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Abstract

We report spatially resolved perpendicular and parallel, to the magnetic field, ion velocity distribution function (IVDF) measurements in an expanding argon helicon plasma. The parallel IVDFs, obtained through laser induced fluorescence (LIF), show an ion beam with $v \approx 8000$ m/s flowing downstream and confined to the center of the discharge. The ion beam is measurable for tens of centimeters along the expansion axis before the LIF signal fades, likely a result of metastable quenching of the beam ions. The parallel ion beam velocity slows in agreement with expectations for the measured parallel electric field. The perpendicular IVDFs show an ion population with a radially outward flow that increases with distance from the plasma axis. Structures aligned to the expanding magnetic field appear in the DC electric field, the electron temperature, and the plasma density in the plasma plume. These measurements demonstrate that at least two-dimensional and perhaps fully three-dimensional models are needed to accurately describe the spontaneous acceleration of ion beams in expanding plasmas.

Keywords

plasma diagnostics, plasma sources, plasma density, laser induced fluorescence, plasma sheaths

Disciplines

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Spatial structure of ion beams in an expanding plasma

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We report spatially resolved perpendicular and parallel, to the magnetic field, ion velocity distribution function (IVDF) measurements in an expanding argon helicon plasma. The parallel IVDFs, obtained through laser induced fluorescence (LIF), show an ion beam with $v \approx 8000$ m/s flowing downstream and confined to the center of the discharge. The ion beam is measurable for tens of centimeters along the expansion axis before the LIF signal fades, likely a result of metastable quenching of the beam ions. The parallel ion beam velocity slows in agreement with expectations for the measured parallel electric field. The perpendicular IVDFs show an ion population with a radially outward flow that increases with distance from the plasma axis. Structures aligned to the expanding magnetic field appear in the DC electric field, the electron temperature, and the plasma density in the plasma plume. These measurements demonstrate that at least two-dimensional and perhaps fully three-dimensional models are needed to accurately describe the spontaneous acceleration of ion beams in expanding plasmas. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5003722>

I. INTRODUCTION

Studies of spontaneously forming, current-free, double layers (DLs) in expanding plasmas have focused on basic plasma science,¹ the use of ion beams accelerated by the double layer for plasma propulsion,^{2–4} and space-relevant plasma phenomena.⁵ A classic plasma double layer (DL) consists of two sheets of opposite charge, one negative and one positive, that appear in a plasma. Unlike sheaths that form at a boundary or on the surface of an object inserted into the plasma, double layers may form anywhere in a plasma. While some recent computational models have included two-dimensional magnetic fields⁶ or tracked particle motion in three-dimensional phase space,⁷ typical theoretical and computational models of DL formation in low temperature plasmas are purely one-dimensional. Those models yield predictions of the neutral pressure threshold for DL formation,^{8–11} of the potential drop across the DL, of the DL thickness in multiples of Debye lengths,^{4,12,13} and of the relative densities of the ion and electron populations needed to sustain the current-free DL.¹⁴ A one-dimensional, diffusion controlled theory, which added an additional group of counter-streaming electrons (formed by reflection at the end of the plasma source chamber) to enforce a current-free condition on the DL, yielded predictions for the neutral pressure threshold and the total potential drop across the DL which were consistent with recent experimental measurements.¹⁵ The diffusion controlled theory also predicted increased ionization upstream of the double layer by the reflected electron population, a prediction consistent with experimental observations.^{16,17}

However, one dimensional models clearly do not encapsulate all the relevant physics. Measurements of the contours of constant electric potential for DLs tied to regions of expanding magnetic fields in space¹⁸ and in laboratory plasmas¹⁹ indicate that DLs are fully three-dimensional “U” or bowl shaped structures. One-dimensional models are also

unable to reproduce electric fields perpendicular to the magnetic field near the throat of the expansion region and the large variations in plasma density transverse to the magnetic field observed downstream of some DLs.²⁰ Recent measurements also indicate the surprising presence of high energy electrons near the edge of the plasma source, which results in enhanced ionization at the edge and creates a radial potential barrier that appears to confine the ions.²⁰ Note that these energetic electrons are reported to move through the expansion region in the same direction as the ions, inconsistent with expectations for a DL. Recently, Singh completed a thorough review of double layer physics which encompasses both laboratory and space plasmas.²¹

Measurements of the spatial structure of the plasma potential²² or the appearance of accelerated charged particle populations downstream of the DL are often used as proxies for the existence of a DL. Both laser induced fluorescence (LIF) and retarding field energy analyzers (RFEAs) are used in our laboratory to characterize the ion beam that appears in the expanding plasma plume.²³ It is important to note that while an RFEA has a lower detection threshold for ion beams than LIF, RFEAs are unable to reliably measure the details of the parallel ion velocity distribution function (IVDF) and are completely incapable of measuring perpendicular velocity distribution functions.²⁴ The thrust generated by the ion beam has been a subject of detailed study because of its potential for commercial application.²⁵ In previous studies using RFEAs, detachment of the ion beam from the expanding magnetic field lines has been observed,²⁶ with beam divergences of less than 6 degrees.²⁷

In this work, we present high resolution, two-dimensional mapping of IVDFs and the electric field in the plume of an expanding helicon source plasma at low neutral pressure. The IVDF measurements are accomplished with LIF parallel and perpendicular to the axis of the experiment.

The electric field measurements are accomplished with a multi-tip, electrostatic probe. Other researchers working in similar systems have reported large perpendicular electric fields, as large as 20 V/cm, at the junction of the source tube and expansion chamber.²⁸ Similar electric field magnitudes are seen in these experiments but are limited to a thin annular region adjacent to the inner boundary of the plasma source that then expands to follow the expanding magnetic field. The IVDF measurements provide a means of identifying distinctly different plasmas in the expanding plume: a central, low density, core containing a well-defined ion beam, an annular region with large radial flows of ions with a broad perpendicular velocity distribution that expands along with the expanding magnetic field, and a downstream background ion population with a superimposed ion beam population.

Electric field fluctuation measurements exhibit spectral characteristics unique to each of these plasma populations. The multi-dimensional electric field and velocity space structures clearly demonstrate that one-dimensional models of DL formation in expanding plasmas are insufficient. Radial flows and transport in these cylindrical plasmas certainly play a key role in the ion beam formation process.

II. EXPERIMENTAL APPARATUS

These experiments were performed in the Hot hELIXon eXperiment (HELIX) and the Large Experiment on Instabilities and Anisotropies (LEIA). HELIX is a 1.5 m long hybrid stainless steel-Pyrex vacuum chamber. The stainless steel chamber opens up into the 2 m diameter, 4.5 m long (LEIA) expansion chamber. Up to 2.0 kW of rf power is coupled through a 19 cm $m = +1$ helical antenna over a frequency range of 6–18 MHz. Ten water cooled electromagnets produce a steady-state, nearly uniform axial magnetic field of 0–1200 G in HELIX. Seven water cooled electromagnets produce a steady-state, uniform axial magnetic field of 0–150 G in LEIA. Three turbomolecular drag pumps provide a base pressure of approximately 10^{-7} Torr. The large pumping rate at the end of the expansion chamber (3200 l/s) results in a hollow neutral pressure radial profile²⁹ and a downstream pressure at least ten times smaller than the neutral pressure in the source. Operating pressures in argon range from 0.1 mTorr to 10 mTorr.

For these experiments, the neutral fill pressure of argon was 0.17 mTorr. The fill pressure corresponds to an operating pressure of 0.90–0.95 mTorr. At this neutral pressure, the ion-neutral charge exchange collision length is tens of centimeters long. Previous studies at WVU established a rf threshold of 11.5 MHz for the formation of an ion beam (due to the frequency coupling of the rf antenna to the plasma).¹⁶ Below this threshold, large electrostatic instabilities develop and destroy the DL (here the antenna frequency was 12.5 MHz with 725 W of total rf power, less than 20 W of which was reflected). Typically, these low pressure plasmas are destructive to the Pyrex tube and careful impedance matching was required to minimize the amount of reflected power and the voltages on the rf antenna (very large antenna voltages result in enhanced ion sputtering of the Pyrex tube, causing the tube to break). The magnetic field in the source

was 860 G and the downstream LEIA magnetic field was 108 G. Previous studies suggested that stable ion beams required large magnetic field ratios ≈ 40 .³⁰ That the ion beams observed in these experiments persisted at a magnetic field ratio of only ≈ 8 appears to be a result of the very low neutral fill pressure used.

LIF is a non-perturbative diagnostic that uses the Doppler effect to directly measure the thermally broadened IVDF. A Matisse-DR tunable ring dye laser is tuned to 611.6616 nm (vacuum wavelength) to pump the Ar II $3d^2G_{7/2}$ metastable state to the $4p^2F_{7/2}$ state, which then decays to the $4s^2D_{5/2}$ state by emitting 461.086 nm photons. The laser light passes through a 5 kHz mechanical chopper and is coupled into an optical fiber for injection into the plasma. Detailed descriptions of the full LIF system are available elsewhere.³¹ For these experiments, the laser light injection and the fluorescent emission collection are accomplished with an *in situ*, scanning, mechanical probe. The probe includes options for simultaneous parallel and perpendicular light injection and moves the measurement location throughout a plane intersecting the plasma source axis and spans the region downstream of the junction between the plasma source and the expansion chamber (see Fig. 1). As the laser's wavelength is scanned, the intensity of the fluorescence is measured with a lock-in amplified photomultiplier tube to isolate the modulated fluorescence. A planar Langmuir probe and a triple probe are attached to the scanning LIF probe but offset in radius to eliminate any interference of the probes on the LIF measurements. The triple probe is comprised of three tungsten filaments (diameter of 0.2 mm and length of 3 mm). Two tips are spaced apart by

FIG. 1. (a) The magnetic field geometry as the plasma expands from the helicon source into the LEIA chamber. The scanning probe accesses the expansion region downstream of the plasma source (identified by the red arrows). (b) A zoomed view of the measurement location. Dashed red arrows indicate the directions of laser injection and the dashed blue arrow indicates the path of emission collection. The Langmuir probe location is marked by the letter L and the triple probe location is marked by the letter T.

2.54 mm along the radial direction. A third tip is located halfway between these two tips, but offset 2.91 mm along the axial direction. The DC potential at the location of each tip is measured by acquiring 50 measurements of a 10 gigapoint time series and then taking the mean of the average time series. The fluctuation spectra at each tip and the frequency dependent phase shift between the tips are averaged over 50 real time measurements of the Fast Fourier transforms (FFTs) and cross power spectra using a LeCroy WaverunnerTM604Zi oscilloscope (400 MHz bandwidth). For the FFT measurements, the time resolution is 20 ns and the frequency resolution is 23.84 Hz. The cross power spectra between the pairs of the tips and their known spacing are then used for determination of the frequency dependent wavelength of the fluctuations along the axial and radial directions. The random error in the power spectra and wavelength measurements follows a $1/\sqrt{M}$ dependence where M is the number of data samples collected.³²

III. IVDF MEASUREMENTS

Classic DL theory requires four populations to establish a steady-state DL: trapped ions downstream of the DL, accelerated ions flowing downstream from upstream, accelerated electrons flowing upstream, and trapped electrons upstream of the DL.¹⁴ Shown in Fig. 2 is a schematic of a typical DL with the various particle populations and the measurement region for these experiments. Using the scanning probe, the accelerated and background ion populations are measured throughout the downstream plasma plume.

A. Parallel IVDF measurements

Figure 3 shows a typical parallel IVDF obtained in the center of the plasma at $z = 164$ cm (the HELIX-LEIA junction occurs at $z = 159$ cm). Evident in the IVDF is a large amplitude ion beam population at 8.0 km/s and a lower density background ion population centered around 0 m/s. A negative velocity means that the ions are traveling downstream from the source into the expansion chamber (towards the source of laser light). Further downstream, at an axial location of $z = 175$, the background ion population with an upstream directed bulk velocity of approximately +500 m/s appears and is larger in magnitude than the ion beam population. At this location, the temperature of the beam and bulk

FIG. 2. A schematic showing the four populations in the classical picture of a double layer. The region between the dashed lines is where the IVDF and probe measurements were obtained.

FIG. 3. The IVDF at $r = 0$ cm and $z = 164$ cm showing an ion beam at 8.0 km/s with little background plasma. A Maxwellian fit yields an ion beam temperature of 0.23 eV.

is virtually identical, 0.23 ± 0.01 eV and 0.24 ± 0.01 eV, respectively. The increase in background ion density relative to the ion beam and the average upstream flow of the background ions is consistent with the assumption that the measurement region is downstream of a DL. Measurements were obtained every 2 cm from $r = -12$ cm to $r = 8$ cm at axial locations $z = 164$ cm, $z = 170$ cm, $z = 175$ cm, and $z = 180$ cm, as shown in Fig. 4, respectively. At radial locations greater than $r = 8$ cm, the body of the probe blocks the plasma from flowing into the LEIA chamber; therefore, the measurement region is asymmetric around the plasma axis. The IVDFs are stacked in an array and plotted as a contour map. Each individual IVDF measurement is scaled to account for the different lock-in gain settings used for each measurement location.

In the LIF signal at $z = 164$ cm, the dominant ion beam population seen in Fig. 3 is noticeably absent. The ion beam population and the background ions (those at zero velocity) do not appear in the plots in the center of the plasma in Fig. 4 because all the IVDF measurements have been plotted with a common color bar and there is a dramatic decrease in overall ion density towards the center of the discharge. As will be shown by the Langmuir probe measurements later, the plasma density drops at least a factor of five from the edge to the center of the discharge. Therefore, although the ion beam population dominates the IVDF at $r = 0$ cm and $z = 164$ cm, the beam does not appear very intense in the center of the plasma in Fig. 4 because the total plasma density on axis is much smaller than the total plasma density at the edge of the measurement region. In other words, the radial variation in plasma density is the dominant visual feature in Fig. 4. Other helicon source groups have also reported a hollow plasma density profile in the plume of an expanding plasma.¹⁹

The black dashed lines in the panels of Fig. 4 lie along a common tube of constant magnetic flux that expands with downstream distance. The IVDF data in Fig. 4 show that the hollow portion of the background plasma density profile expands with the expanding magnetic field. To better

FIG. 4. The parallel IVDF as a function of radial location at (a) $z = 164$ cm, (b) $z = 170$ cm, (c) $z = 175$ cm, and (d) $z = 180$ cm scaled to account for detector sensitivity.

visualize the spatial structure of the ion beam, we normalize each parallel IVDF to its peak value and plot the arrays of normalized IVDFs in Fig. 5. In the normalized plots, there is a well-defined region (from $r = \pm 5$ cm) that is dominated by the ion beam. Outside of that central region, the IVDF is dominated by the background ion population. For downstream distances beyond $z = 164$ cm, the background ion population appears in the central core region of the plasma. Also shown in Fig. 5 are the same two dashed lines, which mark the edges of a cylinder of constant magnetic flux that maps to a flux tube of radius 2 cm in the helicon source. Both the amplitude and the speed, ≈ 8000 m/s, of the metastable ion beam population decrease slightly with increasing downstream distance. There is little to no change in the parallel ion temperatures of the beam and bulk populations with

FIG. 5. The same parallel IVDF as a function of radial location at (a) $z = 164$ cm, (b) $z = 170$ cm, (c) $z = 175$ cm, and (d) $z = 180$ cm as shown in Fig. 4 but with each IVDF normalized to the peak value in the IVDF.

downstream distance or radial location. A faint, low velocity, downstream-flowing, third ion population also appears in the center of the plasma with increasing distance from the DL.

Complex IVDFs similar to this have been observed in LEIA before.⁵ Shown in Fig. 6 are Maxwellian fits to the ion beam and bulk populations, along with a third Maxwellian population fitted to the residue of the IVDF after the beam and bulk populations are subtracted. The third population in Fig. 6 has a net flow of 1.7 km/s directed downstream from the DL. The effective temperature of this third population is 0.42 eV, significantly hotter than the beam and bulk ion temperatures. These ions are most likely beam ions that have slowed down through collisions with background ions or

FIG. 6. The parallel IVDF at $r=0$ cm and $z=175$ cm showing an ion beam of 7.6 km/s and a population of background plasma moving upstream towards the source with $v=+500$ m/s. A third population with $v=-1.7$ km/s is flowing away from the DL.

energetic neutrals created through charge-exchange between the beam ions and background neutrals. The spatial structure of the ion beam portion of the parallel IVDF develops over the region of study as the ion trajectories respond to magnetic forces and electric fields.

To gain a better understanding of the evolving spatial structure of ion beam, just the portion of the unnormalized parallel IVDFs above 4000 m/s, well above the bulk thermal velocity, is shown in Fig. 7. Because the IVDFs in Fig. 7 are not normalized to the background plasma density, they highlight variations in the total amplitude of the beam population, i.e., the variations in the plots include the effects of the strongly radially varying plasma density. The radial profile at $z=164$ cm shows a hollow ion beam amplitude profile with peaks on either side of the central axis. The radial profiles from further downstream show the same hollow structure expanding radially outward.

In the time it takes for the ion beams to traverse 16 cm along the axis of the plasma, the peaks in the radial profiles shift radially outward by approximately 3 cm. Such radial expansion of the hollow ion beam profile exceeds the radial expansion of the magnetic field. Therefore, these parallel IVDF measurements suggest the action of significant additional radial forces pushing the beam ions radially outward as they travel downstream. The axial evolution of the radial ion beam profiles in the IVDFs shown in Fig. 7 provides additional evidence of the beam ion slowing mechanism noted in the previous discussion of the third ion population. With increasing downstream distance, the ion beam distributions elongate and flatten in velocity space, stretching out from a beam peak at 8 km/s to include slower beam ions extending to 4 km/s.

To investigate the effects of collisions on the ion beam velocity and the total parallel IVDF, high spatial resolution measurements were performed at $r=0$ cm in 1 cm steps from $z=170$ cm to $z=191$ cm (see Fig. 8). With increasing downstream distance, the relative ion beam to background intensity decreases and there is a slight decrease in the ion

FIG. 7. The same corrected, but unnormalized, parallel IVDFs shown in Fig. 5 as a function of radial location at (a) $z=164$ cm, (b) $z=170$ cm, (c) $z=175$ cm, and (d) $z=180$ cm, but only for velocities above 4000 m/s.

beam velocity. Note that Fig. 8 begins at $z=170$ cm, well after the background ion population appears in the parallel IVDF. Previous studies of ion beam amplitude decay in expanding plasmas have attributed the decay to quenching of the metastable state probed by LIF due to collisions of the metastable ions with electrons.¹ In other words, the decrease in LIF signal results from the particular requirements of the LIF measurement process and does not necessarily indicate the actual decay of the ion beam amplitude. In fact, RFEA measurements in this plasma plume⁵ and in other experiments²³ have found that the ion beam persists downstream with little reduction in beam density.

An exponential fit to the decaying LIF amplitude yields a 1/e folding distance of 11.4 cm (see Fig. 9). Assuming the

FIG. 8. The normalized parallel IVDF at $r=0$ cm as a function of downstream distance.

$1/e$ folding distance is the effective mean-free-path for the metastable ions ($\lambda \sim 1/e$), these measurements yield a quenching cross section of $2.7 \times 10^{-18} \text{ m}^2$, consistent with results from previous measurements of the effective metastable quenching cross section.^{1,9,23,33} Over an 18 cm distance, there is a slight decrease in the ion beam velocity from 8320 to 8040 m/s shown in Fig. 8. A collisional process would be expected to produce an exponential velocity decrease given that ion momentum loss due to collisions with background neutrals is described by

$$\frac{dv}{dt} = -\nu v, \quad (1)$$

where ν is the relevant collision frequency. Therefore, some non-collisional process must contribute to the slowing of the ion beam. In other words, the nature of the slowing of the beam ions suggests the existence of an upstream directed electric field, completely inconsistent with what would be expected for a DL.

Although the parallel IVDF measurements presented so far were obtained for a relatively strong downstream magnetic field of 108 G, most DL studies in LEIA and elsewhere have employed weak downstream magnetic fields or none at all.^{2,17,30} By simple magnetic moment conservation ($\mu = kT_{i\perp}/2B$ for thermal ions gyrating around a magnetic

FIG. 9. LIF signal amplitude for the peak of the ion beam in the IVDF and exponential fit versus axial position from data of Fig. 8.

field), a weaker downstream magnetic field should yield an increase in the ion beam velocity in addition to any DL acceleration effects. Faster ion beams are of particular importance for spontaneous ion beam generation applications such as plasma thrusters. Shown in Fig. 10 is the effect on the on-axis ion beam velocity due to changing the downstream magnetic field strength from 8 to 108 G. The ion beam velocity is measured well downstream of the DL at $z=171$ cm. All other plasma source parameters were held fixed. The ion beam velocity drops from 12 100 m/s for a downstream magnetic field of 8 G to roughly 8800 m/s for a field of 54 G. As the downstream field increases from 50 G to 110 G, there is a modest, linear decrease in the beam velocity.

Assuming that the ions flow downstream slow enough that μ is an adiabatic invariant in these experiments, energy conservation and measurements of the upstream and downstream perpendicular ion temperatures are enough information to calculate the maximum possible increase in parallel ion flow speed due to μ conservation. For these experiments, the upstream perpendicular ion temperature was 0.55 eV. Conversion of all the perpendicular thermal energy into parallel flow kinetic energy would only accelerate stationary argon ions up to a parallel flow speed of 1150 m/s. However, given that for a downstream magnetic field of $B=108$ G the perpendicular ion temperature at $z=171$ cm is measured to be 0.45 eV (nearly unchanged from the upstream value), it is clear that energy conservation and magnetic moment conservation (if magnetic moment is even conserved in this system) are insufficient to explain the observed ion acceleration, i.e., the existence of additional ion acceleration from upstream to downstream is implied by the parallel IVDF measurements.

For a downstream magnetic field of $B=31$ G, the downstream perpendicular ion temperature was 0.51 eV. Given the small change in perpendicular ion temperature, μ conservation yields at most a 56 m/s increase in the parallel ion velocity. Therefore, the sharp decrease in ion beam velocity as the downstream magnetic field increases from 20 to 50 G must result from a substantial change in the potential difference across whatever electric field structure is responsible for the ion acceleration.

For downstream magnetic fields of 50 to 110 G, it appears that the potential difference across the ion

FIG. 10. The parallel IVDF as a function of the expansion magnetic field at $r=0$ cm and $z=171$ cm.

accelerating structure remains relatively constant. Note that at speeds of 8000–10 000 m/s, beam ions only complete 1/4 of a gyro-orbit while traveling 16 cm in the axial direction. Such ion motion is simply too fast for adiabatic constraints such as μ conservation to hold. It is important to note that the parallel IVDFs shown in Fig. 10 are not self-normalized. The data shown are raw IVDF measurements and therefore Fig. 10 indicates that there is a critical downstream magnetic field for which the background and beam ion densities are largest, approximately 31 G, and above which the ion beam velocity and ion beam density start to decrease. For downstream magnetic fields less than 20 G, the ion beam velocity also decreases—additional confirmation that the observed parallel ion beam velocities cannot be a result of μ conservation. The implications of these measurements are profound with regard to potential use of these systems as plasma thrusters.

Clearly, some downstream field enhances both the specific impulse and the thrust of such a thruster. For the weakest downstream magnetic fields, the collisionality of the plasma also appears to play less of a role. There is a clear reduction in LIF signal for ion velocities between the beam velocity and the background at the weakest downstream fields (visible as a purplish region around 5000 m/s and 10 G in Fig. 10). As there should be no effect of the changing magnetic field on neutrals, it appears that poor ion confinement (and therefore fewer ion-ion collisions) at the smallest downstream magnetic field strengths may reduce the number of ions that are scattering into the slowest velocity ranges in the plasma.

B. Perpendicular IVDF measurements

We measured the perpendicular IVDFs at the same locations as the parallel IVDFs and under the same conditions. While simultaneous parallel and perpendicular IVDF measurements using multiplexing with the scanning LIF probe are possible,³¹ the parallel and perpendicular LIF measurements were obtained sequentially in these experiments. Switching from parallel to perpendicular measurements is accomplished by moving the injection fiber to a different fitting on the external interface of the probe.

Figure 11 shows the self-normalized, perpendicular IVDFs at axial locations of $z = 164$ cm, $z = 170$ cm, $z = 175$ cm, and $z = 180$ cm, respectively. There are a number of significant features in these perpendicular IVDF measurements. In the center of the plasma, in the same central region where the parallel IVDFs show clear evidence of an ion beam, there is an ion population with a finite radial flow that switches sign across the plasma axis. Referring to Fig. 1, it is important to note that in the expansion region the local magnetic field is not purely axial. At the most upstream locations measured, the magnetic field has a significant radial component. These perpendicular IVDF measurements are in the laboratory frame. Thus, any ion beam flowing along the local magnetic field will have velocity components in the radial and axial directions. This projection effect is evident in Fig. 11. Outside of the central core of the plasma, the perpendicular IVDFs show quite complex behavior. Outside of

FIG. 11. The normalized perpendicular IVDF at (a) $z = 164$ cm, (b) $z = 170$ cm, (c) $z = 175$ cm, and (d) $z = 180$ cm as a function of radial location.

$r = \pm 5$ cm, the perpendicular IVDF cannot be described with a single Maxwellian velocity distribution.

Overplotted on the panels in Fig. 11 is a dashed black line marking what the projected perpendicular velocity of the ion beam should be, given the measured parallel velocity at that location and the expected magnetic field angle. Since the magnetic field angle relative to the axial direction is only a few degrees (depending on radial location), the radial velocity should be no larger than a few hundred meters per second. The perpendicular IVDF in the core of the plasma at $z = 180$ cm is generally consistent with the predicted structure. There is a slight positive flow offset that is likely instrumental in nature.

FIG. 12. The perpendicular IVDF at $r = -8$ cm and $z = 170$ cm.

However, moving upstream, the complexity of the perpendicular IVDF increases dramatically. At $z = 170$ cm, there is a clear increase in the difference between the measured radial flow and what is predicted based on the projection of the measured parallel flow. Towards the plasma edge, the perpendicular IVDF becomes broader (hotter) and shows evidence of multiple ion populations. Shown in Fig. 12 is a typical perpendicular IVDF obtained at $z = 170$ cm and $r = -8$ cm. The perpendicular IVDF is well fit with two Maxwellian distributions with temperatures of 0.35 eV and 0.30 eV and relative normalized densities of 1.0 and 0.30 for the bulk and flowing populations, respectively.

By $z = 164$ cm, the discrepancy between the radial flow in the core plasma and the projected parallel flow has further increased. In fact, the perpendicular IVDFs yield a radial speed of 2000–3000 m/s, suggesting a significant additional ion accelerating mechanism in the perpendicular direction—reminiscent of the curved DL structures mentioned earlier and also consistent with the radial expansion of the beam ions identified in Fig. 7. At the edge of the plasma at $z = 164$ cm, the velocity spread has increased so much that a single (and naive) Maxwellian fit to the perpendicular IVDF yields an ion temperature of 1–2 eV. Using a single temperature to describe the perpendicular IVDF is clearly inappropriate, but the substantial spread in velocities suggests the presence of a significant source of particle energization in the perpendicular direction to the local magnetic field. It is important to remember that these IVDF measurements are obtained over long time intervals and therefore the particle energization mechanism is a steady-state phenomenon that is also clearly multi-dimensional.

IV. PROBE MEASUREMENTS

To measure the electric field structure throughout the plasma plume for the same plasma conditions of the IVDF measurements (downstream magnetic field of 108 G), the triple probe was scanned through the same locations while measuring the two-dimensional (radial and axial), steady-state, electric field. The vector electric field in the plasma plume is shown in Fig. 13. Also shown in Fig. 13 as dashed lines is the expansion of magnetic flux tubes in the

FIG. 13. The average DC electric field for a downstream magnetic field of 108 G. Fifty measurements were taken at each location. Because the triple probe is offset in the negative radial direction, the measurement range is asymmetric about the plasma axis.

downstream region. The two outermost flux tubes map back to a radial location approximately 1 cm from the inner surface of the Pyrex vacuum chamber under the rf antenna in the source. Past studies of expanding helicon plasmas have employed emissive probes²⁸ or interpretations of RFEA measurements to determine the local plasma potential throughout the DL region.⁸ Most studies have only measured the plasma potential along the system axis. Those that have measured the radial and axial structure of the plasma potential have reported curved equipotentials.^{19,28,34} Very recent measurements have reported regions of electric fields pointed upstream³⁵ and significant gradients in plasma potential towards the plasma edge.¹⁹

Here we have measured the steady-state electric field directly using the triple probe. In the center of the plasma, the magnitude of the axial electric field is small, between 1 and 10 V/m. For the average axial electric field at $r = 0$ cm, which is 4.78 V/m and points upstream, the ion beam will slow from 8320 m/s to 8070 m/s over 0.18 m. According to the measurements shown in Fig. 14, the velocity drops to 8040 m/s, over this range.

FIG. 14. Ion beam velocity as a function of axial distance for the data of Fig. 8. The black line indicates the velocity at $z = 171$ cm.

Therefore, the electric field is sufficient to explain all (to within measurement error) of the observed ion beam slowing. Ion-neutral collisions³⁶ appear to have little effect on the ion beam velocity. Further downstream, the axial electric field on axis decreases, consistent with other experiments.²⁶ Moving outwards, the axial electric field and the radial electric field increase. Both field components then abruptly switch sign across the outermost flux tube shown in Fig. 13. The switch in sign of the field components maps along the field line over the entire downstream region sampled. This electric field structure is clearly field aligned and is a region of ion density depletion, i.e., an ion hole as $\nabla \cdot E < 0$. The large scale radial flows and broad perpendicular IVDFs, particularly at $z = 164$ cm, are entirely consistent with these measured electric fields. The average radial electric fields from $r = 0$ cm to just before the ion hole are 91.2 V/m, 25.5 V/m, 14.0 V/m, and 29.3 V/m at $z = 164$ cm, $z = 170$ cm, $z = 175$ cm, and $z = 180$ cm, respectively. These field strengths are more than sufficient to accelerate the ions to the perpendicular velocities observed in Fig. 11.

We are unable to access the last few centimeters of the LEIA chamber to perform a measurement of the electric field through the ion acceleration region. However, we are able to

FIG. 15. (a) Electron energy probability function and (b) the plasma potential as a function of radial location at $z = 112$ cm, inside the plasma source.

perform plasma potential measurements in the helicon source upstream. Shown in Fig. 15 are measurements of the electron energy probability function (EEPF) and the plasma potential at $z = 112$ cm. While the plasma potential measurements shown in Fig. 15 extend beyond 5 cm, the actual plasma source tube is only 5 cm in radius. The measurements were performed in the larger diameter stainless steel chamber downstream of the plasma source tube. Along the plasma axis, the upstream plasma potential is 35 V. The plasma potential measurements indicate that within the plasma source there is a radially outward electric field due to a potential drop of 10–15 V. Measurements of the downstream plasma potential on axis yield an upstream-downstream total plasma potential difference of 35 V. This number falls within the range of plasma potential differences reported in other experiments.^{19,35} Strong acceleration of ions outwards into the walls of the glass chamber is consistent with our observations of significant sputtering of the glass walls when the plasma source is operated at the low pressures required to create ion beams. The sputtering is severe enough to create small holes in the glass tube (2–3 mm in diameter) or to completely etch through the glass walls. Similarly strong radial electric fields have been reported in other expanding plasmas at the junction of the plasma source and the expansion chamber.²⁸

The upstream EEPF measurements transition from a single Maxwellian energy distribution in the plasma core to a plasma with a significant energetic, “fast,” electron component by $r = 3$ cm. A calculation of the electron skin depth $\delta = c/\omega_{pe}$ for these plasma conditions yields a value of ~ 2 cm, consistent with location of the potential dip at 3 cm in Fig. 15(b). In other words, the expected radial location for peak rf absorption matches the upstream region with energetic electrons and a strong electric field that then maps along the expanding magnetic field downstream. The same explanation for an observed annulus of fast electrons in an expanding helicon plasma was independently proposed by Takahashi *et al.*³⁷

Significant electrostatic wave activity is also observed in the time-resolved electric field measurements. Shown in Fig. 16 is the low frequency power spectrum as a function of radial location at $z = 164$ cm. The same measurements are

FIG. 16. The low frequency power spectrum for a single tip of the triple probe at $z = 164$ cm as a function of frequency and radial position.

FIG. 17. The low frequency power spectrum for a single tip of the triple probe at $z = 180$ cm as a function of frequency and radial position.

shown in Fig. 17 for $z = 180$ cm. Frequencies below 300 Hz and above 50 kHz are omitted because they show little spatial variation. There is clearly stronger wave activity in the center of the plasma. At the plasma edge, i.e., $r = -12$ cm, there is effectively no wave activity. The radial region with significant wave activity expands in radius further downstream of the double layer, suggesting that waves are excited upstream and damp with distance downstream. Previous measurements in this system have identified a number of instabilities associated with ion beam formation.^{38,39} The 17 kHz wave, propagating primarily axially, was previously determined to be an ion acoustic wave.⁴⁰ The width of the peaks in the power spectra is consistent with an active damping mechanism in these plasmas. Detailed analysis of the wave activity is left for future work.

V. DISCUSSION

These measurements suggest a new model of the DL formation process in expanding, low-density, helicon source plasmas. At low neutral pressures, the rf power couples strongly to electrons within one skin depth of the chamber wall. The electrons are strongly heated, forming a high energy, low collisionality energetic tail. These energetic,

magnetized²¹ electrons exit the source by streaming out along the expanding magnetic field. As they pass through the neutral gas, these energetic electrons create an annulus of increased plasma density through enhanced ionization upstream and downstream of the source-expansion chamber junction. The annulus of increased plasma density appears as a hollow plasma density profile. Hollow plasma density profiles downstream of the DL were recently reported by other researchers^{19,41} and similar hollow profiles are observed in these experiments (see Fig. 18). The ring of high-energy, magnetized, electrons streaming out along the expanding magnetic field naturally creates a significant upstream-downstream charge imbalance. The resulting ambipolar electric field⁴² pushes out a centrally confined cylinder of energetic ions, an ion beam. As noted previously, these ions, with bulk speeds of 8–10 km/s, complete only 1/4 of a gyro-orbit while traveling 16 cm in the axial direction. The ions are essentially unmagnetized and are effectively detached from the magnetic field,²¹ i.e., their motion is too fast for adiabatic constraints such as μ conservation to hold.

It also appears that the beam ions respond to the radial component of the ambipolar electric field established by energized electrons flowing along magnetic field lines near the plasma radial periphery. Since the beam ions get a boost in perpendicular velocity, there is a radial displacement of the hollow beam radial profile as beam ions are tugged along with the expanding electron rich annulus at the plasma periphery. The perpendicular energization of beam ions is strongest at the furthest upstream locations measured because the annulus of energetic electrons is closer to the central axis upstream and because the electric fields are stronger there as well.

The self-consistent physical picture that emerges is that of two nested hollow concentric cylinders of plasma, a hot electron dominated outer cylinder encircling the inner cylindrical ion beam. As the hot electrons and bulk ions follow the magnetic field lines, they drag the beam ions radially outward and downstream through the intermediary electric field. The magnetic forces on beam ions are inconsequential to their radial expansion or their parallel acceleration. The electric field arising from the field-aligned, ion hole structure determines the rate of radial expansion of the beam ions. Since both the energetic electrons and the ion beam travel from the source to the expansion region, i.e., the energetic electrons are not moving antiparallel to the ions, the observed particle motion is inconsistent with expectations for a DL that stretches across the entire expansion region (see Fig. 2).

The hypothesis proposed here for the origins of the strong potential difference between the source and expansion region that spontaneously appears in these low pressures is that expanding plasmas is consistent with a variety of other phenomena that have been reported in these sources. For example, Thakur *et al.* have demonstrated significant changes in ion beam creation, plasma density profiles, instability growth, and plasma rotation depending on whether or not the inner surface of the expansion chamber is conducting or insulating.⁴³ Those observations reflect the critical role electrons in the plasma edge flowing downstream from the

FIG. 18. The electron density throughout the plasma plume as measured with an rf compensated planar Langmuir probe on the scanning probe. The field-aligned, high-density structure occurs in the same region of the plasma plume as the strong electric fields.

source play in setting up the overall potential structure upstream and downstream of the expansion location. *Charles* and *Boswell* were one of the first to identify the neutral pressure threshold for DL formation⁸ and have reported the existence of energetic electrons²⁰ and hollow density profiles¹⁹ in their experiments. Other groups have also reported hints of energetic electrons in their expanding helicon source plasmas.^{35,44,45}

Prior work in our own laboratory found a strong correlation between enhanced upstream density and the appearance of the downstream ion beam. For rf coupling levels that did not result in formation of an ion beam, the upstream plasma density was lower than when a beam formed.¹⁷ This is consistent with the idea that energetic electrons were passing through the upstream plasma with sufficient energy to enhance ionization of the background neutral gas.

While these reports of energetic electrons flowing downstream into the expansion region are inconsistent with a DL, they are consistent with this new paradigm. The perpendicular IVDFs reported here have introduced a fundamentally different perspective in the study of ion beam formation in expanding helicon plasmas. The upstream ions are not only accelerated along the field but also by a complex, multi-dimensional, annular electric field structure that results in an effective radial ion temperature of many eV. The radial electric field strengths are consistent with the measured perpendicular IVDFs.

One interpretation of the perpendicular IVDF measurements is that the perpendicular distribution outside $r = \pm 5$ cm consists of two ion populations. One population, centered around 0 m/s, is created locally by the annulus of hot electrons. The second population consists of ions flowing downstream that have been accelerated radially outwards by the radial electric field. The resultant highly anisotropic ion distributions are likely to drive a variety of plasma instabilities.

As seen in other experiments, LIF measurements of the $v = 8000$ m/s ion beam fade with downstream distance in a manner consistent with quenching of the initial ion metastable state needed for LIF. The calculated quenching cross section of 2.7×10^{-18} m² is comparable to expectations for inelastic collisions of the ions with electrons. Perhaps somewhat surprising was the resonant effect of the downstream magnetic field strength on the ion beam velocity. The ion beam velocity increased from 8000 m/s to 12 000 m/s, and the beam amplitude also increased in these experiments for a downstream magnetic field of 31 G. Therefore, for plasma thruster applications, a finite downstream magnetic field may prove beneficial even though additional resources are required to produce the downstream magnetic field.

VI. CONCLUSION

These measurements suggest a new paradigm for the origin of ion beams observed in expanding helicon plasmas. This paradigm provides a self-consistent explanation for a variety of other phenomena that have been reported in other helicon source experiments when ion beams are observed. Perhaps most importantly, this new model of spontaneous

ion beam creation in expanding plasmas does not require the formation of a classical DL as quasineutrality is enforced by spatially distinct regions of downstream directed ion and electron fluxes and cross field currents. Such an explanation resolves the longstanding inconsistency between DL theory predictions of ion acceleration regions tens of Debye lengths long and measurements that are hundreds of Debye lengths long in helicon and other expanding plasma experiments.^{1,46} Future studies of these plasmas will focus on the electrostatic wave activity and its impact on the complex IVDFs reported here.

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