

Preliminary Experimental Measurements for a Gallium Electromagnetic (GEM) Thruster

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A low-energy gallium plasma source is used to perform a spatially and temporally broad spectroscopic survey in the 220-520 nm range. Neutral, singly, and doubly ionized gallium are present in a 20 J, 1.8 kA (peak) arc discharge operating with a central cathode. When the polarity of the inner electrode is reversed the discharge current and arc voltage waveforms remain similar. Utilizing a central anode configuration, multiple Ga lines are absent in the 270-340 nm range. In addition, neutral and singly ionized Fe spectral lines are present, indicating erosion of the outer electrode. With graphite present on the insulator to facilitate breakdown, line emission from the gallium species is further reduced and while emissions from singly and doubly ionized carbon atoms and molecular carbon (C₂) radicals are observed. These data indicate that a significant fraction of energy is shifted from the gallium and deposited into the various carbon species.

I. Introduction

Gallium as a propellant for high-power electric propulsion appears to have several advantages over propellants presently in use. However, little is known about its properties in high-current arc discharges. Previously, a two-stage gallium electromagnetic (GEM) thruster design was proposed¹ in which the first stage served as a low-energy pulsed gallium plasma source and the second stage operated at high-power to accelerate the ionized plasma, producing thrust. This was followed by further studies showing the advantages of using gallium in electromagnetic thrusters (EMTs)² and estimating the optimum mass flow rate and discharge current for high-power gallium thruster operation.³

In this paper we present spectroscopic measurements obtained using a pulsed, coaxial plasma injector that is prototypical of the first-stage of a GEM thruster. These spectra were acquired to determine the various particle species produced in a relatively low-energy gallium arc discharge. The experimental setup used for obtaining spectroscopic data in a coaxial gallium plasma source is presented in section II and the data collected follows in section III.

II. Experimental Apparatus

A pulsed discharge was employed to produce a gallium plasma, which was photographed and spectroscopically interrogated. In our setup, a coaxial geometry is used with an electrode connected to a 20 J, 20 Hz (400 W) GE/Unison Industries pulser that provides a 12 μ s rise time, non-reversing current pulse using a low inductance circuit containing a free-wheeling diode. Gallium is fed through a sintered tungsten plug, where it is ablated by a

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pulsed arc with a full width at half max (FWHM) duration of $\sim 50 \mu\text{s}$. The repetition rate is controlled using a pulse generator that can be varied between 0.1 Hz and 20 Hz. Initial data from this setup were previously presented by the authors in Ref. [3].

The coaxial gallium pulsed plasma source is shown in Fig. 1. The stainless steel outer electrode has an outer and inner diameter of 5.72 cm (2.25 in) and 2.22 cm (0.88 in), respectively. A boron nitride insulator electrically separates the inner and outer electrode. The inner electrode is a 1.91 cm (0.75 in) SS tube press-fitted with a 1.27 cm (0.5") porous tungsten disk. During operation, the electrodes are mounted into a 5-way vacuum cross, which is attached to the main vacuum chamber. This arrangement provides three windows for diagnostic optical access. A baffle was inserted into the 5-way cross to prevent ejected gallium particles from reaching the main chamber. Vacuum is maintained by a TPH1500 turbomolecular pump, which is backed by two Roots blowers and two Kinney mechanical displacement pumps. A background pressure of 5×10^{-5} torr was maintained during testing. A photograph of the gallium discharge is found in Fig. 2. In the right-hand panel of Fig. 2 we observe that the discharge appears to be nearly symmetric and extends several cm from the electrodes.

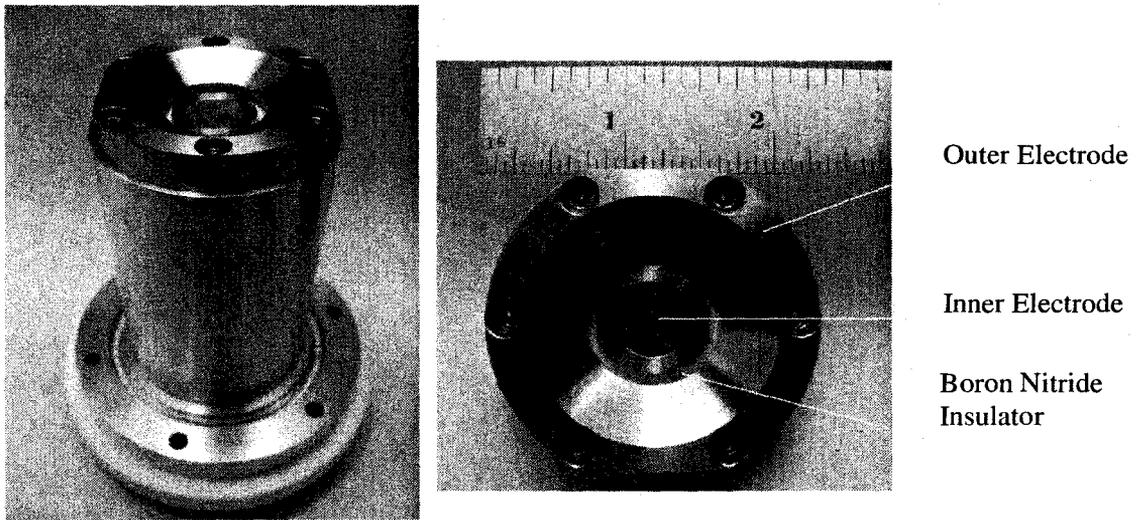


Figure 1. Gallium coaxial pulsed plasma source.

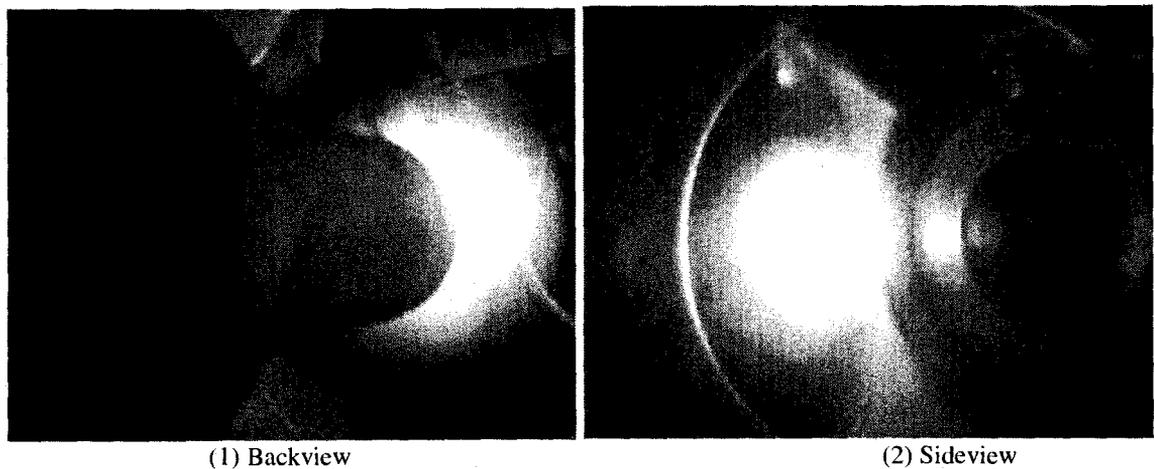


Figure 2. Representative photographs of a pulsed gallium plasma discharge.

The influence of operating polarity on ion trajectory motion in a coaxial, deflagration mode MPDT has been discussed in a previous paper.² In that work, two cases were presented: a central cathode (the traditional configuration for MPDTs) and a central anode (such as is found in PPTs). In the case of the central cathode, ions created near the outer electrode enter a region of strong B -field as they are accelerated radially inward by the electric field, and they are deflected axially by the $e\mathbf{u}\times\mathbf{B}$ force. For a central anode, ions are created along the axis in the region of strong B -field. These ions are more easily deflected axially because they possess a smaller axial velocity, and consequently a smaller Larmor radius, than in the case of a central cathode. In the present experiment, the polarities of the electrodes in the gallium plasma source were reversed to observe any differences in performance.

The terminal voltage and discharge current characteristics of the pulsed discharge for each polarity are presented in Figs. 3 and 4. We see that both the discharge current and the terminal voltage (outside of initial voltage fluctuations) are unchanged by polarity. The voltage level for both polarities is ~ 14 volts as the current varies by an order of magnitude, suggesting an ohmic resistance in the discharge of < 1 m Ω , and total sheath drops of twice the gallium ionization potential of 6.0 V, conditions favorable for high efficiency during high-current thruster operation.

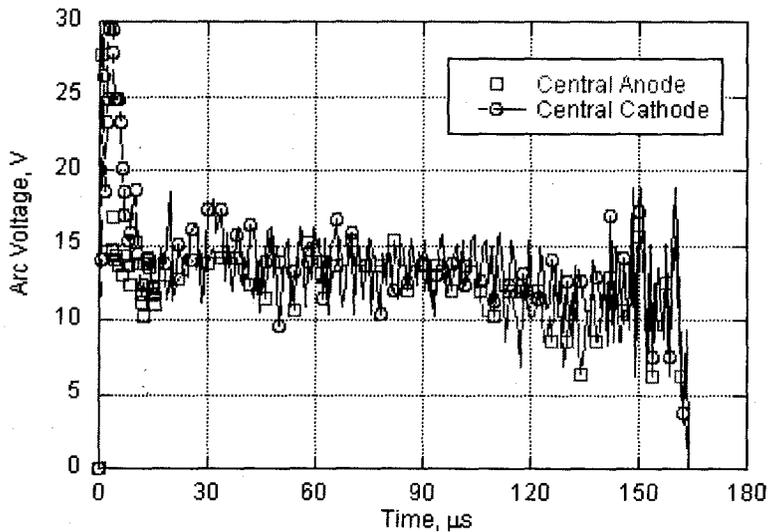


Fig. 3. Representative arc voltage waveform for a 20 J pulse.

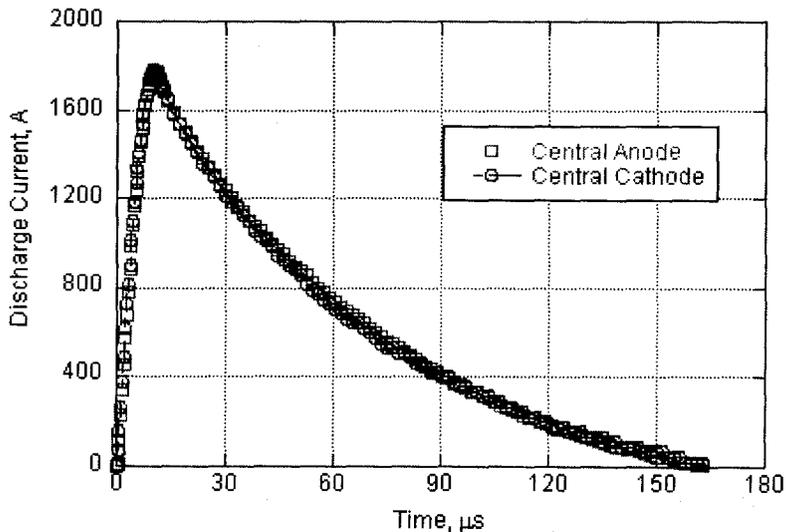


Fig. 4. Representative discharge current waveform for a 20 J pulse.

Two difficulties were initially encountered when operating the plasma source. The first was that the arc preferentially struck the exposed stainless steel on the inner electrode, as opposed to the gallium. This was verified both by examining the terminal voltage trace and through physical inspection of the inner electrode between firings. To remedy this, self-fusing silicone rubber tape was used as an insulator, leaving only metallic gallium exposed. Additionally, it was found that below a pressure of roughly 1 torr, a discharge would not initiate due to the lack of initial charge carriers. This was addressed by bridging the anode and cathode with a thin layer of carbon graphite applied with a spray technique. This technique is commonly employed in vacuum arc thrusters, where the graphite serves as the initial conductive path between the anode and cathode, providing a means for Joule heating at the coating-cathode interface. Neither a trigger electrode nor a specific electrical trigger pulse generator is required; the method has therefore been dubbed “triggerless” arc initiation.^{4,5} Using this technique, the gallium plasma source can be operated at a background pressure of 5×10^{-5} torr.

III. Spectroscopic Data

We acquired spectroscopic data from the discharge to determine which species were present. These spectra were obtained using a 25 mm focal length spectrometer with 5 micron inlet slit, yielding 0.7 nm resolution over the range of 220 nm to 520 nm. Emission was collected using a 12 mm diameter $f/2$ quartz plano convex lens which was focused onto the end of a 400 micron diameter silica fiber. The spectrum was time-integrated over several discharge pulses and spatially integrated over a broad region in which emission was observed. The output of the spectrometer was wavelength-calibrated using a mercury lamp and corrected for relative spectral efficiency using a deuterium lamp. A schematic of the experimental set-up is shown in Fig. 5.

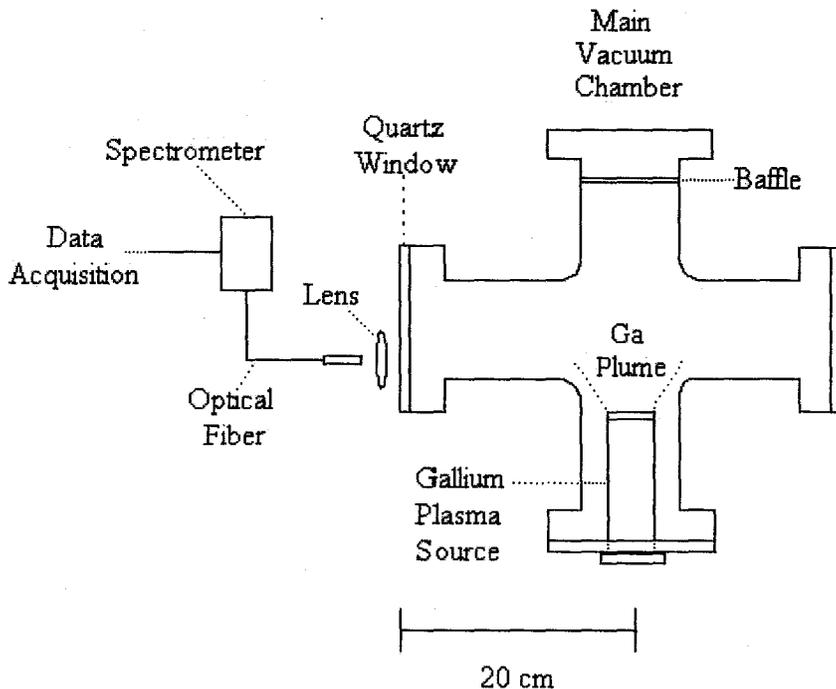


Figure 5. Schematic of the gallium emission spectroscopy setup.

The plasma source was operated in both the central cathode and central anode configurations at a background pressure of 1 torr. In addition, spectral data were obtained in the central cathode configuration at a background pressure of 5×10^{-5} torr. Spectroscopic measurements were obtained for all three conditions.

The spectrum obtained at a background pressure of 1 torr using a central cathode is shown in Fig. 6. We observe the presence of neutral gallium as well as singly ionized (Ga II , $\phi_i = 6.0$ eV) and doubly ionized (Ga III , $\phi_i = 20.5$ eV) gallium in the discharge. A total of twenty spectral lines are observed: six Ga I lines, five Ga II lines, and nine Ga III lines. Some of these lines are overlapping multiplets and therefore represent averages in intensity and

wavelength. Due to the lack of existing Ga III spectral data in the literature, four of these lines are not well characterized. The emission properties of the remaining sixteen lines are summarized in Table 1. The Ga I data was obtained from Ref [6], while the Ga II and Ga III data were tabulated from various sources.⁷⁻¹⁰ No significant emissions from other gases, including the silicone rubber tape used as an insulator on the stainless steel, were observed.

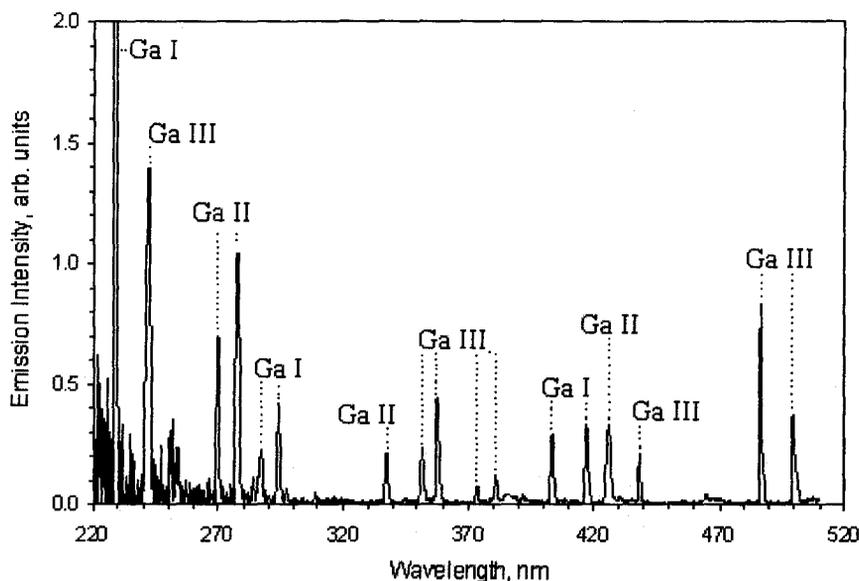


Figure 6. Gallium emission spectrum obtained at a vacuum chamber background pressure of 1 torr utilizing a central cathode.

Table 1. Gallium neutral and ion species present in a low-energy arc discharge.

Specie	Emission Line (nm)	Upper Level Energy, cm ⁻¹	Lower Level	Upper Level	Upper Level Degeneracy	A _{nr} (s ⁻¹)
Ga I	229.419	43574.91	4p ² P _{1/2}	6d ² D _{3/2}	4	7.0 x 10 ⁶
Ga I	229.787	43505.15	4p ² P _{3/2}	8s ² S _{1/2}	2	5.8 x 10 ⁶
Ga I	287.424	34781.66	4p ² P _{1/2}	4d ² D _{3/2}	4	1.2 x 10 ⁸
Ga I	294.364	34787.85	4p ² P _{3/2}	4d ² D _{5/2}	6	1.3 x 10 ⁸
Ga I	294.417	34781.66	4p ² P _{3/2}	4d ² D _{3/2}	4	2.6 x 10 ⁷
Ga I	403.299	24788.53	4p ² P _{1/2}	5s ² S _{1/2}	2	4.9 x 10 ⁷
Ga I	417.204	24788.53	4p ² P _{3/2}	5s ² S _{1/2}	2	9.5 x 10 ⁷
Ga II	270.047	107720.56	4p ¹ P ₁	p ² ¹ D ₂	5	2.3 x 10 ⁷
Ga II	277.998	135639.24	4p ¹ P ₁	5s ¹ S ₀	1	3.9 x 10 ⁸
Ga II	337.494	137342.44	p ² ¹ D ₂	4f ¹ F ₃	7	1.9 x 10 ⁸
Ga II	337.595	137333.33	p ² ¹ D ₂	4f ³ F ₃	7	2.0 x 10 ⁷
Ga II	426.200	137339.64	4d ³ D ₃	4f ³ F ₄	9	1.7 x 10 ⁸
Ga III	241.770	185432.59	4d ² D _{3/2}	4f ² F _{5/2}	6	9.4 x 10 ⁸
Ga III	373.110	187566.51	5p ² P _{1/2}	6s ² S _{1/2}	2	6.3 x 10 ⁸
Ga III	380.660	187566.51	5p ² P _{3/2}	6s ² S _{1/2}	2	8.3 x 10 ⁸
Ga III	499.378	160765.56	5s ² S _{1/2}	5p ² P _{1/2}	2	2.3 x 10 ⁸

The emission spectrum at a background pressure of 1 torr using a central anode is shown in Fig. 7. A comparison with Fig. 6 shows that the line strengths for the central anode configuration are slightly weaker, and that multiple Ga lines are absent in the 270-340 nm range. Additionally, in the central anode case, two neutral and two singly ionized Fe species lines are found in the discharge, suggesting slight erosion of the stainless steel outer electrode.

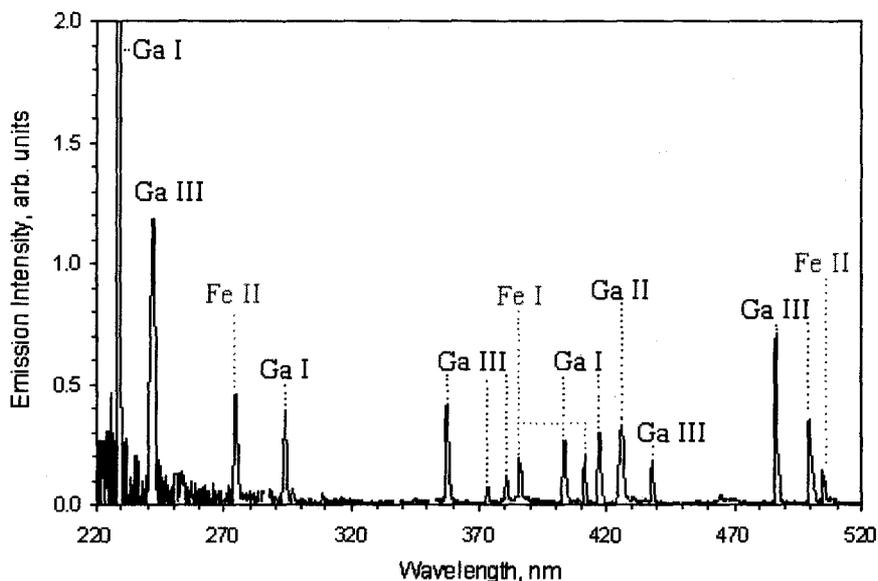


Figure 7. Gallium emission spectrum obtained at a vacuum chamber background pressure of 1 torr utilizing a central anode.

Data from experiments conducted at a background pressure of 5×10^{-5} torr and performed using a graphite layer between the electrodes to facilitate discharge initiation are shown in Fig. 8. During these tests, the diameter of the exposed gallium was reduced from 12.7 mm to 5 mm using silicone tape. Approximately 0.2 grams of graphite bridged the two electrodes, which allowed the pulser to be fired ~120 times before the graphite was expended.

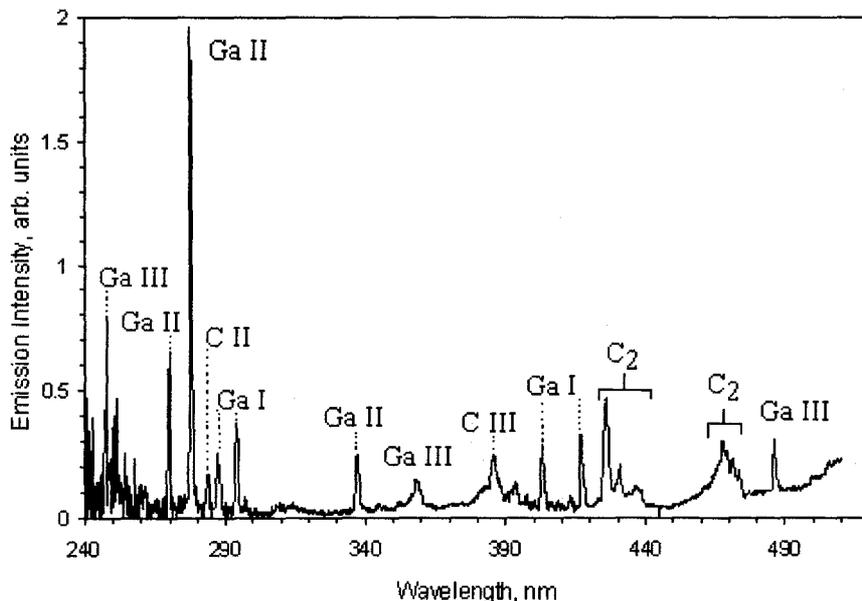


Figure 8. Gallium emission spectrum obtained at a vacuum chamber background pressure of 5×10^{-5} torr and employing a graphite layer to facilitate the breakdown process.

A comparison between Figs. 6 and 8 allows us to make some interesting observations. When the graphite layer is employed at lower background pressure, the peak intensities of the Ga lines are reduced and there are significant emissions from molecular carbon radicals above 430 nm (the so-called Swan bands¹¹). This implies that energy directed into the production of gallium ions in Fig. 6 is shifted into the production of carbon ions and the excitation of molecular carbon states in the situation represented by Fig. 8.

IV. Conclusions

Photographs and spectroscopic data were acquired using a pulsed coaxial gallium plasma source operating at 20 J/pulse and yielding a peak current of 1.8 kA. The influence of discharge polarity at low energy was examined using arc voltage data and emission spectroscopy. Reversing electrode polarity was observed to have little effect on the pulse current and voltage traces, and the voltage trace suggests an arc resistive drop of $< 1\text{ m}\Omega$, with anode and cathode sheath voltages on the order of the gallium 6.0 V ionization potential. Spectroscopic data were presented for a background pressure of 1 torr for both polarities. In addition, a spectrum was shown from experiments performed using a central cathode at a pressure of 5×10^{-5} torr where a graphite bridge between the electrodes had to be employed to facilitate the breakdown process. We observed twenty Ga lines in the higher background pressure cases, owing to emission from neutral, singly, and doubly ionized particles. The line emission intensities in the central anode case were slightly less than for the central cathode configuration, and multiple Ga lines were absent in the 270-340 nm range. Additionally, emission from neutral and singly ionized Fe atoms were present in the spectrum, suggesting slight erosion, potentially from ion impact against the outer stainless steel electrode. When the graphite layer was used, the emission intensity from the atomic and ionized gallium was reduced. In addition, singly and doubly ionized carbon was present in the emission spectrum along with molecular carbon radicals above a wavelength of 430 nm. The data indicate that in this case energy was shifted away from the gallium and into the carbon ion and molecular carbon species. Silicone rubber tape was used to cover the stainless steel portion of the electrode to ensure preferential arc attachment to the gallium. No significant traces of this insulator were found in the emission spectra from the plasma discharge.

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