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Nanosecond optical imaging spectroscopy of an electrothermal radiofrequency plasma thruster plume

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Nanosecond optical imaging spectroscopy is employed to investigate the spatio-temporal dynamics of the plasma plume expanding from a 4.2 mm-diameter, 20 mm-long cylindrical capacitively coupled electrothermal radiofrequency (rf) driven thruster using 10 W of power at 12.50 MHz and an argon pressure of 1.5 Torr. On-axis, the plume exhibits four distinct peaks of optical emission intensity within the rf period. The plume has a spherical shape with a transient radial extension (during half of the rf cycle) at the thruster exit plane due to an rf current to ground when the grounded electrode acts as an anode. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4821738>]

Small-sized plasma sources driven by dc, rf, or microwave power are developed for a variety of applications and are often known as plasma jets, e.g., biomedical applications using atmospheric-pressure helium or argon plasmas,^{1–5} micro-plasma sources or arrays,^{6,7} e.g., surface processing using lower-pressure plasmas in argon or SF₆,^{4,8,9} or micro-thrusters, e.g., using hollow cathode devices,¹⁰ or capillary thrusters for application to electric propulsion.¹¹ Their typical size ranges from micrometers to millimeters, which often restricts the use of electrostatic probes as experimental diagnostics, but favors the use of optical diagnostic techniques.

Recently, an asymmetric, capacitively coupled radiofrequency (rf: 13.56 MHz) cylindrical plasma source has been developed as a new electrothermal thruster (known as “Pocket Rocket”) and currently operates at pressures around a few Torr and rf powers ranging from 1–100 W.^{12–14} The concept behind this thruster is gas heating via ion-neutral collisions in the plasma volume, possibly combined with heating at the cavity’s walls (as in a resisto-jet).¹⁵

Time-averaged and spatially averaged modeling of thrust in a cylindrical collisional thruster has been reported by Fruchtmann.¹⁶ Blackhall and Kachan have used Doppler spectroscopy to investigate the plasma plume of a dc ion charge-exchange thruster operating in hydrogen.¹⁷ Time-resolved imaging has been used to investigate plasma fluctuations and rotating spoke phenomena in the $E \times B$ xenon discharge of a cylindrical Hall thruster.¹⁸

Here, nanosecond optical imaging spectroscopy with 2 ns resolution¹⁹ is undertaken to investigate the dynamics of the plasma plume expanding from the “Pocket Rocket” thruster. Four peaks of optical-emission intensity are observed within the rf cycle. Optical emission, which is related to an rf return current, is also observed to extend over the surface of the grounded electrode that terminates the thruster during approximately half of the rf period, but no spatial instabilities within the plume are observed.

As shown in Figure 1, the “Pocket Rocket” micro-discharge thruster, which is about 2 cm long and 4.2 mm in diameter, is expanded in a 12 cm-long, 5 cm-diameter glass tube. The glass expansion tube is attached to one 20 cm-diameter arm of a six-way cross stainless steel vacuum chamber, which is equipped with a primary pump and convectron gauge. Argon gas is introduced upstream of the thruster into a small grounded cavity or plenum (1.2 cm-wide and 4 cm-diameter) which is also equipped with a convectron gauge. The system is pumped down to a base pressure of $\sim 3 \times 10^{-3}$ Torr, and the gas flow is adjusted to provide a plenum pressure of 1.5 Torr. This pressure corresponds to the minimum plasma breakdown voltage.¹⁴ The pressure measured in the downstream chamber is about 0.5 Torr yielding an estimated pressure inside the thruster of about 1 Torr. These conditions correspond to the “low-flow” regime¹³ and are of particular interest for electric propulsion applications.

10 W of rf power at 12.50 MHz (80 ns period) is coupled to the plasma using a “Pi” matching network. This is equipped with a $\times \frac{1}{1000}$ HV probe to measure the rf voltage, and a Bird power meter is inserted between the rf generator and matching network for measurements of the rf power. The measured peak voltage amplitude on the rf electrode is about 175 V for 10 W of rf power.

“Pocket Rocket” consists of a 2 cm-long, 4.2 mm-inner-diameter, 5.3 mm-outer-diameter ceramic tube that is surrounded by a 5 mm-wide rf ring electrode constructed from copper. This electrode is located at the midpoint of the ceramic tube, and two 3 mm-wide aluminium grounded electrodes are located on either side at a distance of 3 mm towards the plenum cavity and 4 mm towards the expansion chamber, respectively. As shown in Figure 1, $z = 0$ mm is defined as the edge of the grounded electrode that terminates the thruster, i.e., that which is contiguous with the expansion tube.

An intensified charge-coupled-device camera (ICCD) is mounted perpendicularly to the longitudinal (z -direction) axis of the discharge for measurements of the optical emission from the plasma plume. The camera detector, a CCD

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FIG. 1. Schematic of the “Pocket Rocket” microdischarge apparatus that facilitates side-view imaging of the plasma plume with an ICCD camera (focusing lens and 750 nm filter not shown for clarity).

chip with 1024×1024 , $13 \mu\text{m}^2$ pixels, is positioned behind a 105 mm lens for optimum imaging of the incident light. An interference filter with a central wavelength of 750 nm (FWHM 10 nm) is fitted to the camera aperture for the study of the Ar I $2p_1 - 1s_2$ transition at 750.4 nm (>13.48 eV electrons for direct electron-impact excitation from the electronic ground state). A 2-channel arbitrary waveform generator is used to provide a phase-locked reference for both the broadband power amplifier and the camera intensifier. The driving frequency of the discharge is 12.50 MHz (80 ns period), and the intensifier is gated in 80 consecutive 2 ns time steps (each image is generated by accumulating the emission from thousands of acquisitions) to measure the temporal variation in the optical emission throughout two rf cycles. Since the absolute phase between the rf voltage and the optical-emission as detected by the ICCD is unknown, $t=0$ ns is arbitrarily defined. Here 12.50 MHz is chosen because the rf period of 80 ns can be divided into four parts of 10 frames each (convenient for the data analysis), when using 2 ns acquisition gate steps.

The variation in the optical emission with respect to time is shown in Figures 2(a) and 2(b) for two consecutive rf periods at the locations $(r, z)=(0 \text{ mm}, 0 \text{ mm})$ and $(r, z)=(-15 \text{ mm}, 0 \text{ mm})$, respectively. As shown in Figure 2(a), the main body of the plasma plume, which is located about the z -axis, exhibits 4 distinct peaks of optical-emission intensity per rf cycle as labelled A-D. These peaks are observed at regular intervals and correspond to $t=14$, 34, 54, and 74 ns, respectively. As shown in Figure 2(b), during peak B the plasma plume is observed to expand over the surface of the grounded electrode that terminates the thruster (contiguous with the expansion chamber). This behaviour is likely a result of an rf current to ground when this electrode acts as an anode and corresponds to a positive excursion of the voltage at the rf electrode. The effect lasts for approximately half an rf cycle, i.e., $20 < t < 60$ ns during the first period shown in Figure 2(b).

The radial expansion of the plume over the surface of the grounded electrode that terminates the thruster, i.e., that which is contiguous with the expansion tube, is visualised using images of the optical emission. The optical emission from the plasma plume, as measured during acquisition intervals B ($t=34$ ns) and D ($t=74$ ns), is shown in Figures 3(a) and 3(b). The intensity of the optical emission is normalised with respect to the global maximum and this occurs at the spatial coordinate $(r, z)=(0 \text{ mm}, 0 \text{ mm})$ as defined in Figure 1. It is noted that

FIG. 2. (a) and (b) Optical-emission intensity versus time during two rf periods at $z=0$ mm for radial positions (a) $r=0$ mm and (b) $r=-15$ mm, respectively. The solid lines are included to aid visualisation.

each pixel is effectively a line-of-sight perpendicular to the camera.

A global model of this discharge has been developed previously: The discharge is asymmetric with the development of a time-averaged self-bias of about -36 V on the ceramic tube near the rf electrode at 10 W and a time-averaged plasma potential of at least 22 V in the plasma bulk.¹³ Particle-in-cell studies of a cylindrical rf hollow cathode system have suggested that ion-induced secondary electrons, which are accelerated from the ceramic surface along the rf electrode back into the discharge, may be the dominant heating mechanism as distinct from rf sheath heating.²⁰ The energy of the accelerated secondary electrons is well over the excitation and ionisation threshold for argon, and the corresponding optical emission would be strongest near the maximum negative excursion of the rf signal when the rf electrode is acting as a cathode.

The shape of the plume “bulk,” i.e., the optical emission measured close to the z -axis and excluding the portion that extends for larger r over the surface of the grounded electrode, is investigated over the pressure range 0.5–7 Torr for 10 W of rf power. The spatial extent of the plume in the radial and axial directions is defined as the distance over which the optical emission decreases to 20% of the maximum value, as measured along the lines-of-sight $(r, z=0 \text{ mm})$ and $(r=0 \text{ mm}, z)$, respectively, at each pressure level. The measurements correspond to acquisition interval D, as defined in Figure 2(a), since here the degree to which the plume expands radially is relatively low as shown in Figure 2(b).

FIG. 3. (a) and (b) Measurements of the optical emission from the plasma plume undertaken at (a) $t = 34$ ns (peak B in Figure 2) and (b) $t = 74$ ns (peak D in Figure 2) as measured with the ICCD camera for 10 W of rf power and 1.5 Torr argon pressure. Lines of constant optical-emission intensity are shown by the colors, and the intensity is normalised with respect to the global maximum. The positions of the grounded electrode that terminates the thruster and the glass expansion tube are indicated by the vertical-dashed and horizontal-solid lines, respectively. Measurements of optical emission for negative values of z correspond to reflections from the aluminium grounded electrode and glass expansion tube. The z axis is stretched by a factor of 2 compared to the r axis to assist visualisation.

The results for the plume diameter and length are shown in Figures 4(a) and 4(b), respectively. A maximum plume length of 6.0 mm is achieved at the lowest pressure level of 0.5 Torr, and a maximum plume diameter of 8.2 mm is observed under the same conditions. This corresponds to about twice the diameter of the thruster exit (4.2 mm). For plenum pressures greater than 2.5 Torr, there is very little variation in either the plume diameter or length, and both are similar, showing a spherical shape for the plume.

The fact that there are four peaks per rf cycle in the optical emission (Figure 2(a)) suggests that the ionization occurs twice as often as what would be expected from simple rf sheath heating or Gamma electron production in a capacitively coupled discharge and that the plasma production via electron acceleration is more complicated than present systems. This has not been predicted or observed before and would favorably affect the thruster power efficiency. A possible explanation is that the ionization occurs alternatively between the powered electrode and the “upstream” and “downstream” earthed electrodes. The existence of four peaks instead of two suggests that the plasma ionization mechanism occurs over a larger volume than the cavity

FIG. 4. (a) and (b) Variation in the plume (a) diameter and (b) length with respect to plenum pressure for 10 W of rf power at peak D as shown in Figure 2(a). The extent of the plume in the radial and axial directions is defined as the propagation distance over which the intensity of the optical-emission intensity decreases to 20% of the maximum at each pressure level. The diameter of the thruster exit is shown by the dashed line in part (a), and the solid lines are included to aid visualisation.

defined by the width of the power electrode. The emission over the surface of the exit earthed electrode may be a result of the existence of radiofrequency voltages in the plasma, possibly during the discharge from the powered electrode to the downstream earthed electrode. As seen here it strongly modifies the shape of the plume at the exit plane during half of the radiofrequency cycle (Figures 3(a) and 2(b)) but not its overall downstream edge since its length and diameter are found to be largely invariant over the investigated pressure range (Figure 4). The relative lack of dependence on the pressure is probably due to the low pumping rate and axial pressure gradient employed for the experiment. Particle-in-cell simulations of a simplified system with one earthed electrode have shown only two maxima during the radiofrequency cycle which are due to Gamma electrons.²⁰ Clearly, the present experimental configuration is more complicated than the previously reported simulations and requires a more comprehensive model including gas flow and two earthed electrodes.

Finally, the potential presence of any low-frequency plasma instabilities (microsecond to millisecond time scales) is diagnosed using a photodiode for 0.5–7 Torr and 10 W of rf power. The photodiode is oriented towards the plenum and the plume (separately), installed behind a 750 nm filter (FWHM 10 nm), and connected to a spectrum analyser

(Anritsu MS 2661C). No peak in the frequency spectrum over 0–10 MHz is observed, and this suggests that the discharge is “quiet.” However, as shown in Figure 2, on nano-second time scales the optical emission from the discharge is clearly modulated during the rf period. Four peaks in the optical emission are observed from the plasma bulk (about the z -axis) during each rf period with the intensity modulated by up to 45% throughout the cycle. In contrast, the plume exhibits a radial expansion over the surface of the grounded electrode, which exceeds the diameter of the hole at the thruster exit, once per rf period.

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