Ion beam acceleration in a divergent magnetic field

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Two-dimensional argon ion velocity distribution functions (IVDFs) in the expansion region of a helicon plasma source have been measured by laser-induced-fluorescence tomography. Below a threshold value of the magnetic field in the expansion region, the IVDFs show a bimodal structure comprised of a supersonic ion population axially moving away from the source and an isotropic, slow, background, ion population. Increasing the magnetic field divergence leads to an increase in the axial speed of the supersonic component. A maximum axial speed of $\sim 2.9c_s$ was obtained for a source/expansion magnetic field ratio of 43. © *2008 American Institute of Physics*.
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Since first reported in literature,[1,2] the appearance of ion beams in the diverging magnetic field region downstream of low pressure helicon sources [thought to result from the spontaneous formation of a current-free electric double layer (EDL)] has attracted a great deal of interest in plasma physics community.[3] Previous studies have shown that, in addition to the neutral pressure, the shape and strength of the magnetic field plays an important role in EDL formation in helicon discharges.[4,5]

In this letter, we show that magnetic field divergence clearly provides additional ion acceleration in the expansion region. Our conclusions are based on analysis of two-dimensional (2D) (radial and axial) ion velocity distribution function (IVDF) measurements obtained by laser-induced-fluorescence (LIF) tomography.

A detailed description of the Hot hELIcon eXperiment (HELIX) plasma source, the Large Experiment for Instabilities and Anisotropies (LEIA) difussion chamber, the tomographic probe, and tomographic analysis has been presented elsewhere.[6,7] Thus, only a brief account is provided here. The characteristics of the HELIX-LEIA (H-L) system (see Fig. 1) used for these investigations are: the HELIX plasma source consists of a 61 cm long, 10 cm diameter Pyrex tube coaxially mated 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. The plasma produced in the source expands into a 4.5 m long, 2 m diameter, aluminum diffusion chamber. Axial magnetic fields of 0–1.2 kG in HELIX and 0–150 G in LEIA are provided by external electromagnets. The axial magnetic field gradient in the region between the helicon source and LEIA peaks close to the H-L junction, just few centimeters inside the source (Fig. 1). The plasma potential, electron temperature, and density, and 2D IVDF in LEIA were determined with an internal probe.[7] For Ar II LIF we used the three-level scheme $3d'^2G_{9/2} \rightarrow 4p'^2F^0_{7/2} \rightarrow 4s'^2D_{5/2}$. Since the measured IVDFs showed a bimodal structure with peaks separated by $\sim$12 GHz, the dye laser frequency was swept over 20 GHz. Details of the laser used, the injected laser power, and the LIF diagnostic technique are given elsewhere.[8]

Consistent with other experiments,[9,10] our previous investigations revealed that the EDL appears below a threshold pressure of $\sim$2 mTorr in the source and is fixed to the location of the maximum magnetic field gradient.[11] To quantify the effect of the magnetic field divergence on the ions accelerated by the potential drop of the EDL, these measurements were performed downstream of the H-L junction. The divergence of the magnetic field can be changed either by modifying the magnetic field strength in the source (B_H) or in LEIA (B_L). However, changing B_H changes the source plasma properties. Therefore, B_H was held constant and B_L varied to isolate the effects of the field divergence on the EDL accelerated ion beam.

At high B_L values, one ion population is observed in the expansion region. Below a threshold value of $\cong$70 G the IVDF is bimodal showing a second, supersonic ion population in addition to the slow background ion population. Therefore, these experiments were performed at an operating pressure of 1.5 mTorr in the source, input power of 800 W, rf frequency of 9.5 MHz, $B_H=600$ G, and B_L between 14 and 56 G, corresponding to an upstream/downstream magnetic field ratio (expressed as $R=B_H/B_L$ ratio) range of 11–43.

Shown in Fig. 2 are 1D IVDFs (projections of the 3D IVDF along the laser injection direction) obtained 19 cm

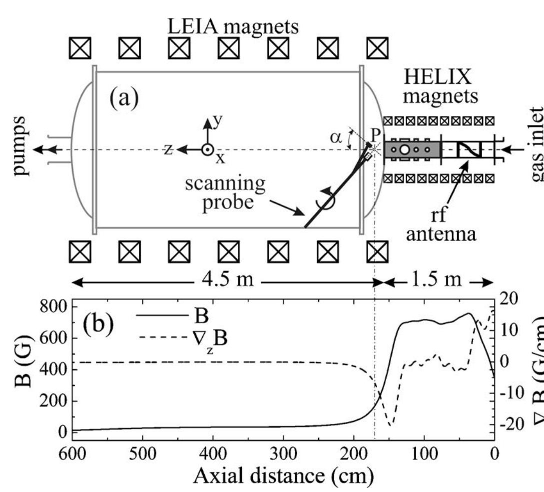

FIG. 1. (a) The H-L system and (b) the magnetic field profile and gradient along the axis of the system.

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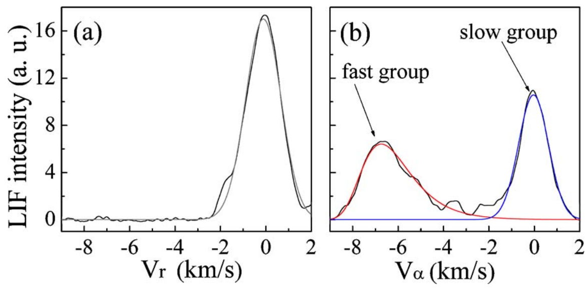

FIG. 2. (Color online) 1D IVDFs obtained in the expansion region: (a) laser injected along x axis and (b) laser injected in a horizontal plane (yz) at an angle $\alpha=52°$ with respect to the z axis.

downstream from the H-L junction on the axis of the system (point P in Fig. 1) for two laser injection orientations: along the x axis and in the horizontal (y,z) plane at an angle α with respect to the z axis. At first glance, the IVDF obtained by laser injection along x might be considered to be the radial IVDF of a single stationary ion population. However, when the laser is injected in the horizontal plane containing the direction of ion flow (z axis), the IVDF exhibits a bimodal structure comprised of two distinct ion populations: a fast ion group with ~ -6.6 km/s drift velocity and a slow moving group drifting at ~ -100 m/s. Negative ion flow velocities are consistent with ion flow into LEIA. To determine velocities along z, the speeds are corrected for the injection angle α of the interrogating laser beam. The slow ion IVDF is well fit by a single Gaussian distribution. However, the fast ion group has a long tail towards slower speeds. The tail is not a result of tilted laser injection relative to the direction of flow since a Gaussian Doppler shifted profile will remain Gaussian for all possible injection angles[12]—as demonstrated by the slow ion group IVDF. We note that similar half-distorted Gaussian LIF profiles were reported in LIF IVDF observations of ions accelerated in an electrostatic presheath.[13] Therefore, the tail of the fast ion IVDF might be a symptom of a drifting distribution slowed down by elastic scattering and/or charge-exchange collisions with the background gas. Nearly identical one-dimensional (1D) IVDFs obtained from retarding field energy analyzer (RFEA) measurements were reported in the expansion region for a similar helicon source.[4]

By rotating the probe about its axis and collecting 1D IVDFs in vertical plane defined by the x and α directions at different laser injection angles φ, and then reconstructing the IVDF by a back-filtering process, the 2D IVDF [a projection of the 3D IVDF onto the (α,x) plane] is obtained. In this technique, known as optical tomography,[14] a complete set of laser injections (I) spans π radians. We rotated our probe in increments $\Delta\varphi$ ($I\Delta\varphi=\pi$) in the two quadrants where the probe does not interfere with plasma flow, the $\pm\pi/2$ quadrants from the position where the injection optics face the helicon source. Shown in Figs. 3(a) and 3(b) as surface plots are two LIF tomographs for $R=14$ and 43, respectively. These tomographs show two completely separated ion populations. The radial velocities of the slow and fast ion populations differ only slightly (tens to a few hundreds m/s). Therefore, the observed single-peak distribution in the 1D radial IVDF [see Fig. 2(a)] is actually a convolution of two different peaks. The velocity space structure is more clearly shown in Figs. 3(c) and 3(d) in which the same tomographs are presented as contour plots. For the sake of comparison,

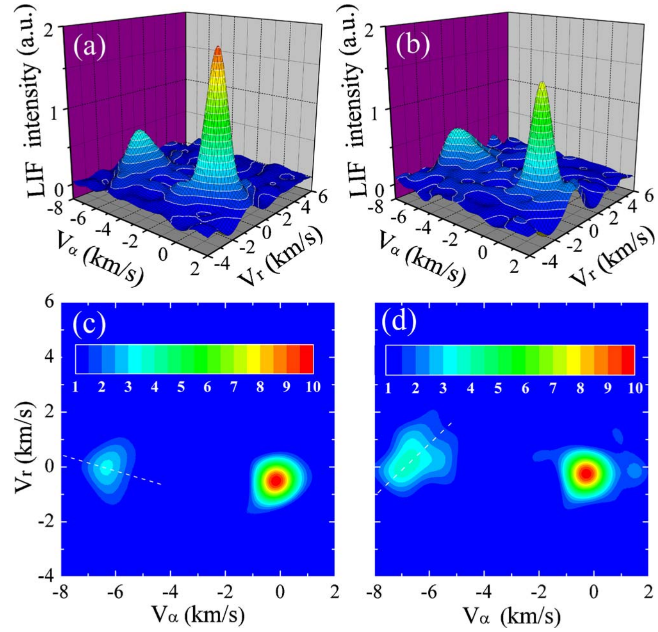

FIG. 3. (Color online) Complete 2D IVDFs 19 cm downstream H-L junction as surface plots and contour maps for two magnetic field ratios $R=B_H/B_L=14$ (left column) and $R=43$ (right column).

the relative intensities of the fast ion populations were normalized to the slow population LIF intensity. To the limits of the reconstruction process, the slow population IVDFs are isotropic [the ratio of the full widths at half maximum (FWHMs) in the radial and α directions $(\Delta V_r/\Delta V_\alpha)_{\mathrm{FWHM}}$ is unity]. Increasing the magnetic field strength ratio R decreases the height of the distribution, but preserves its isotropy. However, the fast population IVDFs are symmetrically stretched along directions that change with changing R (white dashed lines).

Over the range of values of R investigated, the fast ion population parallel velocity increases with increasing R until $R\cong 17$. For $R>17$, the fast ion speed is relatively constant. Since the measurements were performed at $r=0$, there is no azimuthal flow component and the velocity along the α direction (V_α) is a sum of radial (V_r) and axial (V_z) velocity projections. Because $V_r \ll V_\alpha$ and $\alpha=52°$, it follows that $V_z \cong V_\alpha/\cos\alpha$. Thus, V_z increases from ~ 8.8 km/s for $R=11$ to ~ 10.9 km/s for $R=43$. In terms of Mach numbers [$M=V_z/c_s$, with $c_s=(k_B T_e/m)^{1/2}$] and the electron temperature obtained from probe measurements, the supersonic flow varies from $2.4<M<2.9$. The slow ion population axial flow is essentially zero.

These observations are consistent with the slow ions being a background population created by local ionization and the fast ions being created further upstream in the plasma source. Specifically, the slow ion velocity distribution is isotropic and insensitive to changes in R. Previous studies[15] have shown that in collisional helicon plasmas, the local LIF intensity scales as $n_e^2 T_e^{1/2}$. Langmuir probe measurements indicate that $n_e^2 T_e^{1/2}$ exponentially decreases with increasing R in these experiments ($T_e=5.4-6.1$ eV, $n_e=1.1-0.57 \times 10^{11}$ cm^{-3}, for $R=11-43$). The integrated LIF intensity of the slow population scales roughly as $n_e^2 T_e^{1/2}$ while that of the fast population does not—thus pointing to a local origin for the slow ion population. We suggest that the weaker local B_L magnetic field at large values of R reduces the particle confinement downstream of the helicon source, leading to lower

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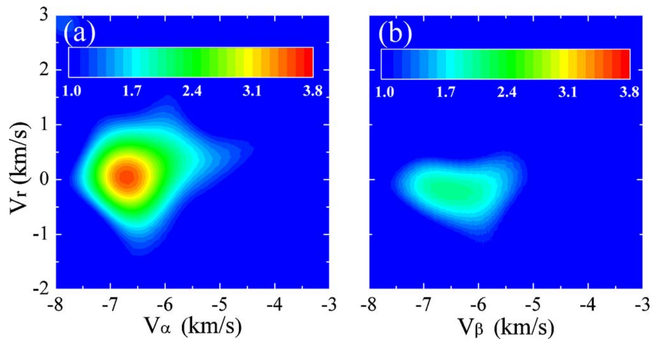

FIG. 4. (Color online) Tomographs of the fast ion group 19 cm (a) and 28 cm (b) downstream from H-L junction for $R=B_H/B_L=21$. Both tomographs have the same color scale.

densities and higher electron temperatures and therefore a decreased bulk ionization rate ($\sim n_e$), a higher diffusion rate ($\sim T_e/B_L^2 \sim T_e R^2$), and reduced LIF amplitude.

The sensitivity of the shape of the fast ion IVDF and the beam energy to R are consistent with fast ions being created upstream and accelerated into the expansion chamber. Our previous studies[6] suggested that a sharp potential drop, i.e., an EDL, forms at the end of the source in the vicinity of the strongest axial magnetic field gradient. Charge-exchange collisions experienced by fast ions after a spatially localized acceleration should result in an IVDF elongated along the flow direction as some ions lose energy to the background neutrals. An expanded view of the fast ion populations showing a faint tail stretching toward slower speeds, similar to IVDF tomographs obtained in the plasma presheath,[16] is shown in Fig. 4. Although these measurements do not show a population of ions extending from beam velocities all the way down to the background population, such IVDFs have been observed in RFEA measurements in similar experimental systems.[3] Based on the available cross sections, the mean free path (mfp) for quenching collisions of this state with ground state neutral Ar is roughly double the charge-exchange mfp. Thus, an ion in the metastable state will be depopulated by quenching long before significant velocity changes result from charge-exchange collisions. That metastable quenching is a significant loss process is demonstrated in Fig. 4(b), where a tomograph obtained 9 cm downstream from point P shows no change in the axial velocity of the distribution (here $\beta=47°$ and $V_z \cong V_\alpha/\cos 52° \cong V_\beta/\cos 47° \cong 10.3$ km/s) but roughly a factor of 1.5 decrease in LIF intensity.

Finally, these measurements show that, besides triggering the EDL formation,[17] the divergent magnetic field somehow provides additional ion acceleration. Complementary LIF measurements performed just downstream of the EDL (4 cm inside the source) indicate only a modest change in the fast ion axial flow speed with increasing R; increasing from 5.9 to 6.1 km/s as R increased from 11 to 43. Thus, the higher ion beam flow speeds (~3–4 km/s increase) observed further downstream (point P) cannot be due to an increase in the potential drop across the EDL. The location of the maximum magnetic field gradient also changes by only a few millimeters as R is varied over the experimental range.

As the ions travel from HELIX into LEIA, they experience the potential drop ($\Phi>0$) of the EDL and the mirror ($-\mu\nabla\mathbf{B}$) force. Conservation of energy and magnetic moment gives

$$V_{L\parallel}^2 = V_{H\parallel}^2 + 2e\Phi/m + V_{H\perp}^2(R-1)/R. \quad (1)$$

Thus, only a fraction of the upstream perpendicular energy is converted into downstream parallel energy. Using the LIF measured velocity components, the perpendicular kinetic energy in HELIX needed to explain the 10–15 eV change in parallel kinetic energy from the end of the EDL into LEIA is 14–21 eV, far too large a quantity to be solely provided by the perpendicular ion temperature. One source of additional energy could be the conversion of azimuthal flow kinetic energy[15] into parallel flow energy. The Lorentz force arising from azimuthal ion velocity and a radial magnetic field component in the diverging region is along the z direction. However, previous measurements found only modest (~0.8 eV) azimuthal flow energy. Another possible ion acceleration mechanism involves the balancing of upstream and downstream plasma flow. Supersonic ion speeds ($\leq 3c_s$) were predicted[18] based on ion acceleration by the electron pressure gradient resulting from plasma expansion. Recent investigations of plasma expansion in the absence of a magnetic field demonstrated ion acceleration to supersonic speeds as the cross-sectional area expansion ratio was increased using different size plasma source chambers.[19] In our case, the chamber diameters are fixed, but conservation of the magnetic flux defines the plasma cross section in LEIA and the ratio of areas becomes $A_L/A_H=B_H/B_L=R$. Further measurements are needed to distinguish between these different possible ion acceleration mechanisms in the diverging magnetic field region.

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