

PLASMA FLOW MEASUREMENTS USING A MACH PROBE CALIBRATED BY ALFVÉN WAVES

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1. Introduction

Recently, the "Mach probe" has been attracted interest in the field of fusion research to measure the plasma drift velocities in the plasma edge region of tokamaks or other magnetic confinement devices. This simple probe is also considered to be applied to *insitu* measurements in the space.

We have developed a new method by putting a Mach probe behind a movable separator located in the upstream region in order to avoid the ion recycling problem occurred at the separator, so that our method is different from that proposed by Chung [1], but the theory in [1] is used to estimate the flow velocity because it gives an analytical solution to the plasma density in the presheath. However, the theory developed in [1] has a problem as pointed out by Hutchinson [2]; Chung chose the parallel contribution of the perpendicular viscous force as $\nabla_{\perp} \cdot (n_i \nabla_{\perp} V_z) \approx (n_{\infty} - n_i)(V_{\infty} - V_z)/a^2$, while Hutchinson insists that this term should be approximated as $n_i(V_{\infty} - V_z)/a^2$, where n_i is the plasma density in the presheath, V_{∞} the flow velocity outside the presheath which we want to know, and a the half size of the object (a probe or separator). However, we emphasize that this term should be approximated as $n_{\infty}(V_{\infty} - V_z)/a^2$ [3], although from this approximation we cannot analytically estimate the plasma density in the presheath, in the same way as Hutchinson's case. There are another ambiguities in the theories, so that we have independently measured the real flow velocity by using the dispersion relation of the shear Alfvén wave (SAW); we have launched the shear Alfvén wave using two helical antennas, one of them being located at the upstream region while the other at the downstream region. From the difference between the two dispersion relations we can exactly know the drift velocities as a function of the radius and calibrate the Mach probe measurements.

2. Plasma flow velocity measured with shear Alfvén wave

The helium plasma was produced by a magneto-plasma-dynamic (MPD) arcjet in a cylindrical linear device (15 cm diameter and 2 m long) under the external magnetic field $B_0 = 0.3$ T. The plasma density and temperature in the experimental region were $5.2 \times 10^{14} \text{ cm}^{-3}$ and $T_e = 3.6 \text{ eV} \sim T_i$, respectively.

First we measured the real plasma flow velocity by using shear Alfvén wave propagation. A helical-type antenna of 14 cm diameter [4,5] as shown in Fig. 1 was used to excite preferentially $m = -1$ (m : the poloidal mode number) mode of frequency less than the ion cyclotron angular frequency $\omega_{ci} = 7.2 \times 10^6 \text{ rad s}^{-1}$. We used two helical antennas as mentioned above, one being used to launch the SAW from the upstream side and the other from the downstream side. The magnetic field component \vec{b}_{θ} of the launched wave packet was detected by two small magnetic probes located with an interval of 20 cm along the field line. The data were processed digitally using FFT to obtain the dispersion relation. Figure 2 shows two dispersion relations, the closed circles corresponding to the wave propagating from the upstream side, while the open circles from the downstream side.

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The solid line indicates a theoretical dispersion relation of the SAW including ion-neutral collisions [6],

$$S \frac{\omega^2}{k_{\parallel}^2 V_A^2} - \left(1 - S^2 \frac{\omega^2}{\omega_{ci}^2}\right) = 0 \quad (1)$$

with the complex factor S given by

$$S = 1 + \frac{\frac{\rho_n}{\rho_0} \omega}{1 - i \frac{\rho_n}{\rho_0} \nu_{in}}, \quad (2)$$

where ρ_0 and ρ_n are, respectively, the mass density of the ion and neutral, and ν_{in} the ion-neutral collision frequency.

Two dashed lines are the dispersion relation shifted from the solid line by drift velocity $\pm 5.0 \times 10^5$ cm/s, respectively. From these best fitting curves, we obtain the real plasma flow velocity $V_{\infty} = 5.0 \times 10^5$ cm s⁻¹ or corresponding Mach number $M_{\infty} = 0.4$.

3. Mach number measured with Mach probe

According to Chung [1], the sheath edge density n_s of the probe behind the separator is obtained as follows,

$$n_s = n_m [(2 + \alpha) - (1 + \alpha)]^{-\delta} \exp \left[\frac{\alpha M_0}{\sqrt{q}} \left\{ \arctan \frac{(1 + \alpha)(2 - M_0)}{\sqrt{q}} - \arctan \frac{(1 + \alpha)M_0}{\sqrt{q}} \right\} \right], \quad (3)$$

where $M_0 = M_0(L_b)$ is the Mach number in the free-presheath generated by the separator, and δ and q are the same as given in [1]. The density n_m is calculated from the following relation,

$$-\frac{L_b}{L_d L} = \int_1^{-1} \frac{n_m G(M)^{-\delta} \exp [H(M)] (1 - M^2)}{1 - n_m G(M)^{-\delta} \exp [H(M)] G(M)} dM, \quad (4)$$

where the functions $G(M)$ and $H(M)$ are defined also in [1], and $L = (a/d)^2$ and $L_d = d^2 C_s / D_{\perp}$. The relation between M_{∞} and M_0 is calculated from the following equation,

$$-\frac{L_b}{L_d} = - \int_1^{-M_0} \frac{[G(M)/(1 - \gamma^2 M_{\infty}^2)]^{-\delta} \exp [H_c(M)] (1 - M^2)}{1 - [G(M)/(1 - \gamma^2 M_{\infty}^2)]^{-\delta} \exp [H_c(M)] G(M)} dM, \quad (5)$$

where $\gamma = (1 + \alpha)/(2 + \alpha)$ and

$$H_c(M) = \frac{\alpha M_{\infty}}{\sqrt{q}} \left[\arctan \left(\frac{(1 + \alpha)(2M - M_{\infty})}{\sqrt{q}} \right) - \arctan \left(\frac{(1 + \alpha)(2\gamma - 1)M_{\infty}}{\sqrt{q}} \right) \right]. \quad (6)$$

It is then possible to calculate the sheath edge density at the probe as a function of L_b/L_d , and comparing it with the experimental values, we obtain $L_d \simeq 15$ cm, and so the phenomenological diffusion constant $D_{\perp} \sim 0.5 D_B$, where D_B is the Bohm diffusion coefficient.

Applying this theory, we can calculate the ratio of the sheath edge density $R = n_{s0}/n_s$, where n_{s0} is the sheath edge density without the separator. Figure 3 shows the schematic drawing of the experimental setup for the Mach probe of diameter $2a = 1.1$ mm and the separator of diameter $2d = 4.0$ mm. Measured ratio R is shown in Fig. 4 vs. the length of bounded presheath L_b together with theoretical ones when $\alpha = 0.5$. From this figure, the

measured Mach numbers are agreed well with the theoretical curve for $M_\infty = 0.5$ beyond $L_b = 1$ cm, which is comparable with the real value $M_\infty = 0.4$. Deviation of the data from the theory in $L_b < 1$ cm may be due to the influence of the finite size of the probe or turbulent flow around the deparator even though the Reynolds number is very small.

Considering some ambiguities of the theoretical background, we could conclude that the Mach theory proposed by Chung is applicable to rough estimation of the plasma flow velocity along the magnetic field line.

Acknowledgements

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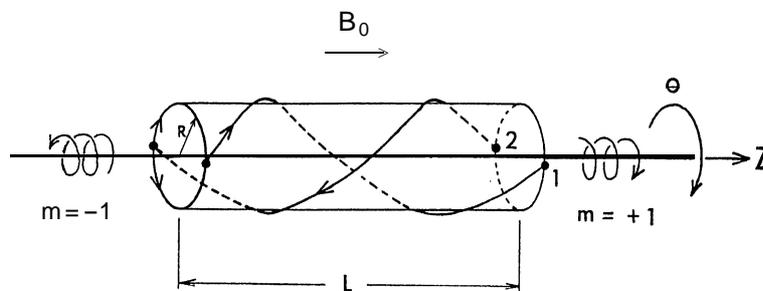


Fig. 1. A helical antenna to excite $m = -1$ shear Alfvén wave

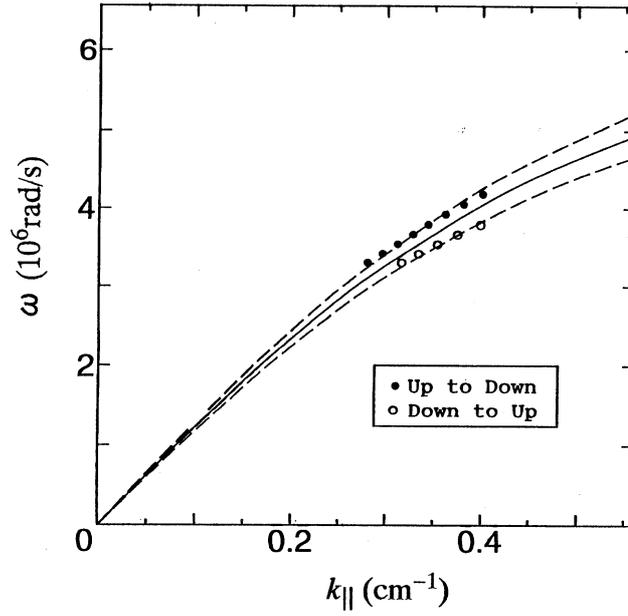


Fig.2 Dispersion relations of shear Alfvén waves.

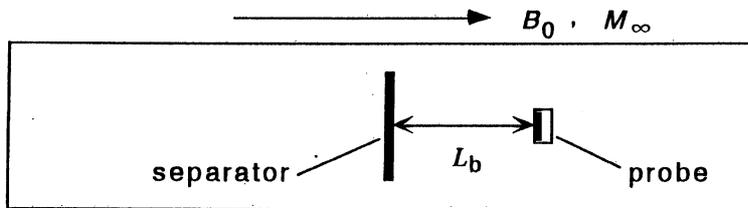


Fig.3 The Mach probe located behind a separator.

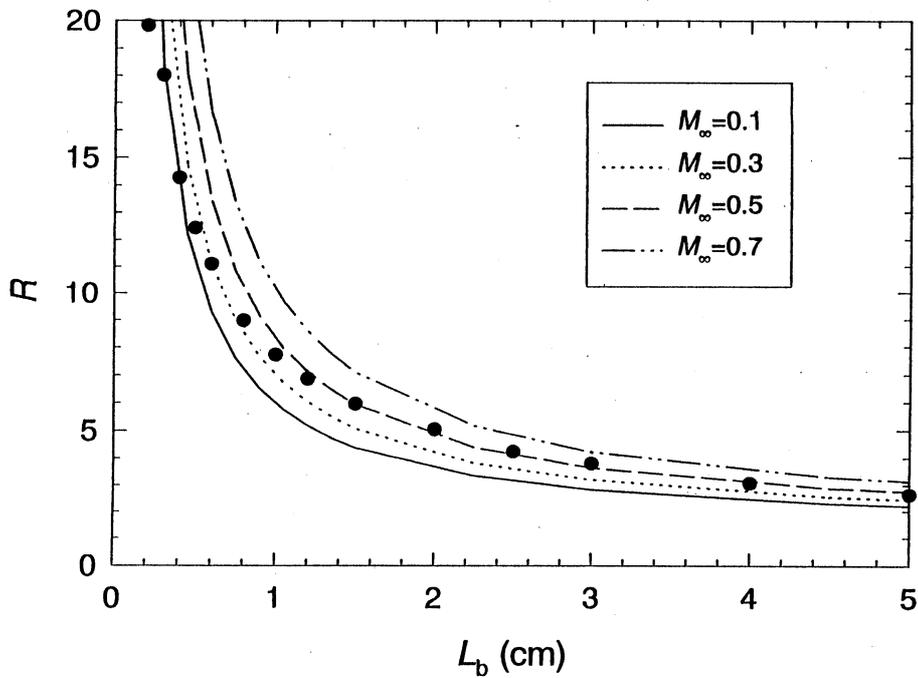


Fig.4 The ratio of measured ion currents vs. L_b together with the theoretical curves for $\alpha = 0.5$.