Comparison of gridded energy analyzer and laser induced fluorescence measurements of a two-component ion distribution[a]

Z. Harvey, S. Chakraborty Thakur, A. Hansen, R. Hardin,
W. S. Przybysz, and E. E. Scime
Department of Physics, West Virginia University, Morgantown, West Virginia 26506-6315, USA

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We present ion velocity distribution function (IVDF) measurements obtained with a five grid retarding field energy analyzer (RFEA) and IVDF measurements obtained with laser induced fluorescence (LIF) for an expanding helicon plasma. The ion population consists of a background population and an energetic ion beam. When the RFEA measurements are corrected for acceleration due to the electric potential difference across the plasma sheath, we find that the RFEA measurements indicate a smaller background to beam density ratio and a much larger parallel ion temperature than the LIF. The energy of the ion beam is the same in both measurements. These results suggest that ion heating occurs during the transit of the background ions through the sheath and that LIF cannot detect the fraction of the ion beam whose metastable population has been eliminated by collisions. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2953411]

I. INTRODUCTION

Recent experiments by a number of groups have suggested that electric double layers can form spontaneously in helicon plasmas expanding in a diverging magnetic field. Double layers (DLs) are narrow, local regions of strong electric potential gradient isolated from plasma boundaries. They often separate regions of plasma with widely different densities and temperatures and are an important mechanism for the acceleration of charged particles along magnetic fields in astrophysical and laboratory plasmas.

Retarding field energy analyzer (RFEA) probes[1] and nonperturbative laser induced fluorescence (LIF) are used to infer the existence of DLs through the detection of ion beams downstream of the expansion region. RFEA probes have also been used to obtain measurements of the local plasma potential in the DL region assuming that the measured acceleration of the bulk ion population results from the electric potential difference between the plasma potential and the grounded front aperture of the RFEA.[2]

However, certain aspects of the observed ion acceleration process are inconsistent with expectations for a classic DL, e.g., the ion acceleration extends over many hundreds of Debye lengths[3] instead of the expected 10–50 Debye lengths.[4] That the mean free paths of the plasma constituents also play a critically important role is borne out by the low pressure threshold for ion beam formation common to all the single species, spontaneous ion beam formation, helicon experiments.[2,3,5] In this work, we compare RFEA and LIF measurements of the ion velocity distribution function (IVDF) downstream of an expanding helicon plasma.

II. APPARATUS

The hot helicon experiment (HELIX) vacuum chamber is a 61 cm long, Pyrex tube of 10 cm in diameter connected to a 91 cm long, 15 cm diameter, stainless steel chamber (Fig. 1). The stainless steel chamber opens into a 2 m diameter, 4.5 m long expansion chamber. Ten electromagnets produce a steady state axial magnetic field of 0–1300 G in the source. Neutral pressures are measured by an ion gauge located at the end of the glass chamber and by a Baratron pressure gauge located 35 cm downstream of the rf antenna. Plasmas are created at neutral pressures (with rf on) ranging from 0.1 to 100 mTorr. rf power of up to 2.0 kW over a frequency range of 6–18 MHz is coupled into a 19 cm half wave, helical antenna to create the steady state plasma. Characteristic electron temperature and densities in the source are $T_e \approx 4$ eV and $n \approx 1\times 10^{13}$ cm^3 as measured with rf compensated, cylindrical, Langmuir probes[6] located 50 cm downstream of the antenna.

For LIF measurements of the argon IVDF, the diode-laser-based LIF laser system (see Ref. 7) is tuned to 611.662 nm (vacuum line) to pump the Ar II $3d^2G_{9/2}$ metastable state to the $4p^2F_{7/2}$ state, which then decays to the $4s^2D_{5/2}$ state by emitting 460.96 nm photons. A typical LIF measurement consists of sweeping the frequency of a very narrow bandwidth laser through a collection of ions or atoms that have a thermally broadened velocity distribution function. The illuminated ions or atoms absorb a photon and are pumped into an excited state when the laser appears at the appropriate frequency in their respective rest frames.

In these experiments, the laser beam is split and 90% is mechanically chopped at ~2 kHz and coupled into a multimode, non-polarization-preserving, fiber optic cable for transport to injection optics aligned along the magnetic axis of the source. As the laser frequency is swept over the typical 20 GHz range, the fluorescent emission from the excited state is collected and transported via a fiber optic to a filtered

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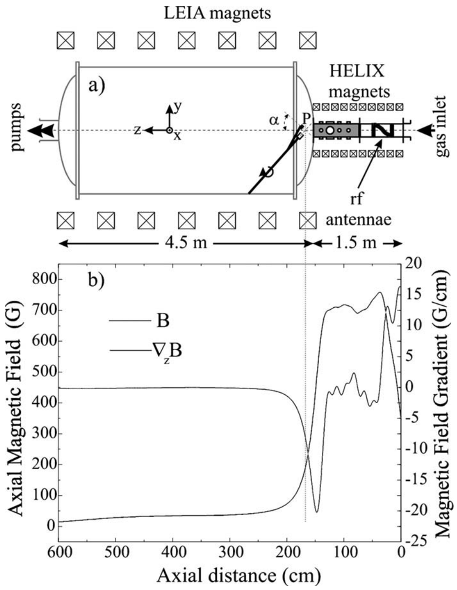

FIG. 1. (a) HELIX diffusion chamber system; (b) the magnetic field profile and the magnetic field gradient on the axis of the system.

(1 nm bandwidth around the fluorescence wavelength) narrowband, high-gain, photomultiplier tube (PMT). The remaining 10% of the beam is passed through an iodine cell for a consistent zero-velocity reference as well as compensation for possible laser drift.[8]

The LIF emission as a function of laser frequency is fit to a either a single or a pair of drifting Maxwellian distributions

$$I_R(\nu) = I(\nu_0)e^{-mc^2(\nu-\nu_0)^2/2k_BT_i\nu_0^2}, \tag{1}$$

where ν_0 is the rest frame frequency of the absorption line, m_i the ion mass, and T_i the ion temperature. For magnetic field strengths in the expansion chamber, less than 100 G, Zeeman splitting is ignorable.[9]

For probe measurements of the IVDF, a compact RFEA is inserted to the axis of the experiment, downstream of the source, and aligned so that the RFEA aperture faces the upstream (helicon source) direction. The RFEA (Fig. 2) consists of four closely spaced mesh screens (250 lines/in. nickel mesh glued to copper support rings) placed behind a grounded aperture and held in grounded probe assembly.[1] The grids are separated by thin mica insulators. The first grid, the electron repeller, is biased from −40 to −70 V depending on the local plasma conditions. Since the typical

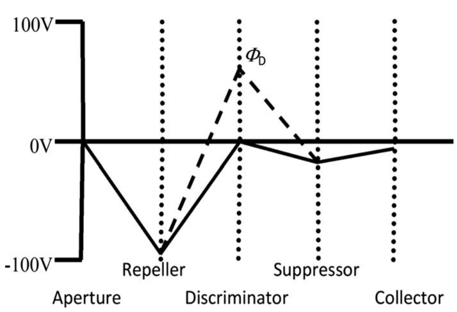

FIG. 2. RFEA bias voltages for each grid (dotted lines). The dashed line indicates the typical range of bias voltages applied to the discriminator.

electron temperature is 5 eV, the repeller bias is sufficient to exclude all but the most energetic electrons in the plasma.

The second grid, the discriminator, is swept from −5 to 75 V with a linear ramp. Ions with energies larger than the discriminator potential continue on to the third grid. We found that because the grids are so closely spaced, discriminator sweep rates larger than 10 mHz resulted in unacceptable levels of capacitive coupling to the third grid, the electron suppressor. Using 9 V batteries, the suppressor grid is biased to −18 V and the fourth grid, the collector, is a solid copper plate biased to −9 V. The current collected by the suppressor grid (due to secondary electrons emitted from the collector with enough energy to overcome the −9 V potential barrier) is added to the collector current with a fast amplifier.[1] We note that with a small, ~2 mm, grounded aperture in front of the grounded first grid, it appeared that a small plasma formed inside the RFEA when the discriminator was swept across its voltage range. Only after the aperture plate was removed, leaving a larger, grounded, circular aperture of approximately 5 mm diameter in front of the grounded first grid, did the RFEA function as expected.

The ion current collected by a RFEA as a function of discriminator potential, Φ_D, due to a single drifting Maxwellian ion distribution (an ion beam) is

$$I(\Phi_D) = \sqrt{\frac{n_b^2e^2}{2m\pi}}[\sqrt{T_b}e^{-((\sqrt{e\Phi_D}-\sqrt{E_b})^2/T_b)} + \sqrt{E_b\pi}\,\mathrm{erfc}[(\sqrt{e\Phi_D}-\sqrt{E_b})/\sqrt{T_b}]], \tag{2}$$

where n_b is the beam density, T_b is the beam temperature, and E_b is the beam energy. Because the derivative of Eq. (2) with respect to the discriminator potential is

$$dI(\Phi_D)/d\Phi_D = -n_be\sqrt{1/2m\pi T_b}e^{-((\sqrt{e\Phi_D}-\sqrt{E_b})^2/T_b)} \tag{3}$$

and in the limit of zero beam energy the right-hand side of Eq. (3) reduces to the original Maxwellian distribution. The derivative of a RFEA measurement is often interpreted as the ion energy distribution. However, such interpretation is only valid for nondrifting ion populations. In fact, the width in energy space predicted by Eq. (3), i.e., the $1/e$ folding points, is $\Delta\Phi_D=4\sqrt{T_bE_b}$. In other words, the width of the peak resulting from a derivative of the collected current of a RFEA is not necessarily a measure of the ion temperature but is, in fact, proportional to square root of the product of the beam energy and the ion temperature.

Since the support structure of the RFEA probe and the first grid are at electrical ground, ions in the plasma are accelerated by the positive plasma potential toward the grounded first grid. Therefore, even if the average velocity of ions in the plasma is zero, the ion population entering the RFEA will do so with a bulk energy of $e\Phi_P$, where Φ_P is the plasma potential, and the complete version of Eq. (2) must be used in analysis of RFEA measurements.

In the case of a bimodal ion population, a beam plus a stationary background, the total RFEA current as a function of discriminator potential is

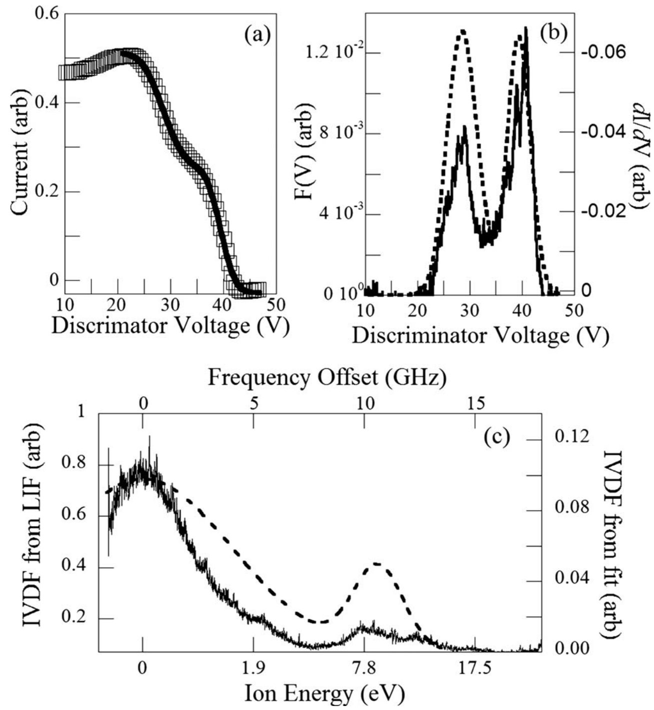

FIG. 3. (a) RFEA data (open squares) and fit of Eq. (4). (b) Derivative of RFEA data with respect to discriminator voltage (solid line) and IVDF obtained from fit of two drifting Maxwellian populations to RFEA data (dashed line). (c) IVDF obtained from fitting of Eq. (4) to RFEA data (dashed line) and LIF measured IVDF (solid line). Lower x axis is the ion energy after removal of acceleration in the sheath, upper x axis is the shift in the LIF absorption line.

$$\frac{I(\Phi_D)}{\sqrt{\frac{e^2}{2m\pi}}} = \Bigg[\left(\frac{n_p}{2}\right)\{\sqrt{T_P}e^{-((\sqrt{e\Phi_D - e\Phi_P} - \sqrt{E_P})^2/T_P)} + \sqrt{E_P\pi}\,\mathrm{erfc}[(\sqrt{e\Phi_D - e\Phi_P} - \sqrt{E_P})/\sqrt{T_P}]\} + n_b\{\sqrt{T_b}e^{-((\sqrt{e\Phi_D - e\Phi_P} - \sqrt{E_b})^2/T_b)} + \sqrt{E_b\pi}\,\mathrm{erfc}[(\sqrt{e\Phi_D - e\Phi_P} - \sqrt{E_b})/\sqrt{T_b}]\}\Bigg], \qquad (4)$$

where a factor of $\frac{1}{2}$ appears in the density of the background plasma, n_p, because only the half of the background distribution traveling toward the probe is measured. The possibility of a drift of the background ion population in addition to the acceleration arising from the plasma potential is explicitly included in Eq. (4) through the E_p energy term.

III. IVDF MEASUREMENTS AND ANALYSIS

IVDF measurements were obtained for argon plasma at a rf power of 700 W, a frequency of 13.56 MHz, a magnetic field of 800 G in the source, and a magnetic field of 14 G in the expansion region. The pressures in the source and expansion regions were 1.3 and 0.1 mTorr, respectively.

Shown in Fig. 3(a) is the RFEA collector current versus discriminator voltage obtained in the expansion chamber near the point "P" in Fig. 1 for a repeller voltage of −45 V. By inspection, it appears that there is one population of ions with energies less than 25 eV and another population of ions with energies less than 35 eV. The derivative of the collected current with respect to the discriminator voltage is shown in Fig. 3(b). Analysis by the simple derivative method would conclude that the local plasma potential is approximately 27 V (corresponding to the energy of the first peak) and that there is an ion beam with an energy of roughly 12 eV relative to the background ion population (assuming both populations have been accelerated through the sheath in front of the probe). The same analysis yields a beam density roughly 50% larger than the background ion density. If the data of Fig. 3(a) are fit by the sum of two drifting ion populations (a background ion population accelerated by the plasma to ground potential difference and an ion beam population) as described by Eq. (2), the best fit yields the parent ion population shown by the dotted line in Fig. 3(b). In this case, the resultant beam density is equal to the background ion density and the energy of the ion beam remains about 12 eV.

However, when the acceleration of the background and beam ion populations through the sheath in front of the RFEA is self-consistently included by fitting the data of Fig. 3(a) with the expression given in Eq. (4), the dashed curve shown in Fig. 3(c) is obtained for the parent ion distribution. Also shown in Fig. 3(c) is the IVDF obtained by LIF at the same location and under the same plasma conditions (solid line). The beam energies obtained by both measurement techniques are in excellent agreement.

However, although the beam density is significantly smaller than the bulk ion density for both measurements, the beam density to bulk ion density ratio is much smaller in the LIF measurement than in the RFEA measurement. There has been a long-standing concern that LIF measurements of ion beams may underestimate the fraction of ions in a beam created upstream of the measurement location because the beam ions are no longer in the appropriate metastable state for detection by LIF (because of metastable state quenching collisions with ions, electrons, and neutrals).[5,10] These data are consistent with the beam-ion metastable quenching hypothesis. Note also that the parallel ion temperature (IVDF width) is considerably larger in the RFEA measurement (~2.5 eV) than in the LIF measurement (~0.9 eV). The substantially larger RFEA parallel ion temperature suggests that sloshing in the rf potential across the plasma sheath in front of the RFEA probe leads to an artificial broadening of an IVDF when measured with a RFEA probe in a rf plasma.

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