Summer Internship May 31, 2005 – Aug. 5, 2005

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Introduction

During the ten week period from May 31st through August 5th, I worked in the Electric Propulsion Lab (run by Professor Edgar Choueiri) at Princeton University. I worked with Luke Uribarri, a graduate student, on an experiment designed to investigate the cause of the condition known as "onset". When the current in a magnetoplasmadynamic (MPD) thruster is raised above a certain level a condition known as "onset" occurs; in this condition, the voltage difference between the anode and cathode oscillates and the anode is rapidly damaged. This anode damage limits MPD thruster currents to below the level that induces onset. The purpose of this experiment is to study the phenomenon that causes onset with the hope of figuring out how to prevent it or raise the threshold at which it occurs. Unfortunately, due to several holdups, we were unable to actually fire the thruster while I was working in the lab, so I was unable to do much analysis of data or theoretical work. Instead, I mostly worked on the experimental setup and firing controller.

The Experiment

The experiment is to be conducted on the Princeton Benchmark Thruster, a quasi-steady state MPD thruster. Quasi-steady state means that it runs on 1 millisecond steady-state pulses. These pulses are produced by a pulse forming network of capacitors and inductors in the basement. Information about what is going on in the thruster will be collected in the form of voltage and current traces collected via probes hooked up to an oscilloscope. Additionally, the anode will be inspected for damage. This information will be collected at a variety of currents under various conditions. Several variables will be manipulated in order to see their affect on the onset threshold. Most simply, the mass flow rate can be altered by changing the pressure on the choked nozzle in the thruster. The gas used can also be changed; the thruster can run on any noble gas, and varying the gas may yield useful information. Another thing to change is the anode itself. The texture of the anode (polished versus rough) can be changed. Also, the material of the anode can be changed. We found both copper and aluminum anodes, but all of the aluminum anodes were too badly damaged to be used. I machined a new anode out of both carbon steel and aluminum, giving us three possible metals with different thermal and electrical characteristics to experiment with.

Problems

Lack of Documentation: The firing system had been built several decades ago and not used in most of a decade. When we started, it was completely dismantled with many parts either broken or missing. There was also very little documentation explaining how it was supposed to work. No schematics and very little explanation of how the system worked. Not knowing how things were supposed to work made it very difficult to fix broken components or even figure out which components were broken.

Funding: We had no budget, so we could not buy devices that would have made the firing system easy to control (a lab view box, for example). Instead, we had to design and build our own solutions.
Safety: It was decided that since the vacuum tank we were using had not been used in several years, it should be inspected to make sure it was still safe to use. The first company hired to do this did a terrible job and gave us no useful information, so we had to wait for somebody else to inspect the tank, preventing us from pumping down for a few weeks.
Sharing: Somebody else had to use our vacuum system during my second to last week in the lab and we were unable to pump down even though we were finally ready to fire.
Vacation: Luke went on vacation during my last week in the lab, so we were unable to fire that week.

Rebuilding the Firing System

In order for the thruster to fire, it needs both propellant and power. The propellant comes from a bottle, and the power comes from a capacitor bank downstairs. The firing controller, which is mounted to the side of the tank controls the timing and controls the rest of the system. Since we had very little documentation on how the system worked, putting it back together was a big job and involved a lot of trial and error. First, we traced all the wires coming out of the firing controller and used an oscilloscope to find out what signals come out of the firing controller and the relative timing of the signals. Then we figured out what each box did. Figuring this out was an experiment of its own. We would change one thing at a time and use a multimeter or an oscilloscope to measure what changed in the box and what its output was in each circumstance. This was made more difficult by the fact that some of the boxes were slightly damaged (a broken switch or loose wires) and that some parts of the system were missing. After a great deal of trial and error, we managed to put the system together more or less how it used to be.

In addition to getting the firing system working, we wanted to automate the firing process. We discovered that somebody had installed relays in parallel with the buttons on the firing controller and had used a Keithsley box (which we no longer have) to automate pressing the buttons. However, we also discovered that these relays could be run off of the parallel port on our computer. The voltage set dials on the firing controller could also be replaced by an analog signal. After spending some time looking for an input/output box or device that was inexpensive enough, we decided to produce this analog signal with a digital to analog converter chip. We had to buy a PCI card parallel port for the computer so we could run the relays (in parallel with the buttons) off of one port and the DAC chip off of the other. I then wrote software in Visual Basic to automate the firing process and fire the thruster at various currents many times.

Shortly after we had completed this level of automation, the firing controller broke. Most likely, one of the chips inside of it burned out. Since we had no schematic and it was too complicated to trace out our own schematic, we decided to replace the firing controller with something newer. This allowed us to move most of the timing control into software and gave us more control of what was going on. We designed and I built a new firing controller with that ran off of the digital signal from one parallel port and the analog signal from the DAC chip. This new firing controller was much simpler because much of the work was now done by a computer in software and in the parallel port. The safety features that the old firing controller had were incorporated into the new one in hardware.

Since the largest problem we had in setting up our experiment was in figuring out how all the old equipment worked, I drew schematics for all the new stuff we made and partial schematics for the old equipment we are still using. I also wrote a prose description of how the whole system works.

Conclusions on My Summer

It is unfortunate that we were unable to fire while I was there and that I did not get to do much work on the theory. However, I think I learned a lot anyway. Most importantly, I learned what it is like to do research and what it is like to be a graduate student. I also learned a lot about electronics and machining. Even though we did not get to analyze data, I learned about plasma science from taking part in conversations at the lab. All in all, I very much enjoyed my summer experience and feel that it was worthwhile to me educationally.

The Firing System (as of August 3, 2005)

Overview:

The computer software (written in Visual Basic) outputs through two parallel ports. This information enters a box through two grey cables. One cable goes to a digital to analog conversion chip which outputs a single analog signal. Both the analog signal and the digital signal from the other cable exit the box through a long, blue cable. This blue cable goes to the firing controller, which reroutes the signals to several separate devices. It also has some safety features hardwired into it. The devices controlled by the firing controller are the gas switch box, propellant valve box, vacuum relay, and power supply. The gas switch box controls a valve allowing air to enter the gas switch. The propellant valve box controls a valve in the thruster that allows propellant to exit the thruster. The vacuum relay, when closed, allows the capacitor bank to discharge through a resistor. The power supply charges the capacitor bank. Each of these parts will now be explained in greater detail.

The software:

The visual basic program (currently titled Firing Scheme 1) is designed to repeatedly fire the thruster at various set voltages. Set voltage is a value between 1 and 10 volts that determines to what voltage the capacitor bank will charge to. The relationship between set voltage and actual voltage is non-linear. "Starting Voltage" is the set voltage that the first shot should fire at. "Ending Voltage" is the highest set voltage that should be used. "Increment" is how much the set voltage should increase each time. "Trials" is the number of firings that should occur at each voltage before incrementing. "Repetitions" is the number of times the entire sweep from starting voltage to ending voltage should occur. "Time Interval" is the amount of time between shots. Invalid inputs should result in an error message. Pressing “Stop” while it is running will pause the program, changing the “Go” button to “Resume”. Pressing “Stop” when it is paused will end the firing and reset the program. If a file name is entered, a text file will be outputted including the date, start time, and end time of the firing as well as the set voltage of each shot. The digital control signals go to the new parallel port (PCI card). The digital signal to the digital to analog conversion chip goes to the computer’s original parallel port.

The Parallel Ports;

Both ports are on the back of the computer
The computer’s original parallel port outputs a high voltage of about 3.4 V and is attached directly to the mother board. This one runs the DAC. It is purple and has a picture of a printer on it. It is located near the serial and monitor ports.
The new parallel port outputs a high voltage of almost exactly 5.00V and is on a PCI card. This one is used for the digital control signals because it has higher voltage, probably can output more current, and would be less disastrous to burn out. It is located in a slot towards the bottom of the computer.
On both ports, pins 2-9 are the data pins. Pin 2 is the least significant bit; 9 the most. Pin 25 is ground.

The First Box:

This box is roughly 5” x 7” x 2”. On one side, the two grey wires that lead to the parallel ports enter. The wire in the middle of the box is the digital signal and should plug into the PCI card. The wire near the right corner of the box goes to the digital to analog converter (DAC) and should plug into the original parallel port. On the other side of the box (above a screwed on panel) is a plug for the long, blue cable. Pins 2-9 on this plug contain the digital directly from the grey wire. Pin 25 is ground. Pin 1 is the analog signal from the DAC. The DAC is an AD558KN. It is an 8-bit DAC. It receives power from a Jameco brand 12V DC power supply that plugs into the box on the same side as the blue cable. The power can be switch on and off on the top of the box.

The Blue Cable:

The blue cable is approximately 15’ long and has a male 25 pin D connector on the end going into the first box and a female connector on the end that goes into the firing controller. The side that goes to the first box has a more rounded black, plastic clip on the connector. The side meant to go to the firing controller has a more boxy, black, plastic clip on the connector. Only 10 of the small wires inside are used, but there are many more unused wires inside. Unfortunately, the pins on one end do not go to the same pins on the other end. This is because it used to be used to interface between the computer and the old firing controller, which had different pin-outs.

Purpose:	**Pin on Male end:**	**Pin on Female End:**
Gas Switch	2	2
Propellant	3	3
Trigger	4	4

Fire	5	5
Vacuum Relay	6	14
Latch	7	15
None	8	16
None	9	17
Analog	1	13
Ground	25	1

<u>The Firing Controller:</u>

The firing controller is roughly 5” x 6” x 4” and is bolted to the bottom of the old firing controller. It is controlled by the blue cable, which plugs into the back of the controller, and in turn controls the propellant and power systems.

The wiring in this box follows a color scheme.

Color	**Purpose**
Red	Power (5V or 9V DC)
Black	Ground
Green	Analog
Purple	Relay control
Blue	Digital signal to BNC
Brown	Miscellaneous

Wires with both ends on the circuit board or both ends on the edge connector on the voltmeter are not color coded. (They are either uninsulated or have clear insulation.)

The box is powered by an SPC brand 9V DC power supply, which plugs into the back of the box and is switched on/off by a switch in the front. This 9V runs into a 5V power regulator, which powers the chips and voltmeter with the appropriate 5V. An LED in series with two 460-ohm resistors is wired from the power switch to ground (in parallel with the power regulator) to indicate when the power is on. There is a large wire nut containing all of the grounds in the box.

The signal for the gas switch box goes through three diodes in forward bias before exiting the box in a BNC connection on the right of the front. The purpose of the diodes is to prevent any signal from going to the gas switch box until it rises above a certain threshold (roughly 2V). This was put in because the gas switch box triggers when it isn’t supposed to otherwise (particularly when the propellant valve box is triggered).

The signal for the propellant valve box goes through the firing controller unaltered and exits it in a BNC connection in the center of the front of the box. The “Trigger” signal is also unaltered and goes to the left BNC connection on the front of the box. The “Trigger” signal is currently unused, but is there for the purpose of triggering an oscilloscope if desired.

The vacuum relay (located in the capacitor bank room) is connected to some circuitry in the right side of the metal thing that the old firing controller was in and the new one is attached underneath. This circuitry contains a small relay. Two wires from this circuitry enter the firing controller through the bottom of the three 5-pin (7 holes on the female side) Amphenol connectors on the back of the firing controller. It is a grey wire going into a black and silver connector. Inside the firing controller, the two wires are brown. They are attached to the normally open contacts of a relay, and when this relay is thrown, the small relay in the other panel will also throw as will the vacuum relay in the capacitor bank room. The coil in this relay is wired to ground and (purple wire) pin 14 of the blue cable. This relay (as are the other 3 relays in the box) is a JWD-172-1.

The analog signal (green wires) runs from pin 13 in the blue cable through the normally open contacts of a relay, and out (along with ground) through the middle of the 5-pin Amphenol connectors on the back of the firing controller, and down to the power supply in the basement. The normally closed connections of the relay are connected to ground and the analog out so that the long analog wire can not act as an antenna, drifting slightly above 0 and therefore telling the power supply to slightly charge the bank. The Amphenol connector is a blue and silver connector going into a grey cable with a green wire attached to it (1 of 2). One end of the coil of this relay is wired to ground. The other is wired to pin 5 of the blue cable through the normally open contacts of two relays. These two relays are there for safety reasons and prevent the bank from charging unless they are thrown.

One of these relays is for the interlocks. The interlocks are little switches that need to be closed to make sure things are safe. They are on such places as the door to the capacitor bank and the door to the high voltage cage over the power intake on the tank. The 6 interlock switches each connect to two wires that enter the firing controller through pins 1-12 of the upper of the two 25-pin D connector on the bottom of the box. Three grey cables, a red wire, and a green wire all enter one of the rounded black connectors. The male end of the connector is on the firing controller box, with the female end on the cable. All of the interlocks are wired in series (by purple wires inside the firing controller) with one of the “safety relays”. The other end of the interlock wires is connected to the 5V coming out of the power regulator and the other end of the relay coil is wired to ground. Therefore, when all the relay switches are closed, the 5V is connected to ground through the relay, and the relay is thrown, allowing the firing signal to pass. An LED in series with one 460-ohm resistor is wired in parallel with the interlocks and relay to indicate when the relays are all closed.

The other of the two “safety relays” is to prevent the bank from charging if it is already above 1kV. Five 100 mega ohm resistors are wired in series to connect both sides of the capacitor bank. This will result in 2mA of current for every 1kV on the bank. This current is measured by a current probe that puts out .5 V for every 1ma. This means that it puts out 1V for every 1kV on the bank. This signal comes upstairs and enters the firing controller through the top of the three 5-pin Amphenol connections. It is a grey cable with a green wire attached going into a blue and silver connector (1 of 2). Inside the firing controller, it goes through a voltage divider consisting of a 1.00 k-ohm and a 9.09 k-ohm resistor in series, approximately dividing the signal by 10. The voltmeter (a Datel Intersil DM-4100D connected to two 30 pin edge connectors) measures the voltage across the smaller resistor (black and green wires). The voltmeter samples 30 times per second when receiving a high input on the brown wire from pin 15 of the blue cable. When receiving a low input on this wire, it maintains its last reading. There are several jumpers on the edge connectors of the voltmeter, which are described in its operating manual. It is jumpered to multiply the voltage by 10, compensating for the voltage divider. This is done so that there are the desired number of digits on either side of the decimal place. The voltmeter outputs each of its decimal digits in binary format. The 1V, 2V, 4V, 8V, 10V, and “over range” pins are all wired into the inputs of two 3-input NOR gates (both on the CD74HCT27E). The two outputs of this run into an AND gate (on the CD74HCT08E). Both chips are powered off of the 5V power regulator. The output of this is wired to one end of the relay coil; the other end of the coil is wired to ground. If the voltmeter reads less than 1V, all of these pins will be low, the NOR gates will be high, and the AND gate will be high, throwing the relay. If the voltmeter reads 1V or more, one or more of these pins will be high, one or both of the NOR gates will be low, and the AND gate will be low, leaving the relay open and rendering it impossible to throw the relay that allows the analog signal to go to the power supply. This means that in order for the bank to charge, the bank has to start at less than 1kV and all of the interlocks must be closed.

The Gas Switch:

The gas switch actually switches the power going to the thruster. It is located in the blue paneling, directly under the power feed on the side of the tank (near the door). Ten coaxial cables connect to it from both the top and the bottom. The outer sheaths of the cables connect to the outside of the gas switch. The inner conductors go through holes and connect to a pair of copper plates (separated from the outside by Plexiglas). The plates are about 2" apart and about 6" in diameter. They each have a hole in the center. The lower plate's hole is connected to some pipes that run to a pump in the basement. This pump can then pump the inside of the switch down to low pressure (on the order of 10 millitorr; depends on the seals and how long you wait). The upper plate's hole is connected to a valve that lets in air. When this valve opens, air enters the switch, raising the pressure enough for the current to arc between the two plates, closing the circuit. The switch is coaxial. The similar looking thing below the switch is believed to be there for the purpose of strain relief (keeping the weight of the cables off of the switch itself) and converting 40 cables to 10. The black thing next to the switch is believed to be an expansion chamber for the gas in the switch.

The Valve:

The valve that lets air into the gas switch is the same type of valve as is in the thruster to release propellant. It is a solenoid valve designed to open when given a 12V 60Hz AC signal. Unfortunately 60Hz is too slow for this purpose and does not open quickly enough to give the necessary rise times. Also, the valve in the thruster will sometimes stick if the pressure is too high.

The Propellant Valve Box:

The purpose of this box is to send a large amount of current into the propellant valve in order to open it quickly. The box receives standard 120V AC power from a wall outlet. It has a switch in the front and a light comes on when the power is on. The rectangular thing on the top of the box is a transformer. The power runs through the transformer and then is rectified to DC current by a pair of diodes. This DC current is used to charge the capacitors. The three cylinders (one smaller than the other two) on top of the box are all capacitors wired in parallel. The capacitors are constantly discharging through a resistor, and if the bleeder switch is held, the bank additionally discharges through a smaller-value resistor, dropping to low voltages in about 10 seconds. There are two BNC connections on the front of the box that go to wires leading to the solenoid valve. On one of the BNC connectors, the center conductor is attached to the positive side of the capacitor. There are two parallel transistors (actually darlington pairs) between the other BNC connection and the negative end of the capacitor. The input signal enters the box through a BNC connection on the back of the box and runs into an inverter chip (powered by a 5V power supply) on the upper of the two circuit boards, which is used to buffer it. The 555 chip next to it is a timer chip used to end the firing pulse. After the box triggers, this chip waits a while, then flips and ends the output pulse. The 10-turn pot on the side of the box is wired as a variable resistor and is used to vary the RC constant and control how long it takes the 555 chip to flip. On the lower circuit board is a transistor chip that sends the signal to the actual large transistors.

What ends up happening is this: if the input signal is more than 1.3V the two large transistors are open and the capacitors will charge up to about 170V in 20-30 seconds. If the input signal drops 1.3V, the box will trigger. The transistors close, discharging whatever charge is in the capacitors through the solenoid valve.

<u>The Gas Switch Box:</u>

This box is a lot like the propellant valve box except for a few differences. When the input is less than 0.6V, the capacitors charge. When it is greater than 0.6V, they discharge through the valve, which plugs into the box in a 2-prong plug. This low trigger voltage can result in the box firing when it isn't supposed to due to noise from other devices. The three diodes in the firing control raise this threshold and prevent this.

<u>Two Other Boxes:</u>

The two coax cables exiting the propellant valve box run through another box before going to the valve. This is a small box (about 4" x 6" x 2") with a relay on top. Normally, this box allows the signal to pass through it unaltered. However, if the box receives 12V 60Hz AC power through the two plugs on the top, the relay will throw and the 12V AC will be passed to the valve instead of whatever the box is outputting. The 12V AC will open the valve and hold it open. This is used for such things as lowering the pressure or flushing the gas out of the thruster. The second box is a 12V AC power supply. It contains a transformer to transform the 120V AC it gets from a standard outlet down to 12V then outputs that through to plugs on the top to the other box. If the power switch (also on top) is flipped to on, the box will output 12V AC; the relay in the other box will throw; the 12V AC will go to the valve in the thruster; the valve will open and stay open until the power switch is flipped back to off.

<u>The Vacuum Relay:</u>

The vacuum relay is mounted on the wall of the capacitor bank room to the left of the bank above the first power supply box. It is a high current relay and is used to discharge the bank without firing the thruster. When closed, the bank will discharge through the large tub of copper sulfate on the floor behind the bank, near the relay. This large tub can absorb a lot of energy without getting too hot.

The Power Supply:

The power supply comes in two boxes. The first box is the shorter box (about 3'6" high) to the left of the capacitor bank. It receives power if the large switch on the other side of the wall (outside the bank room) is switch to on. The starter in the back corner of the box is controlled by the lower right panel of the old firing control. The "KVDC ENABLE" button will close it (indicated by "POWER ON" light). The "KVDC DISABLE RESET" button will open it. Additionally, the large power switch on the right of the box must be set to on. If the box has power, the green light in the middle of the front panel will come on. The box receives 3-phase AC power. It also gets the 0-10V analog signal from the firing control. It will then variably shift the phases of the AC power and add them together. In this way, it produces a variable AC power that depends nonlinearly on the analog signal it receives. This power is then sent to the second power supply box, to the right of the capacitor bank. In it are a transformer and some large rectifiers. (There are actually 3 sets of this, but only 1 is used.) This outputs a DC voltage that is used to charge the capacitor bank.

The Capacitor Bank:

The capacitor bank is designed to output high current for 1 ms. The pulse is designed to be as flat as possible once it reaches peak current, but the rise and fall time is not as important, so is not particularly fast. It consists of forty 322 microfarad capacitors (rated for up to 4000V) and 21 inductors. The capacitors are all in parallel, but with inductors in between them. There are two sets of 20 capacitors with an inductor between every 2. Both terminals of the bank exit on the right side. There is a variable resistor on the top of the bank with a slider that can be moved to adjust it. The resistor should be adjusted so that it is critically damped in order to prevent ringing and reduce the rise and fall times. After the resistor, the power heads upstairs via 40 coaxial cables.