

The inclined Mach probe as a diagnostic for perpendicular flow measurements in a strongly magnetized plasma.

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1. Introduction.

A Mach probe is a powerful diagnostic for the plasma edge since several plasma parameters like the electron temperature and -density, floating potential and plasma flow can be measured simultaneously with a high spatial resolution.

The measurement of flow, parallel to the magnetic field, is very well modeled and assumed to be a routine measurement. For the perpendicular flow this is not the case. It will be demonstrated that a Mach probe is able to measure also perpendicular flows and that the 1D fluid model that we developed to determine the parallel and perpendicular flows from the probe data, delivers reliable Mach numbers.

The Mach probe measurements are performed in the plasma boundary during electrode polarisation discharges in TEXTOR-94, providing the unique possibility to create a radial electric field E_r and ensuing high toroidal and poloidal flows in a controlled way. Hence, the determined Mach numbers can be validated using the radial momentum equation (Eq. 3).

The experimental set-up is described in section 2, the 1D fluid model in section 3 and the measurements in section 4. In section 5, the 1D fluid model is validated and the conclusions are drawn.

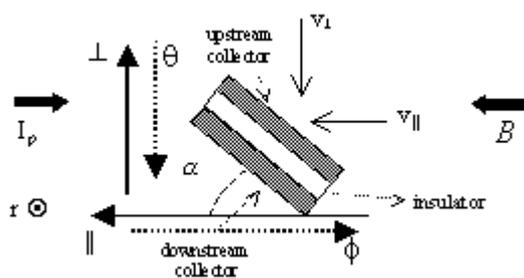


Fig.1: Mach probe geometry.

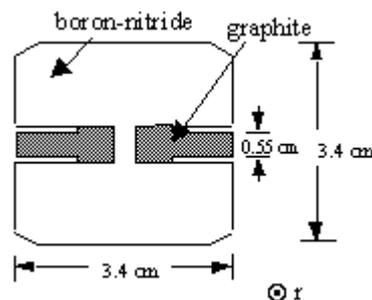


Fig.2: Mach probe: two graphite collectors are flush-mounted in an isolating boron-nitride body.

2. Experimental set-up.

The Mach probe geometry is shown in Figs. 1 and 2; the toroidal and poloidal directions are assumed to match the parallel and perpendicular direction, since the pitch of the magnetic field at the considered radii is very small.

The Mach probe is located in the equatorial outboard plane of TEXTOR-94. The probe can be moved radially between discharges. The rotation angle α , i.e. the angle of the probe

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surfaces with respect to the magnetic field, is changed on a shot-day basis. We measure successively radial profiles at fixed angles with respect to the magnetic field.

The probe consists of two graphite collectors separated by a boron-nitride insulator (Fig. 2). The Mach probe is used in a double probe configuration, the sweeping frequency of the potential applied between the two collectors is 200Hz.

The profile of the radial electric field is determined with the Mach probe by measuring the floating potential of both collectors.

The set-up of the edge polarisation experiment has been described previously [1]. A voltage is applied between the limiter ($r=46\text{cm}$) and an electrode located at 41cm . The bias voltage V_E in the experiments reported here is linearly ramped up from 0 to 700V between $t=1.0\text{s}$ and 1.3s , kept at a constant value for 2.6s and ramped down in 0.4s .

The plasma parameters are $B_T = 2.35\text{ T}$, $I_p = 210\text{ kA}$ and the pre-bias line-averaged electron density is $1.0 \times 10^{13}\text{ cm}^{-3}$.

3. Model

A 1D fluid model, described in [2], is used to derive the parallel and perpendicular Mach number from the experimental data obtained with the Mach probe. The model is an extension of the theory of Hutchinson [3,4] and describes the transport of parallel and perpendicular flow towards an inclined probe surface. The model is valid only for rotation angles that are not too small and gives an expression for the saturation current collected by the probe surface:

$$I_{sat} = n_{sh} c_s A \sin \alpha \approx n_{\infty} \exp\left(M_{\parallel\infty} - \frac{M_{\perp}}{\text{tg}\alpha} - 1\right) c_s A \sin \alpha. \quad (1)$$

A is the surface of the collecting area, n_{sh} the sheath edge density, $M_{\parallel\infty}$ the unperturbed parallel Mach number, M_{\perp} the Mach number of the perpendicular flow. The sound speed c_s is given by $c_s \equiv (k(T_e + T_i) / m_i)^{1/2}$.

For the experiment, the parameter of interest is the ratio of the upstream and downstream saturation currents which we compute from (Eq. 1) and where we introduced a fitting parameter $c(M_{\parallel\infty})$.

$$R = \frac{I_{sat,up}}{I_{sat,down}} = \exp\left(c(M_{\parallel\infty}) \left(M_{\parallel\infty} - \frac{M_{\perp}}{\text{tg}\alpha}\right)\right) \quad (2)$$

$c(M_{\parallel\infty})$ varies slowly with $M_{\parallel\infty}$ but is independent of M_{\perp} and α (see [2]). Its value lies between 2.3 and 2.5.

$\ln(R)$, measured with the probe surface oriented at $\alpha=90^\circ$, gives directly $M_{\parallel\infty}$. At least one further measurement with the probe surface oriented at a different angle is required to deduce M_{\perp} .

4. Measurements.

Fig. 3 shows measured radial profiles of $\ln(R)$ for various angles α . The shown profiles are taken at $t=2.1\text{s}$, i.e. in the bias plateau when E_r is constant. The markers indicate different shots.

Both the parallel and the perpendicular flow will affect $\ln(R)$. The shape of the profiles shows that at radial positions, where a large variation of $\ln(R)$ with α is measured, a substantial perpendicular flow must exist (Eq. 2). At radial positions, where no variation of R with α

is observed, R is only a function of the parallel flow. Figure 3 demonstrates that the inclined Mach probe is sensitive to both perpendicular and parallel flows.

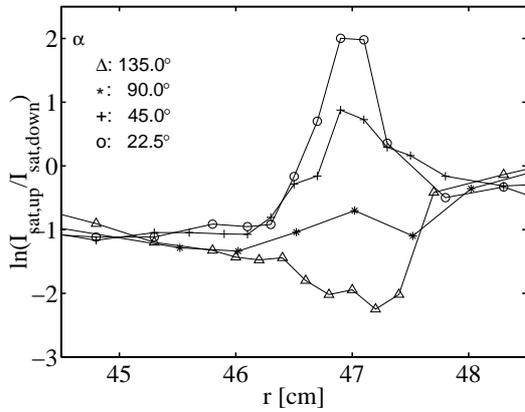


Fig. 3: Radial profiles of $\ln(I_{\text{sat,up}}/I_{\text{sat,down}})$ ($=\ln(R)$) at various angles α vs r ; $\Delta=135.0^\circ$, $*=90.0^\circ$, $+ =45.0^\circ$, $\circ=22.5^\circ$.

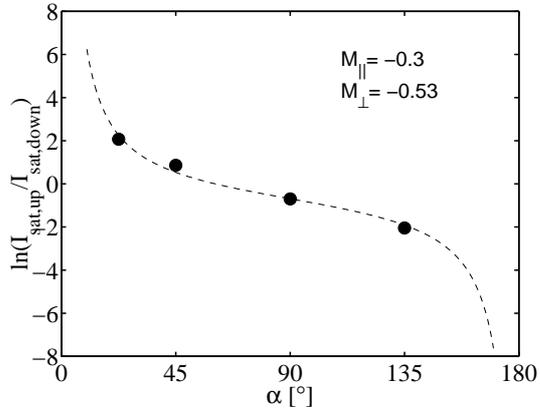


Fig. 4: $\ln(I_{\text{sat,up}}/I_{\text{sat,down}})$ vs α at $r=47.1\text{cm}$; The dashed line shows a fit of the experimental points (\bullet) according to Eq. 2.

The fluid model, Eq. 2, confirms the presumption that R depends on M_\perp , M_\parallel and α . It gives the additional features that a perpendicular flow does not influence R for $\alpha=90^\circ$ and that $\ln(R)$ shows a cotangens behaviour for $\alpha \neq 90^\circ$.

This behaviour is shown in Fig. 4 where $\ln(R)$ is plotted versus α at the radial position, where the variation of $\ln(R)$ with α is maximal in Fig.3, i.e. at $r=47\text{cm}$. Equation 2 is fitted to the data points with M_\parallel and M_\perp as free parameters. By performing this fit at other radial profiles we obtain the radial profile of M_\parallel and M_\perp that is shown in Fig. 5.

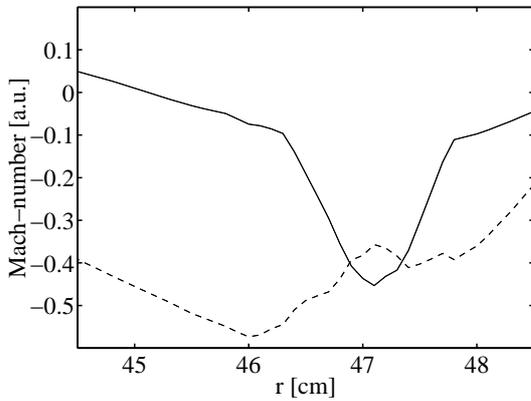


Fig.5: Perpendicular (solid line) and parallel (dashed line) Mach number vs radius.

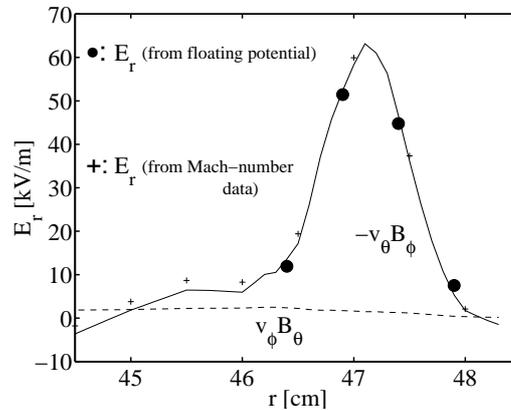


Fig. 6: E_r vs r : measured E_r (\bullet), calculated E_r ($+$), $-v_\theta B_\phi$ (plain curve), $v_\phi B_\theta$ (dashed curve)

5. Discussion

The measured radial electric field is compared with the one calculated from the radial momentum equation:

$$E_r = \frac{1}{en_i} \nabla_r p - v_\theta B_\phi + v_\phi B_\theta. \quad (3)$$

The velocities are calculated from the measured Mach number via $v = M \cdot c_s$. The diamagnetic contribution in Eq. 3 is very small and therefore neglected. In Fig. 6 a comparison of the measured E_r profile with the one calculated by Eq. 3 is shown. It is clear that mainly the poloidal velocity contributes to E_r since the toroidal velocity term is negligible. Profile and magnitude of the measured E_r agree with the calculated field.

6. Summary and conclusions

The experiments show that Mach probe data are affected by parallel and perpendicular flows. Together with the presented model the Mach probe offers a diagnostic which is able to measure Mach numbers with a high spatial resolution.

The 1D fluid model describes the transport of particles towards the probe surfaces. It provides an expression for the ion saturation currents collected by an inclined probe surface and allows to determine the parallel and perpendicular Mach number from the probe data.

According to the radial momentum equation, the measured E_r profile shows a fair agreement with the one deduced by the measured flow velocities. It can be concluded that the fluid model is viable and gives reliable Mach numbers.

Furthermore, we conclude from this comparison that high perpendicular flows are generated in polarisation discharges and that the measured poloidal Mach numbers show that E_r is clearly sustained by the perpendicular flow.

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