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Experimental Investigations on the Plasma-Wall Transition

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Introduction

Laser induced fluorescence is a very powerful tool for the investigation of plasma kinetics. It provides the possibility to determine the ion velocity distribution (ivdf) projected along the laser line. Here it is applied to an argon plasma streaming onto an absorbing target plate. In particular measurements in the immediate vicinity ($-z \approx 5$ cm, i.e. about 1/4 of the mean free path of ion-ion-collisions) were performed. While in a previous paper we reported on the particular situation imposed by the magnetic field [1], here we concentrate on the shape of the distribution functions which become nearly half-sided Maxwellians.

Experimental arrangement

The experiments described in what follows were performed in the linear plasma generator PSI-2 operated in Berlin. Details of the device and the experiments to be discussed are given in [1]. Here it may suffice to say that the magnetized (argon) plasma column extends over a length of about 2.5 m with the diameter varying between 6-8 cm. The laser induced fluorescence (LIF) is carried out by launching a tunable laser beam ($\lambda = 611.5$ nm) from one or the other end of the plasma column exciting the Ar^+ ions. The fluorescence light ($\lambda_f = 461$ nm) is recorded during a wavelength scan perpendicular to the beam at two positions 1) in the bulk plasma about 1 m away from the absorbing target plate and 2) close to this target in a distance of only 5 cm. The wavelength is converted into velocities via Doppler's formula $\lambda' = \lambda \cdot (1 + v/c)$.

Kinetic model of the plasma-wall-transition

Here a simple kinetic model for the plasma wall transition is proposed that only assumes the loss of particles at the wall ignoring any electric field effects.

Particles in this model are assumed to cover a distance without collision with the probability (per unit length)

$$p(z, z_0, v)dz = \exp\left(-\frac{|z - z_0|}{\lambda(v)}\right) dz/\lambda(v), \tag{1}$$

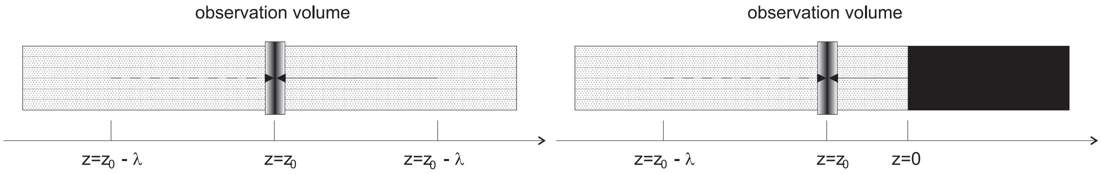

Figure 1: Particles starting within a distance of the mean-free-path length enter the observation volume, establishing there a Maxwellian velocity distribution in case of an unlimited plasma (left). If an absorbing target is introduced at position $z = 0$ (right) an asymmetric distribution will be observed at $z = z_0$.

where the mean free path is a function of the speed v of the particle (see [3] for details).

$$\lambda(v) = \lambda_{th} \frac{|w|\left(1+w^2\right)^{3/2}}{\phi_1\left(\sqrt{1+w^2}\right)} \text{ , with } w = v/v_{th} \text{ and} \quad (2)$$

$$\phi_1(x) = \mathrm{erf}(x) - x \cdot \frac{d}{dx}\mathrm{erf}(x) \text{ , and } \lambda_{i,th} = \frac{8\pi\varepsilon_0^2}{Z^4 e^4 \ln\Lambda} \frac{T_i^2}{n_i} \approx (15 \pm 10) \text{ cm .} \quad (3)$$

Under homogeneous conditions (see Fig.1, left) a certain observed volume is penetrated from the left by particles with positive velocities ($\Theta(v) = 1$ if $v > 0$ and $= 0$ otherwise) and from the right by particles with negative velocities so that the distribution at $z = z_0$ can be written as

$$f_1(v,z_0) = \Theta(v)\int_{-\infty}^{z_0} f_0(v,z)p(z,z_0)dz + \Theta(-v)\int_{z_0}^{\infty} f_0(v,z)p(z,z_0)dz. \quad (4)$$

This integral equation is solved by the Maxwellian velocity distribution $f_1 = f_0$.

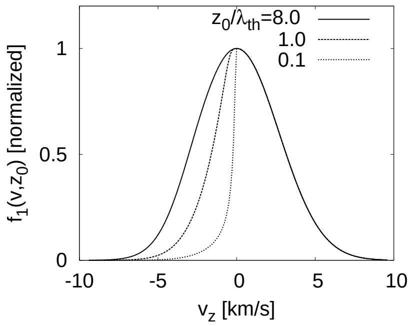

Figure 2: Truncation of the distribution function near an absorbing wall according to Eq.6

If an absorbing target is introduced in the plasma at the position $z = 0$ the upper boundary of the second integral has to be cut at that position and in first order approximation we get:

$$f_1(v,z_0) = \Theta(v)\int_{-\infty}^{z_0} f_0(v,z)p(z,z_0)dz + \Theta(-v)\int_{z_0}^{0} f_0(v,z)p(z,z_0)dz. \quad (5)$$

This equation can be solved analytically yielding

$$\boxed{f_1(v,z_0) = \Theta(v) f_0(v) + \Theta(-v)\left(1 - \exp\left(-|z_0|/\lambda\right)\right) f_0(v)} . \quad (6)$$

Plots for the cases $|z_o|/\lambda_{i,th}$ = 0.1, 1 and 8 are shown in Fig.2

Measured ion velocity distributions

LIF profiles carried out at the two positions are presented in Fig.3. The solid and dotted line curves distinguish between co-and counter-axial directions of the laser. Due to the different beam diameters of the laser near the target plate the signal-to-noise ratio is much worse for the counter axial beam. On the other hand the spatial resolution is much better in this case (only near axial region). Whereas the fluorescence profiles in the case of the bulk plasma are almost ideal Maxwellians (shifted slightly because of the slowly streaming plasma) the profiles change drastically at the 'near target plate' position where roughly half sided Maxwellians are measured.

In Fig.4 a more detailed comparison between the ivdfs found at the two positions is shown. We notice that apart from the suppression in the negative velocity range an enhancement of the positive range is found, possibly indicating an acceleration of the ions toward the target (or an increase T_i).

Some characteristic data are collated in Tab.1. Care is needed with respect to the evaluation of the ion temperatures. Values obtained by fitting either Maxwellians (bulk plasma) or truncated Maxwellians (according to Eq.6, near target) are indicated as $T_{i,fit}$. Conversely, those without index are obtained by evaluating second order momenta $T_i = \left\langle m_i (v - \langle v \rangle)^2 \right\rangle / n_i$. The thermal ion velocity then is then defined by $v_{i,th} = \sqrt{2T_i/m_i}$.

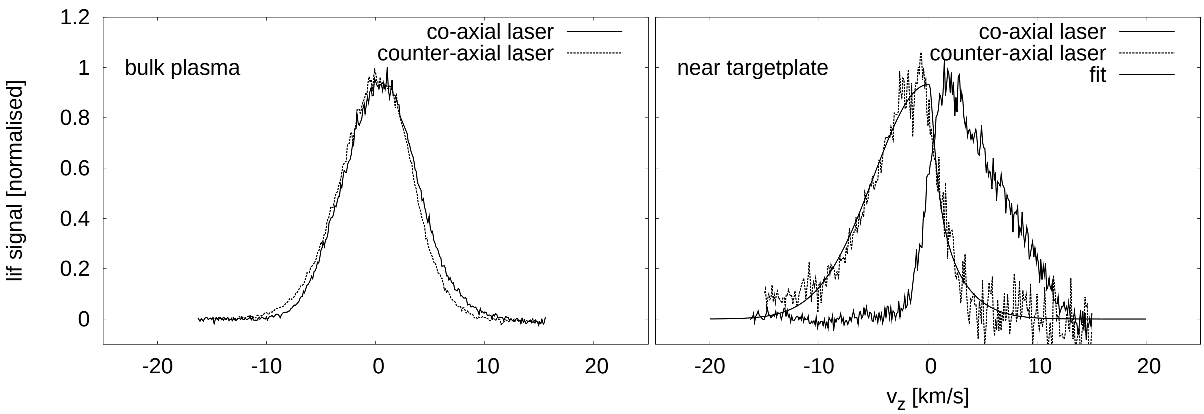

Figure 3: LIF measurements far (∼1 m, left) and close (∼5 cm, right) to the target plate. The measured wavelength shifts were converted into velocities. In the right figure the dashed line curve is approximated with a fit (solid line) basing on Eq.6 with $|z_0|/\lambda = 0.27$, i.e. $\lambda = 20$ cm.

bulk plasma			
$T_{i,fit} = 4.7$ eV	$T_i = 4.5$ eV	$<v>= 330$ m/s	$<v>/v_{i,th} = 0.07$
near target plate			
$T_{i,fit} = 10.4$ eV $z = -5$ cm	$T_i = 4.7$ eV $\lvert z\rvert/\lambda_{th} = 0.27$	$<v>= 2200$ m/s	$<v>/v_{i,th} = 0.47$

Table 1: Evaluation of the measurements.

While the fit temperature shows a rather unreasonable rise from $T_{i,fit} = 4.7$ eV to 10.4 eV the values obtained from second order momenta are about the same.

Summary

Ion distribution functions have been measured at two positions: in the plasma bulk and in front of a target. Within this region the plasma streaming velocity is subthermal. Maxwellians with small shifts (Mach number ~ 0.1) are found in the bulk plasma. In contrast, approximately half-sided Maxwellians are observed close to the target ($z/\lambda_i \sim 1/4$). They can be explained by the lack of ions moving in the counter direction due to the (non-reflecting) target. The measured half-sided ion distribution can be fairly described by a first order approximation basing on Eq.6 ignoring any electric fields in the pre-sheath.

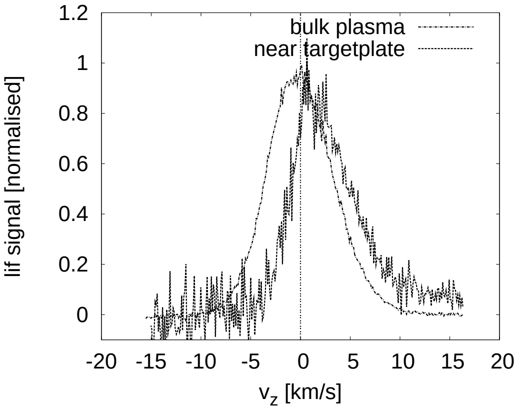

Figure 4: Comparison of the ion-velocity-distributions in the bulk plasma and near the target plate measured by the counter-axial laser.

References

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