Preliminary Thrust Stand Measurements of an Ablative Gallium Electromagnetic (GEM) Thruster

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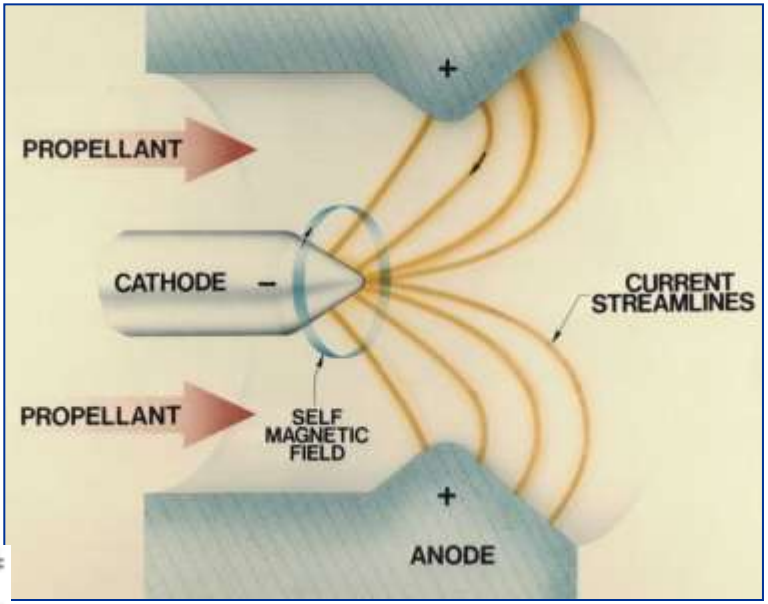
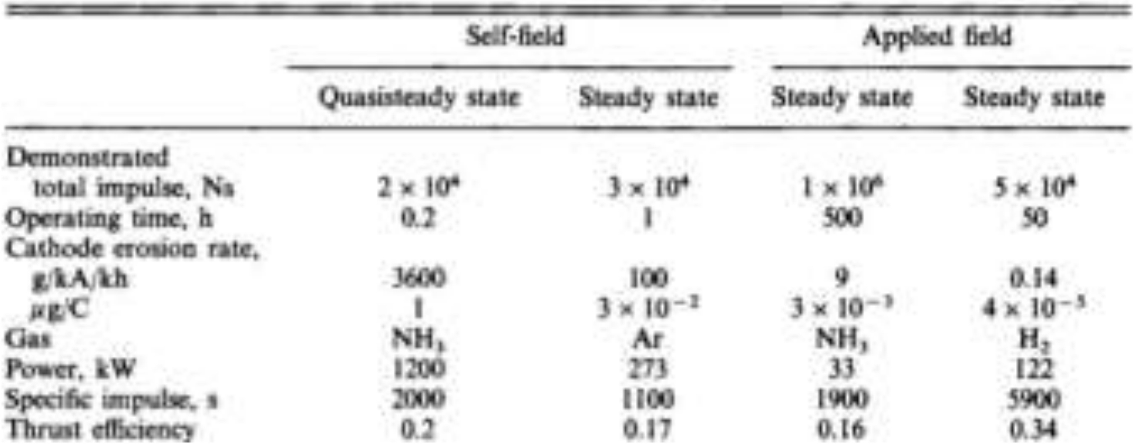
Magnetoplasmadynamic Thrusters (MPDTs)

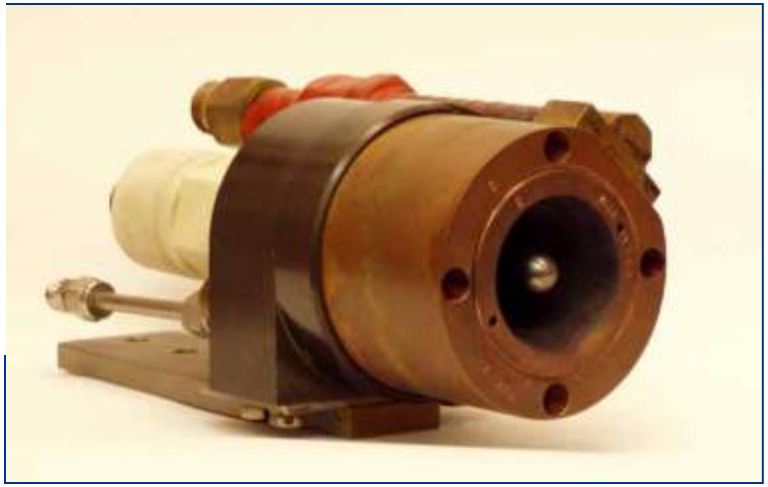
- Investigated since the 1960's, accelerates plasma via the Lorentz force
- Capable of high exhaust velocities (10-100 km/s), processing MW input power, high thrust densities
- Steady-state experiment demonstrated total impulse of 10^6 N-s (33 kW, 500 hours, $\eta = 16\%$)
- Plagued by cathode erosion, low efficiency (<40%)
- GEM thruster conceived to address these issues





	Self-field		Applied field	
	Quasisteady state	Steady state	Steady state	Steady state
Demonstrated total impulse, Ns	2×10^4	3×10^4	1×10^6	5×10^4
Operating time, h	0.2	1	500	50
Cathode erosion rate,				
g/kA/kh	3600	100	9	0.14
μg/C	1	3×10^{-2}	3×10^{-3}	4×10^{-5}
Gas	NH_3	Ar	NH_3	H_2
Power, kW	1200	273	33	122
Specific impulse, s	2000	1100	1900	5900
Thrust efficiency	0.2	0.17	0.16	0.34

Sovey, J. Prop. Power, V. 7, No 1, p. 71



GEM (Gallium Electromagnetic)Thruster Concept

- First EP device to utilize gallium as a propellant
  - sparse research on gallium plasmas

- Approach: Feed liquid Ga through porous electrode to mitigate life-limiting cathode erosion
  - High power (MW), single shot experiments currently using **solid Ga cathode** to characterize mass ablated per pulse over various operating conditions

- Proof-of-concept experiments performed under NASA Fellowship (U. Illinois, MSFC 2006-10)
  - Langmuir probes, B-dot probes, emission spectroscopy used to characterize plasma plume

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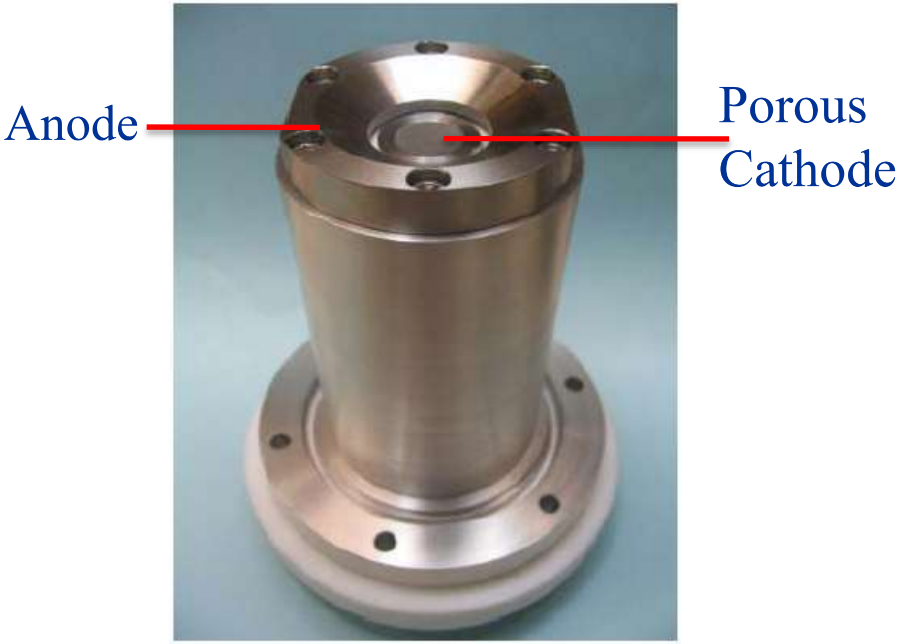
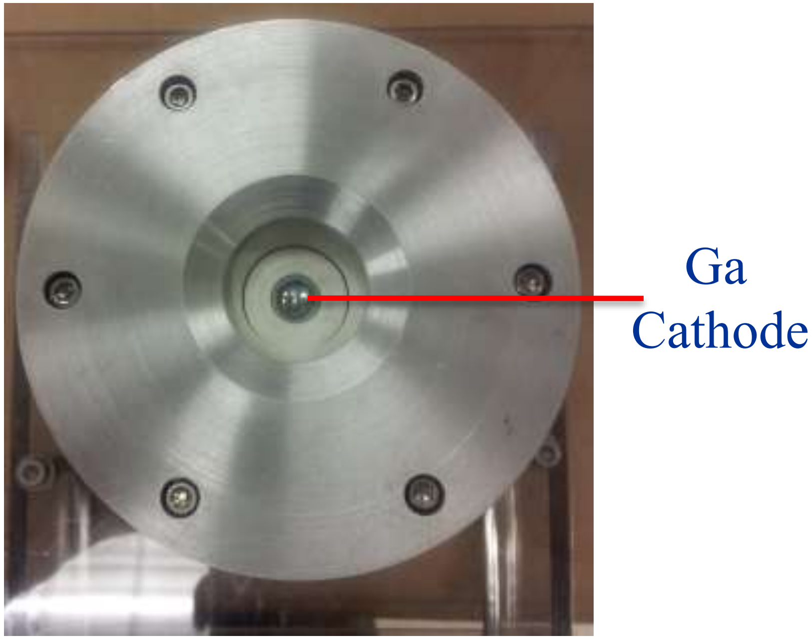


Present Configuration



Why Gallium?

Gallium Physical Properties

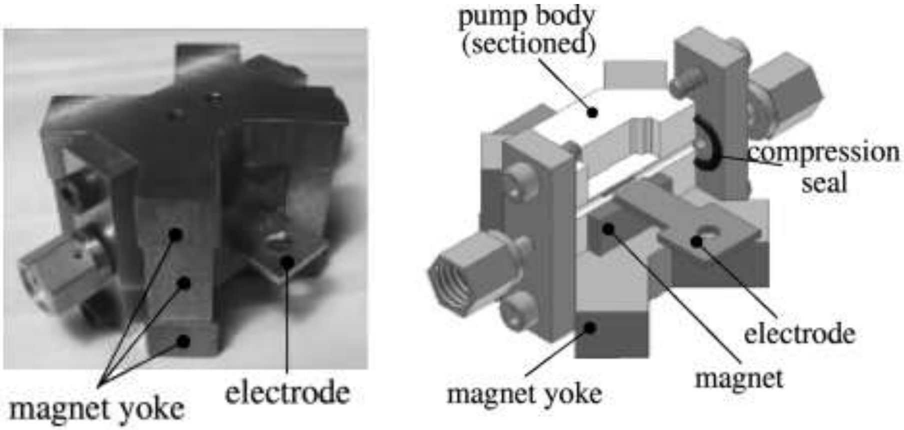
Atomic Mass	70
Melting Point	30 °C
Boiling Point	2204 °C
Density	5.9 g/cm^3
1st Ion. Pot.	6.0 eV
2nd Ion. Pot.	20.5 eV

Proposed Advantages

Non-toxic and non-reactive
- readily handled in laboratory
- pumped (condensed) on baffle

Storability
- can be stored as a solid or dense liquid
- large liquid temperature range (30-2204 °C)
- can be pumped electromagnetically*
- low vapor pressure (minimal boil off losses)

Low Ionization Potential
- easily ionized (6.0, 20.5, 30.7 eV)



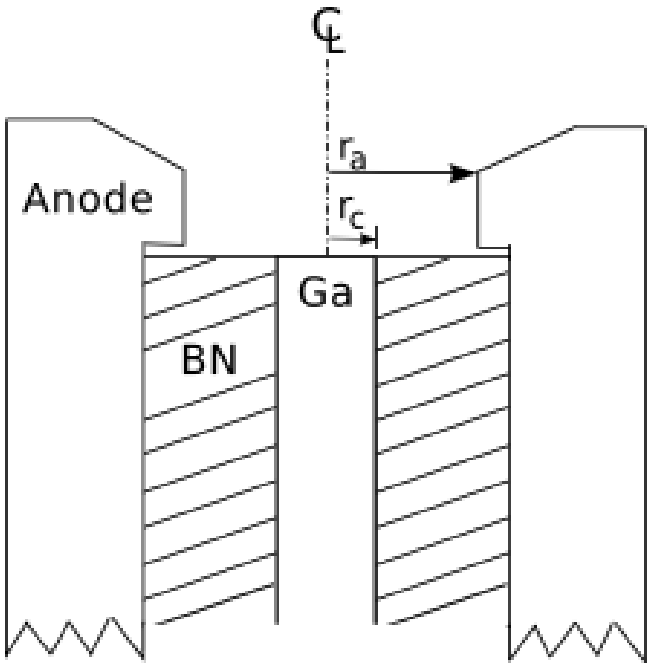
*Polzin, JPP, Vol. 24, p. 1141, 2008

Objectives & Diagnostics

1) Investigate the influence of geometry on ablative thruster performance (two geometries have been tested)
2) Investigate energy loss mechanisms
3) Develop model to accurately predict ablative thruster performance

- Discharge current
- Arc voltage
- Emission spectroscopy
- Impulse bit
- Mass bit

Electromagnetic (EM) Scaling Relations



Thrust:

$$T = bJ^2$$

$J =$ Discharge Current

$$b = \frac{\mu_o}{4\pi}\left(\ln\frac{r_a}{r_c} + \frac{1}{2}\right)$$

Exhaust velocity:

$$u_e = b\frac{J^2}{\dot{m}}$$

- charge carrier starvation limits maximum J^2/mdot

- Ablative thrusters -> mass flow is controlled by arc
- Prior experiments* found that: $\dot{m} \propto J^2 \Rightarrow u_e = \text{const}$
- Electrode radius ratio r_a/r_c needs to be increased for better performance
  - approach used to increase the efficiency in ablative graphite MPDT**

*Thomas AIAA-2010-6529, **Ducati NASA-CR-112144

Experimental Setup and Results

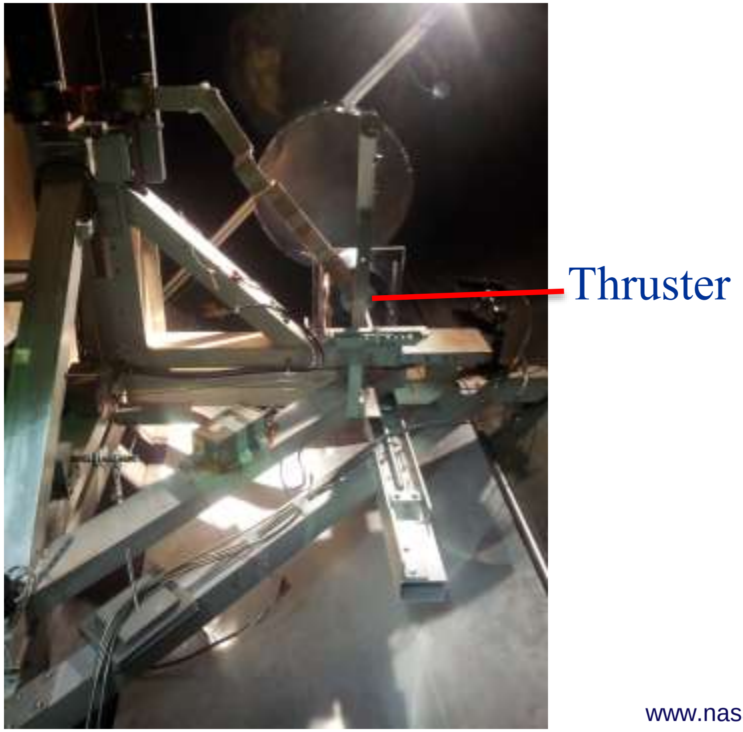
Electrode radius ratios of 2.8 & 3.5 have been tested

- Apparatus
- V-J characteristics
- Emission spectroscopy
- Impulse measurements
- Mass bit measurements
- Comparison with theory

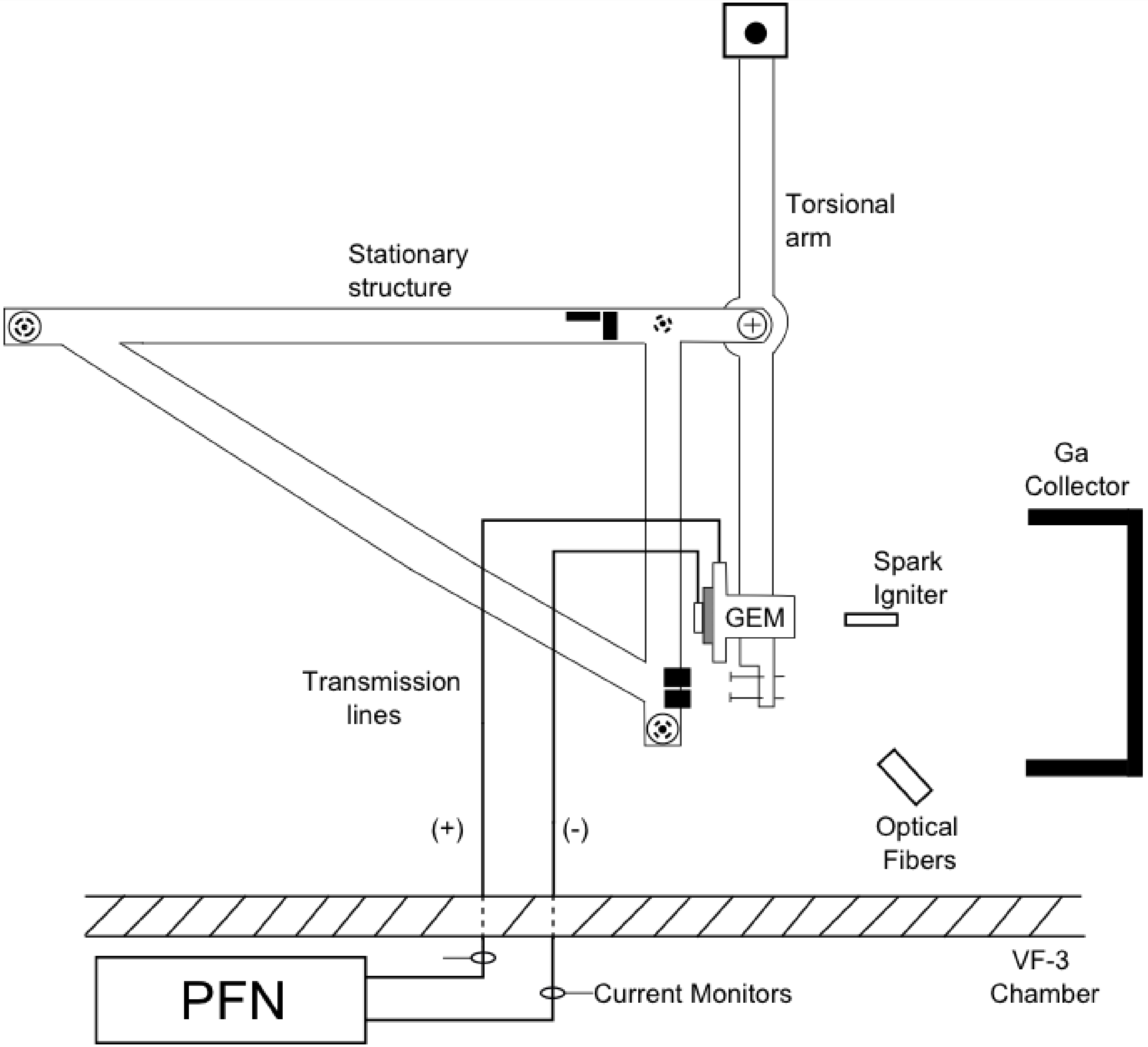
GEM Thruster & Facility

- Thruster OD: 8.9 cm
- Thruster Mass: 8 kg
- Multiple annular electrodes fabricated to test various electrode ratios r_a/r_c
- Minimum cathode diameter limited by macroparticle ejection

- 1.5 x 4.5 m vacuum facility
- Base Pressure: 3 x 10^{-6} torr

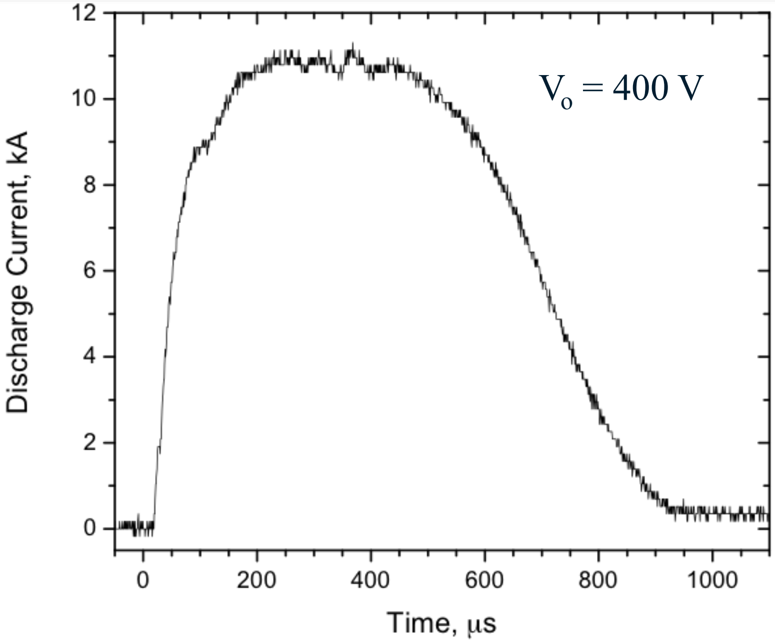


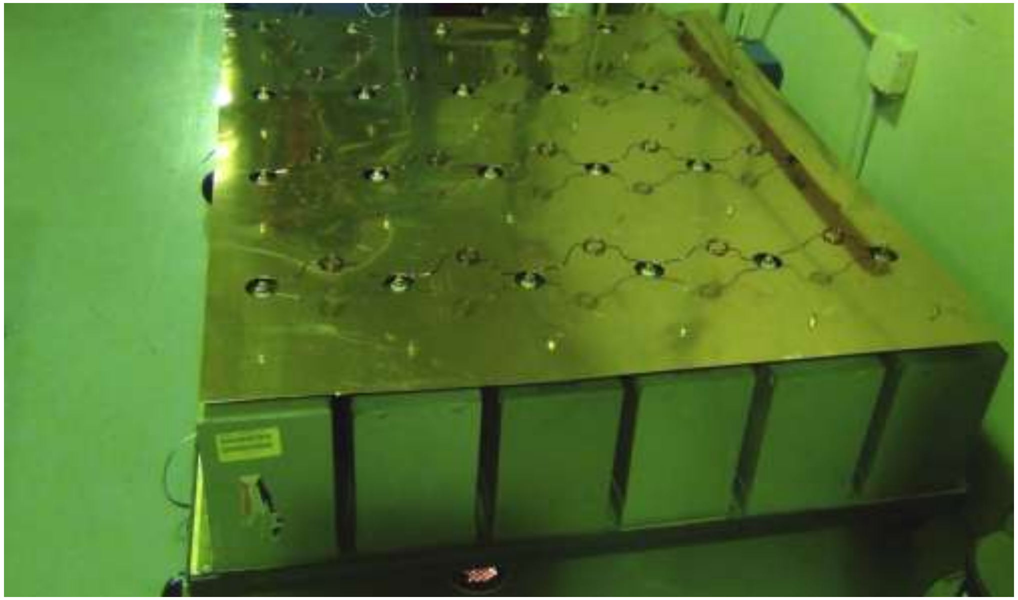
Experimental Apparatus



Pulse Forming Network (PFN)

# of Capacitors:	22
Dimensions (m):	1.3 x 1.4 x 0.4
Capacitance:	600 μF
PFN Impedance:	~12 mΩ
Max Charging Voltage:	800 V
Peak Current:	35 kA
Max Energy:	4.2 kJ





Voltage-Current Characteristics

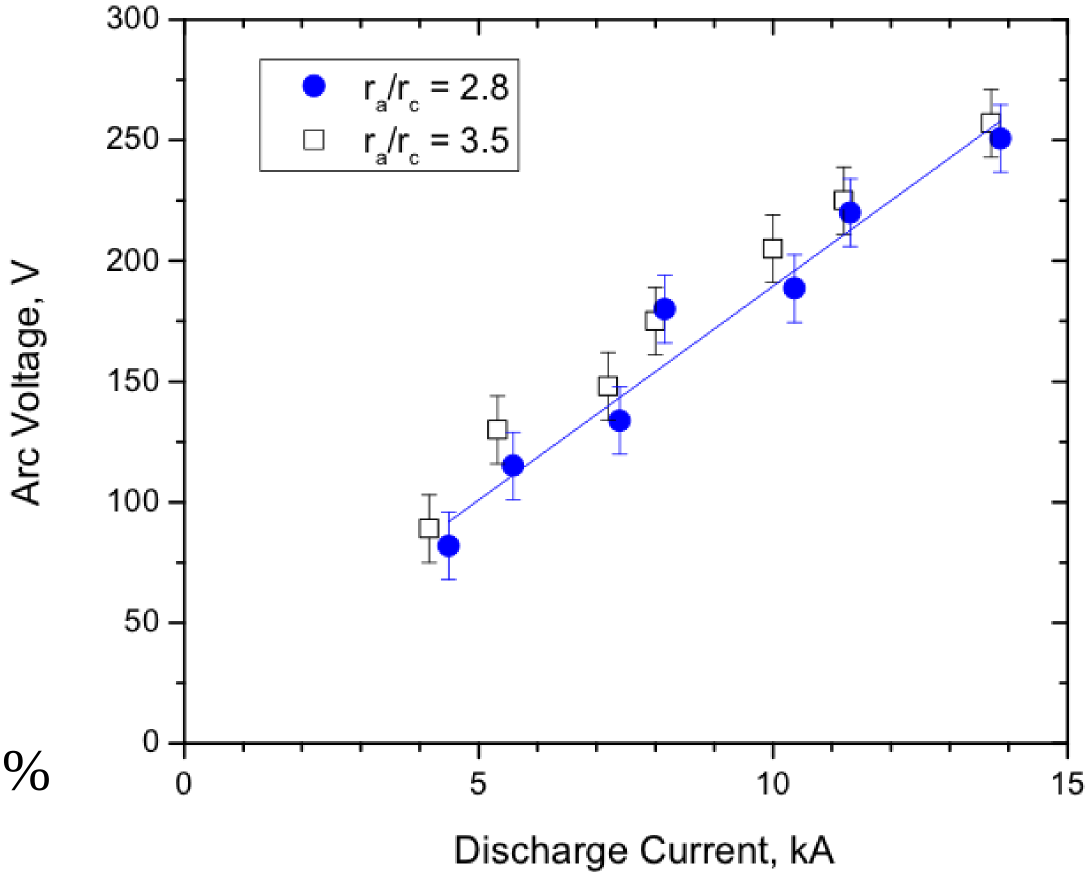
- Voltage linear with discharge current (consistent with J^2/mdot= const)

- Voltage 2-3x higher than anticipated
  - Prior Z_{arc} ~ 6-7 mΩ

Energy Transfer Efficiency

Est. $\eta_t = (J^2 Z_{line} * \tau_p)/E_o = 95\%$

Exp. $\eta_t = \left(\int J(t)V(t)\,\mathrm{dt}\right)/E_o = 85\%$



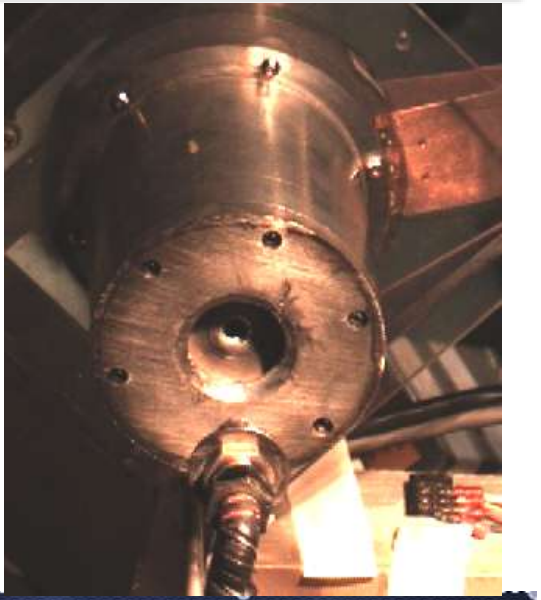
Emission Spectroscopy

- UV/VIS, IR spectrometers used to characterize plasma plume from $E_o = 0.2 - 1.8$ kJ

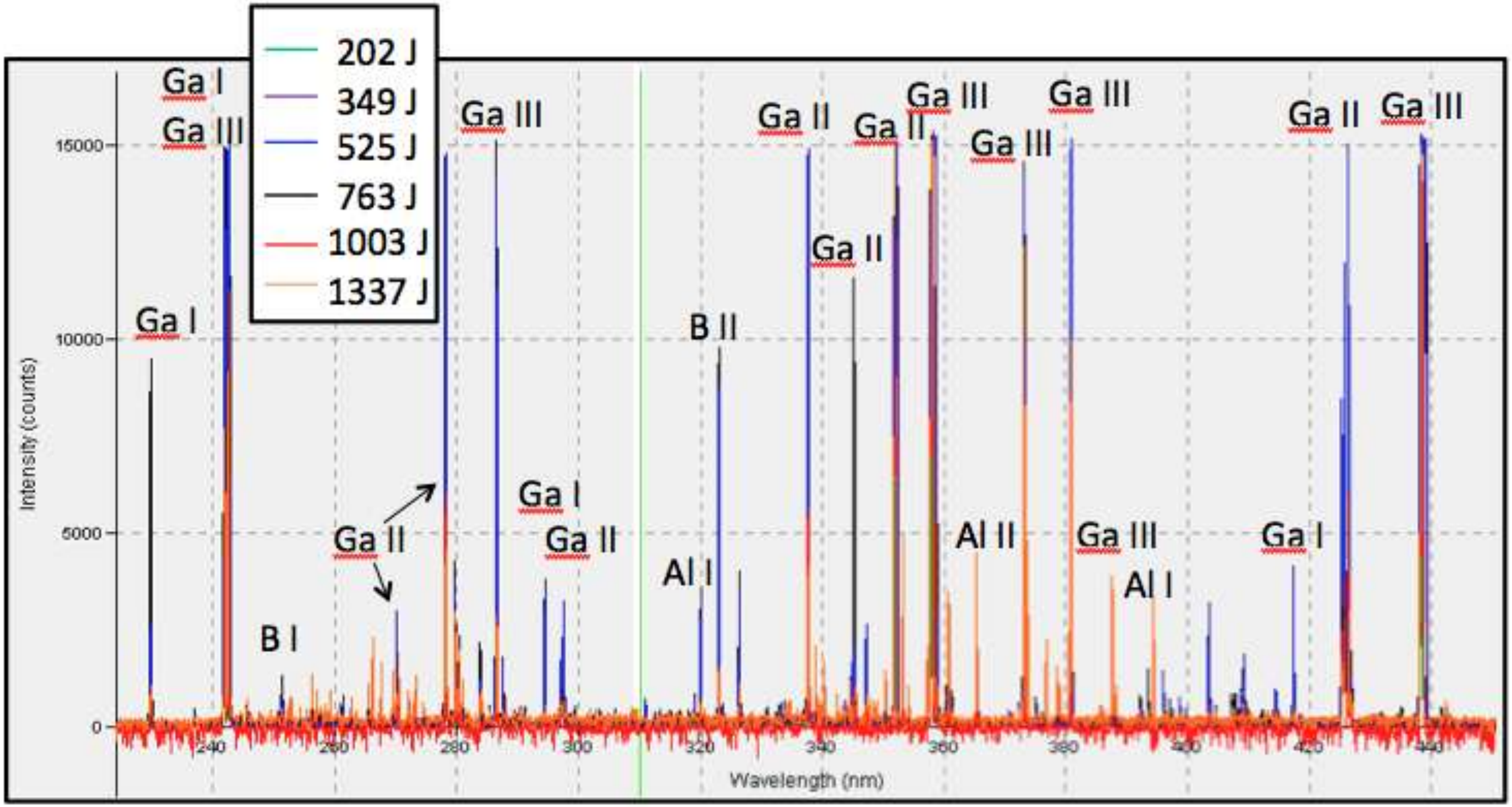
- Wavelength range: 220-850 nm

- Resolution: 0.07 nm

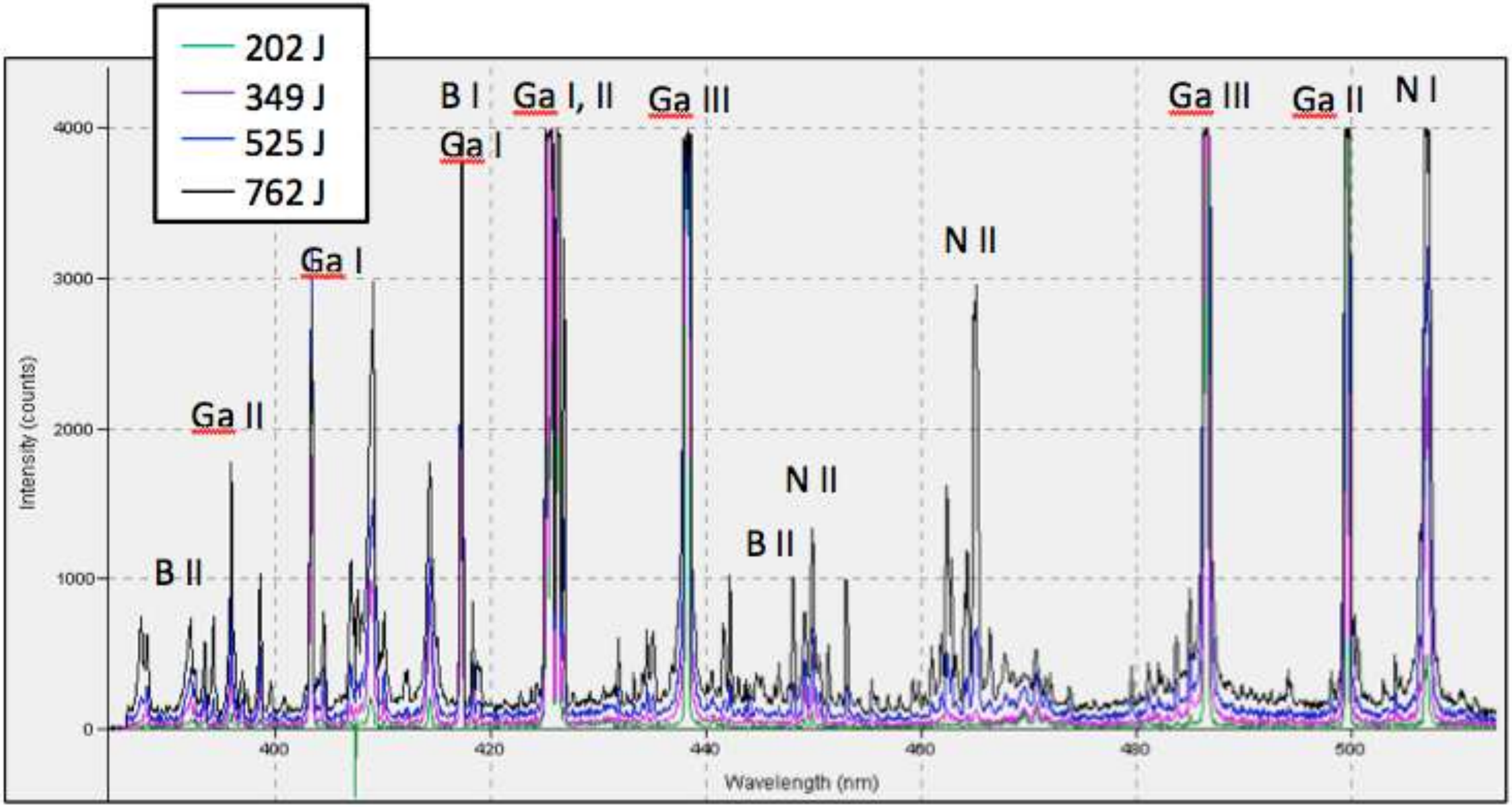
- Optical fibers located 30 cm from face of thruster
  - integrating over hot, warm, cold regions of the discharge



UV/VIS Spectrum (220-440 nm)

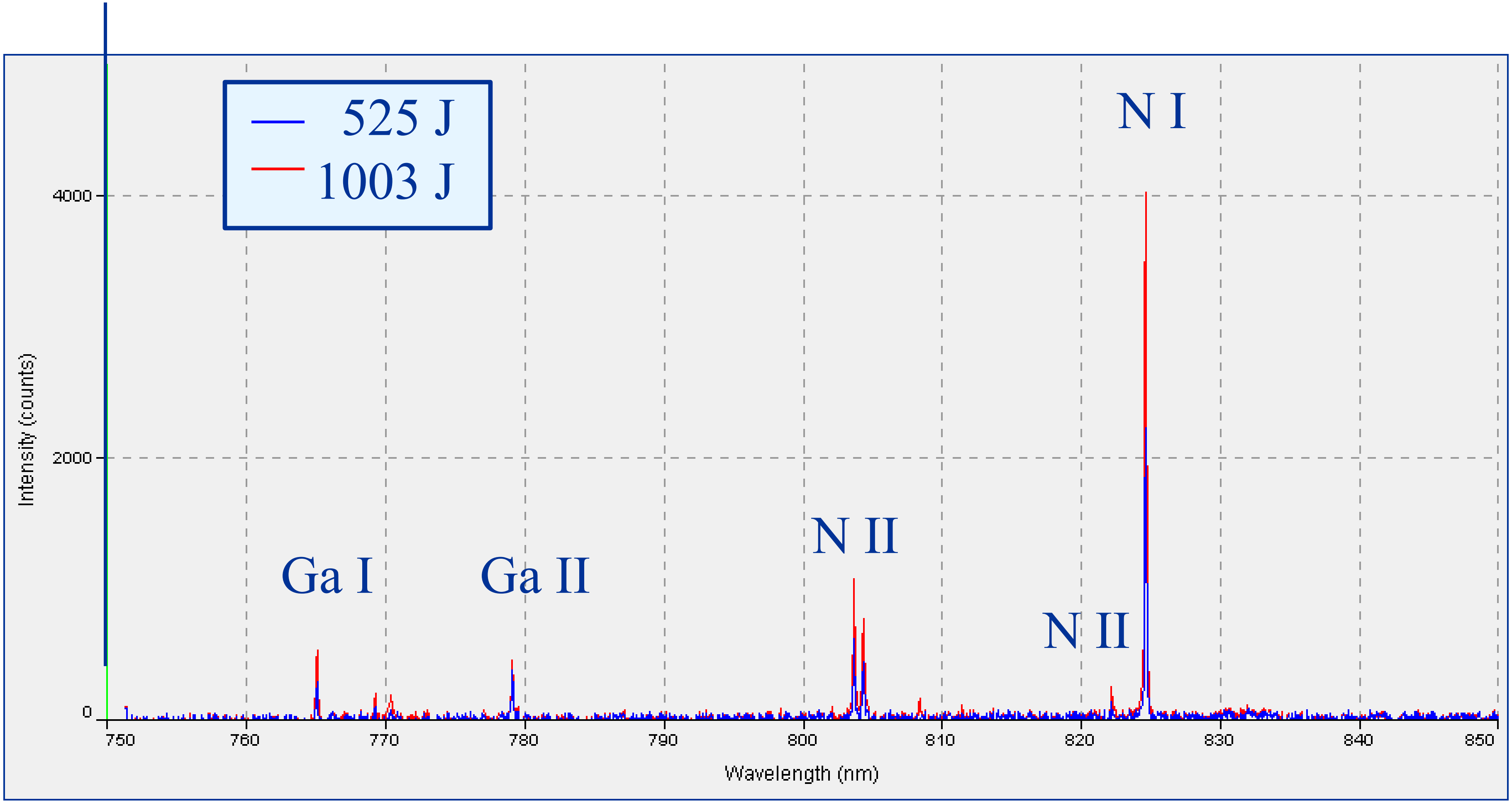


VIS Spectrum (400-520 nm)



IR Spectrum (750-850 nm)

Future Work: 1) Ionization calculations
2) UV spectroscopy (< 200 nm) for Ga IV



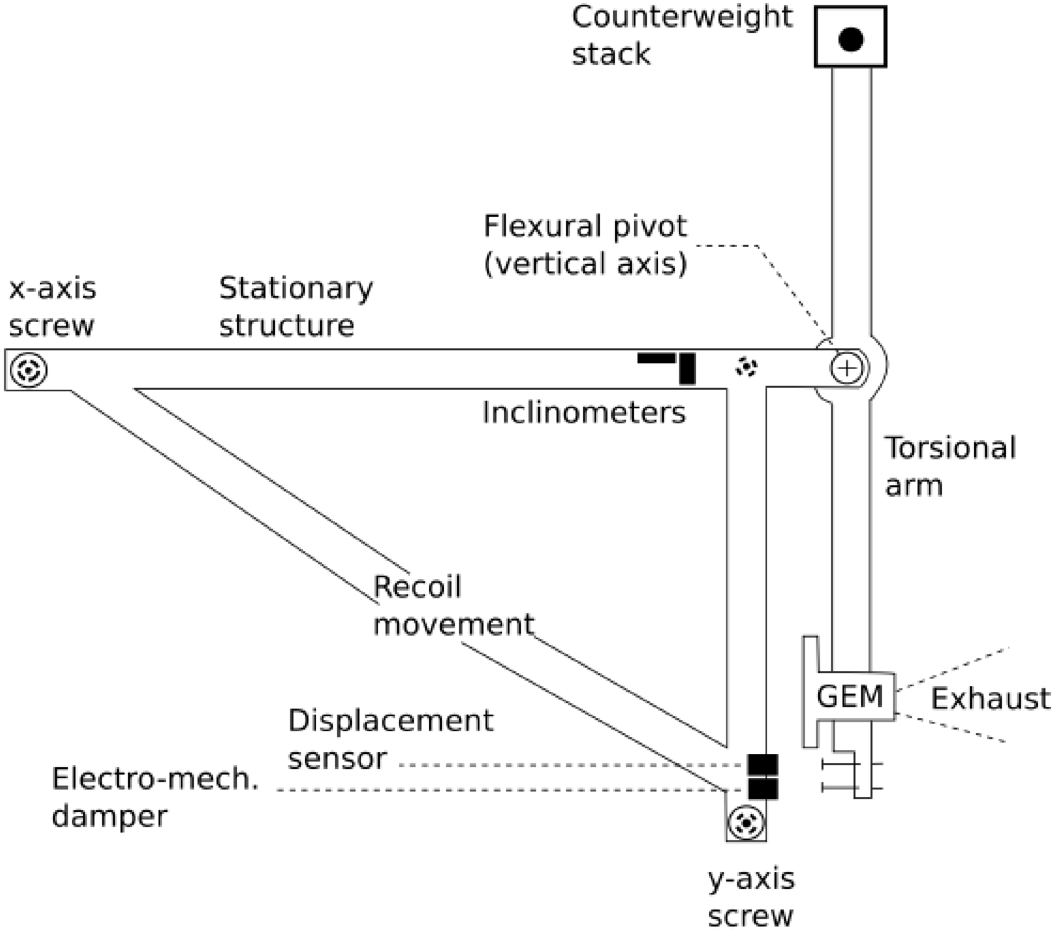
Impulse Measurements

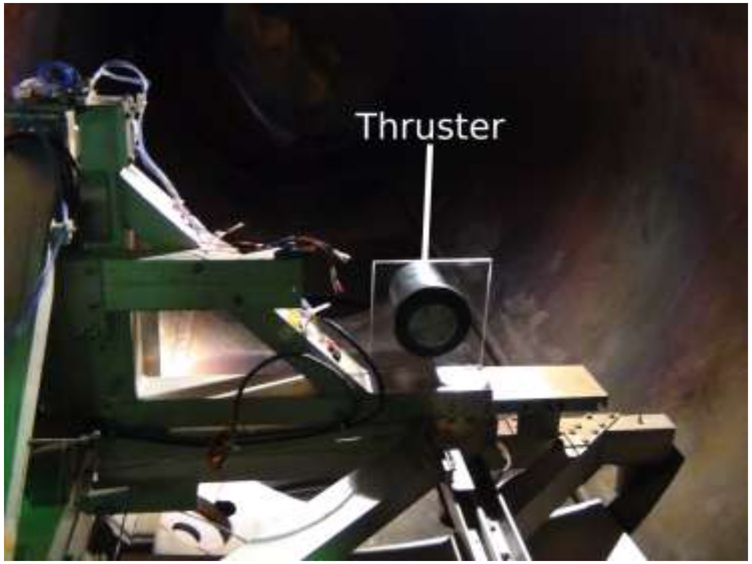
Has Successfully Tested:

1. LES-8/9 PPT
2. High Power PPTs

Impulse bit: $I_b = \frac{kx}{\omega}$

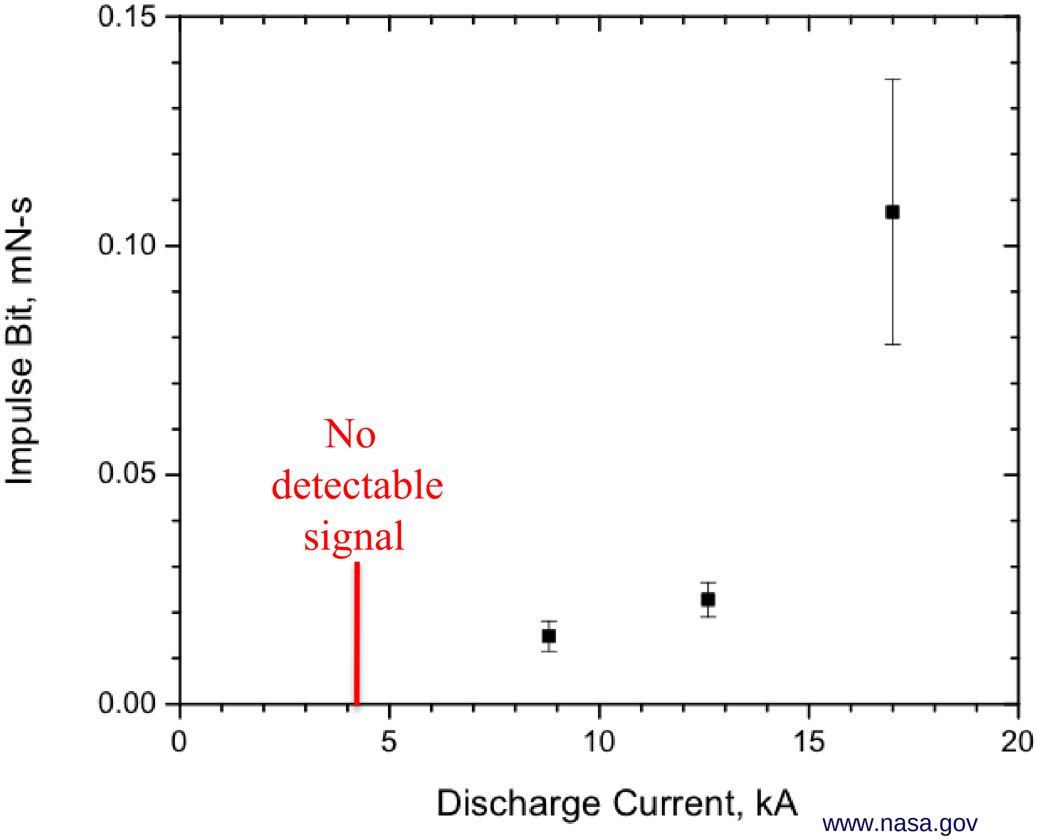
x = max deflection
k = spring constant
ω = natural freq.





Magnetic Tare Measurements

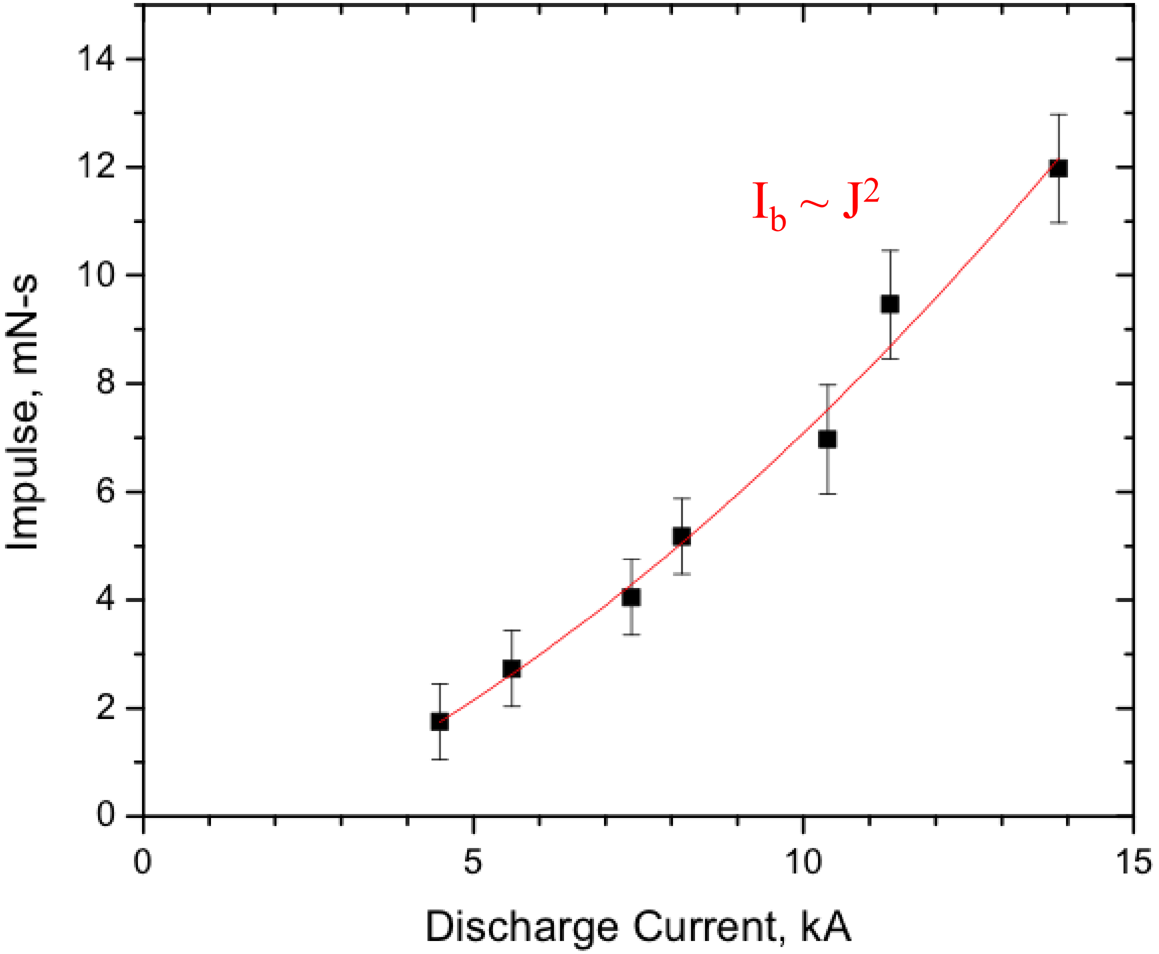
- Mechanical flexure designed to eliminate magnetic perturbations
- Shorting bar placed across anode and cathode
- Impulse (I_{noise}) measured from 5 – 17 kA
- $I_{EM} >> I_{noise}$



Impulse Measurements

EM Theory: $I_b = \int T\,\mathrm{d}t = b \int J^2\,\mathrm{d}t$

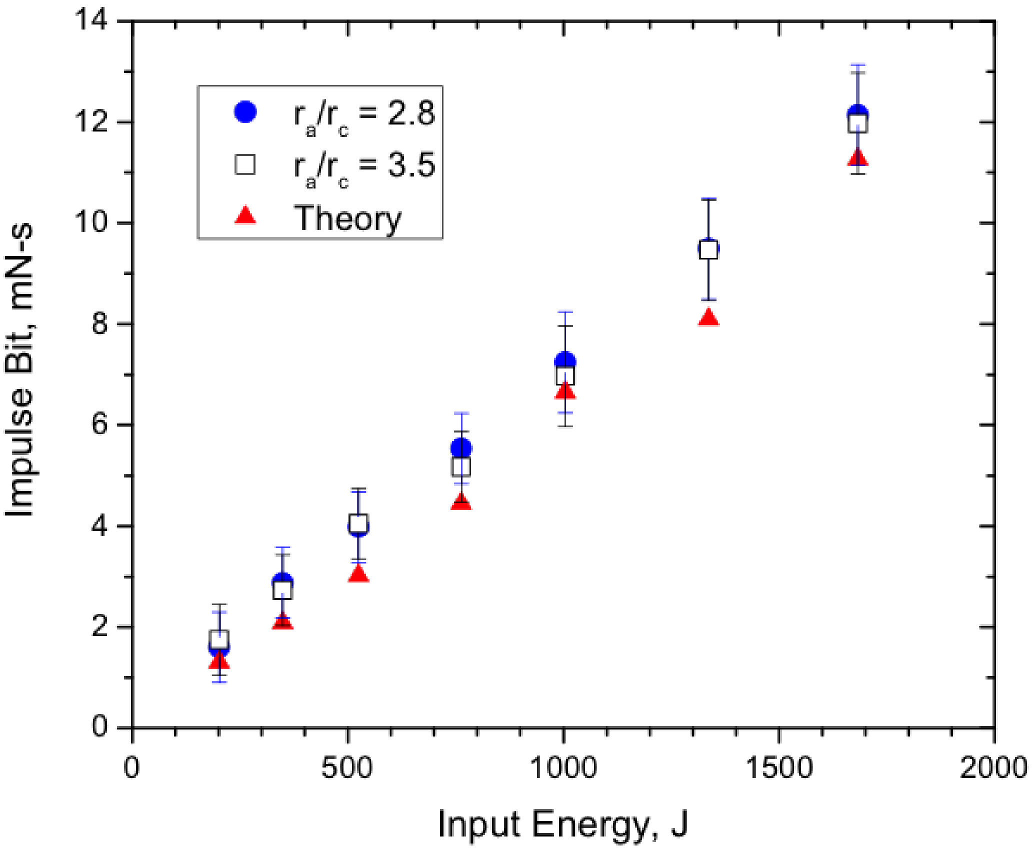
- Data ($r_a/r_c = 3.5$) averaged over ten shots



Impulse Measurements

- Impulse 10-20% higher than calculated value ($r_a/r_c = 3.5$ below)
- $r_a/r_c = 2.8 \to 3.5$ = increases *b* by 16%
- no change in experimental impulse

*Thrust can depend on: current distribution, gasdynamic forces, mdot



*Choueiri, JPP, Vol. 14, p 744, 1998

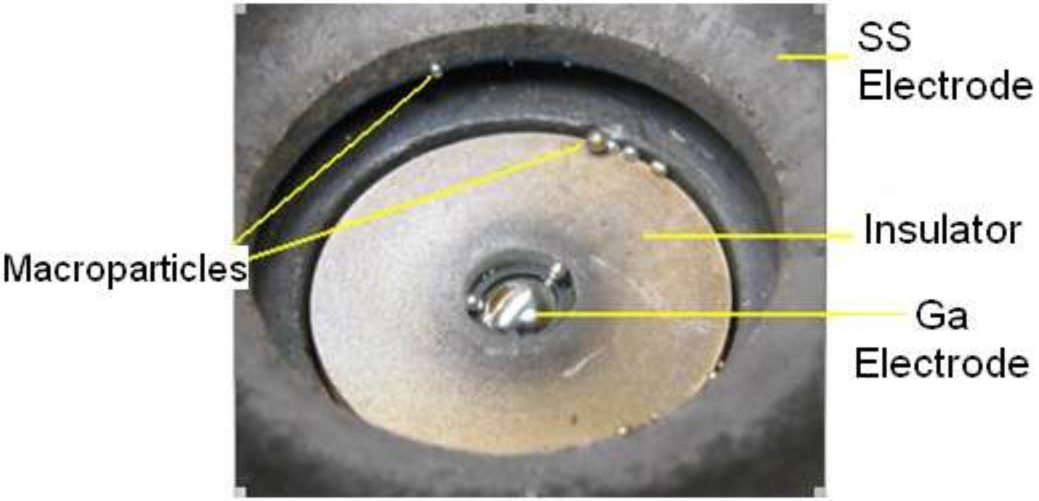
Mass Bit Measurements

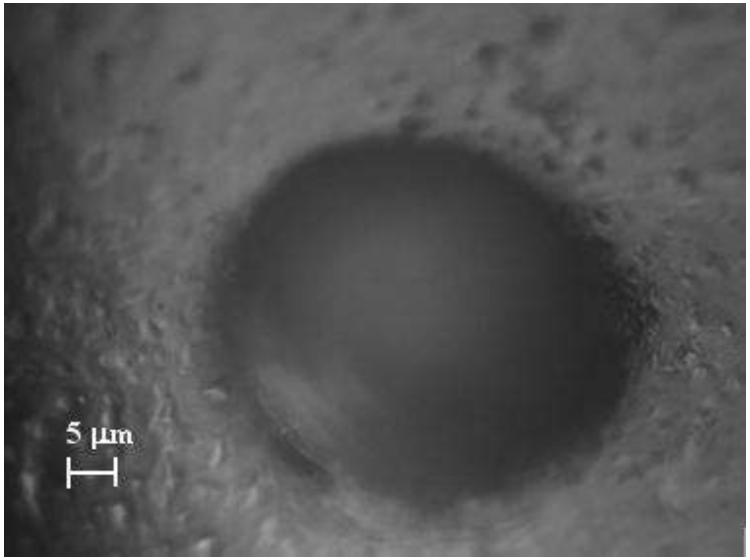
- Electronic balance used to weigh anode & cathode after (50-100) firings

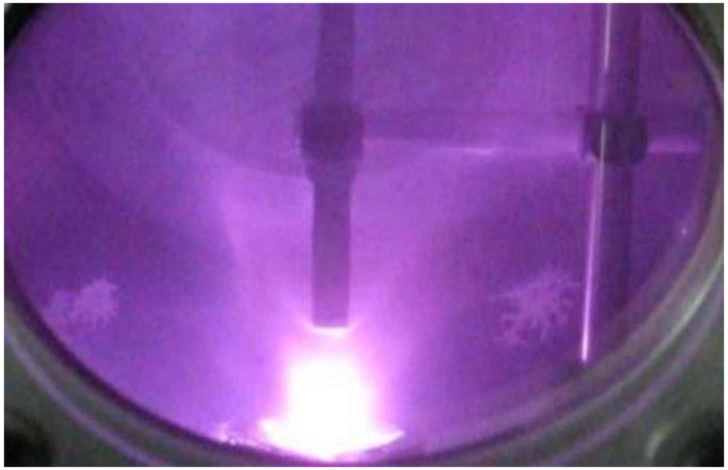
- Gallium accounts for >95% of ablated mass

- At discharge current levels above ~10 kA
  - noticeable erosion patterns on outer anode
  - insulating sleeve placed around anode to prevent arcing to chamber
  - gallium macroparticle ejection
    - poor propellant utilization

Macroparticle Ejection







First Order EM Performance Model

Input Parameters:
1. Discharge Current: *J*
2. *mdot* = f(J^2)
3. *b* = f(ln(r_a/r_c))
4. T_e (3.5 eV, prior experiments)
5. $Z = 2$

Thruster Efficiency:

$$\eta = \frac{T^2}{2\dot{m}P} = \frac{b^2 J^4}{2\dot{m}(JV_{arc})}$$

Specific Impulse:

$$I_{sp} = b\frac{J^2}{\dot{m}g}$$

Arc Voltage:

$$V_{arc} = \frac{(b^2 J^4)}{2\dot{m}J} + \frac{\dot{m}(Ze\Sigma\phi_i + 3/2kT_e)}{Jm_{ion}} + V_{sheath}$$

Electro-magnetic

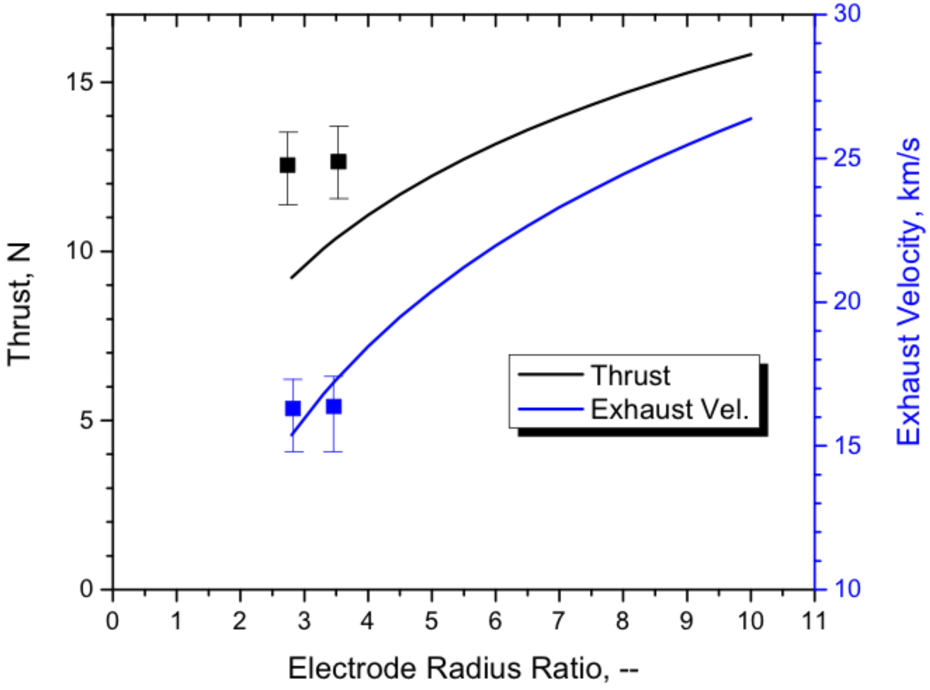
Frozen Flow

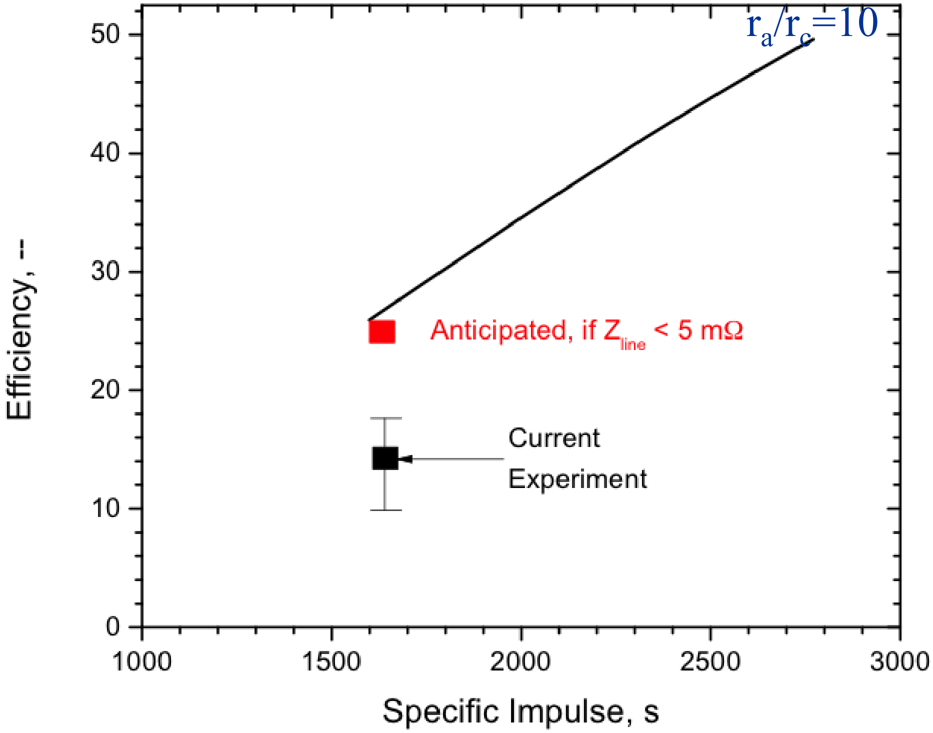
Sheath

Performance Predictions

Operating Condition: J = 8 kA, P_{in} = 1.1 MW

- Thrust ~ 10-25% higher than predicted
- Specific impulse in good agreement with model
- Higher than anticipated measured voltage leads to 10% drop in η





Future Work

- Investigate/ decrease transmission line losses
  - different HV feedthrough
  - shorten line length, increase area
  - SPICE modeling

- Improve propellant utilization
  - shorter pulse lengths may be needed to eliminate macroparticles
  - utilize different anode materials to minimize mass loss

- Use spectroscopy to investigate frozen flow losses
  - Compare excited states of Ga species
  - Detection of Ga IV requires < 200 nm spectroscopy

- Continue testing of larger electrode radius ratios
  - utilize b-dot probe to investigate current distribution

Summary

- GEM thruster conceived to address life-limiting cathode erosion present in MPDTs

- Successfully measured thruster impulse from J = 4-14 kA

  - impulse magnitude, J^2 trend consistent with EM theory

- Ga I-III present in discharge

  - BN and Al lines present at higher energy levels
  - further spectroscopic analysis will investigate frozen flow losses

- Model calculations predict an efficiency of 50% at an Isp of 2800 s

  - Thrust and exhaust velocity within 20% of first order EM model
  - further work (b dot probes, arc voltage) needed to investigate thruster operation as anode geometry is varied

Questions?

Effective Quasi-Steady Pulse Length

Effective Time: $\tau_{eff} \equiv \dfrac{\int J^2(t)\,\mathrm{d}t}{< J^2 >}$

Thrust: $T = I_b / \tau_{eff}$

Mass flow rate: $\dot{m} = m_b / \tau_{eff}$