particle and heat flux are suppressed and thus confinement is improved.

The E_r profiles with and without the ion beam are shown in Fig. 5, where we assume that the central temperatures of ion and electron are 4 keV and the density is 1 × 10^{20} m^{-3}. In the case that the ion beam current exceeds 70 A, there is a possibility to bifurcate in the core region and the width of this region increases

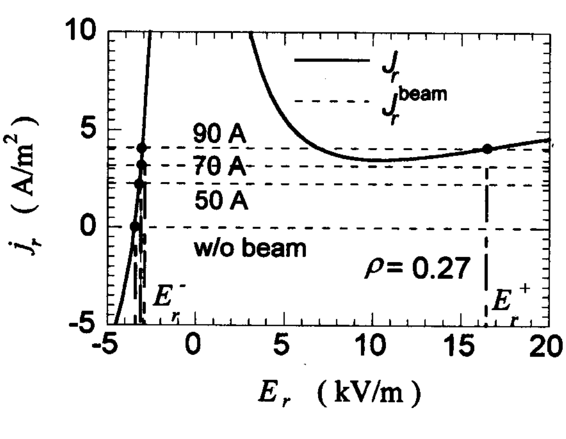

Fig. 4 The left side and the right side of Eq. (4) versus E_r.

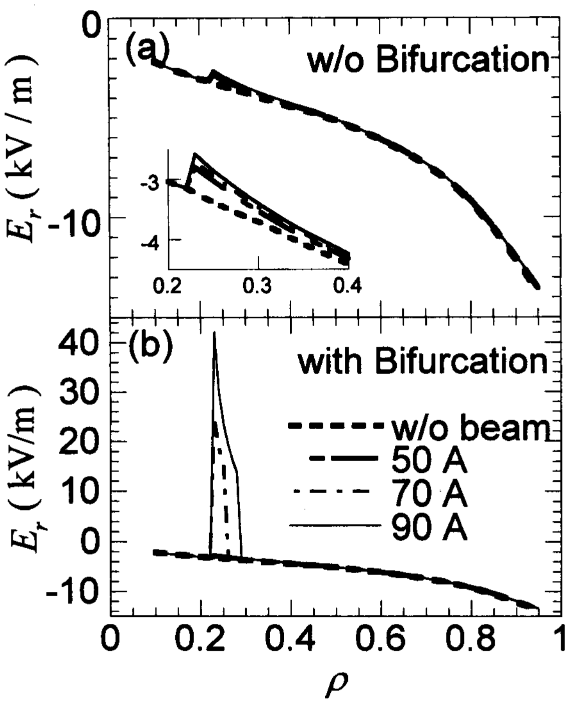

Fig. 5 Change in radial profiles of the radial electric field with ion beam injection. Without bifurcation case (a) and with bifurcation case (b) are shown.

with increases in the beam current. The j_r^{beam} increase with decreases in radius as shown in eq. (4), and hence the center region is easy to achieve the critical condition. When the E_r is bifurcated, the large E_r shear is generated. In this case the shear suppression of the fluctuation can be expected.

4. Summary

As the result of our study, it is possible to conclude the following.

1. The penetration of ions to the core of the plasma in a helical device is demonstrated by the drift orbit calculation, this is the case of the ions belonging to the "loss cone", namely, the case in which trajectories are the "transit orbits". It is possible to launch helically trapped particles from the outside of the magnetic confinement volume and then transform them into blocked particles in the center of the confinement volume.

2. The injected ions can stay in the core of the plasma long enough before retrapping occurs. It is sufficient to produce a non-ambipolar flux across the magnetic surfaces and which generates the radial electric field.

3. The ion beam injection has a strong possibility to trigger the bifurcation of E_r in the core region of the LHD plasma.

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