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# Laser-induced fluorescence measurements in the electrostatic sheath of a high density argon plasma

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## Introduction

Apart from quite exotic exceptions (electron-positron, quark-gluon or negative ion plasmas), plasmas are composed of light electrons and much heavier ions. If the temperature $T_i$ of the ions is of the same order as that of the electrons $T_e$ or even lower their thermal velocities $v_{th} = \sqrt{T/m}$ differ by more than a factor $\sqrt{m_i/m_e} = 43$. When a plasma is in contact with a neutralizing solid object an electrostatic field is established in front of the surface which slows down the electrons and accelerates the ions such that ambipolar flux $n_e u_e = n_i u_i$ is achieved. As early as 1949 D. Bohm [1] showed that this electrostatic sheath can only be stable if the ions reach the edge of this region (the so called sheath edge) at least at the speed of sound $c_s = \sqrt{(T_e + T_i)/m_i}$. This 'Bohm criterion' constitutes an important boundary condition and is applied in many situations in fusion research and technological plasma physics. In the past, several authors (e.g. [2]) found the Bohm criterion satisfied in low density plasmas ($n_e \sim 10^{15}\,\mathrm{m}^{-3}$), while at higher densities streaming velocities of only about $0.5c_s$ were found (e.g. [3]). By improving the spatial resolution of our diagnostics to $\Delta z = 0.5$ mm, we were recently able to show that the final acceleration to $u_i = c_s$ takes place on the last few mm thereby presenting the experimental proof of the Bohm criterion [4] at fusion relevant densities.

In this article we will focus on measurements at even higher spatial resolution ($\Delta z \approx 50\,\mu$m) approaching to resolve the electrostatic sheath region, which, under floating conditions, extends over a distance of several Debye lengths, i.e. about 100 $\mu$m.

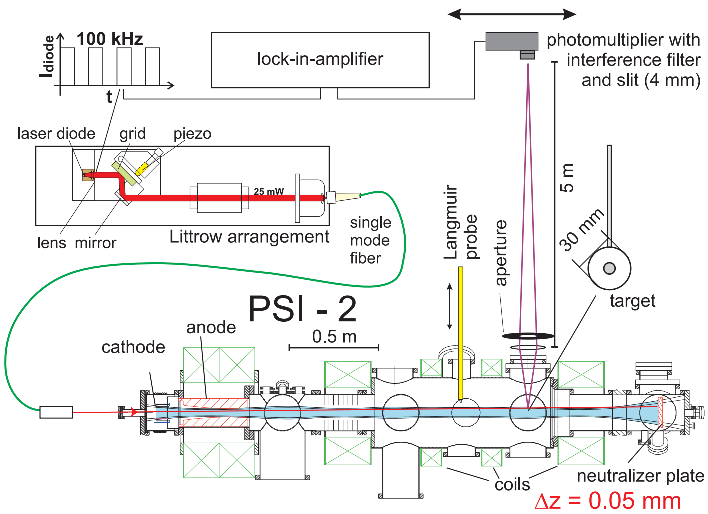


Figure 1: Plasma generator PSI-2 and the laser induced fluorescence diagnostics

## Experimental arrangement

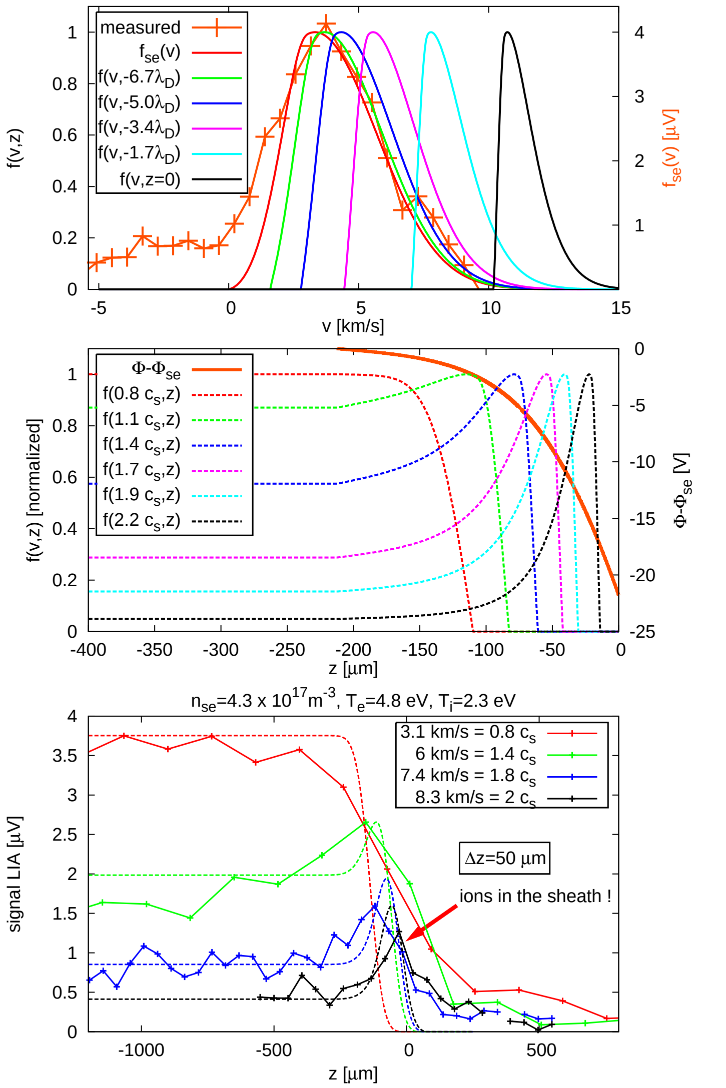


Figure 2: Ion velocity distribution function (Eq. 3) for fixed values $z$ (top) and for fixed $v$ (middle). Bottom: comparison of the blurred profiles (Eq. 4) with the measured LIF signal.

Fig. 1 shows the plasma generator PSI-2 and the laser induced fluorescence diagnostics (LIF) installed there. An argon plasma is produced by a stationary high current arc discharge between anode and cathode. Confined by the magnetic field it streams through the target chamber until it hits the neutralizer plate and is pumped away as gas by turbo molecular pumps. In the target chamber a circular boron nitride disc (∅ 30 mm) is inserted in the plasma where an electrostatic sheath forms.

In order to measure the velocity of the ions a non-invasive diagnostics like LIF is required. A narrow band-width tuneable diode laser excites the ions in the metastable level $3d\ ^4F_{9/2}$ to the $4p\ ^4D_{7/2}$ level (at $\lambda_0 = 664.3698$ nm) causing fluorescence due to the subsequent spontaneous decay to $4s\ ^4P_{5/2}$ at 434.8 nm. This light is collected under 90° by optical lenses and guided to a photomultiplier equipped with an adjustable slit and an interference filter. Scanning the laser wavelength while recording the photomultiplier signal yields the velocity distribution function projected to the direction of the laser. Moving on the other hand the detector scans the position $z$ of the detection volume with respect to the target surface. The large distance between lens and detector (5 m) improves not only the positioning accuracy significantly but also assures an optimum transmission of the filter due to the perpendicular incidence of the light. Due to this (about 10 times) magnifying optical system the slit aperture of 0.5 mm defines a detection volume as small as $\Delta z = 50\,\mu$m in the plasma.

The biggest challenge performing LIF measurements is to detect the small number of photons caused by LIF within the orders of magnitude larger background. This could only be achieved by modulating the laser intensity and detecting the signal by means of a lock-in-amplifier. It is also important to collect as many photons as possible from the detection volume applying large lenses. However, when measuring at such a high spatial resolution the lens diameter ($\varnothing\,100\,$mm) had to be reduced by an aperture to $\varnothing\,50\,$mm. This is necessary in order to achieve a sufficiently large field of depth and to avoid an additional blurring due to the finite laser diameter (2 mm) and the finite space angle.

**Ion distribution function in the sheath**

Due to its very small extension the electrostatic sheath is practically collisionless and energy conservation

$$\frac{1}{2}m_i u_i'^2 + e\Phi(z) = \frac{1}{2}m_i u_i^2 + e\Phi_{se}\ , \tag{1}$$

with the Bohm criterion $u_i = c_s$, is a good assumption for the ions. Taking into account the conservation of ion flux $n_i u_i = const.$, which allows us to write the ion density $n_i(\Phi)$ as a function of the potential $\Phi$, and assuming Boltzmann's relation the Poisson equation becomes

$$\frac{d^2\Phi}{dz^2} = -\frac{en_{se}}{\varepsilon_0}(n_i - n_e) = -\frac{en_{se}}{\varepsilon_0}\left[\left(1 - \frac{2e(\Phi-\Phi_{se})}{m_i c_s^2}\right)^{-1/2} - \exp\left(\frac{e(\Phi-\Phi_{se})}{T_e}\right)\right]\ . \tag{2}$$

Although an approximate analytic solution was found by Sheridan et al. [5] the thick orange curve in Fig. 2 (middle) shows the accurate numerical solution of for $\Phi(z)$.

Since Eq. 1 not only holds for the mean ion velocity $u_i$ but also for the individual ion velocities $v_i$ we can compute the velocity of the distribution function at any position in the sheath given that it is known at the sheath edge. Assuming conservation of the flux $f(v',z)v'dv' = f_{se}(v)vdv$ , where $f_{se}(v)$ is the distribution function at the sheath edge, and $vdv = v'dv'$ following directly from Eq. 1 we obtain

$$f(v',z) = f_{se}\left(\sqrt{v'^2 + \frac{2e}{m_i}(\Phi(z) - \Phi_{se})}\right)\ . \tag{3}$$

For the comparison between experiment and theory it is also convenient to introduce the blurred distribution function

$$f_{blur}(v',z) = \frac{1}{\Delta z\sqrt{\pi}} \int_{-\infty}^{\infty} f(v',z) e^{-(\zeta/\Delta z)^2} d\zeta \ . \tag{4}$$

**Measurements and results**

Fig. 2 shows the measured distribution function at the position $z = -1$ mm (orange curve). It is fitted by a smooth function $f_{se}(v)$ (red curve). The other curves (green, blue, magenta, cyan and black) are the distributions computed from Eq. 3. A different representation of exactly the same distribution function $f(v,z)$ is shown underneath (Fig. 2, middle), but there $v$ is kept constant and $z$ is taken as the independent variable. Such profiles would be expected from LIF measurements with a spatial resolution of the order $\Delta z = 1\ \mu$m keeping the wavelength constant and moving the detector. However, as mentioned before, the real spatial resolution is about $\Delta z = 50\ \mu$m. We blur these profiles artificially over this interval applying formula 4 and compare them with the measurements in the figure at the bottom. The peaks are less pronounced than in the figure above, but they are clearly recognizable. Unfortunately some positioning information was lost before the measurement of the blue and the black curve. These curves were shifted by (the same value) $-250\,\mu$m. However, the peak heights are described consistently by Eq. 4 for all curves.

**Summary**

The ions in an argon plasma were measured by means of LIF in the immediate vicinity of a target surface. Since the spatial resolution of the diagnostics was of the order $\Delta z = 50\,\mu$m, ions in the electrostatic sheath region (extension several Debye lengths $\lambda_D = 25\,\mu$m) contributed significantly to the measured signal. The measured LIF profiles were found in good agreement with the profiles expected for the given resolution. According to our knowledge this is the first direct experimental observation of ions in the electrostatic sheath in a plasma at fusion relevant electron densities ($n_e \sim 10^{18}$ ).

**References**

[1] D. Bohm, in *The Characteristics of Electrical Discharges in Magnetic Fields* (Mc Graw-Hill, New York 1949)

[2] M.J. Goeckner, et al. Phys. Fluids B **4**, 1663 (1992)

[3] L. Oksuz, et al., Phys. Plasmas **8**, 1729 (2001)

[4] T. Lunt, G. Fussmann, O. Waldmann, Phys. Rev. Lett. **100**, 175004 (2008)

[5] T.E. Sheridan, et al., IEEE Transactions on Plasma Science, **17**, 6, 884–888 (1989)