Adaptive Electric Propulsion for ISRU Missions

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- Why ISRU
- FRC thrusters
  - Best suited EP for ISRU
  - How they work
- Experimental Results
  - Injectors
  - RMF PPU thermal testing
  - ELF-160x Performance
- Summary

Why In Situ Resource Utilization

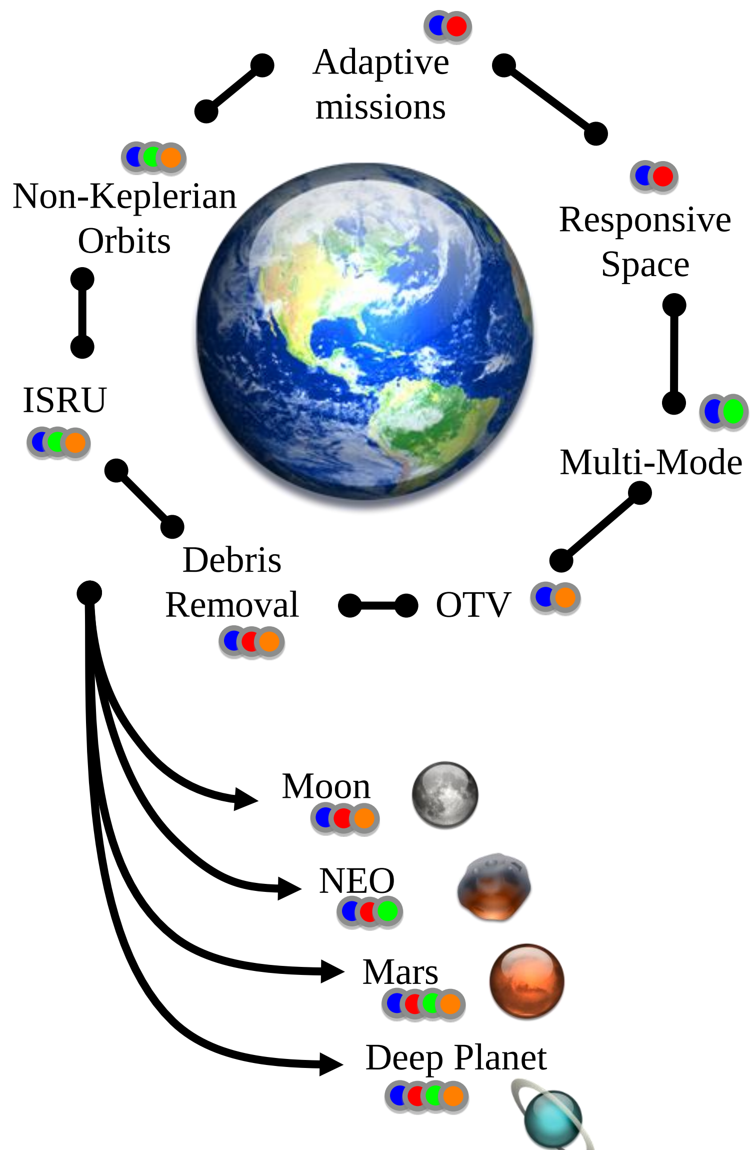
NASA has recommitted its desire for both science and exploration missions to Mars and Near Earth Objects (NEO)

- The "5:1 concept", for Mars has shown that every 1 kg of mass saved on Mars through ISRU is the equivalent of 5 kg in LEO and 85 kg on Earth [1]
- ISRU is particularly important to Martian and asteroid cargo missions, where cost and payload fraction are driving factors, rather than trip time.

MSR Propulsion Choice	Bipropellant	Hall Thruster	ELF with ISRU
Delta V Required: LEO-MOI-LEO	6.5 km/s	8 km/s	8 km/s
Isp	450 s (out) 250 s (return)	3000 s (Xe)	3000 s Xe/Ar
Propellant Mass to Mars [kg]	7,973	2,402	2,402
Propellant Mass from Mars [kg]	2,273	1,851	2,402
Solar Panel and Thruster Mass [kg]	0	1,060	650
Return payload [kg]	204	5,137	7,402
Payload fraction	<2%	49%	71%

Simplified model of a Mars Sample Return Mission. Model uses a Falcon 9 launch vehicle (10,450 kg to LEO), assumes optimal mars orbit, spiral EP trajectories, structure and ACS are part of payload, and 5 kg/kW solar panel mass. Hall thruster is 5 kg/kW and ELF is 1.5 kg/kW with 100 kW of onboard solar power. Assumed no mass penalty in collecting return Argon propellant. All missions would benefit from aerobraking or separate upper stage launchers. Return payload does not include solar panel or EP system mass. Payload is assumed to travel and return.

Why FRC Propulsion



Advantage 1

Scalable: 0.1-1000's of kWs

- One technology, multiple mission applications
- Simplified ground testing
- Accelerated development

Advantage 2

Operating Range: 1000-8000 s of Isp

- Dynamic operation
- Fast response
- Longer mission lifetimes

Advantage 3

Flexible: H_2-H_2O-CO_2-Ar-Xe

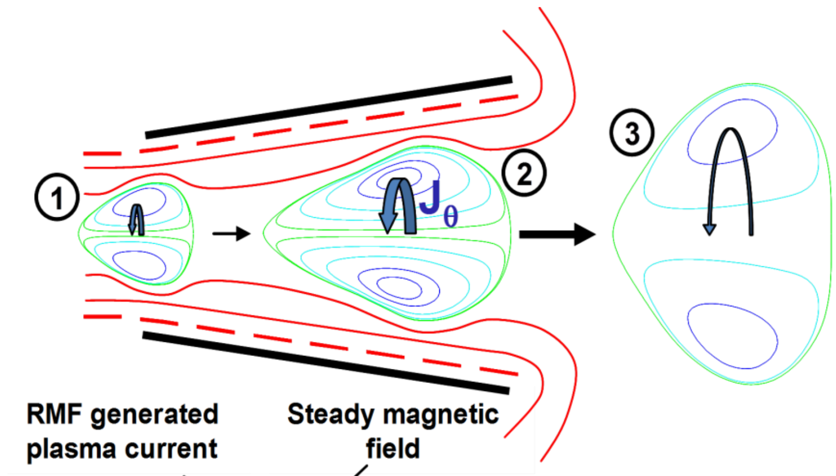
- Mission Versatility
- Increased payload mass fraction
- Extremely large Delta-V capability

Advantage 4

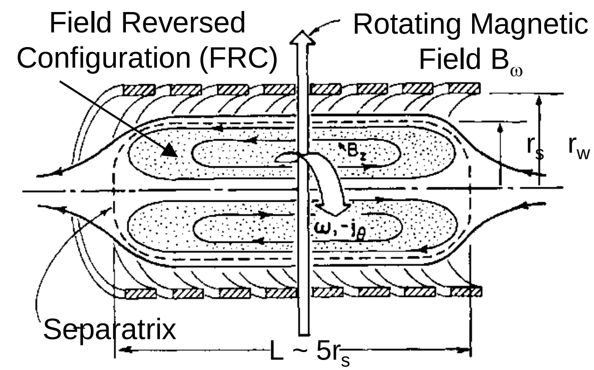
Thrust/Power Density: <1 kg kW

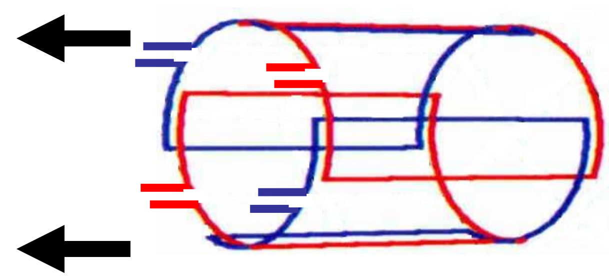
- Low mass at high powers
- Higher payload fraction
- More maneuverable

RF Antenna Configuration for RMF FRC ($\omega_{ce} >> \nu_{ei}$)

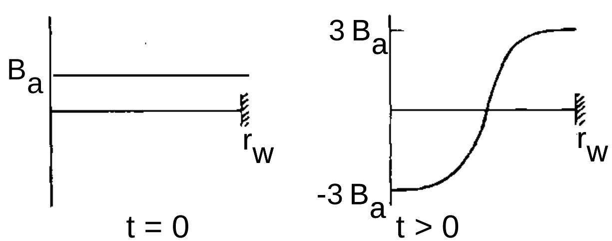


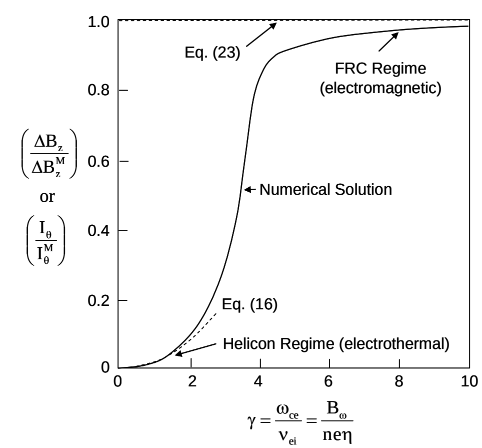
$$F_z = J_\theta x B_r$$





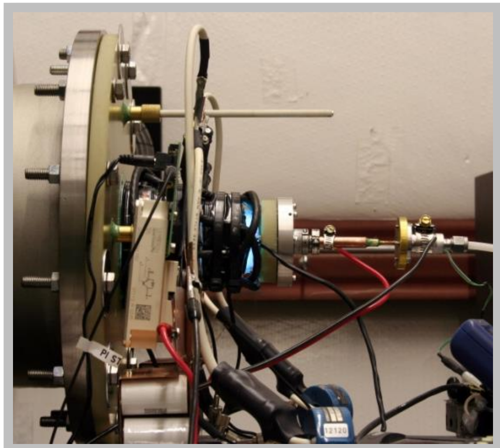
Synchronous electron motion
$\Rightarrow j_\theta(r) = e\, n_e\, \omega\, r$

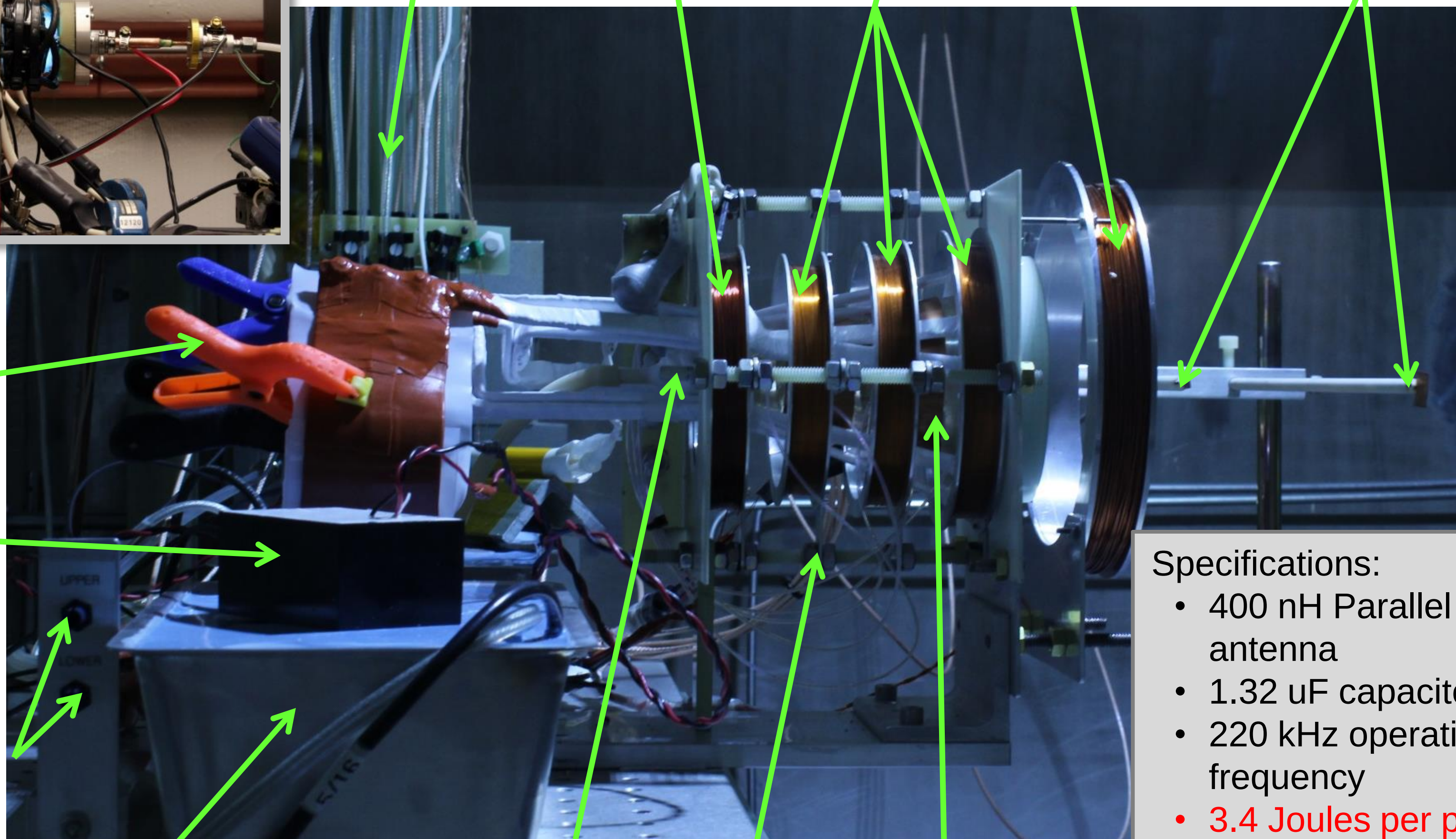




Initial axial magnetic field B_a is reversed by synchronous J_θ current driven by RMF

5 kW Scale Thruster - Mk 5





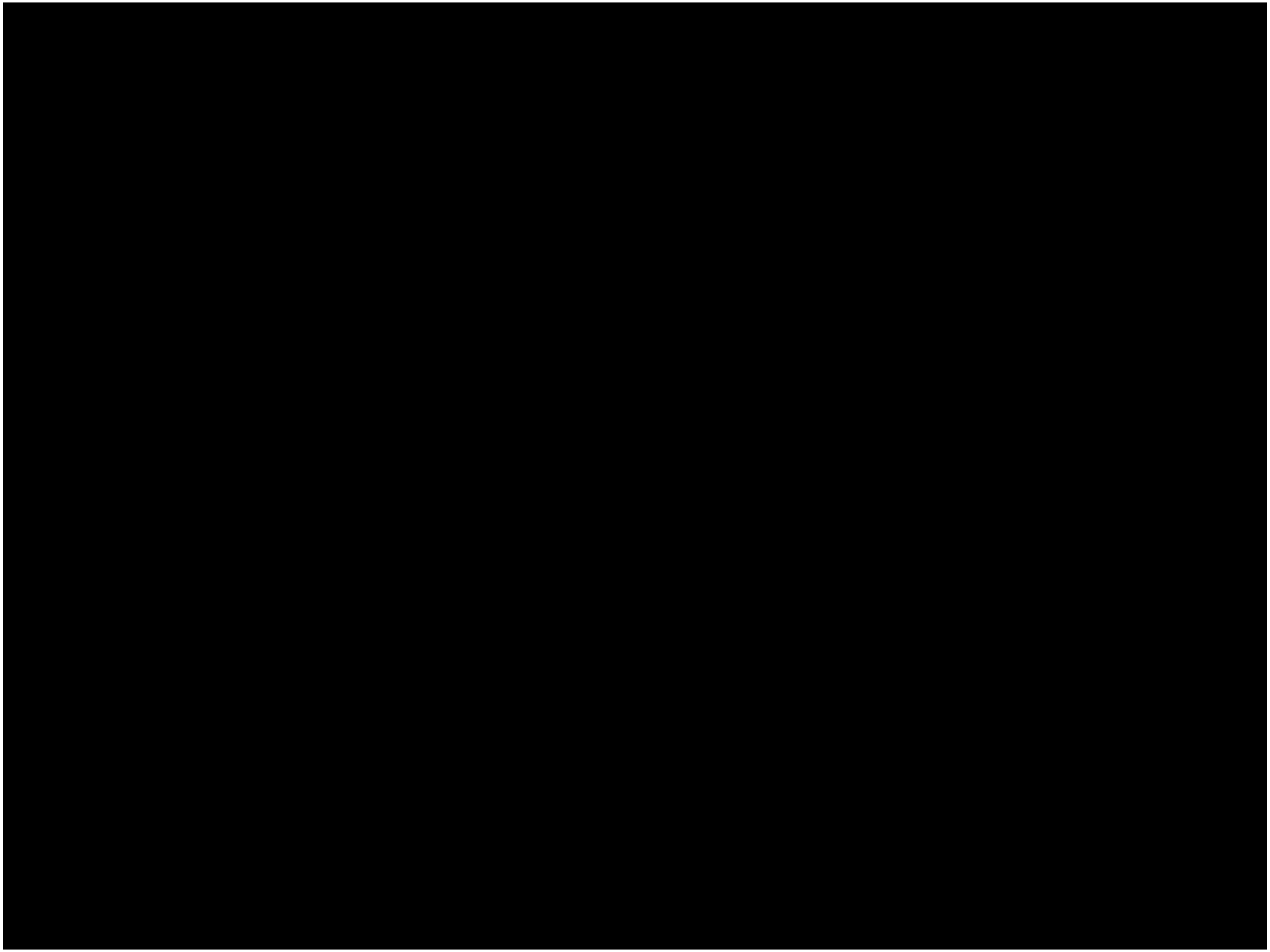
Specifications:

- 400 nH Parallel RMF antenna
- 1.32 uF capacitors
- 220 kHz operational frequency
- 3.4 Joules per pulse

Changes from Mk4

- Higher Energy
- Lower frequency
- Nozzle Coil

Thruster Operation



Steady Operating RF Pre-Ionization

RF inductive discharge

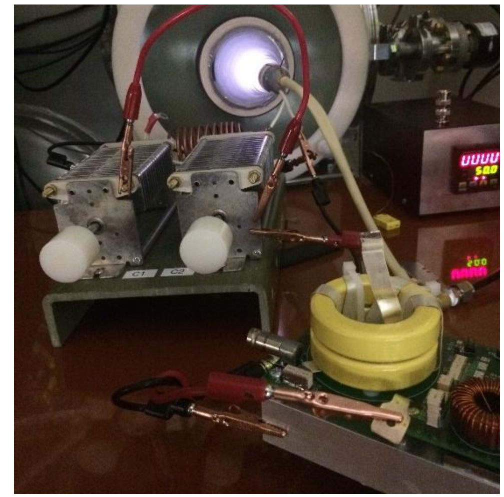
Laboratory Test RF power supply

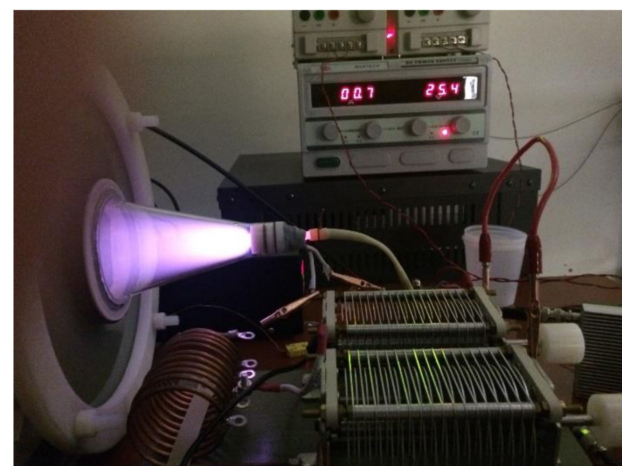
- 13.56 MHz
- 3000 W
- Auto and manual tuning network

AFRL PI

12 awg copper wire
Thin walled alumina tube
Macor faceplate
Outer alumina casing
Ceramic potting
½” 6-Turn = 200 nH
¼” 6-Turn = 80 nH

Proto-flight brass-board

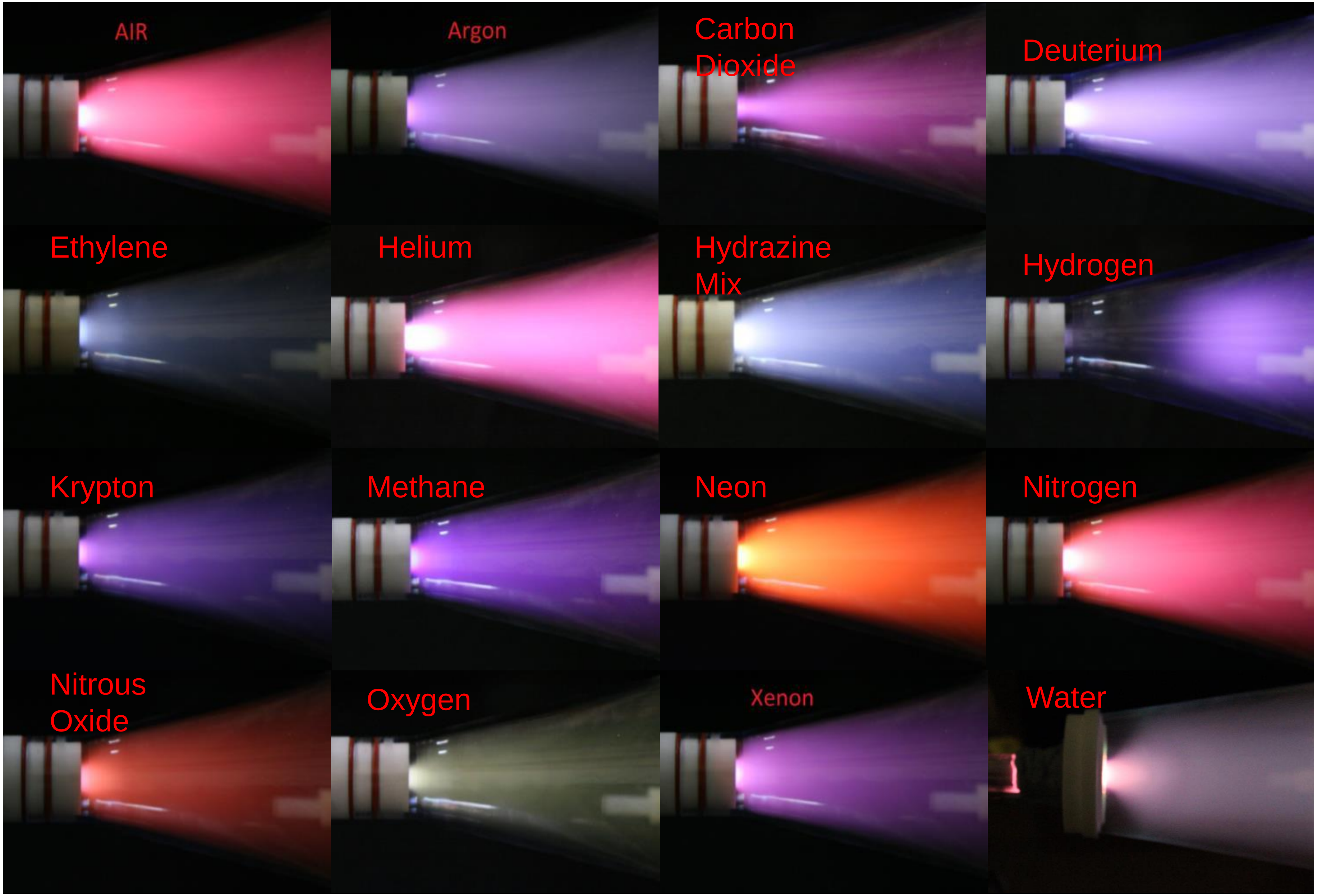




Gas Variety

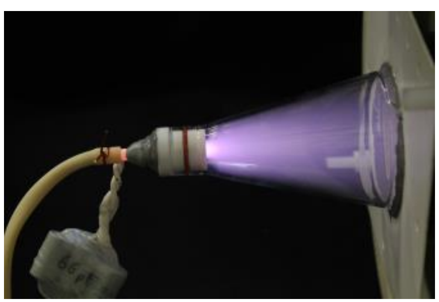
- The gases were all ran at or near 3±0.1 mg/s
- Lighting power listed was the power needed to keep the plasma stable and not flickering

Gas	Molar Weight (amu)	Lighting Power (w)
Air	28.97	6
Argon	39.95	2
Carbon Dioxide	44.01	45
Deuterium	4.02	7
Ethylene	28.05	60
Helium	4.00	6
Hydrazine Mix (33%N_2 67%H_2)	32.04	7
Hydrogen	2.02	10
Krypton	83.78	7
Methane	16.04	50
Neon	20.18	24
Nitrogen	28.00	55
Nitrous Oxide	46.00	30
Oxygen	32.00	14
Xenon	131.29	6


AIR
Argon
Carbon Dioxide
Deuterium
Ethylene
Helium
Hydrazine Mix
Hydrogen
Krypton
Methane
Neon
Nitrogen
Nitrous Oxide
Oxygen
Xenon
Water

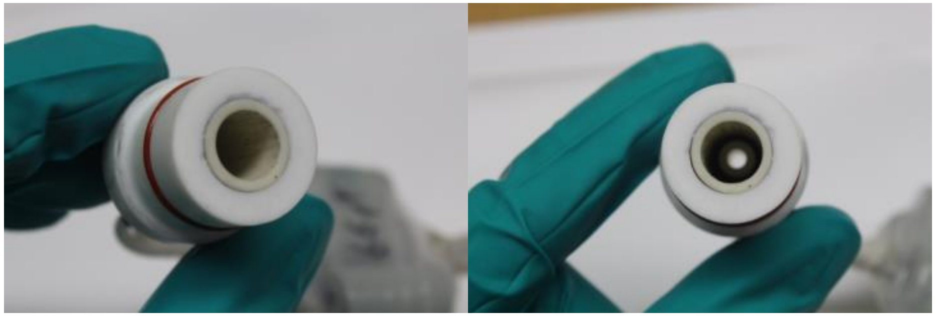
Long Duration Test

- PI was run continuously for 6hr externally.
- The PI was observed to rise to its equilibrium temp in about 10min
- Plasma was stable for the duration of the test

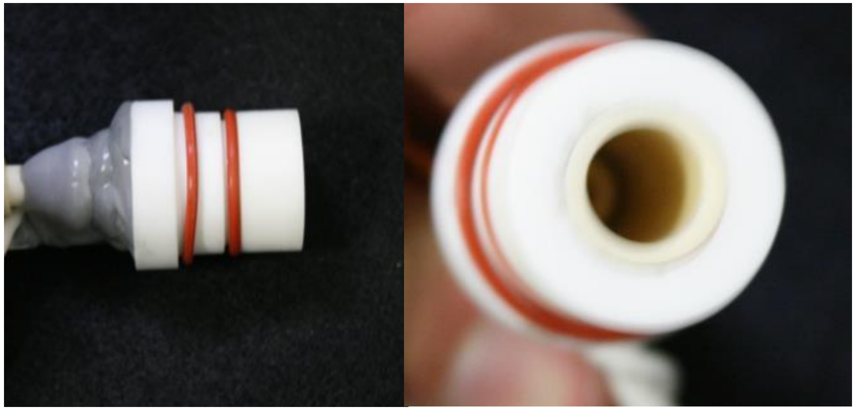


Test Condition	Value
Gas	Argon
Flow Rate (mg/s)	2.9
RF Power (W)	20
Chamber pressure (torr)	2.0×10^{-3}
Equilibrium Temp (^{o}C)	~94
Duration/Photo Rate	6hr/1photo per 5min

Before

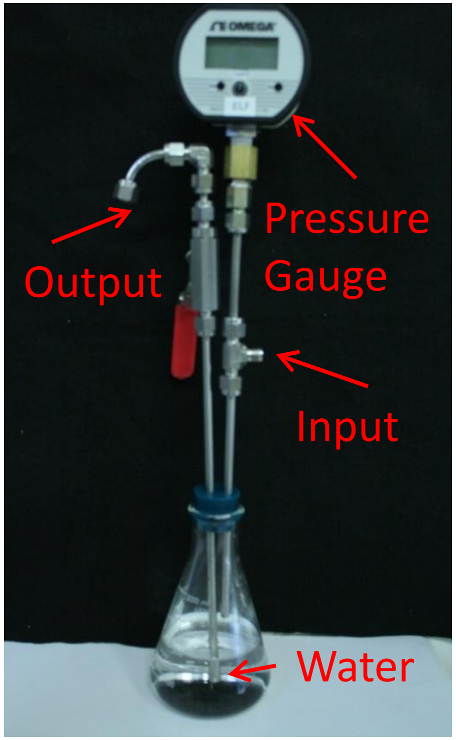


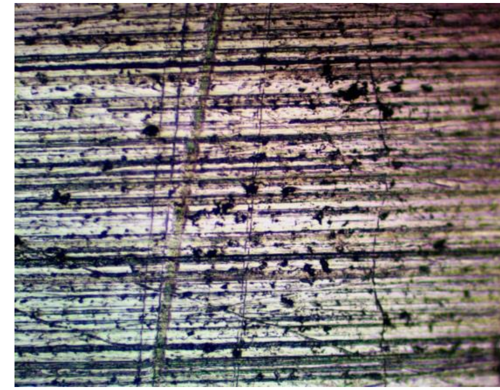
After



There was no noticeable decay/ discoloration done to the PI over the duration of the test

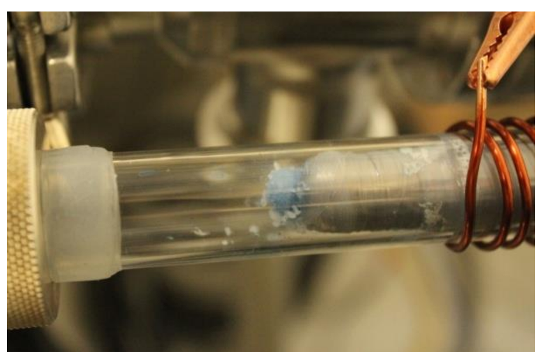
Porous Tungsten Water injector





Pros:

- Good porosity
- Excellent electrical and plasma properties

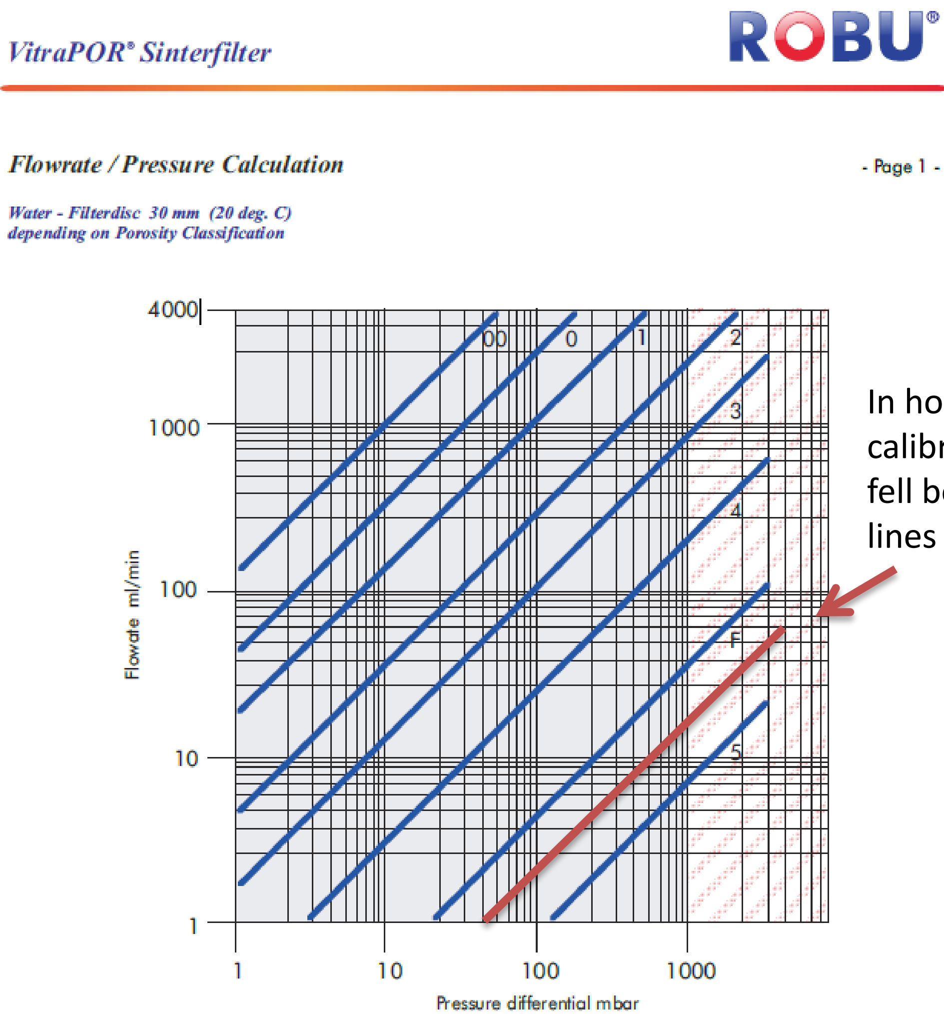


Cons:

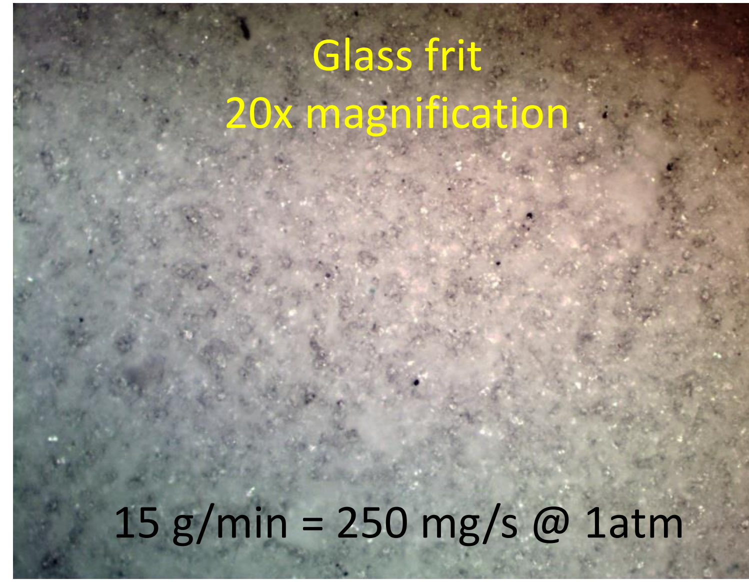
- Too much surface area
- Hard to work with

Ultimately porous tungsten seems ideal for a water injector, but not good for early development

Porous Glass Water injector



In house calibration fell between lines F and 5



Pros:

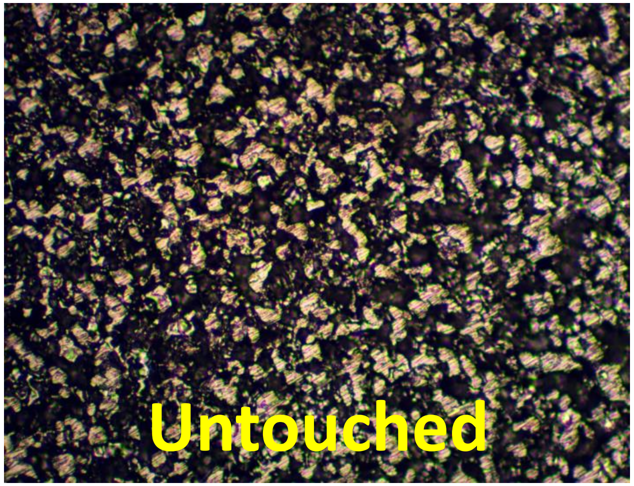
- Dielectric
- Good plasma properties

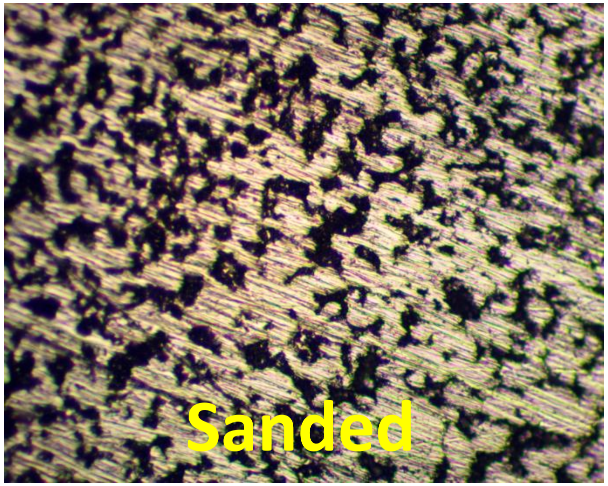
Cons:

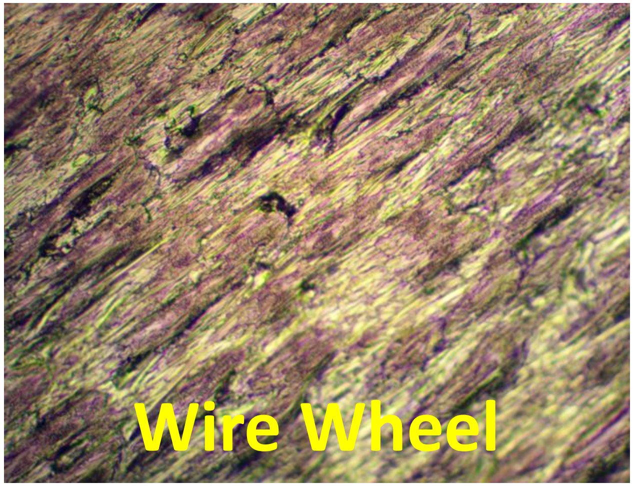
- Too porous
- Hard to work with
- Bad thermal conductivity

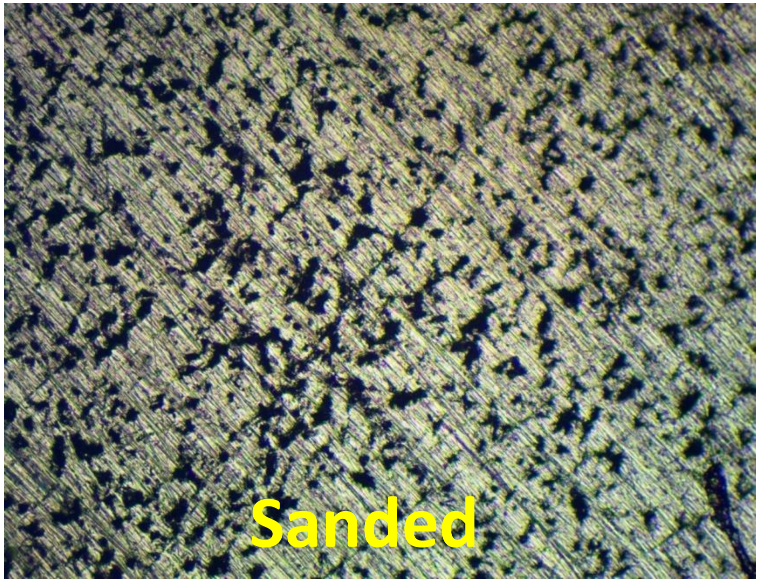
Not the best candidate for liquid propellants. May have some application for gaseous propellants.

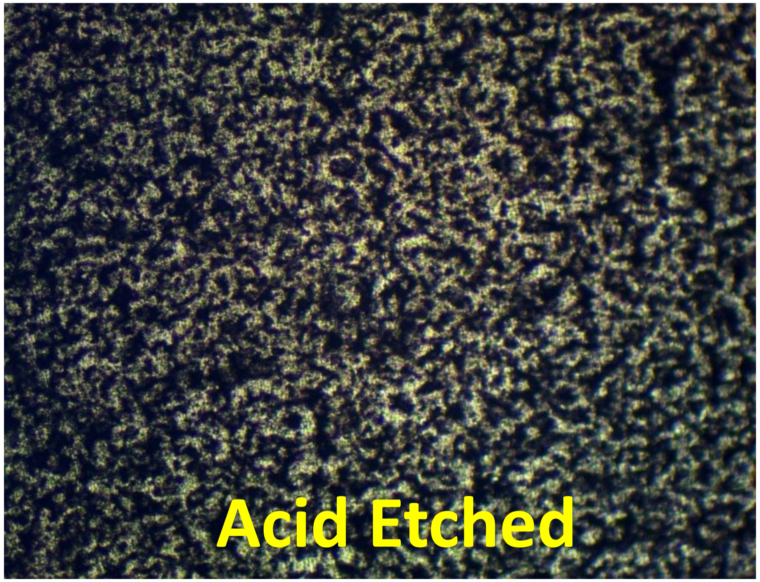
Porous Stainless Steel





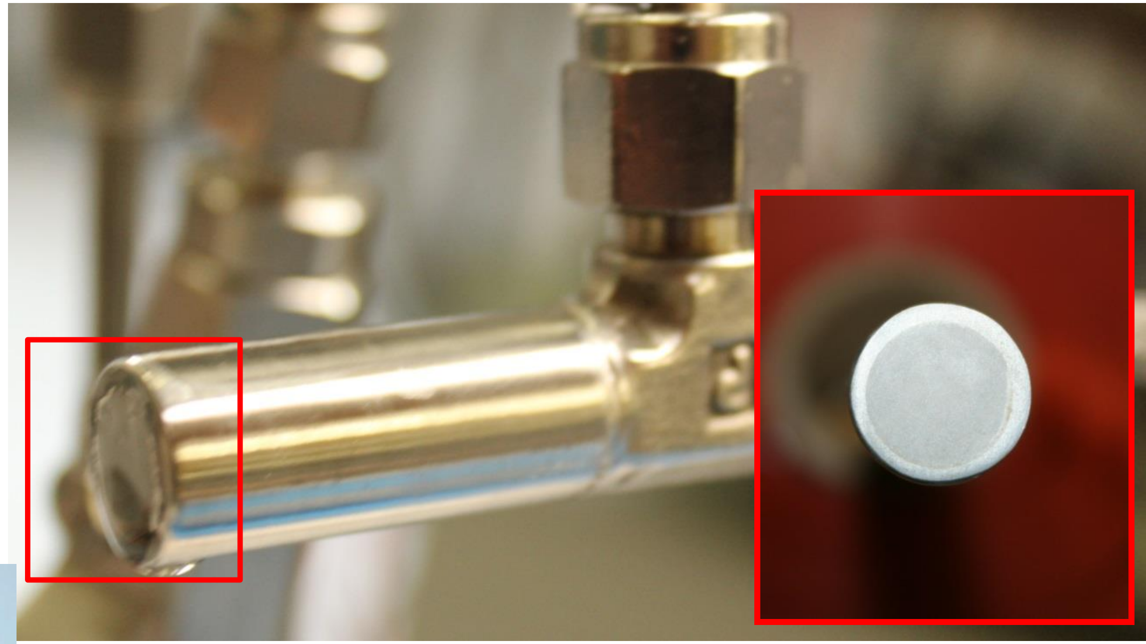


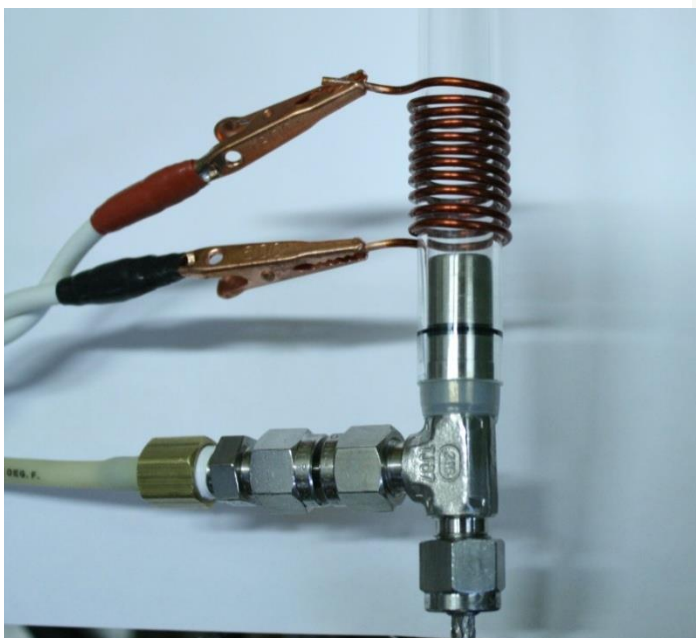




Stainless Steel Injector Housing

- ¼ stainless steel tee
- ½ OD stainless tube
- 10 mm diameter porous SS
- Soldered, sanded, and etched
- Stainless steel 250W tube heater



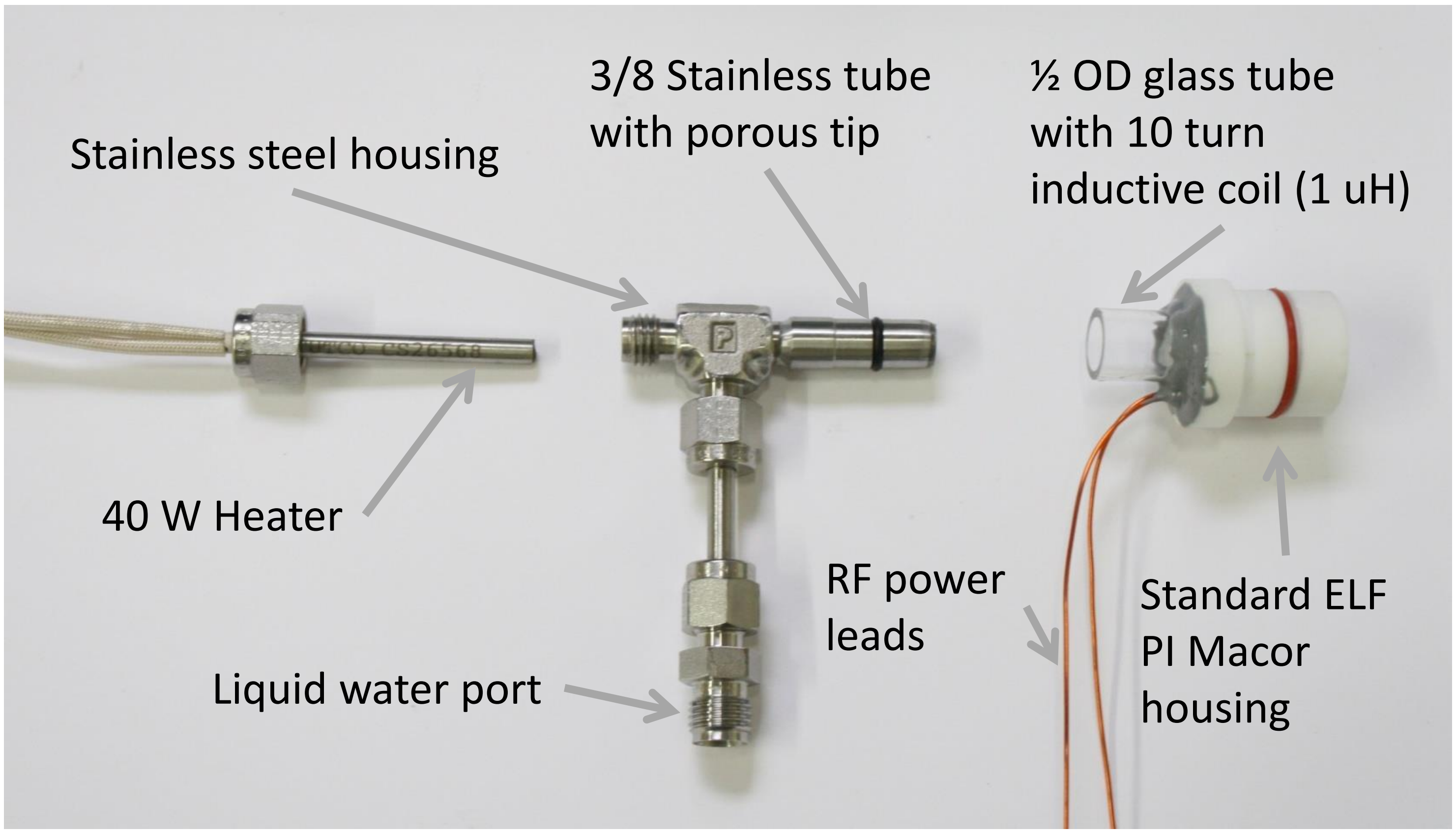


- Designed to flow approximately 2mg/s of water at 1atm
- In air: 1atm -> 1.8mg/s of water
    - Initially had trouble maintaining porosity
    - Several acid etches and ultrasonic cleanings were needed to achieve proper repeatable flow rate

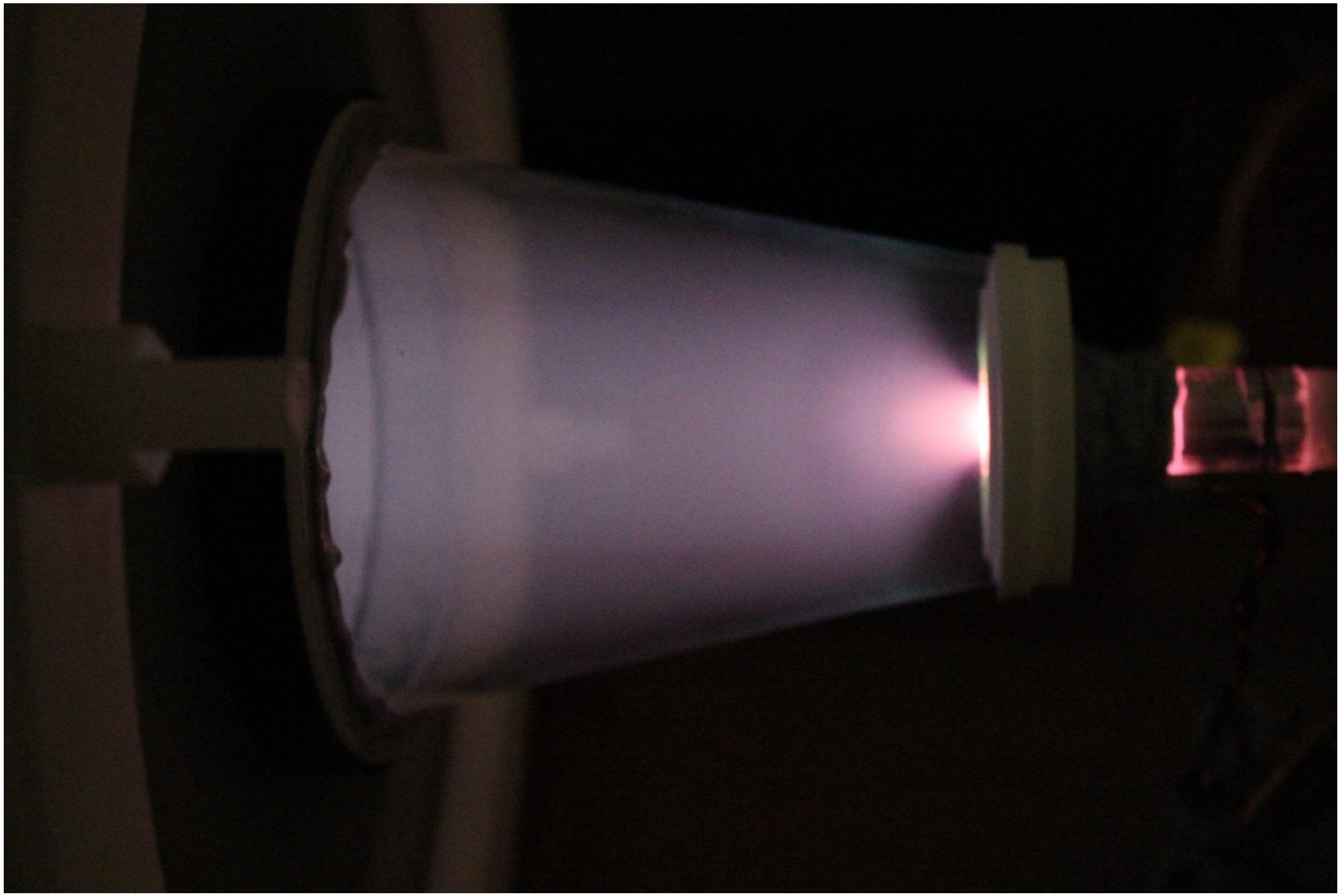
Injector operation & RF ionization

- Plasma lit at 40 W
- RF could be turned off without freezing (condensate formed in tube)
- Ran for 22 minutes continuously
  - 30 W RF power
  - Heater maintained 50 C
  - Flow rate 3 mg/s

Thruster Integration Build



Water Operation in Thruster Geometry

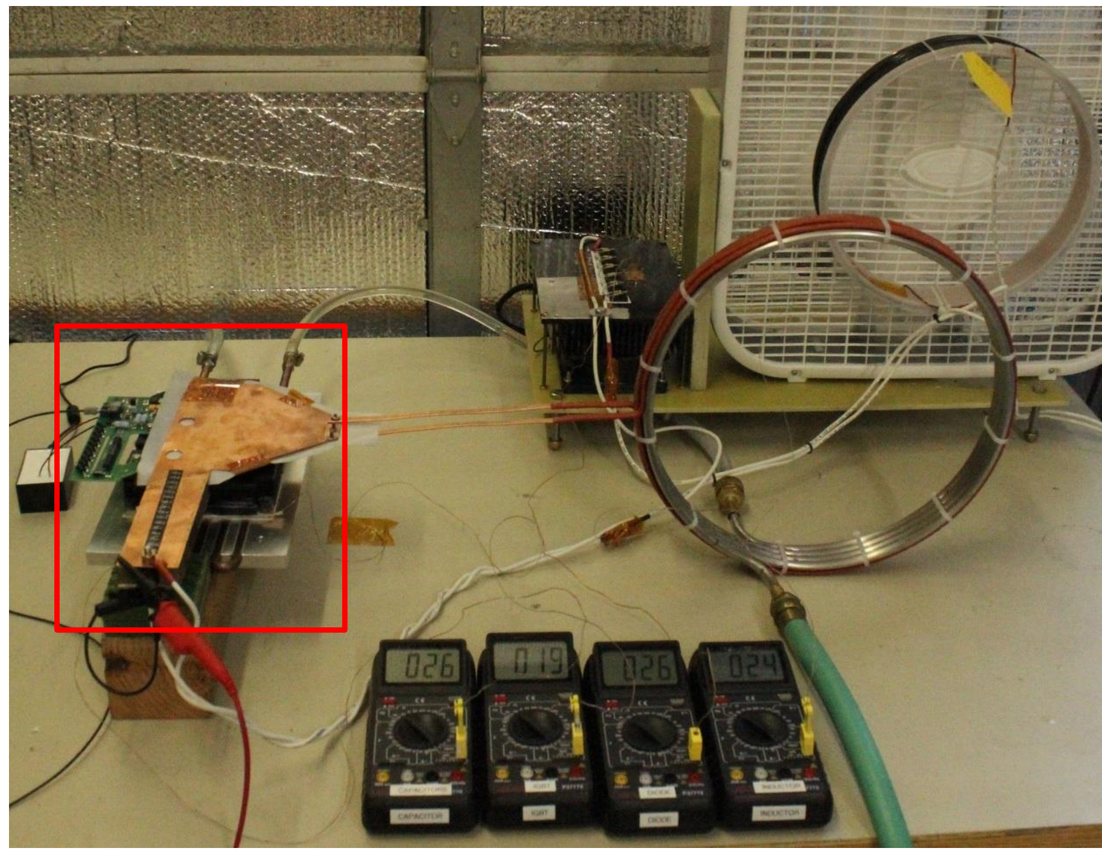


MSNW

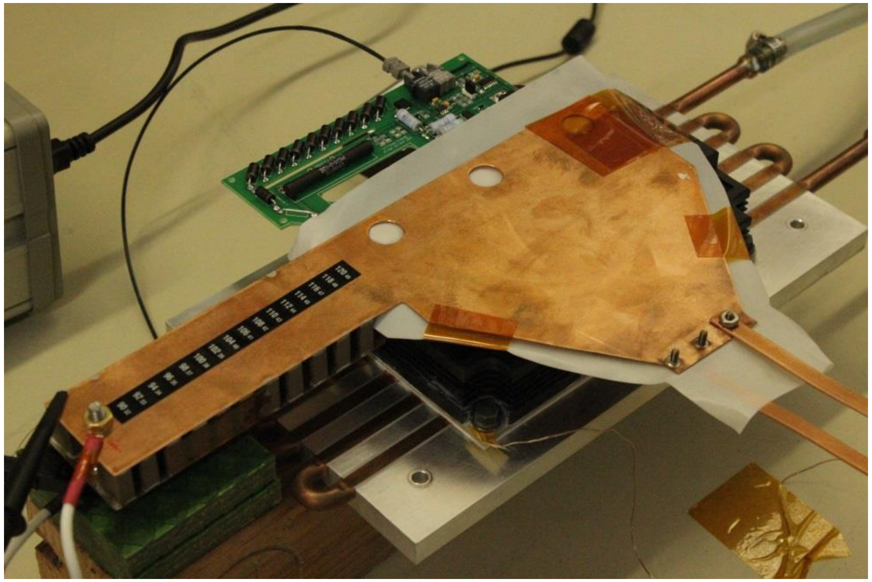
Steady operating 30 kW PPU

Experimental Setup and Testing

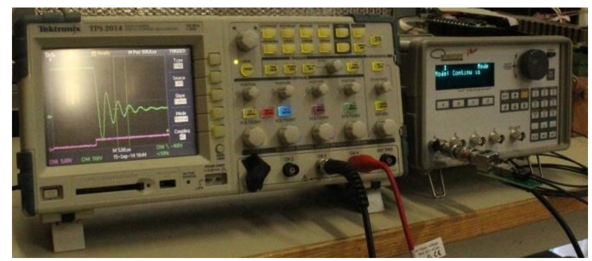
- PPU Specs
  - ABB HiPak IGBT
    - 4500 V
    - 2400 A (9 KA peak)
  - ELF Gate Driver
    - Fiber trigger
    - 28 gate voltage
    - Over voltage protection
  - NOVACAP COG
    - Ultra high Q
    - 4000 V
    - 22 nF x 22 = 484 nF
    - 200 C operating temp

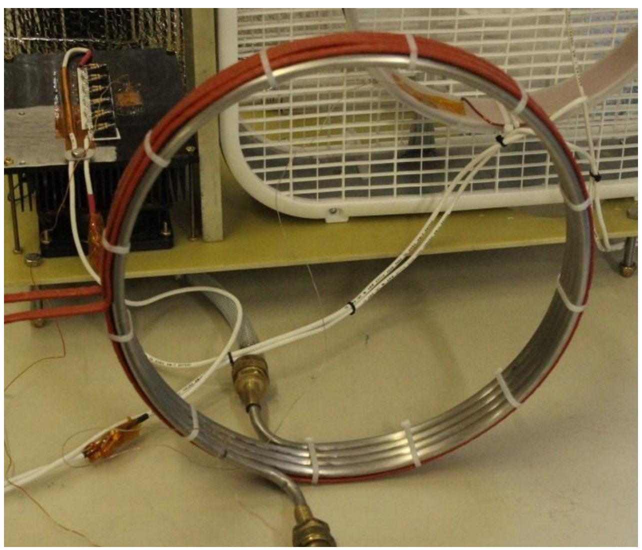


Components



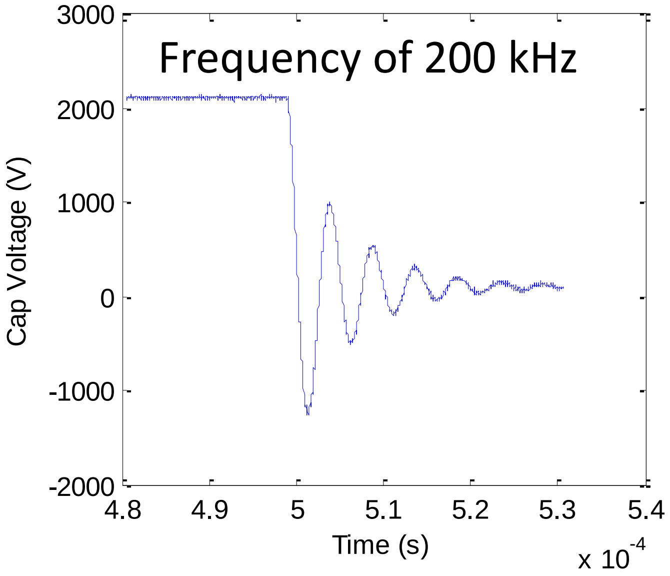
500 V at 20 A (15 kW)

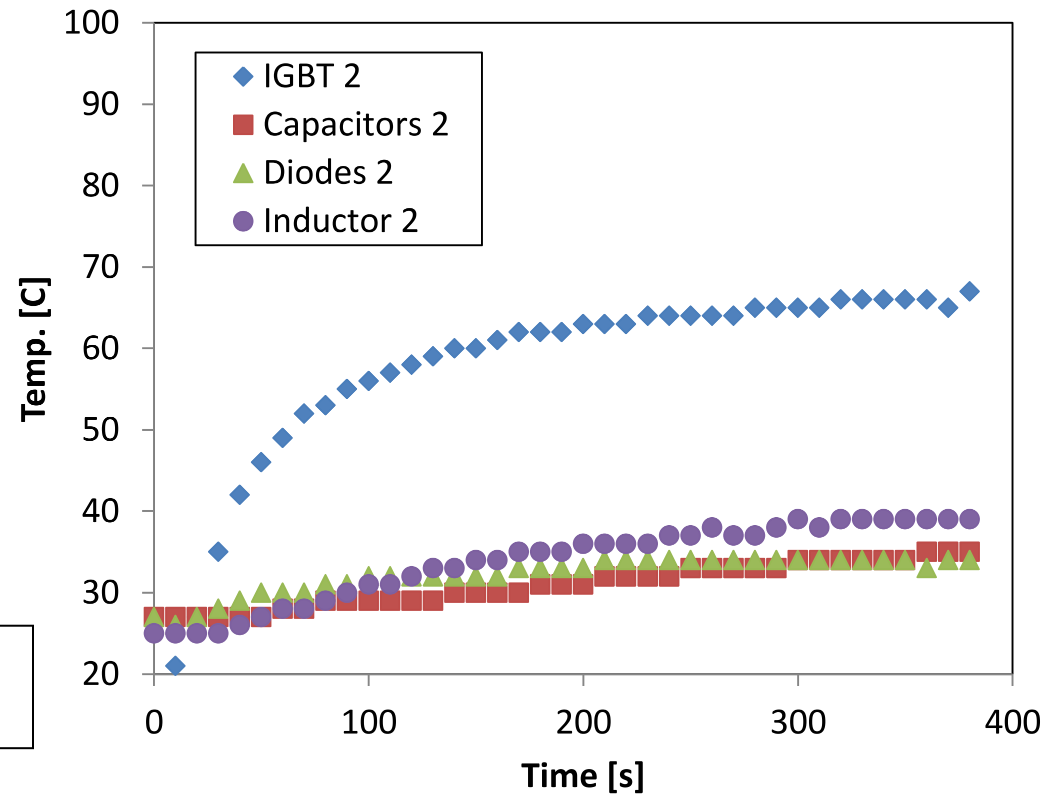




1250 nH inductance

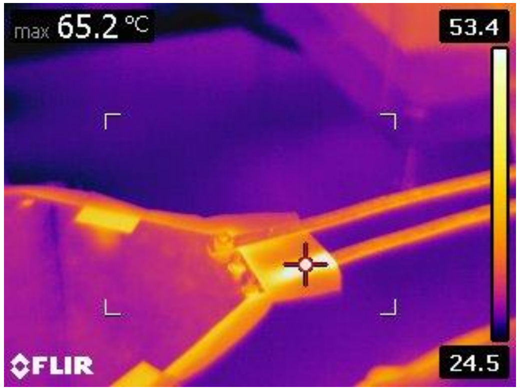
2 kW Thermal Test

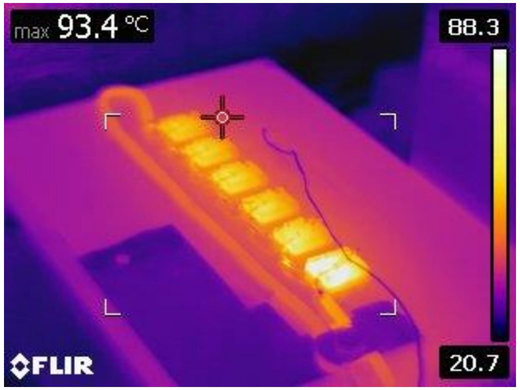


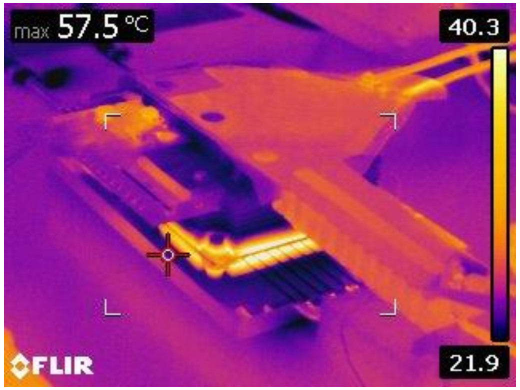


PPU Power
22 nf x 22 = 484 nF
@ 2000 V = 0.97 J
@ 2 kHz = 1936 W

Power Supply
177 V@ 14 A = 2478 W





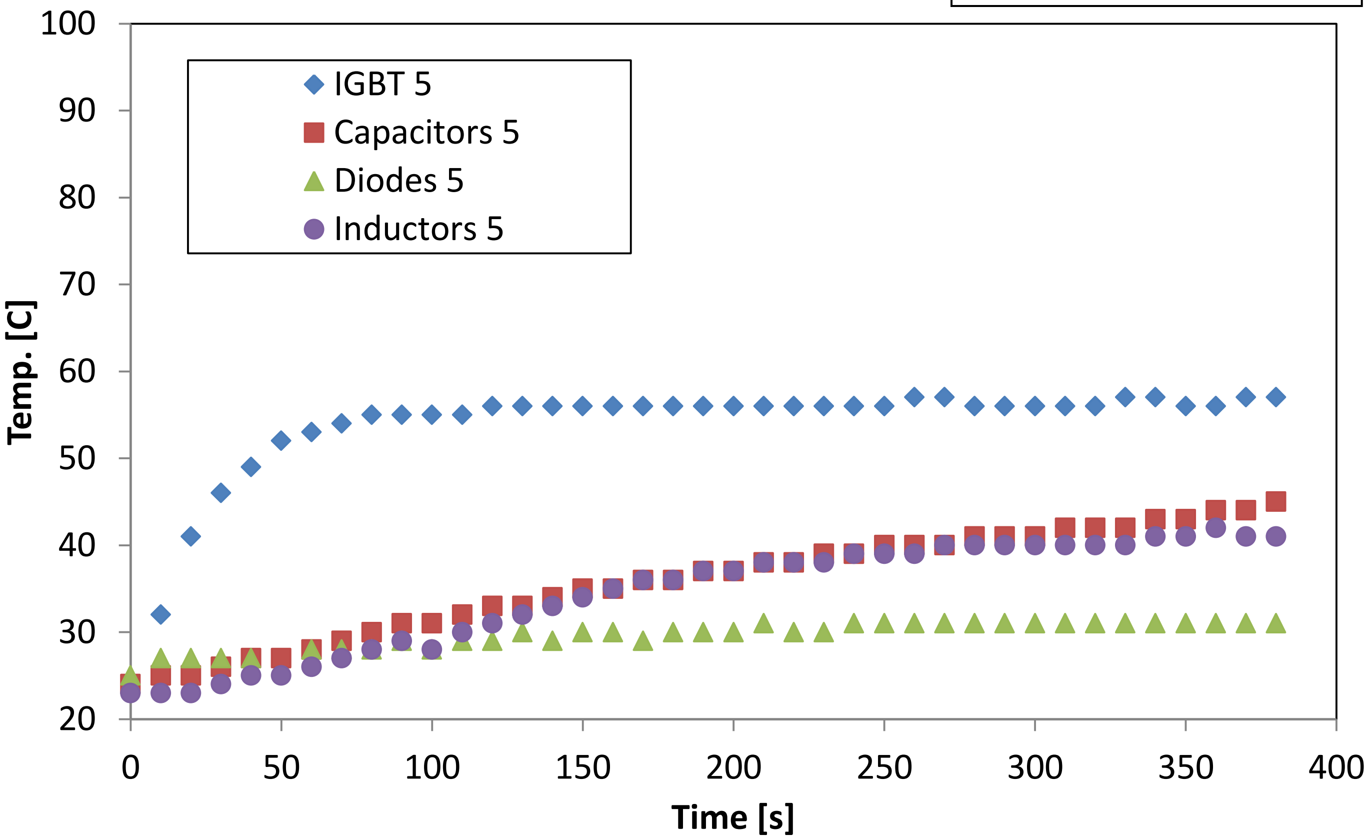


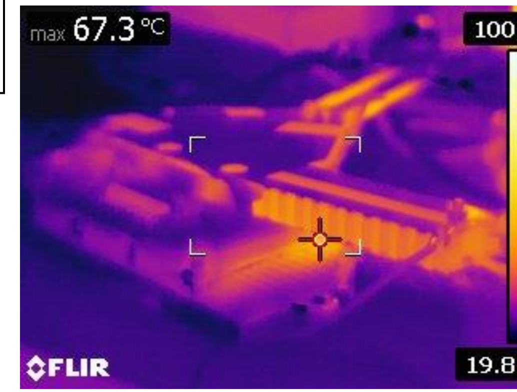
4 kW Thermal Test

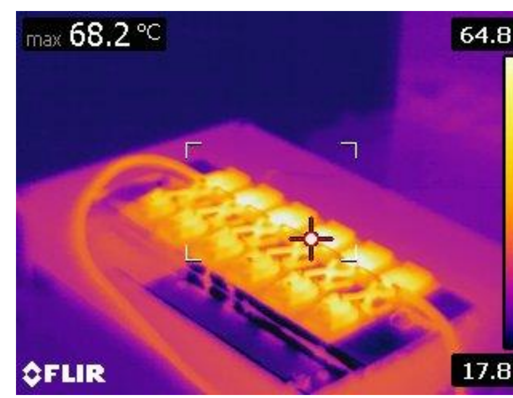
- Corrections to setup
  - Removed Silpad and used thermal grease
  - Added cooling to coil leads
  - Paralleled diode array

Power Supply
270 V@ 19.1 A = 5157 W

PPU Power
22 nf x 22 = 484 nF
@ 3000 V = 2.2 J
@ 2 kHz = 4356 W



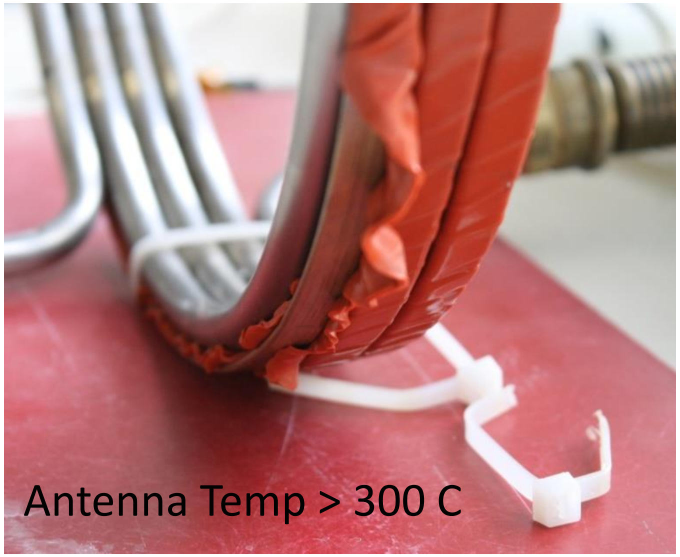


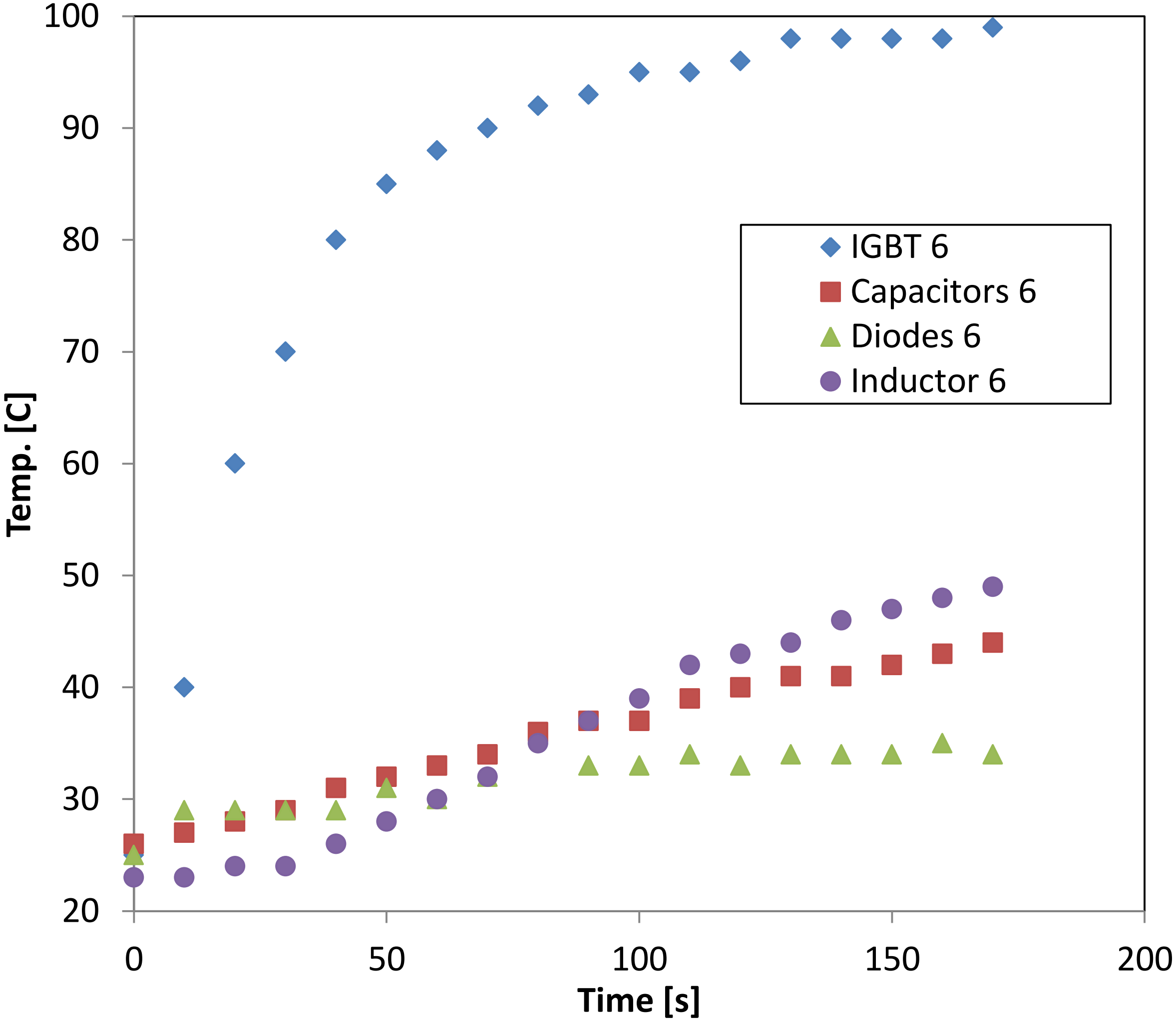


9 kW Thermal Test

Power Supply
463 V@ 22 A = 10186 W

PPU Power
22 nf x 22 = 484 nF
@ 3000 V = 2.2 J
@ 4 kHz = 8712 W



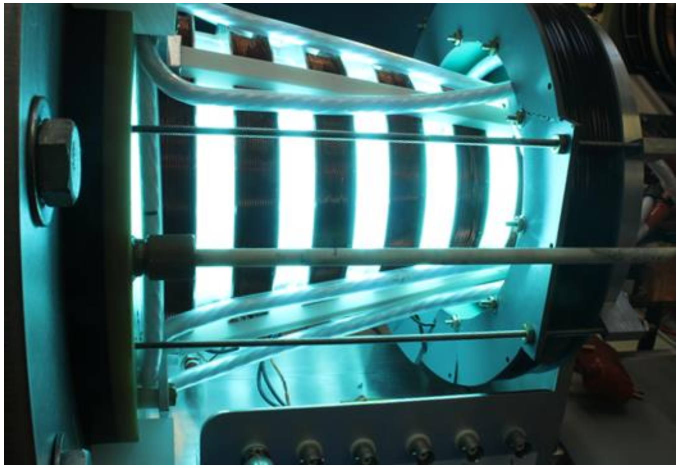


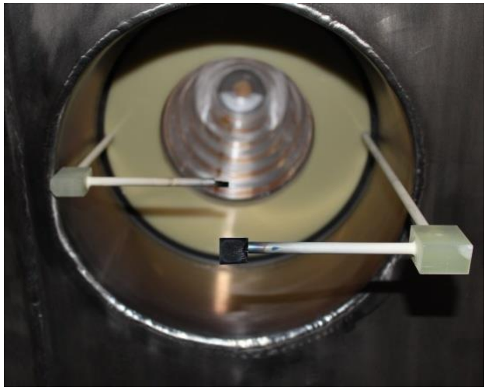
Normal operating temperature for Switch is 125 C

Thruster operation and propellant Characterization

ELF-160 Specs

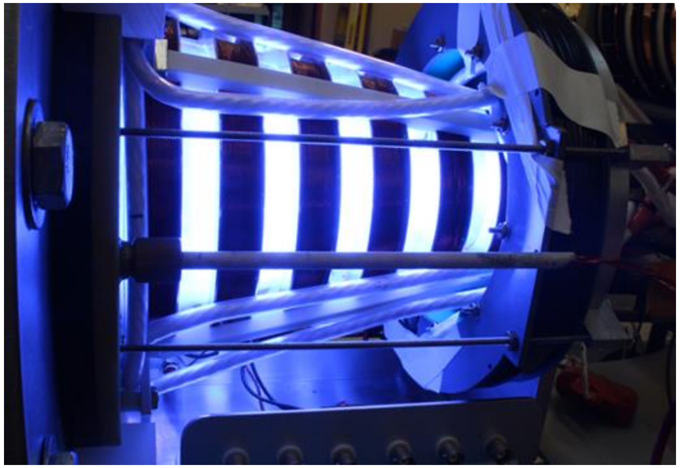
- 2 uF cap
- 4000 V
- 32 J per pulse
- 50 KW (600 us rep rate)
- Baseline on Xe and Ar gas





Time of Flight

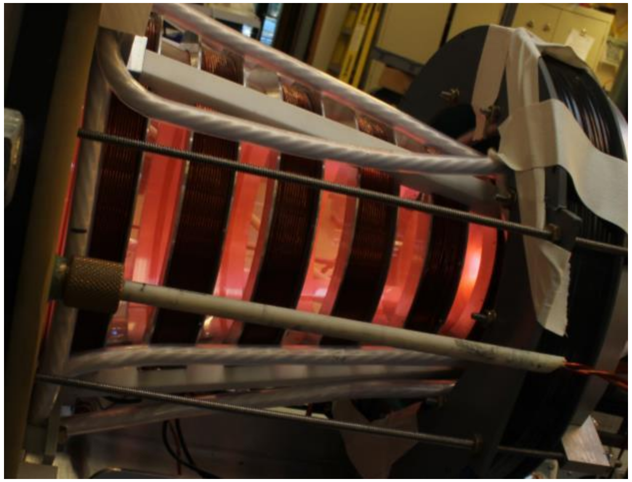
Double Probes are placed on axis 1 thruster radius downstream. Probes are 10 cm apart.

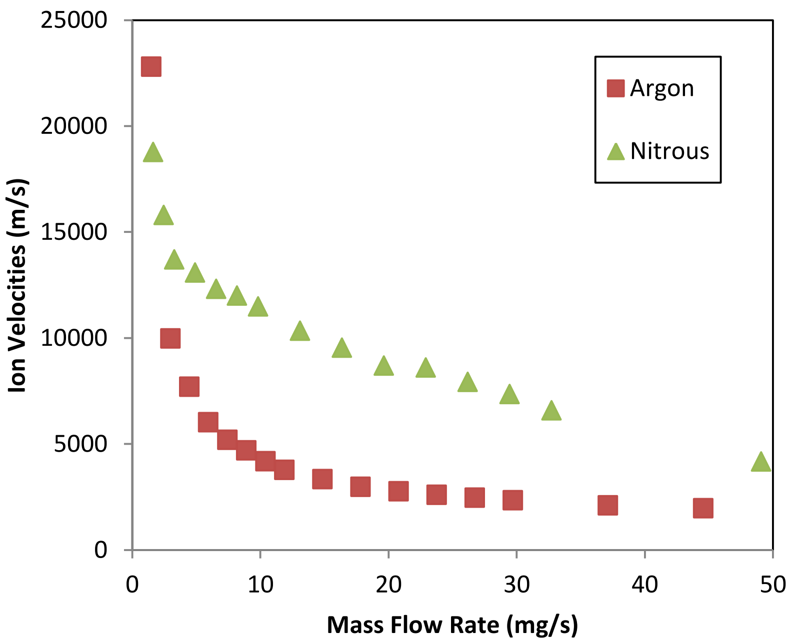


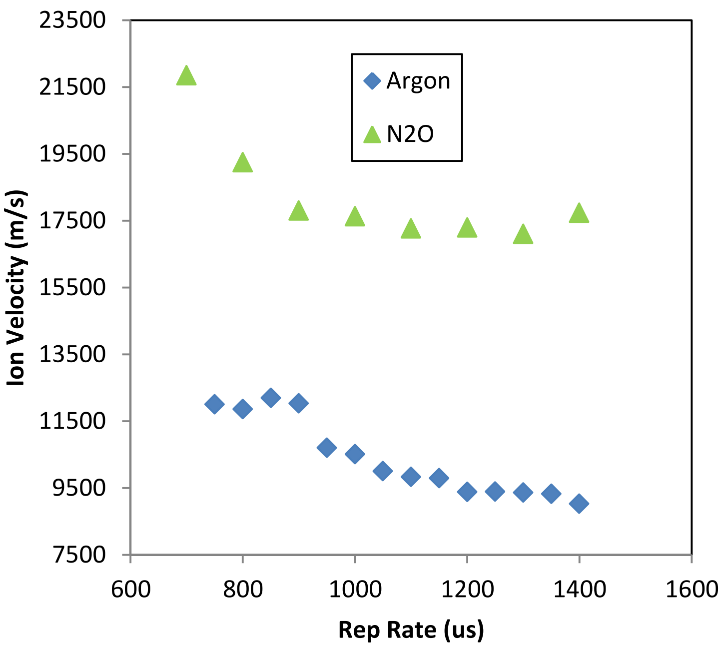
Nitrous Oxide Testing

Shots: 25454-25472

- 250W PI power
- 1000µs rep. rate
- no bias
- More difficult to light than Argon
- Much faster ion velocities







Summary

Clear Applicability to NASA missions

- Icy moon return
- Goldilocks planetary return or rendezvous
- All asteroid missions
- Interplanetary cargo

Technology Demonstrated

- FRC Thruster performance shown
- Full inductive system including pre-ionization
- Ionization on many molecular gases demonstrated
- PPU being validated at relevant power levels

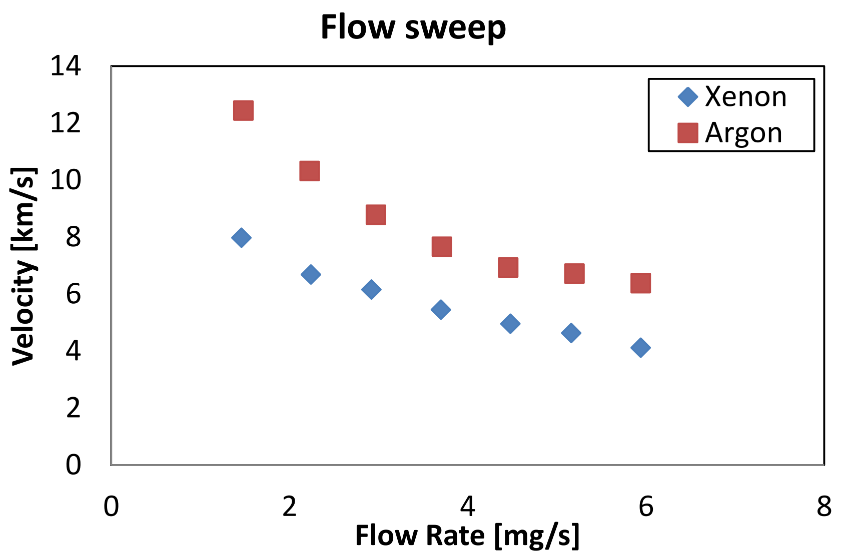
Backups

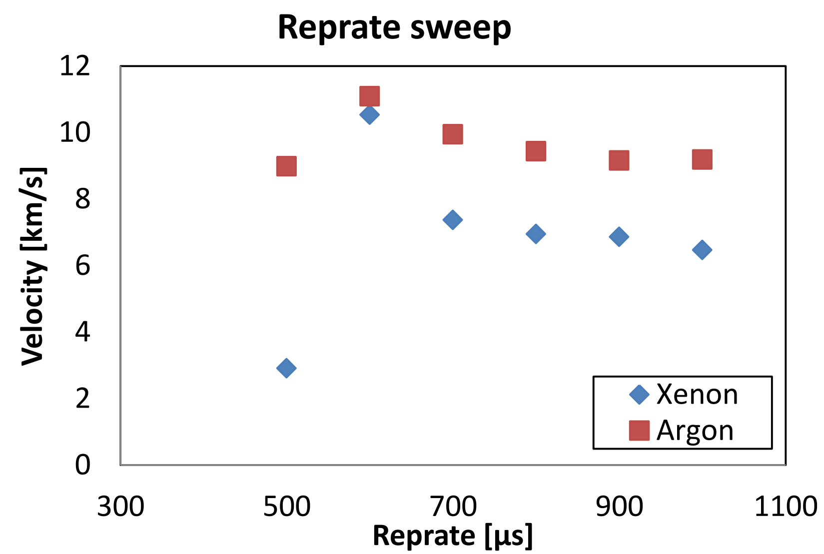
Future Phase I Plans

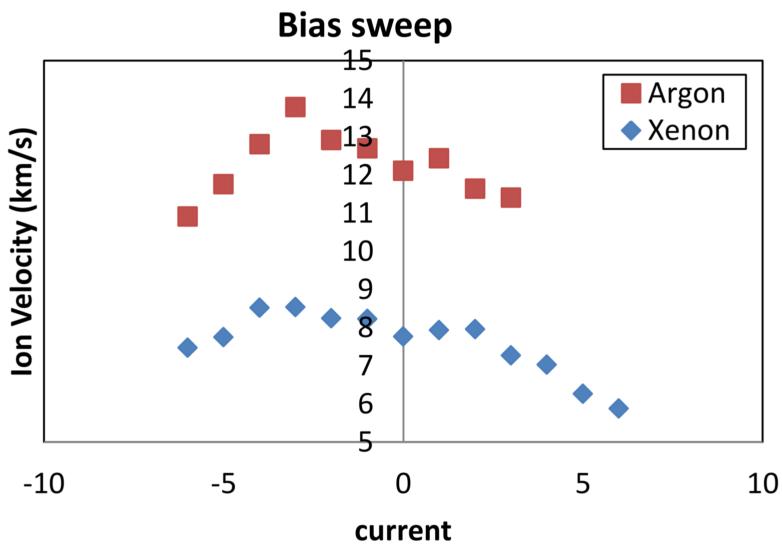
- Interim report due 9/27
- Continuous thruster operation on H_2O
- Custom tungsten injector with stainless properties
- 15 kW PPU thermal test
- Test CO_2 and CH_4
- Composite puffed operation externally
- Move ELF-160 to Thrust stand

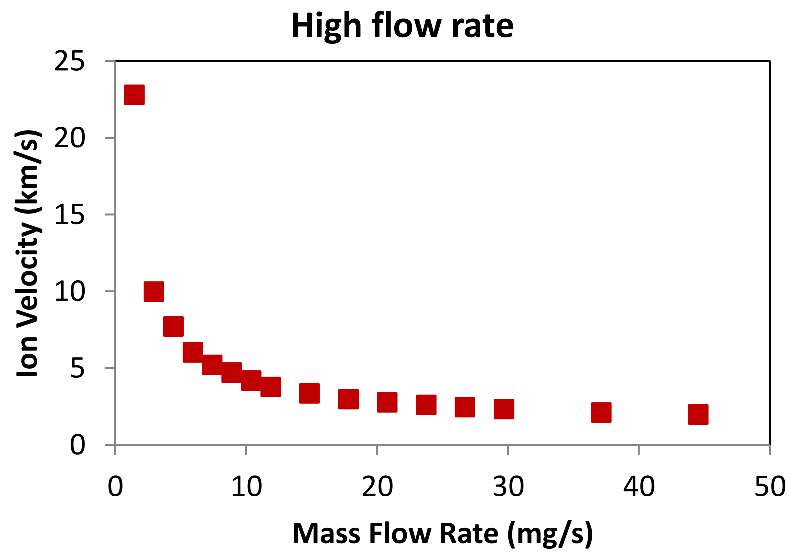
- Phase II Prep
  - Teaming partner
  - Thruster thermal, utilization optimization
  - External facility, long duration operation

Performance Sweeps









MSNW

Comparison of AFRL RF PI

PI ignition results at AFRL's SPEF

Flow rate (sccm)	Background Pressure (torr)	Minimum ignition power (W)
600 (Ar)	1.6e-5	600
200 (Xe)	1.5e-5	600

- Argon would stay lit at 200 sccm and 30 watts
- Xenon would stay lit at 50 sccm and 20 watts

The ½" diameter pre-ionizer that was used at the ARFL was tested in MSNW's facility. It was installed with the exact same feed-through and cabling.

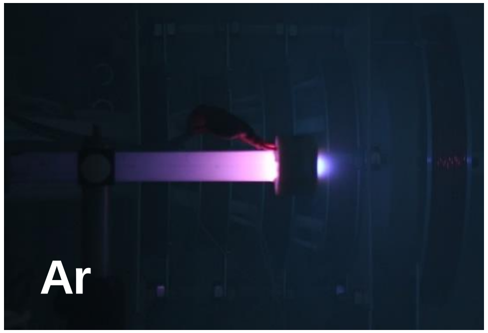
PI ignition results at MSNW

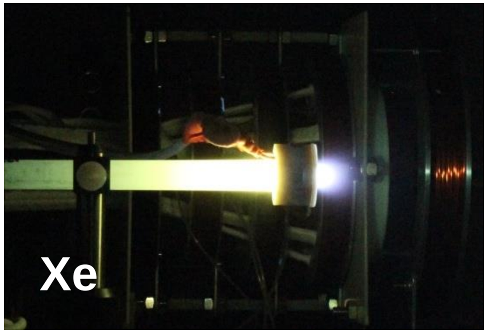
Argon

Flow rate (sccm)	Background Pressure (torr)	Minimum ignition power (W)
200	1e-2	175
150	8.3e-3	210
100	5.5e-3	460
75	3.6e-3	1200

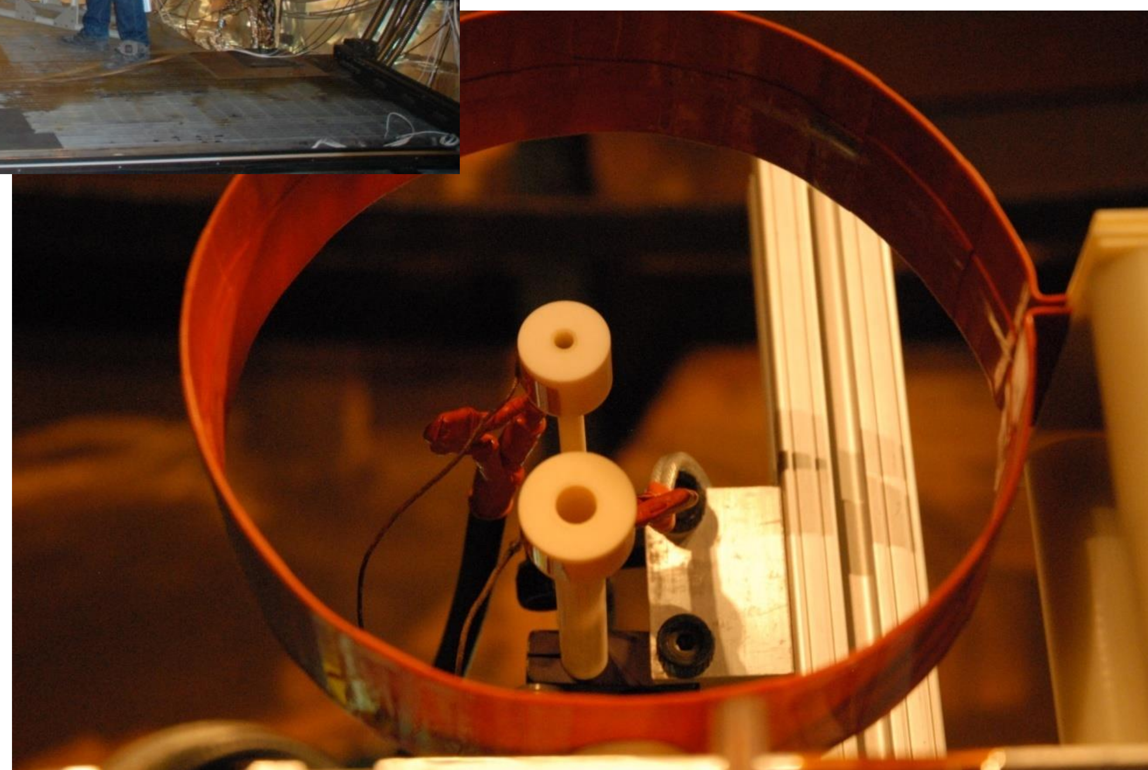
Xenon

Flow rate (sccm)	Background Pressure (torr)	Minimum ignition power (W)
500	7.1e-3	350
400	5.9e-3	480
300	4.4e-3	900



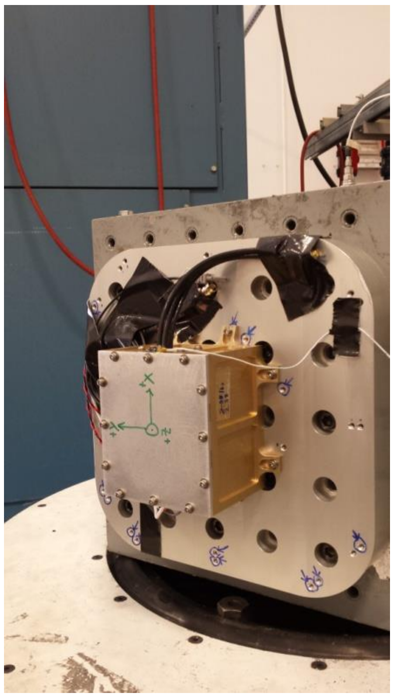


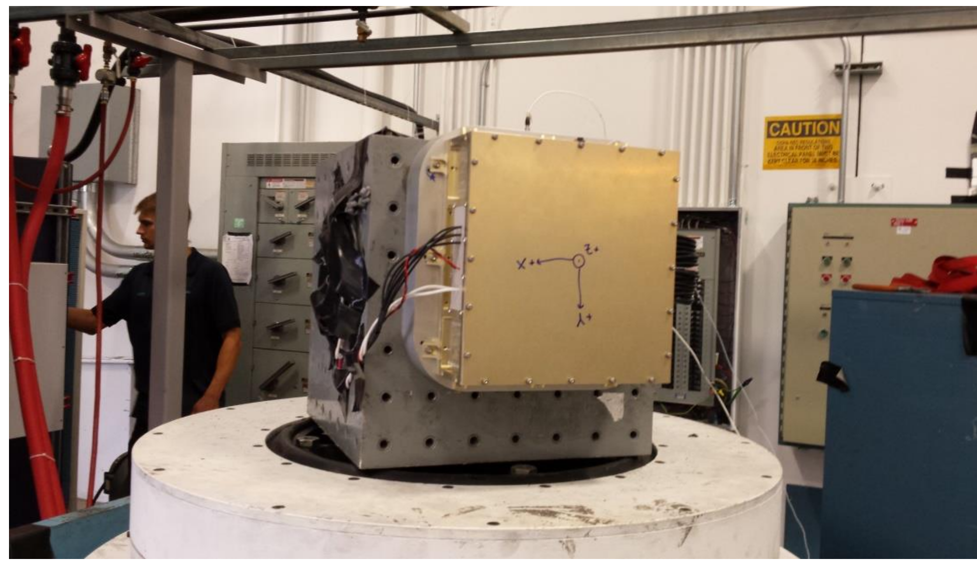
Thruster PI typically light at 40w and 20 sccm of Xe



Extension Accomplishments

- Enclosure Development and External Vibe Test on 1 kW and 5 kW at Element





- Thermal Validation at 1 and 5 kW
- Internal EMI characterization (underway)