# #20 - Direct Drive Solar Powered Arcjet Thruster

SPONSOR – NASA, MARSHALL SPACE FLIGHT CENTER, HUNTSVILLE AL

ADVISORS – DR. GUO, DR. KWAN, DR. ANDREI

SENIOR DESIGN COORDINATORS – DR. AMIN, DR. FRANK

Team Members

Date – 12/3/13

Chris Brolin - ME
Cory Gainus - ME
Gerard Melanson - ECE
Tara Newton - ME
Griffin Valentich - ME
Shane Warner - ECE

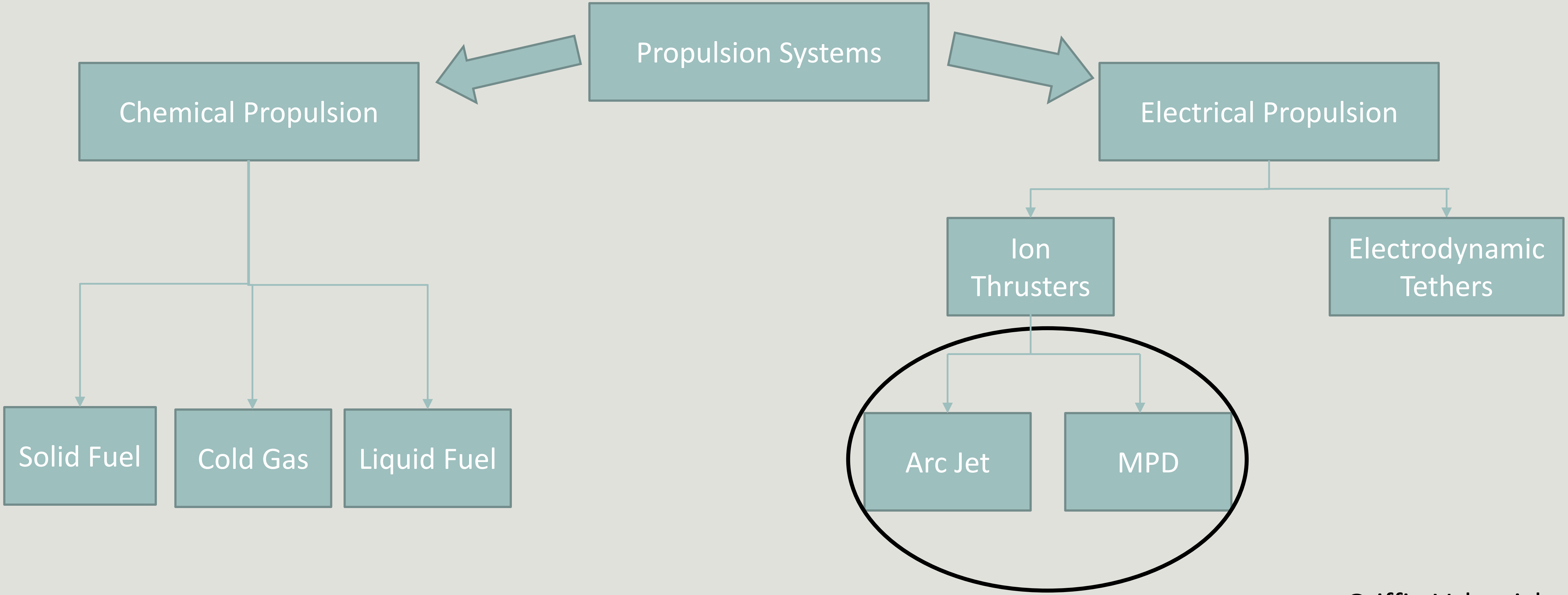
Griffin Valentich

# Agenda

- Background
- Sponsor Requirements/Objectives
- Final Design
  - Mechanical
  - Electrical
- Potential Challenges / Safety
- Procurement
- Future Plans for Spring 2014

Griffin Valentich

# Background



Propulsion Systems

Chemical Propulsion

Electrical Propulsion

Solid Fuel

Cold Gas

Liquid Fuel

Ion Thrusters

Electrodynamic Tethers

Arc Jet

MPD

Griffin Valentich

# Background

- Electrical Propulsion Systems
        - High specific impulse – low thrust
    - Electro-thermal thruster– arcjet
        - Produce thrust by heating gas propellant (Ar) and expelling through C-D Nozzle
    - Electromagnetic thruster – MPD
        - Accelerates particles with applied magnetic force
- Purpose of Electric Propulsion Systems
    - Station keeping – lower overall lifetime costs
    - Satellite altitude and attitude adjustment
- Power Processing Unit (PPU)
    - Expensive and complex
    - Largest prohibitive component to electronic propulsion systems
    - Converts input power to correct current and voltage

Griffin Valentich

# Paschen’s Law

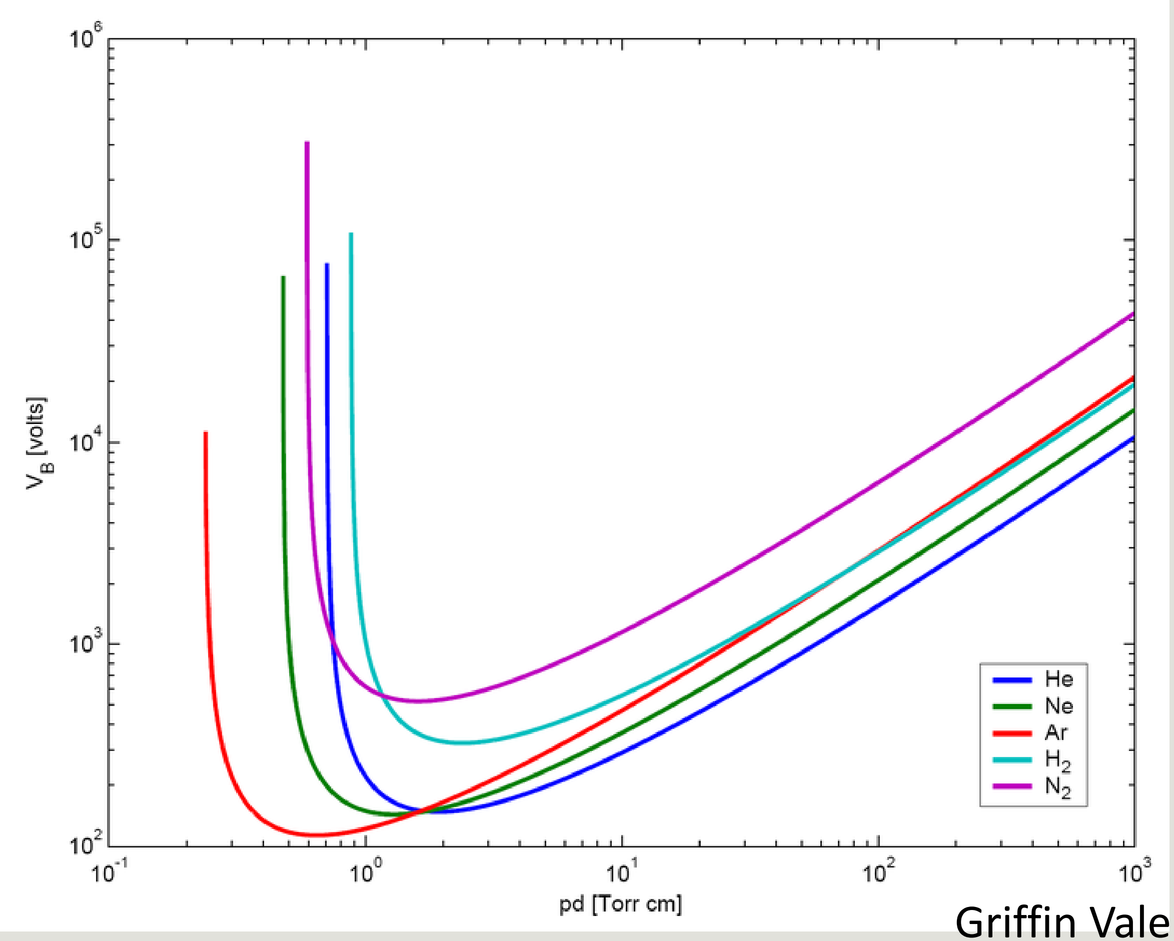
- Relates the product of pressure and distance between anode and cathode to the voltage necessary to initiate breakdown

$$V_{Breakdown} = f(P * d)$$

- Argon had lowest breakdown voltage

$$\sim 137\ V$$

- Good starting point, but values will be different due to complex geometry



Griffin Valentich

# Sponsor Requirements / Objectives

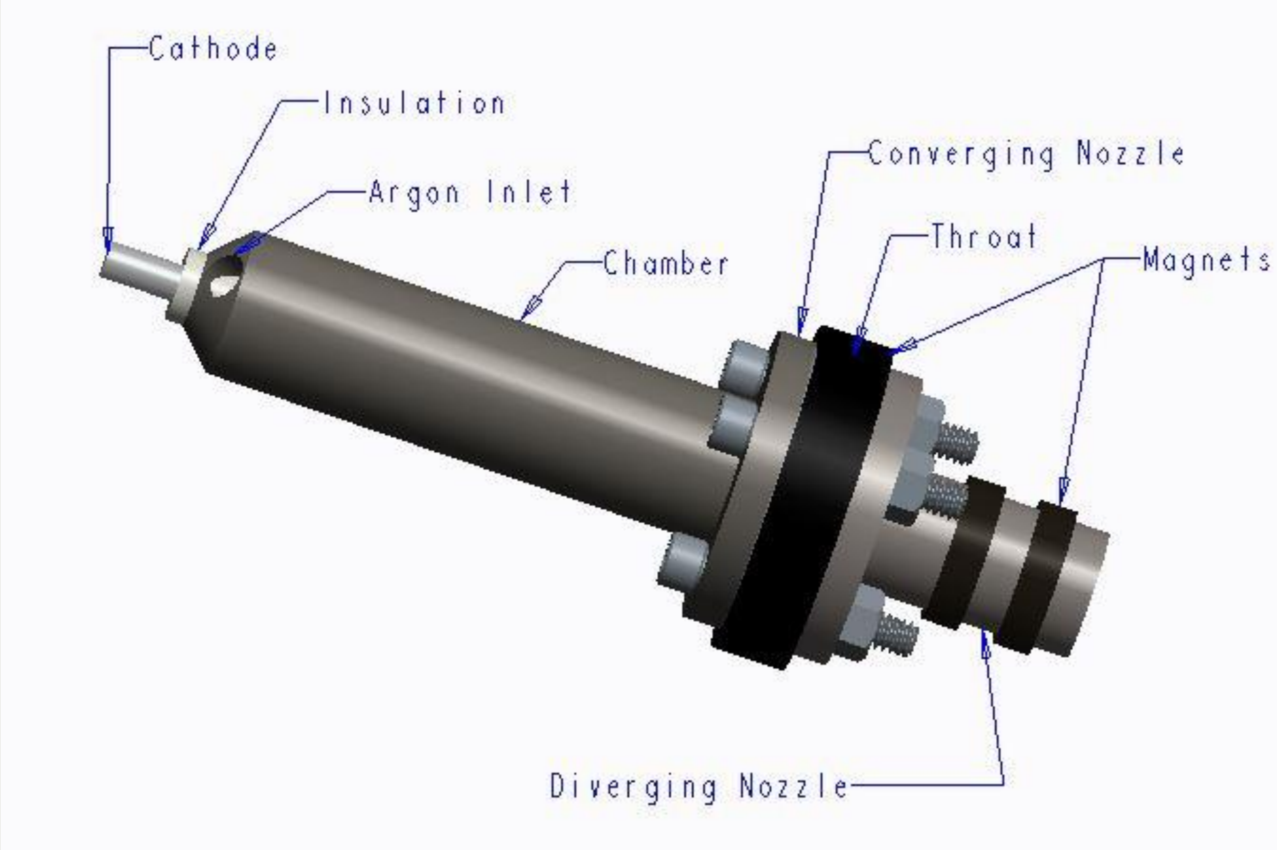
- **Eliminate the PPU**
  - Enable thruster to operate in Direct-Drive Mode
  - Obtain power directly from solar panels
- Design, manufacture, and test an arcjet thruster
  - Utilize permanent magnets to confine high temperature plasma
  - Independently control propellant flow
  - Design mounting apparatus for thruster inside vacuum chamber
  - Measure thrust produced
- Quantify the range of operating conditions over which thruster is effective at operating continuously

Griffin Valentich

# Thruster Design

**Characteristics**

- 3 part nozzle construction
    - Easier machinability
    - Designed for Mach 2 - A/A* = 1.531
- Magnets evenly spaced over nozzle
    - Strongest field at throat of nozzle to protect nozzle walls
- Stagnation Pressure - 550 Pa
- Static Pressure at throat – 267 Pa
    - Pressures from Bernoulli’s Eq with const. mass flow rate
- Anode/Cathode Spacing – 0.15”
- Product of pressure and distance gives breakdown voltage of 137 V
    - well within circuit’s capabilities



Tara Newton

# Thruster Design

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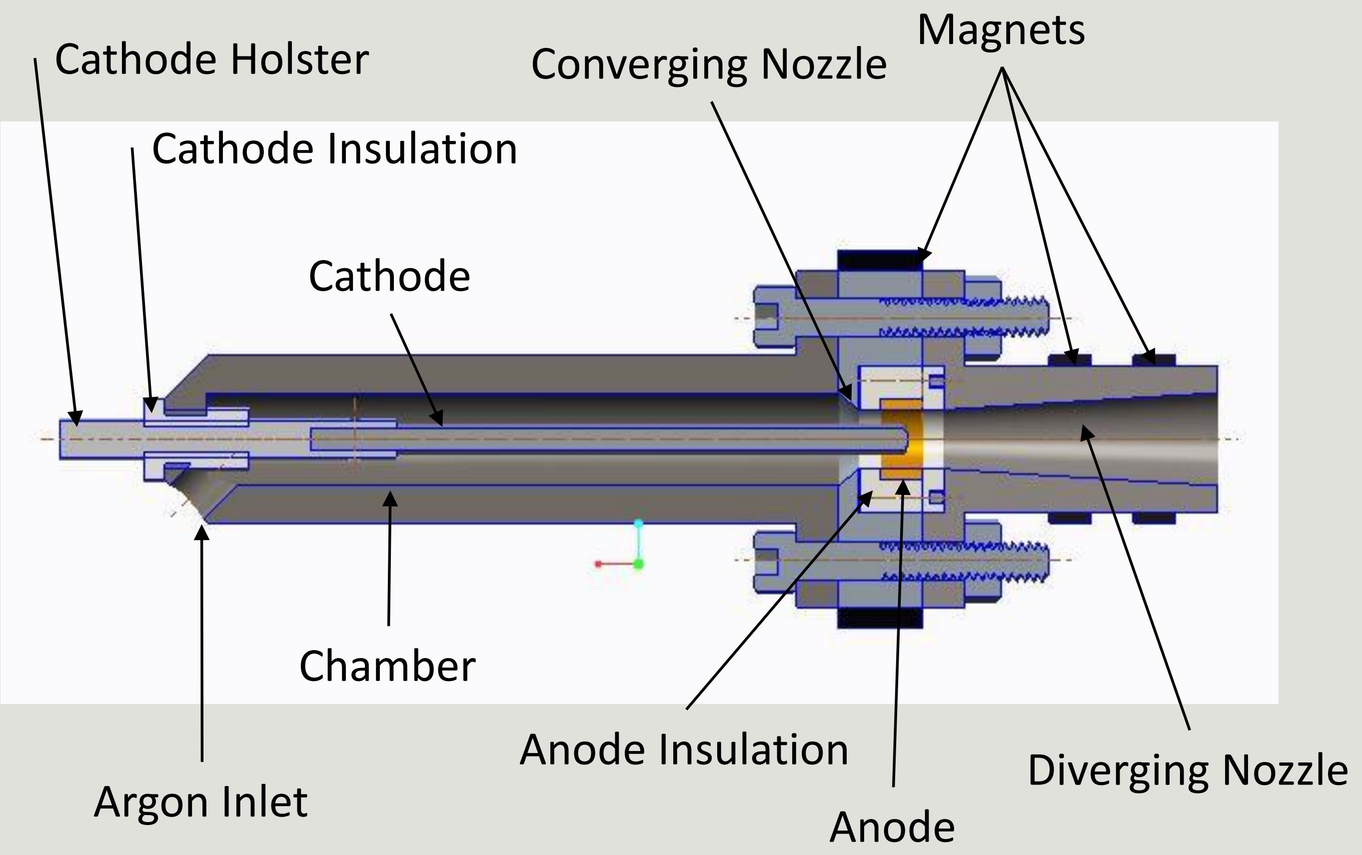
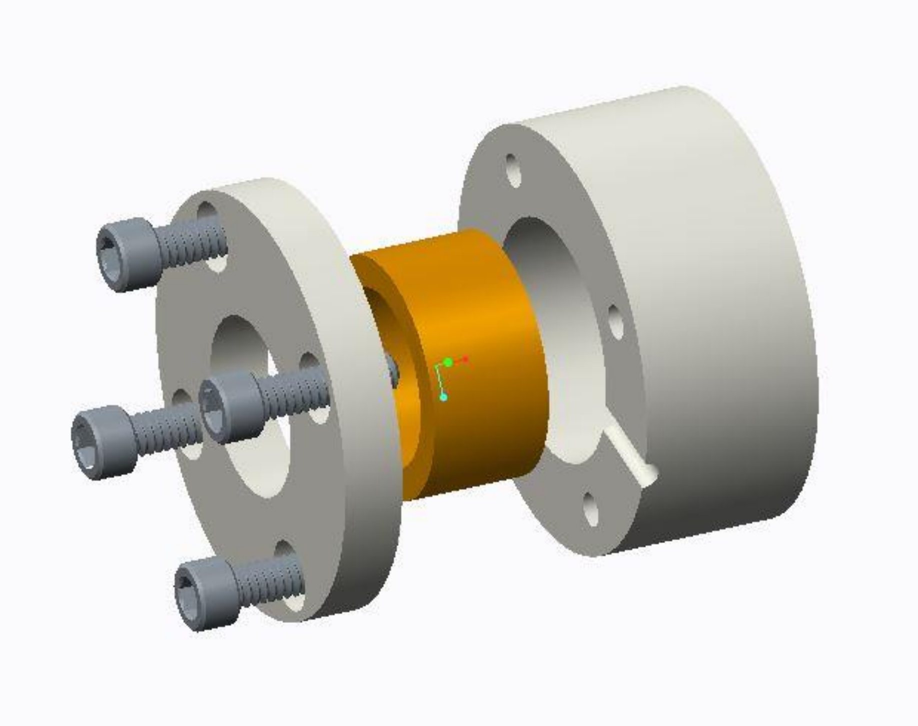


Tara Newton

# Machining Considerations

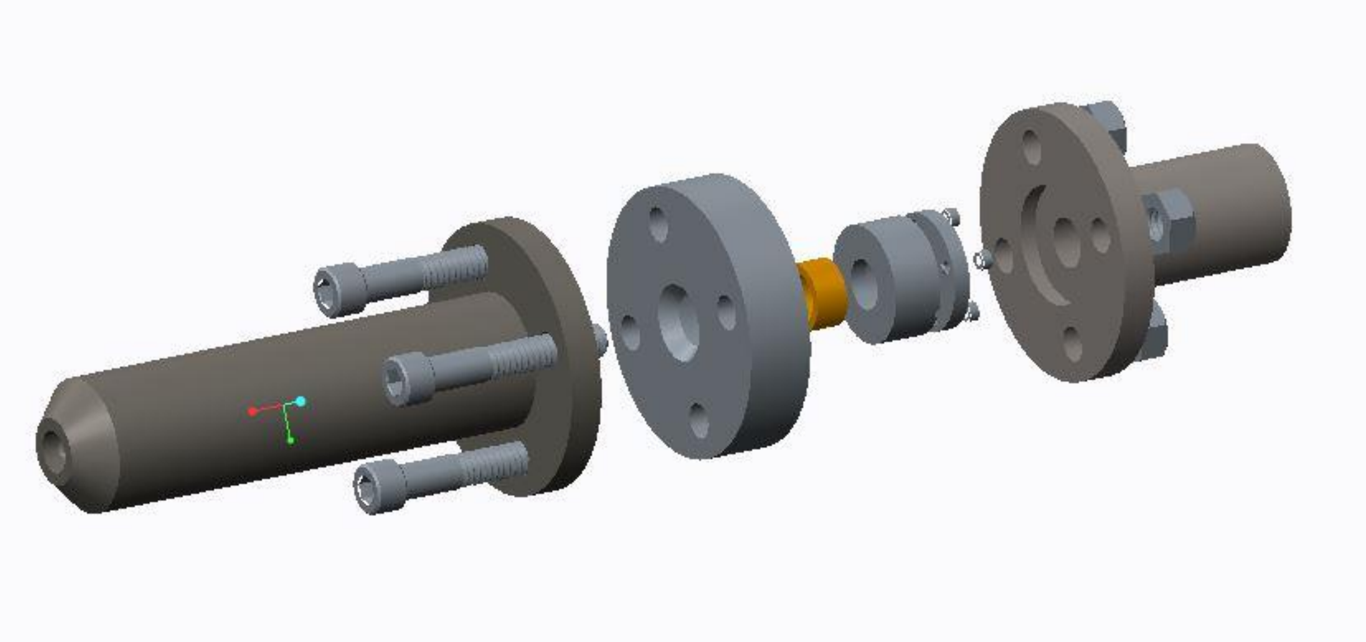
- Anode Assembly
  - Allows anode to be insulated yet easily accessible



Tara Newton

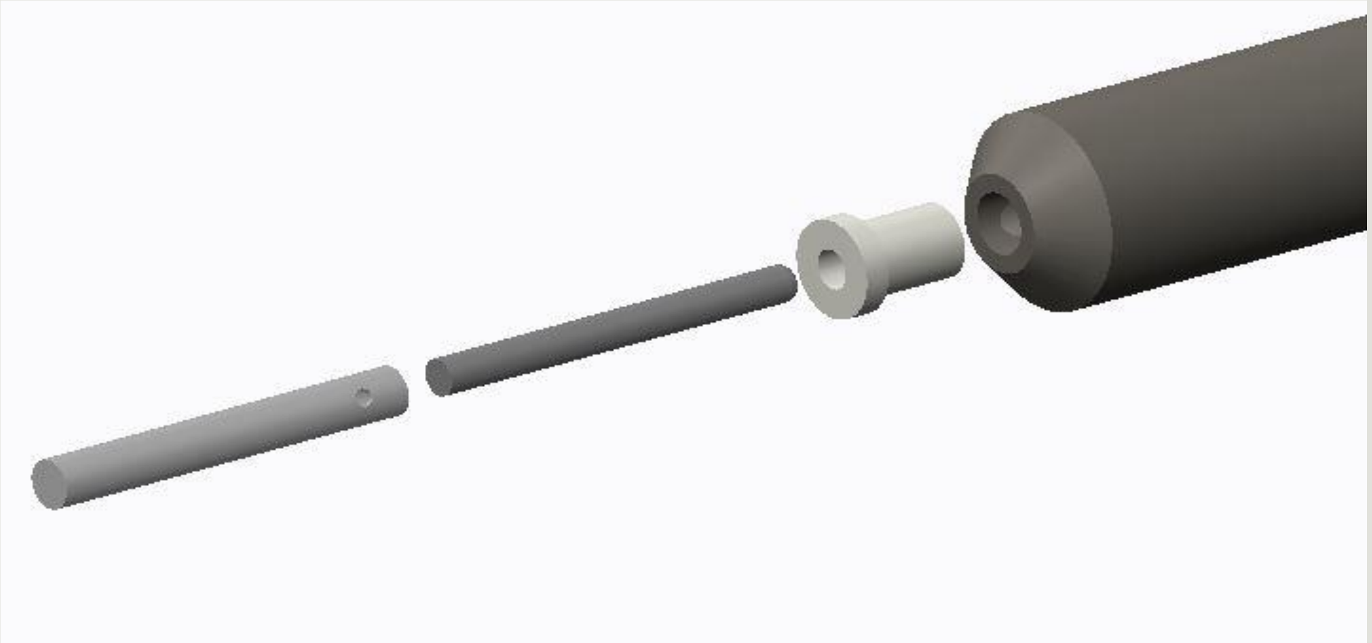
# Machining Considerations

- Nozzle Construction
  - Three main components
    - Converging
    - Throat
    - Diverging



Tara Newton

# Machining Considerations



- Cathode Placement
  - Adjustable using threads
  - Change d on the P*d axis of Paschen's curve
- Cathode Holster
  - Avoid machining tungsten

Tara Newton

# Material Selection

| Component | Material | Rational |
|---|---|---|
| Cathode | Tungsten | High melting point |
| Anode | Type 303 Stainless Steel | Easy to machine, good temp resistance |
| Fuel Supply | Argon Gas | Readily available |
| Chamber | Type 303 Stainless Steel | Easy to machine, good temp resistance |
| Insulation | Macor (Glass Ceramic) | Machinable Ceramic Insulation |
| Nozzle | Type 303 Stainless Steel | Easy to machine, good temp resistance |
| Vacuum Chamber | Glass Bell Jar | Large Volume/ transparent / budget constraints |

Tara Newton

# Testing Apparatus

Vacuum Chamber

- Bell Jar
- Borrowed from Dr. Weatherspoon
- Chamber will be evacuated to 0.5 torr
- Argon and electrical connection input through baseplate

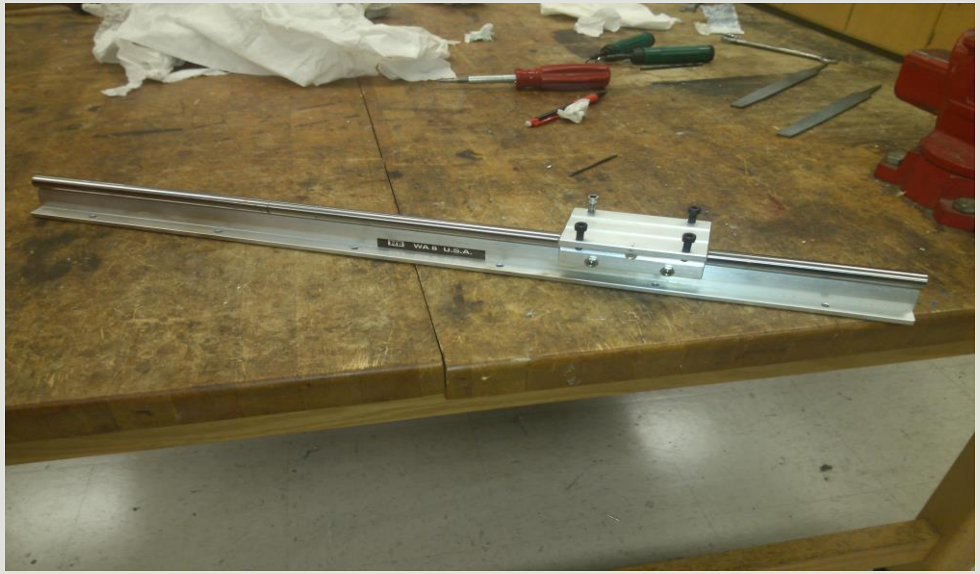
Vacuum Pump

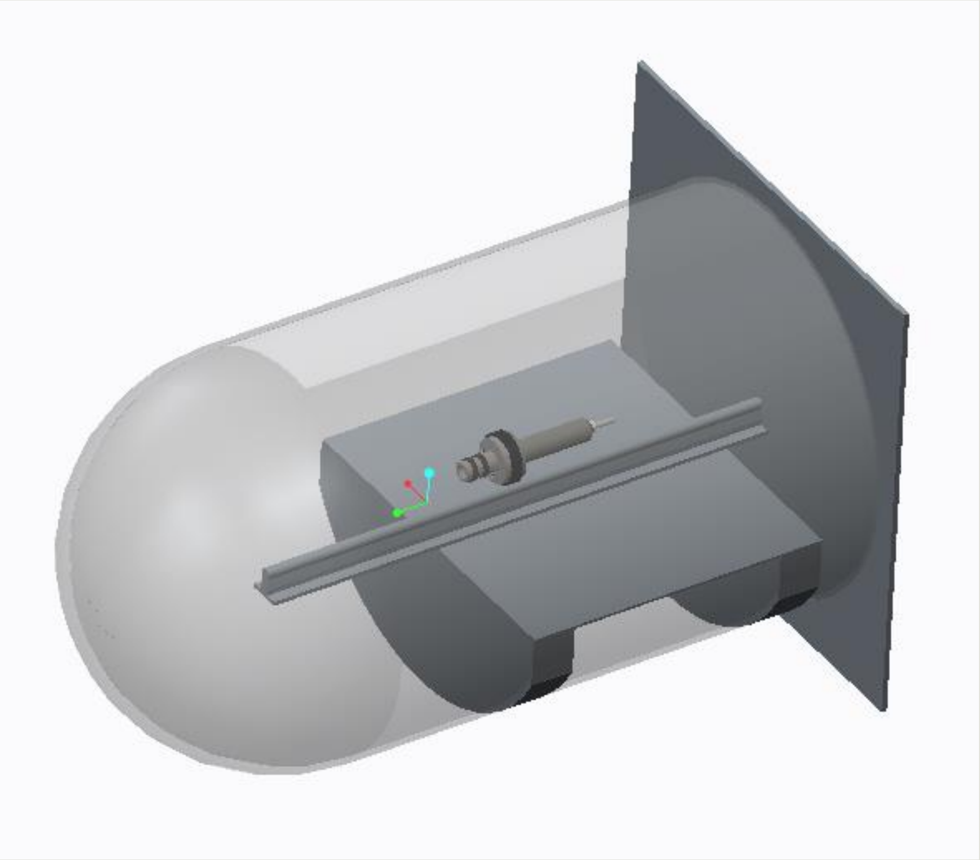
- Borrowed from Dr. Weatherspoon
- Dekker RVL020H
- Vacuum to 0.5 torr
  - Pb = 66 Pa

Cory Gainus

# Experimental Setup

- Force measured with spring and sliding track
  - Max expected force – 1 N
  - Spring Constant – 0.44 lb/in
  - Max deflection – 1.85 in

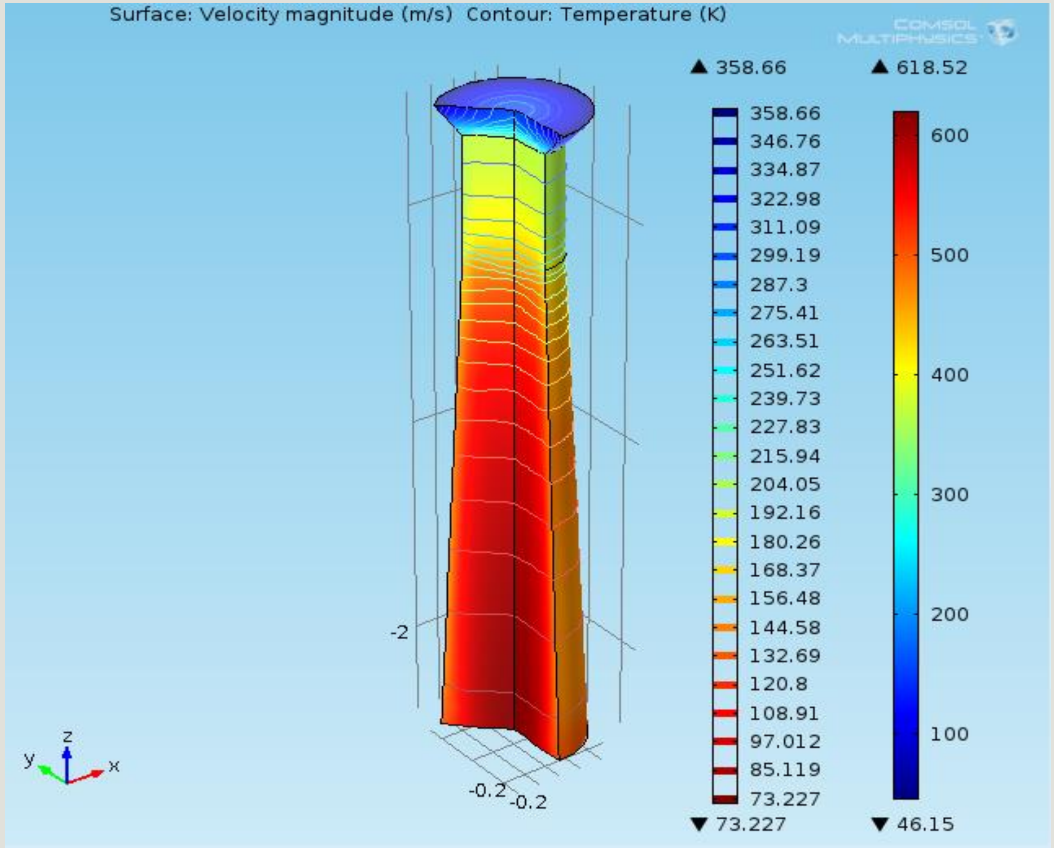




Cory Gainus

# Analytical Model

- Comsol Simulation of the Converging-Diverging Model
  - Simulation run utilizing calculated static and stagnation pressures
  - Gives a exit Mach number of approx. 1.7
    - Nozzle designed for a Mach number of 2
- Simulation not perfect
  - Temperature gradient difficult to model
  - Need to add magnetic field to nozzle



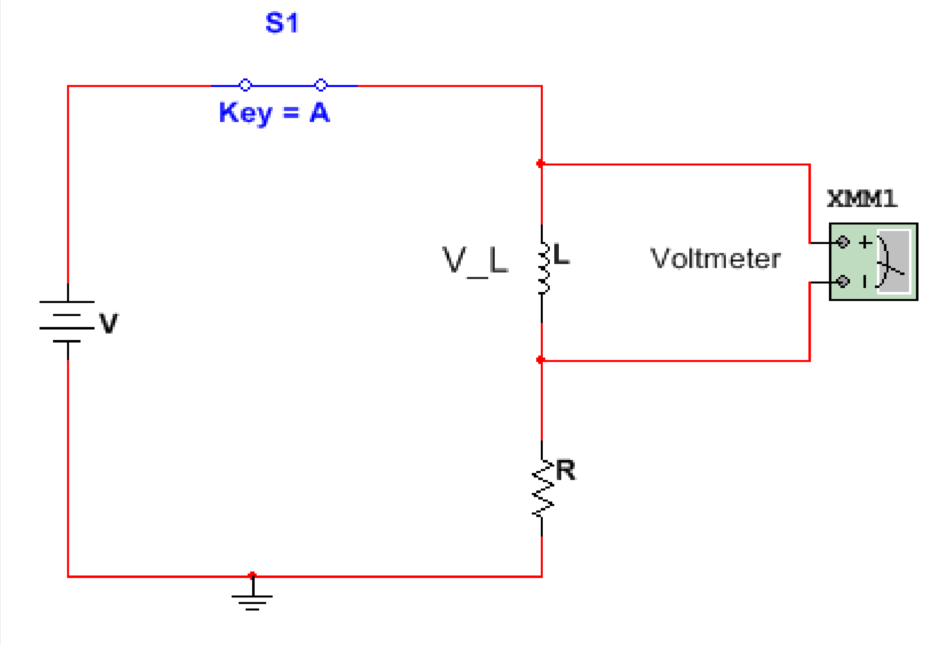
# Electrical Goal #1 – Circuit Design

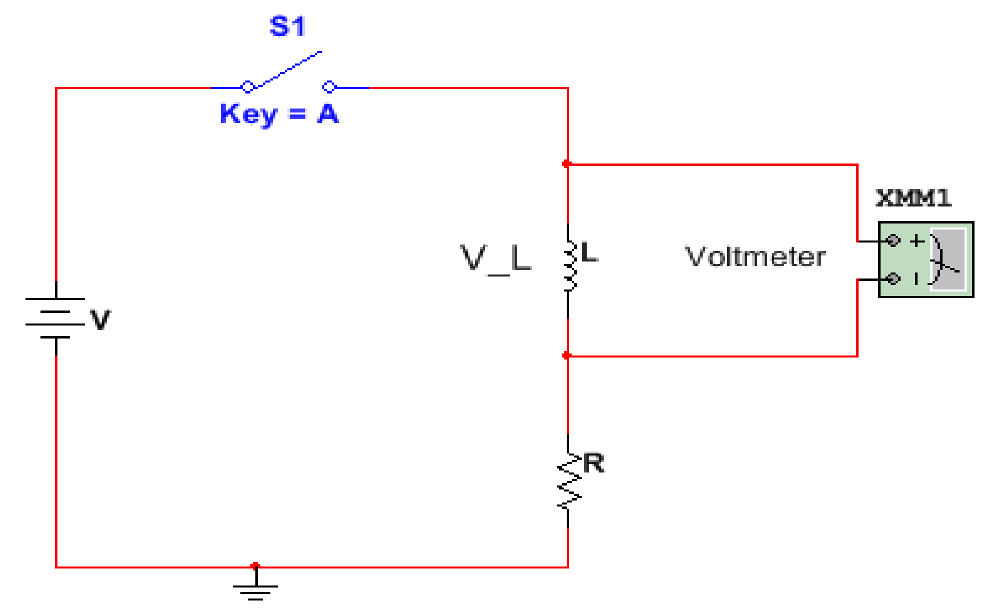
- Input – 4 Aleko 100 W Solar Panels
- Act as approximately 80V Source
- Can sustain approximately 5.5 A
- Produce correct voltage spike with 40V source

Aleko 100 W Solar Panel

Shane Warner

# Inductor Properties



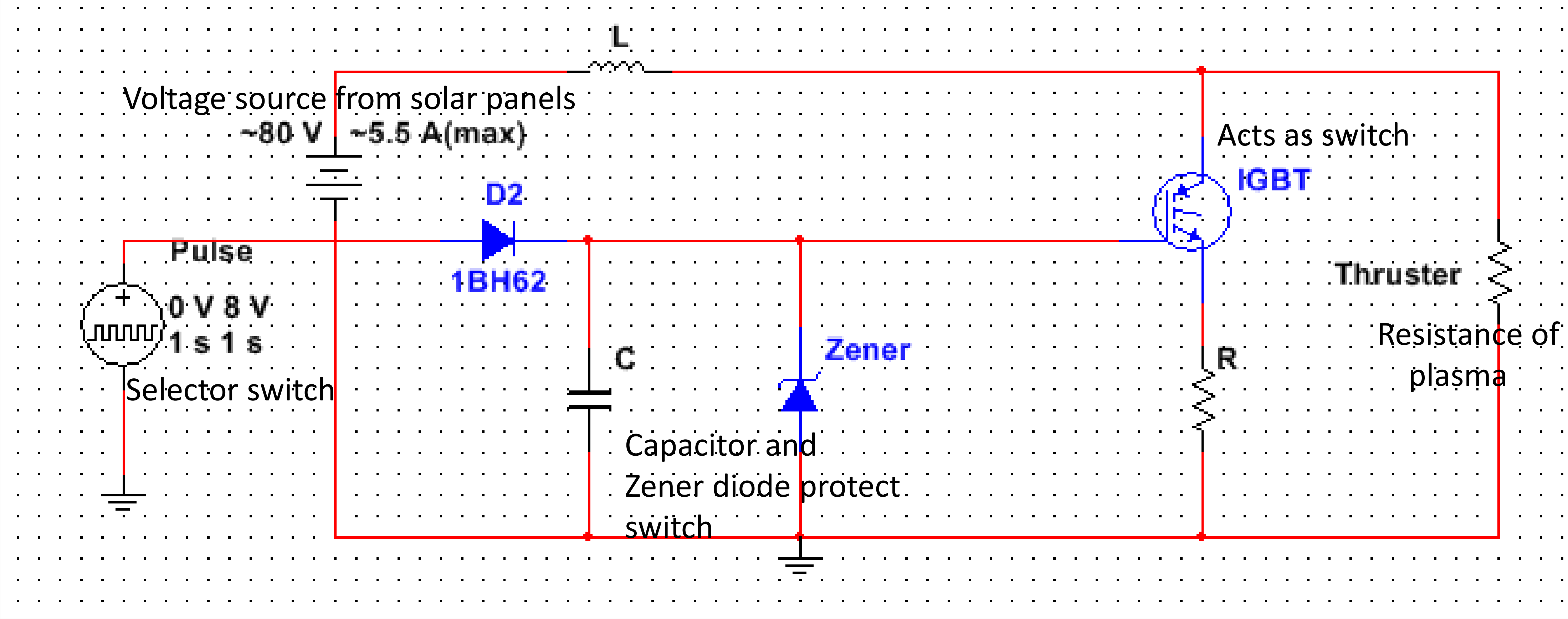


Once in steady state: I = $\frac{V}{R}$

When the switch opens: $V\_L = L\frac{di}{dt} = L\frac{I-0}{dt}$

Shane Warner

# Final Circuit Design



Voltage source from solar panels

Acts as switch

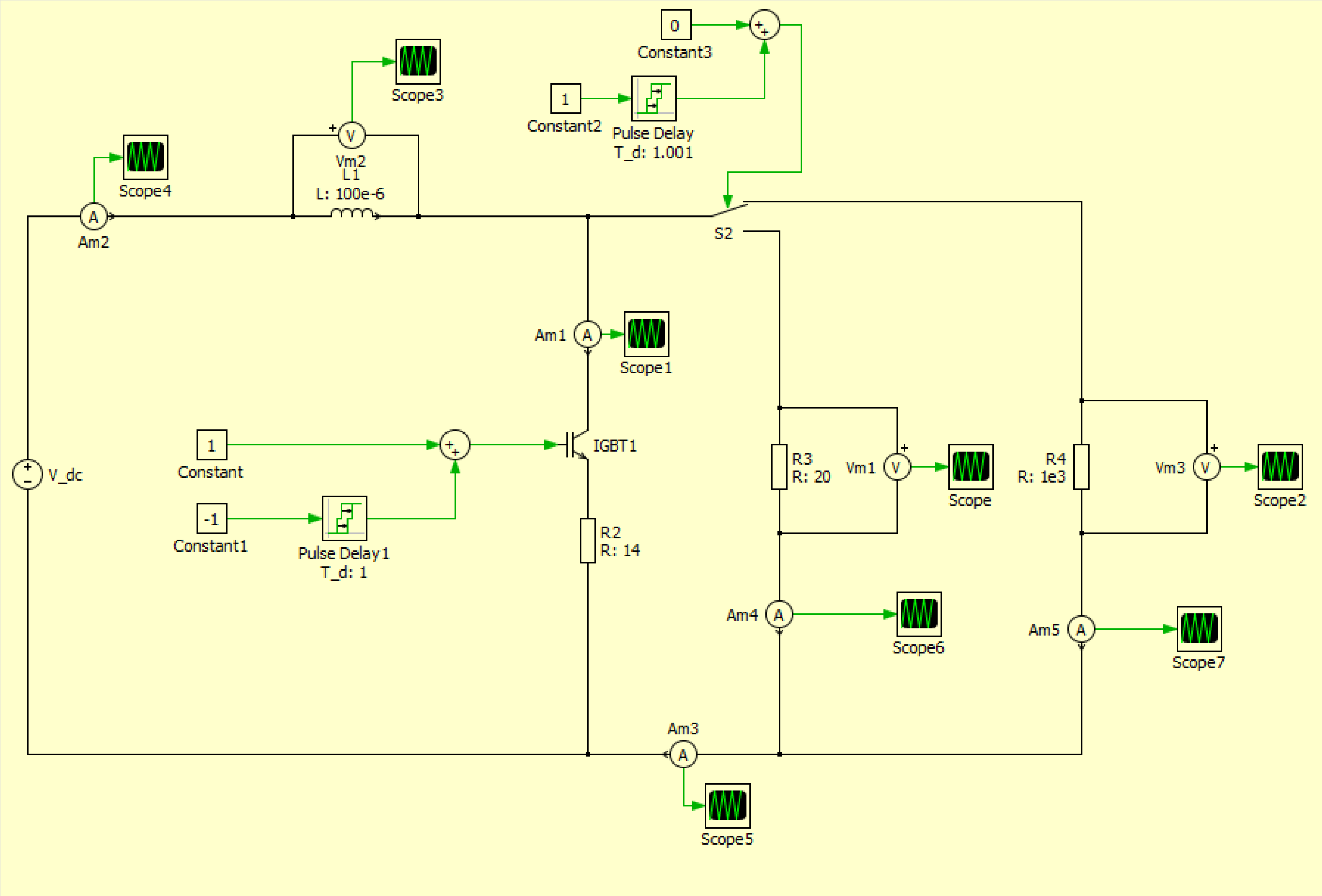
Selector switch

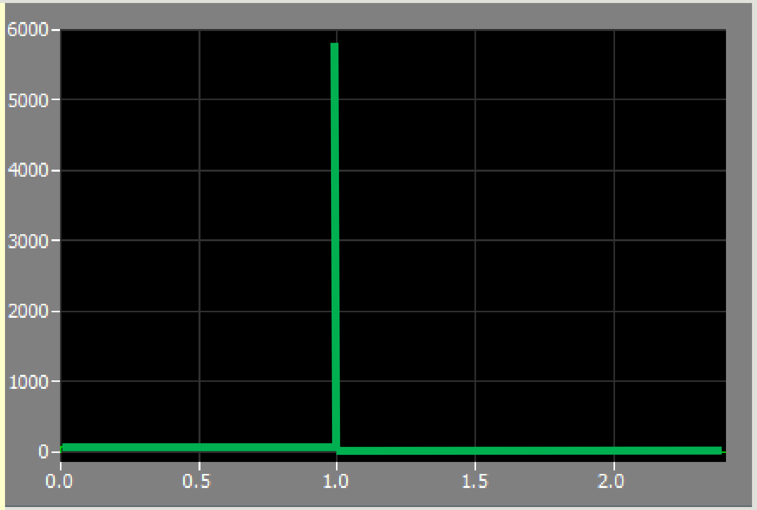
Resistance of plasma

Capacitor and Zener diode protect switch

Shane Warner

# Circuit Simulation using MATLAB



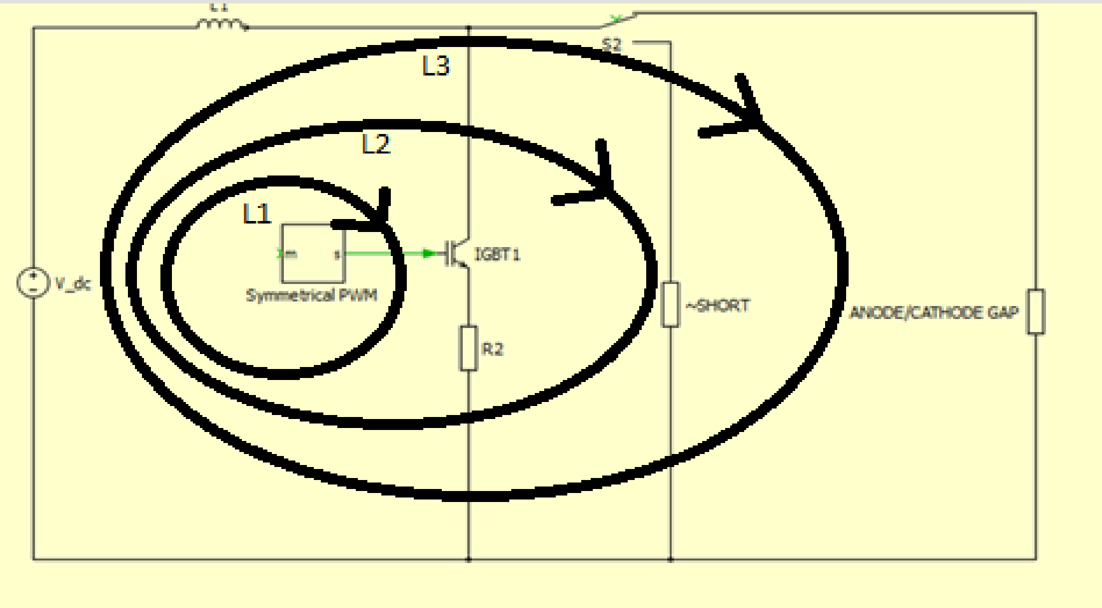


Voltage spike of 5.9kV in MATLAB

Shane Warner

# Circuit Analysis

- The magnitude of the voltage spike is incorrect.
- Can be calculated using KVL in loop L3 as:
- V_breakdown = V_dc + L$\frac{di}{dt}$
- V_breakdown ≅ V_dc + L$\frac{V_{dc}}{R_2 * dt}$
- V_breakdown = 80V + 100μH$\frac{80V}{R_2 * 130ns}$
- When R2 = 1.1kΩ, V_breakdown = 136V
- When R2 = 65Ω, V_breakdown = 1.0kV
- At a voltage of V_dc = 40V => When R2 = 32Ω, V_breakdown = 1kV



Shane Warner

# Component Values

L = 100 uH

R = 15 to 400 Ω

di = 0.2 to 5.5 A

dt = 130 ns (max)

# Output Range

<u>At 80 V</u>

Vmax = 4230 V

Vmin = 154 V

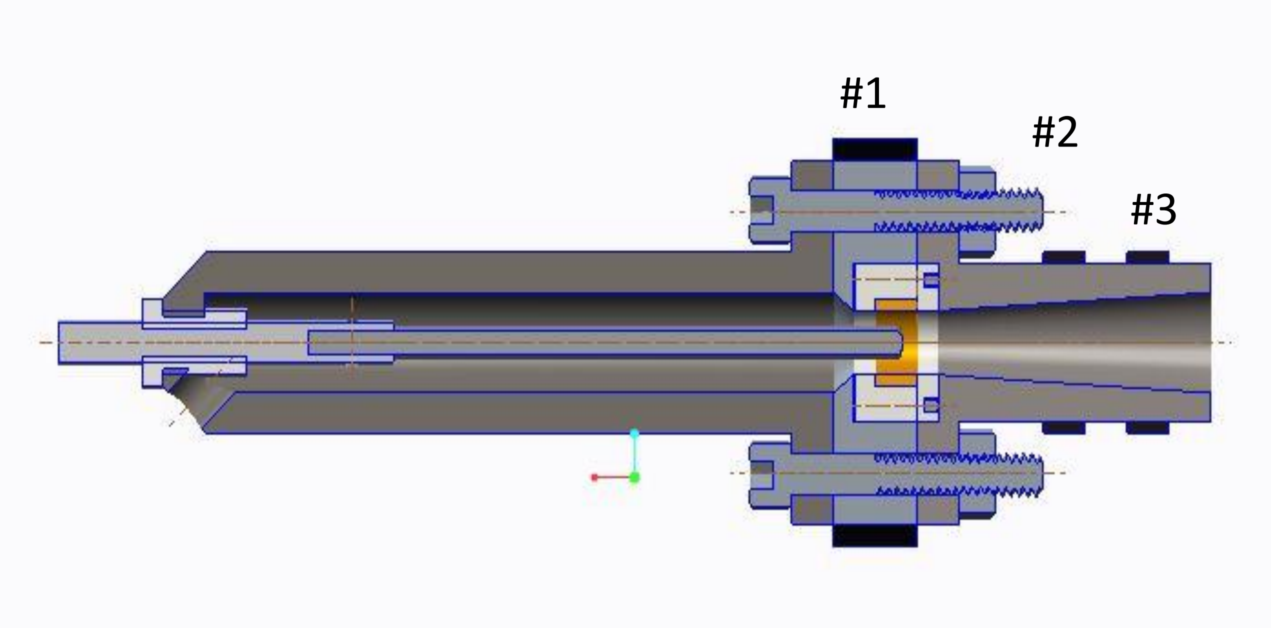
<u>At 40 V</u>

Vmax = 2115V

Vmin = 77 V

Shane Warner

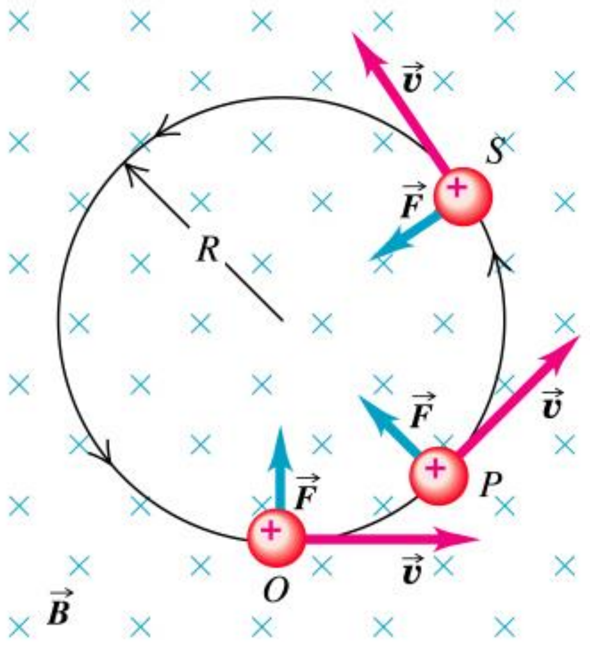
# Electrical Goal #2 – Magnet Design



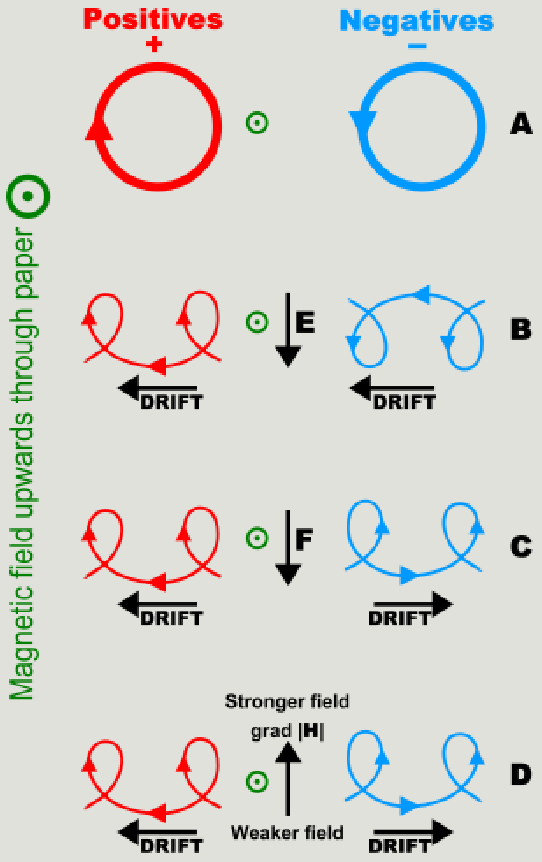
Magnet 1 at $r = 3.81\ mm$
Magnet 2 at $r = 5.82\ mm$
Magnet 3 at $r = 6.63\ mm$

Gerard Melanson

# Charges in Magnetic Field



(a)



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# Magnetic Field

The magnetic field is given by B = $\frac{mv}{qr}$, $v = \sqrt{\frac{20eV}{3m}}$, where m is mass, $v$ is velocity, q is charge, r is radius, $e$V is an electron-voltage, and B is the magnetic field. These equations simplify to give us

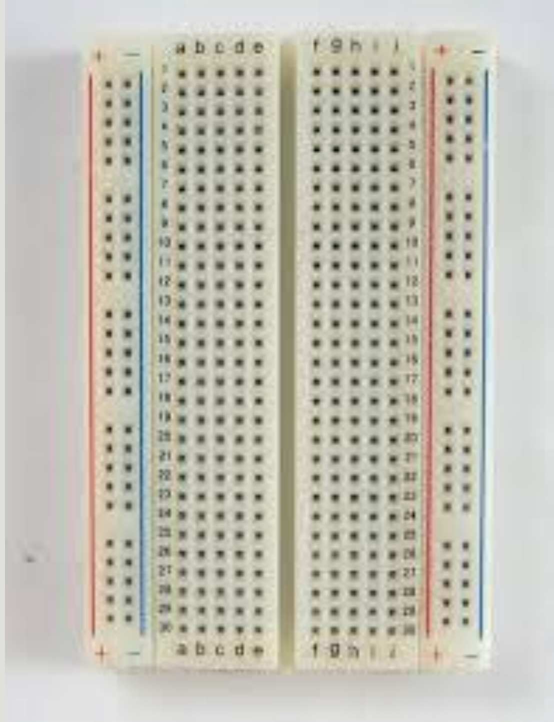
$$B = \frac{3}{r}\ mT$$

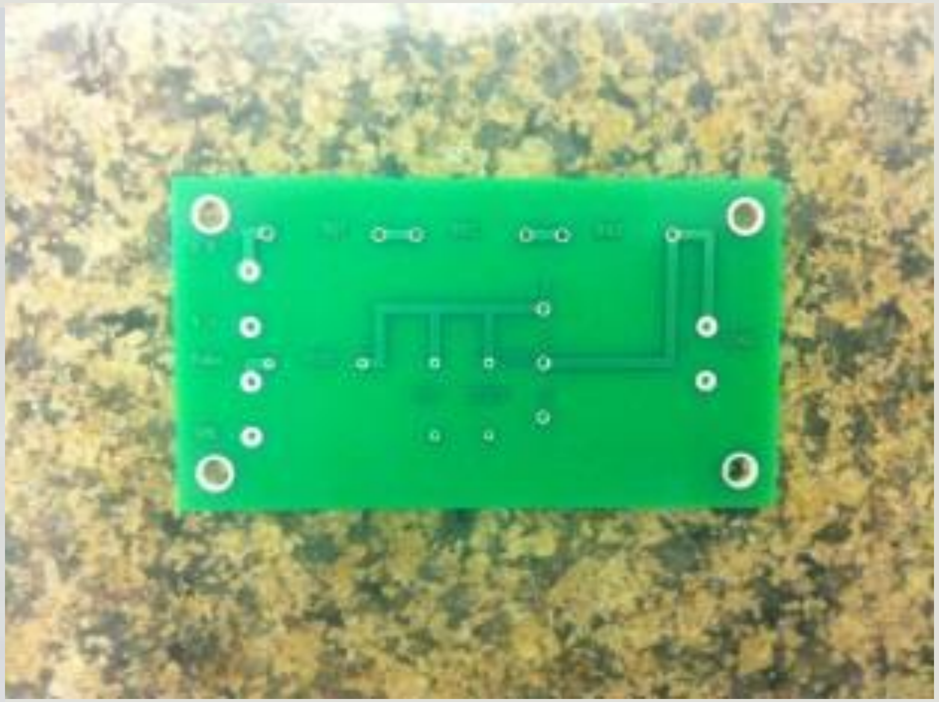
| Magnet at P1 | Magnet at P2 | Magnet at P3 |
|---|---|---|
| 0.787 T | 0.515 T | 0.452 T |

Gerard Melanson

# Circuit Testing and Finalization

- We plan to use a breadboard (left) for testing, and a printed circuit board (right) for the final design

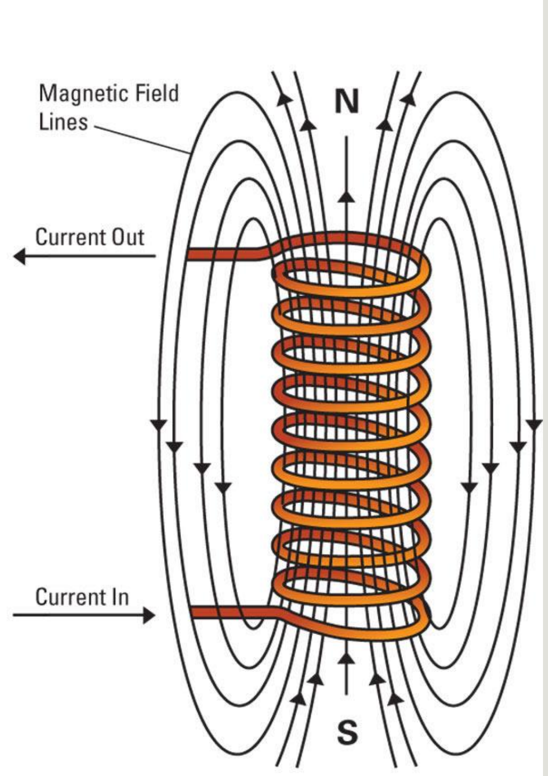




Gerard Melanson

# Magnet Testing and Finalization

- Electromagnets (Left) will be used in initial testing since it is easy to change their strength
- Final Design will feature permanent magnets (Right)



Gerard Melanson

# Potential Challenges/ Safety

**Safety**

- High voltages/currents
- High temperatures
- Ar gas – asphyxiant

**Challenges**

- Lots of assumptions
  - More modeling needed
- Multiple tests needed
- Accurately measure displacement of spring to calc. thrust

Chris Brolin

# Procurement

| Component | Description | Quantity | Cost | Manufacturer |
|---|---|---|---|---|
| Cathode | Tungsten Rod, 3/16" x 6" P#8788A153 | 2 | $ 33.24 | McMaster Carr |
| | Stainless Steel 303, 3/16" x 6' P#8984K93 | 1 | $ 7.77 | McMaster Carr |
| Anode | SS Steel Tube 1/2 OD, 0.37 ID 3' P# 9220K461 | 1 | $ 8.79 | McMaster Carr |
| Argon Gas Cylinder | 20 CF, Welding Cylinder | 1 | $ 77.00 | Welding Supplies from IOC |
| Argon Gas | 20 CF Fill | 1 | TBD | TBD |
| Hose from Arcjet to Baseplate | Air and Water Hose 1' P#5304K9 | 1 | $ 13.97 | McMaster Carr |
| Hose Fitting to Arcjet | ARO-Shape Hose Coupling P#343K74 | 1 | $ 12.90 | McMaster Carr |
| Fitting to Arcjet Fitting | Industiral Shape Hose Coupling P#6534K72 | 1 | $ 4.21 | McMaster Carr |
| Hose Fitting to Baseplate | Through-Wall Coupling P#50785K274 | 1 | $ 11.23 | McMaster Carr |
| Hose Fitting from Baseplate Fitting | Female Barbed Hose Fitting P# 5346K72 | 1 | $ 9.20 | McMaster Carr |
| Hose | 1" x 5' Hose P#5304K45 | 1 | $ 12.65 | McMaster Carr |
| Housing/Nozzle | Stainless Steel 303, 2' Diameter, Stock P#8984K573 | 1 | $ 79.64 | McMaster Carr |

Chris Brolin

# Procurement Cont.

| | | | | |
|---|---|---|---|---|
| Gasket | All Purpose Sheet Gasket 6"x6" P#9470K26 | 2 | $ 6.02 | McMaster Carr |
| Bolts (Anode) | P# 92185A078 | 1 | $ 3.23 | McMaster Carr |
| Mating Bolts | P# 92185A546 | 1 | $ 5.43 | McMaster Carr |
| Nuts for Mating Bolts | P# 91845A029 | 1 | $ 4.57 | McMaster Carr |
| Insulation | Macor Rod P#8489K81 | 1 | $ 72.95 | McMaster Carr |
| IGBT | Part# IRG7PH30K10DPBF | 1 | $ 8.73 | Digi-Key |
| Inductor | 100.0 µH, 6 A PART#1410460C | 1 | $ 2.62 | Digi-Key |
| Switch | PART# C3900BA | 2 | $ 8.92 | Digi-Key |
| Potentiometer | Part# AVT20020E200R0KE | 2 | $ 31.24 | Digi-Key |
| Magnet | Ceramic Ring Magnet, ID 2" | 3 | $ 11.25 | American Science & Surplus |
| Spring | Extension Spring #EBD-012-672-S | 2 | $ 7.50 | The D. R. Templeman Company |
| | | TOTAL | $ 433.06 | |

# Future Plans – Spring 2014

- Submit purchase order – this week
- Submit drawings to machine shop
- Test voltage spike of circuit
- Measure resistance of plasma
  - Determine whether to insert additional resistor or transconductance amplifier
- Design mounting and thrust measurement apparatus
- Create test plan

Chris Brolin

# Questions?