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Investigation of Mach probe geometry effects in weakly magnetized plasmas

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Abstract

Probe geometry dependence of Mach probe diagnostics in weakly magnetized plasmas has been investigated. In order to obtain sufficiently saturated ion currents, and also to experimentally obtain the angular sensitivity of differently shaped probes, the effect of superthermal electrons was measured. When using the theoretical expressions of angular distribution of the ion current as fitting functions, estimated Mach numbers largely depend on the geometry of the probe. However, by taking the ratio of upstream to downstream ion currents, the effect of magnetic field can be eliminated. Furthermore, considering the broadening of the ion collection angles, the deduced Mach numbers show good agreement regardless of the probes geometry, and do not contradict the spectroscopic results.

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1. Introduction

Diagnosis of local plasma flow, especially in the boundary region, is one of the important tasks of fusion-relevant magnetic confinement devices. In the scrape-off layer (SOL) and the divertor region, specifically, the plasma flow determines various phenomena, such as wall recycling and flow reversal [1]. Standard passive spectroscopy has been used for the flow measurements, though it yields only line-integrated emission along the viewing chords. Therefore, to obtain the local flow velocity, alternative diagnostic methods such as the Mach number probe [2], laser-induced fluorescence (LIF) [3], and plume spectroscopy [4] have been developed. Among these, the Mach number probe is widely applied both in large devices and small laboratory apparatuses because of its simplicity and convenience.

In the Mach number probe diagnostics, the ion collection behavior is determined by the degree of plasma magnetization δ_i defined as $\delta_i = a_p/\rho_i$, where a_p is the probe head radius and ρ_i the ion gyro-radius. Under the condition of strongly magnetized plasmas ($\delta_i \gg 1$), theoretical models almost independent of the probe shape geometry were developed [2,5], and the validity of the theory was experimentally confirmed [4,6]. In the unmagnetized plasmas ($\delta_i \ll 1$), on the other hand, the classical free-fall model [7] has been used for a long time, and comprehensive results based on the particle-in-cell (PIC) computer simulation [8,9] have recently been developed. However, in the weakly magnetized cases

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($\delta_i \sim 1$), because of the comparable size of the ion gyroradius to the probe head, the collection of ions might be dependent on the probe geometry. Although several kinds of Mach number probes have been used under such conditions [10–12], the probe geometry dependence has not been investigated heretofore.

In the present paper, we used three differently shaped Mach number probes for the flow measurement in weakly magnetized plasma ($\delta_i = 0.07 \sim 0.2$). The parallel Mach numbers are determined based on both the PIC simulation and the free-fall model, and compared with the results of spectroscopy. Furthermore, in order to confirm the saturation of the ion current, and also to experimentally obtain the angular sensitivity of the probes, the effect of the superthermal electrons [13] is measured.

2. Method

The flow velocity is calculated using both the PIC simulation and the free-fall model. In the PIC simulation model, the angular distribution of the ion current density is written as

$$j_{\mathrm{PIC}}(M,\theta) = j_0 \exp\left\{\frac{1}{2}\sqrt{\frac{T_e + T_i}{T_e}} M[(1+\cos\theta)K_u - (1-\cos\theta)K_d]\right\}, \quad (1)$$

where M is the parallel Mach number, θ the angle between the probe-facing direction and the flow direction, j_0 the base ion current, T_e and T_i the electron and ion temperatures, respectively, and K_u and K_d the empirical constants, respectively. Note that Eq. (1) is identical to that found in Refs. [8,9] by replacing θ to $\theta + \pi$. In the free-fall model, the same equation is written as

$$j_{\mathrm{free-fall}}(M,\theta) = j_0 \exp\left[\frac{1}{2}(M_{\mathrm{th}} + M\cos\theta)^2\right], \quad (2)$$

where M_{th} is the ion thermal Mach number defined as $M_{\mathrm{th}} = v_{\mathrm{th}}/c_s = \sqrt{2T_i/(T_e + T_i)}$. These expressions can generally be written, introducing the ratio of the ion current densities, as

$$\frac{j(\theta)}{j(\theta+\pi)} = \exp(K'M\cos\theta),$$
$$K' = \begin{cases} 2M_{\mathrm{th}}\ (\mathrm{free-fall}) \\ \sqrt{\dfrac{T_e + T_i}{T_e}}(K_u + K_d)\ (\mathrm{PIC}). \end{cases} \quad (3)$$

From another point of view, when the effects of flow and magnetic field can be treated independently, the ion current can be written as [11]

$$j(\theta, M) = j_0 \cdot F_M(\theta) \cdot F_B(\theta), \quad (4)$$

where $F_M(\theta)$ and $F_B(\theta)$ are the functions that describe the effects of flow and magnetic field, respectively. Because the effect of magnetic field is symmetrical in directions both parallel and perpendicular to the magnetic field, the function $F_B(\theta)$ becomes the even function, namely $F_B(\theta) = F_B(\theta + \pi)$. Consequently, the ratio $j(\theta)/j(\theta + \pi)$ gives the function $F_M(\theta)/F_M(\theta + \pi)$, which depends only on the flow effect. This is the case in which the magnetic field effect is eliminated, and Eq. (3), originally applied to unmagnetized plasmas, is then applicable to the weakly magnetized cases.

In contrast to strongly magnetized plasmas, in which the flow can be treated as one-dimensional, the effect of probe geometry should be considered in weakly magnetized plasmas. In order to compare the differently shaped Mach number probes, we modified Eq. (3) by taking into account the broadening of the ion collection angle as

$$\frac{\int_{\theta-\Delta\theta}^{\theta+\Delta\theta} j(\theta)\mathrm{d}\theta}{\int_{\theta-\Delta\theta}^{\theta+\Delta\theta} j(\theta+\pi)\mathrm{d}\theta} = \exp\left(K'M\cos\theta \cdot \frac{\sin\Delta\theta}{\Delta\theta}\right), \quad (5)$$

where $\Delta\theta$ is the collection angle. The broadening of the collection angle is expressed by the term $\sin\Delta\theta/\Delta\theta$, and using the above equation the differently shaped Mach number probes can be treated generally.

3. Experimental setup

The experiments were performed in the linear divertor plasma simulator MAP-II [12,13]. Plasma was generated by the low-pressure dc-arc discharge having a discharge voltage of about 70 V, a discharge current of 30 A, and using pure helium gas as fuel. An axial magnetic field of less than 350 G was generated by eight magnetic field coils and confined the plasmas. The diameter of the plasma column was about 50 mm and the total length of the device about 2 m. A schematic of the target chamber is shown in Fig. 1(a). The measurements were performed under three magnetic field strengths, of 205, 135, and 67 G. The plasma parameters measured by electrical probe are shown in Table 1. The ion temperatures were measured from the Doppler broadening of the HeII spectra and obtained as about 0.5 eV on all conditions.

The Mach number probe was mounted on a reciprocating movable probe system and rotated by a stepping motor with an angular resolution of 0.012°. The three types of probe – standard Mach probe (MP), slit-shaped Mach probe (SP) and directional Langmuir probe (DLP) – were used for measurements. Schematics of these probes are shown in Fig. 1(b). All probes consisted of a tungsten electrode 0.5 mm in diameter and an alumina insulator (Al_2O_3) 4.0 mm in diameter. The distance from the probe to the floating end target plate was about 20 cm and much longer than the length of the presheath. As can be seen in the Refs. [14,15], the experimentally obtained length of the presheath was less than 10 cm.

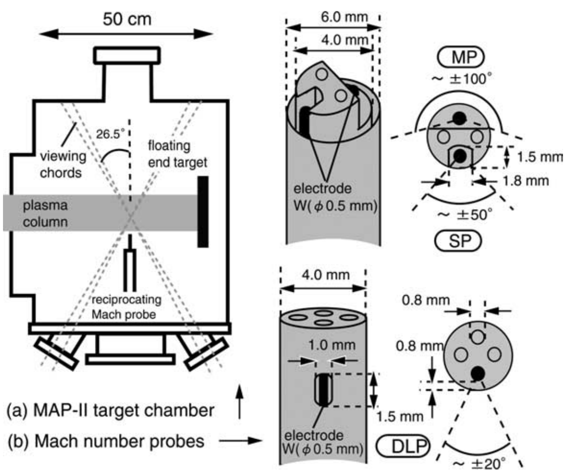

Fig. 1. (a) A schematic of the MAP-II target chamber. From the bottom of the chamber, a reciprocating movable Mach number probe was installed, and vertically aligned spectroscopic viewing chords were located at the ±26.5° directions with respect to the axis perpendicular to the magnetic field. (b) Three types of Mach number probes were used for the measurement, standard Mach probe (MP), slit-shaped Mach probe (SP), and directional Langmuir probe (DLP). The geometrical collection angles were about ±100° for the MP, ±50° for the SP and ±20° for the DLP.

Table 1
Plasma parameters measured by electrical probe under three magnetic field strengths, of $B = 205$, 135, and 67 G

B	205 (G)	135 (G)	67(G)
n_e (m^{-3})	5.7×10^{17}	2.8×10^{17}	9.2×10^{16}
T_e (eV)	5.5	7.4	8.0
ρ_i (mm)	10	15	30
c_s (km/s)	12.0	13.8	14.3

In our case, the magnetic field strength was weaker and the length of the presheath became shorter than the case of the refs., so that the effect of the end target plate could be neglected.

For the purpose of validating absolute flow velocity, the Doppler shift of HeII ($n = 3$–4, 468.57 nm) spectra [12,16] were measured. Vertically aligned viewing chords were located at ±26.5° directions (corresponding to the red and the blue shifts) with respect to the axis perpendicular to the magnetic field with a spatial resolution of about 3.5 mm.

4. Effects of superthermal electrons

In the ion saturation current measurements, electrons at energy higher than the probe biasing voltage can penetrate the negative potential barrier and cause reduction of the ion current [13]. This effect largely depends on the probe shape geometry, since electrons are magnetized and their gyro-radius is much smaller than the probe head radius. In order to experimentally obtain the angular sensitivity of the probes, reduction of the ion current was measured as shown in Fig. 2.

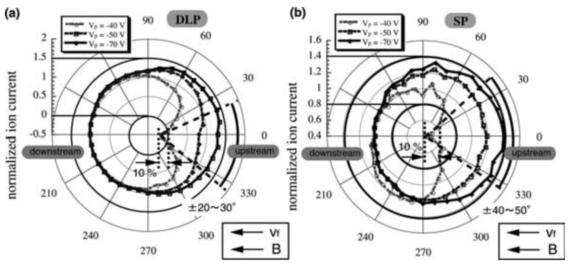

Fig. 2. The angular distribution of the ion current measured by (a) DLP and (b) SP. The r axis represents the ion current normalized by that of measured in the downstream direction and the θ axis represents the probe-facing direction.

As was revealed in our previous research [13], superthermal electrons at the energy corresponding to the discharge voltage can be generated by reducing the fueling gas. In Fig. 2, it is shown that by using a negative probe bias lower than the discharge voltage ($\leqslant -70$ V), a reduction of the ion current occurs in the upstream direction. The reduction has a probe geometry dependence, though this dependence can be modified when using a negative bias higher than the discharge voltage ($\geqslant -70$ V). Here we define the angular sensitivity of the probes as the angular range of 10% of the total ion current reduction, and the sensitivities are estimated as $10 \sim 20$ ° for the DLP and $30 \sim 60°$ for the SP, while that for MP is too broad to be defined. These results are almost same as those for the probe shape geometry.

5. Estimation of the flow velocity

The angular distribution of the ion saturation current densities were measured with rotating the probes at increments of 10°. The obtained ion currents and fitting curves are shown in Fig. 3. From these results, it can be seen that the calculated flow velocity largely depends on the probe geometry, because the angular distribution of the ion current was affected by both the flow and the magnetic field.

On the other hand, when using the ratio of the ion currents $j(\theta)/j(\theta+\pi)$, it can be seen from Fig. 4 that the experimental data are well fitted to the theoretical fitting curve, $\exp(\alpha\cos\theta)$ (α: fitting parameter), regardless of the probe geometry. This means that the effect of magnetic field is eliminated, and the effect of flow can

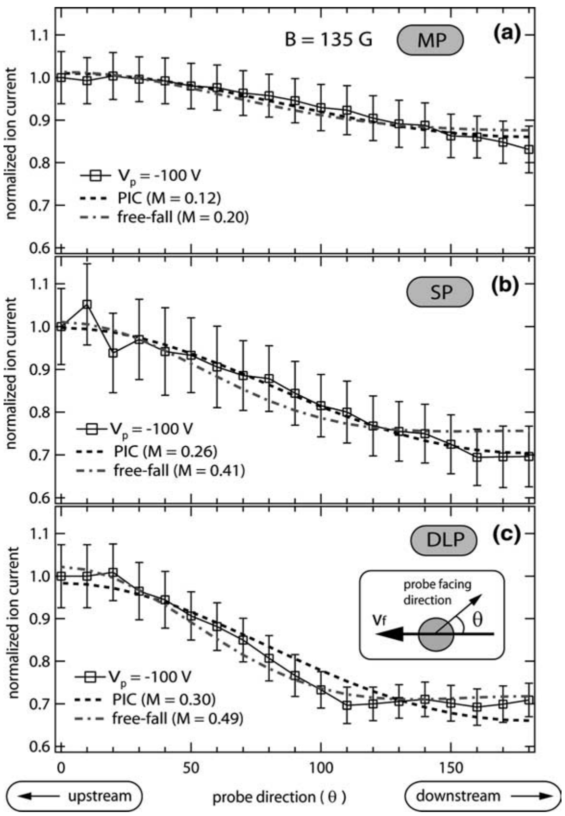

Fig. 3. The angular distribution of the ion current measured by three probes (a) MP, (b) SP, and (c) DLP with the probe biasing voltage of −100 V and the magnetic field strength of 135 G. The plotted ion currents are normalized by that of measured in the upstream direction. The dashed lines represent the fitting results using both the PIC and free-fall model.

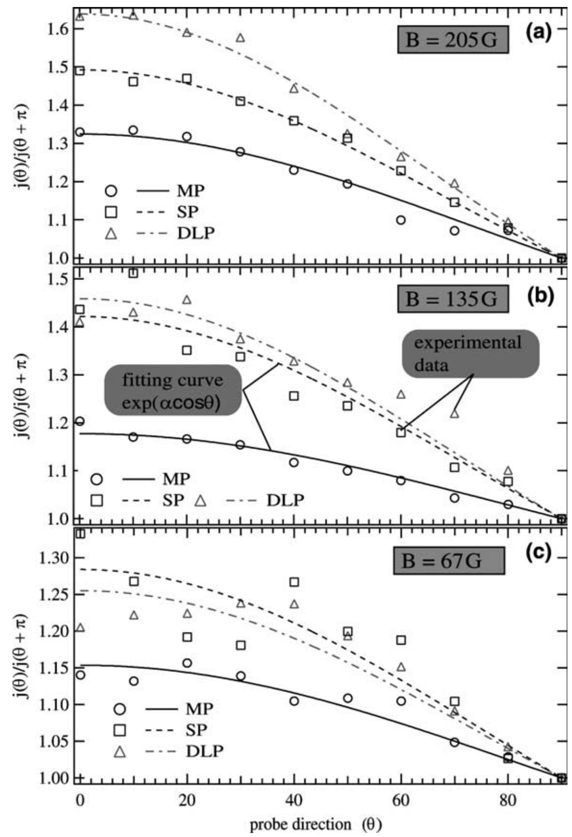

Fig. 4. Fig:ratio The ratio $j(\theta)/j(\theta + \pi)$ under the experimental conditions of (a) 205 G, (b) 135 G, and (c) 67 G. The markers represent the experimental data and lines the fitting curve $\exp(\alpha \cos\theta)$.

be treated independently. The fitting results of the parameter α are listed in Table 2.

To confirm the absolute flow velocity, spectroscopic measurements were performed. From the Doppler shift of the spectra measured at the center of the plasma column, Mach numbers were obtained. It should be noted that in this case, the effect of line-integration along the viewing chord was not considered; consequently the obtained Mach numbers might be slightly under-estimated.

From Eq. (5), the difference in the value α indicates a difference in the factor $\sin\Delta\theta/\Delta\theta$ among probes. The ion collection angle of the DLP can be estimated as about $\Delta\theta \simeq 20°$ from the angular sensitivity of the superthermal electrons. Then, from the ratio α_{MP}/α_{DLP} and α_{SP}/α_{DLP}, which are almost constant under all the magnetic field conditions, the ion collection angles $\Delta\theta$ for the MP and SP are evaluated as about 100° and 60°, respectively. These evaluations for MP and SP almost coincide with those for the probe shape geometry.

Table 2
The fitting results of the parameter α

B	205 (G)	135 (G)	67 (G)
α_{MP} (M_{MP})	0.28 ± 0.07 (0.35 ± 0.09)	0.16 ± 0.09 (0.20 ± 0.11)	0.14 ± 0.08 (0.17 ± 0.10)
α_{SP} (M_{SP})	0.40 ± 0.10 (0.34 ± 0.09)	0.35 ± 0.15 (0.30 ± 0.13)	0.25 ± 0.14 (0.21 ± 0.12)
α_{DLP} (M_{DLP})	0.49 ± 0.08 (0.34 ± 0.06)	0.38 ± 0.10 (0.27 ± 0.07)	0.23 ± 0.10 (0.16 ± 0.07)
Spec.	0.29 ± 0.05	0.21 ± 0.05	

The calculated Mach numbers considering the broadening of the collection angles are shown in the bracket. The row denoted as 'Spec.' indicates the Mach numbers obtained from the Doppler shift of the HeII spectra.

The parallel Mach numbers calculated using the modified PIC model are shown in round brackets in Table 2. One can see that the calculated Mach numbers show good agreement and no contradictions with the spectroscopic results, regardless of the probe shape geometry.

6. Conclusions

Probe geometry dependence of the flow velocity measurement was investigated in weakly magnetized plasmas using three types of Mach number probes. In order to obtain the correct ion saturation current, and also to obtain the angular sensitivity of the probes experimentally, the effect of superthermal electrons was measured. The estimated angular sensitivities of the SP and MP were almost same as those of the probe geometry.

In the estimation of the flow velocity, it was shown that using the ratio of the ion currents, the effect of magnetic field can be eliminated and the effect of flow can be obtained independently. Moreover, including the broadening of the ion collection angles, the theoretical expressions are modified. The experimental data of the ion currents ratios were fitted, and based on the difference in the fitting parameter α, the broadening of the ion collection angles could be estimated as about 100° for the MP and 60° for the SP when an angle of 20° was assumed for the DLP. These angles almost coincide with the probe shape geometrical angles. As a result, including the difference in the collection angles as a modification factor, it was found that the calculated Mach numbers do not depend on the probe geometry, and also do not contradict the results of spectroscopy in the range of error. Thus, it is suggested that the identical Mach number can be measured using these three types of Mach number probe in weakly magnetized plasmas.

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