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On limitations of laser-induced fluorescence diagnostics for xenon ion velocity distribution function measurements in Hall thrusters

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Hall thruster operation is characterized by strong breathing oscillations of the discharge current, the plasma density, the temperature, and the electric field. Probe- and laser-induced fluorescence (LIF) diagnostics were used to measure temporal variations of plasma parameters and the xenon ion velocity distribution function (IVDF) in the near-field plasma plume in regimes with moderate (<18%) external modulations of applied DC discharge voltage at the frequency of the breathing mode. It was shown that the LIF signal collapses while the ion density at the same location is finite. The proposed explanation for this surprising result is based on a strong dependence of the excitation cross-section of metastables on the electron temperature. For large amplitudes of oscillations, the electron temperature at the minimum enters the region of very low cross-section (for the excitation of the xenon ions); thus, significantly reducing the production of metastable ions. Because the residence time of ions in the channel is generally shorter than the time scale of breathing oscillations, the density of the excited ions outside the thruster is low and they cannot be detected. In the range of temperature of oscillations, the ionization cross-section of xenon atoms remains sufficiently large to sustain the discharge. This finding suggests that the commonly used LIF diagnostic of xenon IVDF can be subject to large uncertainties in the regimes with significant oscillations of the electron temperature, or other plasma parameters. *Published by AIP Publishing.*
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I. INTRODUCTION

For many low temperature plasma applications with accelerated ions, such as ion sources, plasma thrusters, sputtering magnetrons, and material processing devices, the ion velocity distribution function (IVDF) is a key parameter characterizing ion dynamics. For measurements of IVDF, laser-induced fluorescence (LIF) based on the detection of the fluorescent signal from the de-excitation of the metastable state of ions became a standard non-invasive diagnostic technique. Difficulties in interpretation of LIF measurements arise when IVDF oscillates due to unstable behavior of the plasma. In this paper, we demonstrate the limitations of LIF for measurements of IVDF in Hall thrusters. This limitation is due to strong low frequency temperature oscillations that are commonly observed in these plasma devices.

The Hall thruster is a plasma propulsion device in which ions are accelerated by crossed electric and magnetic fields applied in a quasineutral plasma with magnetized electrons and non-magnetized ions.[1] The operation of a typical Hall thruster is characterized by two most powerful modes of low frequency oscillations (∼10–30 kHz), namely longitudinally propagating breathing oscillations[2–4] and azimuthal propagating spoke oscillations.[5,6] Although both these modes are not well understood, it is commonly accepted that the breathing mode is due to ionization instability, while the azimuthal mode is due to a coupling between electrostatic and ionization instabilities. In both modes, plasma properties, including the electron temperature, the plasma density and the space potential, change both in time and space. It is believed that these modes are responsible for the anomalous current, which cannot be predicted by a classical collisional mechanism.[7] In the present work, we are focused on the breathing mode, but the main conclusions are applicable to azimuthal oscillations as well.

The breathing mode is usually observed as discharge current oscillations.[8] Depending on the thruster input parameters, including the magnetic field, the discharge voltage and the gas flow rate, the breathing mode may become strong with the amplitude of current oscillations reaching almost 100% of the time-averaged value of the discharge current. The correlation between the amplitude of current oscillations and the thruster performance is not so clear, but it is known that high performance regimes are not free of breathing oscillations.[9,10]

Breathing can be synchronized via application of the external modulations of the anode[11–13] or the cathode-keeper voltage.[14] This technique has been used in Time-Resolved Laser-Induced Fluorescence (TR-LIF) diagnostics for the studies of breathing[15,16] oscillations. In contrast, spoke[17,18] oscillations can be studied without such modulations.

In these previous studies, the modulation amplitude was limited to a few percent of the discharge voltage. In the present paper, our goal was to study the effect of strong breathing oscillations on LIF measurements of IVDF by applying 5%–20% modulations (of the discharge voltage).

II. EXPERIMENT AND DIAGNOSTIC DESCRIPTION

The experiments were conducted on the small Hall thruster facility at the Princeton Plasma Physics Laboratory. This facility consists of a 0.5 m^3 vacuum chamber equipped

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with a turbo-molecular pump and a mechanical pump. A 200 W cylindrical Hall thruster (CHT) with the channel diameter and length of 2.6 cm and 2 cm, respectively, was operated at the applied DC discharge voltage of 220 V, using xenon gas. The xenon flow rates through the anode and the hollow cathode-neutralizer were 3.5 sccm and 2 sccm, respectively. Under such conditions, the background pressure in the chamber did not exceed 70 μTorr. The thruster facility and CHT are described elsewhere.[12,19] For the modulation of the discharge voltage, the thruster discharge circuitry has a driving power source (a 200 W bi-polar Kepco amplifier driven by a functional generator) connected in series with the main 600 W thruster power supply.[20]

For the measurement of breathing oscillations, the thruster discharge circuitry includes a low-impedance shunt resistor connected in series between the thruster anode and the modulating power supply. Current oscillations were recorded on an oscilloscope and using a data-acquisition board controlled by LabVIEW software simultaneously with the LIF measurements. Under the above thruster operating conditions, the frequency of breathing oscillations without modulation was 13 kHz [Figs. 1(a) and 1(b)]. The modulated voltage was applied with respect to this DC voltage and with the same frequency [Figs. 1(c) and 1(d)] as the natural breathing mode.

All plasma measurements were conducted in the near-field plasma plume, 1.3 cm downstream of the thruster exit. The following diagnostics were used: LIF for the measurement of IVDF, floating emissive and biased probes for the measurement of oscillations of the plasma potential and density, respectively. The LIF diagnostic setup used in these experiments is described elsewhere.[21] The setup is built around a TLB-6917 VortexTM II laser head. In the described experiments, it probes xenon ions at the metastable level $5d[4]_{7/2}$, which is commonly used for similar thruster studies. For LIF measurements, these ions are excited by the laser to the $6p[3]_{5/2}$ (centered at 834.724 nm; air) level. The de-excitation state is $6s[2]_{3/2}$, leading to a fluorescent signal at 541.915 nm. A majority of previous studies of xenon LIF often uses the assumption that dynamics of these metastable ions represents well the dynamics of the whole ion population. However, since this LIF transition scheme is not connected to the ground state of xenon ions, it is more reliable to say that the LIF measures the profile of IVDF.

In order to correlate LIF measurements with the discharge current oscillations, the laser beam can be modulated using an acoustic opto-modulator (AOM). Therefore, emission from the plasma contains two periodic components: one from the discharge current oscillations and another from the fluorescence light. The ion velocity is deduced from the Doppler shift of the signal detected by a PMT with an optical setup that includes a narrow bandpass filter of 2 nm width.[21] In the present work, we measured the axial component of the

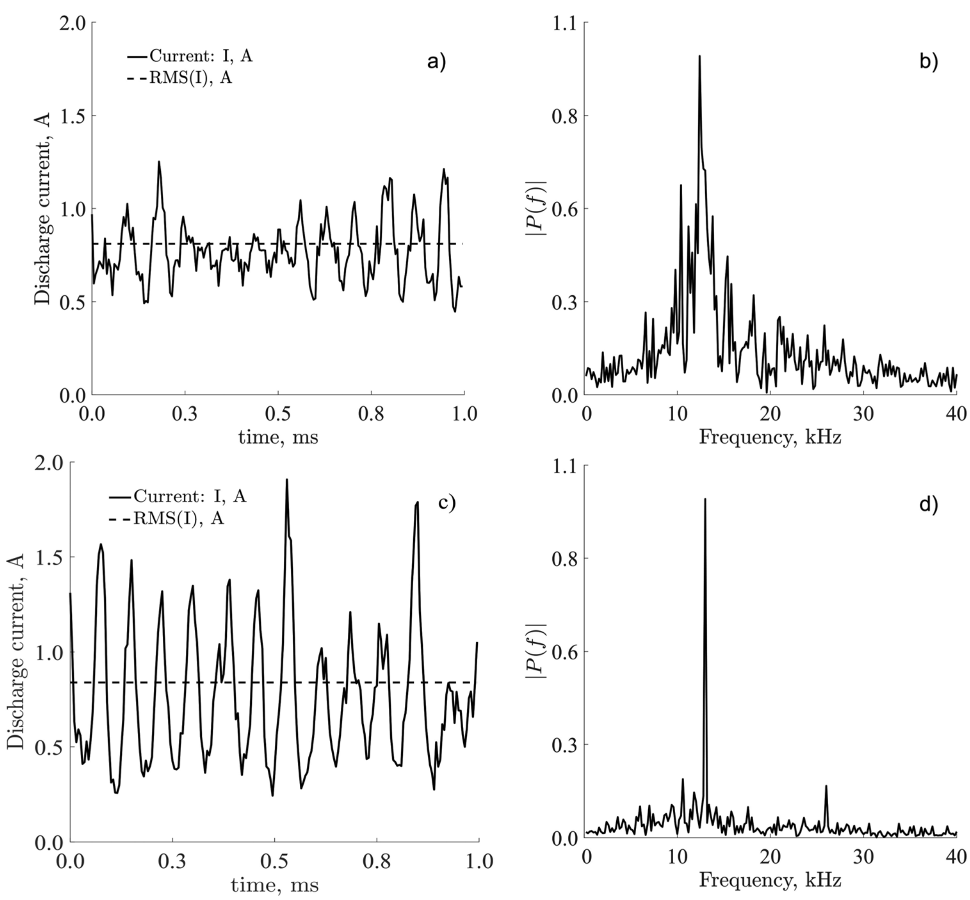

FIG. 1. Effect of the external drive on the discharge current: (a) discharge current trace without applied driving of the anode voltage, I_{rms}=0.81 A; (b) the corresponding FFT of the discharge current trace, f_{max}= 12.9 kHz; (c) discharge current trace with the anode voltage driving at 32 V peak-to-peak amplitude, I_{rms}=0.84 A; and (d) the corresponding FFT of the discharge current trace, f_{max} = 13.0 kHz.

ion velocity, i.e., the laser beam of nm diameter was directed along the axis. The PMT collected light was normal to the thruster axis with the focus on the thruster axis. The characteristic size of the collection volume is about 0.5 mm. The signal from the PMT is sent into a lock-in amplifier, which enables the extraction of the LIF component based on homodyne detection technique.[21,22]

The plasma density was deduced from measurements of the ion saturation current using a 0.05 cm diameter planar probe biased −40 V with respect to the floating potential. For the emissive probe, a 0.2 cm filament made from a 0.01 cm diameter thoriated tungsten wire was operated in the regimes with strong electron emission (hot probe) and no-emission (cold probe), respectively. Assuming Maxwellian electron energy distribution function, the plasma potential and the electron temperature were estimated from the measured floating potentials of hot and cold probes using a standard procedure described in Refs. 23 and 24. The deduced electron temperature was also used to estimate the ion Bohm velocity and then, the ion density from the measured ion saturation current collected by the planar probe.

The following procedure of LIF measurements was applied. The excitation of the LIF signal was only applied at certain points of the discharge current oscillations. For example, Fig. 2 shows the discharge current oscillation and laser pulses for two situations when the laser pulse was locked to the maximum and the minimum of the discharge current. This was achieved using a lock-in amplifier which kept a selected phase shift between the AOM-modulated laser beam of the LIF and the modulated thruster discharge voltage. The exposure of the laser beam to the near-field plasma plume was pulsed using the AOM. The pulse duration was ∼15 μs shorter than the oscillation period (∼75 μs). This is in order to minimize the changes in the plasma parameters during a short time when LIF measurement is taken. It was found that this pulse duration was sufficient to achieve an acceptable signal-to-noise (not less than 3). Moreover, the frequency of LIF pulses was smaller than the frequency of the current oscillations (Fig. 2). This is in order for the lock-in amplifier to distinguish between two periodical components of the signal: one from the background light and one from the induced fluorescence. Finally, this measurement procedure was repeated over a large number of current oscillation cycles with these different phase shifts to ensure measurement accuracy.

Note that the discharge current path between the anode and the cathode in the near-field plasma plume is unknown. Therefore, there may be a time lag between the oscillations of the discharge current measured in the electric circuitry and the LIF measurements of ion velocities measured in the plume. A rough estimate of the time of flight of ions from the anode to the location of the LIF measurements: $\tau = L/V_i$, where $L \approx 3$ cm is the ion path from the anode to the location of LIF measurements and $V_i \sim 10^6$ cm/s is the average ion velocity along the path, gives the time lag of 3 μs that is much smaller than the duration of the LIF pulse (15 μs).

III. RESULTS AND DISCUSSION

The results of time-resolving LIF measurements for three different modulating amplitudes are shown in Fig. 3. Each figure shows the IVDF profiles measured during the discharge current oscillations and averaged for the maximum and minimum values of the current. For low and moderate amplitudes, 8 V_{pp} and 16 V_{pp} [Figs. 3(a) and 3(b)], the IVDF centers (or the most probable ion velocities) follow the modulated voltage. For the maximum peak voltage, the most probable velocity is higher than that of the minimum voltage. This result is generally similar to the results reported in Ref. 12. There are also changes in the peak values of the most probable ion velocity corresponding to the maximum and minimum currents measured at these modulating voltages. However, these changes are insignificant as compared to the results of the large modulating voltage of 32 V_{pp} [Fig. 3(c)]. In this regime, the IVDF profile is detected only at the maximum discharge current [see Fig. 3(c)], while the LIF signal collapses at the minimum current.

This surprising result is in strong contradiction with the probe measurements of the ion density in the plume (Fig. 4). Ions are present during the whole cycle of the discharge current oscillations and their density remain well above the LIF detection limit.

One could consider the collapse of the IVDF at the minimum current as a result of a strong outward shift of the ion acceleration region to the near-field plasma plume.[25] However,

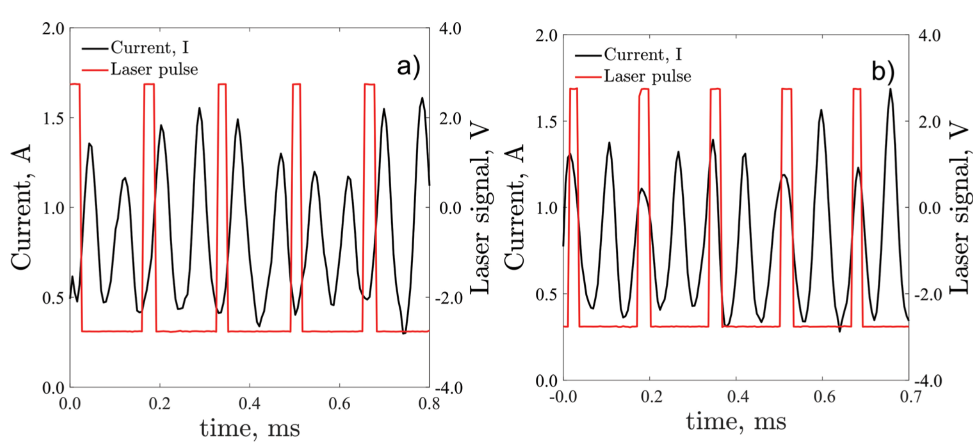

FIG. 2. Laser pulse locked (a) at the minimum and (b) at the maximum (b) of the discharge current oscillations.

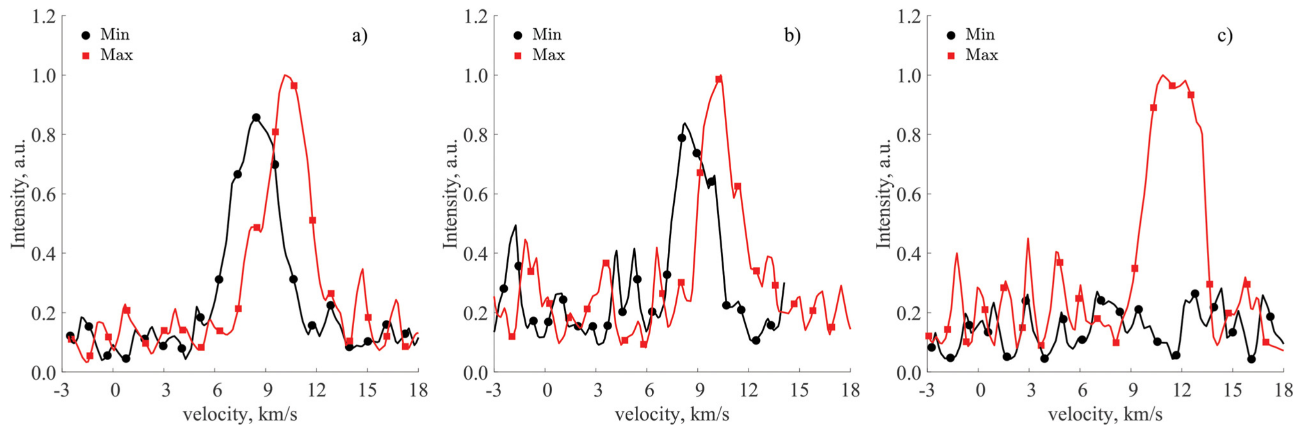

FIG. 3. Ion velocity distribution functions at the minimum (black circles) and the maximum (red squares) of the discharge at: (a) 8 V_{pp}; (b) 16 V_{pp}; and (c) 32 V_{pp}. Intensities are normalized to the maximum intensity of the LIF signal at the highest point of the discharge oscillations.

Fig. 5 shows that changes in the accelerating voltage drop are insufficient to explain the collapse of IVDF. Here, the accelerating voltage was estimated as $V_{accel} = V_d \pm V_{pp}/2 - V_{pl}$, where V_d is the discharge voltage and V_{pl} is the plasma potential measured by the emissive probe. Even if changes in the position of the acceleration region would lead to the redistribution between different components of ion velocities, they would not lead to the collapse of IVDF measured in the axial direction. This is because, if the radial component would increase, there would be a distribution closer to zero velocity in axial IVDF which is not observed in experiments.

The current oscillations appear to have a strong effect on the electron temperature, but less effect on the ion density and the accelerating voltage. Figure 6 shows a strong increase in the oscillation amplitude of the electron temperature, along with a decrease in the RMS and minimum values. The RMS value dropped from 9.2 eV to 8.3 eV, and the minimum value dropped from 7.4 to 6.3 eV. This decrease is larger than the experimental uncertainty, which is of the order of 1.0 eV.

Increase of the amplitude of the electron temperature oscillations from ~5 eV to ~9 eV (Figs. 6(a) and 6(b), respectively) provides a clue to the most likely mechanism of the signal loss in the strongly nonlinear driving regime. Our hypothesis is that for large amplitudes of discharge current oscillations, the electron temperature enters the regime of very low excitation cross-sections of xenon ions. Figure 7 compares the cross-sections for excitation of xenon ions[26] and ionization of xenon atoms.[27] There is an assumption, that excited metastables mainly are produced from election-neutral collisions, rather than electron-ion collisions, because for typical thruster conditions the density of ions is smaller than the density of atoms (at least an order of the magnitude) and because the cross-section of excitation collisions of ions is much smaller than that of the atoms.[28] In the present experiments, we did not have access to probes to measure the electron temperature inside the thruster channel. However, for the range of the electron temperatures between 20 and 30 eV, which is typical for Hall thrusters, the excitation cross-section shows a sharp drop, while the ionization cross-section remains significant. Therefore, temperature oscillations in this range would cause a significant drop in the population of density of metastable ions, leading to the loss of the LIF signal, but not the density of ions.

Since the residence time of ions (~μs) is much shorter than the time scale of discharge current oscillations (~10's of μs), the ions born during the low electron temperature phase corresponding to the small ion excitation cross-sections can escape from the channel without being excited by electrons. These ions are measured by the biased probe, but not detected by the LIF.

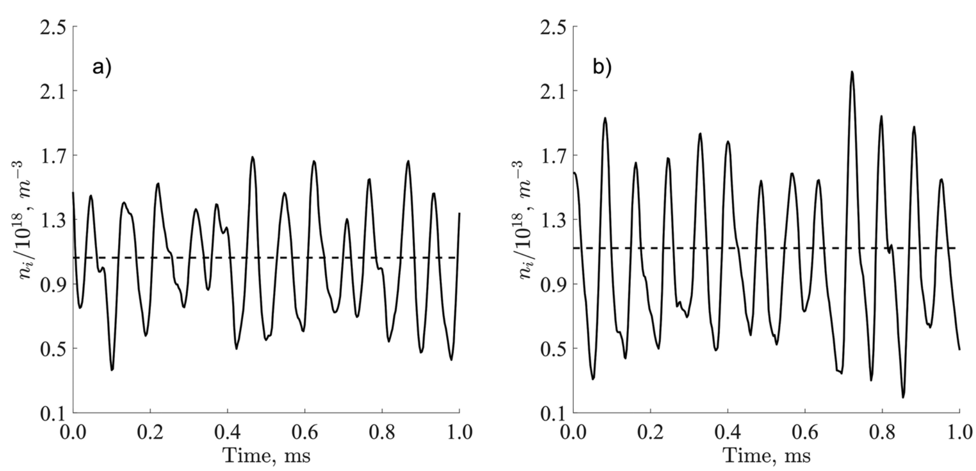

FIG. 4. Plasma density measurements at (a) 16 V_{pp} and (b) 32 V_{pp} driving voltage amplitude. Dashed line is the RMS value of the density.

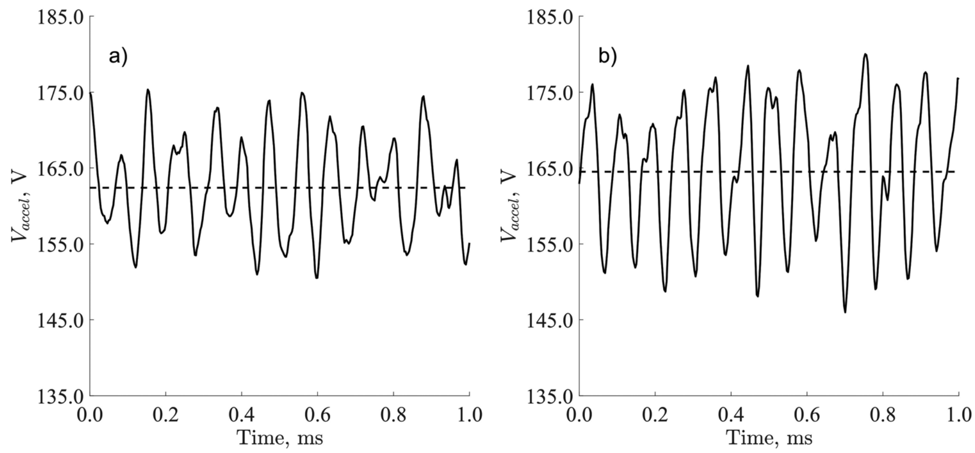

FIG. 5. Acceleration potential measurements at (a) 16 V_{pp} and (b) 32 V_{pp} driving voltage amplitude. Dashed line shows RMS values of the acceleration potential.

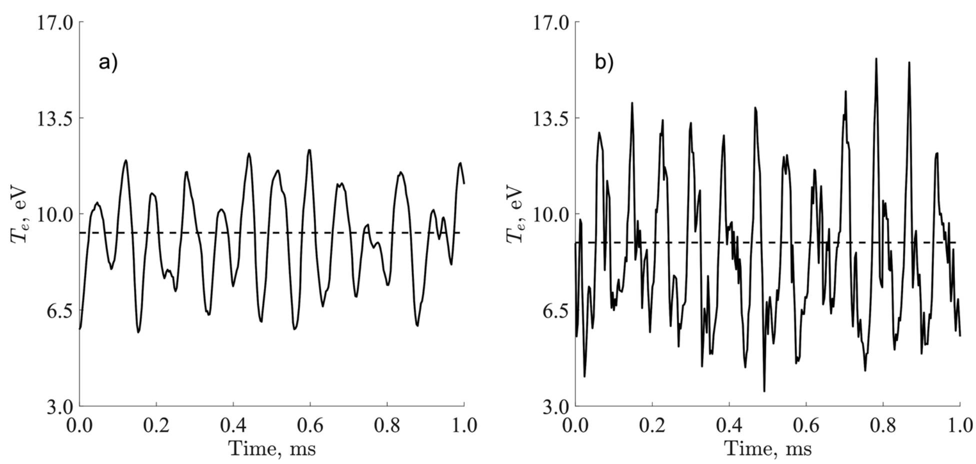

FIG. 6. Electron temperature measurements at (a) 16 V_{pp} and (b) 32 V_{pp} driving voltage amplitude. Dashed line shows RMS values of the electron temperature.

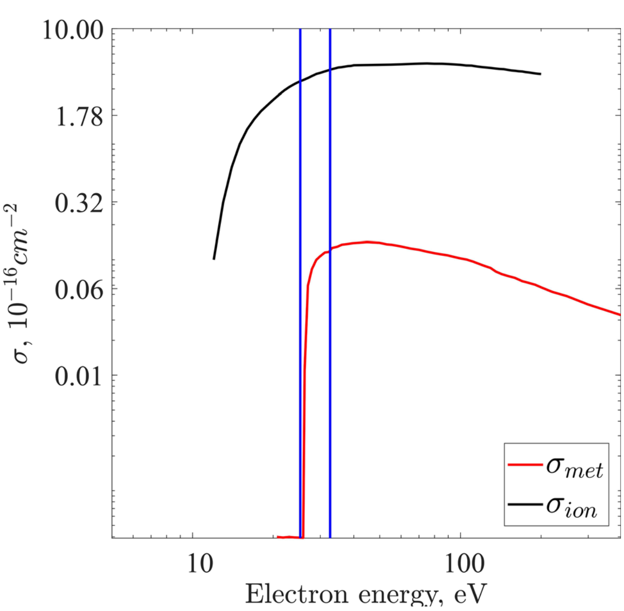

FIG. 7. Ionization (black) and metastable excitation (red) cross-sections for Xe ions. Data are taken from Refs. 25 and 26.

IV. CONCLUSIONS

The effects of plasma parameter oscillations on LIF diagnostics in the cylindrical Hall thruster were performed in regimes with the breathing mode. These measurements included LIF detection of the xenon ion VDF and measurement of the electron temperature and ion density in the near-field plasma plume of the thruster. We have demonstrated that for a Hall thruster operating with large amplitude discharge current oscillations ($\sim$100% of the steady-state discharge current) corresponding to a typical strong breathing mode, the collapse of the LIF signal occurs. Our probe measurements show the ion density oscillations can affect the LIF signal, however, the oscillating total ion density remains sufficiently large to sustain the discharge, and well above the LIF detection limit. Thus, oscillations of the ion density alone cannot explain the observed collapse of the IVDF corresponding to the minimum amplitude of the discharge current oscillations. The proposed explanation of the loss of the LIF signal is that the minimum value of oscillating electron temperature can cross the range corresponding to the sharp reduction of the cross-section for the excitation of ions, while the temperature can still be sufficient to produce ground-state ions. In this situation, the density of metastable ions is too low for such LIF diagnostic to work, even though the total ion density is large in the plasma flow of the thruster and the near-field plasma plume. In this paper, this result has been obtained for the thruster operating with xenon gas, but a similar situation may occur in the thruster operating with other gases. The observed collapse of the LIF signal poses a question about the limitations of the conventional LIF technique for measurements of IVDF in plasma thrusters and other plasma applications where oscillations of the electron temperature can be significant (e.g., sputtering magnetrons, ExB Penning discharges). It is worth noting that the production of metastable ions may also be affected by strong nonlinear oscillations of the plasma density and the electric field,[29] which could lead to the modification of the electron distribution function, in particular, the high energy tail. The role in and the relative contribution of the oscillations of the electron distribution function to the production of metastable ions require further experimental and theoretical studies.

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