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The Study about the Relationship between Plasma Current in Open Magnetic Field and the Formation of Closed Flux Surface in CPD

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We investigate the physics of the formation of closed flux surfaces under the condition that a radio frequency (RF) wave is injected into the Compact Plasma Wall Interaction Experimental Device (CPD). From the orbits of the energetic electrons calculated for the open magnetic flux configuration, we estimate the plasma current I_{es} due to energetic electrons. We find that I_{es} increases with decreasing poloidal magnetic field, and observe the formation of closed flux surfaces in the experiments under the condition of low poloidal magnetic field (i.e., high I_{es} condition). This result suggests that the condition of high I_{es} is suitable for forming closed flux surfaces and that I_{es} can be used as an indicator to optimize the operational magnetic field condition for forming closed flux surfaces.

Keywords: spherical tokamak, plasma current start-up, RF injection, energetic electron orbit, closed flux surface

1. Introduction

Because of the possibility of high beta, spherical tokamaks (STs) have recently gained importance in the study of magnetic confinement fusion reactors. STs have a small aspect ratio ($A = R_0/a$, where R_0 is the major radius and a is the minor radius of tokamak plasmas) and their central space is quite limited [1]. The capacity of supplying magnetic flux needed to induce plasma current in STs is less than that in conventional tokamaks, where induced toroidal electric fields are enough to drive the plasma current, even for low temperature plasmas, because sufficient magnetic flux can be supplied by the central solenoid (CS) coils.

Because CS coils do not supply sufficient magnetic flux in STs, a non-inductive method such as electron cyclotron heating (ECH) due to radio frequency (RF) wave injection [2] can be used to start the plasma current. Even in ohmic heating (OH) assistance by ECH is needed (ECH + OH) [3]. Some researchers perform experiments on plasma current start-up in STs without CS coils [4]. Thus, plasma start-up without the assistance of an inductive electric field is an important issue in the operation of STs.

For RF injection, energetic electrons accelerated by RF waves are important for plasma current initiation in the open magnetic flux configuration [5]. Because of the low aspect ratio, grad B is larger in STs than in conventional tokamaks, and this condition facilitates the confinement of energetic electrons in the open magnetic field. Judging from these features, the ST configuration is good for driving plasma current with energetic electrons. Current ramp-up with energetic electrons is needed in superconductive tokamaks because the inductive electric field is weak. ECH assistance is also used for superconductive tokamaks. Therefore, knowledge of the use of energetic electrons for plasma ramp-up in an ST is useful for operating superconductive tokamaks such as ITER.

The plasma current start-up phase is divided into three phases, A, B, and C. Phase A is before breakdown, phase B is between breakdown and the formation of a closed flux surface, and phase C is after the formation of a closed flux surface. The conditions required for phases A and C have been studied for many devices. Estimating whether or not breakdown occurs can be done using the Townsend avalanche theory [6]. After establishment of a maintained closed flux surface, the plasma behavior can be estimated from the equilibrium, which can be obtained by solving the Grad Shafranov equation [7]. In phase B, the question of how to obtain the most suitable condition for forming a closed magnetic flux surface is still unanswered.

The main purpose of this letter is thus to find the proper conditions in phase B to initiate the plasma current with energetic electrons and to form closed flux surfaces. To achieve this goal, we need to establish an indicator that determines the relative ease of current driving. In phase B, where single particle orbits play an essential role, collisions between energetic electrons and other electrons and ions are infrequent [8].

In this letter, we estimate the current due to energetic

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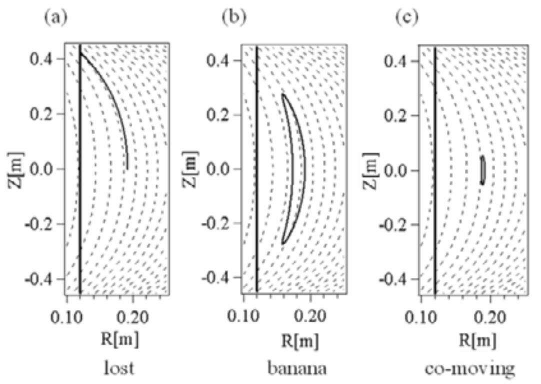

Fig.1 Orbits of electrons in open magnetic flux configuration. Solid lines show orbits projection, and dashed lines show magnetic line projection on poloidal plane.

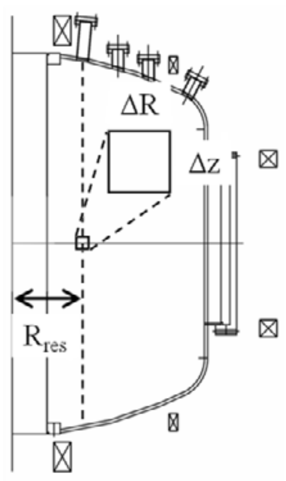

Fig.2 Volume in which we assume that electrons exist. In this study, ΔR = ΔZ = 0.005m and Rres = 0.19m. Hence, V has a cylindrical shape which has 0.19m inner radius, 0.005m thickness and 0.005m height.

electrons accelerated by RF waves for the various magnetic configurations and compare the results with the experimental results from CPD. From the results of comparison, the indicator which suggests the relative ease of current start-up is proposed. In Section 2, we discuss electron orbits and the method of estimating the current. The experimental apparatus is described in Section 3, and experimental results and analysis are given in Section 4. We discuss the results of numerical calculations in Section 5 and present a summary and conclusion in Section 6.

2. Electron Orbits in Open Magnetic Flux Configuration and the Method of Current Estimation

Figure1 shows some examples of electron orbits in the open magnetic flux configuration. Electron orbits are classified into three patterns: “lost”(a), “banana”(b), and “co-moving”(c). Electrons whose orbits do not return to mid-plane but instead attain the wall are classified as lost. Banana electrons are trapped by the magnetic mirror because of the dependence of the toroidal field on the major radius. Co-moving electrons are confined even in the open magnetic flux configuration without stagnating in the mirror trap.

The guiding center of electron orbits in the tokamak configuration has two poloidal velocities. One is the poloidal component of velocity along the magnetic field line and the other is the drift velocity generated by the toroidal field curvature and gradient. When these two velocities have opposite directions and nearly the same value, electrons barely move on a poloidal cross section, but remain confined in small areas in the open magnetic flux configuration. The current carried by these confined electrons is unidirectional, so that they can contribute to the plasma current in the open magnetic configuration. However, “lost” electrons are believed to not remain in the vacuum vessel long enough to carry plasma current [7].

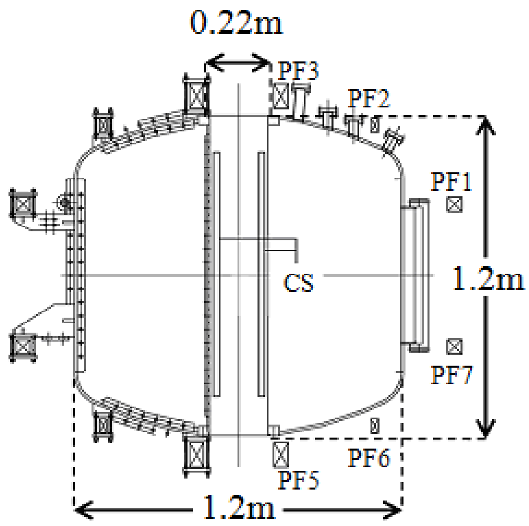

Fig.3 Side view of CPD including PF coils

The electron orbits strongly depend on their initial velocity, pitch angle, and poloidal field shape and strength. In particular, the n-index of the poloidal open magnetic flux configuration is a key to confining electrons.

The current driven by confined electrons is estimated as follows. The current I_{sp} carried by confined electron is

$$I_{sp} = \frac{eN}{t}. \tag{1}$$

where e is the fundamental charge of the electron, N is the number of rotations executed on the toroidal plane in time t, and t is the time required to complete one closed orbit in the poloidal plane [see Figs. 1(b) and (c)]. The entire current I_{es} is estimated by

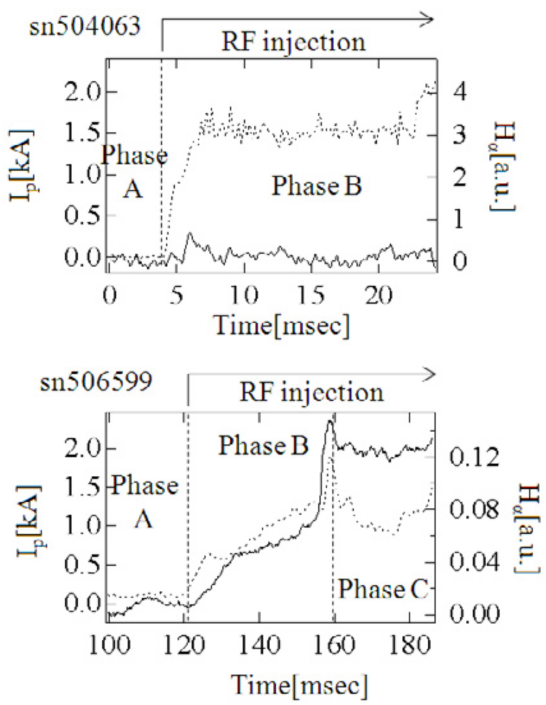

Fig.4 Time evolution of plasma current (solid line) and Hα (dashed line). RF power in sn504063 is 70kW and in sn506599 is 50kW. B_p in sn504063 is 120 Gauss and in 506599 is 40 Gauss.

$$I_{es} = V\int f(v) I_{sp} dv$$

$$f(v) = 2\pi n(\cos\theta_1 - \cos\theta_2)\left(\frac{m}{2\pi kT}\right)^2 \times v^2 \exp\left(-\frac{mv^2}{2kT}\right), \quad (2)$$

where V is the volume in which the electrons exist and θ_1 and θ_2 indicate the range of pitch angle considered. We assume that energetic electrons (between 1 and 30 keV) exist uniformly in the toroidal direction with density 10^{17} m^{-3}. The orbit calculation is started where the electron cyclotron resonance (ECR) layer crosses the mid plane. The volume V for the elemental area $dRdZ$ near the start point (R_{res}, Z_{mid}) is shown in Fig. 2.

3. Experimental Apparatus

Figure 3 shows a schematic of CPD, which is a compact ST ($R_0 \geq 0.3$ m, $a \leq 0.2$ m, aspect ratio $A \geq 1.5$) with one CS coil and three sets of poloidal field (PF) coils. The inner diameter of the vacuum chamber is 0.22 m and the outer wall diameter and height are 1.2 m. Four toroidal field (TF) coils produce a toroidal magnetic field $B_t = 0.25$ T at R = 0.3 m with a TF coil current of 90 kA. A set of 8.2 GHz klystrons of up to 200 kW are used for ECH. In this experiment, the ECR layer is at R = 0.19 m.

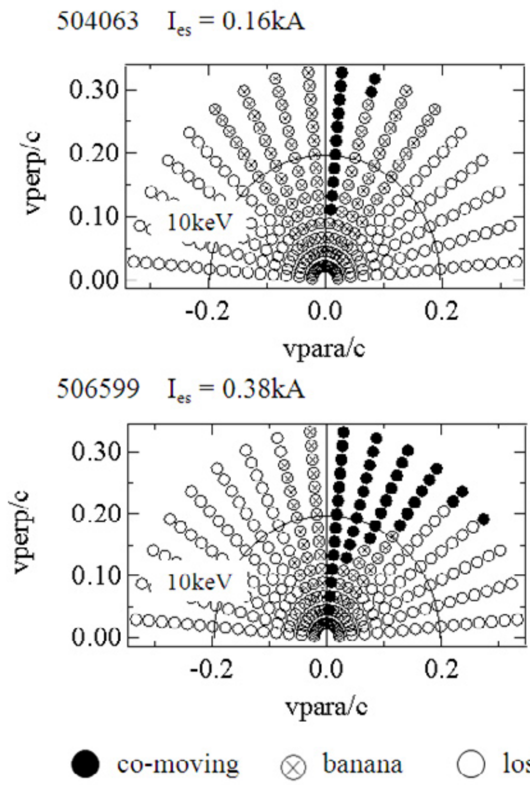

Fig.5 Energetic electron orbits in velocity space are shown. Horizontal axis shows electron velocity along magnetic line, vpara, and vertical axis shows electron velocity perpendicular to magnetic line, vperp. These two velocities are normalized by light speed. The position of each symbol shows the velocity of electron at the initial point of orbital calculation where the ECR layer crosses the mid plane. The sort of symbol shows the sort of orbit which the electron traces, co-moving, banana and lost. (See Fig.1) I_{es} is calculated without considering the contribution of lost electrons. The energy shown by most outside symbols is 30 keV, which is max energy considered in the calculation of I_{es}.

4. Experimental Results and Analysis

Figure 4 shows the evolution of the plasma current I_p and the Balmer line intensity H_α. In sn504063, RF injection starts at 4 msec and breakdown occurs soon after the start of RF injection. But the plasma current does not increase and no closed flux surface is formed. This phase is classified as phase B. However, in sn506599, the moment RF injection starts at 120 msec, the H_α signal and the plasma current start to increase. At 156 msec, the plasma current suddenly increases by 1 kA for a few milliseconds. This rapid increase in plasma current is called the “current jump” and closed flux surfaces are thought to be formed via the current jump. In this shot, a closed flux surface is thought to form just after the current jump [9].

The main difference between sn504063 and

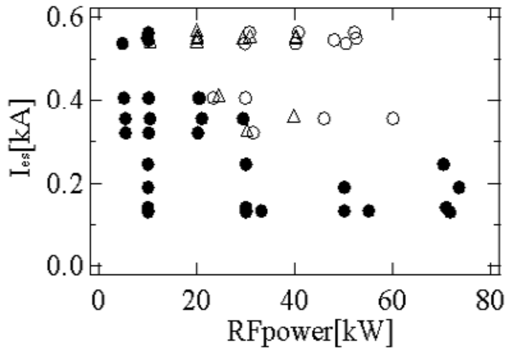

Fig.6 The map of formation of closed flux surface on I_{es} and injected RF power. The calculation of I_{es} was done at the various magnetic configuration with the condition of T = 1keV, $n = 10^{17}$ m^{-3} and R_{res} = 0.19m. ○ shows the condition that B_{pp} / B_{pc} > 2.0, where B_{pp} is the value of poloidal magnetic field made by plasma current and B_{pc} is the one made by PF coil at the inner limiter. In this condition, formation of closed flux surface is confirmed experimentally. Δ Shows the condition that 1.0 < B_{pp} / B_{pc} <=2.0 and ● shows the condition that B_{pp} / B_{pc} < 1.0.

sn506599 is the condition of the poloidal magnetic field. In sn504063, the poloidal magnetic field strength B_p is about 120 Gauss, whereas in sn506599 B_p = 40 Gauss. The reduced B_p causes a different confinement of the energetic electrons in the open magnetic field, as shown in Fig. 5. The result is that the plasma current ramps up more easily. The co-moving area in sn506599 is broader than in sn504063, suggesting that more co-moving electrons are confined in the open magnetic field in sn506599 than in 504063. In addition, the estimated current I_{es} carried by confined energetic electrons in sn506599 (where the closed flux surface is observed) is 0.38 kA, which is larger than that the 0.16 kA observed in sn504063 (where no closed flux surface is observed).

Judging from these results, we believe that the condition where I_{es} takes high value can be good for the formation of closed flux surfaces. Such a relation between the condition of high I_{es} and the formation of closed flux surfaces is observed in many shots. Figure 6 shows the map of the formation of closed flux surface on I_{es} as a function of the injected RF power. The open circles indicate the operational conditions for which a closed flux surface formed, which is only in the region of high I_{es} and high RF power. This result supports the conclusion that the condition of high I_{es} can be good for the formation of closed flux surfaces and shows that the RF power has a threshold for the formation of closed flux surfaces. Thus, we believe that confined energetic electrons generated by RF injection play an important role in forming closed flux surfaces and that the RF power level seems to be related

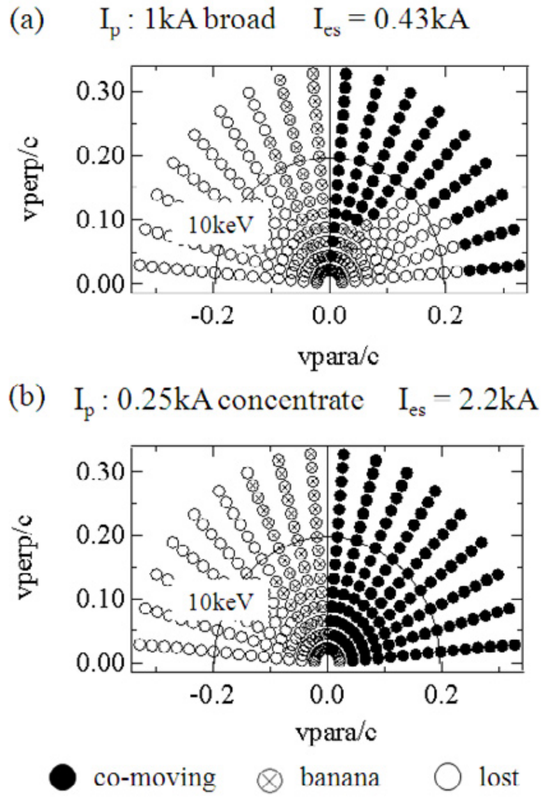

Fig.7 Improvement of confinement condition by the plasma current. The meaning of symbols is shown in the caption of Fig.5. Figure (a) shows the case in which 1kA plasma current distributes in broad area and figure (b) shows the case of concentration plasma current of 0.25kA.

with the generation of energetic electrons. Under these conditions, I_{es} can be used as an indicator to optimize the operational conditions to form closed flux surfaces with energetic electrons.

5. Discussion

As mentioned in Section 4, closed flux surfaces are formed via the current jump. In this section, we discuss the current jump mechanism.

In sn506599, the current jump occurs when the plasma current in the open magnetic field becomes large. Just before current jump, the magnetic field shape is modified by the plasma current in the open magnetic field. Modification of the magnetic field can change the confinement condition of the energetic electrons, which is possibly the source of the current jump. Thus, for sn506599, I_{es} is calculated with the plasma current effect added to the magnetic field generated by the PF coils.

The calculation is done assuming two distributions of the plasma current. In one distribution, the plasma current exists in a broad area on the poloidal projection of the magnetic line near the ECR layer. In the other distribution, the plasma current is concentrated at one point. In the former case, the assumed plasma current imitates the current carried by banana electrons, whereas in the latter case it imitates co-moving current. The change in the confinement condition and I_{es} is shown in Fig. 7. For this calculation, plasma current is set at 1 kA for the broad distribution and 0.25 kA for the concentrated distribution. The plasma current leads to an improvement in both the confinement condition and I_{es}. In particular, the concentrated plasma current can change the confinement condition dramatically, even for the condition of small plasma current. Thus, if the plasma current is concentrated, a small increase in the current can change the confinement condition rapidly and we believe that such a rapid change in magnetic field can contribute to the rapid increase in plasma current (i.e., the current jump). Moreover, it is easy for confined electrons to get more energy from the RF wave because these electrons pass through the ECR layer many times. Thus, improving the confinement condition can cause an increase in the temperature of the energetic electrons, which is also a possible source of the current jump.

Experimental verification of this model is the subject of future work.

6. Summary and Conclusion

To investigate the physics of the plasma current initiation phase and to establish an index for optimization of the operational conditions that form closed flux surfaces with energetic electrons, we calculate the electron orbits and estimate the current. From the results of the ECH plasma current start-up experiment at the CPD, we believe that high I_{es} facilitates the formation of the closed flux surface. Thus, we proposed using I_{es} as an index for optimization of the operational conditions to form closed flux surfaces with energetic electrons.

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