Two-Dimensional Argon-Ion Velocity Distributions in the Expansion Region of a Helicon Plasma Source

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***Abstract*—Two-dimensional argon ion velocity distribution functions in the expansion region of a helicon plasma source have been obtained by laser-induced-fluorescence tomography. Below a threshold value of the magnetic field in the expansion region, a fast ion population moving away from the source appears in addition to the nearly isotropic, slow, background, ion population.**

***Index Terms*—Electric double layer, helicon plasma, ion beam, ion velocity distribution function, laser induced fluorescence tomography.**

SINCE first reported in the literature, the spontaneous appearance of ion beams in the diverging magnetic field region downstream of low pressure helicon sources [1], [2] [believed to result from the formation of a current-free electric double layer (EDL)], has attracted a great deal of interest due to its possible applications in electric propulsion. The EDLs are oriented with the higher potential side toward the helicon source and the lower potential side toward the diffusion chamber, thus ions are accelerated out of the source; this potential difference is self-consistently generated by the plasma itself and there is no steady-state current in the external circuit. In magnetized helicon discharges, these current-free EDLs appear at pressures below 1–2 mtorr, with thicknesses from a few tens to a few hundreds of Debye lengths. Their strength, i.e., the height of the potential barrier, is two–three times the local electron thermal energy ($k_\mathrm{B}T_\mathrm{e}$). In the various experiments reporting ion beams emanating from helicon sources, the EDLs are located in the vicinity of the plasma source-diffusion chamber junction; in the region where the magnetic field lines from the source begin to diverge sharply [3]. The influence of the magnetic field divergence on EDL creation and subsequent ion acceleration is a subject of continuing experimental investigation [4], [5].

A key parameter in studies of EDL physics is the ion velocity (energy) distribution function (IVDF). One method for obtaining IVDF in plasma is laser-induced-fluorecence (LIF). However, standard LIF measurements provide only 1-D velocity information since the obtained IVDF is the projection of the 3-D IVDF on the laser propagation direction $\boldsymbol{k}_L$. By rotating $\boldsymbol{k}_L$ and employing filtered back-projection, the complete 2-D ion-velocity space distribution function can be acquired via optical tomography [6], [7].

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The characteristics of the HELIX-LEIA (H-L) system used for these investigations are as follows [8]: the HELIX machine consists of a 61-cm long, 10-cm diameter Pyrex tube mated coaxially with a 91-cm long, 15-cm diameter stainless steel tube. A 19-cm long, half-wave, $m = +1$, helical antenna couples the RF energy into the plasma. An RF power source furnishes up to 2 kW over a frequency range of 6–18 MHz. The source plasma expands into a 4.5-m long 2-m diameter aluminum diffusion chamber-LEIA. A magnetic field of 0–1.2 kG along the HELIX axis and 0–150 G in the expansion chamber is provided by external electromagnets.

Two-dimensional IVDFs in LEIA were obtained with an internal, scanning LIF probe [9]. To detect the fast ion population accelerated by passing through the EDL, measurements were performed as close as possible to the source-expansion chamber junction in the divergent magnetic field region (19 cm downstream from the H-L junction). For Ar II LIF we used the three-level LIF scheme $3d'^2G_{9/2} \longrightarrow 4p'^2F_{7/2} \longrightarrow 4s'^2D_{5/2}$. To measure the full IVDF, the laser frequency was swept over 20 GHz. The injected laser power density was ~ 11 mW/mm^2, i.e., the LIF was performed in a linear regime [10].

For LIF tomographs, the laser injection optics were rotated in 5° increments in a vertical plane tilted at an angle of 52° with respect to a vertical plane containing axial direction (z-axis). The z-axis is the magnetic axis of the H-L system and points from HELIX toward LEIA. Assuming cylindrical symmetry, the radial component of the ion flow velocity is [11]

$$V_r = V_x = V_y = \lambda_0 \Delta\nu^{\pm 90^\circ} \quad (1)$$

where $\lambda_0 = 611.6616$ nm is the vacuum wavelength of the pump transition and $\Delta\nu^{\pm 90^\circ}$ is the Doppler shift in the fluorescence spectrum of 1-D LIF scans at $\pm 90^\circ$ (perpendicular to the horizontal plane containing the z-axis). The axial speed V_z is determined from the scan at 0° after accounting for tilt of the injection optics relative to the z-axis

$$V_z \cong \lambda_0 \Delta\nu^{0^\circ} / \cos 52^\circ. \quad (2)$$

The LIF tomographs shown in Fig. 1 correspond to two different operating conditions: a relatively high magnetic field (100 G) in the expansion region for which the IVDF is a

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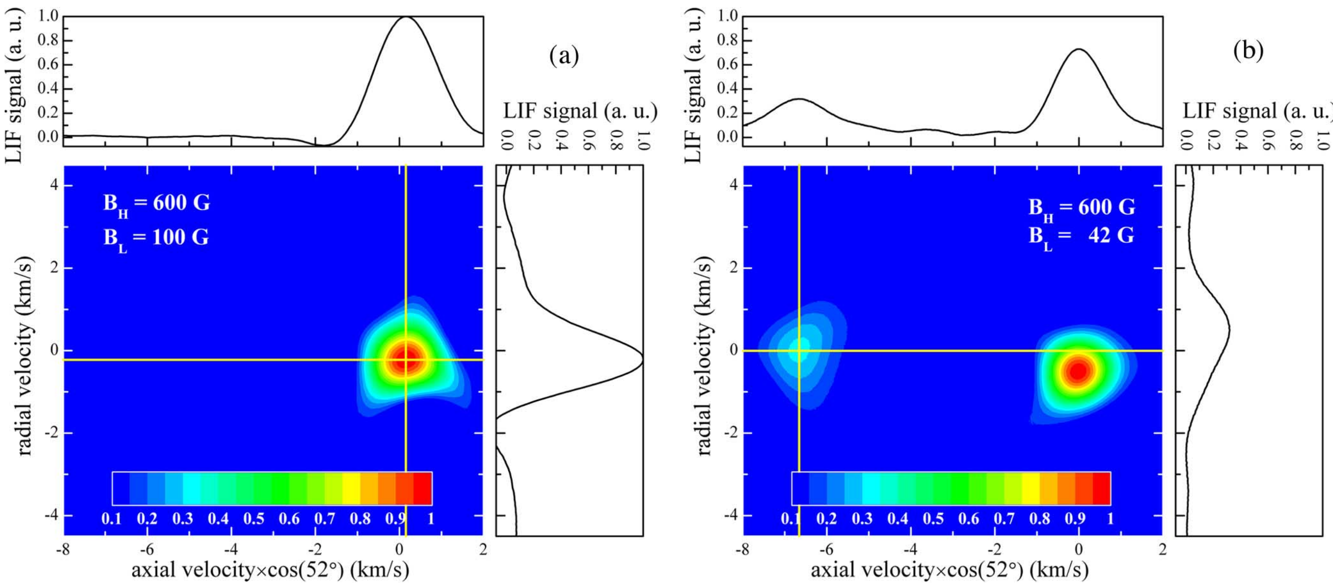

Fig. 1. Two-dimensional argon IVDFs in the expansion region of the H-L system obtained by LIF tomography: (a) For 600 G magnetic field in HELIX and 100 G magnetic field in LEIA, a single ion population is observed. (b) As the magnetic field in the expansion region is decreased, a fast ion population appears. The color bar in both figures is the normalized LIF signal intensity. The top and side graphs with each color figure are horizontal and vertical slices (along yellow lines) through the 2-D IVDF at the center of the (a) slow and (b) fast ion distributions, respectively. The negative value for the fast group axial velocity is because the ions are flowing out of the source toward the direction from which the laser is injected.

single, nearly stationary, population and a low expansion region magnetic field case (42 G) for which the IVDF shows the presence of an additional ion population. The slow ion group population has an approximately isotropic distribution with zero axial velocity. The fast group axial velocity calculated according to (2) is 9.8 km/s. In terms of Mach number (M $= V_z/c_s$, with $c_s = (k_{\rm B}T_{\rm e}/m)^{1/2}$ the ion sound velocity and the electron temperature from probe measurements), M $\sim$ 2.7, a supersonic velocity. The fast ion population velocity increases further as the external magnetic field in LEIA is decreased, reaching 10.7 km/s for a LEIA magnetic field of 14 G. 2-D IVDFs in the presheath of an ICP plasma also showed fast and slow ion drifting populations [12]. Different from these results, in our measurements, the two populations are well separated in velocity space by the relatively large (compared to the presheath measurements) EDL potential.

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