Studies of Electron Confinement in Heliotron DR using a New Stellarator Diode Method

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1. Introduction

Confinement of alpha particles is a crucial research item for realizing helical fusion reactors. From this viewpoint, we have studied behavior of energetic (E<1keV) electrons at relatively low magnetic field intensity (B~500G) in the Heliotron DR using the stellarator tetrode method [1,2]. The experiment has shown that electron confinement becomes worse when electrons are launched from the outboard side of the torus at relatively high energies.   This result has been explained by increase of electrons which have higher pitch angles and easily lost the vessel wall. Confinement improvement by inward shift of magnetic axis has also been observed in consistent with theoretical prediction. A problem of the tetrode method is that a transparent screen must be set in a poloidal cross section of the torus.   In the present study, we have tested a new stellarator diode method and investigated electron confinement in the Heliotron DR. Figure 1 shows schematically principles of the stellarator diode methods. In conventional method [3,4], a small voltage (10~20V) is applied between filament and vacuum vessel and the impedance between them is measured as a function of the filament position. Therefore, information on magnetic field structure is obtained.   In the present method, however, a screen anode is put in front of the filament and a defined bias voltage is applied between them.   Thus, by measuring the electron currents flowing into the vacuum vessel, we can get information about orbits of electrons with a defined energy and a defined birth point.
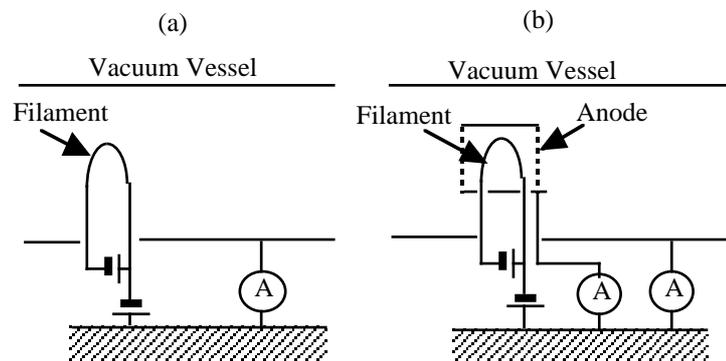

Fig.1 Principles of (a) conventional and (b) modified stellarator diode methods.

2. Experimental procedure

We have applied this method to the Heliotron DR which is a conventional $l=2$ heliotron/torsatron device (major radius = 0.9m, the average plasma minor radius ~0.07m, central and edge rotational transform = 0.8 and 1.9) [5].   The experiment has been done at the toroidal magnetic field on the minor axis, B_o~500G. The electron gun has a tungsten filament (0.1mm dia.) and a cylindrical (3mm dia.) stainless-steel mesh anode (transparency ~50%). The bias voltage between the filament and the anode, V_B has been changed from 10V to 800V. Thus, the electron Larmor radii normalized by the plasma minor radius become those for alpha particles in fusion reactors. Although the electrons are supposed to be emitted from the filament in all directions, their pitch angle distribution would not be uniform when they pass through the anode.   Previously, the pitch angle distribution was calculated and shown to be rather uniform

at the high bias voltages of $V_B \sim 800V$ [1]. Before the experiment of the diode method, we measured spatial potential distributions in the vacuum vessel generated by electrons emitted from the fixed electron gun.
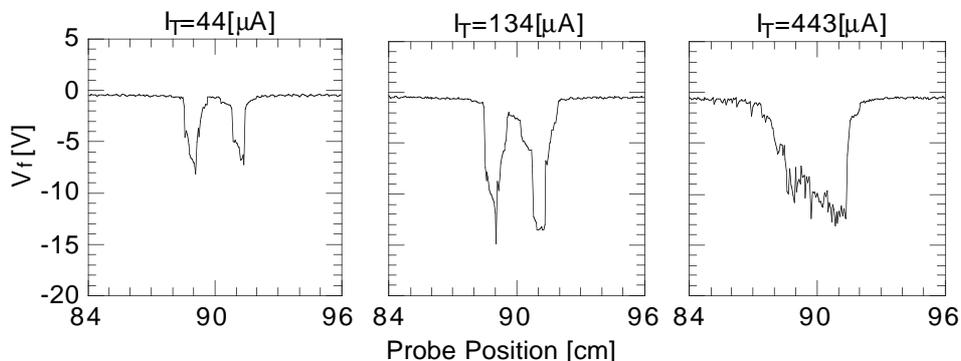

Fig.2 Potential distributions measured by a Langmuir probe for different emission currents I_T.

Figure 2 shows horizontal distributions measured with an electrostatic probe for different emission currents I_T. At relatively low emission currents ($I_T \leq 200\mu A$), sharp double peaks are observed which suggests that the electrons distribute around annular magnetic surfaces. At higher emission currents, however, the peaks become broader and merge with each other indicating increased space charge and/or collision effects. The broadening of the profile also occurs when the back ground neutral pressure becomes higher than $p \sim 1 \times 10^{-5}$ torr. The experiments of the diode method were done mainly at $I_T \leq 150\mu A$ and $p < 0.7 \times 10^{-6}$torr. During the electron gun was scanned horizontally from inboard side to outboard side of the torus ($\sim 20s$), the emission currents I_T, the currents flowing into the anode (I_A) and into the vacuum vessel wall (I_w) were measured.

3. Results and discussions

Figure 3 shows typical electron currents flowing into each electrode as a function of the horizontal electron gun position R. Here, the electron energy is rather low ($V_B = 55V$) and the result might represents magnetic surface structure. The arrows mean the magnetic axis (AXIS) and the last closed flux surface (LCFS), respectively. The emission current $I_T \sim 120\mu A$, which is nearly same as that in the conventional diode method for magnetic surface measurement [3]. In the conventional method, $I_T = I_w$ and it changes depending on the length of magnetic field line on which the filament is located. In the present case, however, I_T is kept almost constant and only I_w is
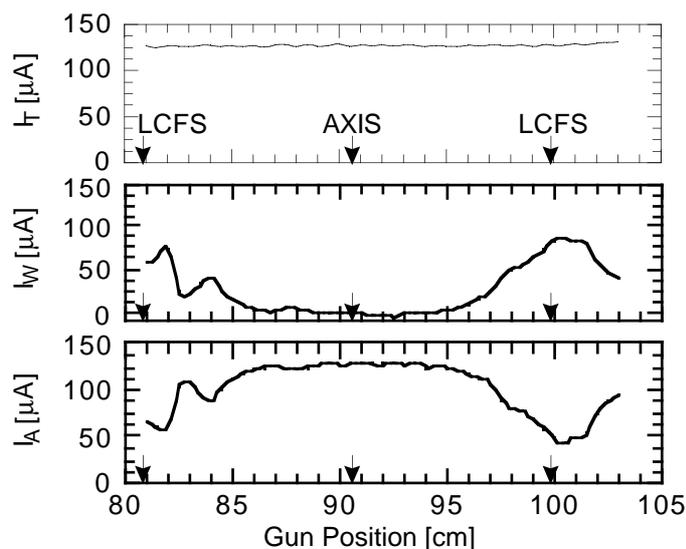

Fig.3 Electron currents into each electrode as a function of the horizontal electron gun position R.

changed. When the electron gun is located at the central part (86cm ≤ R ≤ 95cm), almost all electrons emitted from the filament flow into the anode and the wall current is almost 0. However, it grows up at outer region of $\iota/2\pi \geq 1$ indicating possibility of magnetic surface destruction. We also observe a peak of I_w at R~84cm ($\iota/2\pi$~1.3) of which the reason is not clear.

Radial distributions of the wall currents for different bias voltages are shown in Fig.4. Here, the data obtained in three magnetic configurations with different magnetic axis positions (Δ) are presented. We can see that with increase of V_B, the electron confinement becomes worse in the peripheral regions at both outboard and inboard (peak at R~84cm in Δ=0mm case) sides of the torus. We also see that the confinement deterioration starts even at low values of V_B~10V. This result is not consistent with that from the tetrode method in which the confinement deterioration is observed only at high voltages of V_B~800V. A possible reason of the difference might be different methods for confinement evaluation. In the tetrode method, measure of the electron confinement is the screen current and it depends on the transparency of the screen. When the transparency of the screen is lower, confinement is estimated better. Direct comparison of data obtained by both methods is not so simple.

We have calculated drift orbits of the electrons launched from R=84cm (inboard side of the torus) and 97cm (outboard side of the torus) with different energies E, and pitch angles θ. It has been confirmed that all electrons launched from R=84cm are well confined in the vacuum vessel even at high energies of E~800eV. On the other hand, the orbits of electrons launched from R=97cm are various depending on their initial pitch angles a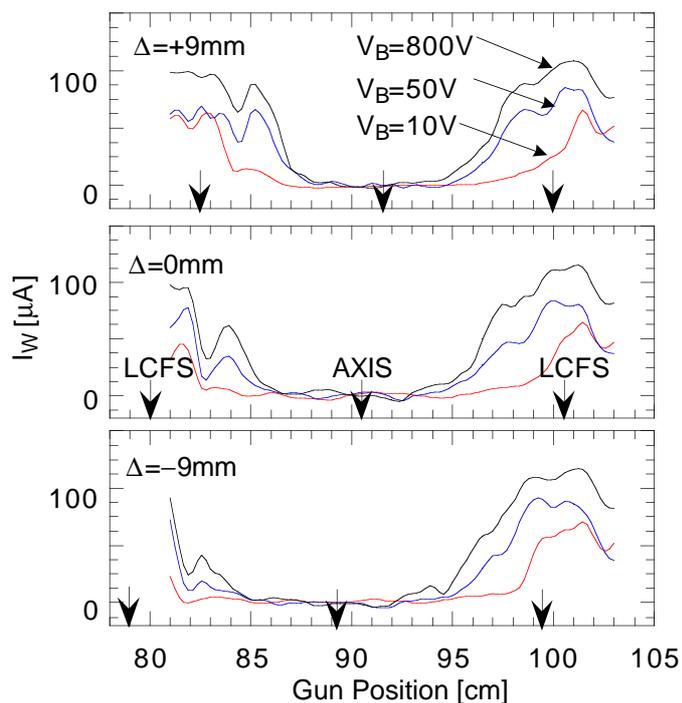nd energies. Figure 5 shows such trajectories projected to a poloidal cross section. The electrons are passing particles at all energies for $\theta \leq 55^o$ whereas they become helically trapped particles for $\theta \geq 65^o$. When θ~60°, the electrons are helically passing particles at low energies but they become trapped particles at E≥200eV. Although the threshold pitch angel tends to decrease with increase of the particle energy, its dependence is not so strong. Thus, we consider that the confinement deterioration is due to increase of electrons with higher pitch angles with increase of the bias voltage.

As for the effect of magnetic axis shift, we can see improvement of confinement by the inward shift of magnetic axis (Fig.4). At the outboard side of the torus, when the magnetic axis is shifted inward, the bad confinement region is not shifted and therefore good confinement region expands relatively. This result is consistent with the result obtained by the tetrode method [1] and agrees qualitatively with theoretical predictions. At the inboard side of the torus, the peak of the wall current is also decreased by the inward shift of the magnetic axis.
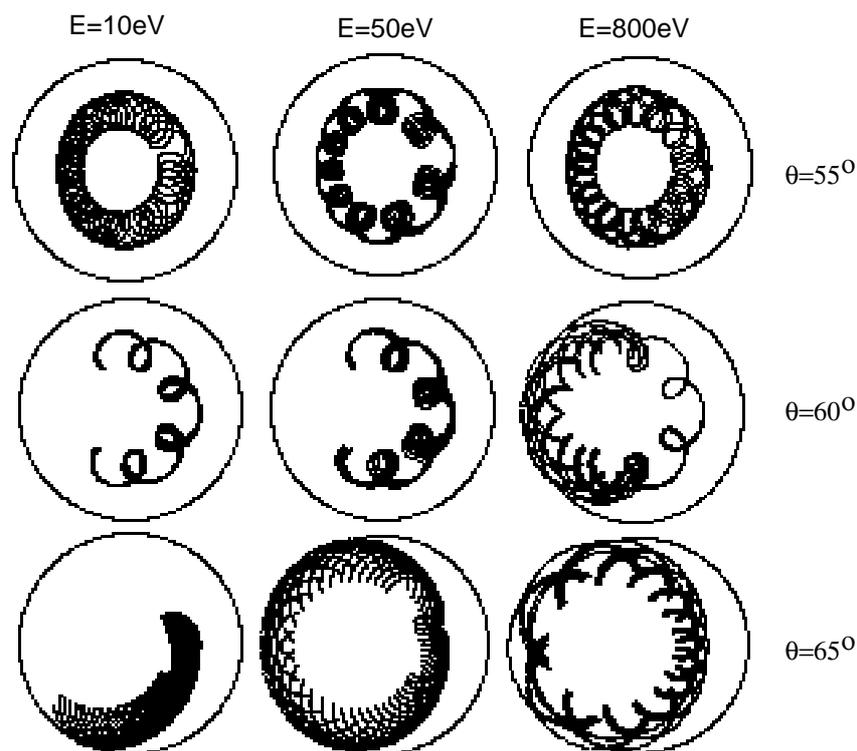

Fig.4 Radial distributions of the wall currents for different bias voltages V_B.

E=10eV   E=50eV   E=800eV

$\theta=55^{O}$

$\theta=60^{O}$

$\theta=65^{O}$

Fig. 5 Drift orbits of electrons with different pitch angles and energies.
The circles denote the vacuum vessel wall of the Heliotron DR.

4. Summary

Electron confinement in Heliotron DR has been studied experimentally and theoretically. A new (modified) stellarator diode method was developed in which electrons with defined energies (10eV ~800eV) were launched from a small electron gun (3mm diam.) and the current to the vessel wall was detected. By using this electron gun at small emission current ($\leq$150μA) and low back ground neutral pressure ($\leq$0.7x10^{-6}torr), the effects of space charge and collisions are sufficiently decreased. Electron confinement was observed to be deteriorated with increase of the bias voltage at both outboard and inboard sides of the torus. We also observed confinement improvement by inward shift of magnetic axis in qualitative agreement with theoretical predictions. Drift orbits of electrons launched from both inboard and outboard sides of the torus were computed. It is shown that the threshold pitch angle at which electron changes from passing to helically trapped particle tends to decrease with increase of electron energy.

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