Pressure dependence of an ion beam accelerating structure in an expanding helicon plasma

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(Received 7 December 2017; accepted 11 January 2018; published online 2 February 2018)

We present measurements of the parallel ion velocity distribution function and electric field in an expanding helicon source plasma plume as a function of downstream gas pressure and radial and axial positions. The ion beam that appears spontaneously in the plume persists for all downstream pressures investigated, with the largest parallel ion beam velocities obtained for the lowest downstream pressures. However, the change in ion beam velocity exceeds what would be expected simply for a change in the collisionality of the system. Electric field measurements confirm that it is the magnitude of the potential structure responsible for accelerating the ion beam that changes with downstream pressure. Interestingly, the ion density radial profile is hollow close to the end of the plasma source for all pressures, but it is hollow at downstream distances far from the source only at the highest downstream neutral pressures. Published by AIP Publishing.

https://doi.org/10.1063/1.5018583

I. INTRODUCTION

Ion beams appearing spontaneously in helicon plasmas expanding into a divergent magnetic field have been the subject of many studies since their discovery over a decade ago.1 The ion beam appears in low pressure, expanding helicon plasmas regardless of source size, magnetic field ratio (upstream to downstream), and overall magnetic field strength.2–5 The spontaneous creation of ion beams in an expanding plasma is of particular relevance to the development of helicon source plasma thrusters,6,7 to solar wind acceleration models,8 and to particle acceleration processes during magnetic reconnection.9

Soon after their discovery, various researchers proposed explanations for the ion beam creation process that focused on current-free, double layers (DLs) as the phenomenon responsible for the ion beams. DLs are narrow, local regions of strong electric potential gradient isolated from plasma boundaries. In its simplest form, a DL consists of two spatially separated charge layers, one positive and one negative, and acts very much like a sheath. DLs are free-standing structures that can appear anywhere within the plasma, and the field-aligned potential difference in magnetized plasmas is self-consistently generated by the plasma itself.1 Because classic DL theory requires the existence of four particle populations—a trapped electron population in the high potential (upstream) region, a trapped ion population in the low potential (downstream) region, an electron population that is accelerated from downstream to upstream, and an ion population that is accelerated from upstream to downstream—the appearance of an ion beam accelerated from upstream to downstream has been used as a signature of DL existence in subsequent experimental studies. In such studies, the ion velocity distribution function (IVDF) is typically measured with laser induced fluorescence (LIF)10,11 or a retarding field energy analyzer (RFEA).1 RFEAs and emissive probes have also been used to map the rapid change in plasma potential that appears where the magnetic field gradient is the largest in expanding helicon plasmas.4,12

While ion beams in these expanding plasmas are reported for sources with1,10,11 or without12 an applied, downstream, dc magnetic field, the specific roles in ion beam formation played by source geometry and other plasma source control parameters remain unclear. For example, Chen predicted that the spatial location of the acceleration region is determined by where the plasma chamber expands and not the location of the peak of the magnetic field gradient.13 Thakur et al. showed experimentally that the conductivity of the downstream vacuum chamber walls plays an important role in ion beam formation.14 There is no uncertainty about the importance of the plasma source neutral gas pressure as a key control parameter for ion beam formation in helicon sources. Common to nearly all ion beam observations in helicon sources is a pressure threshold of a few mTorr in the plasma source.15 Previous studies in our experimental facility have also suggested a significant decrease in the ion beam velocity with increasing downstream neutral gas pressure—even when all other source parameters, including plasma source pressure, are held fixed.16 What was not clear in those studies, however, was if the decrease in ion beam velocity is purely a result of collisional slowing of the beam (and/or charge exchange with neutrals) or from a reduction in the accelerating electric field in response to increasing downstream neutral pressure.

In the new paradigm for ion beam formation in expanding helicon source plasmas recently proposed by Aguirre et al.,17 downstream plasma conditions play a critical role in determining the structure of the ion accelerating electric field
through modification of the collisionality of fast electrons created in the helicon source. Therefore, the experiments described here focus exclusively on the effects of the downstream neutral pressure on the ion beam velocity and the structure of the ion accelerating electric field (holding all other plasma source parameters constant). As noted by others, the electric field structure responsible for the ion acceleration is a multi-dimensional, “U” shaped region, and therefore, multi-dimensional measurements of the electric field and the ion beam are required to fully investigate the response of the ion beam formation process to changing downstream neutral pressure.

II. EXPERIMENTAL APPARATUS

The Hot hELIcon eXperiment (HELIX) plasma source consists of a 61 cm long, 10 cm diameter Pyrex tube connected to a 91 cm long, 15 cm diameter stainless steel chamber. Ten water-cooled electromagnets produce a steady state axial magnetic field of 0–1200 G in the source. An rf amplifier supplies up to 2 kW power over a frequency range of 6–18 MHz through a π matching circuit and a 19 cm half wave helical antenna to create the plasma. The source plasma expands into a large vacuum chamber, the Large Experiment on Instabilities and Anisotropies (LEIA), which consists of a 61 cm long, 10 cm diameter Pyrex tube connected to a 91 cm long, 15 cm diameter stainless steel chamber. Ten water-cooled electromagnets produce a steady state axial magnetic field of 0–150 G in the expansion chamber. For these experiments, the rf power was held fixed at 740 W with less than 15 W reflected power for an antenna frequency of 12.5 MHz. The source magnetic field strength was kept constant at 860 G, and the downstream magnetic field strength in the expansion chamber was held fixed at 108 G.

Three turbomolecular drag pumps maintain the base pressure in the system at \( \sim 1 \times 10^{-7} \) Torr. A precision MKS mass flow controller injects argon gas into the source chamber. The downstream pressure is measured with a capacitive manometer located 35 cm downstream of the junction between the plasma source and the expansion chamber. For all of these experiments, the gas flow was fixed at 5.5 sccm into the plasma source chamber, and the measured source pressure was \( 3.4 \times 10^{-4} \) Torr. The two 1600 l/s pumps located at the end of LEIA create a pressure differential of one order of magnitude between the source chamber and the expansion chamber. The 550 l/s pump is located at the end of HELIX and maintains the source pressure at the fixed pressure noted above.

While RFEAs are more sensitive to beam ions and are able to measure an ion beam with metastable state ion densities too small for LIF to detect, the sheath in front of the RFEA distorts the true nature of the parallel IVDF. RFEAs are also a perturbative diagnostic technique. LIF provides a direct and non-perturbative measurement of the ion velocity distribution function. For the LIF measurement of the argon IVDF, a ring dye laser system is tuned to 611.662 nm (vacuum wavelength) to pump the Ar II 3\(^2\)D\(_{5/2}\) metastable state to the 4\(^p^2\)F\(_{7/2}\) state, which then decays to the 4\(^p^2\)D\(_{5/2}\) state by emitting a 460.96 nm photon. In these experiments, the laser is swept over 27 GHz to cover the entire IVDF. Approximately 10% of the laser beam is split off as a reference signal for the measurement with a wavemeter and transmission through a reference iodine cell. The remaining 90% is modulated with a 5 kHz mechanical chopper and coupled into an in situ scanning probe inside the LEIA chamber. The injection direction is selectable between parallel and perpendicular to the system axis. The fluorescent emission is collected by the same probe and coupled into a filtered photomultiplier detector. The modulated signal is lock-in amplified with a long time constant, \( \sim 3 \) s, for each IVDF measurement. A typical LIF measurement along with the reference molecular iodine cell spectrum is shown in Fig. 2. The molecular iodine spectrum provides a zero-velocity reference for the measurement of the absolute velocity of the argon ions. When the measured IVDF is close to Maxwellian, the bulk ion velocity and ion temperature are obtained from a Maxwellian fit to the measured IVDF. Noise and uncertainty in the measured wavelength limit the accuracy of the flow measurements to \( \sim \pm 50 \) m/s. Typical errors in the ion temperature determination are \( \pm 0.01 \) eV. Doppler broadening dominates over other line broadening mechanisms (Stark broadening, power broadening, and instrumental broadening) and is larger than the natural linewidth of the absorption line. The in situ probe includes a three tip electrostatic probe offset 2 cm in the radial direction from the LIF.
measurement. The electrostatic probe provides measurements of fluctuation spectra and steady-state electric field in the axial and radial directions.

III. EXPERIMENTAL RESULTS

To vary the downstream neutral pressure for fixed plasma source conditions, the two downstream, 1600 l/s turbomolecular drag pumps were set to one of the three possible speeds: 0 Hz (that is, the gate valve in line with the pump was closed), 400 Hz, and 600 Hz. With two pumps, the five possible combinations (600/600, 400/600, 400/400, 0/600, and 0/400) yield downstream pressures of $3.4 \times 10^{-5}$ Torr, $3.8 \times 10^{-5}$ Torr, $4.2 \times 10^{-5}$ Torr, $7.0 \times 10^{-5}$ Torr, and $7.6 \times 10^{-5}$ Torr, respectively.

Three representative parallel IVDFs are shown in Figs. 3(a)–3(c) for a downstream pressure of $4.2 \times 10^{-5}$ Torr (pump speeds of 400/400). All four were obtained at an axial position of $z = 164$ cm, approximately 5 cm downstream of the junction of the plasma source with the expansion chamber. The parallel IVDF shown in Fig. 3(a), obtained at a radial location of $r = -10$ cm, is that of a single, stationary, ion population. Closer to the axis of the system, at $r = 4$ cm, the parallel IVDF is dominated by an ion beam at a velocity of $-9020$ m/s [Fig. 3(b)]. Because the laser injection direction is towards the source, a negative flow corresponds to ion flow into the expansion chamber. At an intermediate radial distance of $r = 6$ cm [Fig. 3(c)], both the stationary ion population and the ion beam population coexist. The ion beam velocity is slightly larger at the intermediate radial distance, $-9654$ m/s, and the two populations are nearly equal in amplitude.

Increasing the downstream pressure [Fig. 3(d)] to $7.6 \times 10^{-5}$ Torr by dropping the downstream pumping speeds to 0/400 introduces a significant change in the parallel IVDF at $r = 10$ cm. In addition to the stationary background population, an ion beam population appears at a velocity of $-7148$ m/s and a third ion population appears at roughly $-1000$ m/s. At this pressure, the ion beam population is considerably smaller in amplitude than the background stationary ion population. For less than a doubling of the downstream neutral pressure, there is a substantial change in the properties of the ion acceleration region in the expanding plasma.

To provide a more complete understanding of the evolution of the parallel IVDF at the same axial location ($z = 164$ cm) for pressures of $7.6 \times 10^{-5}$ Torr and $3.8 \times 10^{-5}$ Torr, IVDF measurements obtained every 2 cm in the radial direction (from $r = -10$ cm to $r = 10$ cm) are stacked in two-dimensional plots as a function of radial location and velocity and plotted in Fig. 4. In Fig. 4(a) and 4(c), each IVDF measured is corrected for differences in the detection system gain across the radial scan (the gain is changed to maintain the LIF signal-to-noise at an acceptable level as the plasma density decreases approximately a factor of five from the outer plasma to the inner plasma in the expansion region). The amplitude of the LIF signal provides a measure of the density of the initial metastable ion state used in the LIF scheme, which is proportional to a function of the ion density, the electron density, and the electron temperature. Hollow density profiles are to be expected given the low neutral pressure and relatively large rf powers used (the hollow neutral profile may also result from neutral depletion).
In Figs. 4(b) and 4(d), the same measurements are normalized to the peak amplitude of the IVDF measurement. The normalization process has the effect of removing the strong density dependence in the LIF contour plots and therefore highlights the localization of the ion beam structure in plasma. The ion beam velocity increases from \( \sim 9.2 \text{ km/s} \) to \( \sim 7.1 \text{ km/s} \) as the pressure is decreased. In both types of normalized plots, it is clear that the ion beam dominates the parallel IVDF in the inner core of the plasma. At the larger radial locations, the ion population is essentially a stationary single Maxwellian population. The difference in argon beam velocities from 9.2 km/s to 7.1 km/s corresponds to a change in the accelerating potential difference (based on the change in ion beam energy) of 15.1 V to 10.2 V.

The change in the ion beam velocity measured on axis \((r = 0 \text{ cm})\) as a function of pressure is shown in Fig. 5 for three different axial locations \(z = 164 \text{ cm}, z = 170 \text{ cm},\) and \(z = 175 \text{ cm}\). The amplitudes of the IVDFs in Fig. 5 have been self-normalized as described above. These measurements provide a means of distinguishing between two factors influencing the measured ion beam velocity: changes in the magnitude of the accelerating potential due to changes in the downstream pressure or slowing of the ion beam due to increased collisionality. At the furthermost upstream location, \(z = 164 \text{ cm}\), any beam slowing due to collisions is minimal due to proximity of the measurement location to the region where the acceleration occurs. At this axial location, there is a 1.1 km/s decrease in ion beam velocity from...
8.5 km/s to 7.4 km/s, suggesting a change in the potential difference (based on the ion beam energy) upstream to downstream from 15 V to 11.4 V. At \( z = 170 \) cm, the ion beam velocity decreases from 8.25 km/s to 7.34 km/s, a velocity change of 0.91 km/s.

At the furthest downstream location measured, the ion beam velocity decreases by 1.0 km/s from 8.2 km/s to 7.2 km/s with pressure, an energy change of 3.2 eV. Attributing the nearly constant ~0.9 km/s component of the decrease in ion beam velocity to changes in the potential difference due to the increased downstream pressure, the remaining ~0.2 km/s decrease in beam velocity must result from collisional slowing of the ions by collisions with ions and neutrals.

Based on Langmuir probe density measurements and the scale of the vacuum chamber, the ion and neutral densities are constant over the 11 cm measurement range. Therefore, the collisional slowing of the ion beam velocity due to collisions, for a nearly constant beam velocity, is approximated by

\[
\Delta E = \frac{1}{2} \left( m v_i^2 \right) - \frac{1}{2} \left( m v_i^2 \right) \approx \int_1^2 \nu m v_i^2 dt / 2
\]

\[
= \int_1^2 (m v_i^2 / 2) (n_i \sigma_{ii} + n_0 \sigma_{in}) dx, \tag{1}
\]

where \( \Delta E \) is the change in energy, \( \nu \) is the total collision frequency, and the integral is over the initial to the final measurement position. Through the definition of the collision frequency, \( \nu_{ib} = n_i \sigma_{ii} \), the integral over time is converted to an integral over the travel distance of the ions. \( \sigma_{ii} \) is the ion-ion collision cross section, \( n_i \) is the background ion density, \( \sigma_{in} \) is the ion-neutral collision cross section, \( n_0 \) is the background neutral density. Using the measured ion density of \( n_i = 5 \times 10^9 \text{ cm}^{-3} \) (from probe measurements) for a downstream neutral pressure of \( 4.2 \times 10^{-5} \text{ Torr} \) \( (n_0 = 1.2 \times 10^{12} \text{ cm}^{-3} \text{ at } 300 \text{ K}) \), an ion temperature of 0.26 eV (from LIF) to calculate the ion-ion Coulomb collision cross section\(^{21} \) \( (6 \times 10^{-14} \text{ cm}^2) \), and the ion-neutral charge-exchange cross section for the argon beam ions at energies of ~13 eV (Ref. 24) \( (4 \times 10^{-15} \text{ cm}^2) \), Eq. (1) becomes

\[
0.7 \text{ eV} = (11 \text{ cm})(13 \text{ eV})(4.6 \times 10^{-4} \text{ cm}^{-1}) + 4.8 \times 10^{-3} \text{ cm}^{-1}, \tag{2}
\]

where the first term on the right hand side is the ion-ion contribution and the second term is the much larger, by a factor of nearly 10, ion-neutral contribution. The predicted energy decrease of 0.7 eV is considerably smaller than the measured change in beam energy.

The significant aspect of this analysis is that the slowing of the beam due to ion-neutral collisions is too small to account for the total observed change of 3.2 eV in ion beam energy as the downstream pressure is increased. Therefore, the bulk of the change in the ion beam velocity likely arises from changes in the upstream to downstream potential difference responsible for accelerating the ions (and thus the ion beam energy is reflective of the upstream to downstream potential difference). In other words, the increased collisionality arising from increased downstream neutral pressure is insufficient to explain the decrease in ion beam velocity. The accelerating electric field structure must also depend on the downstream neutral pressure.

Consistent with the hypothesis that changes in the downstream pressure introduce a fundamental change in the potential difference in the expansion region are the measurements of the downstream electric field at \( z = 164 \) cm and \( z = 170 \) cm shown in Fig. 6. As the downstream neutral pressure increases, the electric field at \( z = 164 \) cm undergoes significant changes in amplitude, particularly along the edges of the plasma where energetic electrons are observed to stream out from the source into the expansion chamber.\(^{17,25} \) The energetic electrons create an annulus of increased plasma density through enhanced ionization upstream and downstream of the source-expansion chamber junction. The radius of the annulus maps along the divergent magnetic field to a radius of one electron skin depth from the rf antenna in the plasma source.\(^{17} \) Previous measurements demonstrate that

FIG. 6. The steady-state electric field at (a) \( z = 164 \text{ cm} \) and (b) \( z = 170 \text{ cm} \) as a function of radius and downstream neutral pressure. The inset legend provides a scale for the magnitude of the electric field.
the energetic electrons are created upstream by damping of the injected rf power used to create the plasma.\textsuperscript{17} The combination of the annulus of energetic electrons and the ion beam localized to the center of the discharge enforces an overall quasineutral flux of plasma from upstream to downstream without formation of a double-layer structure.\textsuperscript{17} While collisional slowing of the ions is not responsible for the change in ion velocity, it seems very possible that increased downstream pressure could reduce the mean free path of the energetic electrons and thereby affect the ambipolar electric field created by the annulus of energetic electrons.

To better understand the nature of the bipolar (as a function of radial location), magnetic-field aligned, electric field structure evident in Fig. 6, the net charge density is calculated from the spatial structure of the electric field

$$\nabla \cdot \mathbf{E} = -e(n_i - n_e)/\epsilon_0. \quad (3)$$

Shown in Fig. 7 is the radial derivative of the electric field at two different downstream locations, $z = 164$ cm and $z = 170$ cm, and two different downstream pressures, 7.6 $\times$ 10$^{-5}$ and 3.8 $\times$ 10$^{-5}$ Torr. The large positive peaks correspond to a depletion of ions relative to electrons, i.e., an ion hole.\textsuperscript{26–28} In relative density units ($\Delta n/n$), the depth of the ion hole is relatively small, less than 0.1%. At both downstream locations, the radial location of the ion hole moves inward with increasing downstream pressure. The change in the radial location of the ion hole region is consistent with the LIF measurements of the spatial extent of the background ion population. At $z = 164$ cm, the inner edge of the background ion population shifts outward from $r = -2.5$ cm to $r = -3.5$ cm as the pressure decreases from 7.6 $\times$ 10$^{-5}$ Torr to 3.8 $\times$ 10$^{-5}$ Torr.

These measurements indicate a spreading of the annulus of energetic electrons with decreasing pressures, suggesting that the radial extent of the energetic electrons depends strongly on the downstream neutral pressure. Along the axis of the source, the weak electric field changes in both the magnitude and the direction as the pressure increases. The axial electric field in the center (at $r = 0$ cm) is small and in the range from 3.0 to 14.0 V/m. When integrated over the 11 cm measurement range, the expected change in the ion beam velocity is 0.1–0.45 km/s, is consistent with the observed change of 0.2–0.3 km/s at different pressures. Close to the ion hole, the axial electric field is larger at lower pressure than that at high pressure. Thus, there is a larger potential gradient change ($|\nabla \Phi| = |\mathbf{E}|$) in the axial direction along the sides of the ion hole at lower pressure.

We note that dependence of the accelerating electric field magnitude on downstream neutral pressure is not entirely inconsistent with the predictions of the theoretical model of ion beam formation based on creation of a current-free double layer by Lieberman et al.\textsuperscript{29} In their model, a double layer forms due to a requirement to balance upstream and downstream particle fluxes to the chamber walls. If the spatial distribution of an annulus of energetic electrons, and therefore the downstream plasma density profile, is strongly modified by the downstream pressure, the accelerating structure that forms in the plasma expansion region would also change with downstream neutral pressure.

The highly localized electric field radial gradients in Fig. 7 should give rise to sheared azimuthal flows, and sheared azimuthal flows are often associated with the excitation of a wide range of plasma instabilities.\textsuperscript{30} Shown in Fig. 8 are power spectra of fluctuations measured with a single tip of the triple probe at $z = 164$ cm for two different pressures as a function of radial location. Previous work at WVU demonstrated a strong correlation between low frequency wave activity on axis and DL strength.\textsuperscript{31–33} There is a clear radial structure in the broadband activity below 15 kHz and in the distinct peaks above 15 kHz. As in the prior on-axis measurements, the case with more wave activity (the higher pressure case) is associated with a slower ion beam. For both pressures, the bulk of the wave activity is confined to the center of the discharge—the region where the ion beam is observed. Note that because the probe accesses the plasma from the “positive r side,” measurements at large negative radial locations are affected by the body of the probe blocking some of the plasma plume. In other words, the spatial asymmetry in the probe measurements is likely an instrumental artifact and therefore our analysis is restricted to the structures seen in the upper half of Fig. 8.
Above 15 kHz, the power spectrum along the axis ($r = 0$ cm) of the lower pressure case is dominated by a wave at a fundamental frequency of 17.5 kHz and what appears to be its harmonic at 35 kHz. Towards the edge of the plasma plume, another wave peak appears around 22 kHz along with its apparent harmonic at 45 kHz. In the higher pressure case, the first spectral feature along the axis appears at 21 kHz and there is only a weak additional wave at 42 kHz.

Surprisingly, the higher frequency waves are not harmonics. In the frequency spectrum versus pressure data shown in Fig. 9(a), at $r = 6$ cm and $z = 164$ cm, the amplitude of the discrete peaks fades with increasing pressure and new peaks appear at distinctly different frequencies at the highest pressure. Further downstream at $z = 170$ cm and $z = 175$ cm [as shown in Figs. 9(b) and 9(c)], the frequency of the $\sim 17.5$ kHz wave shifts downward with increasing pressure while the frequency of the higher frequency peak at $\sim 35$ kHz shifts upward with increasing pressure. Based on measured frequencies and wavelengths, previous studies have identified these electrostatic waves as beam driven ion acoustic instabilities. While increasing neutral pressure increases wave damping and could therefore explain the decrease in wave amplitude at higher pressures, an explanation for the oppositely directed frequency shifts of the two other major peaks has not been identified. The behavior is consistent with both peaks being parametrically driven daughter waves from two coupled waves, one at a fixed frequency and one whose frequency increases with increasing neutral pressure. Such a process would shift the difference wave lower in frequency and the sum wave to a higher frequency. However, while parametric waves have been identified in helicon sources before, there are no significant peaks in the fluctuation spectra at $\sim 9$ kHz and 25 kHz, the parent frequencies required to explain the observed spectra.

Additional evidence in support of the hypothesis that the ion beam accelerating structure undergoes substantial changes with increasing downstream neutral pressure is the dramatic change in the radial profile of the parallel IVDF with changing downstream (Fig. 10). Shown in Fig. 10 are normalized contour plots of parallel IVDFs obtained at $z = 175$ cm as a function of radial location and velocity at four different downstream pressures. Somewhat counterintuitively, the radial distribution of the background ion populations is hollow at higher pressure, and low energy ions appear at all radial locations at lower downstream pressures. Since collisions are reduced for the lower downstream neutral pressures, the filling in of the low energy portion of the IVDF at lower neutral pressures suggests that at lower neutral pressures, the gradient in upstream to downstream potential steepens (becoming more “double-layer” like), thereby allowing the ions produced locally by electron-impact ionization to move further upstream before being reflected by the higher upstream potential.

IV. SUMMARY

Measurements of the argon parallel IVDF in the plume of an expanding helicon source indicate that the downstream neutral pressure plays a key role in controlling the velocity of the ion beam ejected from the helicon plasma. This result has important ramifications for the development of plasma thrusters based on the phenomenon of spontaneous ion beam formation in expanding rf plasmas. All tests of such systems have been performed in laboratory chambers with various levels of downstream pressure. The downstream pressure in a space application is likely to be significantly different. Therefore, thruster performance in space may differ significantly from expectations. Projecting to zero downstream pressure based on the measurements shown in Fig. 10 yields an ion beam velocity of 10.8 km/s (a potential drop equal to the final beam energy of 24 eV); a roughly 50% increase in beam velocity over the velocity at the highest pressure is reported here.

The radial derivative of the electric field is consistent with the formation of a magnetic field-aligned ion hole that weakens in strength and moves radially inward with increasing downstream pressure. Electric field fluctuation measurements show that instabilities, probably driven by the
strong shear flows at the boundaries of the ion hole, are confined to the region of the plasma where the ion beam dominates the IVDF.

ACKNOWLEDGMENTS

This work was supported by U.S. National Science Foundation Grant No. PHY-1360278 and the China Scholarship Council (award to Xiao Zhang for one year study abroad at West Virginia University).


FIG. 9. The low frequency electrostatic fluctuation power spectrum from a single tip of the triple probe at \( r = 6 \) cm as a function of downstream neutral pressure for positions of (a) \( z = 164 \) cm, (b) \( z = 170 \) cm, and (c) \( z = 175 \) cm.

FIG. 10. Normalized contour plots of the parallel IVDF as a function of radial location and velocity at \( z = 175 \) cm for downstream pressures of (a) \( 7.6 \times 10^{-3} \) Torr, (b) \( 7.0 \times 10^{-3} \) Torr, (c) \( 4.2 \times 10^{-3} \) Torr, and (d) \( 3.5 \times 10^{-3} \) Torr.
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