Proceedings of ITC18, 2008

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 is correspond with the equipotential surfaces. Contrary to the experimental observation, there are no electrons inward penetrating.

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

1 Introduction

Research on nonneutral plasmas confined on 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 plasmas are produced. In experiments on devices of the Compact Helical System (CHS) [3] and the Heliotron J [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 (LCFS) and just ejected thermal electrons in the SMR. Then, within the order of 10 μs after the injection, those have penetrated deeply in the helical magnetic surfaces (HMS), spread rapidly in the whole of the closed surfaces, and finally formed 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 outputted some outward orbits that extend to inward part of closed helical vacuum magnetic region [7]. Data have clearly shown that the pitch angle of electron injected into the stochastic magnetic region is scattered considerably due to the presence of self space potential ϕ_s. Eventually, the injected electron turns to be a helically trapped particle [9, 10], and start an inward movement along one of the $|B_{min}|$ contours [3, 7, 10]. Once penetrating deeply, the electron can never escape from the LCFS because the negative ϕ_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.

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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.

Firstly, in experiments, substantial ϕ_s (down to ~ -400V) has been clearly measured [6] in the SMR just after thermal electrons are injected from the e-gun with the acceleration voltage V_{acc} is -1.2kV. This is because the lines of force in the SMR are chaotic, the connection lengths of those to the grounded chamber wall are very long. Therefore, there are no doubt that the thermal electrons injected from the e-gun are confined there. So we assume the presence of the EPS which extend to the SMR and model a radial profile of ϕ_s from the experimental data, as seen from the solid curve in Fig. 1. Figure. 2 shows the ϕ_s distribution at the $\phi = 0^o$ plane. On the SMR and its

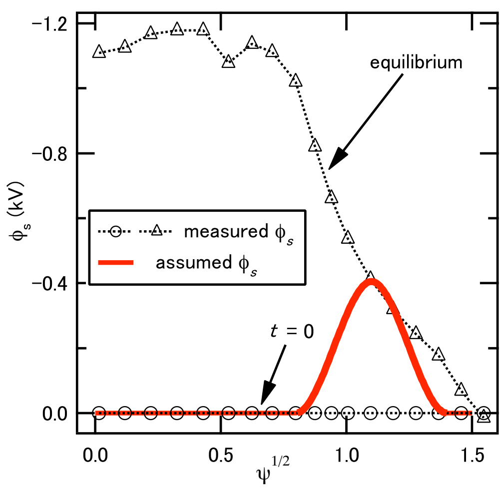

Fig. 1 The modeled self electrostatic potential ϕ_s in the stochastic magnetic region (SMR) and its vicinity. The profile is determined from the measured data.

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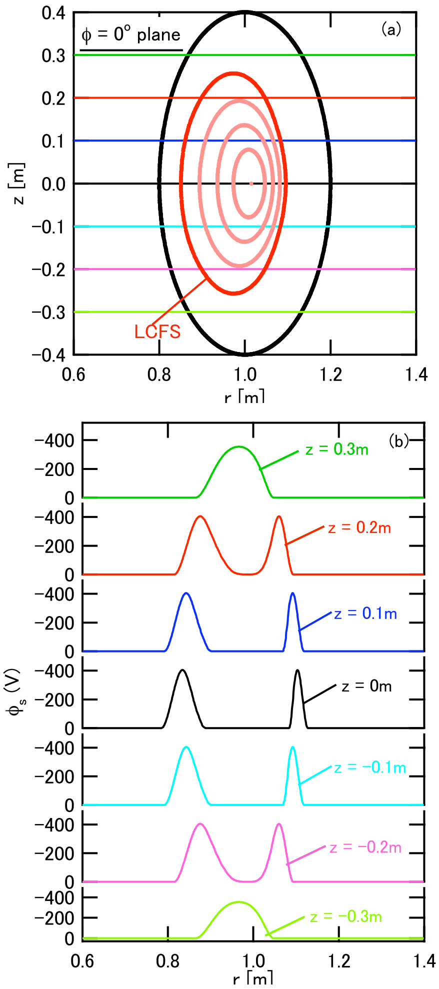

Fig. 2 The example of ϕ_s distribution (a) at the $\phi = 0^o$ poloidal plane and (b) on horizontal line. At this calculation, the value of ϕ_s is calculated as the function of normalized minor radius.

vicinity, there is electrostatic potential, as experimentally.

Secondly, to calculate full gyro-orbits of the electron ijected in the SMR, we solve the equation of motion $\dot{\mathbf{v}} = -e(\mathbf{v} \times \mathbf{B} + \mathbf{E})/m_e$, we employ the 6^{th} order Runge-Kutta-Verner method in cylindrical coordinates. Here, q and m_e are the charge and mass of an electron, respectively. In calculation, we have varied the injection angle a of the e-gun. Other parameters listed below are fixed as follows; the strength of $\mathbf{B}$ at manetic axis R_{ax} = 101.6 cm is 0.9 kG and the value of V_{acc} is −1.2kV. The injection position of a single electron is at $\Psi^{1/2} = 1.1$ on the equatorial plane at the $\phi = 29.5^o$ cross-section, where $\Psi^{1/2}$ is the normalized minor radius and ϕ is the toroidal angle, respectively. These are exactly the same condition as the experimental setting.

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^o. Figure 3 shows the time evolutions of all parameters of injected electron. The injected electron sticks around the LCFS, 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 transition electron 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

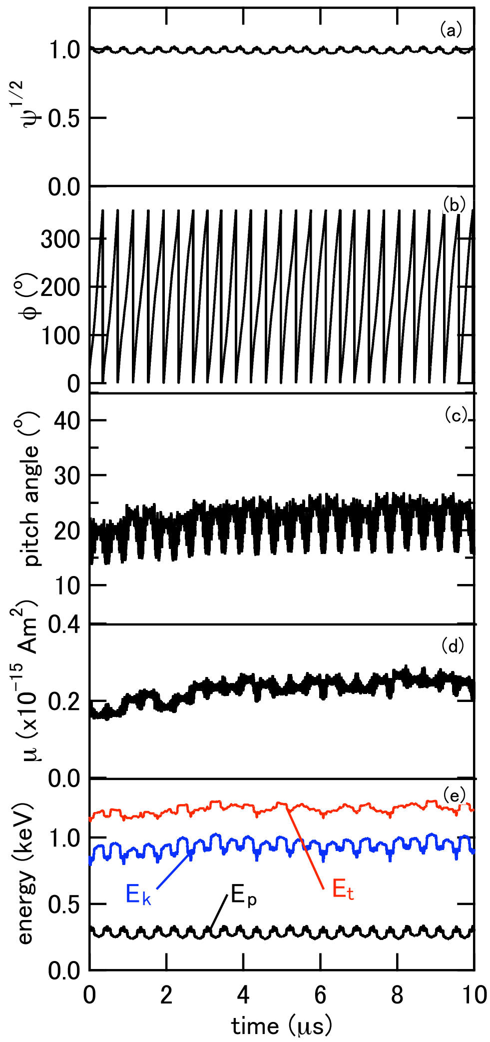

Fig. 3 Time evolutions of (a) normalized position, (b) toroidal angle, (c) pitch angle, (d) magnetic moment and (e) total energy E_t, kinetic energy E_k and potential energy E_p of the injected electron, for the case of $v_\perp/v_\parallel \sim 16^o$. In this case, the electron has been always in the state of passing particle in the SMR.

become a helically trapped particle[7]. Then, the helically trapped electron travels inwardly along $|B_{min}|$ contours where the strength of **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 plasmas[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 theinjected electron occurs, because the transition to a helically trapped particle is never happened.

As long as ϕ_s is independent of time and depends only on coordinates, it follows from the equations of motion that total energy E_t is conserved;

$$\begin{aligned} 0 &= \mathbf{v}\cdot\dot{\mathbf{v}} - \frac{q}{m_e}\mathbf{v}\cdot(\mathbf{v}\times\mathbf{B}+\mathbf{E}) \\ &= \mathbf{v}\cdot\dot{\mathbf{v}} + \frac{q}{m_e}\dot{\mathbf{r}}\cdot\nabla\phi_s \\ &= \frac{d}{dt}\left(\frac{v^2}{2}+\frac{q}{m_e}\phi_s\right), \end{aligned} \tag{1}$$

so eqn.(1) can be written as

$$\text{const} = \frac{m_e v^2}{2} + q\phi_s. \tag{2}$$

As seen from Fig. 3 (d, e), magnetic moment μ and E_t of the injected electron are conserved.

3.2 Helically Trapped Orbit

In the case of initial pitch angle $\sim 126^o$, but the penetration across the HMS 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 HMS. This is because the injected electron must become a helically trapped particle on the inboard $|B_{min}|$ 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 HMS 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_{acc} (equivalently, beam energy in experiments): V_{acc} = −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 μs. The symbol of × on the map represents in-successful penetration. As recognized from Fig. 5, the inward penetration across the HMS is independent of initial V_{acc} and pitch angle. This is because that when the center of EPS is correspond with that of HMS, the electrostatic field is always perpendicular to magnetic force line. As mentioned, the pitch angle of the injected electrons must be scattered on the inboard $|B_{min}|$ 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 $v_{\|}$. Figure 6 shows the contours of strength of $E_{\|}$ when the center of EPS is shifted from that of HMS. As seen higher right from Fig. 6, there are regions that have large $E_{\|}$. So when the center of the EPS is shifted from that of HMS, we enter into that the electrons decelerated the motion of direction of the magnetic

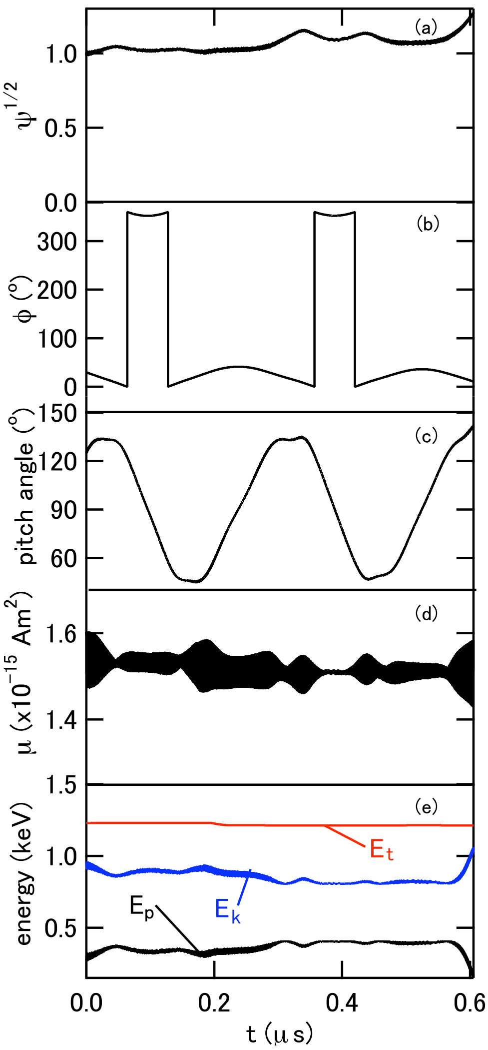

Fig. 4 Time evolutions of all parameters for the case of $v_{\perp}/v_{\|} \sim 126^o$. Parameters here are the same as those in Fig. 3, for reader's convenience. As recognized, no penetration of the injected electron occurs for this case, too. In this case, the electron is reflected from magnetic mirror and finally hits to the grounded chamber wall at $t \sim 0.6\mu$s.

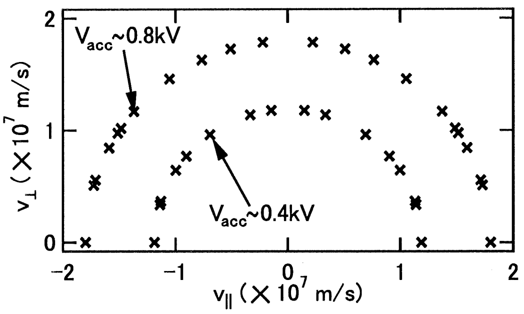

Fig. 5 The velocity map for the electron launched from the e-gun placed at the point (r, θ, z) =(1.183, 29.5, 0). As recognized, there are no electrons which happen the inward penetration across the HMS.

force line in this region become helically trapped 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_{ax} is fixed to be R_{ax} = 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 6^{th} Runge-Kutta method to include the effect of Larmor 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 s of $v_\perp/v_\parallel$. This is because no electrostatic field which is parallel to magnetic field line, so pitch angle of the injected electron is not scattered effectively.

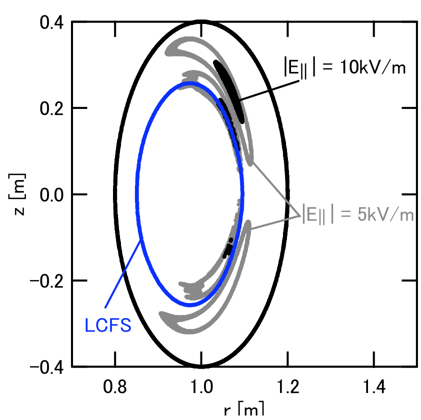

Fig. 6 The contours of strength of $E_\parallel$ when the center of EPS is shifted from that of HMS at $\phi = 0^o$ poloidal plane. This shift cause large $E_\parallel$ in the SMR.

Acknowledgment

The authors are grateful to Drs. A. Shimizu, K. Matsuoka, and S. Okamura of NIFS for their continuous encouragements. This work is performed under the aupices of the NIFS CHS Research Collaboration, No. NIFS07KZPH002.

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