2011

Ignition of a Large Volume Plasma with a Plasma Jet

M. Laroussi
Old Dominion University, mlarouss@odu.edu

M. A. Akman
Old Dominion University

Repository Citation

Laroussi, M. and Akman, M. A., "Ignition of a Large Volume Plasma with a Plasma Jet" (2011). *Electrical & Computer Engineering Faculty Publications*. 6.
https://digitalcommons.odu.edu/ece_fac_pubs/6

Original Publication Citation

Laroussi, M., & Akman, M.A. (2011). Ignition of a large volume plasma with a plasma jet. *AIP Advances, 1*(3), 032138. doi: 10.1063/1.3630924

AIP Advances

Ignition of a large volume plasma with a plasma jet

M. Laroussi and M. A. Akman

Citation: AIP Advances **1**, 032138 (2011); doi: 10.1063/1.3630924
View online: http://dx.doi.org/10.1063/1.3630924
View Table of Contents: http://scitation.aip.org/content/aip/journal/adva/1/3?ver=pdfcov
Published by the AIP Publishing

AIP ADVANCES **1**, 032138 (2011)

Ignition of a large volume plasma with a plasma jet

M. Laroussi[a] and M. A. Akman
Laser and Plasma Engineering Institute, Old Dominion University, Norfolk, VA, USA

(Received 16 June 2011; accepted 2 August 2011; published online 17 August 2011)

Here we report on a method to generate a long plasma plume and to ignite a large volume plasma by means of the jet. The plasma plume is generated by our tube reactor and then introduced into a chamber where the pressure is controlled. We discovered there are three operating phases: A phase where the plume length remains approximately constant, followed by a second phase where the jet increases in length as the pressure decreases. Then at pressures below 70 Torr a mode transition occurs where the plume length decreases and the plasma expands until the entire chamber is filled. *Copyright 2011 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License*. [doi:10.1063/1.3630924]

In recent years low temperature plasma jets have been the subject of many investigations and been used in various biomedical applications.[1–13] The plumes generated by these plasma jets were found to consist of plasma packets/bullets traveling at high velocity.[2,3] For the case of pulsed devices and when helium is used as the operating gas, two main factors influence the plasma bullet lifetime and therefore the length of the plume. These factors are the helium mole fraction in the gas channel and the width of the applied voltage pulse. It is found that, in general, the helium mole fraction should be more than a critical limit to sustain the plasma bullet propagation.[9] However, the width of the applied high voltage pulse also plays a crucial role. Wider pulses resulted in longer plumes (assuming all other parameters being constant). To date the plumes generated by plasma jets have been emitted in ambient air at atmospheric pressure. This was motivated by the fact that atmospheric conditions were desired for most applications. In this paper, as a departure from this scenario, we investigate the behavior of the plasma plume in a case where the atmosphere in which the plume propagates can be controlled in terms of pressure and contents. Figure 1 is a schematic illustrating what we embarked on investigating. The device generating the plasma jet, tube reactor, consists of a cylindrical acrylic tube with 3 mm inner diameter and two copper foil electrodes wrapped around the tube (see Figure 2). The electrodes are separated by a distance of 15 mm. Helium as a working gas is fed by a mass flow meter (Bronkhorst High-Tech) with an adjustable flow rate. An 8 kV high voltage pulse, 2 μs in width is applied with a 5 kHz repetition rate during all experiments. The acrylic tube which makes the body/housing of the jet source is inserted into one end of the long arm of a cross-shaped large Pyrex chamber. The remaining ports of the Pyrex chamber are used to connect a vacuum pump, a view port (equipped with a fused silica window), and a vacuum gauge. The pressure inside the chamber is controlled by regulating the gas in-flow and evacuation rate.

It was shown in our prior work that the plasma plumes are the foot print of a train of plasma packets/bullets that travel within the helium channel at supersonic speeds.[8,9] The propagation of these bullets was explained with a photoionization model similar to that of cathode directed streamers.[3] In addition, we showed that the bullets travel within the helium channel then quench when the helium mole fraction falls below a certain value, as it mixes with air.[9] Therefore, controlling the helium flow (for example laminar versus turbulent) affects directly the plume stability and length. In the following experiments, the plume/jet is injected into a chamber where the background pressure can be controlled. Thus, by lowering the pressure, less air molecules will be interacting with the helium

---

[a] Author to whom correspondence should be sent: mlarouss@odu.edu

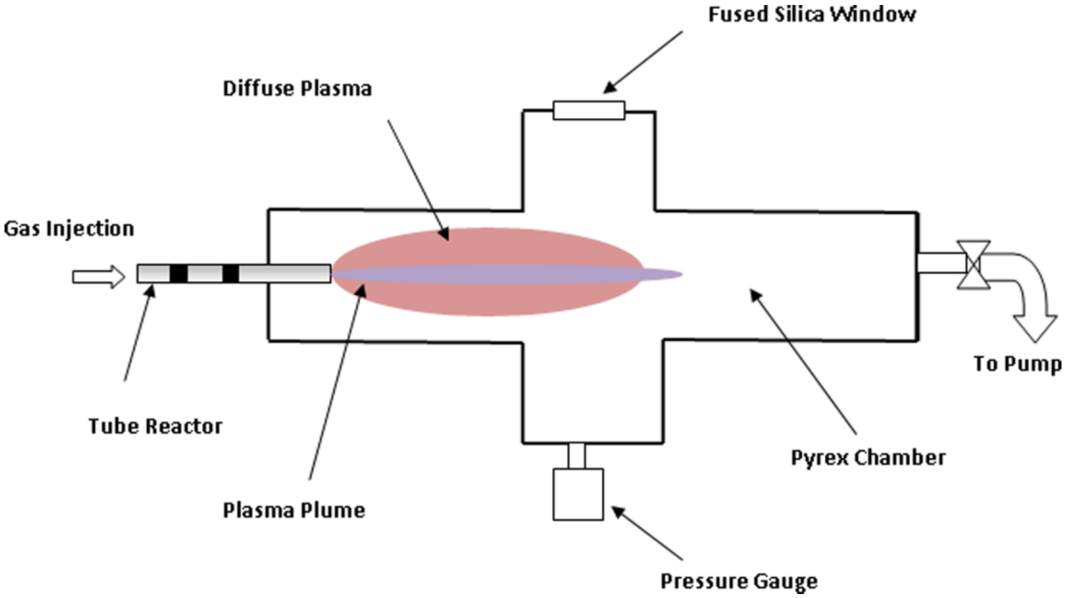

FIG. 1. Experimental setup, showing how a plasma jet is introduced into a secondary Pyrex chamber where pressure can be controlled. The length of one arm of the cross-shaped chamber is 45 cm while that of the second arm is 40 cm.

flow and a longer helium channel can be achieved. However, we discovered that the behavior of the plume is much more complicated as the pressure changes. In fact, from atmospheric pressure to about 200 Torr, the plume increases relatively slightly in length. Below a pressure of 200 Torr and down to 70 Torr, we observed a rapid increase in the length of the plasma plume. However, below 70 Torr, the length of the plume starts decreasing rather quickly while at the same time the plasma starts expanding in all directions, starting at the tip of the acrylic tube inside the chamber. Figure 3, a plot of plume length versus pressure, illustrates the above observations. Figure 4, which shows photographs of the plasma plume/jet inside the chamber at 3 different pressures, 760 Torr, 180 Torr, and 75 Torr, illustrates well the dramatic increase of the plume length for pressures below 200 Torr but above 70 Torr (the photo of the plume at 760 Torr is used a reference). The plasma plume/jet length reaches up to 25 cm at a pressure of 75 Torr. This is due to the fact that the ratio of helium mole fraction to that of air stays above the quenching threshold for longer distances.

Figure 5 shows the discharge current at the three indicated pressures in the chamber along with the applied high voltage pulse. The peak amplitudes of the current increase as the pressure decreases indicating plasmas with higher densities of electrons and ions. Another phenomenon is observed in this figure as current peaks' temporal position shifts for both the primary and secondary discharges. Primary and secondary discharges are characteristics of pulsed plasma sources of the dielectric barrier type.[14] The primary discharge ignites at the rising edge of the voltage pulse and the secondary discharge occurs at the falling edge.[14,15] Figure 5 shows that the primary and secondary discharges take place earlier with decreased pressure. One possible explanation for this can be attributed to the fact that breakdown voltage of the working gas (helium in this case) decreases with reduced pressure (decreasing pd from about 1000 Torr-cm to about 100 Torr-cm), in accordance with Paschen's Law. Due to the reduced breakdown strength of the gas and an applied pulse with a finite rise time (∼30ns), electrical breakdown can happen earlier at lower electric fields.

When the pressure in the chamber is lowered below 70 Torr, instead of seeing an additional lengthening of the plume, a dramatic decrease in the length takes place. At the same time, starting at the tip of the acrylic tube, plasma starts to expand in all directions inside the chamber, especially when the pressure reaches the 20-25 Torr range. Figure 6 is a photograph illustrating the above visual observations. The image in Figure 6, which was taken at a pressure of 18 Torr, shows clearly a shorter plume (as compared to the 75 Torr case) while a diffuse plasma is expanding from the tip of

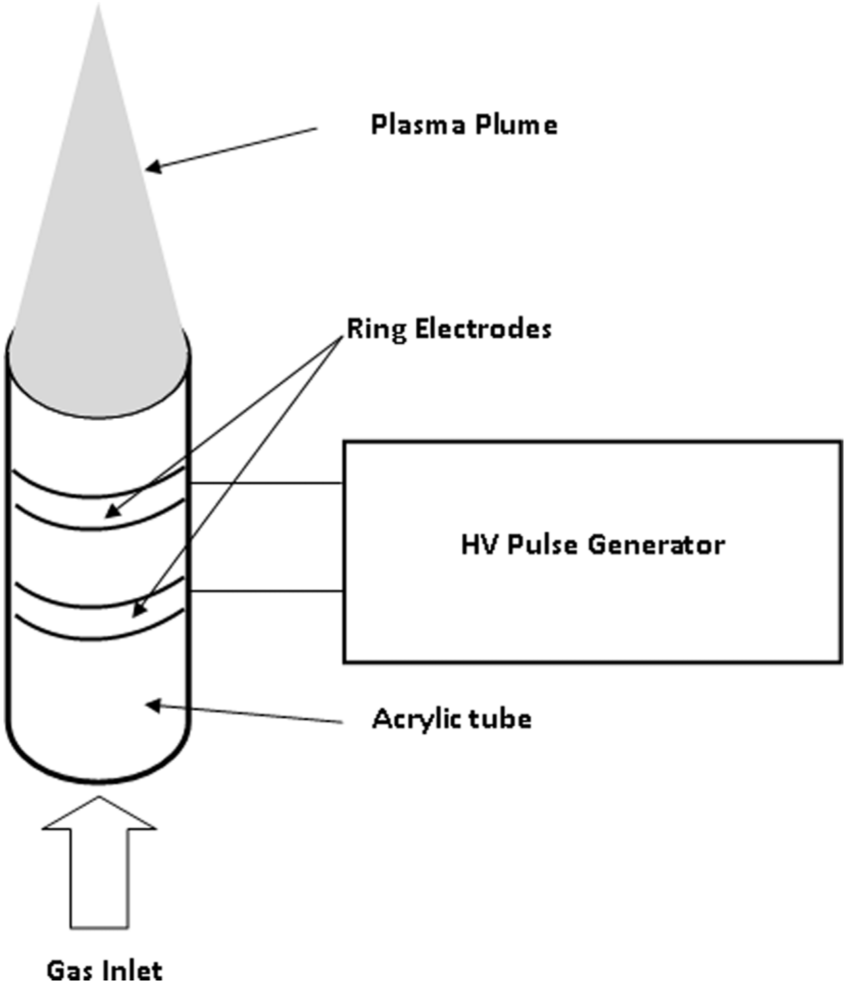

FIG. 2. Schematic of the jet source/generator, the tube reactor.

the acrylic tube. Figure 7(a) and 7(b) are images taken with an intensified CCD camera (DiCam-Pro ICCD) that show the early onset of this transition. These images are 3 ns snapshots taken at 1.34 μs and 2.2 μs following the applied pulse showing the plasma spreading from the tip of the acrylic tube to the rest of the Pyrex chamber as the plume length decreases. Further lowering the pressure to 10 Torr leads to half the volume of the chamber filling with plasma while at pressures around 2 – 3 Torr plasma fills almost $\frac{3}{4}$ of the chamber. Below 2 Torr the entire volume of the chamber fills up with uniform and diffuse plasma. Figure 8 is a long exposure picture showing this uniform plasma that has filled almost the entirety of the chamber.

The sudden shortening of the plume, immediately followed by the ignition of a large volume uniform plasma is an intriguing new observation and constitutes an interesting transition mode (from jet to large volume diffuse plasma) that beckons further detailed investigations which can lead to various interesting applications. The photoionization model proposed by Lu & Laroussi[3] predicts that the plasma would extend in all directions under low pressure conditions. This is what eventually happens, but it only becomes visually apparent when the pressure is below about 75 Torr. At pressures between 760 and 75 Torr, according to the images of the plasma jet, a more or less distinct helium channel exists (less as the pressure approaches 75 Torr) and the plasma jet remains mainly confined in the helium gas channel. When the jet length decreases an expansion of plasma is observed at the tip of the acrylic tube inside the chamber. This observation suggests that with the increased percentage of helium in the chamber compared to the background air, plasma is no

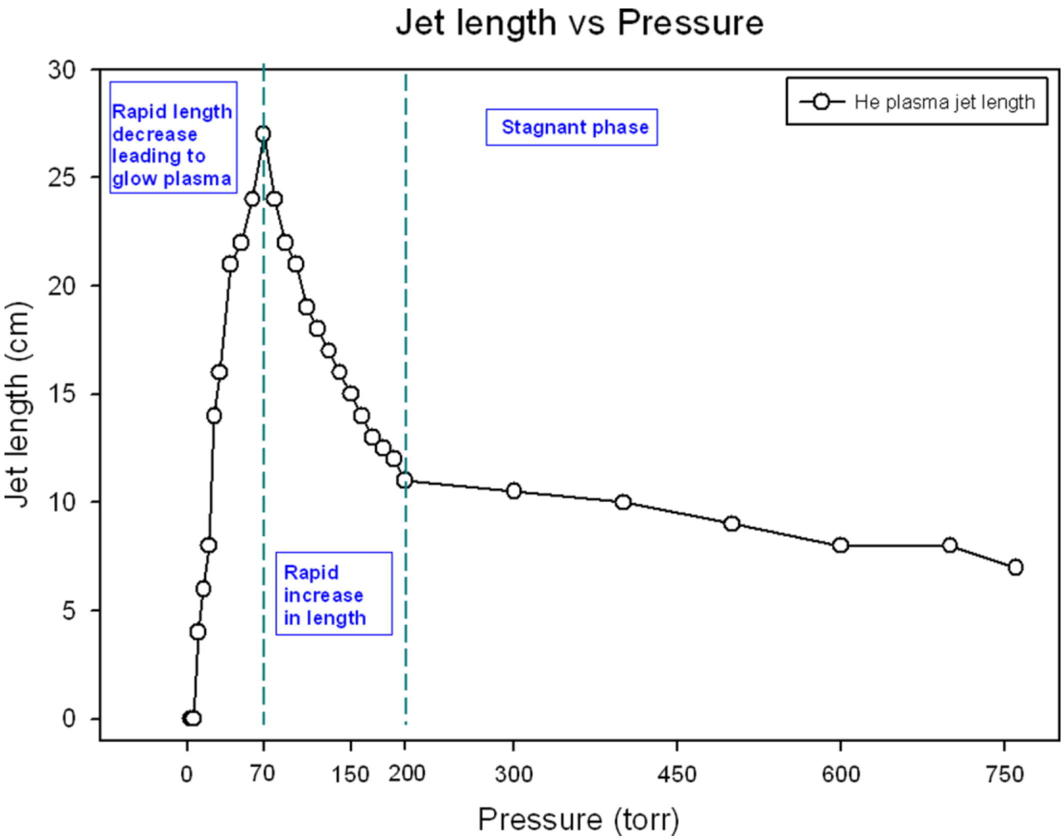

FIG. 3. Plasma plume length versus pressure inside the chamber.

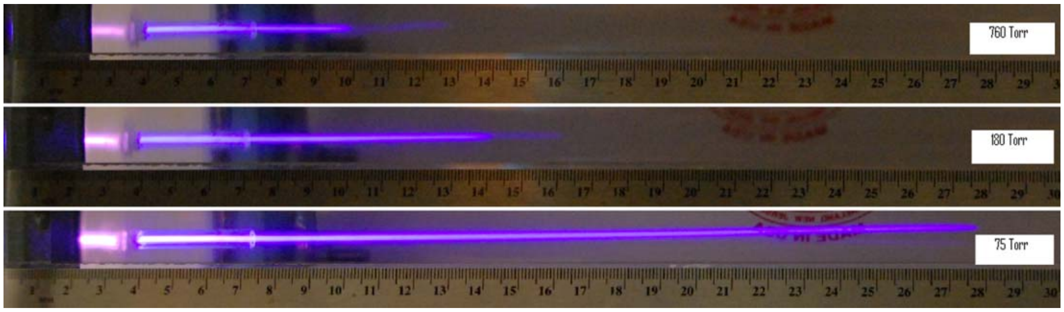

FIG. 4. Plasma plume inside the Pyrex chamber at three pressures: 760, 180, and 75 Torr. The voltage pulse amplitude and width, for this figure and the remaining figures, are 8 kV and 2 μs respectively.

longer strictly sustained in a jet phase, but rather in a diffuse fashion. At pressures below 20 Torr this expansion takes over the jet phase as only diffuse plasma is observed. Photons at these pressures are able to ionize the surrounding gas in all directions, leading to a non-jet-like diffuse plasma as illustrated by the images shown in this manuscript. The transition from a jet to a large volume diffuse plasma also causes a variation in the plasma bullet shape as seen in the ICCD images. Under these transitional conditions the plasma bullet takes a "cometary" shape as it expands inside the Pyrex chamber. This is quite different from the previously reported bullet structure that was observed when plasma jets/plumes were launched into room air.[2,3,8]

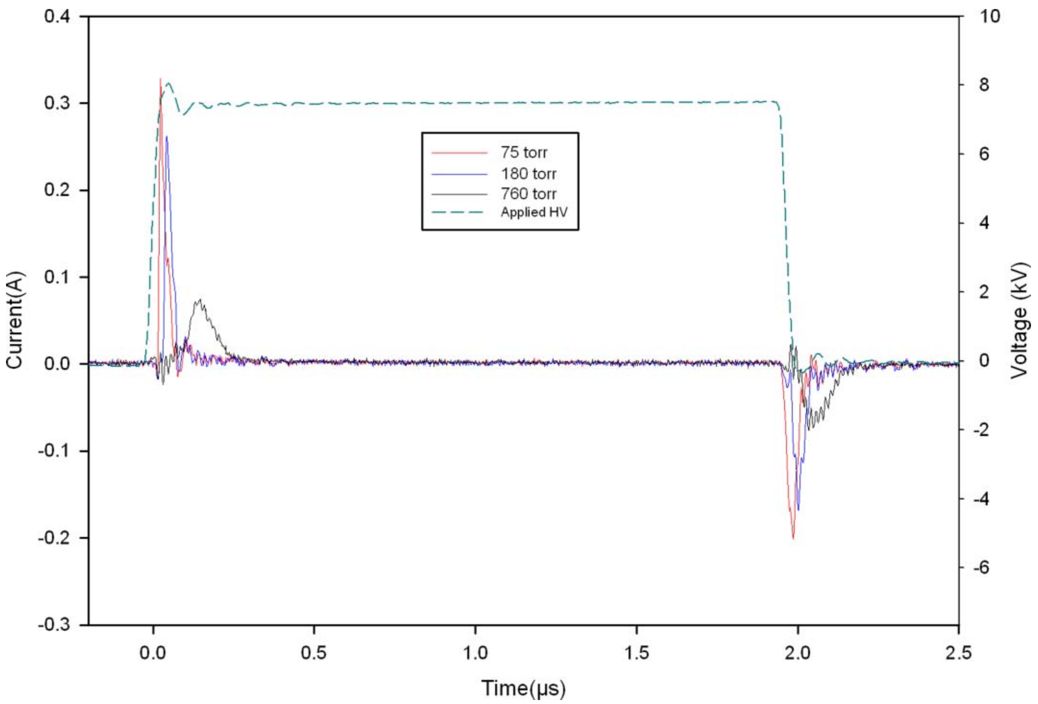

FIG. 5. Current voltage characteristics under three pressure conditions: 760, 180, and 75 Torr.

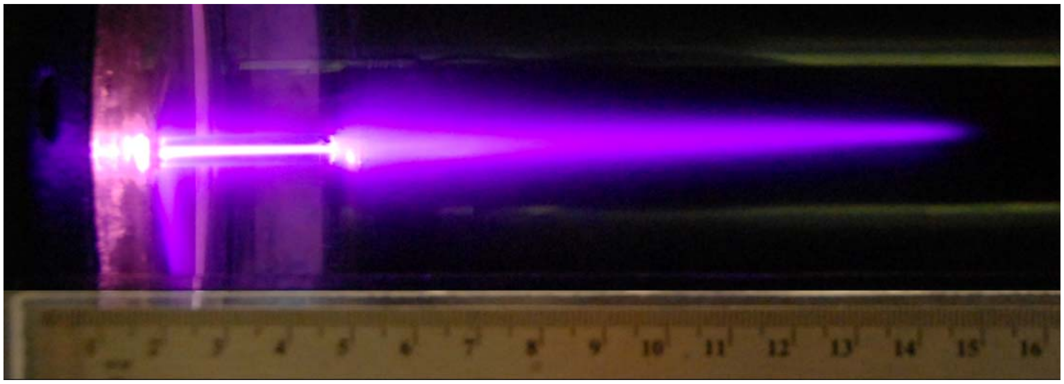

FIG. 6. Photograph showing a plume and an expanding diffuse plasma at the tip of the acrylic tube. The pressure is 18 Torr.

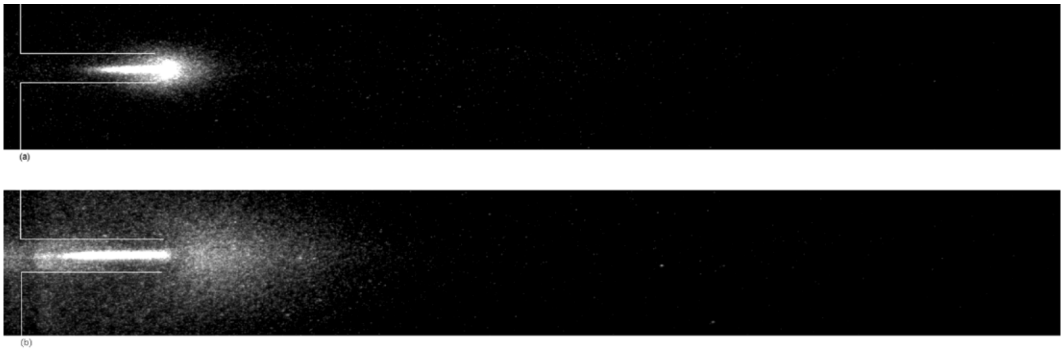

FIG. 7. ICCD images of the expanding plasma (a) at 1340 ns; (b) at 2200 ns. The pressure is 10 Torr.

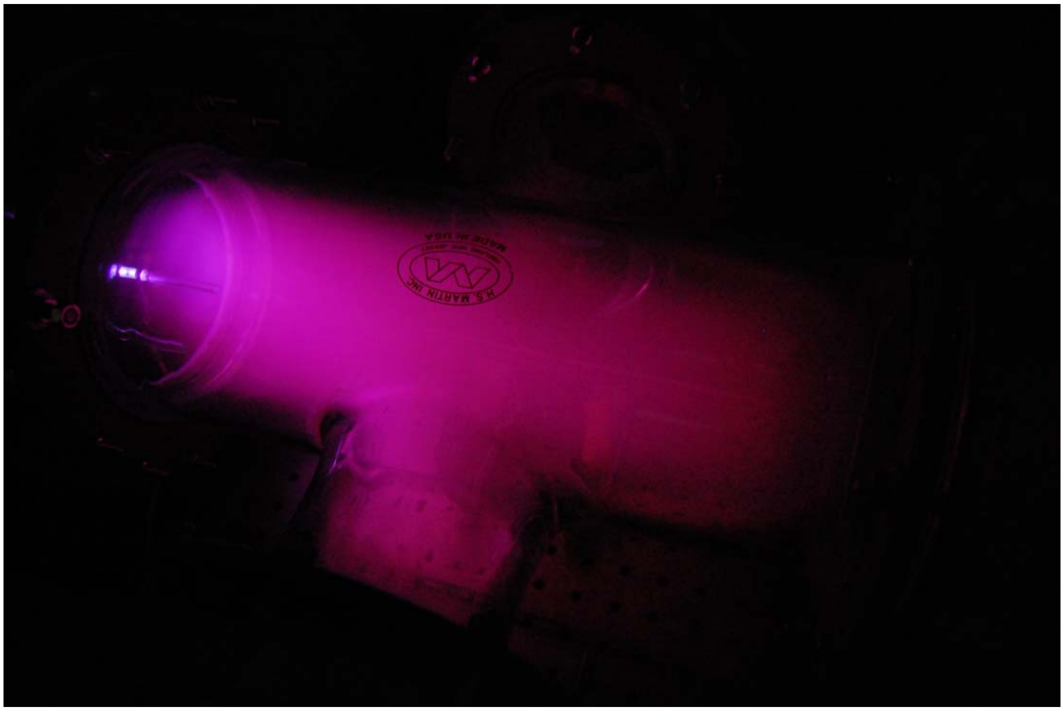

FIG. 8. Long exposure photograph showing a diffuse plasma filling the entire Pyrex chamber. The jet source (tube reactor) is visible to the far left.

ACKNOWLEDGMENT

Work supported by an AFOSR grant.

[1] M. Laroussi and X. Lu, Appl. Phys. Lett. **87**, 113902, (2005).
[2] M. Teschke, J. Kedzierski, E. G. Finantu-Dinu, D. Korzec, and J. Engemann, IEEE Trans. Plasma Sci. **33**, 310, (2005).
[3] X. Lu and M. Laroussi, J. Appl. Phys. **100**, 063302, (2006).
[4] M. Laroussi and T. Akan, Plasma Processes and Polymers **4**, 777, (2007).
[5] J. L. Walsh and M. G. Kong, Appl. Phys. Lett. **93**, 111501, (2008).
[6] B. L. Sands, B. N. Ganguly, K. Tachibana, Appl. Phys. Lett. **92**, 151503, (2008).
[7] Q. Xiong, X. Lu, J. Liu, Y. Xian, Z. Xiong, F. Zou, C. Zou, W. Gong, J. Hu, K. Chen, X. Pei, Z. Jiang, Y. Pan, J. Appl. Phys. **106**, 083302, (2009).
[8] N. Mericam-Bourdet, M. Laroussi, A. Begum, E. Karakas, J. Phys. D: Appl. Phys. **42**, 055207, (2009).
[9] E. Karakas, M. Koklu, M. Laroussi, J. Phys. D: Appl. Phys. **43**, 155202, (2010).
[10] E. Karakas and M. Laroussi, J. Appl. Physics **108**, 063305, (2010).
[11] J. Jarrige, M. Laroussi, and E. Karakas, Plasma Sources Sci. Technol. **19**, 065005, (2010).
[12] M. Laroussi, IEEE Trans. Plasma Sci. **37**, 714, (2009).
[13] X. Lu, T. Ye, Y. Cao, Z. Sun, Q. Xiong, Z. Tang, Z. Xiong, J. Hu, Z. Jiang, Y. Pan, J. Appl. Phys. **104**, 053309, (2008).
[14] M. Laroussi, X. Lu, V. Kolobov, and R. Arslanbekov, J. Appl. Phys. **6**, 3028, (2004).
[15] X. Lu and M. Laroussi, J. Phys. D: Appl. Phys. **39**, 1127, (2006).