Numerical study on formation process of helical nonneutral plasmas using electron injection from outside magnetic surfaces

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In order to investigate the formation process of helical nonneutral plasmas, we calculate the orbits of electron injected in the stochastic magnetic field when the closed helical magnetic surfaces are correspond with the equipotential surfaces. Contrary to the experimental observation, there are no electrons inward penetrating.

Keywords: Orbit calculation, Nonneutral plasma, Helical, Electron injection, Stochastic magnetic region

1 Introduction

Research on nonneutral plasmas confined in toroidal magnetic surfaces has been intensively conducted in recent years [1, 2]. Despite the closed magnetic surfaces, no break-up of those is required when the plasma is produced. In experiments on devices of the Compact Helical System (CHS) [3] and the Heliotron [4], an electron-gun (hereafter, e-gun) has been installed in the stochastic (or ergodic) magnetic region (SMR) [5] surrounding the last closed flux surface (LCSF) and just injected thermal electrons in the SMR. Then, within the order of 10 ps after the injection, some have penetrated deeply in the helical magnetic surfaces (HMS), spread rapidly in the whole of the closed surfaces, and finally forms a helical nonneutral plasma there [6].

Regarding the mechanism of the inward penetration of electrons, recent three-dimensional orbit calculations including two experimental findings which are that (1) there is a electrostatic potential and (2) the center of equipotential surfaces (EPS) is shifted from that of HMS have finally predicted some outward orbits (at extend to inward part of closed helical vacuum magnetic region [7]. Data have clearly shown that the pitch angle of electrons injected into the stochastic magnetic region is scattered considerably due to the presence of self space potential $\phi_s$. Eventually, the injected electron turns to be a helically trapped particle [9, 10], and start an inward movement along one of the $\phi_{\text{rms}}$ contours [3, 7, 10]. Once penetrating deeply, the electron can never escape from the LCSF because the negative $\phi_s$ acts as a potential barrier.

In this paper, we report the result of orbit calculation and the velocity map in the case that the center of EPS is corresponded with that of HMS. Then no electrons penetrate across the HMS. In Sec. 2, the model employed in this computation is briefly explained. Data obtained from the calculation and the velocity map are given in Sec. 3. Finally, a summary is given in Sec. 4.

2 Calculation Model

As mentioned, when the center of the EPS is shifted from that of HMS, it has known that some electrons injected in the SMR can penetrate the HMS and are trapped [7]. So we ensure the orbits when the center of the EPS is correspond with that of HMS. We mention the calculation model as follows.

Fig. 1 The modeled self electrostatic potential $\phi_s$ in the stochastic magnetic region (SMR) and its vicinity. The profile is determined from the measured data.

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3 Calculation Results

In calculation, we have varied the initial absolute value of velocity and pitch angle of the e-gun. We show the calculation results as follows.

3.1 Passing Orbit

In this subsection, we show the orbit whose initial pitch angle is 16°. Figure 3 shows the time evolutions of all parameters of the injected electron. The injected electron sticks around the LCSF, as shown in Fig. 3 (a). For this case, as recognized from Fig. 3 (b), the electron rotates the torus at all times from $t = 0$ $\mu$s to the calculation end. No transversal motion or helically trapped one can be found for this case at all. The injected electron has been in the state of passing particle, all the time.

Precisely, the penetration across the HMS is happened when the pitch angle of injected electron is scattered by the electrostatic field and the electron turns to

Fig. 2 The example of $a_{\phi}$ distribution (a) at the $\phi = 0$ poloidal plane and (b) on horizontal line. At this calculation, the value of $a_{\phi}$ is calculated as the function of normalized minor radius.

Fig. 3 Time evolutions of (a) normalized position, (b) toroidal angle, (c) pitch angle, (d) magnetic moment and (e) total energy $E$, kinetic energy $E_k$ and potential energy $E_p$ of the injected electron, for the case of $\nu_{\parallel} = 16^\circ$. In this case, the electron has been always in the state of passing particle in the SMR.
become a helically trapped particle[7]. Then, the helically trapped electron travels inwardly along \( \mathbf{B} \mathbf{n} \) contours where the strength of \( \mathbf{B} \) is weaker compared to the neighborhood region on each magnetic surface, which is just same as the motion of helically trapped electron of neutral plasma[5, 10]. But in this case, the variation of the pitch angle of injected electron is very small, as seen from Fig. 3 (c). Consequently, no penetration of the injected electron occurs, because the transition to a helically trapped particle is never happened.

As long as \( \phi_0 \) is independent of time and depends only on coordinates, it follows from the equations of motion that total energy is conserved:

\[
0 = \mathbf{v} \cdot \mathbf{a} = \frac{m_0}{\eta E_0} (\mathbf{v} \times \mathbf{B} + \mathbf{E})
\]

\[
= v \times \mathbf{B} \times \frac{\mathbf{v} \times \mathbf{B} + \mathbf{E}}{\eta E_0}
\]

\[
= -\frac{d (\mathbf{v}^2)}{dt} + \frac{d}{dt} (\mathbf{v} \times \mathbf{B})
\]

so eqn. (1) can be written as

\[
\text{const} = \frac{m_0 c^2}{2} + q_0 E_0
\]

As seen from Fig. 3 (a, c), magnetic moment \( \mu \) and \( E_0 \) of the injected electron are conserved.

3.2 Helically Trapped Orbit

In the case of initial pitch angle \( \sim 120^\circ \), but the penetration across the HIMS is not observed, either. Figure 4 shows the time evolutions of all parameters of injected electron. As seen from Fig. 4 (b, c), the injected electron doesn’t move to toroidal direction and becomes helically trapped particle. But in this case, the injected electron hits the grounded chamber wall, doesn’t penetrate across the HIMS. This is because the injected electron must become a helically trapped particle on the inbound \( \mathbf{B} \mathbf{n} \) contours[7]. So in this case, the penetration of injected electron is not observed.

3.3 Velocity Mapping

As explained above, the inward penetration across the HIMS has depend on whether the transition to a helically trapped particle occurs or not, and moreover, the transition is affected much by the initial pitch angle of the injected electron. Thus, we have performed a mapping of the initial pitch angle of the pitch angle with changing its kinetic energy \( V_{kin} \) (equivalently, beam energy in experiments). \( V_{kin} \) = \( -0.8 \) and \( -0.4 \) kV.

Figure 5 shows the velocity map for electrons injected in the SMR. Orbit calculations are conducted up to \( 20 \mu s \). The symbol of \( x \) on the map represents in-successful penetration. As recognized from Fig. 5, the inward penetration across the HIMS is independent of initial \( V_{kin} \) and pitch angle. This is because that when the center of EPS is correspond with that of HIMS, the electrostatic field is always perpendicular to magnetic force line. As mentioned, the pitch angle of the injected electrons must be scattered on the inbound \( \mathbf{B} \mathbf{n} \) contours. Then, the electrostatic field which is parallel to magnetic force line operates powerfully to this scattering, because the scattering results from the change of the value of \( v_0 \). Figure 6 shows the contours of strength of \( E_0 \) when the center of EPS is shifted from that of HIMS. As seen higher right from Fig. 6, there are regions that have large \( E_0 \). So when the center of the EPS is shifted from that of HIMS, we enter into that the electrons decelerated the motion of direction of the magnetic
Fig. 5 The velocity map for the electron launched from the o-gas placed at the point (r,θ,φ) = (-0.3, 29.5, 0). As recognized, there are no electrons which happen the inward penetration across the HMS.

force line in this region become helically mapped particle, and some electrons injected in the SMR penetrate across the HMS [11].

4 Summary

In order to investigate the formation process of helical non-neutral plasmas, we have numerically performed a mapping of velocity space of outward electrons whose orbits extend to inward part of closed helical vacuum magnetic region of the Compact Helical System machine, especially in the case the center of EPS is correspond with that of HMS. In calculations presented here, the magnetic axis R_m is fixed to be R_m = 101.6 cm and the magnetic field strength is B = 0.9 kG. Those are exactly the same as those in the settings of actual experiments. And, in this computation, electron full orbits are solved using the 6th Range-Kutta method to include the effect of Arnoldi motion.

In experiments on CHS, it is observed that electron penetrating across the closed HMS any ejecting angle. However data show that in the case the center of EPS is correspond with that of HMS, no penetration is observed in computation with any value of v_e/v_B. This is because no electrostatic field which is parallel to magnetic field line, so pitch angle of the injected electron is not scattered effectivly.

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Fig. 6 The contours of strength of E_theta when the center of EPS is shifted from that of HMS at ϕ = 0 poloidal plane. This shift cause large E_theta in the SMR.