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Observation of Non-Uniformity of Space Potential on Magnetic Surfaces in Helical Nonneutral Plasmas

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It is observed, for the first time, that the space potential is non-uniform on magnetic surfaces in nonneutral helical plasmas. Electron plasmas are generated in a stellarator magnetic field by injection from an electron gun. Electrons are launched out with the acceleration voltage (V_{acc}) from 300V to 1kV. The potential non-uniformity is almost proportional to V_{acc}. Experimental errors such as missalignment of the measurement probe and the perturbing effect of probe insertion are carefully checked, and confirmed not to be the reason of the observed potential variation.

Key Words: non-neutral plasma, magnetic surface, space potential

Magnetic surface is one of the most important and fundamental concepts in toroidal plasma confinement devices such as tokamaks and stellarators. In quasi-neutral fusion plasmas, physical parameters such as pressure and potential are thought to be constant on a magnetic surface. Irregularity of density is rapidly smoothed out along the magnetic field line of force. And potential hump on the magnetic surface is also smoothed out or Debye shielded in shorter than 0.1 mm (typically for n_e~$1x10^{19}$ m^{-3}, T_e~1 keV). Many analyses such as Grad-Shafranov equation have been performed on this basis that the parameters are magnetic surface quantities.

In recent years, nonneutral plasmas in toroidal magnetic configurations have also been of great interest[1,2] as the basis for a variety of applications, such as simultaneous confinement of multi-species of charged particles in arbitrary non-neutrality and anti-matters[3], as well as generation of fast flow by means of ExB drift due to the strong self electric field.

In the equilibrium state, the force balance equation of the electron fluid is written as:

$$m_e n_e \vec{v}_e \cdot \nabla \vec{v}_e = -en_e \vec{v}_e \times \vec{B} + en_e \nabla \phi - \nabla p,$$

where m_e, n_e, v_e, ϕ and p stand for the mass, density, velocity , electric potential and pressure of the electron fluid, respectively. When n_e is far below the Brillouin limit, the term on the left hand side of this equation vanishes[4]. And if the electron temperature T_e =0, the last term on the right hand side also vanishes and the force balance comes to:

$$\vec{v}_e \times \vec{B} = \nabla \phi.$$

This leads to

$$\vec{B} \cdot \nabla \phi = 0$$

and one can find that the potential must be constant along the magnetic field lines of force, consequently, on the magnetic surfaces.

However, if T_e is finite and the electrons have finite pressure, that is not the case. The parallel component of force balance is written as

$$en_e \nabla_{||} \phi = \nabla_{||} p,$$

where $\nabla_{||}$ stands for the derivative along a magnetic field line of force. Assuming that T_e is constant on the magnetic surfaces, this equation can be written as

$$en_e \nabla_{\|} \phi = T_e \nabla_{\|} n_e ,$$

which leads to the Maxwell-Boltzmann distribution. And also, ϕ and n_e must be related to each other by the Poisson equation, which leads to the equilibrium equation for a pure electron plasma on magnetic surfaces shown in ref. 2.

As we can see in the equation above, if T_e is finite and n_e is not uniform, the pressure gradient should be balanced with the parallel component of the Coulomb force. So the potential can vary along the magnetic field lines of force, as well as on the magnetic surfaces.

In toroidal electron plasmas, toroidicity itself makes electrons shift inward to balance the hoop force with the electric force by the image charges on the chamber wall, resulting in an uneven distribution of density on magnetic surfaces. Furthermore, in three dimensional asymmetric configurations such as stellarators, asymmetric boundary condition may encourage the irregularity of density. Indeed there is a numerical work verifying the existence of $E_{//}$ in nonneutral plasmas in two dimesional magnetic surfaces with asymmetric boundaries[5].

In order to study experimentally the possibility of space potential variation on the magnetic surfaces, we have generated electron plasmas in a stellarator by electron injection through the edge region of a stellarator magnetic field[6], and measured spatial distribution of space potential ϕ_s.

The experiments were performed in a medium-sized stellarator, Compact Helical System (CHS)[7], whose major and averaged minor radii are 1m and 0.2m, respectively. An electron gun (e-gun) is inserted horizontally along the major radius (*r*-axis as shown in Fig. 1). Electrons are launched out into the vacuum magnetic field B of ~0.09T with acceleration voltage V_{acc} up to 1kV and emission beam current I_b up to 100mA. The electron plasma is generated by continuous injection of electrons for 40ms. For diagnostics, a pair of Langmuir emissive probes are inserted horizontally and vertically along the *r* and the *z* axes, respectively[8]. We will refer to these probes as *r*- and *z*-probes in the followings. The e-gun and two probes are separated by about 90 degrees from each other in the toroidal direction. The probes are terminated with 100MΩ impedence to measure the space potential ϕ_s of the electron plasma[9].

The probe signal comes to a steady state within 1ms after the injection starts, and we take the time average of the signal for the last 5ms of each shot to determine the value of ϕ_s. The z-probe can be drived from edge to edge through the magnetic surfaces as is shown in Fig. 1. Thus ϕ_s can be measured at two different points on each magnetic surface.

Figure 2 shows profiles of ϕ_s measured by the z-probe. The vertical axis indicates the values of ϕ_s. Since electron plasmas are treated, the values of ϕ_s are negative. The horizontal axis is shown in the normalized minor radius ρ. ρ=0 and 1 correspond to the magnetic axis and the last closed magnetic surface, respectively. Because the magnetic surfaces are shifted outward from the probe drive range, the z-probe does not intersect with the magnetic axis, and lower limit of ρ is 0.3 in this configuration. Three data sets are shown for V_{acc}=300V, 600V and 1kV. The position of the e-gun (ρ_{gun}) is 0.9 in this measurement.

Substantial differences of ϕ_s are clearly recognized on each magnetic surface, especially at the boundary region of the electron plasma. The denoted two profiles of ϕ_s for each V_{acc} are measured in the z>0 and z<0 regions each other, and values at z>0 are negatively larger than z<0. The difference between the two profiles is alomost proportional to V_{acc}, which implies that the variation is closely related to the electron energy.

When ρ_{gun} is changed, profile of ϕ_s also changes. Figure 3 shows profiles of ϕ_s measured by the z-probe for ρ_{gun}=0.6 and 0.9. As the e-gun is moved inward, profiles of ϕ_s for z>0 and z<0 approach each other and ϕ_s becomes nearly constant with respect to ρ. The reason why ϕ_s variation decreases when the e-gun is moved inward is not clear, but two possible reasons could be considered. One is that the natural equilibrium of the electron plasma is interrupted by the inserted bare metal of the e-gun, resulting in the modification of ϕ_s profile. The other is that when the electrons are launched out in the inner region of the magnetic surfaces, confinement of electrons becomes better, and ionization of the background gas increases. Then the non-neutrality of the plasma decreases, and the ϕ_s profile reaches that of the neutral plasma, in which the image charge is not induced on the wall. No matter what the reason is, the fact that in a case ϕ_s varies and in other case ϕ_s is constant on the magnetic surfaces can be an indirect evidence that the observed ϕ_s variations are not due to misalignment of the measurement probe.

One may ask on the perturbing effect of the probe itself. In order to check the effect, we have measured ϕ_s by r-probe varying the position z_p of the z-probe. Figure 4 shows the measured profiles of ϕ_s when the z-probe is outside the magnetic surfaces (z_p=25cm), half inserted (z_p=0cm) and fully inserted (z_p=-20cm) in the magnetic surfaces. We can recognize slight increase in ϕ_s by a few tens of volts when the z-probe is placed deep inside the magnetic surfaces, and this increase is thought to be a result of perturbation by probe insertion. However, the change in ϕ_s is in the opposite direction and much smaller than the observed ϕ_s variation. Thus, this is not the cause of the variation.

Lastly, we mention about the existence of magnetic islands on CHS. By a magnetic field mapping experiment, magnetic islands have been identified on the n/m=1/2 and 1/3 major rational surfaces on the CHS magnetic field[10]. The width of n/m=1/2 island is about a few centimeters when the field strength is 0.09T. The existence of magnetic islands may influence on local structure of space potential around the rational surfaces. However, the observed potential variation is not limited at the region near the rational surfaces. So the potential non-uniformity is not induced by the existence of magnetic islands.

By a dimensional analysis of the force balance equation, one can find that the value of potential variation on a magnetic field line of force can be on the same order of T_e. According to some brief measurements, T_e is estimated to be a few hundreds of eV, which seems to be approximately consistent with the observed potential variations. Further investigations quantitatively verifying the pontential variations are being performed.

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[1]Z. Yoshida, Y. Ogawa, Y. Morikawa *et al.*, AIP Conf. Proc. 498, 397 (1999)

[2]T. S. Pedersen and A. H. Boozer, Phys. Rev. Lett. **88**, 205002 (2002).

[3]T. S. Pedersen, A. H. Boozer J. P. Kremer *et al.*, Phys. Plasmas **11**, 2377 (2004).

[4]A. H. Boozer, Phys. Plasmas **11**, 4709 (2004).

[5]T. S. Pedersen, Phys. Plasmas **10**, 334 (2003).

[6]H. Himura, H. Wakabayashi, M. Fukao *et al.*, Phys. Plasmas **11**, 492 (2004).

[7]K. Matsuoka, R. Akiyama, A. Fujisawa *et al.*, Plasma Phys. Cont. Fusion **42**, 1145 (2000).

[8]H. Wakabayashi, H. Himura, M.Fukao *et al*., AIP Conf. Proc. **692**, 332 (2003).

[9]H. Himura, M. Fukao, H. Wakabayashi *et al.*, Rev. Sci. Inst. **74**, 4658 (2003).

[10]H. Yamada, K. Matsuoka, S. Okamura *et al*., Rev. Sci. Inst. **61**,686 (1990)

Fig. 1 (A) Schematic of three-dimensional structure of CHS vacuum vessel. The frame indicates the position of 6-U measurement port. (B) Cross section of the 6-U measurement port. The *z*-probe is inserted and can be drived along the vertical arrow on the figure. The magnetic axis and 10 Poincare plots of the magnetic surfaces are also shown here. Each of them correspond to ρ=0~1. ϕ_s can be measured on two different points (z>0 and z<0) on each magnetic surface. Points (a), (b) and (c) correspond to data points on fig.2, indicating the probe drive direction.

Fig. 2 Profiles of ϕ_s measured by the *z*-probe. V_{acc} is varied from 300V to 1kV. The horizontal axis is shown in the normalized minor radiius ρ, which is equivalent to the toroidal magnetic flux enclosed by the magnetic surface. Two arrows on the figure indicate the direction of the probe drive, corresponding to the vertical arrow in fig.1. Points (a), (b) and (c) are same as those in fig.1. Variations of ϕ_s on the magnetic surfaces (ρ=const) are recognized. The upper and lower series correspond to z>0 and z<0, respectively. The difference between two series is almost proportional to V_{acc}.

Fig. 3 Profiles of ϕ_s for two positions of the e-gun. When the e-gun is moved inward from ρ_{gun}=0.9 to 0.6, ϕ_s becomes nearly constant on the magnetic surfaces. The reason why ϕ_s becomes nearly constant when the e-gun is moved inward is not clear so far and should be investigated. However, the fact that in a case ϕ_s is constant and in other case ϕ_s varies on the magnetic surfaces can be an indirect evidence that the observed ϕ_s variation is not due to miss-installation of the measurement probe.

Fig. 4 Profiles of ϕ_s measured by the *r*-probe changing position of the *z*-probe. Only slight purturbation is recognized by probe insertion. And ϕ_s becomes negatively larger when the *z*-probe is inserted into the lower region of the measurement port, while values of ϕ_s are smaller in z<0 than z>0. Thus, the probe insertion is not the cause of the observed variation of ϕ_s.

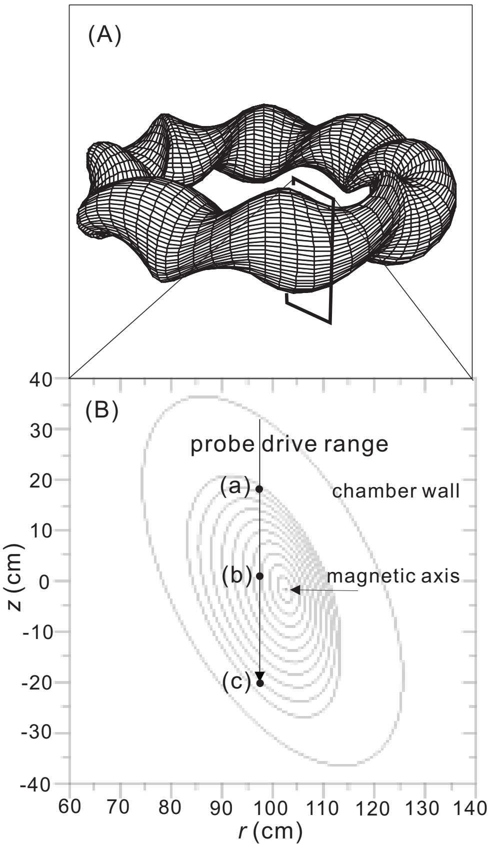

Fig.1 Wakabayashi

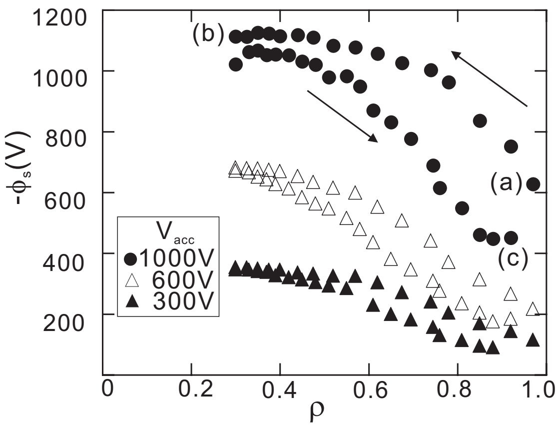

Fig.2 Wakabayashi

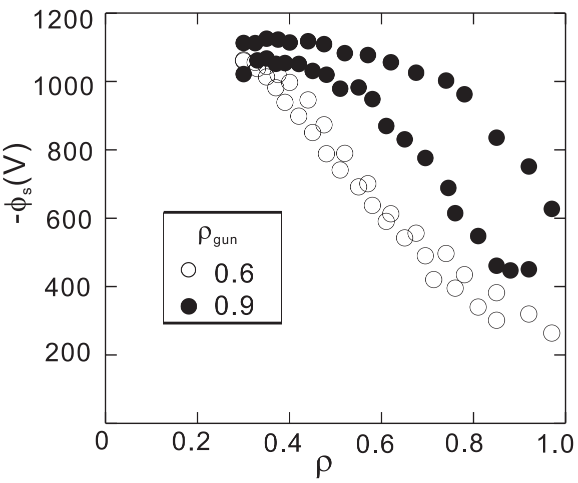

Fig. 3　Wakabayashi

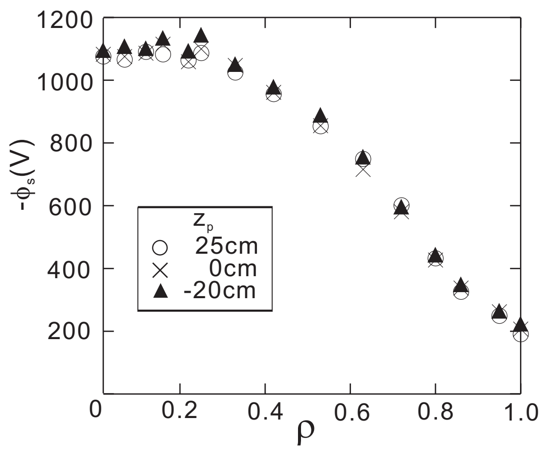

Fig.4　Wakabayashi