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Delays of the order of tens of milliseconds in the appearance of the fast argon ion population in the expansion region of a pulsed helicon plasma are observed in time-resolved, laser induced fluorescence measurements. The fast ion population is a proxy for the presence of a double layer. The magnitude of the time delay depends strongly on the length of the interval between plasma pulses; the shorter the time between pulses, the shorter the time delay. The time delay approaches zero for inter-pulse intervals smaller than 30 ms. The double layer strength is not affected by plasma source modulation frequency. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3204014]

The energetic ion beam generated by the current-free electric double layer (EDL) which forms spontaneously in the magnetic expansion region of low pressure helicon plasma sources[1] could provide the thrust needed for extraterrestrial spacecraft propulsion. The EDL forms with the high potential side toward the helicon source and the low potential side toward the expansion region. The resultant ion acceleration to supersonic speeds and the characteristic high ion densities of helicon discharges motivated researchers from the Australian National University (ANU) to propose the helicon double layer thruster (HDLT) concept.[2] Although the specific impulse and thrust of the HDTL are low compared to conventional thrusters, the possibility of electrically steering the ejected ion beam,[3] stable operation at very low pressure in a variety of gases,[4] and the possibility of high energy efficiency[5] are sufficiently intriguing that HDLT optimization studies have continued. For example, recent studies have shown that the overall energy efficiency can be significantly improved by replacing the heavy solenoids used to generate the axial magnetic fields with smaller and lighter permanent magnets.[6,7] The dependence of the ion beam velocity on the source driving frequency has also been recently demonstrated.[8] Pulsing the helicon discharge might solve remaining important HDLT thruster issues such as plasma detachment, turbulent cross-field diffusion, and antenna heating. Therefore, a detailed understanding of the temporal evolution of the EDL is required to identify the optimal operational parameters (duty cycle, pulse length, input power, driving frequency, etc.) of a pulsed helicon source thruster.

In this letter, we present measurements of the time delay, typically a few milliseconds to a few tens of milliseconds, between plasma ignition and the appearance of an accelerated (supersonic) ion population. The measurements of the argon ion velocity distribution function (ivdf) in the expansion region of a helicon plasma source are obtained by time resolved laser induced fluorescence (LIF).

The experiments were performed in the HELIX-LEIA (HL) helicon source-diffusion chamber system described in detail elsewhere.[9] Briefly, the helicon source (HELIX) consists of two coaxial tubes of a total length of 1.5 m. The Pyrex source tube is 10 cm in diameter and is surrounded by a 19 cm long, half wave, $m=+1$, helical antenna that couples the rf power into the plasma. The rf antenna is 37 cm from the closed end of the source tube. The second, 15 cm diameter, stainless-steel tube connects the plasma generation region with plasma expansion region, a 4.5 m long, 2 m diameter aluminum diffusion chamber (LEIA). The axial magnetic field of 0–1.2 kG in HELIX and 0–150 G in LEIA is created by external solenoids. Previous investigations have shown that the EDL is localized to the region of strong axial magnetic field gradient which, for the HL system, is a maximum close to steel tube-aluminum chamber junction. To investigate the temporal evolution of the ivdf, the discharge was pulsed at different frequencies and duty cycles; two function generators, one to provide the 9.5 MHz driving frequency and one to amplitude modulate the rf wave were used in conjunction with a wide bandwidth rf amplifier. The electronic rise and decay times in the case of the square wave pulses used for these investigations were ~70 ns, much shorter than the intervals between plasma pulses, which were tens to hundreds of milliseconds.

For Ar^+ LIF, we used the classic three-level LIF scheme in which the metastable $3d\ ^2G_{9/2}$ state is optically pumped by 611.6616 nm (vacuum wavelength) radiation to the short living $4p\ ^2F^0_{7/2}$ state, which then decays to the $4s\ ^2D_{5/2}$ state by emitting a photon at 461.09 nm (vacuum wavelength). Details of the laser used and the time resolved LIF diagnostic technique are given elsewhere.[10] The injected laser light is modulated with an acousto-optic modulator (AOM) at 10 kHz and then transported with a multimode, nonpolarization preserving, optical fiber to the injection optics. A high-frequency lock-in amplifier provided the reference modulation signal for the AOM driver. Adequate signal-to-noise ratios of 10:1 were obtained by averaging the LIF signal at each laser wavelength over 400 plasma pulses. To obtain a data record long enough to cover the entire plasma pulse, the LIF signals were sampled at a digitization rate of 10 kHz. Thus, a time resolution of 100 μs is theoretically possible. However, for the lock-in LIF detection scheme, the time resolution is limited to 1 ms by the 1 ms integration time of the lock-in amplifier; needed to obtain sufficient photon counting statistics (ten on/off chopping cycles of the AOM). To determine the parallel ivdf, laser light was injected at an angle of 52° (with respect to the direction of flow) and the fluorescence signal detected by an integrated collection optics-photomultiplier tube mounted on a scanning probe.[11] Due to

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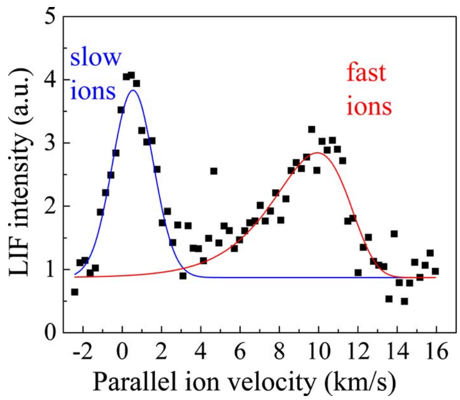

FIG. 1. (Color online) Parallel ivdf at $t=25$ ms into the pulse for 10 Hz modulation frequency: raw data (points); fits (solid lines) of the slow and fast ion distributions.

an error in our previous publications,[12,13] the reported values of the parallel ion speeds were uncorrected for the laser injection angle, i.e., underestimated by a factor of $\sim 1.6\times$. Because the plasma conditions were chosen to foster EDL formation, the detected ivdf is bimodal, with peaks separated by ~ 10 GHz. For reliable velocity and temperature resolution, the ivdf was sampled at 71 equally spaced laser frequencies over a range of 20 GHz (see Fig. 1).

The evolution of the parallel argon ivdf at 19 cm downstream of helicon source-diffusion chamber junction for a 50% duty cycle, 10 Hz pulse frequency is shown in Fig. 2. Since previous investigations showed oscillations of the LIF signal with a characteristic frequency of 1 kHz when the lower hybrid frequency in the source was comparable to the driving frequency,[11] the source was operated at magnetic field strengths of 600 G in the source (to avoid the lower-hybrid frequency) and 35 G in the diffusion chamber. Neutral pressure in the helicon source was 2 mTorr, sufficient pressure for a good LIF signal, but low enough to allow formation of the EDL. The pressure in the expansion chamber was 0.24 mTorr. To determine the absolute flow of each distribution component, at each time step the background light levels were subtracted from the measured ivdf, normalized to the peak signal value. The processed ivdf was then fit with Gauss and LogNormal functions for the slow and fast ion

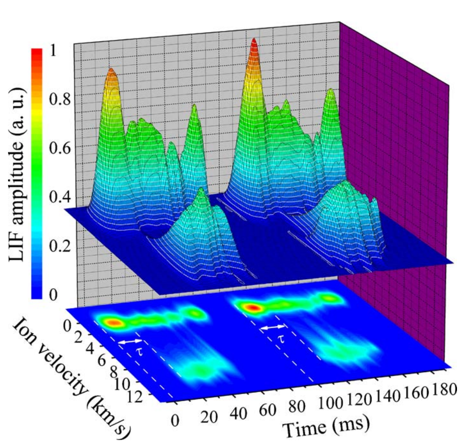

FIG. 2. (Color online) The evolution of the argon ion parallel ivdf during two cycles of a 50 ms plasma pulse: top—surface plot showing fast (~ 10 km/s) and a slow (~ 0.5 km/s) ion populations; bottom—a contour projection showing the time lag ($\tau \sim 19$ ms) in the appearance of the fast ion population.

populations, respectively. The LogNormal function was used to include the tail of the fast ion ivdf toward slower speeds that arises from elastic scattering and/or charge-exchange collisions with the background neutrals and ions.[12] Although LIF only provides detailed information about the population of a certain excited state—in our case the metastable $Ar^+(3d\ ^2G_{9/2})$ state—the large level degeneracy ratio (17:1) of the metastable ion relative to the ground state ion,[14] which makes the main channel for the formation of this state the two-step, electron impact process of ionization (15.8 eV) followed by excitation (19.1 eV), as well as our previous studies that demonstrated that the LIF signal $\sim n_e^2 \times T_e^{1/2}$, leads us to expect that the measured ivdfs accurately represent the ivdfs of the entire ion population.

Consistent with measurements in steady-state helicon plasmas, the slow ion population exhibits a bulk speed of ~ 0.5 km/s and the fast ion population a bulk flow speed of ~ 10 km/s.[15] These observations are consistent with different origins for the two ion populations: (a) the slow ions are a background population created by local ionization; their parallel flow speed is slightly slower than the neutral gas flow speed (~ 600 m/s) estimated at HELIX-LEIA junction based on the mass flow rate, the pressure difference, and gas conductance under the assumption of molecular flow; (b) the fast ions are created upstream in the plasma source and accelerated by the EDL and magnetic expansion on their way from the helicon source toward diffusion chamber.[1] For slightly different steady-state plasma parameters, electrostatic probe measurements indicated a potential drop of ~ 18 V from plasma source to expansion chamber,[16] corresponding to an EDL strength of $\sim 3k_BT_e/e$—sufficient to accelerate the fast ions to the measured speeds. The different durations of the ivdf components during pulsed operation also point toward different origins for each component. The slow ion population appears at the start of the rf pulse and persists for ~ 30 ms after the rf pulse terminates. The existence of an argon afterglow plasma is typically attributed to the long lifetime of the $3d\ ^2G_{9/2}$ state (6.1 s) in low collisionality systems. Given that the quenching cross-section for collisions of the $3d\ ^2G_{9/2}$ state with ground state neutral argon is 1×10^{-14} cm^2,[17] at the LIF detection location in the expansion region the quenching mean free path (mfp) is quite long ~ 12.5 cm. However, the resulting 2.4×10^3 s^{-1} quenching frequency is still too large to explain the observed 30 ms afterglow plasma. Close inspection of the ivdf temporal evolution shows that after pulse termination, the LIF signal of the slow ion population does not immediately decay but actually increases for about 20 ms and then decays. This overshoot of LIF signal might be related to continued excitation into the $3d\ ^2G_{9/2}$ by low energy electron impact from well populated lower ionic metastable states.[18]

The LIF signal for the fast ion population appears ~ 19 ms after the start of the plasma pulse and has a short afterglow (~ 7 ms). The 7 ms decay time is consistent with rapid disappearance of the fast ion population convolved with the 1 ms lock-in integration time (which artificially stretches out any rapidly terminating phenomena over a few milliseconds).[19] The rapid disappearance of the fast ion population suggests the rapid termination of the mechanism that generates, accelerates and then injects the fast ions in the diffusion chamber. Given that the EDL forms 4–5 cm inside the source, where the pressure is roughly one order of mag-

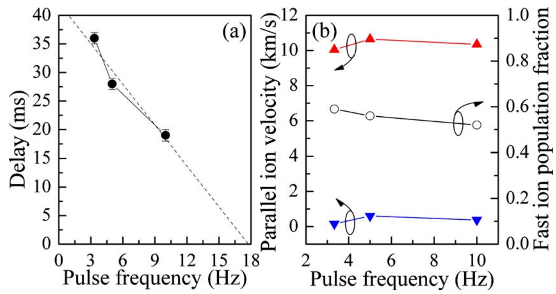

FIG. 3. (Color online) (a) Dependence of the delay on modulation frequency and a linear extrapolation to zero delay. (b) Dependence of the slow (down triangles) and fast (up triangles) ion parallel velocities and fast ion population fraction (circles) on modulation frequency. For all three frequencies the duty cycle was 50%.

nitude higher than in the expansion region, it follows that in the absence of ongoing ionization rapid quenching of the $3d\ ^2G_{9/2}$ metastable state in the source occurs; the ~1.5 cm quenching mfp and ~10 km/s ion drift velocity yield a ~15 μs decay time. Similar fast population decay times of ~10 μs were observed for current-free EDLs appearing in a two-electron population plasma when the discharge was switched off.[20] The most significant feature of the fast population time evolution is the ~19 ms time lag in its appearance after the plasma pulse begins. Such a time lag is too long to result from the plasma relaxation time—the time needed to establish steady-state conditions (which is roughly equal to the transit time across the system of an ion traveling at acoustic speed).[21] For an electron temperature of 6 eV from probe measurements, the acoustic ion speed c_s [$c_s=(gk_BT_e/m)^{1/2}$, where m is the ion mass and γ is assumed 1 for isothermal expansion] of ~3.8 km/s yields a transit time of ~0.5 ms. The time lag is also unlikely to result from the propagation of the EDL, such as those observed in collisionless expanding plasmas, because the motion of those EDLs stagnated after only 0.2–0.3 ms.[22] Two other possible explanations are that time is needed to build up a sufficient population of the $3d\ ^2G_{9/2}$ ionic state to allow detection by LIF or that the EDL requires some many ms to form. Since LIF signal from the slow population, observed in the same $3d\ ^2G_{9/2}$ ionic state, appears immediately at the onset of the plasma pulse, it seems most likely that the time lag arises from a delay in formation of the EDL. Qualitatively, the time lag can be interpreted as the time needed after the breakdown of the gas to generate the downstream plasma, establish the equilibrium between the two different plasmas, and then to allow for charge separation to occur at their interface.

To investigate the effects of pulsing conditions on the observed time lag for fast ion creation in the LIF data, ivdfs were measured for the same duty cycle and different modulation frequencies (3.33, 5, and 10 Hz). As shown in Fig. 3(a), the higher the modulation frequency the shorter the observed time lags. We hypothesize that long lived neutral and ionic metastable states survive during "plasma off" time, making the plasma ignition and apparently ion beam formation faster for shorter time off intervals. Having longer "plasma off" times leads to complete extinguishment of excited states between pulses, followed by a completely "new" breakdown and a new EDL formation. That the plasma off time controls the time lag in the appearance of the fast ion population was confirmed by holding the modulation frequency fixed at 5 Hz and varying the duty cycle from 50% to 80%.[14] Decreasing the "plasma off" time from 100 to 40 ms resulted in a decreased (28 versus 7 ms) time lag in the appearance of the fast ion population. A linear extrapolation to zero time lag predicts that no delay in the appearance of the fast ion population will occur for modulation frequencies larger than 17 Hz (~30 ms plasma off time).

These observations suggest a resolution for an outstanding discrepancy between previous, time-resolved, LIF and resolved retarding field energy analyzer (RFEA) measurements in the ANU helicon source[23] and in an identical helicon source constructed at the L'Ecole Polytechnique Paris (LPTP).[24] The time resolved RFEA measurements indicated the presence of a small, but finite population of fast ion population within 150–200 μs of the beginning of the rf pulse. Besides the mechanical differences between HELIX-LEIA and Chi-Kung helicon sources, those RFEA measurements were obtained for considerably shorter plasma "off" intervals in a pulsed system; plasma on/off=2/10 ms in the ANU experiments and 750/500 μs for the LPTP measurements.

Note that the slow and fast ion population parallel velocities do not vary with "plasma on" time: ~0.5 and ~10 km/s for the parallel flow speed of the slow and fast ion populations [see Fig. 3(b)]. Since the parallel velocity of fast ion population is independent of the length of the plasma pulse, the energy of the ejected ion beam appears to be fixed for a given system geometry and/or magnetic field configuration. Since the relative fast ion population density (obtained from the integration of LIF signals) depends only modestly on the modulation frequency (from 0.6 at 3.33 Hz to 0.52 at 10 Hz), the overall thrust generated by a HDLT should be invariant under changes in pulsing frequency.

[1] C. Charles, Plasma Sources Sci. Technol. **16**, R1 (2007).
[2] C. Charles, R. W. Boswell, P. Alexander, C. Costa, and O. Sutherland, Proceedings of 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Sacramento, CA, 2006.
[3] C. Charles, R. W. Boswell, W. Cox, R. Laine, and P. MacLellan, Appl. Phys. Lett. **93**, 201501 (2008).
[4] C. Charles, R. W. Boswell, R. Laine, and P. MacLellan, J. Phys. D: Appl. Phys. **41**, 175213 (2008).
[5] C. Charles and R. W. Boswell, IEEE Trans. Plasma Sci. **36**, 2141 (2008).
[6] F. F. Chen, IEEE Trans. Plasma Sci. **36**, 2095 (2008).
[7] K. Takahashi and T. Fujiwara, Appl. Phys. Lett. **94**, 061502 (2009).
[8] S. Chakraborty Thakur, Z. Harvey, I. A. Biloiu, A. Hansen, R. A. Hardin, W. S. Przybysz, and E. E. Scime, Phys. Rev. Lett. **102**, 035004 (2009).
[9] C. Biloiu, X. Sun, E. Choueri, F. Doss, E. Scime, R. Spektor, J. Heard, and D. Ventura, Plasma Sources Sci. Technol. **14**, 766 (2005).
[10] I. A. Biloiu, X. Sun, and E. E. Scime, Rev. Sci. Instrum. **77**, 10F301 (2006).
[11] I. A. Biloiu, E. E. Scime, and C. Biloiu, Plasma Sources Sci. Technol. **18**, 025012 (2009).
[12] I. A. Biloiu and E. E. Scime, IEEE Trans. Plasma Sci. **36**, 1376 (2008).
[13] I. A. Biloiu, Ph.D. thesis, West Virginia University, 2009.
[14] K. P. Giapis, N. Sadeghi, J. Margot, R. A. Gottscho, and T. C. John Lee, J. Appl. Phys. **73**, 7188 (1993).
[15] I. A. Biloiu, E. E. Scime, and C. Biloiu, Appl. Phys. Lett. **92**, 191502 (2008).
[16] X. Sun, A. M. Keesee, C. Biloiu, E. E. Scime, A. Meige, C. Charles, and R. W. Boswell, Phys. Rev. Lett. **95**, 025004 (2005).
[17] F. Skiff, G. Bachet, and F. Doveil, Phys. Plasmas **8**, 3139 (2001).
[18] B. Pelissier and N. Sadeghi, Rev. Sci. Instrum. **67**, 3405 (1996).
[19] E. Scime, C. Biloiu, C. Compton, F. Doss, D. Ventura, J. Heard, E. Choueiri, and R. Spektor, Rev. Sci. Instrum. **76**, 026107 (2005).
[20] G. Hairapetian and R. L. Stenzel, Phys. Rev. Lett. **65**, 175 (1990).
[21] A. B. Sefkow and S. A. Cohen, Phys. Plasmas **16**, 053501 (2009).
[22] G. Hairapetian and R. L. Stenzel, Phys. Fluids B **3**, 899 (1991).
[23] C. Charles and R. W. Boswell, Phys. Plasmas **11**, 3808 (2004).
[24] N. Plihon, P. Chabert, and C. S. Corr, Phys. Plasmas **14**, 013506 (2007).