

Effects of Ignition on Discharge Symmetry in Gas-Fed Pulsed Plasma Thrusters *

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Abstract

We present the results from a new diagnostic tool for investigating the effects of ignition on the discharge symmetry in gas-fed pulsed plasma thrusters (GF-PPTs). Using a fast-framing camera, up to 16 individual pictures of a single GFPPT discharge can be captured at frequencies as high as 20 MHz. This high framing rate capability allows the discharge initiation and current sheet formation to be visualized with a large degree of temporal resolution. Varying the frame rate, number and size of pictures per discharge, as well as the trigger delay sent to the camera allowed multiple discharges at different stages to be visualized. Various configurations of GFPPT electrode geometry and discharge ignition systems were photographed in operation. It is shown that the large surface flash-over igniters used in early GFPPT designs are unreliable in providing a constant, symmetric discharge initiation. Smaller semi-conductor spark gap igniters used in later GFPPT designs have demon-

strated more reliable ignition individually, however, asymmetries in the entire discharge still exist. The effect of a modification to the propellant feed system on the asymmetry of the discharge is also presented.

1 Introduction

Pulsed plasma thrusters (PPTs) are the subject of active research due to their relatively high specific impulse and variable thrust capabilities at low power, typically less than 20 W. Originally studied in the late 1960's, both ablative pulsed plasma thrusters (APPTs) and Gas-fed pulsed plasma thrusters (GF-PPTs) have returned to modern research laboratories as well as experimental satellite applications. In both types of PPTs, the electronics required to breakdown and accelerate the propellant are similar, however, the physical processes themselves are somewhat different. In terms of the initial breakdown and creation of a plasma, both types of thrusters use high voltage "spark plug" igniters to ionize a small fraction of propellant and begin the current sheet formation. In GFPPTs, it has been shown that the initial gas loading profile is crucial to the effectiveness of the initiation and acceleration phases of the discharge pulse in terms of both a uniform breakdown and the propellant accumulation or "sweeping" process[1, 2, 3]. Different designs of igniters have been tested in the past by measuring the voltage and current waveforms to infer the energy efficiency[4] but few images of the

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initiation history of a GFPPT discharge exist in the literature.

Recently, a family of high-repetition rate coaxial geometry GFPPTs have been introduced and tested by Science Research Labs, Inc. and Princeton University [5, 6]. The high-repetition rate allows a propellant utilization of nearly 100% by stringing multiple pulses together into a tight burst. The short time between pulses, 100-300 μ s, however, makes tailoring the initial mass distribution between each pulse difficult. In addition, the electronics required to uniformly break-down the gas throughout the inter-electrode volume are not trivial. Studies into the effects of propellant distribution and initiation circuitry on the current sheet formation are ongoing at Princeton with the use of a new diagnostic tool: the Imacon fast-framing camera. This tool allows the current sheet formation and propagation to be visualized at rates up to 20 MHz for a single pulse. A schematic of the entire experiment is shown in figure 1.

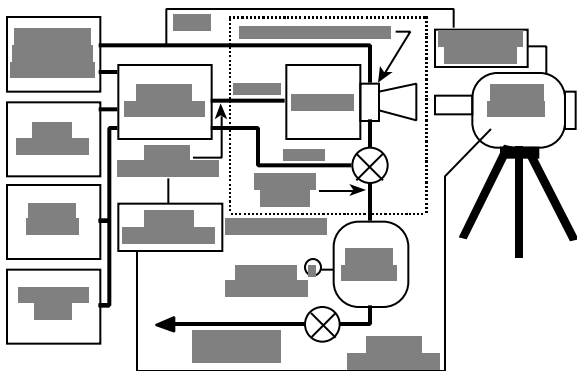


Figure 1: Schematic of the SRL-GFPPT experiment including the Imacon camera and related equipment.

This paper will focus on the use of the Imacon camera to visualize and record the discharge dynamics while varying the thruster and discharge ignition set-up. First, the various configurations of the SRL-GFPPTs will be described including electrode geometry, spark plug type and placement, propellant distribution, and thruster power conditioning. Next, the Imacon camera will be discussed in more detail with sample data obtained from recent experiments. The effect of changing the discharge initiation circuitry and the propellant injection manifold will be discussed in terms of the formation and propagation of a symmetric and uniform current sheet. Finally, the

entire set of results will be discussed and an overview of future research goals will be presented.

2 The Fourth and Fifth Generation SRL Gas-Fed PPTs

The SRL4-GFPPT has been introduced before in refs [5, 6], therefore, only the most important points of the thruster construction and operation will be highlighted here. A schematic of the SRL4-GFPPT is shown in figure 2.

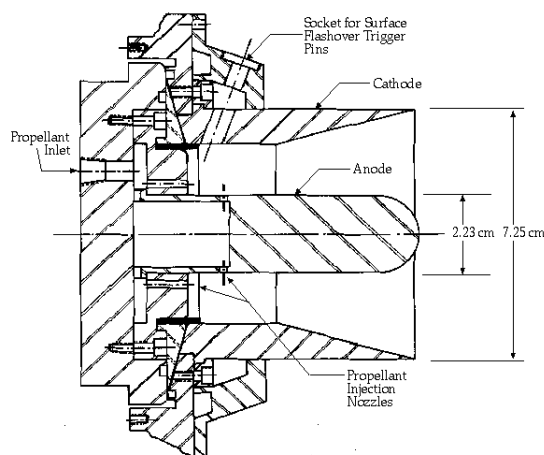


Figure 2: Schematic of the SRL4-GFPPT.

The fifth generation design is very similar to the previous version but with a larger outer electrode radius. The SRL5-GFPPT has gone through four iterations (labeled here simply a, b, c, and d) including changes in outer electrode design, spark plug type and placement, as well as propellant distribution. These iterations will be discussed in the following sections.

2.1 Outer Electrode Construction and Spark Plug Manifold

Both versions of the GFPPT have stainless steel, coaxial electrodes with a slight expansion near the exit. The outer to inner electrode radius ratio is 3.25 for the SRL4-GFPPT and a little more than 4 for the SRL5-GFPPT (all iterations) with both having about the same absolute inner electrode radius.

The first iteration of SRL5-GFPPT, now labeled SRL5a-GFPPT, had a solid outer electrode with

eight large surface flash-over spark plugs. The ignitors were mounted evenly around the outer electrode in a propellant manifold. Similar to the design of the fourth generation thruster, the manifold provides a small amount of gas flow over the surface of each of the spark plugs before, during, and after the discharge.

The second iteration was the largest change in outer electrode design. SRL5b-GFPPT had an outer electrode constructed of 24 evenly spaced rods mounted to the top of the spark plug manifold. These rod electrodes were used to allow visualization of the current sheet propagation from a side view of the thruster while still providing a conducting surface for the discharge current.

Iteration 5c went back to a solid outer electrode but used a different, smaller type of semi-conductor spark plug (described in the next section) that did not require direct propellant flow to work effectively. For that reason, the spark plug manifold was removed and the spark plugs were mounted directly to the outer electrode.

The SRL5d-GFPPT has the same outer electrode configuration as iteration 5c.

2.2 Spark Plug Type and Placement

The SRL5a and 5b-GFPPT used the same type of large surface flash-over spark plugs that were originally used in the SRL4-GFPPT. With a larger outer electrode radius, however, the SRL5a and 5b-GFPPT used eight ignitors where the SRL4-GFPPT used only four. In the third and fourth iteration of the SRL5-GFPPT, the type of spark plug was changed to the same semi-conductor spark gap ignitor used in the LES 8/9 APPT. These ignitors require a lower break down voltage without any extra propellant mass flow. The breakdown voltage for normal operation of the smaller semi-conductor spark-gap ignitor is ≈ 1000 V which is much smaller than what was required for the original larger surface breakdown plugs, ≈ 5000 V. The SRL5c-GFPPT also went through changes in the discharge initiation circuitry to try to balance the energy distributed between each plug. All the spark plugs in each SRL-GFPPT are connected in parallel to a discharge initiation capacitor that is charged once for each pulse. More details on changes to the discharge initiation circuitry will be provided in section 6.

2.3 Propellant Distribution

In all the SRL-GFPPT designs the propellant flow is controlled by a solenoid valve and a sonic orifice connected to the main propellant line. A gas feed line connects the solenoid valve to a small reservoir behind the back-plate of the thruster. As shown in figure 2, the inlet to the reservoir is slightly off center to insure that all the propellant doesn't leave the reservoir through the center electrode. Both the back-plate of the thruster and the center electrode contain propellant injectors that attempt to provide a $1/r$ gas density profile before each pulse. After examining a series of asymmetric Imacon photos of SRL5c-GFPPT and the condition of the propellant feeding system, the off-center nature of the propellant inlet was questioned. Suspected to be a possible cause of the asymmetries, a new path for gas flow to the other side of the reservoir was constructed and tested to create the last iteration used in this paper, the SRL5d-GFPPT.

2.4 Thruster Power Conditioning

All versions and iterations of the SRL-GFPPT used the same solid-state control modulator and could be fired at energy levels between 3-10 J at rates up to 4 kHz. Typically six pulses were fired per burst, however, this number can be set to higher levels depending on the desired thrust level. The discharge initiation power is produced by a separate high voltage supply. On every version of the SRL-GFPPT so far, the inner electrode is at a positive potential (anode) and the outer electrode is held at ground potential (cathode). The main discharge capacitors are mounted directly to the electrodes and the gaps between the conductors are kept at a minimum to reduce the initial inductance to 5-10 nH.

The capacitance for each of the configurations is provided here. In general, all the SRL thrusters use modular capacitor boards with typical increments of 45-90 μF . For the data presented in this paper, the SRL4-GFPPT has a total capacitance of either 180 or 270 μF ; the SRL5a and 5b-GFPPT used capacitors with a lower internal resistance value (however, a larger specific volume) that provided a total of 90 μF ; the SRL5c and 5d-GFPPT returned to the original, smaller volume capacitor type with a total of 270 μF .

3 Imaging the Discharge Initiation and Propagation

One of the key features for understanding the dynamics and symmetry of a GFPPT discharge is visualization of the plasma itself. It has been shown in previous work[7] with co-axial, quasi-steady pulsed plasma thrusters that the luminous patterns in the arc discharge are a good indication of magnetic field and current conduction symmetry. In this section, the technique for visually capturing the development of the discharge including the ignition phase will be presented.

3.1 The Imacon 20 Megahertz Fast Framing Camera

The Imacon fast-framing camera allows multiple black and white (grayscale) images to be taken on one 3.25" by 4.25" polaroid photo at rates of either 2×10^7 or 5×10^5 frames per second depending on the selected oscillator module. The camera is triggered from a pulse delay generator which is in turn triggered off the high voltage leads to the spark plugs themselves. Since there is slight delay in the high voltage applied to the ignitors and the actual breakdown, the pulse delay generator can be set to activate the camera just before the discharge begins. In all references to time in this paper, $t = 0$ occurs when the break-down actually begins and current begins to flow.

3.2 Output Picture Description

The Imacon camera uses a photo multiplier tube and a cathode ray tube to project the subject image onto a phosphorus screen. This image can be viewed directly, or a polaroid camera can be set up and exposed to the phosphor image. When the camera is activated, the thruster image will jump from the bottom to top of the screen and back again after each exposure as shown in figure 3. Since there is a limited screen area, the number of images one photograph can capture is inversely related to the area and resolution of the desired image. The area of the image on the screen is controlled by the focal length of the imaging lens and a small screening card that can be placed inside the Imacon camera. The number of exposures captured on one screen can be set manually and ranges between 4 and 32. For the GFPPT experiments, the 20 MHz oscillator module was used to image approximately 16 small images of the thruster

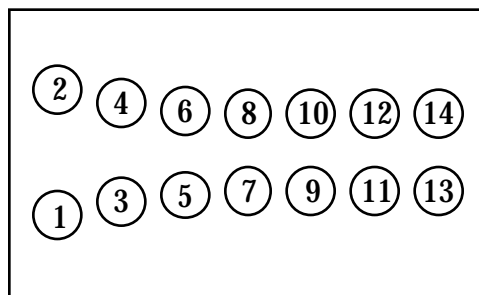


Figure 3: Schematic of photographic output from the Imacon fast-framing camera showing the order in which the exposures are taken.

covering a total of $0.8 \mu\text{s}$, and the 500 kHz oscillator module was used to image approximately 6 larger images of the thruster for a total of $12 \mu\text{s}$. These two configurations along with a variable delay timing allowed all phases of the discharge to be visualized effectively.

Along with the visual output, the Imacon camera has an electrical monitor line that pulses when the camera takes a picture. In coordination with voltage and current data saved on a high sampling rate digital oscilloscope, see figure 1, the pictures can be placed in the correct time frame of the discharge. A drawing demonstrating this concept is shown in figure 4.

4 Asymmetric Ignition and Discharge Data from the SRL4-GFPPT

Until recently, the discharge of the SRL4-GFPPT was thought to be uniform during every pulse. As shown in figure 5, this is not the case as one pulse displays a symmetrical break-down near all four ignitors, and the other appears to have only two ignitors working effectively. The top picture shows a uniform initiation, and the bottom picture shows a two point, asymmetric initiation. After viewing many discharges, the thruster ignition is considered sporadic. In most cases, after a large number of pulses, the same one or two spark plugs would fire reliably. Only on rare occasions did all four ignitors provide a symmetric discharge routinely.

As shown in the longer duration photos in figure 6, the top picture shows a uniform initiation while the middle picture shows a two point, asymmetric initia-

Figure 4: Chopped images from a typical Imacon photographic output (5×10^5 frames per second, $0.5 \mu\text{s}$ delay) corresponding to the voltage and current traces taken at the same time. Images show the initiation occurring at two spark plugs in the SRL5b-GFPPT firing at 5 J/pulse with a $0.5 \mu\text{g}$ argon mass bit.

tion, and the bottom picture shows a two point, symmetric initiation. When all four ignitors work well, the discharge seems to continue to propagate symmetrically. Even when only two oppositely oriented plugs fire, the discharge seems to recover its uniform, symmetric nature. When two adjacent plugs initiate the discharge, however, it appears that the discharge remains asymmetric for its entire lifetime.

5 Ignition Data from the SRL5b-GFPPT

The SRL5a and 5b-GFPPT showed even more random behavior, especially during the first few firings after the experiment had been dormant for a while. Figure 7 shows the best and the worst operation of the SRL5b-GFPPT. The top picture shows a uniform initiation with four and then eight ignition points, while the bottom picture shows a one point, asymmetric initiation. From these pictures and the many pulses where only one (but not always the same one) ignitor performed adequately, the conclusion was reached that the larger distance between the electrodes made obtaining a uniform discharge more difficult.

As an interesting visualization of the propagation

Figure 5: The $270 \mu\text{F}$ SRL4-GFPPT firing at 5 J/pulse with a $0.5 \mu\text{g}$ argon mass bit. Framing rate: 50 ns per image with a $0.8 \mu\text{s}$ delay on both.

of the current sheet, the SRL5b-GFPPT was fitted with rod outer electrodes and photographed from the side. As shown in figure 8, the luminous region appears to be diffuse in nature although there is clearly motion of the extent of the plasma. The rod electrodes mounted on the spark plug manifold are visible as the discharge moves past the electrodes, and a “glow” remains. The discharge looks somewhat non-uniform and at an angle with the discharge near the center electrode further along than the rest. Knowing the length of the rod electrodes to be 5 cm, and the duration between the exposures to be $2 \mu\text{s}$, we can calculate a rough velocity to be 25 km/s. Also, it seems as if the bulk of the discharge has left the electrodes by the fourth frame. At this point, there is still charge on the capacitor, however, and the electrodes seem to glow slightly. This glow was noticed in many pictures after the discharge seemed to have reached the extent of the electrodes.

6 Effect of Changes to the Discharge Initiation Circuitry and Propellant Distribution

After the large surface flash-over ignitors were found to be an unreliable method for discharge initiation, it was decided to switch to four of the smaller semiconductor type plugs used in the LES 8/9 APPT. As mentioned previously, these ignitors do not require a

propellant flow or high voltage source to work well. In fact, immediately upon use, the plugs demonstrated a repeatability that was not seen in the other type of ignitor. Although only two plugs provided an adequate discharge initiation source, it was the same two ignitors that worked every time.

In an attempt to fix this problem, a 3000 V, 2.7 μF capacitor was placed in series with the anode of each spark plug. Since the spark plugs were connected in parallel, this was postulated as a way to distribute the discharge initiation capacitor energy in a more uniform manner. Upon testing, it was seen that still only two spark plugs operated reliably. Although the spark plugs had been rotated to a new position on the outer electrode, the same ignitors did not work routinely. The spark plugs in the same sockets as the previously working ignitors, however, provided the same reliable performance.

At that point, it was decided to investigate the mass distribution inside the SRL5c-GFPPT. After examining the Imacon pictures and the condition of individual ignitors, it was determined that the reliably working spark plugs were physically aligned with the off-center propellant inlet. As an attempt to bring about symmetric discharge initiation, another propellant inlet was constructed on the opposite side of the reservoir. The effect of this modification is shown in figure 9. Although there is still an asymmetric discharge, now three ignitors seem to be working effectively. There is no correlation, however, yet discovered between the new inlet configuration and the ignitor that remains dormant as both the inlets to the reservoir are located 45 degrees away from any ignitor.

7 Summary and Comments

Images of the discharge initiation and propagation have been taken for a variety of thruster geometries and ignitor configurations. It was shown that discharge initiation plays a key role in the symmetry of the current sheet. Lower frequency exposures show that symmetric ignitions maintain a uniform nature while asymmetric ignitions lead to non-uniform, off-center luminous patterns. Finally, the addition of capacitors in series with the ignitors and the modification of the propellant feed system in the latest iteration of the SRL5-GFPPT seemed to have a beneficial effect on the number of ignitors that work effectively.

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Figure 7: The SRL5b-GFPPT firing at 8 J/pulse with a 1.0 μg argon mass bit. Framing rate: 50 ns per image with approximately a 0.5 μs delay on both.

Figure 6: The 180 μF SRL4-GFPPT firing at 8 and 5 J/pulse with a 1.0 μg argon mass bit. The top picture shows an 8 J pulse, and the middle and bottom picture show a 5 J pulse. Framing rate: 2 μs per image with delays of 1.2 μs , -1.0 μs , and -1.1 μs for the top, middle, and bottom pictures, respectively. The delay on the middle and bottom pictures are negative because the first frame is taken before the discharge begins and is, therefore, blank.

Figure 8: Side view of the SRL5b-GFPPT firing at 8 J/pulse with a 1.0 μg argon mass bit. Framing rate: 2 μs per image with approximately a -0.5 μs delay (first frame blank).

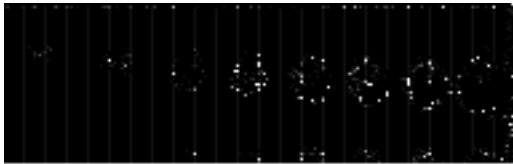


Figure 9: The top picture shows the SRL5c-GFPPT and the bottom picture shows the SRL5d-GFPPT with the propellant feeding system modification. Both thrusters are being fired at 5 J/pulse and with a 1.0 μg argon mass bit. Framing rate: 50 ns per image with a 0.8 μs delay on both.