Updated Performance Measurements of the Phase Four RF Thruster

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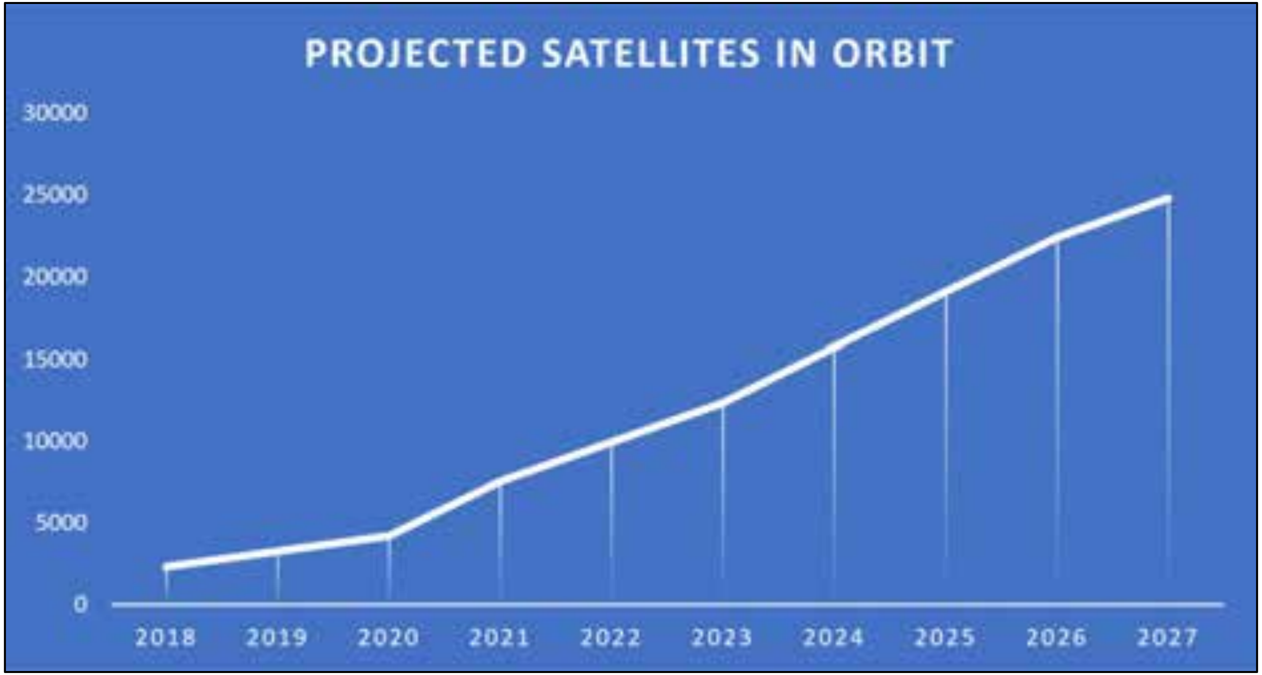
Small Satellite Market Driving Rapid Innovation



In 10 years, 10x satellites in Earth orbit

Need: mass-manufacturable propulsion system to move from launch orbit to value-generating orbit.

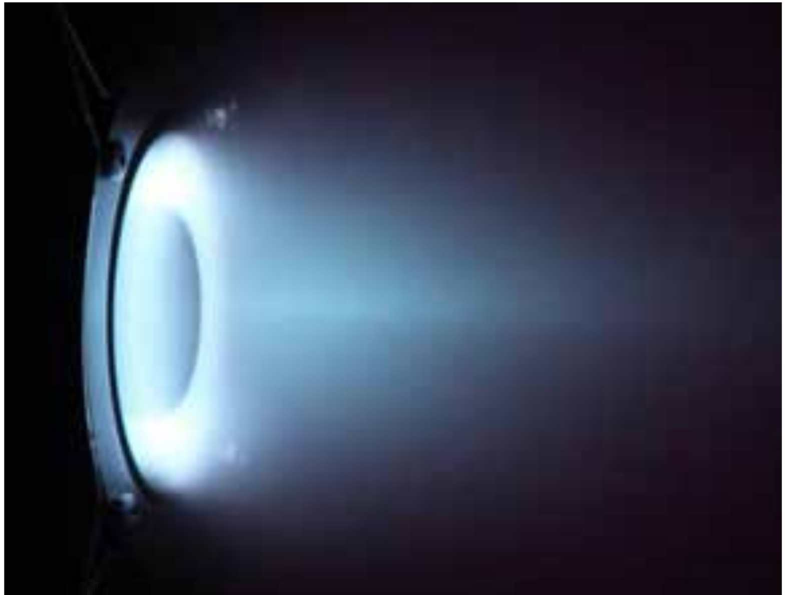
Traditional Electric Propulsion Systems

Advantages:

- Gridded Ion Engines (GIEs) and Hall Effect Thrusters (HETs) create thrust with very high fuel efficiency
- GIEs and HETs have been developed for decades, have flight heritage, and are trusted technologies

Disadvantages:

- Require an anode and cathode, which erode over time
- High voltage, complex power electronics
- Precision designs can be difficult to manufacture
- Subsystems are traditionally large, available in low volume



Hall Effect Thruster (credit: JPL)

Problem: traditional electric propulsion systems are complex and difficult to build

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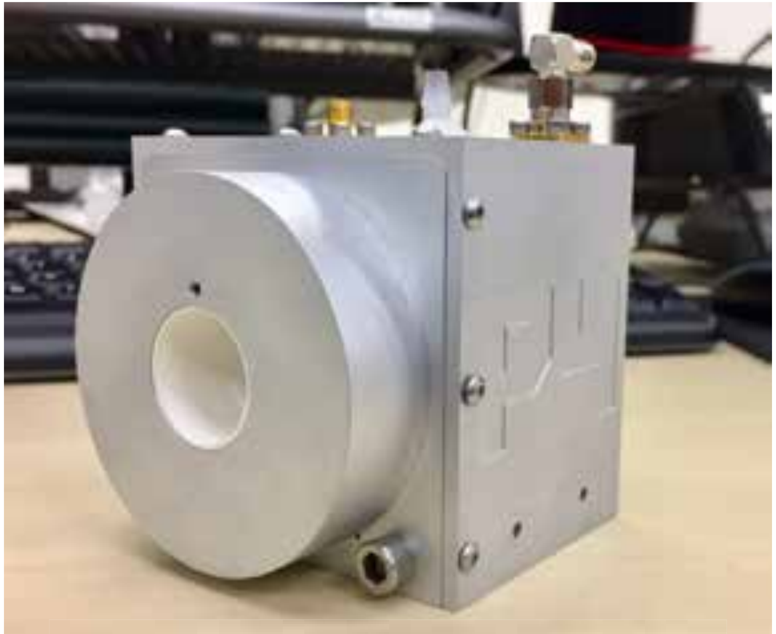
RF Electric Propulsion Systems

<u>Advantages:</u>

- Technology does not require an anode or cathode
- System does not require high voltage electronics
- Thruster geometry and subcomponents are simply manufactured

<u>Disadvantages:</u>

- New technology without flight heritage
- No compelling performance ever demonstrated



The Phase Four RFT-2 test unit on a computer desk.

Problem: RF thrusters are promising but have so far have only been unproven concepts.

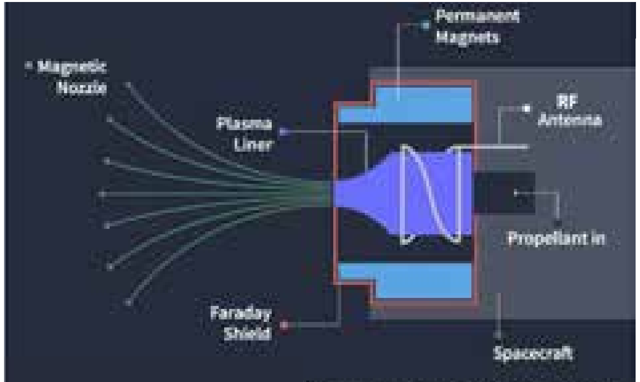
The Phase Four RF Thruster

Differentiating Approach:

- Leverage small scale DC-RF electronics miniaturization
- Miniaturize the plasma volume to maximize heating
- Full R&D cycle in house at P4 - design/mfg/test
- Simple design - most complex fabrication involves 3 axis CNC mill

Enables:

- RF thrusters to scale from CubeSat applications to large satellite applications
- Reduced thruster costs, manufacturable at scale
- High performance, electrodeless, low cost, low mass electric satellite thruster



A diagram of the Phase Four RFT.

The Phase Four RFT firing at 120 W in the laboratory.

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Testing The Phase Four RF Thruster

The Phase Four RFT-0 on the thrust stand.

- Torsional pendulum thrust stand at The Aerospace Corporation
- Pendulum deflects when thruster fires
- Pendulum displacement calibrated to known force, revealing thruster output

The Phase Four RFT-2 on the thrust stand during a hot fire (side view).

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Previously Tested RFT-0 Validates Concept

Metric	Phase Four RFT-0[1]	Takahashi 2011[2]	Shabshelowitz 2013[3]	Williams 2013[4]
Thrust [mN]	3.5 to 5	2.7	4.9	6
Specific Impulse [s]	120 to 170	459	120	350
Power [W]	102 to 121	700	961	840
Mass [kg]	2.8	>50	>50	>50
Size	3U CubeSat	Table Top	Table Top	Table Top

Miniaturized RFT-0 achieves same performance as tested RF thrusters at fraction of size, power, & mass

Problem: RFT still not close to meeting performance of existing HETs and GIEs

[1] Presented at International Electric Propulsion Conference, 2017 (Siddiqui et al., IEPC-2017-431)
[2] Takahashi et al., APL, 98, 141503, 2011
[3] Shabshelowitz et al., JPP, 29, 3, 2013
[4] Williams et al., JPP, 29, 3, 2013

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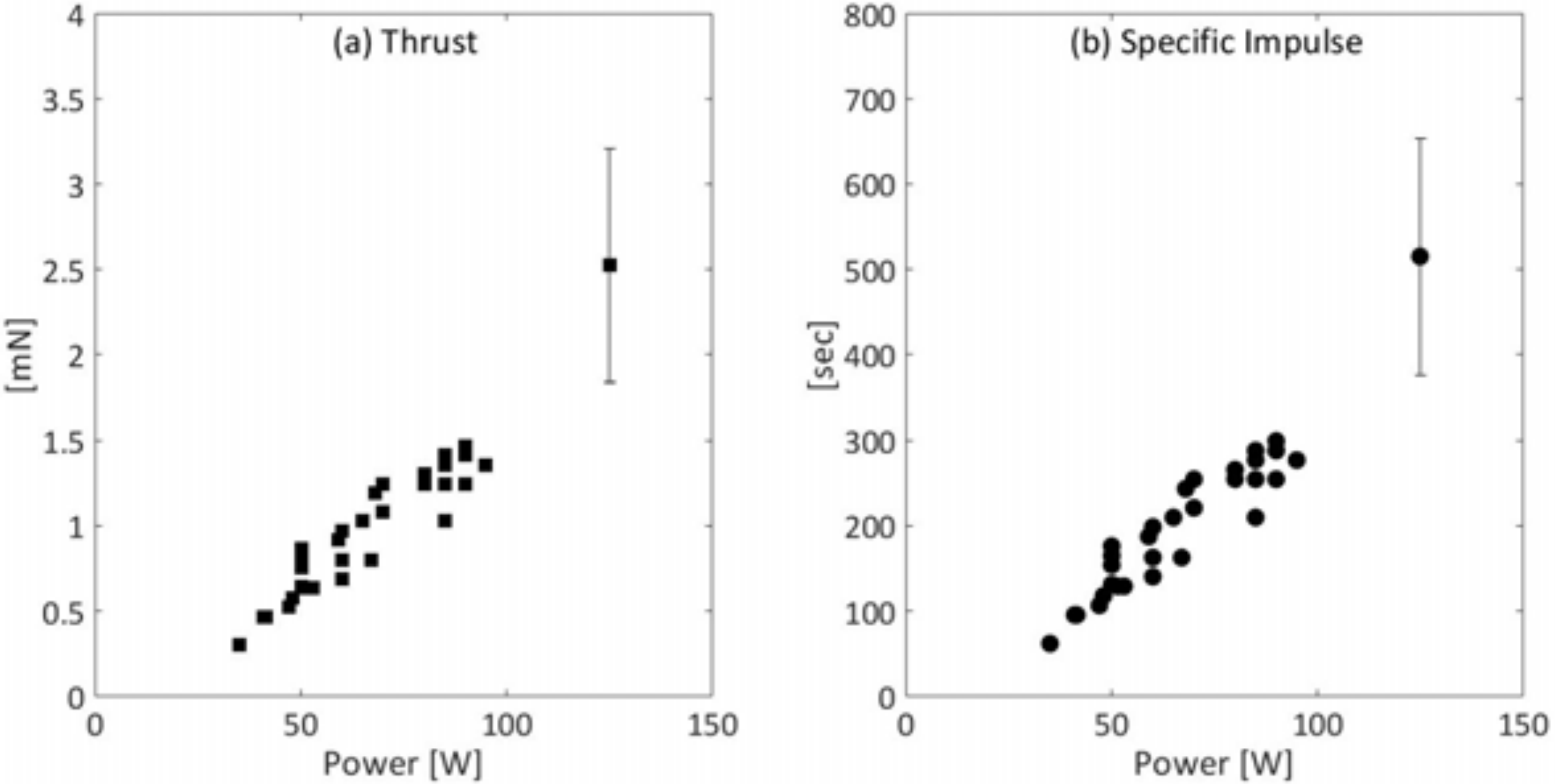
RFT-2 Demonstrates First RF Thruster Scaling



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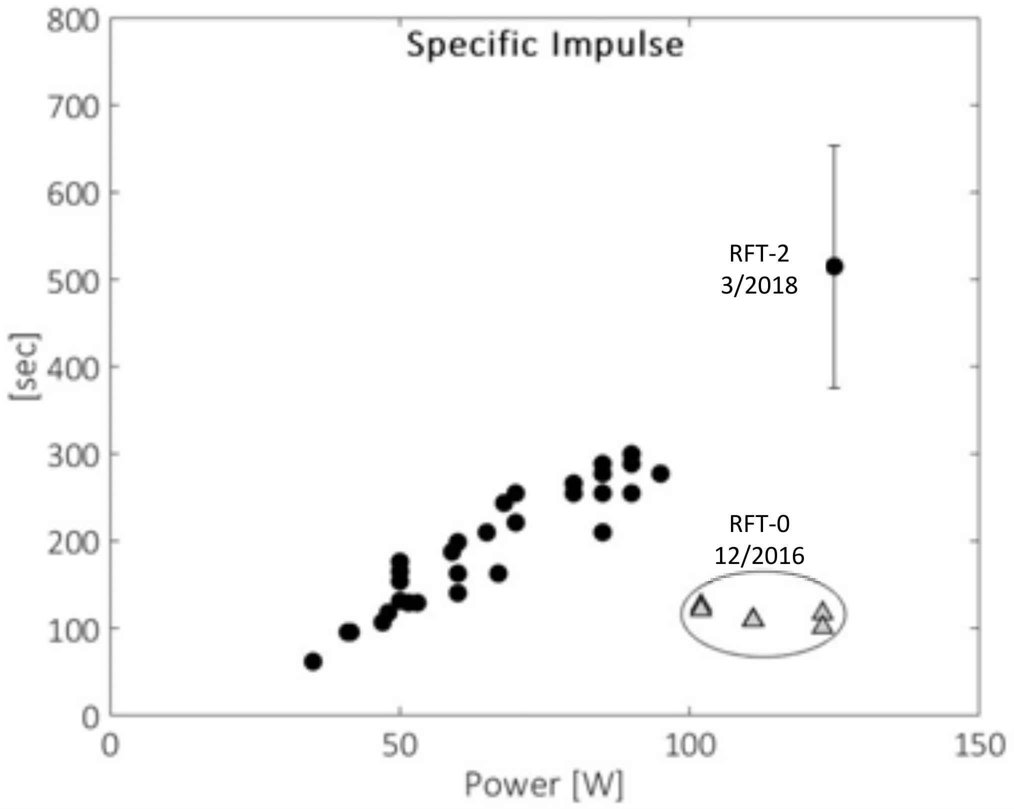
Comparison to Previous Generation

- Isp scaling: 3.5 to 6.5 seconds per Watt
- 4x to 6.5x improvement at 120 W compared to RFT-0
- Meets or exceeds every RF thruster ever directly tested, at < 10% mass and < 20% power input

RFT-2 is the highest performance (Isp/Power) electrodeless RF thruster demonstrated



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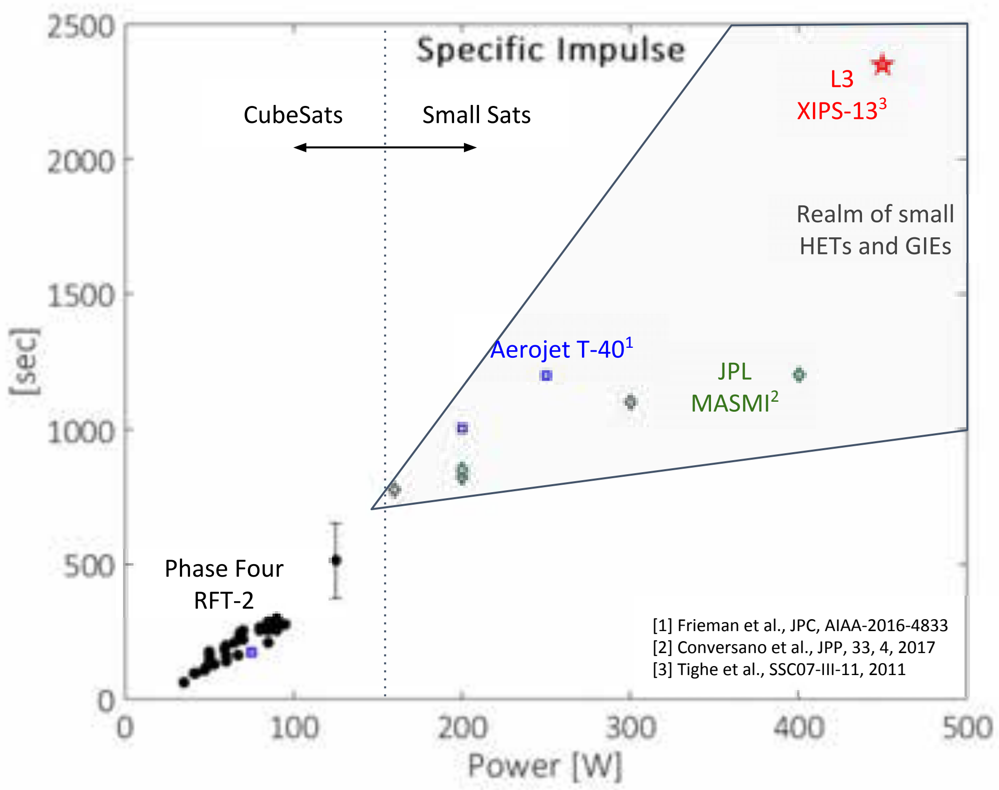
Comparison to Existing State of the Art

- Isp scaling: 3.5 to 6.5 seconds per Watt
- Comparable Isp scaling to small HET and GIE thrusters
- RFT-2 entering high power test regime to measure performance scaling & long duration testing up to 400 W
- Results to be presented at AIAA P&E Forum, 7/2018

RFT-2 testing is about to enter regime dominated by small HET and GIE thrusters



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Summary

- Phase Four RFT uses miniaturization of electronics and thruster to achieve high performance, electrodeless RF thruster
- Results demonstrate Isp/Power scaling in CubeSat power regime comparable to small HET/GIE scaling
- Upcoming measurements to demonstrate performance and long duration results this summer


Top down view of the RFT-2 firing in the laboratory.

RFT-2 represents true electrodeless, low cost, mass manufacturable thruster with performance scaling comparable to SoA

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