Temporal Evolution of Bimodal Argon-Ion Velocity Distribution in an Expanding Helicon Plasma

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***Abstract*—Laser-induced-fluorescence (LIF) measurements, with 1-ms resolution, of the temporal evolution of the argon-ion velocity distribution function in the expansion region of a pulsed helicon plasma show two ion populations 19 cm downstream of the helicon source: a slow population that forms as soon as the 200-ms-long discharge is created and persists for few milliseconds after the RF pulse terminates and a fast population whose LIF signature appears ∼28 ms after the RF pulse begins.**

***Index Terms*—Electric double layer, helicon plasma, ion beam, ion velocity distribution function, time-resolved laser induced fluorescence.**

SPONTANEOUSLY appearing ion beams in the diverging magnetic field region downstream of low-pressure helicon sources [believed to result from the formation of a current-free electric double layer (EDL)] might provide an alternative to classical chemical propulsion for spacecraft [1], [2]. In a thruster application, the ejected plasma flux and the ion exit velocity are the critical parameters. Promising levels of ion production ($\sim 10^{13}$-cm^{-3} plasma density) by helicon sources and supersonic ion exit speeds (between 8 and 15 km/s) [3] have generated considerable interest in the possibility of a helicon source EDL thruster. Pulsing the helicon discharge might solve some important thruster issues such as plasma detachment, turbulent cross-field diffusion, and antenna heating. Therefore, for thruster applications, an understanding of the temporal evolution of the ion velocity distribution function (IVDF) downstream of an expanding helicon source is needed to choose the optimal operational parameters (duty cycle, pulse length, input power, driving frequency, etc.) to obtain the desired specific impulse along the expansion direction while minimizing the ion energy in the perpendicular direction.

Two diagnostic techniques are capable of investigating the temporal behavior of the IVDF in pulsed argon helicon plasma: 1) a time-resolved retarding field energy analyzer (RFEA) [1] and 2) time-resolved laser-induced fluorescence (LIF) [4]. Each method has its own advantages and disadvantages. The RFEA method is perturbative and requires conversion of energy-space measurements into IVDF measurements—a process that is very sensitive to the effects of the sheath created in the front of the grounded RFEA probe. LIF directly measures the IVDF without perturbation. However, the RFEA method provides information on the entire ion population, whereas the LIF-measured IVDF only reflects the behavior of the population of a particular excited ion state (for the three-level LIF scheme $\mathrm{3d'^2G_{9/2}} \rightarrow \mathrm{4p'^2F^0_{7/2}} \rightarrow \mathrm{4s'^2D_{5/2}}$ usually employed for Ar II investigation, it is the metastable state $\mathrm{3d'^2G_{9/2}}$). For time-resolved IVDF, the LIF detection scheme has to include a multichannel scaler, a boxcar integrator/averager, or a digital oscilloscope—lock-in combination [5], [6]. With such a detection scheme, the LIF time resolution is a few microseconds.

These experiments were performed in a helicon plasma source (discussed in detail elsewhere [7]). The source RF power was pulsed by square wave amplitude modulation (5 Hz at a 50% duty cycle) of the 9.5-MHz driving frequency. For parallel argon ion LIF, we used the classic three-level LIF scheme described earlier. After excitation, the $\mathrm{4p'^2F^0_{7/2}}$ state decays to $\mathrm{4s'^2D_{5/2}}$ state by emission at 461.09 nm (vacuum wavelength). To determine the parallel IVDF, laser light was injected along the axis of the source and the fluorescence signal detected by an integrated collection optics-photomultiplier tube mounted on a scanning probe [8]. A 1-ms temporal resolution was achieved by modulation of the laser beam with an acousto-optic modulator at 10 kHz. The in-phase and out-of-phase lock-in amplifier signals were recorded with a digital oscilloscope synchronized to the RF modulation signal. For a good signal-to-noise (S/N) ratio, the LIF signals were averaged over 400 plasma pulses at each of the 71 equally spaced laser wavelengths. After subtraction of the time-dependent background, the S/N ratio was better than 10 : 1.

The evolution of the parallel IVDF 19 cm downstream of a helicon source diffusion chamber junction is shown in Fig. 1. Since previous investigations showed oscillations of the LIF signal with characteristic frequency of 1 kHz [9] when the lower hybrid frequency in the source was comparable to the RF frequency, the source was operated at magnetic fields of 600 G in the source and 35 G in the diffusion chamber. Consistent with RFEA observations, the IVDF exhibits a bimodal structure: a fast population with flow speeds of ∼7.1 km/s and a slow population with speeds of ∼0.4 km/s. For similar steady-state plasma parameters, probe measurements indicated a potential drop of ∼18 V, corresponding to an EDL strength of $\sim 3k_B T_e/e$ [3]—sufficient to accelerate the fast ions. The slow population is most likely produced by local ionization of background neutrals. The slow group LIF intensity is higher at the beginning of the pulse and persists for a few milliseconds after the RF pulse terminates. The LIF signal for the fast ion population disappears at the end of the RF pulse, most likely

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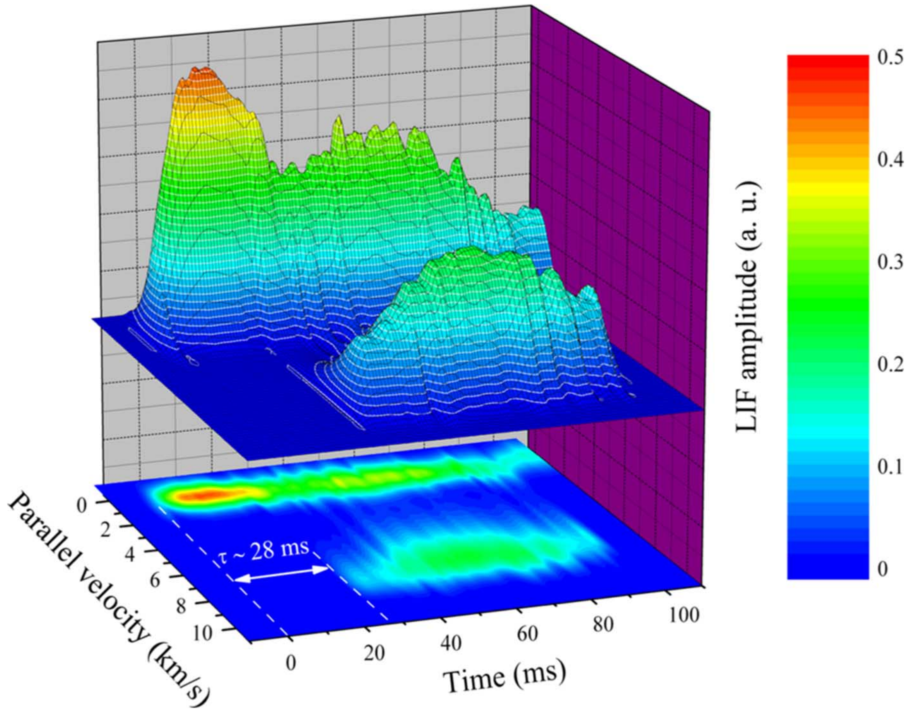

Fig. 1. With 1-ms time resolution, the LIF-determined argon IVDF during a 100-ms plasma pulse: Surface plot showing fast (∼7.1 km/s) and slow (∼0.4 km/s) ion populations; contour plot showing the time lag (∼28 ms) in the appearance of the fast ion population.

an effect of rapid quenching of the $3\mathrm{d}'^2\mathrm{G}_{9/2}$ metastable state. The most significant feature in the measurements is the 28-ms delay before the fast ion population appears. This observation does not necessarily contradict previous RFEA measurements in another helicon source that indicated the presence of a small but finite fast ion population from the very beginning of the RF pulse [10]. RFEA measurements are essentially current measurements and are therefore particularly sensitive to fast ions. The observed time lag for fast ion creation in the LIF data could be specific to our experiment or could simply reflect the time necessary for the population of the $3\mathrm{d}'^2\mathrm{G}_{9/2}$ level to become large enough for a measurable LIF signal.

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