Initial Thrust Measurements of Marshall's Ion-ioN Thruster

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Overview

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Introduction to Electronegative Ion Thrusters

Project Motivation & Goals

Marshall's Ion-ioN Thruster

- Design of the MINT
- Calculated Performance

Experimental Set-Up

- Thruster Operating Conditions
- Facility & Diagnostics

Results & Analysis

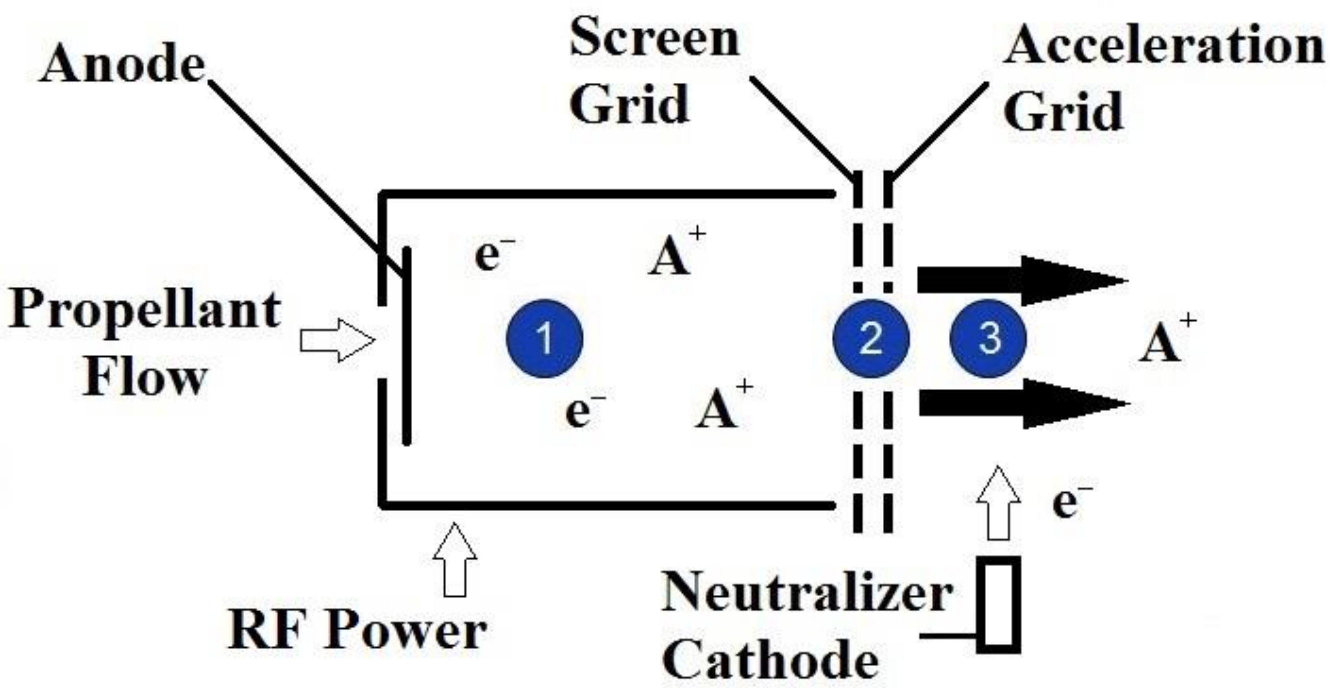
- Configuration C1
- Configuration C2

Conclusions

Future Work

References

Classic RF Gridded Ion Thruster Diagram:



Stage 1:

Ionization of noble gas yields electrons and positive ions.

Stage 2:

Positive ions accelerate through grid assembly.

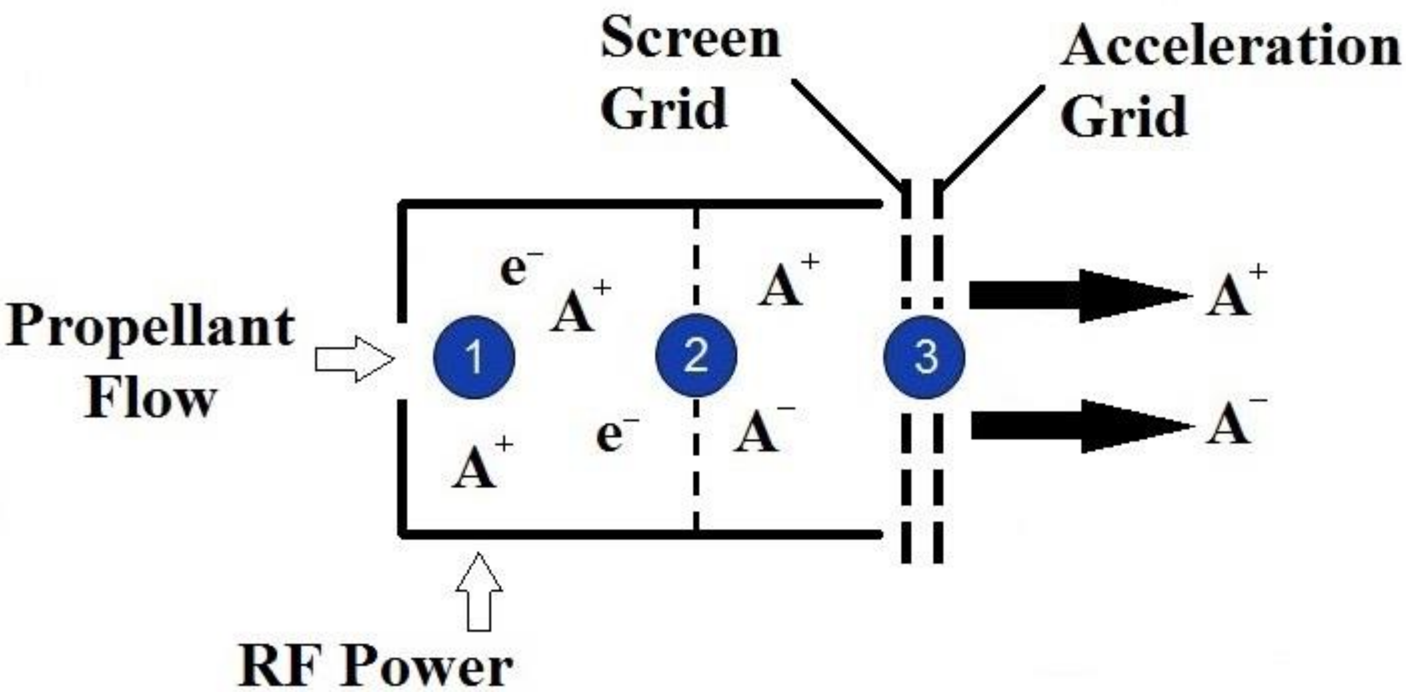
Stage 3:

Electrons ejected from neutralizer cathode into positive ion beam.

Drawbacks of Ion Thrusters

- Lifetime Limiting Components:
  - Acceleration Grids.
  - Neutralizer Cathode.
- Constraints:
  - High purity source (often xenon) required for cathode operation.

Electronegative Ion Thruster Diagram:



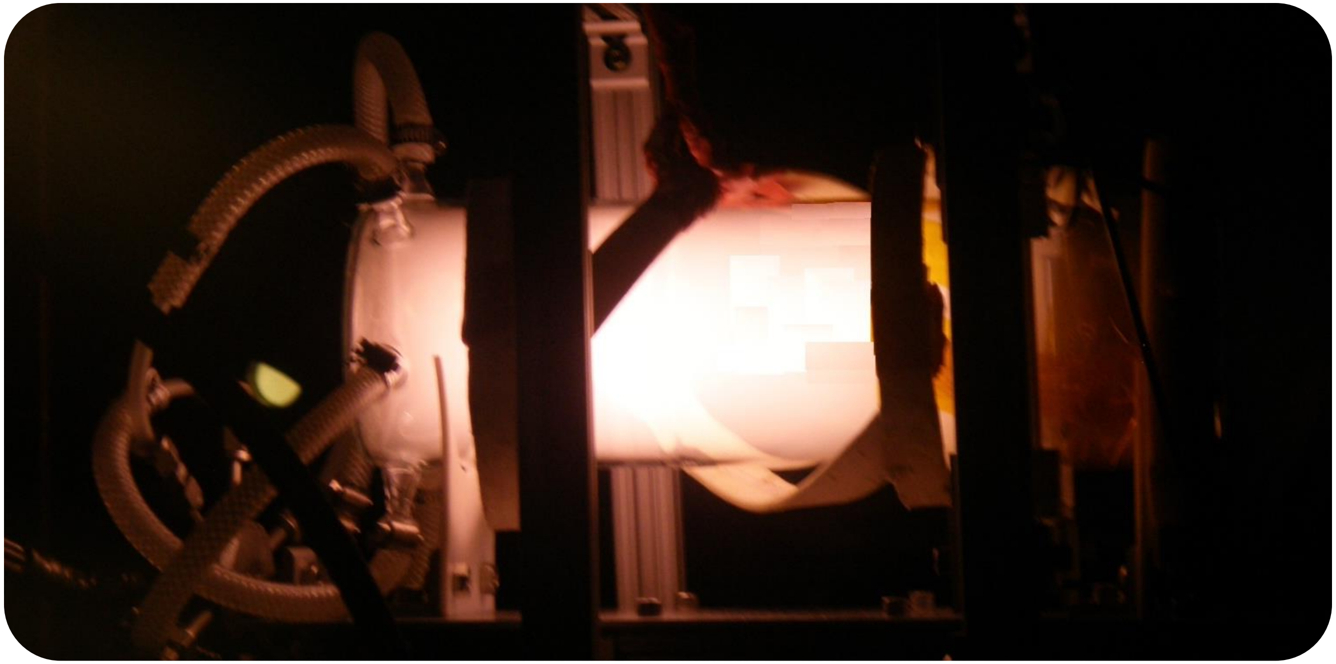
Stage 1:	Stage 2:	Stage 3:
Ionization of an electronegative propellant.	Ion-ion plasma formation.	Positive and negative ion acceleration.

REF. [2-5]

Project Motivation

- Benefits:
  - Elimination of neutralizer cathode.
  - Faster recombination in plume.
  - Thrust generation by both charge species.

1st domestic investment in electronegative thruster concept.



Marshall's Ion-ioN Thruster

Project Goals

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- **<u>Determine feasibility of electronegative ion thrusters through direct thrust measurement enables:</u>**
  - Assessment of key design drivers impacting thruster operations.
  - System level analysis and comparison to classic gridded ion thrusters and Hall thrusters.
  - Elevation of Technology Readiness Level from TRL2 to TRL3.

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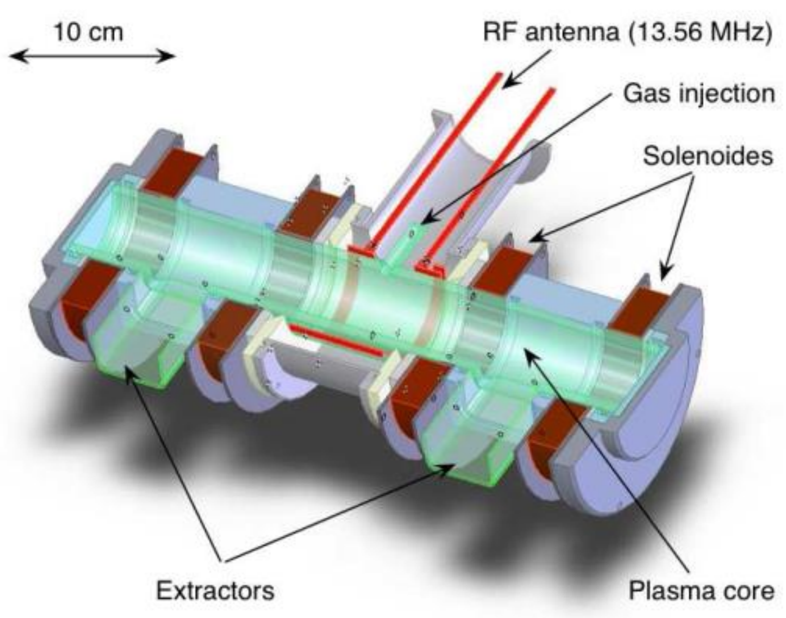
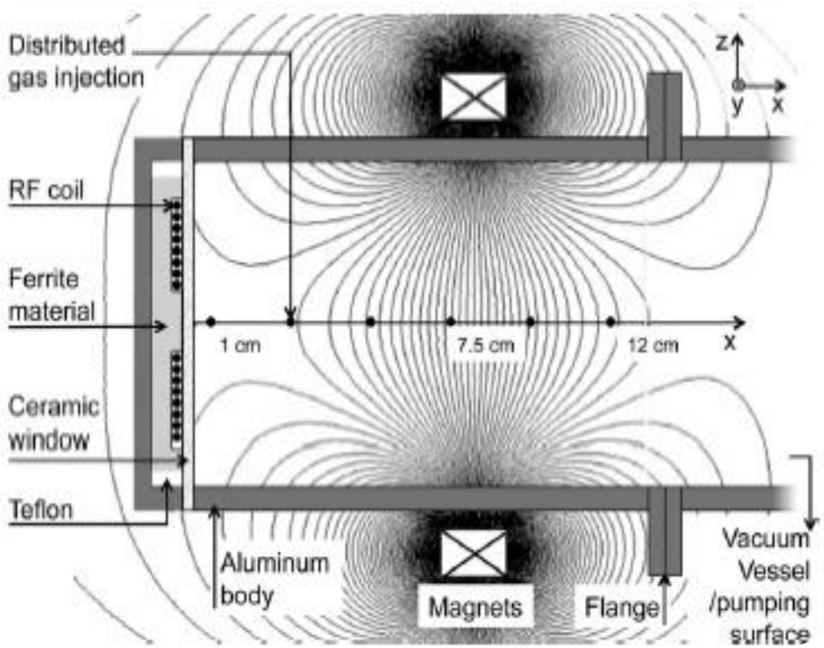
Advancements to Date

- Electronegative ion thruster concept patent by École Polytechnique accepted in 2007. [Ref. 4]
- PEGASES: Plasma Propulsion with Electronegative GASES.
- Previous focus on diagnostics required to characterize quasineutral plume.



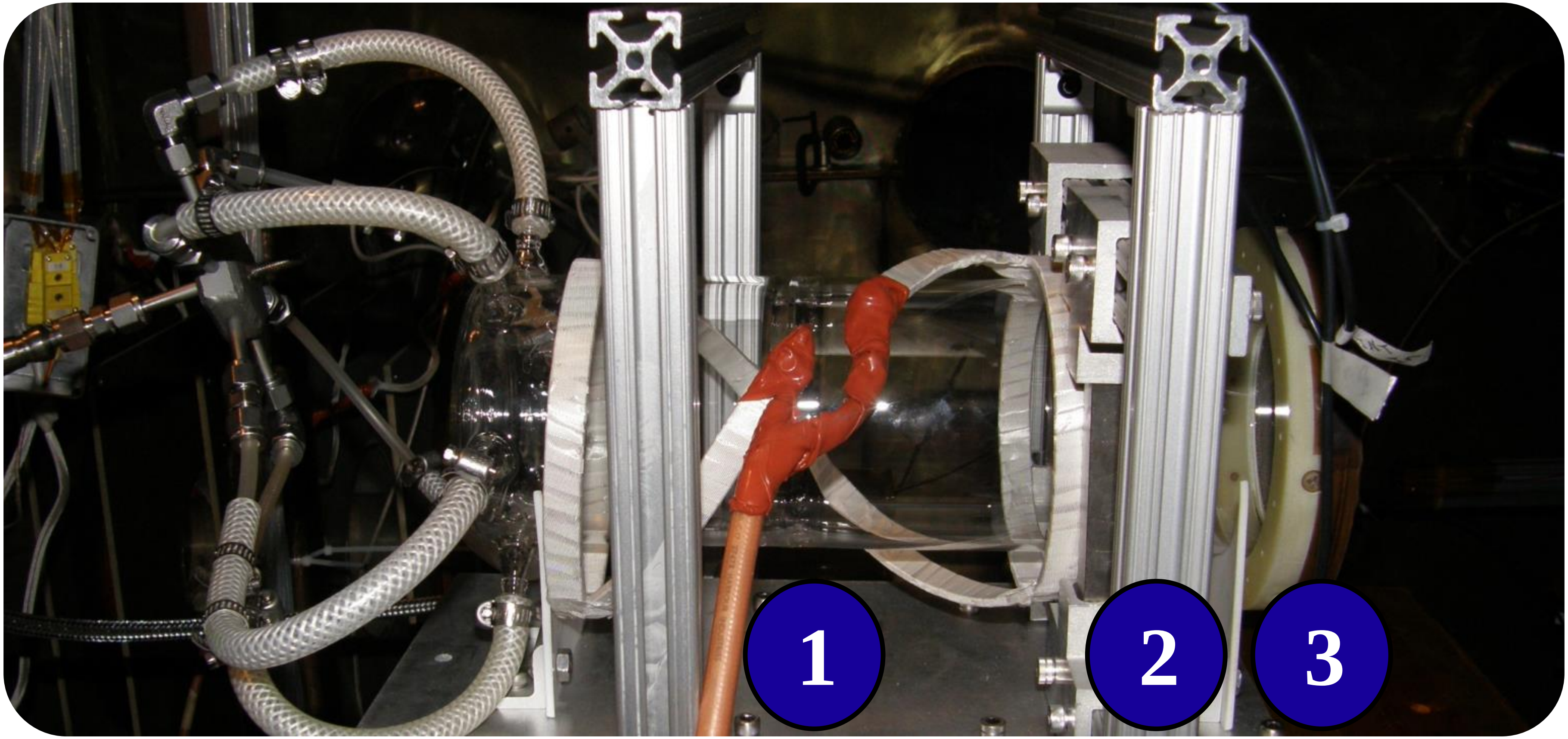
[Ref. 5]



[Ref. 8]

Thruster Design

Marshall's Ion-ioN Thruster (MINT)



Stage 1:

Ionization of propellant using double-helix, half-turn Nagoya antenna.

Stage 2:

Electron filtering using 250 Gauss magnetic filter with Neodymium magnets.

Stage 3:

Positive and negative ion acceleration through alternating bias grids.

Calculated Performance

MINT Performance Estimates:

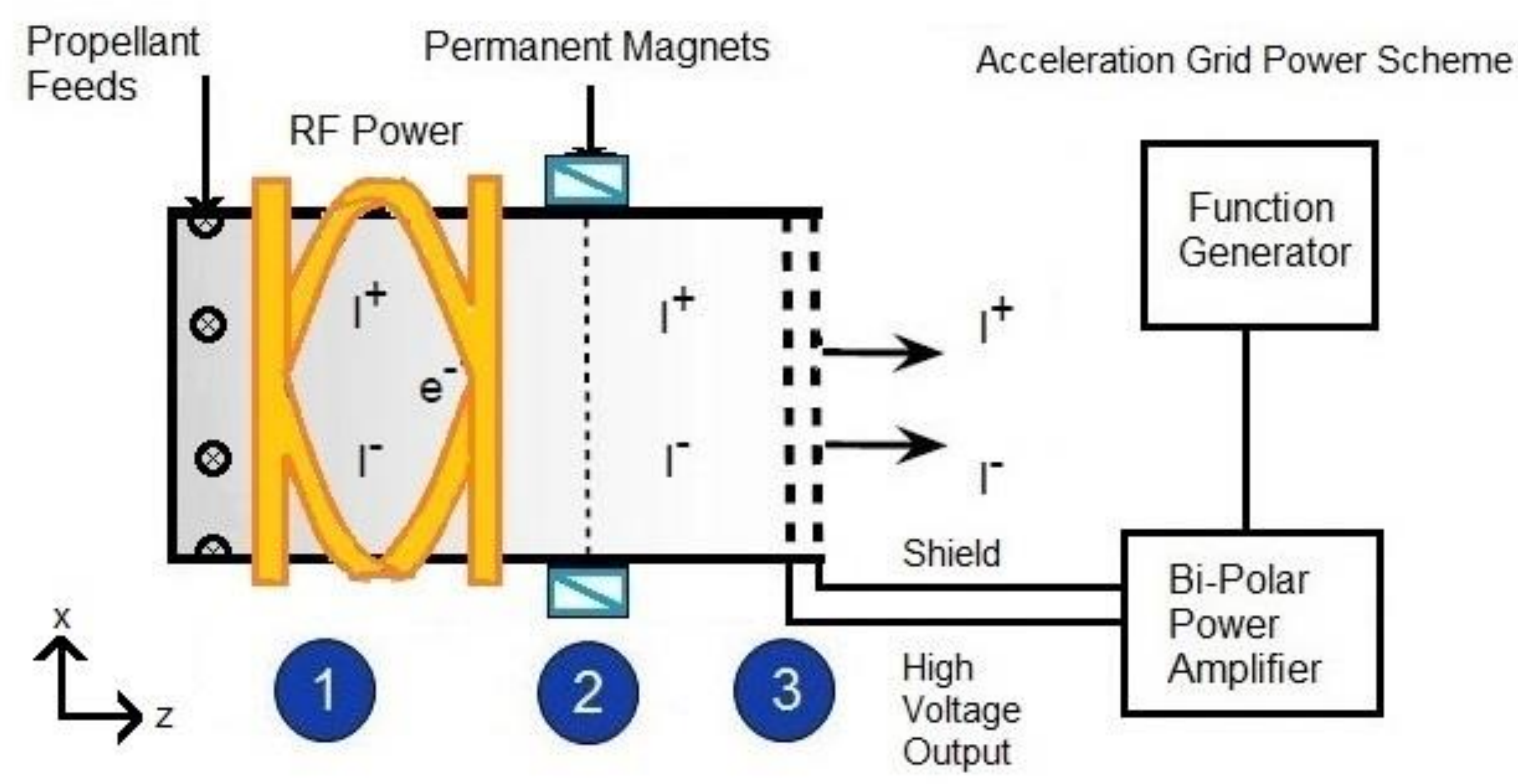
Property	Value	Units	Description
γ	0.958	-	Thrust Correction Factor[1]
V_s	350	V	Screen Grid Bias
V_a	0	V	Acceleration Grid Bias
V_b	315	V	Beam Voltage
P_{in}	700	W	Total Input Power
T_{opt}	0.65	-	Physical Grid Transparency
J_{ions}	~1.5	mA/cm^2	Ion Current Density
T_{MAX}	~1.2	mN	Maximum Possible Thrust

- Assumptions:
  - Child-Langmuir Law for round apertures.
  - Nitrogen:argon volumetric propellant mixture 5:1.
  - Classical grid design techniques as described in [Ref. 1].

Acceleration Grid Assembly.

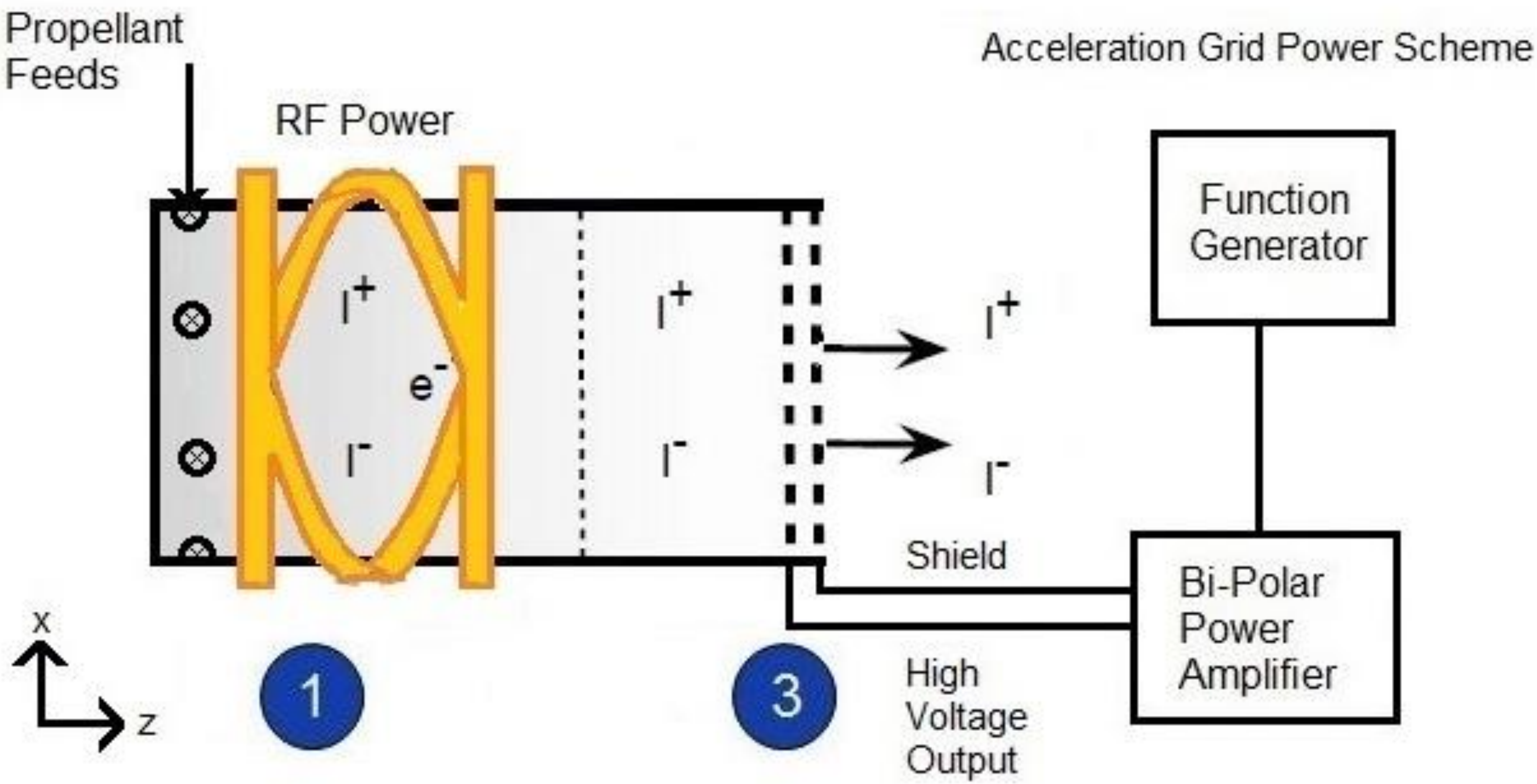
Thruster Configurations:

- Configuration C1: Complete thruster including all 3 electronegative ion thruster stages.



Thruster Configurations:

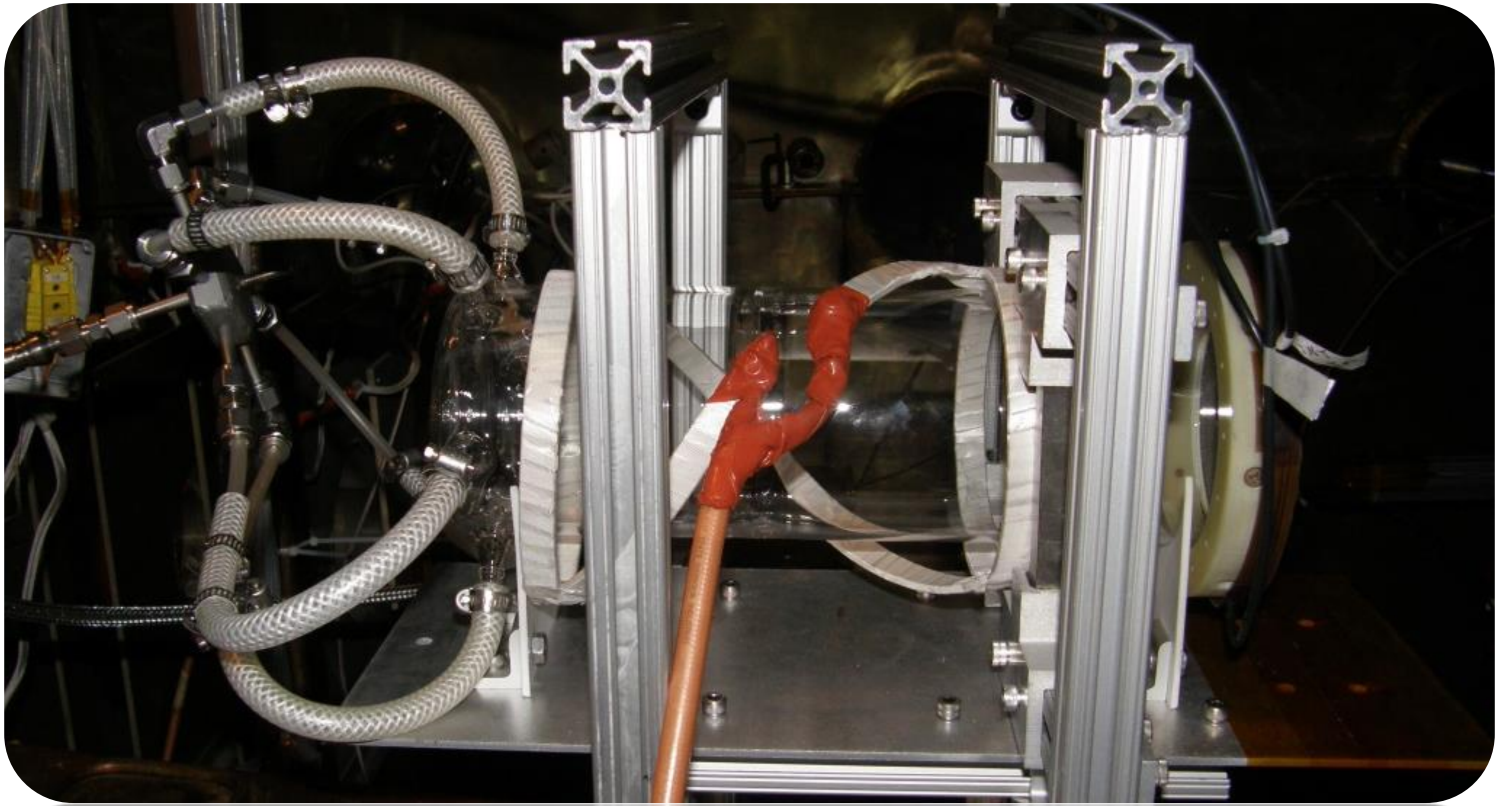
- Configuration C2: Magnetic filter removed enabling thruster to operate as a cathode-less, traditional gridded ion engine.



Thruster Operating Conditions

Operating Conditions:

- Volumetric Flow Rates: 5:1 Nitrogen to Argon ratio at 6, 12, and 24 sccm.
- 150 and 350 Watts forward RF power.
- 13.56 MHz RF with a Standing Wave Ratio (SWR) $\leq$ 1.05.



Thruster Operating Conditions

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Acceleration Grid Biasing Schemes:

- An Agilent 33220A 20MHz Function/Arbitrary Waveform Generator sends a sinusoidal or square waveform at a frequency of 4, 10, 25, 125, or 225 kHz.
- A Trek Model PZD350A M/S bi-polar power amplifier with a current limit of 400 mA that biases the upstream screen grid (±350 V) relative to the downstream acceleration grid.

Grid Biasing Schemes	Waveform	Frequency (kHz)
1	Sinusoidal	25
2	Sinusoidal	125
3	Sinusoidal	225
4	Square	4
5	Square	10
6	Square	25
7	Square	125
8	Square	225

Facility & Diagnostics

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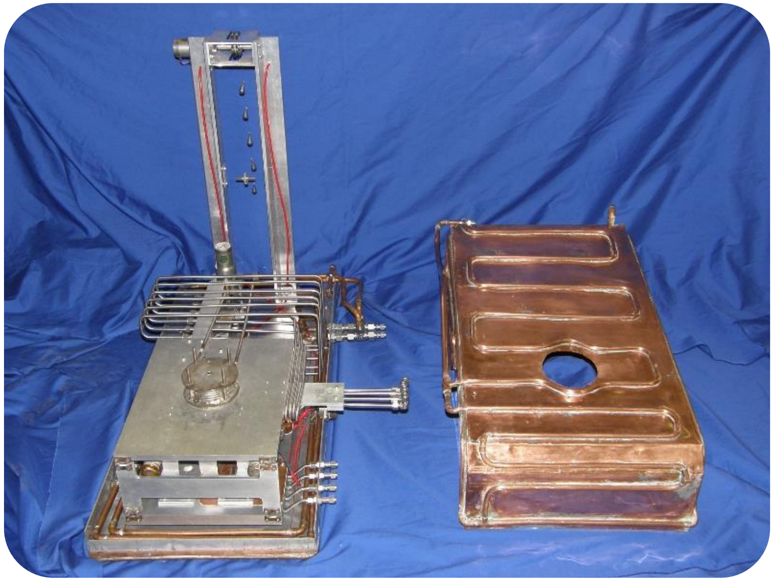
Vacuum Test Facility-1:

- Effective pumping speed of 125,000 L/s on argon.
- Base Pressure: [2.4×10^{-5}] torr.
- Operating Pressure: [4.8 to 5.7×10^{-5}] torr over full range of flow rates.

Thrust Stand:

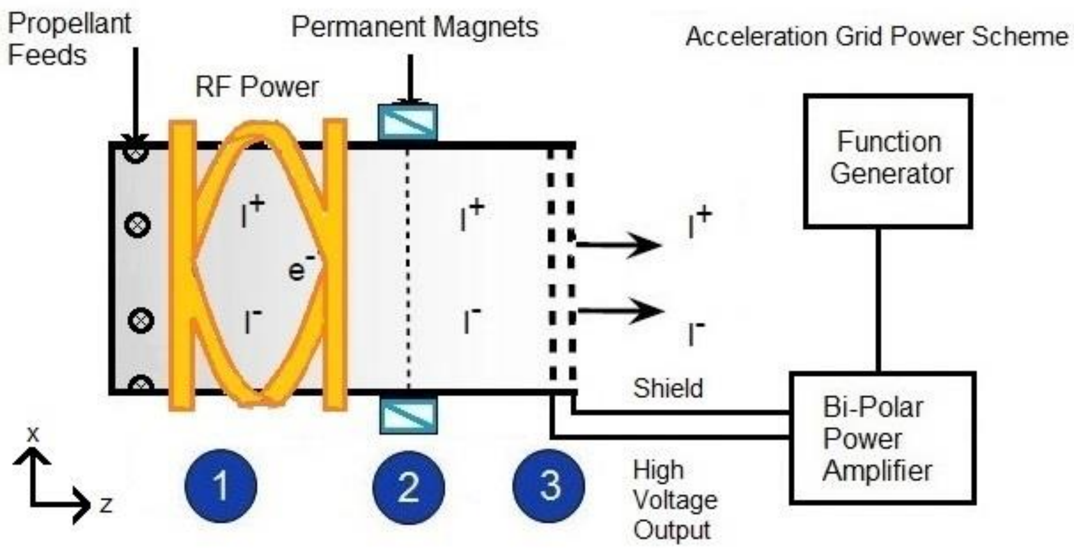
- Null-type, inverted pendulum.
- LVDT measures position, (2) E.M. actuators control assembly motion.
- Recorded null coil current corresponds to thrust generation.



Results: Configuration C1

Grid Bias Scheme 2:

- Sinusoidal waveform at 125 kHz.
- Only successful sinusoidal grid bias scheme required 24 sccm.
- Initial thrust spike of 3.75 mN that immediately falls below thrust stand noise floor.

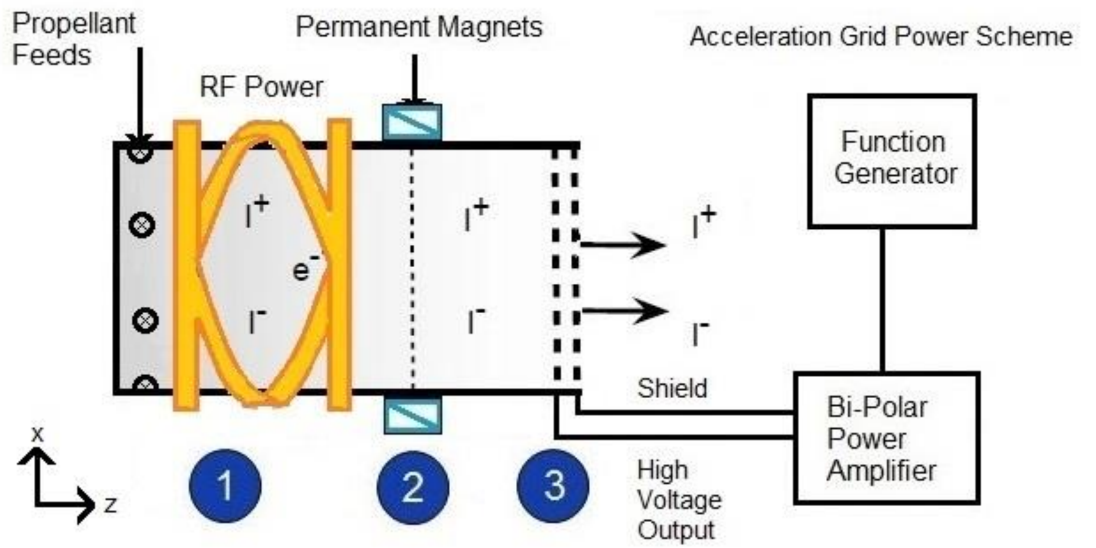


Grid Bias Scheme	Total Vol. Flow Rate	Ar:N Ratio	RF Pwr	Potential Thrust	Thrust Error	Description of Thrust Behavior
2	24 sccm	5:1	350 W	~3.75 mN	±3mN	Single spike
5	6 sccm	5:1	150 W	~4.5 mN	±3 mN	Single spike at grid start up
5	10 sccm	5:0	350 W	~3 mN	±1.75 mN	Single spike at grid start up
5	12 sccm	5:1	350 W	~4.25 mN	±3.75 mN	Single spike at grid start up
5	24 sccm	5:1	150 W	~3 mN	±2.5 mN	Repeated spikes

Results: Configuration C1

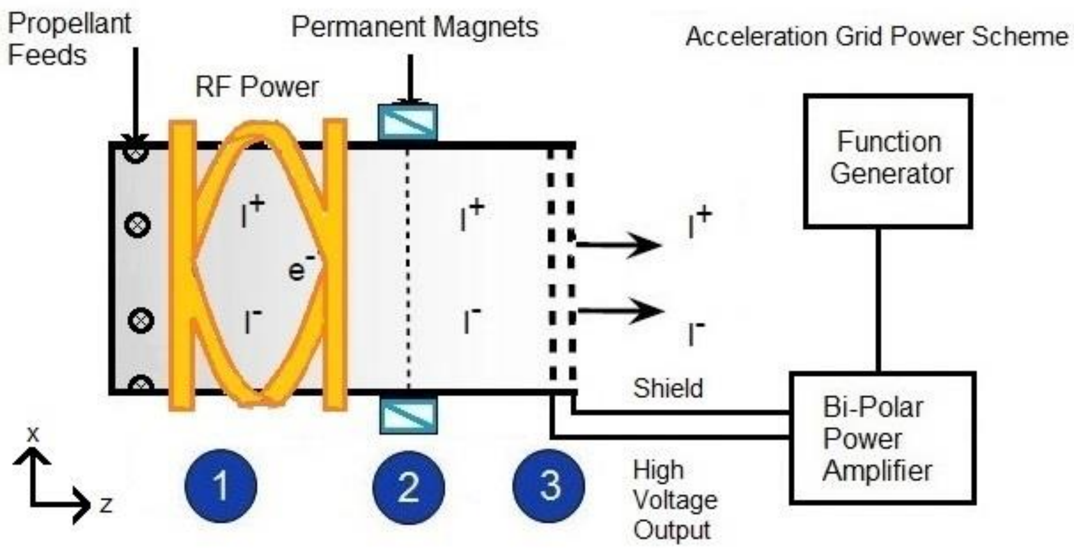
Grid Bias Scheme 5:

- Square waveform at 10 kHz.
- All cases exhibit single thrust spike at start of thruster operation with the exception of the 24 sccm case.
- 24 sccm case exhibits repeated spikes of thrust.



Grid Bias Scheme	Total Vol. Flow Rate	Ar:N Ratio	RF Pwr	Potential Thrust	Thrust Error	Description of Thrust Behavior
2	24 sccm	5:1	350 W	~3.75 mN	±3mN	Single spike
5	6 sccm	5:1	150 W	~4.5 mN	±3 mN	Single spike at grid start up
5	10 sccm	5:0	350 W	~3 mN	±1.75 mN	Single spike at grid start up
5	12 sccm	5:1	350 W	~4.25 mN	±3.75 mN	Single spike at grid start up
5	24 sccm	5:1	150 W	~3 mN	±2.5 mN	Repeated spikes

Analysis: Configuration C1



Grid Biasing:

- Success of square waveform grid biasing consistent with results of simulations from Reference 2.

Confirmation:

- Thrust data recorded during stand alone operation of grid assembly confirms thermal and electrical loading did not contribute to thrust.
- RF ignition occurs before activation of grids and initial thrust spike.

General Plasma Behavior: Extinction

- Thruster self extinguished at 6 sccm, 150 Watt RF power operating condition – original design operating condition.
- Additional volumetric flow rate required for steady operation will decrease specific impulse and propellant utilization.

Analysis: Configuration C1

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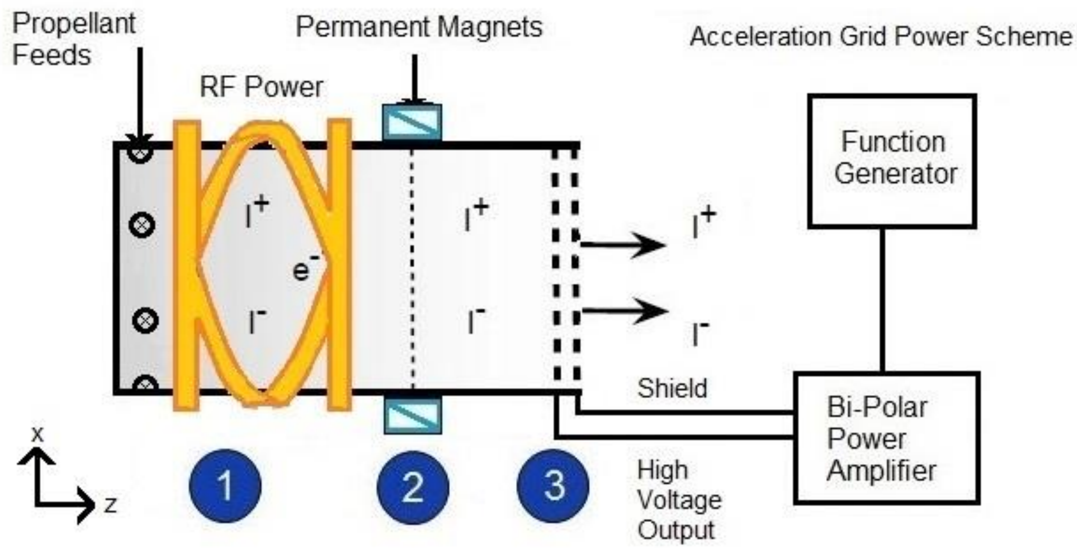
High Vac Plasma Behavior:

- 30 sccm minimum flow and 300W RF required at high vac
- Sinusoidal and square waveforms degrade to triangular waveforms



Final Observations on C1

- Continuous thrust no observed in any grid biasing scheme tested
- Scheme 5 (square wave, 10 kHz) was ‘best’, yielding thrust ‘spikes’ at various operating parameters
- Perhaps owing to N2 not being electronegative-enough to form sufficient nubers of negative ions
- A better electronegative gas (SF_6 or I_2) may produce better results

Results: Configuration C2

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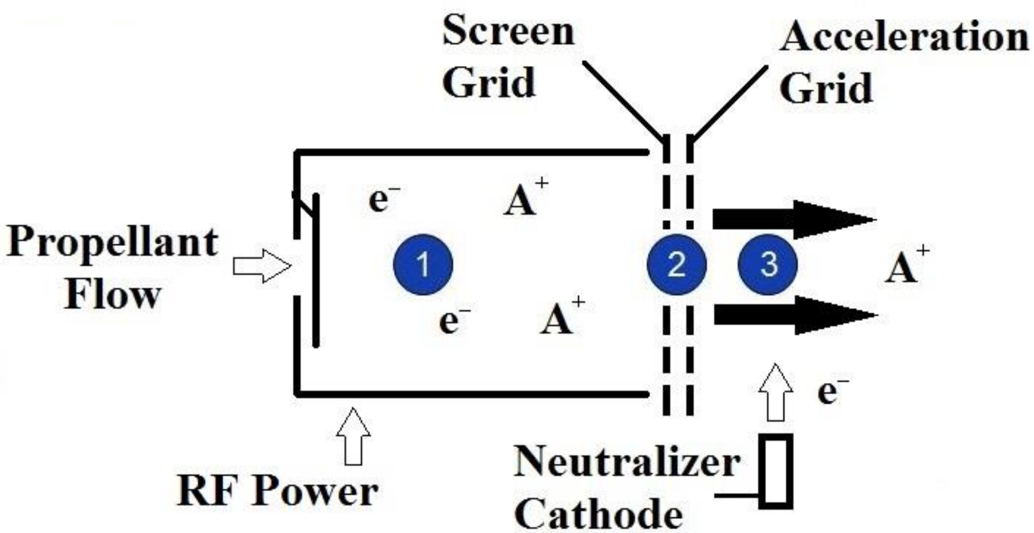
Operation as a traditional ion thruster (no electron filter)

- No ignition at high vacuum
- Ignition at 1.3×10^{-4} torr, 40 sccm, and 1 kW RF power
- After ignition, testing performed at $4.8\text{-}5.7 \times 10^{-5}$ torr



Observations on C2

- No combination of operating conditions tested yielded discernable, sustained thrust
- Brief thrust spikes in the
- Scheme 5 (square wave, 10 kHz) was ‘best’, yielding thrust ‘spikes’ at various operating parameters
- Perhaps owing to N2 not being electronegative-enough to form sufficient nubers of negative ions
- A better electronegative gas (SF_6 or I_2) may produce better results
- At 125 and 225 kHz, 6 sccm, visible depletion of the plasma upstream of the grids

Future Direction

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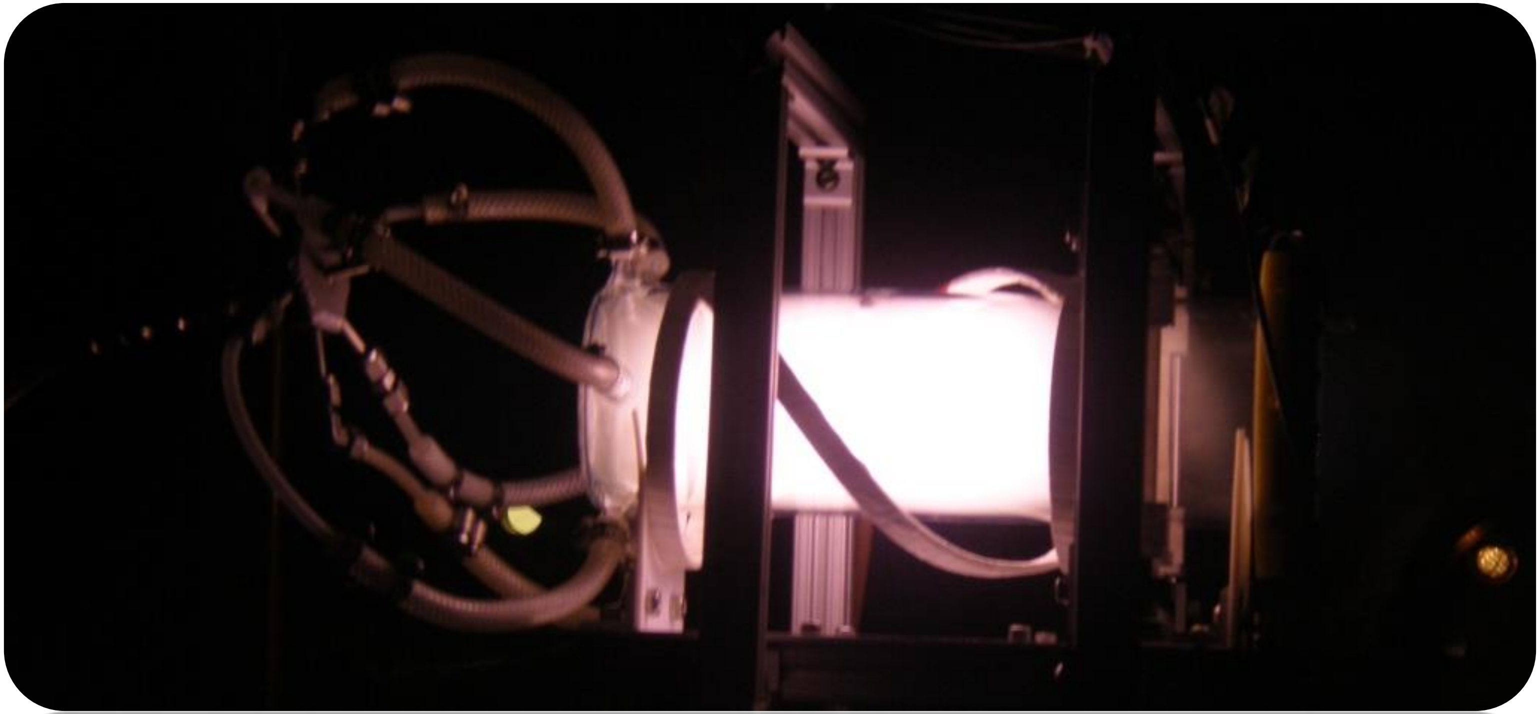
<u>Upcoming:</u> Direct Thrust Measurements conducted at Marshall Space Flight Center with a propellant mixture of argon and sulfur hexafluoride focusing on Grid Bias Schemes 2 and 5.



Thank you for your attention.

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Georgia Tech

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Advised by:

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