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Ion Flows Measurement using a Rotating Mach Probe on the CASTOR Tokamak

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Abstract

Poloidal flows are measured using a rotating Mach probe located in the edge plasma of the Castor tokamak ($R = 0.4\ m$, $a = 85\ mm$, $B_T = 1\ T$, $I_p \simeq 9\ kA$, $\bar{n} \simeq 1 \cdot 10^{19}\ m^{-3}$). The probe consists of two parallel planar Langmuir probes operating in the ion saturation current mode. One revolution of the probe is typically 3 – 6 ms.

A 1D fluid model has been developed to interpret the probe data. In particular, the ratio of the upstream and downstream signals is calculated for all the inclination angles. This theoretical ratio is compared with the experimental one and a remarkably good agreement is found if the parallel and perpendicular Mach numbers are properly chosen. Measurements carried out in polarized discharges show a substantial increase of the poloidal as well as toroidal flows in the proximity of the separatrix.

1. Rotating Mach probe

Direct measurements of flow velocities with a sufficient spatial resolution are highly desirable for a better understanding of the reduction of the turbulent transport and the consequent formation of transport barriers [1]. One of the most reliable diagnostics, particularly at the plasma edge, is a directional electrical probe, i.e. a planar probe inclined by some angle with respect to the magnetic field lines [2,3,4].

Here we report a novel design of so called rotating Mach probe and first results of its testing on the Castor tokamak. The construction of the probe head is apparent from a schematic picture shown in Fig. 1a. The probe consists of two rectangular plates, parallel each other, with nearly identical areas ($3\ mm \times 5\ mm$). The plates measure the ion saturation current, the signals are digitized at the sampling rate $1 MS/s$. The arrangement enables to rotate the probe with a speed up to $2 \cdot 10^4\ rpm$. Duration of one revolution is $T \geq 3\ ms$ that represents the best temporal resolution. The inclination of the plate is monitored by an auxiliary contact which marks a defined angular position ($\theta_0 \doteq 29^o$).

The probe is located at the top of the torus and radially fixed at $r_p = 72\ mm$. Since the plasma column is shifted downwards by $5 \div 10\ mm$, this radial position roughly corresponds to the position of the velocity shear layer ($E_r \approx 0$) during ohmic discharges (see Fig. 1b). In polarized discharges, however, the probe head appears in the region with a positive radial electric field E_r because the biasing electrode is located deeper in the confinement region, typically at

$r_b = 50 \div 60\ mm$ and biased up to $\sim +300\ V$.

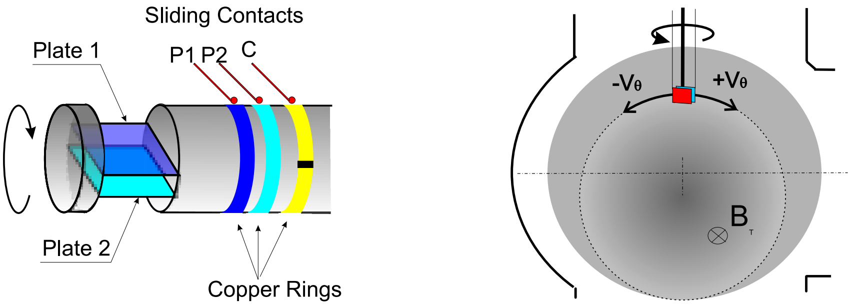

Fig. 1: a) Probe construction. b) Position of the Mach probe (poloidal cross-section)

The angular variation of the ion saturation current can be recovered from its temporal evolution during a single revolution of the probe. A typical modulation of the probe signal is apparent from Fig. 2a.

2. Determination of Mach numbers

The normalized value of the ion saturation current flowing to an inclined plate is according our model [5]:

$$I_s/(Aen_\infty c_s) = n_B(\theta) M_B \quad , \tag{1}$$

where A is the probe area, c_s – the ion sound velocity. The density at the probe sheath $n_B(\theta)$, normalized to the unperturbed density n_∞ far away from the probe, can be calculated as:

$$n = 1 + \int_{M_\infty}^{M_B} \frac{dn}{dM} dM \qquad \text{where} \quad \frac{dn}{dM} = n \frac{(1-n)M - (M_\infty - M)}{(M_\infty - M)M - (1-n)} \quad , \tag{2}$$

n, M are the the density and the Mach number in the flux tube in front of the probe. $M_\infty = M_{||} \sin\theta + M_\perp \cos\theta$ is the normalized velocity in the untouched plasma, $M_{||}$ and $M_\perp$ are the parallel and perpendicular Mach numbers.

Solution (2) is obtained assuming that the velocity field has a potential form and that it can be represented in the vicinity of the probe as a gradient of functions ϕ_∞ and ϕ:

$$\mathbf{v} = \nabla(\phi_\infty + \phi) \tag{3}$$

where ϕ_∞ and ϕ are potentials that determine the flows in the unperturbed plasma far away from the probe and in the vicinity of the magnetic pre-sheath entrance, respectively.

To solve equation (2) we have to fix the boundary condition. It can be chosen as in [4,6]:

$$M_B = |sin\theta| \tag{4}$$

However, this form is in a strong contradiction with the experimentally observed angular dependencies of the ion saturation current. Comparison with experimental data has shown that

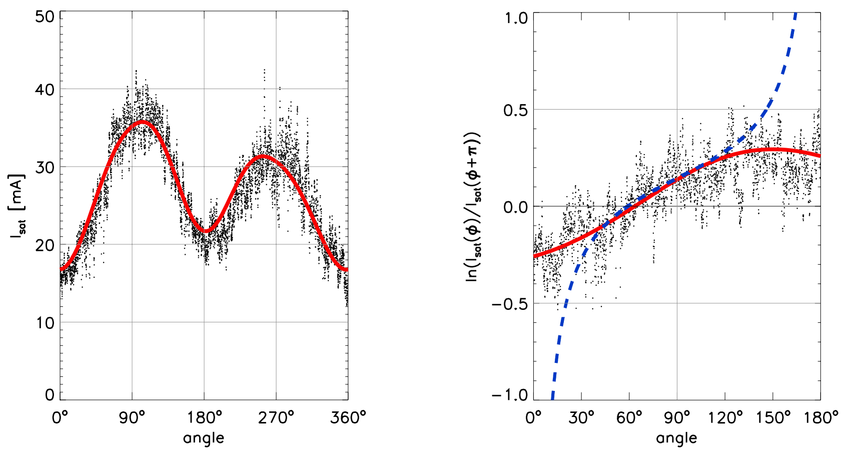

Fig. 2: a) Angular dependence of the ion saturation current to an inclined plate. Maxima at $\theta \doteq 90^o$ and $\theta \doteq 270^o$ correspond to the upstream and downstream orientations of the plate. Minima are observed when the probe is parallel to the magnetic filed lines. Different amplitudes of the maxima imply an existence of the parallel flow while a difference between the minimum values is an indication of the poloidal flows. Positions of maxima differ from 90^o and 270^o if the poloidal rotation is present. The red full line shows a result of our theoretical modeling — eq. (1);
b) Angular dependence of ratio R: experimental points are over-plotted by a full red line – the result of our modeling [5] ($M_{||} = 0.06$, $M_{\perp} = -0.12$) and by a dashed green line – approximation by eq. (4) ($M_{||} = 0.06$, $M_{\perp} = -0.1$).

rather good agreement with the experiment can be obtained when a phenomenological boundary conditions is used:

$$M_B = 1 - \gamma |\cos\theta| \tag{5}$$

where $\gamma = 0.73 \div 0.77$ is a parameter independent on $M_{||}$, $M_{\perp}$ which is valid for the broad range of experimental data. The calculated angular variation of the ion saturation current is compared with the experimental data in Fig. 2a.

Ratio $R = I_{sat}(\theta)/I_{sat}(\theta+\pi)$ can be easy calculated from the model and compared with the experimental data. Fig. 2b shows an example of such comparison (solid line) for all inclination angles. It is evident that the theoretical prediction follows the experimental data even at the grazing incidence. The analytical estimate of the ratio R:

$$R = \exp(c(M_{||} - M_{\perp}/\mathrm{tg}\theta)) \qquad \text{with a parameter} \quad c = 2.3 \div 2.5 \tag{6}$$

derived by an alternative model of Van Goubergen [4] is plotted by dashed lines in the same figure. It is evident that this prediction follows the experiment only in a limited range of incident angles ($\sim 30^o \div 150^o$).

We have to emphasize that the ratio R is practically independent on the boundary condition M_B whether chosen according to eq. (4) or eq. (6) [4,6]. The proper choice of the boundary conditions is important only for the description of the ion saturation current angular dependence.

The systematic measurements with the Mach probe are performed at polarized discharges [7]. The resulting parallel and perpendicular Mach numbers are plotted as a function of the radial electric field in Fig. 3. We can see that the imposed radial electric field forces plasma rotation simultaneously in the perpendicular as well as in parallel directions.

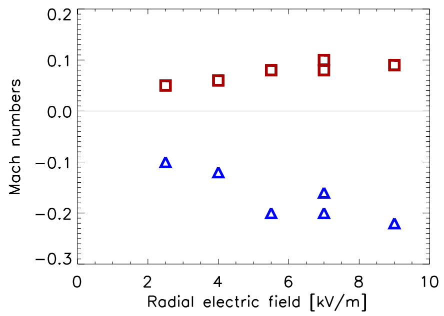

Fig. 3: Dependencies of the $M_{||}$ (red squares) and $M_{\perp}$ (blue triangles) versus the radial electric field.

3. Summary

The rotating Mach probe has been designed and tested on the Castor tokamak. A one-dimensional MHD model for interpretation of the probe data has been developed. The probe data are compared with this model that allows to determine the Mach numbers. It is demonstrated that this model follows well the experiment at least for the flow Mach numbers $|M_{||,\perp}| \leq 0.3$. Our approximation leads to a solution for the density near the probe that has exactly the same form as the Hutchinson's one [8] but it allows to deduce not only the parallel but also the perpendicular Mach numbers.

The biasing scheme of plasma polarization was applied to control the radial electric field at the plasma edge. Measurements of the parallel and perpendicular Mach numbers have shown that the imposed radial electric field increases simultaneously both the perpendicular as well as the parallel flows.

Acknowledgments

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