Modification of Probe Characteristics in a Supersonic Plasma Flow

Sho WATANABE, Haruhiko SAITOH and Zensho YOSHIDA

Department of Advanced Energy, University of Tokyo, Kashiwa 277-8561, Japan

(Received 6 August 2007 / Accepted 25 March 2008)

The effects of a supersonic plasma flow on emissive Langmuir probes were experimentally investigated using a Pockels electric field sensor. When the flow velocity exceeded the ion sound speed, the probe characteristics were modified, and the emissive probe overestimated the plasma potential. The modification of probe characteristics is explained by the formation of a humped potential profile, caused by a shock in the supersonic plasma flow.

Keywords: flowing plasma, emissive Langmuir probe, Pockels sensor, shock wave, electric field measurement

DOI: 10.1585/pfr.3.019

Recent years have seen increasing interest in the role of electric field structures in plasma physics. A radial electric field may restrain ripple-loss in helical devices, and in tokamaks, the role of electric fields in H-mode has been studied both theoretically and experimentally. In a dipole magnetic field configuration, where the measurement of electric field and flow are especially important, a new relaxation state of a plasma with a strong flow has been studied [1,2]. Emissive Langmuir probes are widely used diagnostic tools for measuring electric fields in plasmas; however, a strong plasma flow can present problems for electric probes. In this study, we report on the effects of a supersonic plasma flow on emissive probe measurements, using a Pockels electric field sensor.

The experiment was conducted in a magnetospheric device, Proto-RT (Prototype Ring Trap) [3]. A plasma was produced by a 13.56 MHz radio-frequency wave introduced through an inductively coupled antenna, as illustrated in Fig. 1. Proto-RT is equipped with a torus-shaped electrode on the internal conductor that generates a radial electric field and a toroidal flow [4]. Typical plasma parameters are summarized in Table 1. The ion gyro frequency was much higher than the ion-neutral collision frequency, and the ions were magnetized. Potential profiles were measured by both an emissive Langmuir probe and a Pockels electric field sensor [5]. The tip of the Langmuir probe was a thoria-tungsten spiral filament 0.28 mm in diameter; it was used to measure thermoelectronic emission. We compared the current (I) and voltage (V) characteristics of cold and emissive probes, and the potential at which the two characteristics began to disagree is identified as a “space potential” ϕ_L [6]. The Pockels effect is a linear electro-optical effect, where an external electric field induces a modification in the refractive index of a medium in proportion to the field strength. In this study, we used a $LiNbO_3$ crystal Pockels sensor [7] for direct measurement of electric fields in the plasma. The sensor was covered by a quartz tube (ϕ10 mm), and inserted horizontally into the plasma at $z = 0$ mm. Because the plasma was mag-

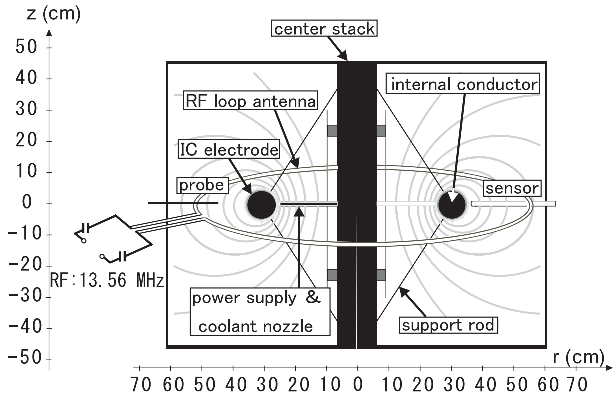

Fig. 1 Poloidal view of the experimental setup in Proto-RT.

Table 1 Typical plasma parameters in Proto-RT.

magnetic field strength	0.01 T
neutral gas density	2×10^{19} m^{-3}
plasma electron density	1×10^{15} m^{-3}
electron temperature	10 eV
ion temperature	1 eV
electron gyro-radius	0.8 mm
ion gyro-radius	10 mm
Debye length	0.8 mm
ion sound speed	3×10^{4} m/s
ion gyro frequency	1×10^{6} s^{-1}
ion-neutral collision frequency	1×10^{5} s^{-1}

author’s e-mail: watanabe@ppl.k.u-tokyo.ac.jp

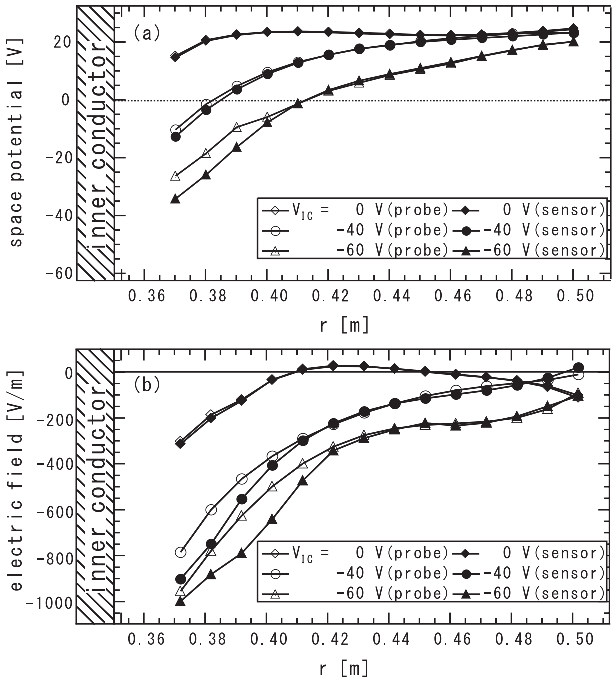

Fig. 2 (a) Space potential and (b) electric field profiles measured by the emissive Langmuir probe and Pockels sensor. The space potential data of the Pockels sensor were obtained by integrating the measured radial electric field strengths. The electric field data of the emissive Langmuir probe were obtained by differentiating the measured potential profiles.

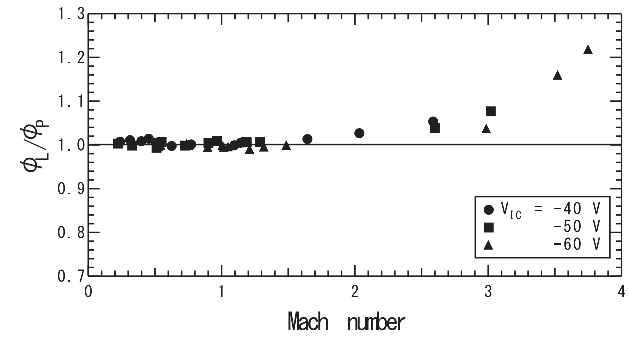

Fig. 3 The ratio of space potentials measured by the emissive Langmuir probe and the Pockels sensor as a function of the Mach number of the plasma flow.

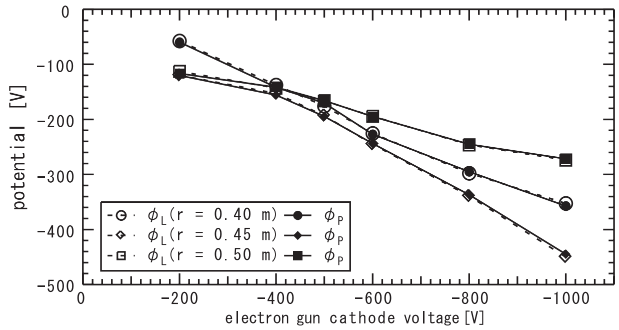

Fig. 4 Pure electron plasma potentials against electron gun cathode voltage. The IC electrode was grounded. ϕ_L agreed with ϕ_P within an error of 3%.

netized, the flow velocity of the plasma is calculated as $\boldsymbol{v} = \boldsymbol{E} \times \boldsymbol{B}/B^2$. Here $\boldsymbol{E}$ is the measured electric field, and $\boldsymbol{B}$ is a magnetic field generated by the dipole coil currents. We calculated the space potential ϕ_P by radially integrating the measured electric field. The boundary condition was given at the surface of the internal conductor, where the potential V_{IC} was set by a power supply.

Figure 2 shows the (a) space potential and (b) electric field strength distributions, measured by the emissive probe and the Pockels sensor, for varying V_{IC}. Although both the space potential and electric field strength, as measured by the two diagnostic tools agreed quite satisfactorily when the electric field strength was small, differences between the two measurements appeared in a strong electric field. When the internal conductor (IC) electrode was grounded ($V_{IC} = 0$ V), ϕ_L and ϕ_P agreed within an error of 3.5%. In contrast, ϕ_L was 8 V higher than ϕ_P at $r = 0.37$ m at $V_{IC} = -60$ V. As shown in Fig. 2 (a), the profiles of ϕ_L do not connect to V_{IC} smoothly, implying some disparity between ϕ_L and the space potential. In Fig. 3, we compare ϕ_P and ϕ_L by plotting their ratio as a function of the Mach number $M = v/c_s$ of the flow velocity. Here, $c_s = (k_B T_e/m_i)^{1/2}$ is the ion sound speed, where k_B is the Boltzmann constant, m_i is the ion mass, and T_e is the electron temperature measured by a Langmuir probe. We observed that ϕ_L was larger than ϕ_P in a supersonic flow, and the difference became prominent at $M > 1.5$.

The significant difference between ϕ_P and ϕ_L in a fast flow was observed only in neutral plasmas. Figure 4 shows the pure electron plasma potentials measured by the Langmuir probe and the Pockels sensor. We changed the cathode voltage of the electron gun and compared ϕ_P with ϕ_L at three points. ϕ_P showed good agreement with ϕ_L when the electron plasma had a strong electric field and a resultant fast flow of up to 2×10^5 m/s.

The observed discrepancy in ϕ_L and ϕ_P is explained by the formation of ion acoustic shock in the plasma and the resultant modification of the Langmuir probe characteristics. When the electrode of the emissive Langmuir probe is placed in a supersonic flow, it creates a shock electric field upstream of the probe tip. Using a one-dimensional electrostatic model, we confirmed that the electric field near the probe is modified by the shock structure when the plasma has a supersonic flow. Because of the potential hump near the probe tip, thermoelectrons from the emissive probe are emitted even when the probe potential is higher than the space potential. Therefore, the emissive Langmuir probe overestimates the space potential. Figure 5 shows the geometries of the emissive Langmuir probe, Pockels sensor, plasma flow, and potential hump. In a supersonic plasma

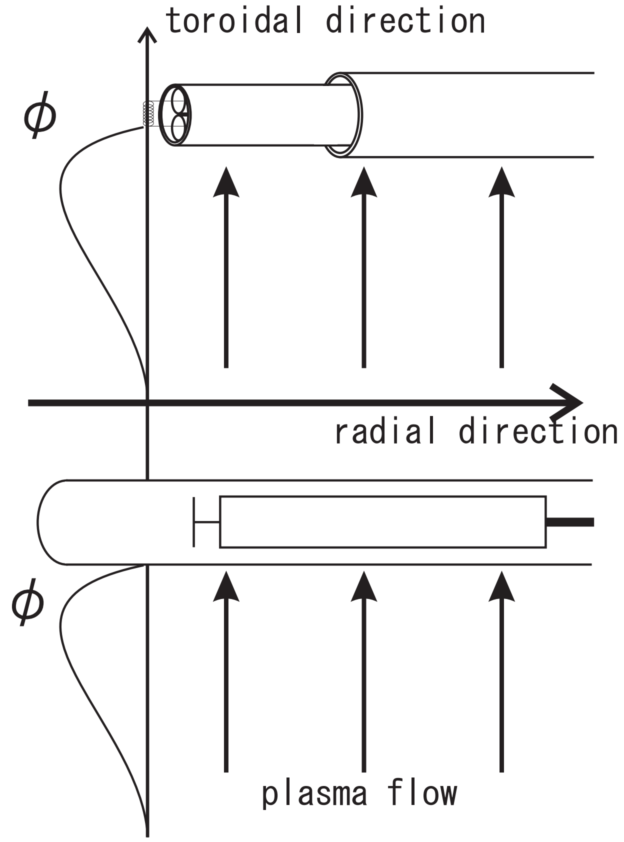

Fig. 5 Geometries of the emissive probe, Pockels sensor, and plasma flow. Because the potential structure of the shock (ϕ) is modified in the toroidal direction, the Pockels sensor measurements are not affected by the shock.

flow, a shock structure is created in the upstream side of the probes. Because the emissive Langmuir probe and the Pockels sensor are much larger than the Debye length, we can apply the aforementioned simplified one-dimensional model. As a result, shock structures are created upstream of the Langmuir probe and the Pockels sensor in a supersonic plasma flow. In contrast to the Langmuir probe, the Pockels sensor is not affected by the shock potential hump, because the shock modifies the potential structure only in the toroidal (plasma flow) direction, which is perpendicular to the radial electric field. Thus, the Pockels sensor measurement gives correct values even in a supersonic flow. A detailed numerical analysis of the shock effect will be reported in a future paper.

In conclusion, we investigated the effects of a supersonic plasma flow on emissive Langmuir probes, in comparison with the Pockels sensor. Differences between the two measurements were observed when M was greater than 1.5. This phenomenon is explained by a one-dimensional model of the formation of ion acoustic shock in a plasma. The potential structures created by the shock cause emission of thermoelectrons from the emissive probe even when the probe potential is higher than the space potential; thus, the emissive probe overestimates the plasma potential. The shock modifies the potential structure only in the flow direction and does not affect the radial electric field. Therefore, the Pockels sensor, which measures the radial electric field directly, gives reasonable results even when the plasma flow becomes supersonic.

[1] S.M. Mahajan and Z. Yoshida, Phys. Rev. Lett. **81**, 4863 (1998).
[2] Z. Yoshida and S.M. Mahajan, Phys. Rev. Lett. **88**, 095001 (2002).
[3] Z. Yoshida *et al.*, *17th IAEA Fusion Energy Conference*, Yokohama, 1998, IAEA-CN-69/ICP/10(R).
[4] H. Saitoh *et al.*, Phys. Plasmas. **11** 3331 (2004).
[5] K. Yagi *et al.*, J. Plasma Fusion Res. Series **4**, 595 (2001).
[6] F.F. Chen, *Plasma Diagnostic Techniques*, edited by R.H. Huddlestone and S.L. Leonard (Academic, New York, 1965), p. 113.
[7] T. Ichikawa *et al.*, Opt. Lett. **23-14**, 1134 (1998).