Gas-Fed Pulsed Plasma Thrusters: From Spark Plugs to Laser Initiation*

Ephraim Chen§
Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL)
Department of Mechanical and Aerospace Engineering, Princeton University
Princeton, NJ 08544

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Abstract

The work involved in assembling the components of a spark plug-initiated GFPPT is described. The project objective was to compare measurements made between a spark plug-initiated GFPPT and a laser-initiated GFPPT in order to help determine the value of transitioning from spark plugs to lasers for thruster initiation. In the end, the thruster fails to fire; reasons why are suggested. The motivation for switching from spark plugs to lasers is presented.

1 Introduction

This report describes research conducted in Princeton University's Electric Propulsion and Plasma Dynamics Laboratory, as part of the Program in Plasma Science and Technology's Summer 2006 Undergraduate Internship Program.

Electric propulsion is characterized as spacecraft propulsion using electrical processes (in contrast with chemical reactions) to produce thrust. This type of propulsion can lead to high exhaust velocities, resulting in better mass utilization efficiency for spacecraft.

Gas-fed pulsed plasma thrusters (GFPPTs) are a manifestation of electromagnetic propulsion—a subcategory of electric propulsion where electric and magnetic forces act on a propellant. GFPPTs operate through short bursts of power; that way, the thruster can draw low steady-state power from a spacecraft while delivering high efficiency as a result of the high instantaneous power.[1]

A GFPPT generally operates as follows: (1) An electric potential is established between two electrodes. (2) A puff of propellant gas is injected into the electrode gap. (3) Some initial spark of electrons starts gas breakdown, leading to an arc discharge between the electrodes in the form of a current sheet. (4) The sheet's induced magnetic field exerts a Lorentz force on itself, accelerating it down the gap and pushing any unionized propellant gas for thrust. (5) The process restarts for pulsed procedure.

Figure 1 is a schematic of a coaxial GFPPT (i.e. the electrodes are symmetric with respect to a common axis). Propellant gas comes in from the inlets near the back. Spark plugs are placed near that area to start ionization.

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* Research supported by the Program in Plasma Science and Technology, Princeton University
§ Undergraduate Summer Intern at EPPDyL

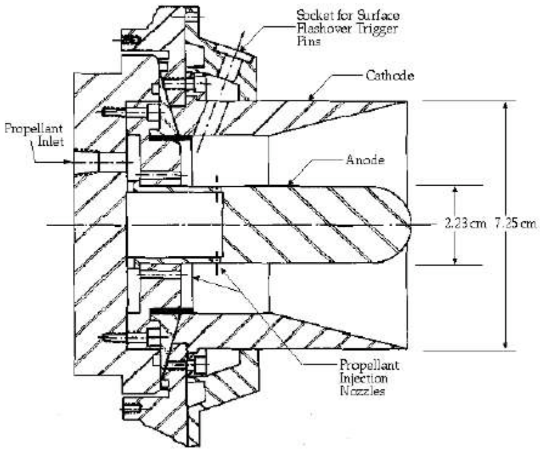

Figure 1: Coaxial GFPPT schematic. From http://alfven.princeton.edu.

The spark that starts the thruster can take several forms to this date: First, using spark plugs, plasma formation begins with pulses of electrons from sparks. Second, in microwave-initiation, resonant cavity operation produces plasma. Thirdly, shining a laser onto the cathode can set off propellant breakdown through processes like the photoelectric effect, thermionic emission, and/or cathode vaporization.

This research focused on spark plug-initiation and laser-initiation as part of an effort to compare the two methods. Spark plug-initiation has many disadvantages: Non-uniform current sheets are formed because of the tendency for plasma creation to begin near the plug where the spark originates. Having uniform current sheets produces higher efficiency for the thruster overall. Also, spark plugs are characterized by high erosion rates that severely limit their useful lifetime.[2] On the other hand, laser-initiation holds mirroring potential advantages: Uniform laser impingement onto the cathode can produce more uniform current sheets. Larger current attachment areas also decrease the rate of erosion (in this case, of the cathode itself).

The objective of this research was a measurement comparison of spark plug-initiated and laser-initiated GFPPTs to help determine the merit of switching to laser-initiation from today's more prevalent spark plug-initiation. Parameters to measure would include thrust, the current through the discharge, and breakdown voltages.

This report will describe in detail the work involved in assembling a spark plug-initiated GFPPT. Then, the results and conclusions drawn from this work are presented. The report will finish with suggestions for future work.

2 Assembling a Spark-Plug Initiated GFPPT

Components for a spark plug-initiated GFPPT were worked on during summer 2005. As such, this research was founded upon three basic steps: "salvaging" available technology, determining points of concern, and addressing those concerns with additional work.

The components necessary for the specific thruster this research focused on include spark plugs, spark plug holders, a discharge initiation circuit, a gas valve, a gas valve control circuit, an electrical pulse generator, a thruster body with capacitors, and power supplies. Each part is elaborated upon in the paragraphs to follow.

Figure 2 illustrates what a general GFPPT system would entail:

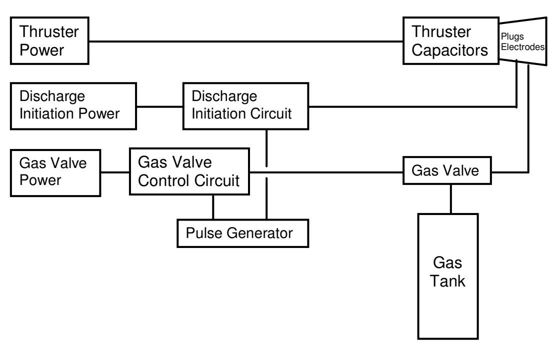

Figure 2: GFPPT system overview.

2.1 Spark Plugs

The spark plugs provide the pulse of electrons necessary for propellant ionization.

The available technology “left over” from work done during summer 2005 included four functional Bendix semiconductor-type spark plugs (see Figure 3). Accordingly, they all had low breakdown voltages (ranging from 1,500 to 3,000 V) compared to automobile plugs (which typically break down at ~15,000 V). However, the breakdown voltages were not equal; this was probably unavoidable, due to slight differences between the four plugs that involve corrosion, contamination, and natural wear-and-tear.

These observations bring us to concerns about the plugs. One concern certainly rested on the plugs’ corruptible surfaces leading to different breakdown voltages. In addition, their sparking was erratic—given the same potential difference, a single plug would produce slightly different intensity sparks. And in general, spark plugs are very nonlinear devices, making them difficult to model or predict.

For additional work, the spark plugs were each cleaned with acetone to help reduce the grime deposited on the plug surfaces. Other than that, it proved too difficult to alter the plugs themselves.

Figure 3: Bendix semiconductor-type, low breakdown voltage spark plugs.

2.2 Spark Plug Holders

For the thruster body available to us, it became apparent that something was needed to fasten the spark plugs in place within the thruster for a strong electrical connection between the thruster and the plugs’ outer electrodes.

No effort was made in this area during last summer’s work.

Appropriate holder pieces were designed and measured to fit the thruster holes’ threading while holding the plugs in place (see Figure 4). Hexagonal rods of aluminum were machined to allow easier tightening of the holders with wrenches.

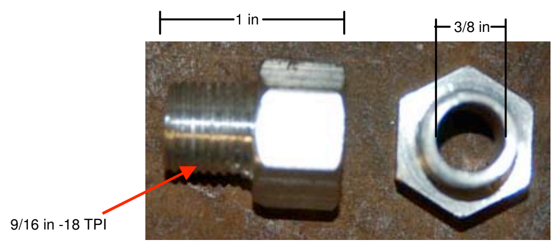

Figure 4: Spark plug holders.

2.3 Discharge Initiation Circuit

The discharge initiation (DI) circuit fires all the spark plugs simultaneously upon receiving an electrical pulse. Many circuit designs would be able to complete this task. The DI circuit implemented in this research can be simplified to Figure 5 below:

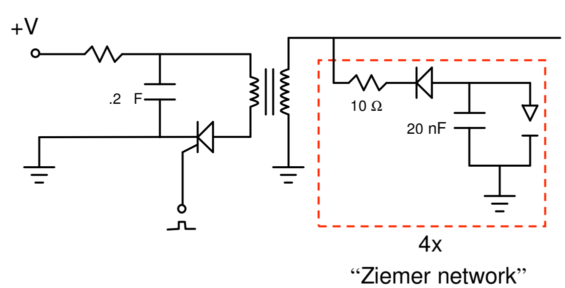

Figure 5: Simplified DI circuit schematic. From Ziemer's PhD thesis “Performance Scaling of Gas-Fed Pulsed Plasma Thrusters.”

This particular design is presented in John Ziemer's PhD thesis titled "Performance Scaling of Gas-Fed Pulsed Plasma Thrusters." The capacitor on the primary side of the transformer is discharged when the SCR (silicon-controlled rectifier) is fired by a voltage pulse. The transformer steps-up the voltage by some ratio, allowing the spark plugs on the secondary side to fire through the capacitors in parallel with them.

The "Ziemer networks" on the secondary side are repeated four times for each plug. Recall that each spark plug is unique, and as such have different breakdown voltages and other characteristics. The purpose of the networks is to make sure no single plug can draw current from the other spark plugs due to miniscule (on the order of microseconds) delays between the plugs sparking. If one plug sparks before the other three do, the diodes in the networks will be reverse-biased and prevent the plug from drawing current from the other plugs (of course, the polarity of the transformer's output must be adjusted accordingly). This is crucial to the formation of an as-uniform-as-possible current sheet, since having the spark plugs fire at different intervals would result in very irregular plasma formation in the electrode gap.

Available technology was relatively substantial (see Figure 6). A box containing the primary capacitor and SCR were wired to a 1:50 ratio pulse transformer. Parts of Ziemer networks were put together and ready to connect to the spark plugs.

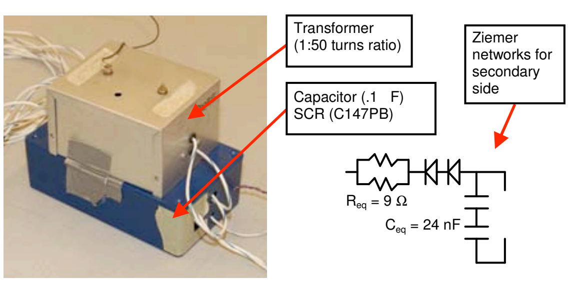

Figure 6: DI circuit components from work done during summer 2005.

Many concerns revolved around the DI circuit. The polarity of the transformer would have to be reversed to ensure that the diodes in the Ziemer networks would be reverse-biased if their associated plugs tried to steal current from other plugs. Many issues arose over the SCR because of its fragile semiconductor nature. Too much voltage (~600 V) would burn out the SCR, and a minimum latching current and pulse length was required to fire it. The transformer built last summer also presented great difficulties. The 1:50 voltage step-up ratio began to deteriorate for unknown reasons until the transformer only outputted at a ratio of 1:3. Having slightly different spark plugs on the secondary side also meant having varying loads on the transformer's secondary side and thus perhaps varying voltage outputs. In addition, inexplicable voltage loss through the Ziemer networks prevented the spark plugs from receiving enough voltage.

In the end, all of these concerns were addressed to a certain extent. The leads on the transformer's primary side were simply reversed to provide the necessary polarity for the Ziemer networks to function. A different model SCR proved far easier to latch than the model used last summer, though it was still susceptible to burnout if the input voltage was too high. Twisted pairs of wires, like the one shown below, were used whenever longer lengths of wire were needed.

Figure 7: Twisted pair. Reduces parasitics.

These pairs helped couple the magnetic energy associated with current traveling through wires and aided in reducing parasitics. Parasitics were the best explanation this research could arrive at to explain the transformer's inefficiency, since there might have been an insufficient number of windings on the primary, resulting in leaking magnetic field lines and ineffective magnetic coupling through the transformer core. Figure 8 demonstrates the transformer's abnormal behavior by displaying the transformer's passbands at various numbers of turns (note the irregularly shaped passband when tested with just 2 turns on each side and thus insufficient magnetic coupling):

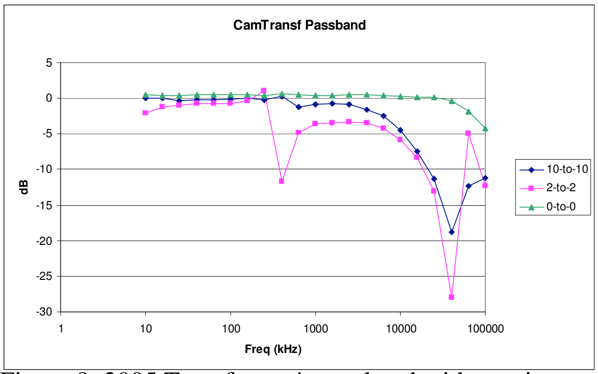

Figure 8: 2005 Transformer's passband with varying number of turns.

(In the figure above, the trace labeled "0-to-0" was just a diagnostic test of our measurement equipment to see if the mysterious dip in the "2-to-2" passband was a result of our own equipment malfunction; no core or turns were used, just straight wires. Its normal looking trace suggests our equipment was operating optimally.)

Figure 9 shows the difference between an ideal and a real-world transformer with parasitics:

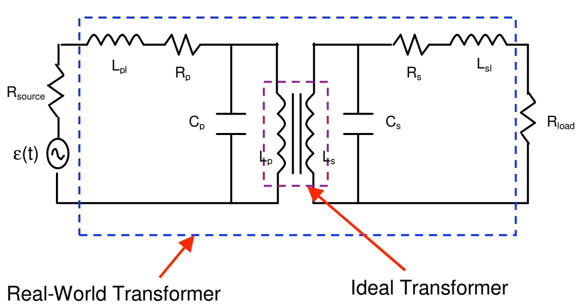

Figure 9: Schematic of real-world transformer, including parasitics.

Other leakage inductances, series resistances, and stray capacitances were also probably inherent in the transformer design that was developed last summer, since the transformer had 2 turns on the primary and 100 turns on the secondary to produce the "1:50" ratio. However, correcting these design flaws was determined to be less preferable than just building a completely new transformer. The old transformer was kept, while a higher input voltage was used to deal with the transformer's reduced efficiency. The final SCR and transformer changes are shown below in Figure 10:

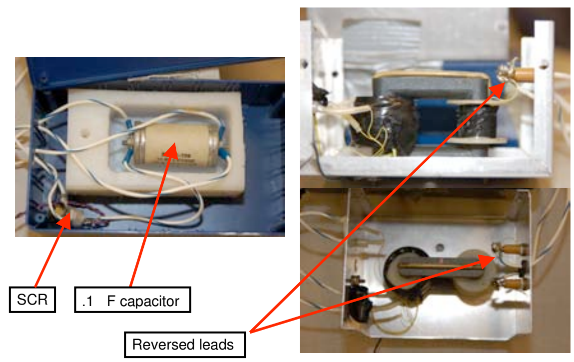

Figure 10: 2005 DI circuit components, after modifications.

The voltage loss through the Ziemer network was accounted for by decreasing the capacitance in parallel with each plug. The larger capacitances (~20 nF) were preventing the plugs from receiving the required breakdown voltage. Replacing the capacitors with ~20 pF capacitors immediately allowed the plugs to fire.

The equations below might help illustrate the situation:

$$Q = CV$$

$$\frac{dQ}{dt} = I = C\frac{dV}{dt} \quad \Rightarrow \quad dV = \frac{I}{C}dt$$

The charge Q on a capacitor is its capacitance C times the potential difference V across it. For any fixed voltage change dV, a larger C draws a larger current I (assuming the time intervals are equal). And since the amount of actual current flowing through a Ziemer network is fixed, a larger C limits the amount of voltage that reaches the spark plug.

The final DI circuit schematic used in this research is shown below in Figure 11 (the wrapped-wire symbols indicate twisted pairs, and the spark plug outer electrodes are electrically connected as shown because they are all fixed into the metallic thruster body):

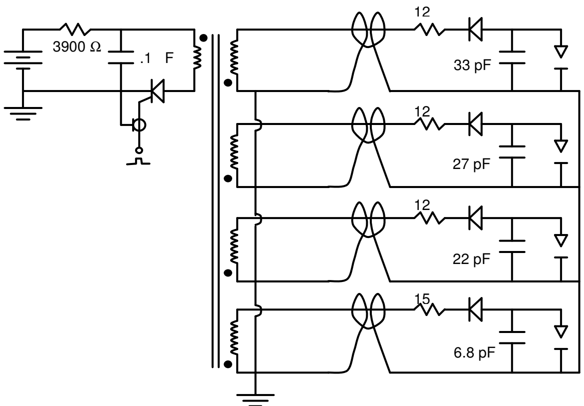

Figure 11: DI circuit schematic, final.

The transformer this research used implemented four secondary windings as shown, which is theoretically equivalent to having one secondary winding and four Ziemer networks in parallel. The varying loads presented on the transformer's secondary side by each unique spark plug may also have brought different output voltages from the transformer.

2.4 Gas Valve

The purpose of the gas valve is to release and stop the flow of propellant gas into the electrode gap.

Already available was a functioning solenoid gas valve, pictured below in Figure 12:

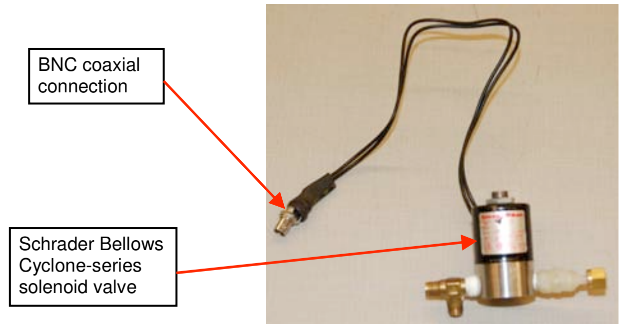

Figure 12: Solenoid gas valve.

2.5 Gas Valve Control Circuit

Like the spark plugs, the gas valve also needs a control circuit to momentarily open it and release a puff of gas upon receiving an electrical pulse.

There was no available technology.

The design of the circuit was not difficult, involving simple electrical switching concepts. Care was taken to use diodes in parallel with the precious solenoid valve and transistor to make sure when the magnetic field in the solenoid collapsed that the resulting back EMF would not destroy them. The schematic of the circuit is given below in Figure 13:

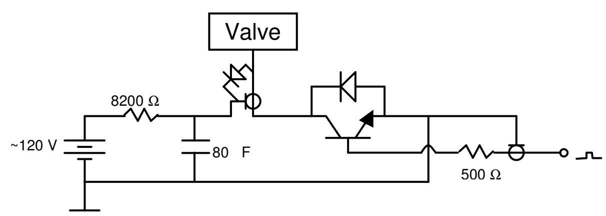

Figure 13: Gas valve control circuit schematic.

Building the circuit did not prove difficult, and it is shown below in Figure 14:

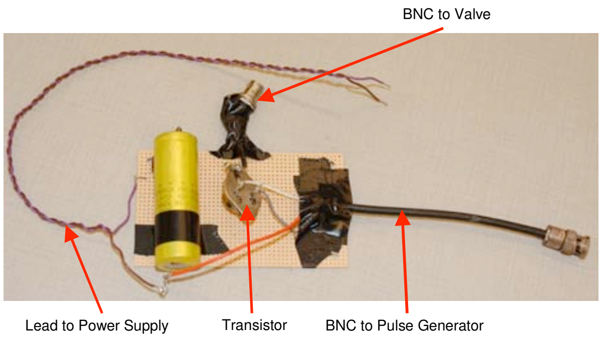

Figure 14: Gas valve control circuit.

2.6 Pulse Generator

To send the activating pulses to the DI circuit and gas valve control circuit, this research relied on SRS DG535 digital delay/pulse generators (DDGs), pictured below in Figure 15 (above the DDG is a Kepco power supply):

Figure 15: DDG (below). High voltage power supply (above).

The pulse sent to the SCR was about 2 s long and 5 V in amplitude. The gas valve required a 100 ms pulse, also 5 V in amplitude.

2.7 Thruster

Of course, for our thruster and main bank capacitors, this research had available SRL's PT4 coaxial GFPPT:

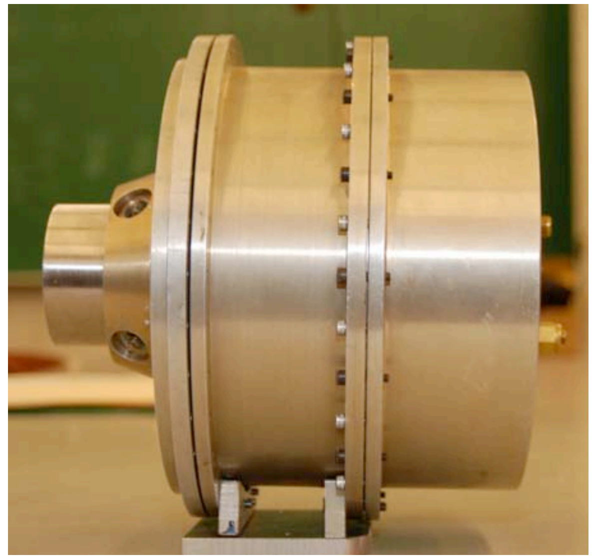

Figure 16a: SRL PT4 thruster, side view.

Figure 17: SRL PT4 thruster, front view.

The center rod was treated as the cathode while the cylinder surrounding it served as the anode. The spark plugs screwed into the four larger holes shown in the thruster body, in contact with the anode. The small holes in the electrode gap serve as propellant inlets. The cathode and anode are insulated from each other.

3 Testing the Spark Plug-Initiated GFPPT

3.1 Experimental Setup

Figure 17 is a picture of the four Ziemer networks before installation onto the thruster:

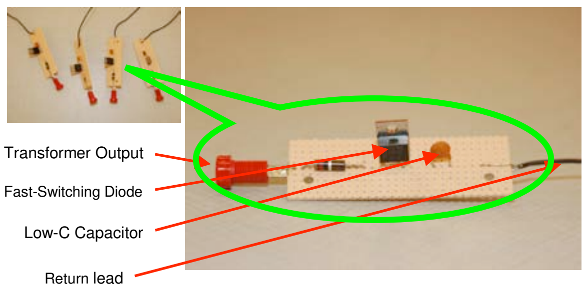

Figure 17: Ziemer networks.

The final thruster setup is shown below in Figure 18:

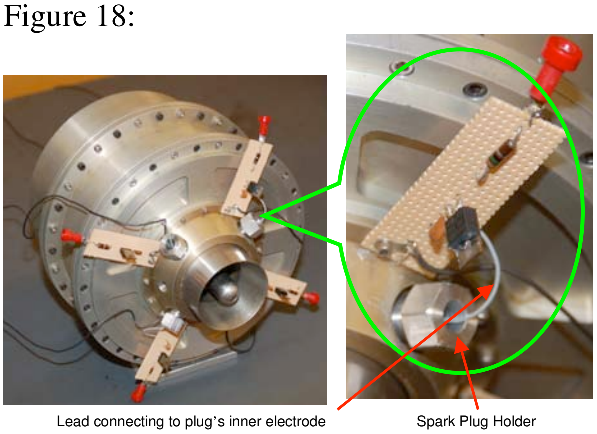

Figure 18: Thruster with Ziemer networks mounted.

It was decided to mount the Ziemer networks directly onto the thruster to reduce parasitics and make sure the spark plugs are as close as possible to their associated discharging capacitors.

The transformer inputs led to the red banana receptacles and the black leads (connected to the spark plugs' outer electrodes because they are both in contact with the thruster body) led back to the transformer. The spark plug holders screwed into the four holes and tightened sufficiently well to keep the plugs in place. The spark plugs were open to the electrode gap, where the propellant gas would be injected.

With all components completed and tested individually, the thruster system was assembled as a whole. The thruster (with attached Ziemer networks) was placed into a Plexiglas tank where the test firing would take place. Gas tubing and coaxial cable to power the thruster capacitors ran from the rear of the thruster to windows in the tank. The coaxial cable ran to a high voltage power supply while the gas tubing ran to the valve and then onto the gas valve control circuit. Four twisted pairs (eight wires altogether) ran from each Ziemer network to another window, where they led back to the transformer and the rest of the DI circuit.

The Plexiglas tank was evacuated to a pressure below 10 mTorr – the exact pressure was unknown because no suitable probe was in place to measure pressures that low.

3.2 Experimental Methods

The danger from high voltage was quite real. All power supplies and circuits kept outside the Plexiglas were either kept from human reach or covered with plastic boxes. An optical-isolator was used between the DI and gas valve control circuits and the DDGs, where human activity would occur.

To fire the thruster, a button on the DDG sends out one 100 ms-long pulse to the gas valve control circuit to open the valve. This first pulse triggered a 2 s-long pulse to travel, after a set delay time t_d after the first pulse, to the DI circuit and fire the spark plugs. The delay t_d is the amount of time needed for the puff of propellant gas to travel along the gas tubing and fill a significant volume of the electrode gap.

4 Results

Both the gas valve control circuit and DI circuit operated well – the gas valve opened and closed quickly, and the spark plugs fired (whether simultaneously or not remains to be determined).

However, no plasma formed and the thruster failed to fire. Various values for t_d were tried, ranging from 5 ms to 100 ms, under the suggestions of graduate students. All efforts proved unsuccessful in achieving gas breakdown.

5 Conclusions

After wrestling with the various electronic components for a spark plug-initiated GFPPT, one must conclude that it is very difficult to use spark plugs for precisely-timed, consistent firing of sparks. The uniqueness of each plug presents different impedances for the mutually coupled secondary transformer windings. Over time, spark plugs become unpredictable. This alone can be a strong impetus for development of laser-initiation.

Proper pulse transformer design must be carefully thought out if high efficiency standards are to be met. Parasitics must be reduced as better understanding of transformer theory leads to more reliable transformers.

Furthermore, the use of semiconductors for repeated high voltage use is unsustainable; other methods of high-speed switching for pulsed thrusters like GFPPTs should be looked into.

6 Future Work

Foremost on the list of future work to be undertaken is determining the correct value, or range of values, for t_d to increase the probability of the thruster firing. Further testing must be done as to what is preventing the GFPPT from operating correctly. Other ways of improving its chances include improving transformer performance and thus deliver higher voltage to the spark plugs, and producing identical spark plugs to present equal impedances to the transformer. A new, more robust DI circuit design at the fundamental level may even be necessary. Bob Sorenson, senior lab technician at the EPPDyL, suggested four separate transformers for each spark plug to eliminate mutual coupling effects and eliminating the need for Ziemer networks:

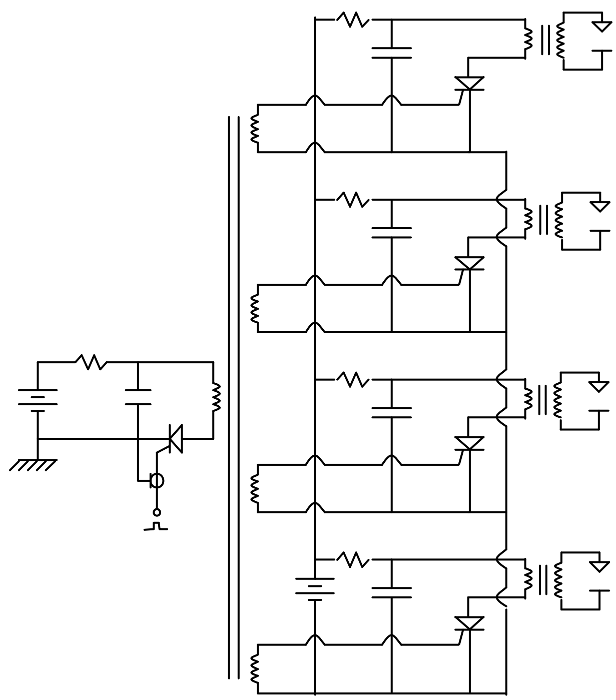

Figure 19: B. Sorenson's more robust DI circuit design.

The next major step in achieving the project objective is developing a laser-initiated GFPPT—something never fully completed before. Lenses for laser positioning are ready for use at the EPPDyL.

For the measurement comparisons to be made in the future, effective measurement techniques that reduce transmission line effects while having minimal effect on thruster operation should be used.

Acknowledgments

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References

[1] Jahn, Choueiri: Electric Propulsion.
[2] Berkery, Choueiri: Laser Discharge Initiation for GFPPTs.