32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-1.005 (2005)

Ion temperature measurements by means of a combined force - Mach - Langmuir probe

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Introduction

With respect to plasma-wall interactions, particle and energy fluxes are commonly of particular interest. Although typical pressures in plasma experiments are four (edge layer of fusion devices) to six (cold discharges) orders of magnitude smaller than atmospheric pressure, a force sensor such as that developed by Chavers [1] shown in Fig.1, immersed in a streaming plasma is sensitive enough to measure momentum fluxes on its target surface. In the edge layer of fusion plasmas, the measurement of ion temperature constitutes a particular problem. Although ion sensitive electrical probes, developed by Katsumata [2] and Ratynskaia et al.[3] and tested by Ezumi [4] offer advantages like a high spatial and temporal resolution, considerable theoretical efforts [5] have to be made to interpret the measured data correctly. These probes basing on the difference in Lamor radii, are sensitive to strength and orientation of the magnetic field. Charge exchange measurements, on the other hand, become inappropriate for ion temperatures lower than $\sim$100 eV and are thus unsuitable for the edge layer. As electron temperature and density can be determined by Langmuir probes, the missing parameter can also be obtained from the force sensor, which is sensitive to the total pressure $p = n(T_i + T_e)$. Although this type of diagnostic will have a limited time resolution due to mechanical inertia as compared to electrical probes, the interpretation of data will be less questionable. Furthermore the sensor will also be applicable to fully ionized

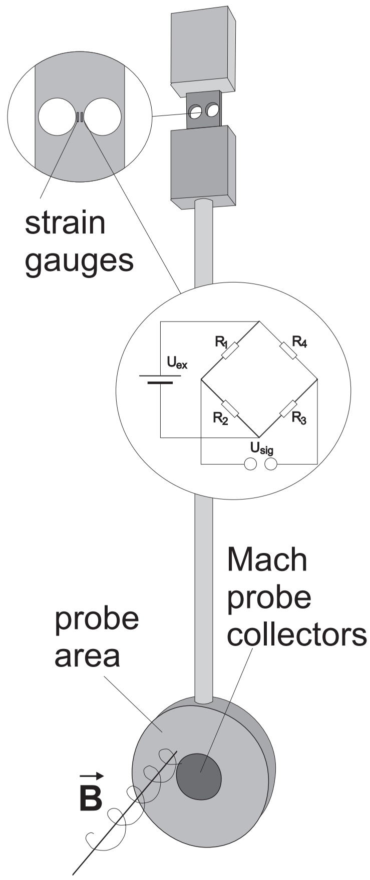


Figure 1: Combined force-Mach-Langmuir probe in a magnetic field

plasmas, where optical methods fail.

Combined force-Mach-Langmuir probe

The arrangement of the probe is shown in Fig. 1. The force is measured by means of strain gauges wired as a Wheatstone bridge which determines the strain in the rod onto which the probe head is mounted. The two conducting collectors on each side measure the ion saturation currents just as a common Mach probe. The difference here is that voltage ramps are driven on the collectors in order to measure the electron temperatures. A_p denotes the probe surface areas. If A_c is the collector area the ion saturation current is

$$I = A_c \cdot n_{se} \cdot e \cdot c_s, \tag{1}$$

where $c_s = \sqrt{(T_e + \gamma_i T_i)/m_i}$ is the ion sound speed and $n_{se} \approx n/2$ the density at edge of the electrostatic sheath (see below). Here $A_c = \pi(4\text{ mm})^2$ and $A_p = \pi(15\text{ mm})^2$.

Momentum deposition on the force sensor

The force density $\vec{\mathscr{F}} = d\vec{F}/dV$ is defined by the divergence of the momentum flux tensor $\overleftrightarrow{P}$

$$\vec{\mathscr{F}} = -\nabla \cdot \overleftrightarrow{P}, \qquad \text{defined by} \qquad P_{ij} = \sum_\alpha P_{ij}^\alpha = \sum_\alpha \int m_\alpha v_i v_j f_\alpha d^3v, \tag{2}$$

where the sum is taken over all particle species α and the integral extends over all velocity space.

Since the distribution functions f_α change significantly over the last few Debye lengths to the surface due to the electrostatic sheath it is very difficult to determine this tensor in the immediate vicinity of the probe surface. At the sheath edge (se), however, the situation is supposed to be well known since the Bohm condition can be assumed. The force can then be determined by integrating $\vec{\mathscr{F}}$ over a cylindrical volume with one surface s_1 coinciding with the sheath edge and the other lying inside the probe head. The Gaussian divergence theorem can then be applied:

$$\vec{F} = -\int \nabla \cdot \overleftrightarrow{P} d^3x = -\oint \overleftrightarrow{P} \cdot d\vec{f} = A_p P_{zz}(z_{se})\vec{e}_z \tag{3}$$

such that only s_1 contributes to the integral. The distributions in Eq.3 were assumed to be homogeneous in x and y and symmetric in v_x and v_y directions ($P_{xz} = P_{yz} = 0$).

With the common definitions of density n_α, streaming velocity u_α, pressure p_α, temperature T_α and the random velocity, introduced as $\vec{w} = \vec{v} - \vec{u}^\alpha$, the z-component of the force can be written as

$$F = A_p \sum_\alpha \int m_\alpha (u_\alpha + w_z)^2 f_\alpha(z_{se}, v_z) d^3v = A_p \sum_\alpha \left(m_\alpha n_\alpha u_\alpha^2 + p_\alpha\right)_{se}. \tag{4}$$

In the last step isotropic distributions $f^{\alpha}(\vec{v}-\vec{u}_{\alpha}) = f^{\alpha}(|\vec{v}-\vec{u}_{\alpha}|)$ were assumed. Due to ambipolarity $\Gamma_i = \Gamma_e$ and quasineutrality $n_i = n_e = n$, the streaming velocities of electrons and ions are the same, so that the electron streaming term in Eq. 4 can be neglected. Neutral particles are also neglected completely due to their small velocity with respect to the speed of sound ($n_n \cdot u_n^2 = n \cdot c_s \cdot u_n << n \cdot c_s^2$). Applying the Bohm condition, $u_i = c_s$, for one ion species with $Z = 1$ the force on the plate becomes

$$F = A_p n \left(m_i c_s^2 + T_e + T_i \right)\Big|_{se} \tag{5}$$

For the case of $\gamma_i = 1$ this simplyfies to $F = 2A_p n_{se} m_i c_s^2$. Taking into account $n_{se} = n/2$ this agrees with the intuitively expected result $F = A_p \left(p_i + p_e\right)$, where this time the pressure refers to the unperturbed plasma far away form the probe.

Evaluation of probe data

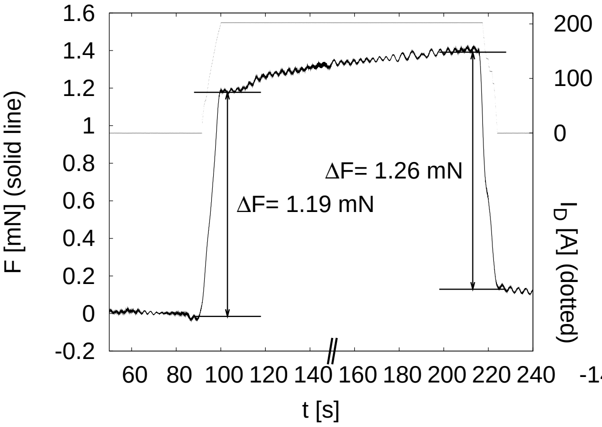
If in addition to the saturation currents and the electron temperatures the forces on each surface could be measured, it would be possible to determine also the ion temperatures from the ratios $\left(F_j/I_j\right) = 2C\sqrt{T_{e,j} + T_{i,j}}$, where the the label $j = 1,2$ is used to distinguish the two sides of the probe and $C = \frac{A_p\sqrt{m_i}}{A_c e}$. However, because only $\Delta F = F_1 - F_2$ is measured by the probe, an additional assumption is required. Here, like elsewhere, we assume $T_{i1} = T_{i2} = T_i$. Most simple relations are then obtained for $T_{e1} = T_{e2} = T_e$ and $\gamma_i = 1$ leading to $T_i = (2C)^{-2}\left(\Delta F/\Delta I\right)^2 - T_e$, with $\Delta I = I_{s1} - I_{s2}$. But also in the more general case, $\gamma_i > 1$, and $T_{e1} \neq T_{e2}$, the ion temperature can be evaluated by solving numerically the equation

$$\Delta F = C\left[I_{s1}\frac{2T_{e1} + (\gamma_i + 1)\,T_i}{\sqrt{T_{e1} + \gamma_i T_i}} - I_{s2}\frac{2T_{e2} + (\gamma_i + 1)\,T_i}{\sqrt{T_{e2} + \gamma_i T_i}} \right]. \tag{6}$$

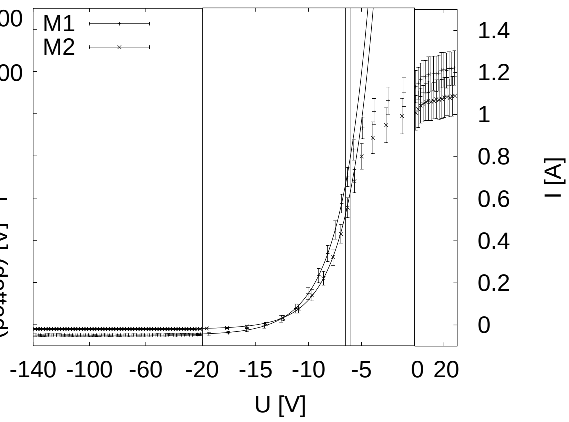
First experimental tests

A first test of the probe was performed at the linear plasma generator PSI-2 in Berlin. Although regular discharges at PSI-2 are steady state here the plasma was turned on and off with periods of several minutes (see Fig. 2.a). This was in particular necessary because of zero point drifts of the strain gauges. The solid line curve shows the smoothed recorded signal while the dotted one represents the discharge current. After 150 s the force measurement was interrupted in order to perform the electrical measurements shown in Fig. 2.b.

The results are presented in Tab.1. A value of $T_i = 2.2 \pm 0.5$ eV results from an evaluation with $\gamma_i = 3$.



2.a: Force measurement during a plasma discharge



2.b: Current-voltage characteristics on the two Mach probe collectors. Notice the stretched scale in the range $-20 < U < 0$.

$I_{sat1} =$	-48.52 ± 0.09 mA		$I_{sat2} =$	-19.98 ± 0.08 mA
$T_{e1} =$	2.7 ± 0.2 eV		$T_{e2} =$	2.5 ± 0.2 eV
$n_1 =$	$1.75 \pm 0.09\ 10^{18}\mathrm{m}^{-3}$		$n_2 =$	$7.3 \pm 0.4\ 10^{17}\mathrm{m}^{-3}$
$c_s =$	4900 ± 300 m s^{-1}		$u =$	1700 ± 100 m s^{-1}
$\Delta F =$	1.23 ± 0.08 mN		$T_i\|_{\gamma_i=3} =$	2.2 ± 0.5 eV

Table 1: Quantities measured by the combined force Mach Langmuir probe

Summary

For the first time momentum flux, ion saturation currents and electron temperature were determined simultaneously by means of a combined force-Mach-Langmuir probe. The T_i value obtained (2.2 ± 0.5 eV) for $\gamma_i = 3$ is in reasonable agreement with the empirical rule $T_i \approx 2/3T_e$ found in PSI-2. If isothermal ions would be assumed ($\gamma_i = 1$) the ion temperature would be almost equal to T_e. Further investigations will be needed to test the method over a broader range of parameters.

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