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Abstract
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Keywords
ion beam, double layer, helicon plasma

Disciplines
Atomic, Molecular and Optical Physics | Physics | Plasma and Beam Physics

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Ion beams in multi-species plasmas

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I. INTRODUCTION

In 1929, Irving Langmuir was the first to study double layers in the laboratory when he called them double-sheaths.[1] Since then, double layers have been invoked in studies of basic plasma science,[2] the use of ion beams accelerated by the double layer for plasma propulsion,[3–5] and space-relevant plasma phenomena.[6] Double layers are simply adjacent layers of opposite charge, resulting in a large potential drop. The effect of this large potential drop is to accelerate particles to supersonic speeds, much like a sheath. Double layers act like sheaths, but double layers can form anywhere in a plasma whereas sheaths form near the surface of an object inserted into a plasma or at a boundary. Sheath thicknesses are on the order of the Debye length, but double layers can be a few Debye lengths thick[7] or several hundred.[8] Recent work suggests that ion beams created in expanding helicon plasmas are not formed by a true double layer because the length of the acceleration region is so much longer than the Debye length.[9,10]

Ions entering a sheath must obey the Bohm criterion.[11] For single ion species plasmas, the Bohm criterion requires that ions entering a sheath have a velocity $v = c_s = \sqrt{k_B T_e/m_i}$. A presheath forms before the sheath to accelerate the ions up to the Bohm speed. A generalization of the Bohm criterion to plasmas with multiple ion species was proposed by Riemann.[12] Two equally valid solutions are possible. In the first, the ions reach their individual Bohm speeds at the sheath edge. In the second solution, the ions reach a common sound speed given by

$$c_s = \sum_i \left[c_{s,i}^2 \left(\frac{n_i}{n_e} \right) \right]^{1/2}, \quad (1)$$

where $\sum_i$ is the summation over the gas species i. Experiments in weakly collisional, weakly ionized plasmas containing two ion species with comparable ion densities found ion speeds consistent with the second solution.[13] No mechanism to achieve the second solution was identified until Baalrud *et al.*[14] developed a theory which demonstrated that friction arising from ion-ion instabilities could provide the necessary coupling between the different ion species. The Baalrud *et al.*[14] theory predicts that adding a lighter ion mass will result in an increase in the ion beam speed when the ion densities are equal. Conversely, adding a heavier ion mass should slow the ion beam. Recent experiments in multi-dipole devices, in which the ion infall speed was measured as a function of relative ion species density, validated the Baalrud *et al.* theory.[15–19] Experiments by Yip *et al.*[16] maintained a constant pressure at 0.7 mTorr. Severn *et al.*[17] used a Ar-Xe mixture of 0.1 mTorr (argon) and 0.04 mTorr (xenon) while adding various amounts of krypton or neon.

Low pressure, expanding helicon plasmas spontaneously form an acceleration structure, similar to a double layer, that results in an ion beam. The ions gradually accelerate over a distance of a few cm and then accelerate sharply over a narrower region, much like a presheath-sheath. Biloiu and Scime[20] conducted experiments in multi-ion, expanding helicon plasmas to determine if the infall speeds of each species behaved as predicted for different ion species in a sheath. It is important to note that Biloiu and Scime did not measure the individual ion densities by launching ion acoustic waves, but relied on the neutral gas composition fractions. The total input gas flow rate was maintained at 10 sccm. Ar-Xe and Ar-He gas mixtures were studied, but only argon and xenon ions are accessible to existing laser induced fluorescence (LIF) schemes for direct ion velocity distribution function (IVDF) measurement. The argon ion beam velocity increased linearly with the addition of xenon from ∼6.7 km/s in pure argon to ∼8 km/s for a 4% xenon fraction in the plasma source. Measurements of the argon IVDF for various Ar-He compositions revealed that, as helium was added for fractions up to 30%, the LIF signal decreased and the argon ion beam increased in velocity. In both cases, argon pressure was reduced to accommodate the additive mixture at a constant flow rate. The Ar-He (Ar-Xe) measurements were (were not) consistent with the predictions by Baalrud and Hegna for sheaths.[21]

A very different analysis of the effects of gas mixing in helicon sources was recently described by Kabir and

Niknam.[22] They argued that differences in the ionization potentials, the ionization cross sections, and the electron neutral cross sections of different ion species play a critical role in determining the plasma resistance and rf absorption profiles of mixed gas helicon sources. For example, they found that increasing the xenon fraction in an Ar-Xe mixture leads to a lower plasma resistance which, they argue, should lead to increased total ion flow speeds out of a helicon plasma thruster. An important distinction of the Kabir and Niknam work is that the calculations were for neutral gas pressures of 5 mTorr, an order of magnitude larger than the pressures usually employed in expanding helicon source experiments.

In this work, we present measurements of the effects of gas species density and pressure on the velocity of ion beams emanating from an expanding helicon plasma. Argon and xenon beam velocities are presented for five different gas mixtures: argon and helium, xenon and helium, argon and xenon, xenon only, and argon only. In all cases, the dominant beam velocity control mechanism appears to be collisionality of the downstream plasma. The theories of Baalrud *et al.*[14] do not appear to apply to the ion acceleration process in these plasmas, confirming that the ion acceleration is unlikely to result from a double layer.[10]

II. EXPERIMENTAL APPARATUS

These experiments were performed in the Hot hELIcon 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 a 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 8–18 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^{-8} Torr. High levels of ionization result in a hollow neutral pressure radial profile[23] and the large pumping rate at the end of the expansion chamber (3200 l/s) yields 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 was varied between 0.10 mTorr and 3 mTorr. At this neutral pressure, the mean free path for ion-neutral charge exchange collisions is many tens of centimeters. Previous studies at WVU established an rf frequency threshold of 11.5 MHz for the formation of a double layer (due to the frequency coupling of the rf antenna to the plasma).[24] Below this threshold, large electrostatic instabilities develop and destroy the double layer. Here, the antenna frequency was 12.5 MHz with 725 W of total rf power, less than 20 W of which was reflected. The magnetic field in the source was 860 G and the downstream LEIA magnetic field was 31 G. The measurement location was in the center of the plasma, 5 cm on the downstream side of the source/expansion chamber junction at $(r, z) = (0, 164)$ cm.

LIF is a non-perturbative diagnostic that uses the Doppler effect to directly measure the thermally broadened IVDF. For argon LIF, 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. For xenon, the laser is tuned to 605.2781 nm to pump the Xe II 5 $d^4D_{7/2}$ metastable state to the $6p^4P_{5/2}$ state, which then decays to the 6 $s^4P_{5/2}$ state by emitting 529.369 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.[25] 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.

III. LIF MEASUREMENTS

The ion beam speed downstream of the acceleration region is measured in the same location, $(r, z) = (0, 164)$ cm, for three different gas mixtures: argon and xenon, argon, and helium, xenon, and helium. A helium ion LIF scheme does not exist so only argon and xenon IVDFs are measured.

A. Single-ion species baseline

Pressure has a well-known and significant effect on ion beam formation in single-ion species plasmas.[26,27] The ion beam speed versus pressure for an argon plasma was measured to establish a baseline for the effects of pressure. Shown in Fig. 2 is the normalized IVDF (each IVDF is normalized to a maximum value of unity) versus argon neutral pressure. The argon ion beam speed decreases as pressure is increased and the distinct ion beam plus background

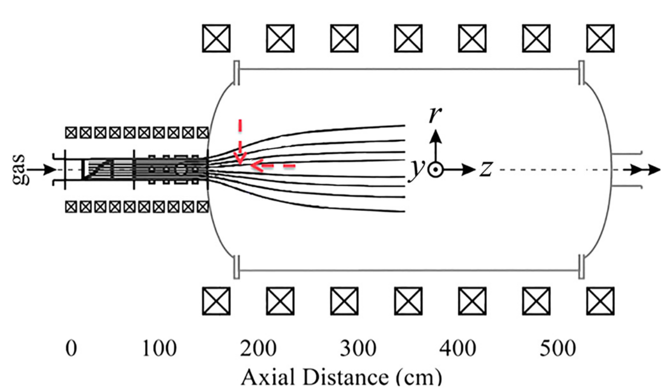

FIG. 1. The magnetic field geometry as the plasma expands from the helicon source into the LEIA chamber. The scanning probe accesses the expansion region downstream of the plasma source (identified by the red arrows). Reprinted with permission from Phys. Plasmas **24**, 123510 (2017). Copyright 2017 AIP Publishing LLC.

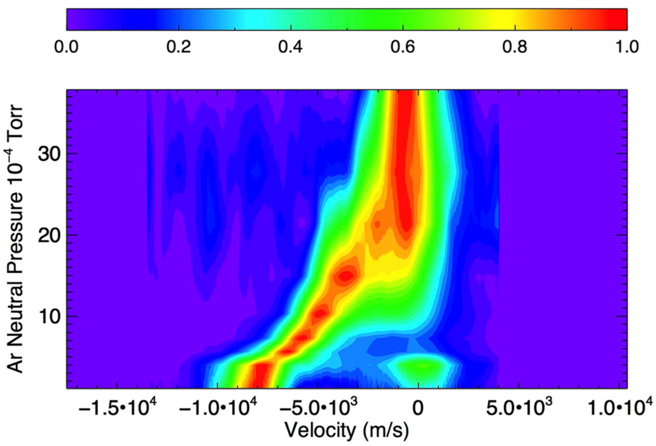

FIG. 2. The normalized parallel argon IVDF at $(r, z) = (0, 164)$ cm as a function of pressure.

population IVDF disappears around 2.5 mTorr. The reader should be aware that the units of pressure for all figures are 10^{-4} Torr. Two explanations are possible. The first is that pressure increase changes the accelerating structure, in other words, the pressure introduces a fundamental change in the nature of the ion beam accelerating structure. The second is that the mean free path for ion-neutral collisions (charge exchange and elastic collisions) decreases with increasing pressure, thereby scattering the ions before they gain significant energy. The result in Fig. 2 is likely a combination of both processes.[26]

Shown in Fig. 3 is a similar baseline case for xenon. IVDFs with a distinct xenon ion beam and background ion population also disappear at a few mTorr. Assuming that the accelerating structure is the same, the difference in ion beam speed for xenon and argon at the same pressure should be related by

$$\frac{v_{B,1}}{v_{B,2}} = \sqrt{\frac{m_2}{m_1}} = \sqrt{\frac{131}{40}} \sim 1.81, \qquad (2)$$

where species 1 is argon with a mass of 40 amu and species 2 is xenon with a mass of 131 amu. For a pressure of 0.1 mTorr, the measured argon and xenon ion beam speeds are,

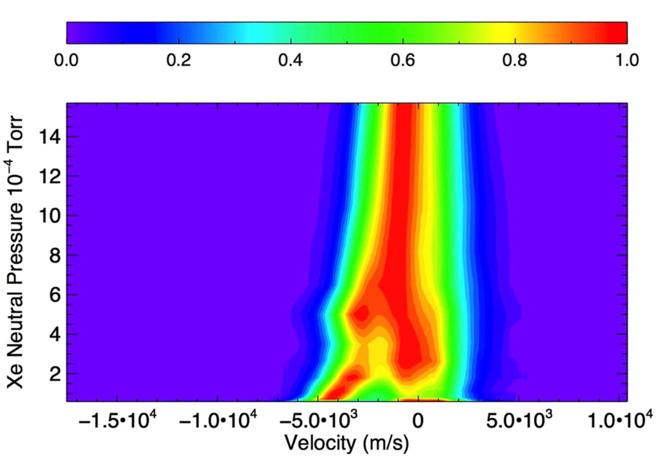

FIG. 3. The normalized parallel xenon IVDF at $(r, z) = (0, 164)$ cm as a function of pressure.

respectively, 4.5 km/s and 8.3 km/s yielding a measured ratio of $v_{Ar}/v_{Xe} = 1.84$. For a pressure of 0.4 mTorr (0.56 mTorr), the ratio is 2.9 (4.3). Therefore, the electric field structure appears to change as a function of pressure, consistent with other work.[28] The density for an argon only plasma at a pressure of 0.1 mTorr is $4.3 \times 10^9\,\mathrm{cm}^{-3}$. For xenon, previous measurements suggest the density is slightly higher.[20] The ion beam velocities decrease exponentially with increasing pressure for argon and xenon as shown in Fig. 4. Collisional processes are expected to produce an exponential velocity decrease given that ion momentum loss due to collisions with background neutrals is described by

$$\frac{d\mathbf{v}}{dt} = -\nu \mathbf{v}, \qquad (3)$$

where ν is the relevant collision frequency. Therefore, these baseline cases demonstrate that the ion beam is created upstream from the measurement location and slows down as a result of collisions during transit of the ions to the measurement location.

B. Argon LIF in Ar-He and Ar-Xe plasmas

Figure 5 shows the argon IVDF for a case in which the argon partial pressure and helium partial pressure were changed, but the total pressure was held constant like the conditions in the Biloiu and Scime study. As the argon partial pressure is lowered, the ion beam speed increases, consistent with Fig. 2. At the same time, the helium partial pressure increases. Note that the pressure range covered in Fig. 5 is only a fraction of the pressure range shown in Fig. 2. The Baalrud and Hegna[21] model predicts that if sheath physics creates the ion beam, the argon ion speed should increase up to the average ion sound speed given by Eq. (1) at whatever neutral pressures result in equal argon and helium plasma densities (which has to occur at some ratio of argon and helium pressures between essentially 100% argon and essentially 100% helium). The mechanisms responsible for the change in argon ion beam speed in Fig. 5 are unclear

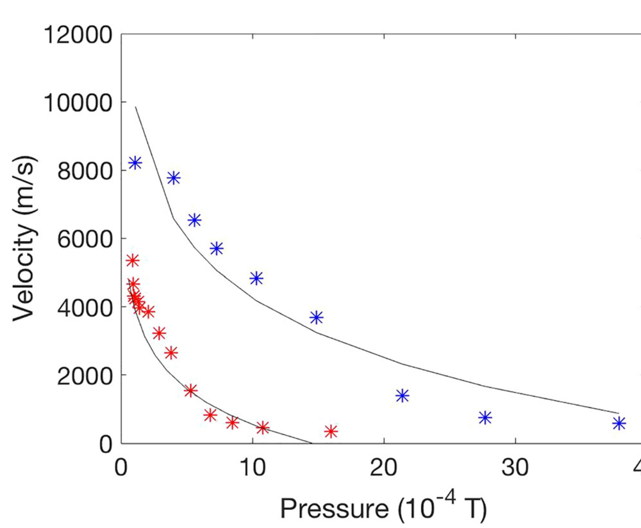

FIG. 4. The bulk velocity of argon (blue) and xenon (red) as a function of pressure from Figs. 2 and 3 with exponential fits.

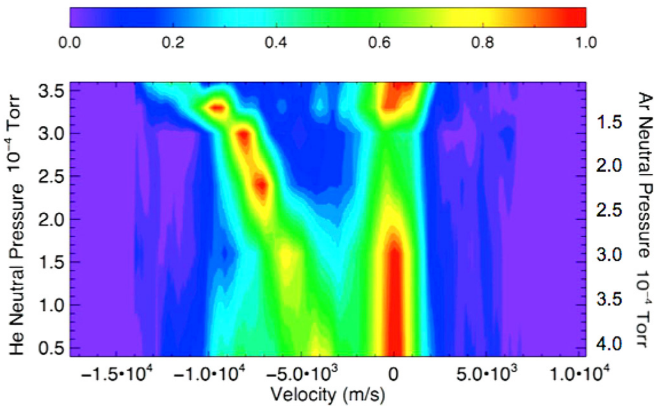

FIG. 5. The normalized parallel argon IVDF at $(r, z) = (0, 164)$ cm as a function of both helium and argon pressure. The total pressure, 0.47 mTorr, was kept constant.

because both the argon and helium partial pressures are changing simultaneously.

As shown in Fig. 6, increasing the neutral argon pressure for a constant value of helium partial pressure also results in slowing of the argon ion beam. The helium partial pressure in Fig. 6 is 0.71 mTorr and the argon partial pressures are significantly lower than the pressures shown in Fig. 2. The maximum argon pressure in Fig. 6 is 0.1 mTorr, nearly the same pressure as the lowest pressure in Fig. 2. Such low argon partial pressures are used for two reasons. First, a high partial pressure of helium, along with high rf power, is required to produce helium ions. Raising the total pressure further by adding an equal pressure of argon nearly destroys the argon ion beam. The second reason is best illustrated with a third case in which the total argon pressure is held constant. The argon IVDF was measured for a constant argon pressure of 0.17 mTorr while adding various amounts of helium to the plasma. Figure 7 shows that the argon ion beam slows linearly with increasing amounts of helium. This suggests that helium acts as a drag force on the argon ions thereby slowing them, a very different result than the multi-dipole experiments discussed earlier. The measured argon ion beam speed for a pressure of 0.1 mTorr (0.8 mTorr) in an argon only plasma was 8.3 km/s (5.3 km/s). With an argon

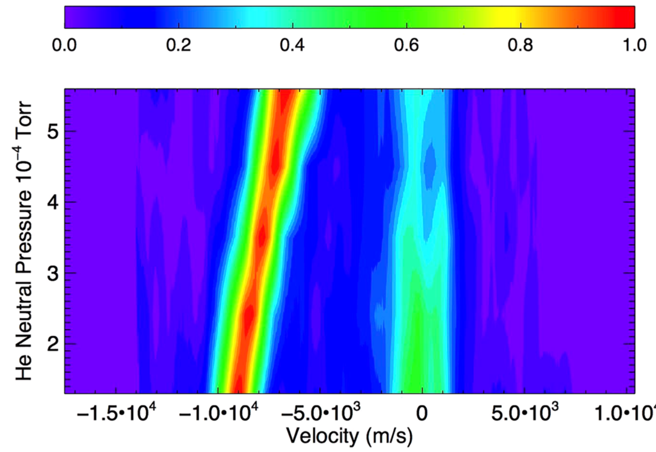

FIG. 7. The normalized parallel argon IVDF at $(r, z) = (0, 164)$ cm as a function of helium pressure with a constant argon pressure of 0.17 mTorr.

pressure of 0.1 mTorr and a helium pressure of 0.70 mTorr, the argon ion beam speed is 6.7 km/s (see top end of Fig. 6). Therefore, the argon ion beam speed is faster, with the addition of helium, than it would have been at the same total pressure under an argon only plasma. Assuming hard sphere collisions, the total neutral cross section is simply $\sigma = \pi(2r_1)^2$ for like atoms and $\sigma = \pi(r_1 + r_2)^2$ for different atoms, where r_1 and r_2 are the atomic radii of species 1 and 2, respectively. The cross section for an argon only plasma is $4.44 \times 10^{-19}\,\mathrm{m}^2$. With the addition of helium, the average cross section is 3.38 $\times 10^{-19}\,\mathrm{m}^2$ (31%), smaller than the argon only plasma. The ion beam speed is 26.4% higher with the addition of helium, which is comparable to the reduction in the cross section. In other words, the increase in ion beam speed is explainable by just the reduced collisionality of the argon-helium mixture. There is no need to invoke the effect described by Baalrud and Hegna.[21]

The argon ion beam speed was also studied as a function of xenon partial pressure. Xenon has an ionization potential of 12.13 eV, lower than the ionization potential of argon (15.76 eV). Therefore, adding xenon to an argon plasma quickly changes the argon plasma into a xenon plasma. Figure 8 shows the argon IVDF as a function of xenon partial pressure. The argon partial pressure was kept constant at

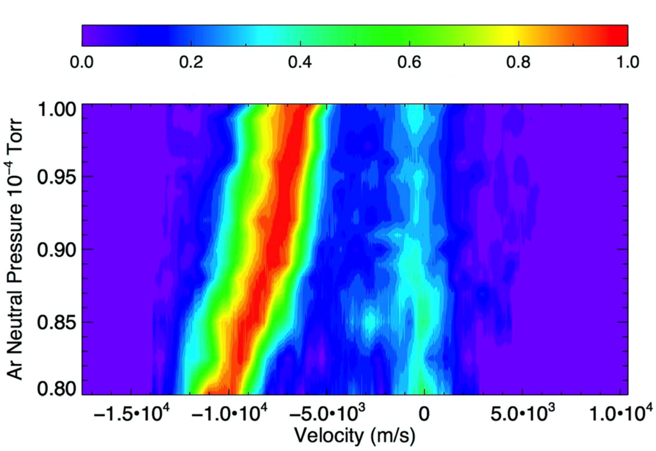

FIG. 6. The normalized parallel argon IVDF at $(r, z) = (0, 164)$ cm as a function of argon pressure with a constant helium pressure of 0.71 mTorr.

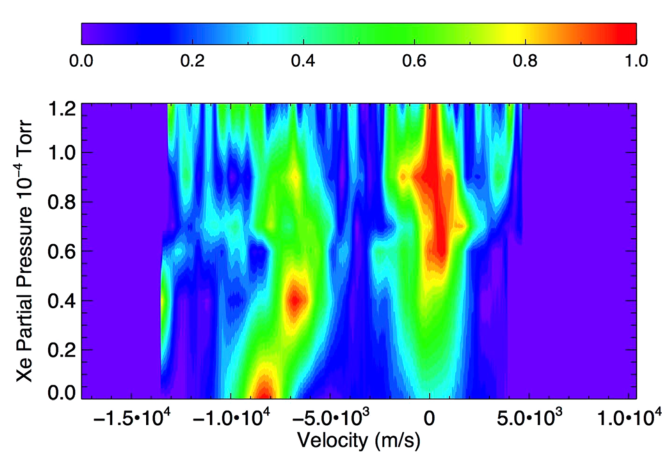

FIG. 8. The normalized parallel argon IVDF at $(r, z) = (0, 164)$ cm as a function of xenon pressure with a constant argon pressure of 0.17 mTorr.

0.17 mTorr yielding an ion beam with $v = 8.2$ km/s. For a xenon partial pressure of 0.04 mTorr, the argon ion beam slowed to 6.7 km/s. Increasing the xenon partial pressure further does not result in slowing of the argon ion beam. In fact, the argon ion beam speed increases slightly with the addition of xenon from 6.9 km/s at a xenon pressure of 0.04 mTorr to 7.1 km/s at a xenon pressure of 0.09 mTorr. This result is completely at odds with the prediction from Baalrud and Hegna.[21] Eventually, with enough xenon, the argon LIF signal is lost and the plasma turns from a predominantly argon plasma (purple) to a xenon plasma (light blue). The multi-dipole sheath experiments discussed earlier measured the individual ion densities by launching ion acoustic waves and using the dispersion relation to solve for n_i. The present experiment does not use this method. Instead, the individual ion densities are inferred by the color change of the plasma. In Fig. 8, the xenon and argon ion densities must be equal somewhere between the two extremes of pure argon and predominantly xenon. In Fig. 8, a xenon partial pressure above 1.0×10^{-4} Torr results in no argon LIF signal. The calculated average neutral cross sections for an argon only plasma and a Xe-Ar plasma, at a gas ratio of 35–65, are $4.44 \times 10^{-19}\,\mathrm{m}^2$ and $4.93 \times 10^{-19}\,\mathrm{m}^2$, respectively. The increase in the average neutral cross section of 11.0% is comparable to the decrease in ion beam speed of 12.7% shown in Fig. 8.

C. Xenon LIF in Xe-Ar and Xe-He plasmas

Shown in Fig. 9 is the xenon IVDF as a function of argon partial pressure with a constant xenon pressure of 0.09 mTorr. Argon is the lighter mass in this case and the xenon speed decreases rather than increases. It is difficult to describe the xenon IVDF as having a clear ion beam because the total pressure is high enough that the ion beam is no longer present. Instead, the measured xenon flow is more similar to ambipolar diffusion obeying the Boltzmann relation.[26] The neutral pressure of argon (higher ionization potential) must be large in order to produce any argon ions in a xenon plasma. A similar requirement was necessary for the case shown in Fig. 6 with argon and helium.

The large discrepancy between the xenon and helium masses, 131 amu and 4 amu, respectively, presents an

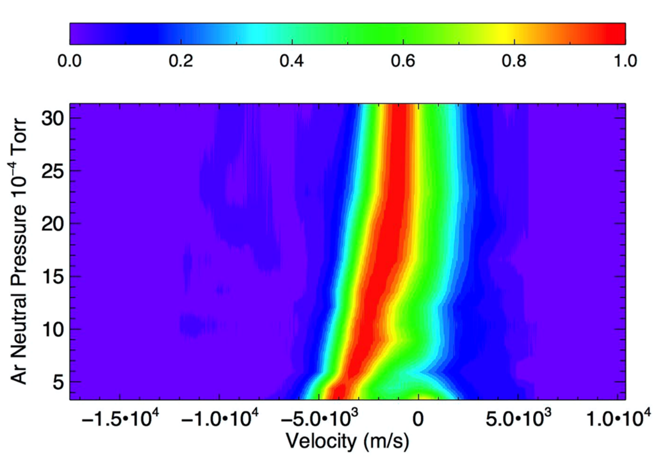

FIG. 9. The normalized parallel xenon IVDF at $(r, z) = (0, 164)$ cm as a function of argon pressure with a constant xenon pressure of 0.09 mTorr.

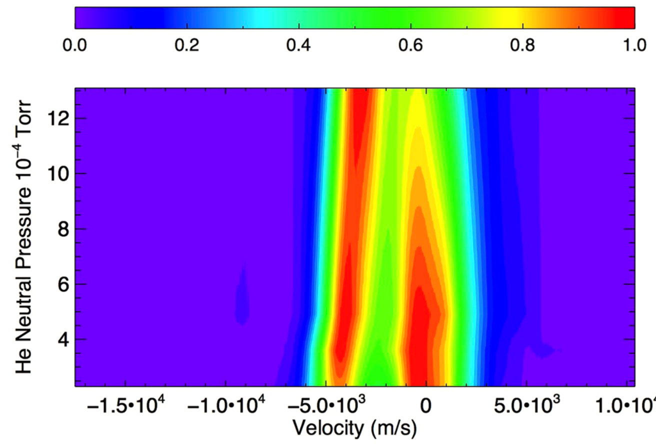

FIG. 10. The normalized parallel xenon IVDF at $(r, z) = (0, 164)$ cm as a function of helium pressure with a constant xenon pressure of 0.09 mTorr.

interesting case. Figure 10 shows the xenon IVDF as a function of helium partial pressure with the xenon partial pressure kept constant at 0.09 mTorr. The xenon ion beam clearly slows with the addition of helium. It is unlikely, given the experimental setup, that any significant amount of helium ions are produced in a xenon-helium plasma unless the partial pressure of helium is sufficiently high. The ionization energy of helium is 24.59 eV, double that of xenon. By the time any helium ions are produced, the pressure threshold of ion beam formation has been surpassed. The measured xenon ion beam speed for a pressure of 0.09 mTorr in a xenon only plasma was 4.5 km/s. With a xenon pressure of 0.09 mTorr and a helium pressure of 1.0 mTorr, the xenon ion beam speed is 3.3 km/s (see Fig. 10). For the data shown in Fig. 3, the xenon ion beam disappears above pressures of 0.50 mTorr. The xenon ion beam persists for higher total pressures with helium than it would have in a xenon only plasma.

IV. CONCLUSIONS

Experiments in pure argon and pure xenon plasmas determined that the accelerating electric field is the same only for low pressures. At higher pressures, the electric field amplitude decreases and its spatial structure changes.[28] For multi-ion species plasmas, the work presented here arrives at a different conclusion than Biloiu and Scime.[20] The reason for this discrepancy is because Biloiu and Scime[20] kept the total flow rate equal to 10 sccm for the duration of their experiment. In this work, a similar case with argon and helium is shown in Fig. 5. The effect of each gas is unclear from these measurements alone. Therefore, additional measurements were conducted to isolate the effect of each gas species. The effect of adding a second gas at fixed total pressure is to slow the ion beam regardless of the relative individual densities. However, the ion beam is faster with addition of a light species compared to the baseline single species plasmas. A light species has a smaller atomic radius and will produce less drag which will result in a faster ion beam. The theoretical prediction by Baalrud *et al.*[14] for multi-ion sheaths is not necessarily refuted, rather it is simply not applicable to the accelerating structures that appear in expanding helicon plasmas. Experiments by Yip *et al*. and Severn *et al*. did not isolate the effect of each gas as we have done nor did they account for changes due to collisions. If sheath physics was really responsible for the ion acceleration in expanding helicon sources, it might be tempting to combine mixtures of ion species to maximize both thrust and specific impulse in a helicon based thruster. However, these measurements suggest that the effects on beam velocity are explainable by simple collisional processes. Recent work also suggests that the potential structure in our multi-species plasmas is dependent on electron-neutral collisions that weaken the rf coupling and on the different ionization potentials of the gases.[22]

ACKNOWLEDGMENTS

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