Role of Negative Potential Barrier Formed by Electrons Confined in the Stochastic Magnetic Region of Helical Nonneutral Plasmas

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Nonneutral plasmas confined in the helical magnetic surface (HMS) region can be produced by injecting electrons from outside the last closed flux surface (LCFS). Recently, we numerically calculated outward electron orbits that extend to the inner HMS region. Once it penetrates the HMS region, the injected electron is never lost to the chamber wall, because the negative self-electric potential ϕ_s in the stochastic magnetic region (SMR) acts as a potential barrier. Remarkably, during the reflection process at the potential barrier, the electron is still trapped in the foot of the negative ϕ_s region, although it completely overcomes the SMR. The electron then resumes inward movement across the HMS.

Keywords: toroidal nonneutral plasma, pure electron plasma, stochastic magnetic region, helically trapped particle, inward electron orbit, shifted equipotential surface, potential barrier

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1. Introduction

Although toroidal neutral plasmas confined on magnetic surfaces have been studied for more than fifty years, studies of toroidally confined nonneutral plasmas [1] began only recently. Experiments on toroidal nonneutral plasmas [2, 3] confined by pure magnetic fields B have been performed only on helical machines. This is because helical magnetic surfaces (HMS) can be statically formed with only a set of external magnetic coils around the vacuum chambers. No plasma current is needed to close the magnetic surfaces.

In these experiments, despite the closed HMS, no breakup of the magnetic surfaces is in fact required when nonneutral helical plasmas are produced. On both the Compact Helical System (CHS) [4] and Heliotron J [5] devices, an electron gun (e-gun) has been installed in the stochastic (or ergodic) magnetic region (SMR) surrounding the last closed flux surface (LCFS) of the HMS and has ejected thermal electrons there. Then, within a time of the order of 10 μs, the injected electrons have penetrated deeply into the HMS region, and spread rapidly throughout it. Finally, those particles formed a helical nonneutral plasma there.

The reason for the observed inward penetration [6] of the injected electrons was a conundrum for a long time. To investigate the physical mechanism, we calculated the orbits of a single electron injected into the SMR, where a negative space potential ϕ_s is extended [6]. In addition, the numerical code has taken into account the recently established fact that the equipotential surfaces do not coincide with the HMS [2]. Recently, we found inward electron orbits extending to the inner part of the closed HMS region [7]. The obtained results have clearly shown that in the SMR, the pitch angle of the injected electron changes considerably while it circulates there. Due to pitch angle scattering, the particle sometimes becomes a helically trapped particle in the upper region of the HMS and starts a downward movement along one of the $|B_{\mathrm{min}}|$ contours [8], i.e., an inward drift motion across the HMS region.

Surprisingly, numerical calculation also reveals that once it penetrates the HMS region, the helically trapped electron is never lost to the chamber wall. In fact, the particle is trapped in the foot of the finite negative ϕ_s region in the SMR. This result indicates that ϕ_s in the SMR acts as a potential barrier to the electron [7]. However, no details of how the electron reflects at the potential barrier in the SMR have been determined yet.

In this paper, we show the detailed time histories of all the physical parameters of the electron before and after reflection at the potential barrier in the SMR. Remarkably, the helically trapped electron completely overcomes the SMR when it emerges from the lower side of the HMS. Nevertheless, the electron is trapped in the foot of the potential barrier. The trapped electron finally resumes inward movement across the HMS. Section 2 presents a brief review of the penetration of electrons injected into the SMR, where finite negative ϕ_s forms. Data obtained by calculation are described in section 3. Finally, a summary is given in section 4.

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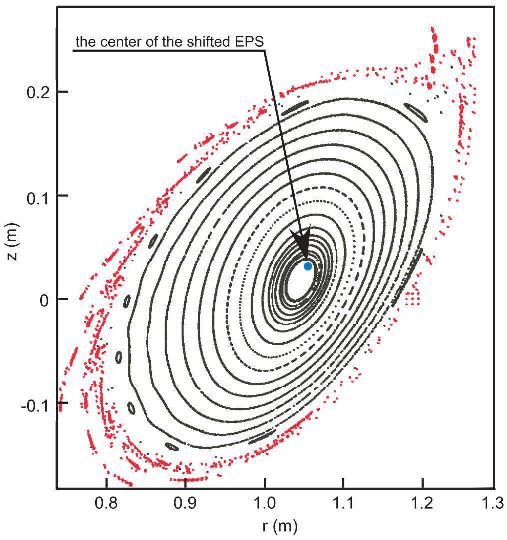

Fig. 1 Poincaré maps of magnetic field lines (black points) and an electron orbit (red points) depicted on a poloidal cross-section of the CHS for R_{ax} = 101.6 cm. The orbit of an electron injected into the SMR never connects with the closed HMS region unless ϕ_s forms in the SMR. As explained later, the center of the equipotential surface (EPS: blue circle) is shifted by ~ 2 cm from that of the HMS.

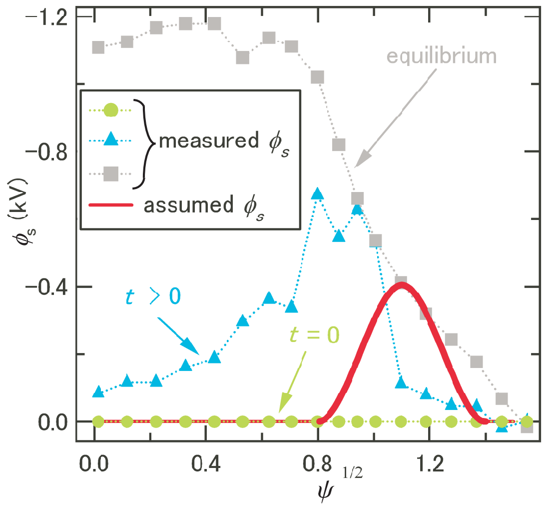

Fig. 2 Modeled electrostatic potential ϕ_s (red curve) in the SMR. Profile is determined from plotted data measured experimentally [7].

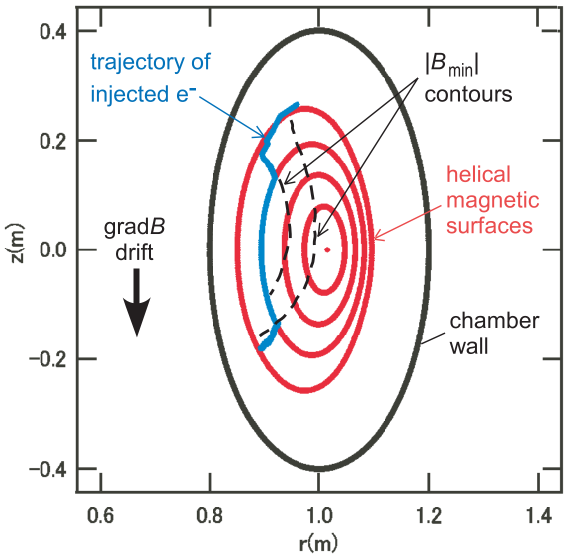

Fig. 3 Typical trajectory of electron projected onto the $\phi = 315°$ and 135° poloidal planes. $|B_{min}|$ contours and HMS are indicated. The helically trapped electron penetrates the HMS region from above. Then, the particle travels on one of HMS. Finally, it drifts outward across the LCFS from the lower region [7].

2. Brief Review of Electron Penetration

As stated above, HMS are closed without plasma currents. Figure 1 shows a Poincaré map (red points) of an electron orbit that intersects a poloidal crosssection of the CHS, assuming no finite negative ϕ_s exists in the SMR. The black points in Fig. 1, on the other hand, represent a Poincaré map of magnetic field lines for R_{ax} = 101.6 cm, where R_{ax} is the radius of the plane magnetic axis of the HMS of the CHS device [4]. As recognized, the LCFS lies just medial to the visible magnetic islands surrounding it. Outside the LCFS, magnetic surfaces are not closed in the vacuum chamber. Since the electron has been injected into the SMR outside the LCFS, no red points (the electron orbit) connect with the black points (the region inside the LCFS). Thus, an electron injected into the SMR never penetrates the closed HMS region for this case where ϕ_s = 0 V in the SMR.

As already explained, substantial ϕ_s (down to −400 V) has been measured [6] in the SMR just after thermal electrons are injected from the e-gun with an acceleration voltage V_{acc} = −1.2 kV. The solid curve in Fig. 2 shows the assumed ϕ_s. The plotted data are typical of the experimentally measured time evolution of ϕ_s. Another established fact is that ϕ_s on each HMS is never constant. Therefore, we assume symmetrical equipotential surfaces (EPS) of ϕ_s that are exactly the same as the elliptical HMS of the CHS, except that the center of the EPS is shifted from that of the HMS by ~ 2 cm [7].

Considerable penetration of the injected electrons into the HMS region has been clearly observed in the orbit calculation explained above. The numerical code solves the equation of motion for an electron injected into the SMR using the sixth-order Runge-Kutta-Verner method in cylindrical coordinates [9]. Here we briefly explain the penetration. Details are available in Ref. [7].

An electron is initially injected into the SMR, where a shifted negative ϕ_s is assumed. Figure 3 shows projections of the HMS of the CHS for B_{ax} = 101.6 cm (red curves), contours of $|B_{min}|$ (black dashed curves), and the electron trajectory onto the $\phi = 315°$ poloidal plane (blue curve), where ϕ is the toroidal angle. The $|B_{min}|$ contours are contour plots of the weaker magnetic field, showing the bottom of the magnetic ripple [8]. Comparing the trajectory of the electron with the $|B_{min}|$ contours reveals that the electron trajectory follows one of the $|B_{min}|$ contour curves whenever the electron drifts across the HMS region. Also, the injected electron always moves from the upper ($z > 0$) to the lower ($z < 0$) side in the HMS region when it starts to drift. This direction is consistent with that of the ∇B drift of electrons. Therefore, we concluded that this inward penetration is caused by the drift motion of a helically trapped electron [7].

3. Reflection at Lower Side of HMS Region

Figure 4 shows the time evolution of the principal parameters of the helically trapped electron before and after reflection at the lower region. As seen from the data of $\Psi^{1/2}$, after the electron reaches the LCFS (at $t \sim 13.5\,\mu s$), it completely overcomes the LCFS and enters the SMR, where $\Psi^{1/2} > 1$. Note that $\Psi^{1/2} = 0$ and 1 correspond to R_{ax} and the LCFS, respectively. As explained, finite ϕ_s exists in the SMR, which is clearly recognized from the data for $\phi_s(t)$ in Fig. 4. The presence of ϕ_s in the SMR causes considerable scattering of the pitch angle of the electron there. Furthermore, the kinetic energy of the electron changed in the SMR, whereas the total energy is always conserved. During this time, the electron moves outward, finally arriving at $\Psi^{1/2} \sim 1.2$ at $t \sim 15\,\mu s$.

However, this outward propagation stops at that time. In other words, the electron will never escape to the chamber wall, despite being almost at the outermost edge of the negative ϕ_s in the SMR (see also Fig. 2). In fact, as the data indicates, the electron remains in the vicinity there for a while; and gradually moves inward after $t \sim 15.5\,\mu s$.

The above motion is clearly seen in Fig. 5, where the electron orbit is projected onto the $\Psi^{1/2} - \phi$ plane. As seen in Fig. 5, the electron emerges approximately from the poloidal plane of $\phi = 135°$ (see also Fig. 3). Subsequently, the particle remains in the SMR with finite ϕ_s (blue region with diagonal lines) and continues toroidal bouncing motions there. Throughout this, the electron actually overcomes the ϕ_s region in the SMR. Nonetheless, again, the electron is never lost to the chamber wall. In fact, as recognized from Fig. 5, the electron is completely trapped in the foot of the ϕ_s region in the SMR. It thus seems that ϕ_s in the SMR acts as a potential barrier to the electron.

As Fig. 5 also shows, during the bouncing motion in the SMR, the toroidal angle ϕ of the electron fluctuates in time around $\phi \sim 135°$. However, as seen from the data in Fig. 4, the time-mean value of ϕ gradually changes from $\sim 135°$ to $\sim 90°$ (see also Fig. 5.) Then, the electron finally resumes inward movement across the LCFS from the poloidal plane of $\phi = 90°$, subsequently penetrating the HMS region again along one of the B_{min} contours as a helically trapped electron, as shown in Fig. 6.

Since the ∇B drift of the electron with negative charge is in fact from the upper to the lower side of the HMS region along the machine axis (the z-axis), the electron must return to the upper side when it resumes the inward movement along one of the $|B_{min}|$ contours (see also Fig. 3). This is also understood from Fig. 6, in which the electron clearly returns to the upper side of the HMS region before resuming inward movement across the HMS region for $t > 16.5\,\mu s$. Thus, if this event happens continuously for some of the following electrons launched from the e-gun, the number of helically trapped electrons would increase with time in the closed HMS region. Thus, these region would fill up with them from the outermost to the innermost part. Finally, a helical nonneutral plasma [2, 6] would form there, even though the electron injection occurred outside the closed HMS region.

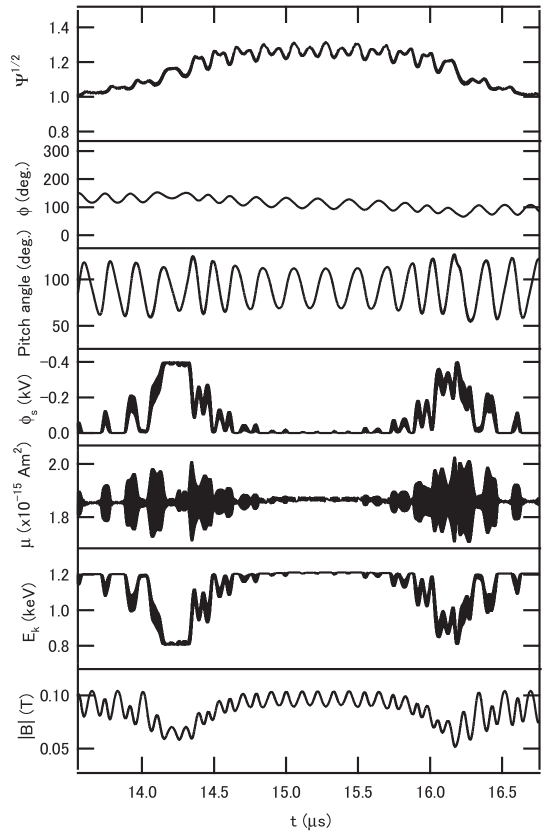

Fig. 4 Typical time evolution of normalized position, toroidal angle, pitch angle, electrostatic potential, magnetic moment, kinetic energy, and magnetic field strength where the electron exists. At $t \sim 13.5\,\mu s$, the electron drifts outward across the LCFS where $\Psi^{1/2} = 1$. Then, the electron completely overcomes the SMR with a finite ϕ_s region at $t \sim 15\,\mu s$. Nonetheless, the electron is still trapped in the SMR and finally resumes inward movement across the LCFS at $t \sim 17\,\mu s$.

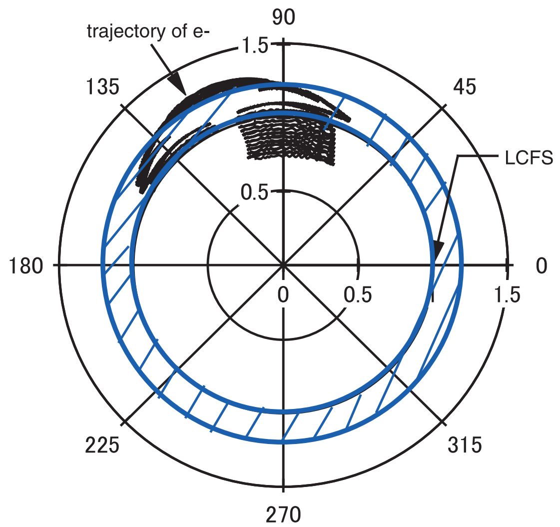

Fig. 5 The electron orbit projected onto the $\Psi^{1/2} - \phi$ plane for $13.5 < t < 19.1\,\mu$s. In the region painted with diagonal lines, finite negative space potential ϕ_s exists. the electron approximately comes out from the poloidal plane of $\phi = 135°$ and still continues a toroidal bounce motion even in the SMR. And finally, the electron resumes the inward movement across the HMS from the poloidal plane of $\phi \sim 90°$.

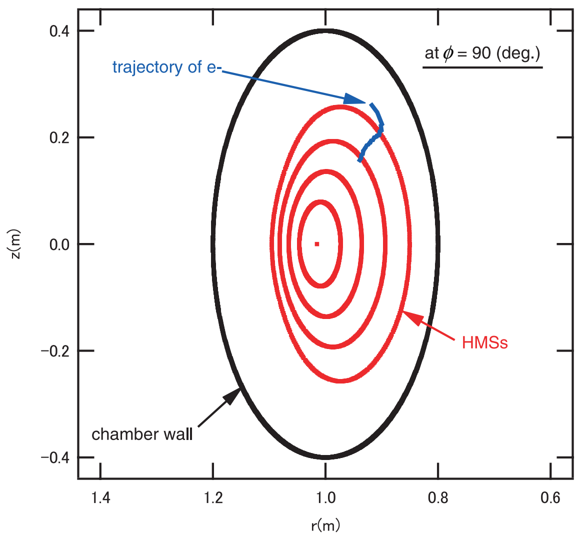

Fig. 6 Trajectory of electron projected onto the $\phi = 90°$ poloidal plane. Electron clearly returns to the upper region before resuming inward movement across the HMS.

4. Summary

Orbits of a single electron injected into the SMR are calculated numerically, taking into account two experimentally established facts about the SMR. For some values of the injection angle of the electron, outward electron orbits extending to the inward part of the closed HMS region surrounded by shifted negative ϕ_s have been found. The data clearly show that this is caused by a helically trapped electron, although this electron actually emerges from the closed HMS region along one of the $|B_{min}|$ contours.

However, the helically trapped electron will never be lost to the chamber wall. This is because it is trapped in the foot of the shifted negative ϕ_s in the SMR. In other words, ϕ_s in the SMR seems to act as a potential barrier to a helically trapped electron escaping from the closed HMS region. In fact, it should be emphasized that although the helically trapped electron completely overcomes the negative ϕ_s region and arrives almost at the outermost edge of the SMR, it gradually returns to the upper side of the HMS region. Then, the trapped electron finally resume inward movement across the HMS region as a helically trapped particle.

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