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TWO-DIMENSIONAL PIC SIMULATIONS ON FACE-TO-FACE DOUBLE PROBE

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Introduction

Plasma flow is one of the important subjects to investigate phenomena observed in plasmas. So far, various measurement methods such as the Mach probe, the directional probe *etc*. have been proposed and used in laboratory plasma experiments and in space plasma observations. Another probe method to measure Mach number of a plasma flow with a spatial resolution has been proposed, which is named Face-to-face Double Probe (FDP) [1, 2]. Details on the probe are described in the next section.

In this paper, a feasibility of the FDP method to estimate Mach number of a plasma flow is investigated using a two-dimensional particle-in-cell (PIC) simulation [3].

Face-to-face Double Probe --- FDP ---

The FDP measurement system consists of a pair of electrodes which are face to face each other, a variable power supply, and an ammeter. A schematic drawing of the system is shown in Fig. 1. A current, flowing into an electrode of a probe placed in a plasma, is derived by a presheath in front of the electrode in general. In case of a conventional Mach probe (CMP), which is shown at the top of Fig. 2, the presheath is far extended. In Fig. 2, the presheath is symbolized by a gradation from black to white. In contrast, in case of the FDP, which is shown at the bottom of Fig. 2, an expansion of the presheath formed in front of one electrode is restricted by another electrode. With taking into account the fact that charged particles in the presheath are diffused from surrounding plasma, the expansion of the presheath determines a spatial resolution of the probe. The FDP method has an important advantage over the conventional CMP method in this regard, that is, the FDP method has a distinctive feature in its

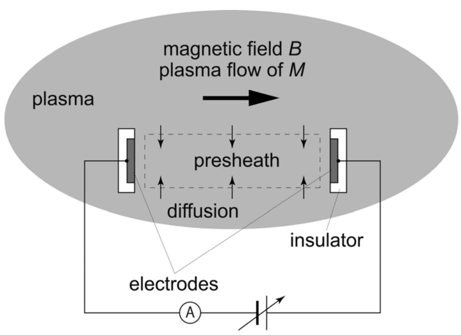

Figure 1: Schematic drawing of face-to-face double probe (FDP) and its measurement circuit.

good spatial resolution.

The *V-I* characteristics of the FDP can be calculated by the steady state fluid model [4]:

$$\frac{d\tilde{n}M}{d\xi} = 1 - \tilde{n}, \qquad (1)$$

$$\tilde{n}M\frac{dM}{d\xi} + \frac{d\tilde{n}}{d\xi} = (1+\alpha)(1-\tilde{n})(M_\infty - M), \qquad (2)$$

where $\tilde{n}$ is the normalized density, M and M_∞ the Mach numbers of plasmas inside and outside the electrodes, respectively, ξ the normalized spatial coordinate, and α the normalized viscosity. After tedious calculation, a following relation is obtained:

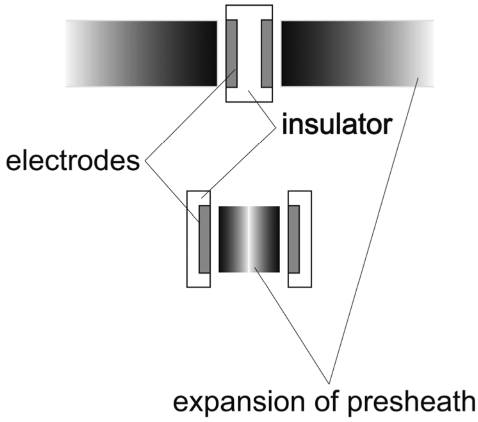

Figure 2: Difference in an expansion of presheath (gradation from black to white) between CMP (top) and FDP

$$\frac{eV_0}{k_B T_e} = \ln\left[\frac{2+\alpha+(1+\alpha)M_\infty}{2+\alpha-(1+\alpha)M_\infty}\right]^\delta + \frac{\alpha M_\infty}{\sqrt{q}}\left\{\tan^{-1}\left[\frac{(1+\alpha)(2-M_\infty)}{\sqrt{q}}\right] + \tan^{-1}\left[\frac{(1+\alpha)(2+M_\infty)}{\sqrt{q}}\right]\right\}, \qquad (3)$$

where e is the elementary charge, V_0 the voltage when a net current flowing through the electrodes is 0, k_B the Boltzmann constant, and T_e the electron temperature of the plasma between the electrodes, respectively. The parameters δ and q are given as follows:

$$\delta = \frac{2+\alpha}{2(1+\alpha)}, \qquad (4)$$

$$q = 4(1+\alpha) - (1+\alpha)^2 M_\infty^2. \qquad (5)$$

For -1 < M_∞ < 1, the solution can be approximated as follows:

$$M_\infty \simeq \frac{\dfrac{eV_0}{k_B T_e}}{1 + \dfrac{\alpha}{\sqrt{1+\alpha}}\tan^{-1}\sqrt{1+\alpha}} \propto \frac{eV_0}{k_B T_e}. \qquad (6)$$

It is found that the Mach number is proportional to the voltage V_0 as long as the electron temperature is constant. In applying this method to experiments, Mach number can be estimated by measuring the voltage V_0 and the electron temperature T_e. Figure 3 in Ref. [1] is helpful to see the relation between V_0 and M_∞ more detail. In the following sections, a notation M is used instead of M_∞.

PIC Simulation

A two-dimensional PIC simulation on FDP was performed to investigate a potential formation due to the plasma flow. Schematic drawing of the simulation region is shown in Fig. 3. In the figure, the spatial variables are normalized as follows: $X = x / \lambda_D$, and $Y = y / \lambda_D$, where λ_D is the Debye length. The spatial steps are $dX = dY = 0.1$. The simulation region is symmetric against $Y = 0$. The time is normalized as $\tau = \omega_{pi}\, t$, where ω_{pi} is the ion plasma angular frequency. The temporal step is $d\tau = 0.01$. A mass ratio of the ion versus the electron, m_i / m_e, is 200, and a temperature ratio of the ion versus the electron, T_i / T_e, is 1, respectively. The electrostatic potential, ϕ, is normalized as $\Phi = e\phi / k_B T_e$. Two electrodes are located at $0 \leq Y \leq 12.8$ if $X = 0$ or 6.4. The other boundaries, except for $Y = 0$ and the electrodes, are free boundaries. A potential of each electrode is a floating potential. Outside region of the electrodes, $Y > 12.8$, a Mach number of the ion flow is given with $0 < M < 1$. The flow direction is parallel to X-axis. Existence of a normalized magnetic field, $B_n = |e|\, B / \omega_{pi}\, m_i$, of 5.645 in strength is also assumed along X-axis. Because the FDP is designed under the assumption that the charged particles are diffused from outside plasma to the space between the electrodes, Bohm diffusion is took into account.

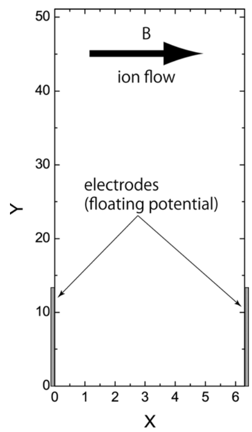

Figure 3: Simulation region with directions of the magnetic field and the ion flow, and a location of the electrodes.

Results and Discussion

A spatial distribution of the two-dimensional electrostatic potential was calculated for several Mach numbers. An example of the result in case of $M = 0.4$ is shown in Fig. 4. The outside area of the electrodes, $Y > 12.8$, contour lines of Φ is almost parallel to the X-axis. The inside area of the electrodes, $Y < 12.8$, the potential shows an asymmetry between the left-hand and the right-hand sides. The plasma flow made the floating potentials of the electrodes different and, as a result, induced the asymmetrical potential distribution. In the present case, the plasma flows from left to right, the potential of the right-hand side electrode, Φ_R, is expected to be higher than that of the left-hand side one, Φ_L. In fact, Φ_R is larger than Φ_L as shown in Fig. 5.

The potential difference, $\Delta\Phi = \Phi_R - \Phi_L$, increases linearly with increasing Mach number as shown in Fig. 5. Equation (6) shows that the potential difference is proportional to the Mach number for $|M| < 1$. The result of the simulation coincides with this theoretical result. It is considered that the FDP method is applicable to measure the Mach number of the plasma flow of $|M| < 1$.

It may be worth considering the size of FDP to use it in laboratory experiments *etc*., though the size estimation is based on one-dimensional fluid model. The size of the electrode, a, may have to be larger than the ion gyro radius, ρ_i, to assure the one-dimensionality: $a \gg \rho_i$. In the fluid model described above, it is assumed that the existence of a plasma between the electrodes. If so, the distance of the electrodes, d, may have to be sufficiently larger than the Debye length, λ_D: $d \gg \lambda_D$.

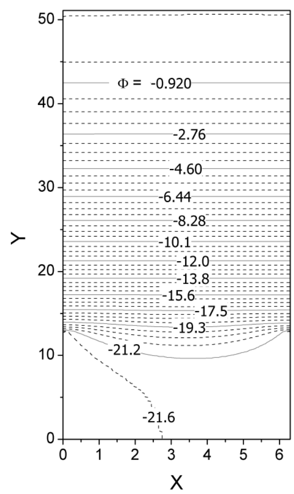

Figure 4: Example of two-dimensional electrostatic potential distribution in case of

Summary

The simulations on the FDP were performed using the two-dimensional PIC code. The difference in the electrostatic potential of the floating electrodes increases linearly with increasing Mach number. This suggests that the FDP method is possible to estimate the Mach number of the plasma flow. To convert the potential difference to a Mach number, it is required to estimate the electron temperature of the plasma between the electrodes. The electron temperature has to be estimated in the simulation as one of our future works. It is also our future work to determine the minimum size of the electrodes and their minimum distance using the PIC simulation and to check the performance of the FDP method in laboratory experiments and space plasma observations.

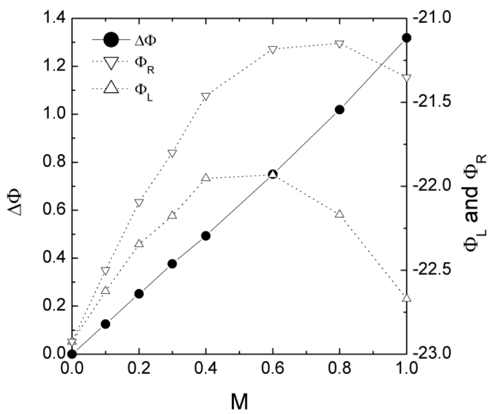

Figure 5: Dependences of $\Delta\Phi$, Φ_R, and Φ_L on M.

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