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Laser induced fluorescence measurements in an argon plasma in front of a tungsten target under oblique incidence

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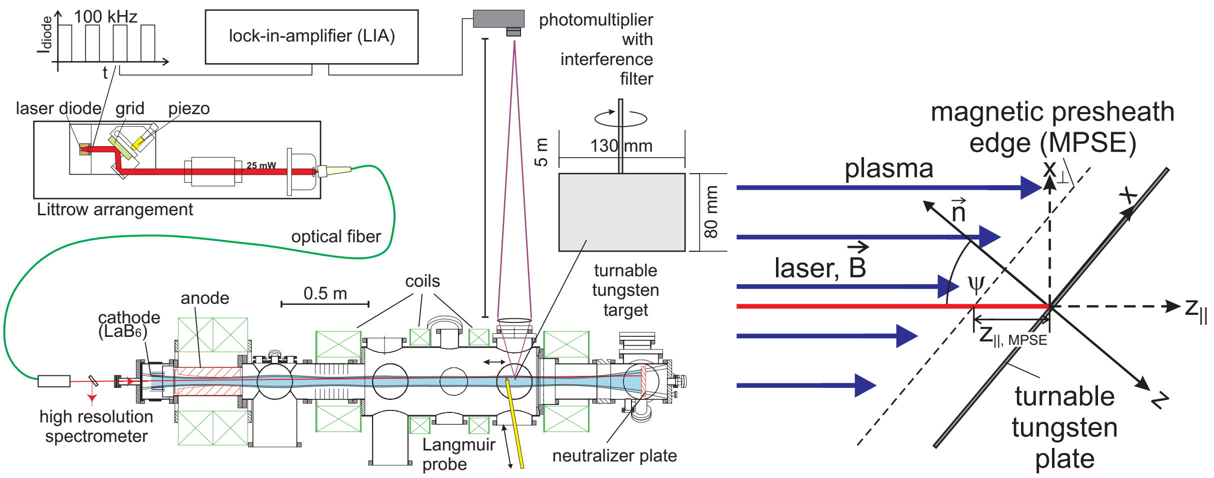
Motivation

In order to spread the power flux onto the target plates in a divertor over a large area, the incidence angle of the field lines is chosen as large as possible. This situation, which is significantly different to the plasma-wall transition under normal incidence, was first addressed by Chodura [1]. Although this problem is well investigated from the theoretical point of view [1, 2, 3, 4], experimental data is far more rare. With this article, we want to fill this gap by reporting on measurements by means of laser induced fluorescence (LIF) in front of a tungsten target exposed to an argon plasma under oblique incidence.

Experiment

Fig. 1(a) shows the linear plasma generator PSI-2. Between the heated cylindrical cathode and the anode a stationary high current ($I_D \approx 200$ A) arc discharge is sustained. Here the primary plasma (argon) is produced and heated. Confined by an axial magnetic field ($|\vec{B}| \approx 0.1$ T) and driven by the pressure gradient it streams towards the neutralizer plate at the end of the device. During the experiments we report on below, however, practically the whole plasma streams onto an electrically floating rectangular tungsten plate (size $130 \times 80\,\mathrm{mm}^2$) which is introduced into the target chamber. The angle Ψ of the surface with respect to the field lines (cf. 1(b)) can be adjusted from outside the vessel. Along the field lines a laser beam, generated by a narrow band-width tunable diode laser, is launched into the plasma, where it excites the argon ions in front of the target plate. The fluorescence originating from these ions is collected by an optical system and detected by a photomultiplier far away from the discharge (cf. 1(a)). By scanning the laser wavelength and simultaneously detecting the fluorescence we are able to measure the ion velocity distribution at different axial positions along the laser beam. More about this technique and a simple model of the PSI-2 discharge can be found in [5] or in our last year's EPS contribution [6].

In addition to the LIF experiments measurements with a Langmuir probe were performed, which was axially movable in front of the target (Fig. 1(a)). While we use the T_e values here, the n_e profiles which were also measured in H_2 and D_2 will be discussed in a future publication.



(a) LIF diagnostics installed in the plasma generator PSI-2.

(b) Plasma streaming onto the target under oblique incidence.

Figure 1: Experimental arrangement

Modeling

According to Chodura [1] in the case of non-normal incidence we have to distinguish not only the usual (Debye) sheath and pre-sheath, but also a third region in between the two, the so called magnetic pre-sheath (MPS). In the pre-sheath the plasma streams parallel to the $\vec{B}$-field and quasi-neutrality ($n_e = n_i$) is fulfilled. While the latter is still given in the MPS, $\vec{E}$ and $\vec{B}$ are not parallel anymore and the $\vec{E}\times\vec{B}$ drift plays an important role. Finally, the $\vec{E}$ field in the sheath becomes so strong that $n_i = n_e$ is violated and that it dominates the motion of the particles completely. As the magnetic field does not play any role in the sheath we can assume the Bohm criterion at its edge for the velocity component pointing towards the surface as commonly done. In order to describe the physics in the MPS we start from the usual continuity and momentum equations, in contrast to Chodura, however, we take into account sources and collisions. If the size of the MPS is much smaller than the extension of the target (and the plasma) we can make use of the symmetry and assume that all plasma parameters are constant on planes parallel to the surface. Rotating the coordinate axes $x_\perp$, $y_\perp$, $z_{||}$ by the angle Ψ, i.e.

$$x = x_\perp \cos\Psi + z_{||}\sin\Psi \qquad y = y_\perp \qquad z = -x_\perp \sin\Psi + z_{||}\cos\Psi \tag{1}$$

as indicated in Fig. 1(b) all derivatives $\partial/\partial x = \partial/\partial y = 0$ vanish. Assuming isothermal electrons and ions and that the $\vec{E}$-field is given by $\vec{E} = -(T_e/e)\vec{e}_z n'/n$, where $' = \partial/\partial z$, continuity and momentum equations take the form

$$(n\vec{u}_i)' = \vec{e}_z n \nu_i \text{ , and} \tag{2}$$

$$u_{iz}\vec{u}_i{}' = \frac{e}{m_i}\vec{u}_i \times \vec{B} + \frac{c_s^2}{u_{iz}}\left(u_{iz}' - \nu_i\right)\vec{e}_z - \nu_t \vec{u}_i \text{ ,} \tag{3}$$

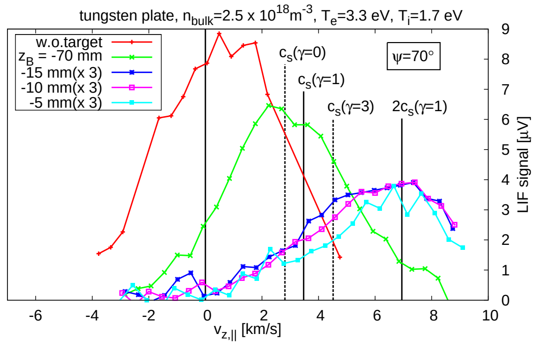
where n is the density, $\vec{u}_i$ the streaming velocity of the ions and $\nu_t = \nu_i + \nu_{cx} + \nu_{el}$ total collision frequency composed of ionization (ν_i), charge exchange (ν_{cx}) and elastic collsions (ν_{el}). $c_s = [(T_e + \gamma_i T_i)/m_i]^{1/2}$ is the speed of sound (here we assume $\gamma_e = \gamma_i = 1$). Although $\vec{u}_i$ is not parallel to $\vec{B}$ inside the magnetic pre-sheath and we have to solve the equation for all the three components of the vector, it is important to note that the problem is only one dimensional. Resolving this equation component-wise with respect to $\vec{u}_i'$ we can determine the $\vec{u}_i(z)$ profile iteratively $\vec{u}_i(z+\Delta z) = \vec{u}_i(z) + \vec{u}_i'(z)\Delta z$, where Δz is a small but finite distance. In the particular case $\nu_i = \nu_t = 0$ Chodura found that a stable (i.e. non-oscillating) MPS is only possible if $u_{iz} \geq c_s \cos\Psi$ at the edge of this region (magnetic pre-sheath edge, MPSE). With the transformation 1 we introduce the Mach number parallel to $\vec{B}$

$$M_{||} = \frac{u_{ix}\sin\psi + u_{iz}\cos\psi}{c_s} \qquad (4)$$

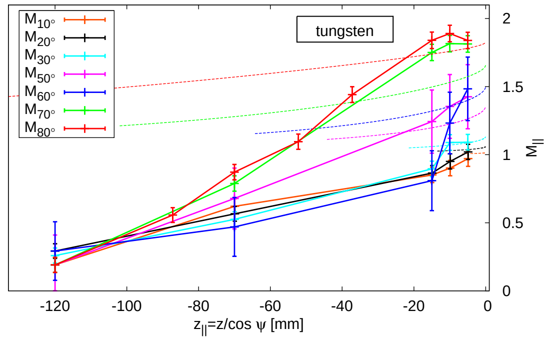
this also reads $M_{||}|_{MPSE} \geq 1$ since $\vec{u}_i$ is still parallel to $\vec{B}$ there. It can be shown that this condition can significantly differ if sources and collisions are taken into account.

Results

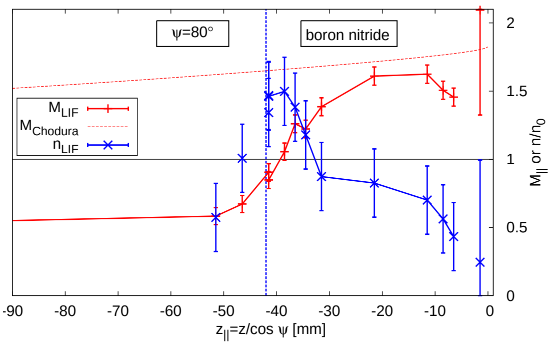
Fig. 2(a) shows typical measurements of the ion velocity distribution function (ivdf) at different positions $z_{||} = z/\cos\Psi$ in front of the target plate. As a first qualitative result we observe that the streaming velocity close to the surface is clearly higher than c_s as predicted by Chodura. Fitting Maxwellian distributions to the measured ivdfs we can determine the streaming velocity and the Mach number as shown in Fig. 2(b). Although the values of $M_{||}$ immediately in front of the surface are predicted fairly well by Chodura, neither the $M_{||}(z_{||})$ profiles, nor the size of the



(a) Measured ivdfs at different positions $z_{||}$ in front of a tungsten target.



(b) Mach number parallel to the field lines measured by LIF in front of a tungsten target. The dotted lines indicate the predictions of the Chodura model. Their lengths indicate the size of the MPS, respectively.



(c) The same as (b) but for a boron nitride target at $\Psi = 80°$.

Figure 2: LIF measurements

MPS are consistent with the model. This discrepancy can probably be attributed to the finite ionization and collision frequencies which affect Eqs. (2) and (3) sensitively. Up to now, however, it has not been possible to find a (global) value for the neutral gas density such that all profiles fit the experimental data simultaneously. Furthermore, for $\nu_i = 3.3\,\mathrm{kHz}$ and $\nu_t = 27\,\mathrm{kHz}$ non-oscillating $M_{||}(z_{||})$ profiles are only possible for Mach numbers around 3.5. In [5] we showed that the radial plasma profile plays an important role in PSI-2 and so it is not surprising that a 1D approach explains the measurements rather poorly.
Finally, we can make the statement that the $M_{||}(z_{||})$ profile does not depend very much on the target material. Fig. 2(c) shows the $M_{||}(z_{||})$ (and the $n(z_{||})$) profile measured in front of a boron nitride target. The size of the MPS and the final value $M_{||}(z_{||})$ are quite similar to that measured for tungsten.

Summary

The Mach number $M_{||}$ parallel to the field lines was measured non-invasively at different positions $z_{||}$ in front of a tungsten target under different incident angles by means of LIF. The supersonic fluxes found in the immediate vicinity of the surface are described fairly well by the one dimensional model developed by Chodura [1], which neglects sources and collisions. By contrast, the size of this region is much smaller than predicted by this model and the Mach number decreases to values smaller than one on a much shorter scale. This effect might be explained by the finite ionization and collision frequencies, which play an important role in argon discharges in PSI-2. However, values as large as $M_{||} \approx 3.5$ as predicted for the estimated frequencies were not observed in the experiment. Presumably a 3D model is required to explain this discrepancy. The results were furthermore compared to the measurements in front of a boron nitride target, were a similar $M_{||}(z_{||})$ profile was found.

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