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# Studies of Nonneutral Plasmas Confined on Helical Magnetic Surfaces of Heliotron J

Daichi SUGIMOTO[1)], Haruhiko HIMURA[1)], Kazutaka NAKAMURA[1)],
Sadao MASAMUNE[1)], Akio SANPEI[1)], Hiroyuki OKADA[2)], Satoshi YAMAMOTO[2)],
Shinji KOBAYASHI[2)], Tohru MIZUUCHI[2)], and Fumimichi SANO[2)]

[1)]*Department of Electronics, Kyoto Institute of Technology, Matsugasaki, Kyoto 606-0855, Japan*
[2)]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

Nonneutral plasmas confined on helical magnetic surfaces becomes have different characteristics from those of neutral plasmas. The most significant one observed in experiments is that both space potential $\phi_s$ and plasma density $n_e$ are not constant on closed magnetic surfaces. This strongly implies that such plasma parameters vary also along each magnetic field line ($B$-field line) with which closed magnetic surfaces are formed. In this paper, we have numerically estimated the variations of $\phi_s$ and $n_e$ along helical $B$-field lines of the Heliotron J machine. Data show that on the magnetic axis, variatios of $\phi_s$ and $n_e$ are about 7 V and $2 \times 10^7$ m$^{-3}$ for the case of $B \sim 0.3$ kG. Other accessible $B$-field lines and the estimated variations of $\phi_s$ and $n_e$ on them are also presented.

Keywords: toroidal nonneutral plasmas, pure electron plasmas, magnetic surface confinement, equilibrium of helical nonneutral plasmas, variation of plasma parameters on magnetic surface

## 1. Introduction

Experiments on nonneutral plasmas have been conducted on various machines such as the Penning trap [1], Paul trap [2], and toroidal devices.[3] Recently, experimental studies on toroidal nonneutral plasmas confined on helical magnetic surfaces (HMS) have been initiated. Contrary to toroidal neutral plasmas, both space potential $\phi_s$ and electron density $n_e$ of toroidal nonneutral one are nonconstant on HMS[4]-[6]. This phenomenon can be approximately explained by the theory [7] which shows that in nonneutral plasmas, parallel electrostatic force balances with the parallel pressure gradient force. This actually calls for variations of $\phi_s$ and $n_e$ along magnetic field lines ($B$-field lines) on closed magnetic surfaces.

However, variations of $\phi_s$ and $n_e$ are so far observed on the HMS, not along $B$-field lines. Obviously, in order to compare the observed variations with the theory, studies on those plasma parameters must be conducted along $B$-field lines.

In this paper, we have numerically estimated the variations of $\phi_s$ and $n_e$ along helical $B$-field lines of the Heliotron J machine. Data show that on the magnetic axis, variatios of $\phi_s$ and $n_e$ are about 7 V and $2 \times 10^7$ m$^{-3}$ for the case of $B \sim 0.3$ kG. Other accessible $B$-field lines and the estimated variations of $\phi_s$ and $n_e$ on them are also presented.

## 2. Apparatus

Experiments of nonneutral plasmas confined on the HMS are performed in a middle size machine of quasi-advanced stellarator, Heliotron J. The averaged major and minor radii of the machine are 1.2 and 0.38 m, respectively. Figure 1 shows a poloidal cross-section of Heliotron J on which an electrostatic probe is installed in the vacuum chamber.

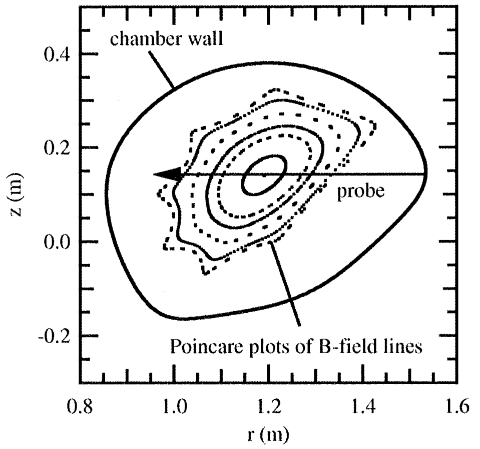

Fig. 1 A view of the 11.5 cross-section of Heliotron J. The chamber wall is drawn by the black solid curve. Poincare plots of B-field lines are shown. The solid arrow shows the location of the probe. The shaft length of the probe is about 60 cm so that values of plasma parameters can be mesured at two different points on each magnetic surface.

Electrons are injected by an electron gun (e-gun), which has a LaB$_6$ emitter as the cathode. [8] The e-gun is inserted horizontally along the $r$ axis and set on 1 cm outside from the last closed flux surface (LCFS). The acceler-

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*author's e-mail: sugimo07@nuclear.es.kit.ac.jp* ation voltage $V_{acc}$ of the electrons are variable. But, typically, it is fixed to $V_{acc} = -600$ (V). The pulth width of $V_{acc}$ is also variable in the range between ~ 10 ($\mu$s) and ~ 100 (ms). Plasma parameters of $\phi_s$, $n_e$ and electron temperature $T_e$ are measured by an emissive and Langmuir probe. The e-gun and the probe are located on poloidal cross-sections at $\varphi$ = 71.05° and $\varphi$ = 251.05° (henceforth, called the 3.5 and 11.5 cross-sections, respectively). Here, $\varphi$ is the toroidal angle. The shaft of the employed probe is long enough, which can reach the edge of LCFS at the inboard side. The magnetic field ($B$-field) is operated as static for this experimental study, and the maximum strength of $B$-field on the magnetic axis at the 11.5 cross-section is about $3 \times 10^{-2}$ T.

## 3. Brief review of observed variation

Figure 2 shows a set of preliminary results of measured radial profiles of $\phi_s$, $n_e$, $T_e$ of helical nonneutral plasmas produced on Heliotron J, and calculated $B$ strength. The radial position is described by $\Psi^{1/2}$, where $\Psi^{1/2} = 0$ and 1 correspond to the the magnetic axis and the LCFS, respectively. As mentioned, all values of $\phi_s$, $n_e$, $T_e$ and $|B|$ are measured at two different measurement points on each HMS. The dark and black colors indicate the data on the inboard - and the outboard side, respectively. Clearly, considerable variation of $\phi_s$ is recognized in the HMS. The observed variation becomes larger near the LCFS. On the other hand, the variation of $n_e$ is seen even in the plasma core. Contrary to those, little variation of $T_e$ is so far measured. Anyhow, data strongly suggest that those plasma parameters are varied along $B$-field lines.

## 4. Magnetic field line tracing

To precisely measure both $\phi_s$ and $n_e$ along helical $B$-field lines, we must exactly know where each $B$-field line circulates in the vacuum vessel. For the purpose, we have numerically traced the helical $B$-field lines in Heliotron J. Figure 3 explains two examples of $B$-field lines for which the $B$-field line tracing is conducted. The black circle shows the $B$-field line which passes through the magnetic axis at $\Psi^{1/2} = 0$, while the black triangle is one of $B$-field lines that is off the magnetic axis where $\Psi^{1/2} \sim 0.25$. For both cases, the $B$-field line tracing is started from the 11.5 cross-section.

Figure 4 shows the strength of $|B|$ along the $B$-field line on the magnetic axis. It is seen from the data that the value of $|B|$ changes slightly for the case. On the other hand, for the $B$-field line at $\Psi^{1/2} \sim 0.25$, the change in $|B|$ is larger, as shown in Fig. 5. It should be noted here that the value of $|B|$ on the cross-section at $\varphi = 251.05°$ is different when the $B$-field returns there after a single toroidal circulation. This is due to the rotational transform that causes the $B$-field get back to a different position on the cross-section.

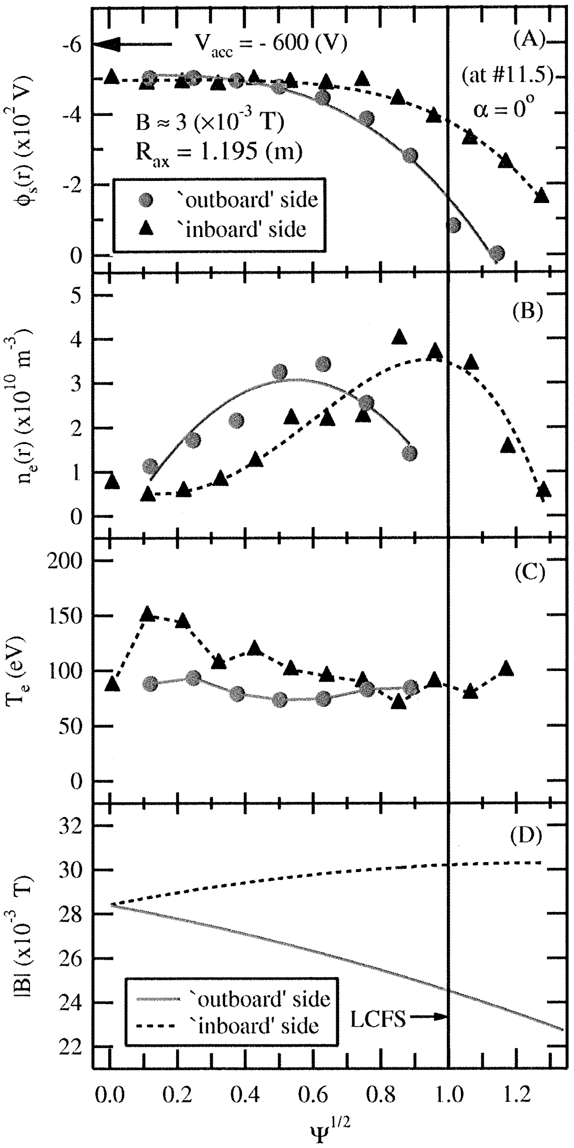

Fig. 2 First resalt of nonneutral plasmas confined on Heliotron J. (A) ~ (D) show measured radial profiles of space ptential $\phi_s(r)$, electron density $n_e(r)$, electron temperature $T_e(r)$ and $B$-field strength $|B|(r)$ at the 11.5 cross section. The horizontal axis is the normalized minor radius.The light marks and solid lines are outboard side profiles and darks and broken lines are inboard side profiles.

## 5. Estimated variations of $\phi_s$ and $n_e$

In this section, we estimate values of expected variations along $B$-field lines. As presented in Sec. 3, apparent differences in $\phi_s$ have been observed on each magnetic surface. On the other hand, the $B$-field strength is also varied on them. Using these results, we can thus relate the difference in $\phi_s$ with the $B$-field strength. Figure 6 shows the relationship between the potential variation $d\phi_s$ and the $B$-field strength. From this result, we assume

$$d\phi_s \propto (\Psi^{1/2})^2, \qquad (1)$$

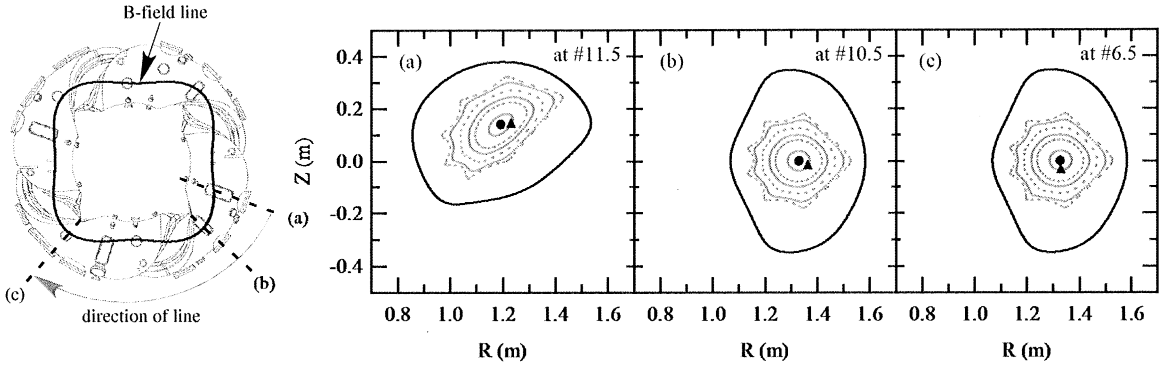

Fig. 3 Top view of Heliotron J and poloidal cross-sections at different toroidal angles. The cutting planes labeled as (a), (b) and (c) in the left figure correspond to the cross sections in the right one. The dotted points show Poincare plots of B-field lines. The circle and the triangle show $B$-field lines at $\Psi^{1/2} = 0$ (on the magnetic axis) and ~ 0.25 (off the magnetic axis).

$$dB \propto \Psi^{1/2}. \tag{2}$$

Thus, the value of $d\phi_s$ can be written as

$$d\phi_s \propto (dB)^2. \tag{3}$$

From the experimental data, we can obtain

$$d\phi_s \approx -242(\Psi^{1/2})^2 + 28.5, \tag{4}$$

and

$$dB \approx 5.7 \times 10^{-3}\Psi^{1/2}. \tag{5}$$

Therefore, the relationship between $d\phi_s$ and $dB$ is represented as

$$d\phi_s \approx -75.8 \times 10^5 (dB)^2 + 28.5. \tag{6}$$

Assuming that the Eq. (6) holds also along $B$-field lines, we calculate variations of both $\phi_s$ and $n_e$. For the case of $B$-field line at $\Psi^{1/2} = 0$ (on the magnetic axis), the difference in $|B|$ between the 11.5 and 6.5 cross-sections is about $dB \sim -1.67 \times 10^{-3}$ (T). The obtained negative value of $dB$ means that the value of $|B|$ at the 11.5 cross-section is larger than that at the 6.5 cross-section. Thus, the value of $d\phi_s$ can be calculated to be ~ 7.4 (V). On the other hand, for the case of $B$-field line at $\Psi^{1/2} \sim 0.25$, two values of $dB$ are existed, as mentioned in Sec. 4. When $dB \approx -2.19 \times 10^{-3}$ (T) is applied, $d\phi_s$ is about −7.80 (V). If $dB \approx -5.63 \times 10^{-4}$ (T) is used, $d\phi_s \sim 26.1$ (V) is obtained.

Secondly, regarding the $n_e$ variation, we consider the fluid force balance equation for a low density pure electron plasmas. The variation of $n_e$ along a $B$-field line is expressed as

$$\frac{dn_e}{n_e} \approx \left(\frac{a}{\lambda_D}\right)^2 \frac{d\phi_s}{\phi_s}. \tag{7}$$

Here, $a$ is the typical scale length so that we regard it as the averaged minor radius of Heliotron J. Also, $\lambda_D = \sqrt{\epsilon_0 \kappa T_e / n_e e^2}$ shows the Debye length[7]. Substituting the value of $d\phi_s$ for Eq. (7), the value of $dn_e$ is estimated to be $\sim -2.22 \times 10^7$ ($\mathrm{m}^{-3}$) for the $B$-field line at $\Psi^{1/2} = 0$ (on the magnetic axis). For the case of $B$-field line at $\Psi^{1/2} \sim 0.25$ (off the magnetic axis), $dn_e$ is about $1.61. \times 10^8$ ($\mathrm{m}^{-3}$) at the 6.5 cross section, while $-5.38 \times 10^8$ ($\mathrm{m}^{-3}$) at the 10.5 cross section.

As understood from above results, the estimated $dn_e$ is much smaller than $n_e$, which calls for better resolution for measurements in the next series of Heliotron J experiments. Another important thing to perform next experiments would be to either increase $n_e$ or decrease $T_e$. This is because $\lambda_D$ is the key parameter to decide the variation of $n_e$ along $B$-field lines. In fact, smaller $\lambda_D$ gives rise to larger $dn_e$. Since $T_e$ is probably affected by $V_{acc}$ strongly, experiments using smaller $V_{acc}$ should be required. In fact, if $T_e$ becomes 1/10 times smaller, $dn_e$ would then become 10 times larger. Experiments will be performed soon.

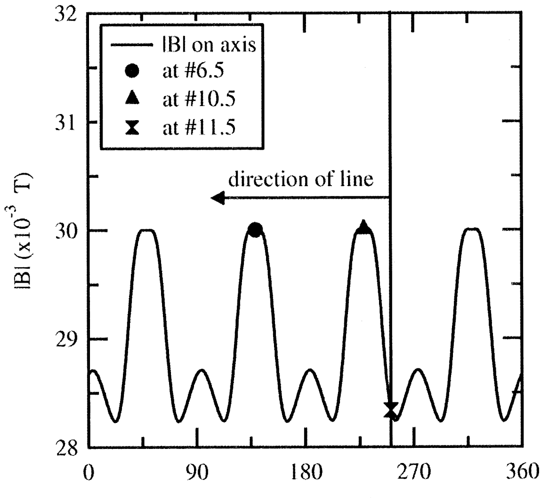

Fig. 4 The variation of $B$-field strengh $|B|$ along the $B$-field line at $\Psi^{1/2} = 0$ (on the helical magnetic axis).

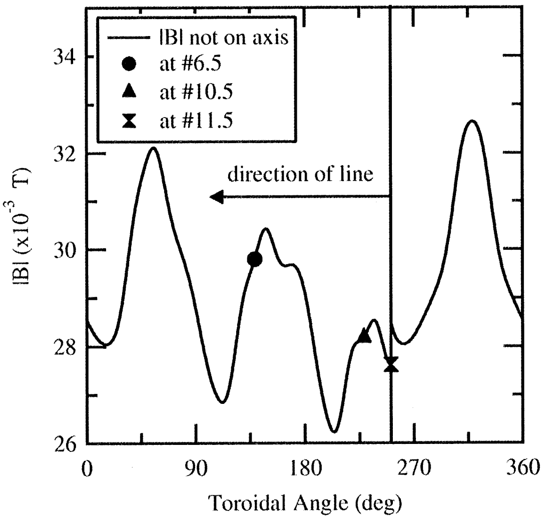

Fig. 5 The variation of $B$-field strengh $|B|$ along the $B$-field line at $\Psi^{1/2} \sim 0.25$ (off the helical magnetic axis).

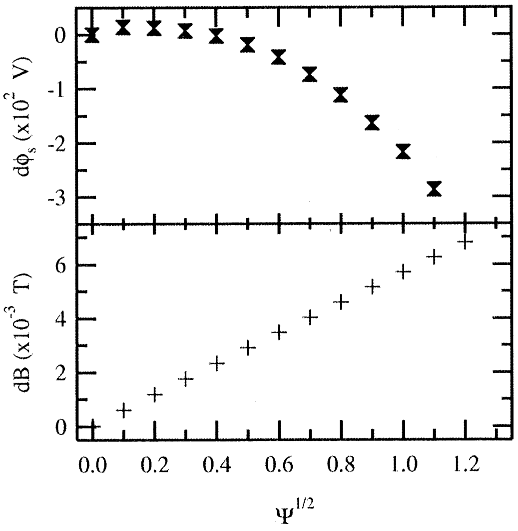

Fig. 6 Dependences of both $d\phi_s$ and $dB$ on $\Psi^{1/2}$. Here, $d\phi_s$ and $dB$ present differences in $\phi_s$ and $B$ on each magnetic surface, respectively.

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