PHASE FOUR

Lessons Learned from Maxwell

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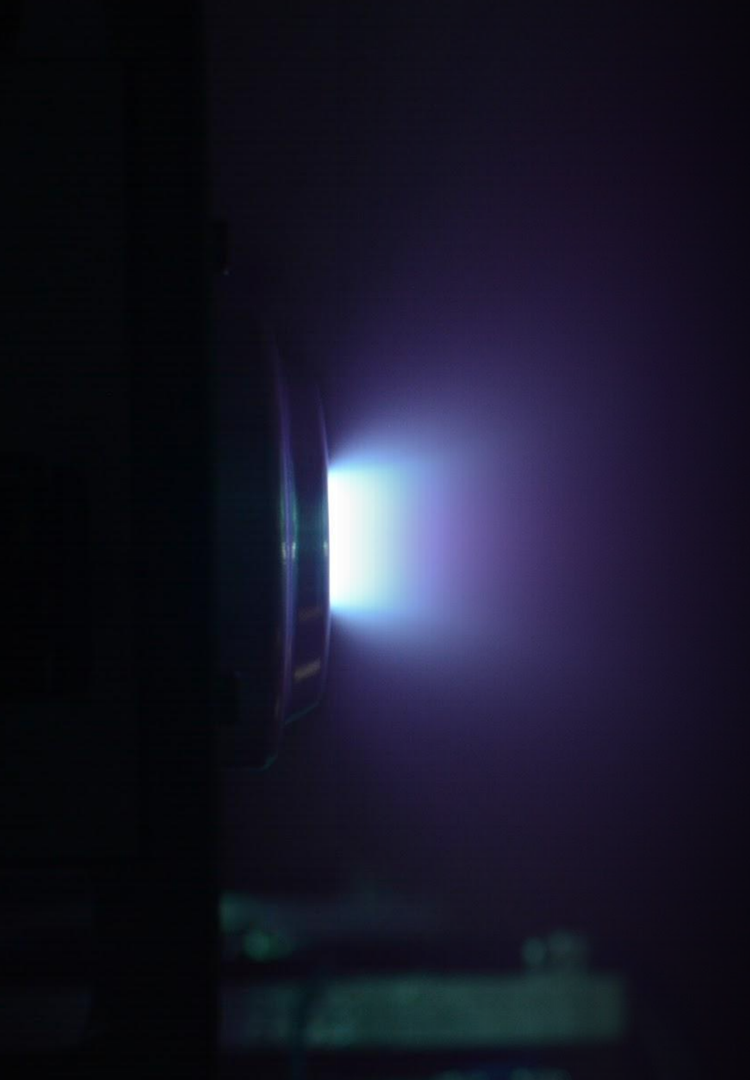
ISSC Conference
Session C: Propulsion and Launch Capabilities
May 11, 2020



Agenda

- Phase Four overview
- Small sat electrodeless propulsion
- Design enablers and challenges
- The future of electrodeless thruster development
- Conclusions

Phase Four Overview

2014-2015
Tech Origin

April, 2015
Company
Founded

August, 2015
$1M TTO Contract

December, 2016
First Thrust
Validation

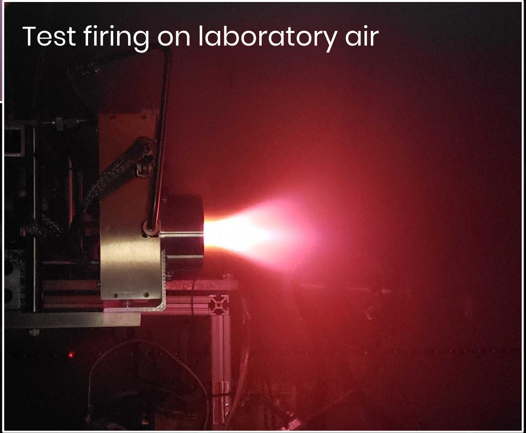
July, 2018
First release of
500 W, 10% efficiency

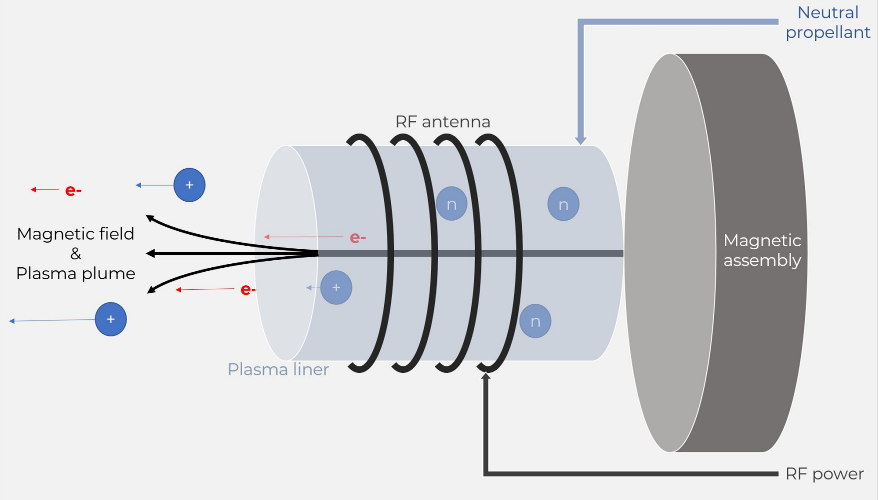
December, 2018
Product and customer
announcement

Q1 2020
First flight hardware delivery

Radio-Frequency Thruster Overview

How do RFTs work?





Non-representative diagram of RFT core components

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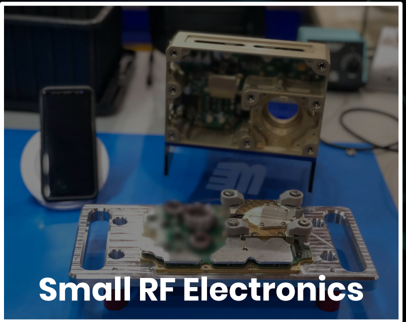
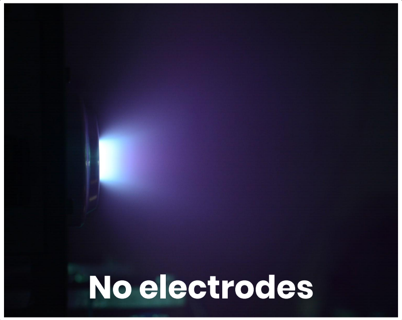
Core Technology Innovations:





Enabling Technology Capabilities:

Mass-manufactured, redundant supply chain

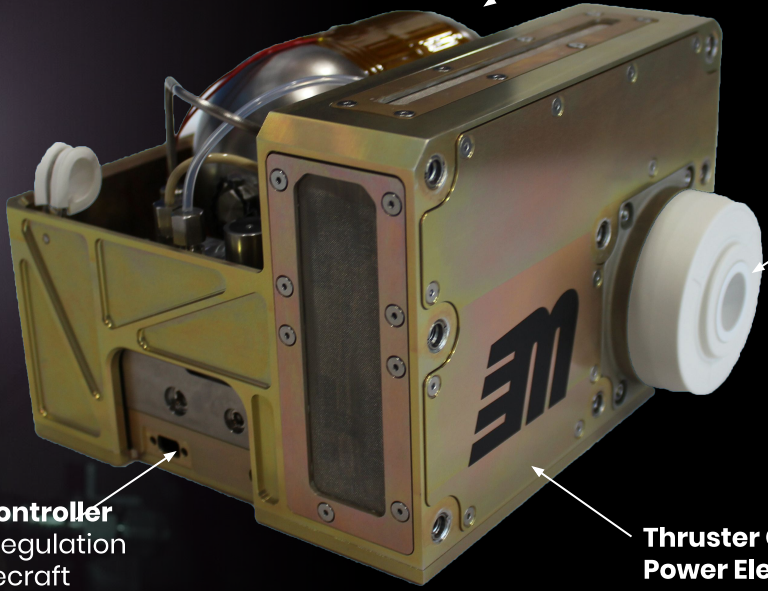
Plasma propulsion that fits on small sats

Uniquely able to operate with many propellants

Enables low cost, high delta-V missions

Maxwell Overview

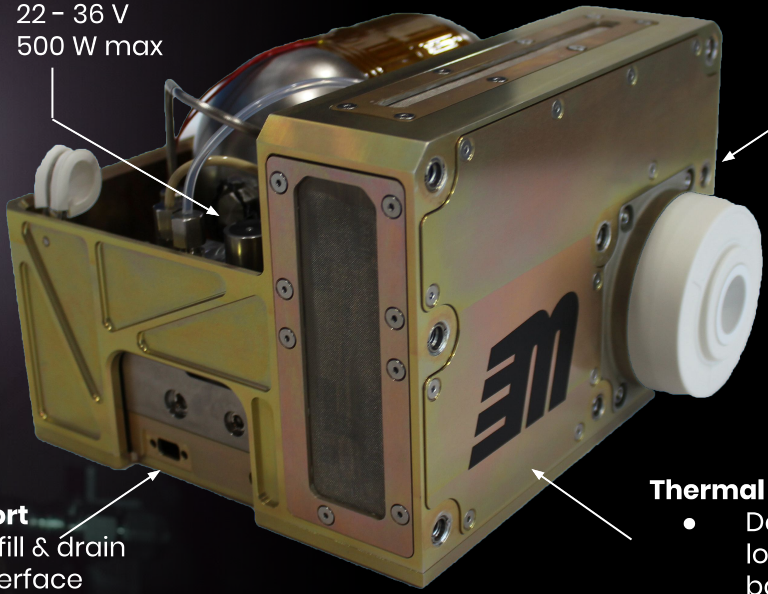
Size:	7.5” x 7.5” x 5.5”
Mass:	7 kg wet
Power:	Up to 500 W
Thrust:	4-10 mN
Impulse:	Up to 10 kNs



Maxwell Overview

Telemetry (hidden)
- 9 pin socket
- RS-422

Power (hidden)
- 4 pin header
- 22 - 36 V
- 500 W max



Mechanical
- 8 x ¼-20 screws in front panel

Communication Protocol:
- RS-422

Residual Dipole Moment
- < 2 Am^2

Ground Support
- Xenon fill & drain
- GSE interface
  - 9 pin socket

Thermal
- Defined heat conduction load through front panel based on operating condition

Customer example

Why RF propulsion for small satellites?

Why Maxwell?
The only engine that…

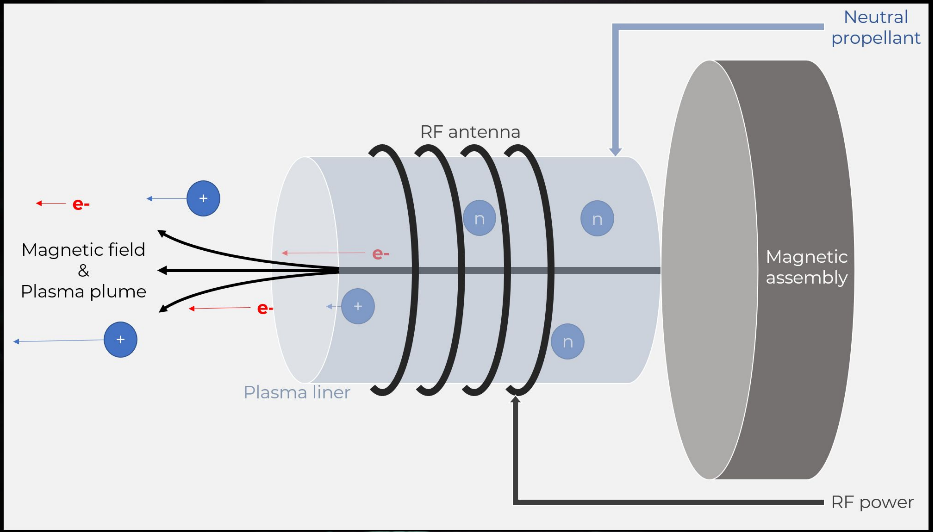
- Provides several mN of thrust
- Provides several kN-s of total impulse
- Fits

Capella Space

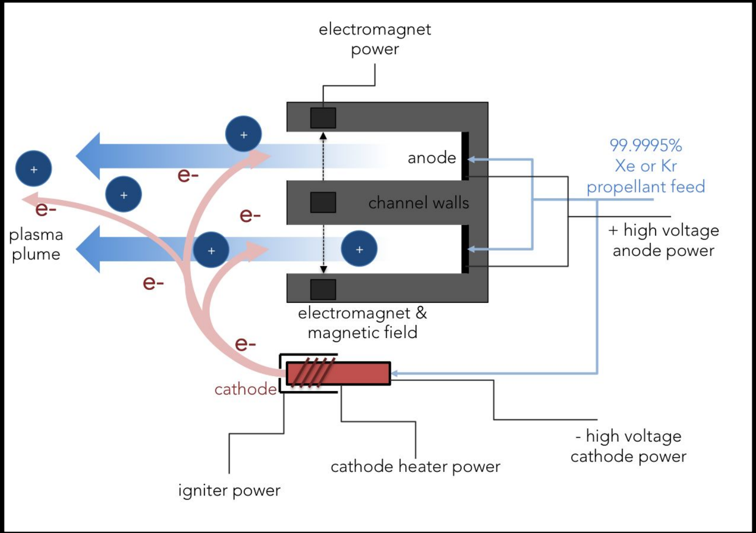
PHASEFOUR

Lessons learned - Technology enablers

No hollow cathode simplifies operations and reduces size



P4 RFT operational diagram



HET operational diagram
Adapted from [1]

[1] Pinero et al., "High Input Voltage Discharge Supply for High Power Hall Thrusters Using Silicon Carbide Devices," IEPC-2013-388 (2013)

Lessons learned - Technology enablers

No hollow cathode simplifies operations and reduces size

To ignite an electrodeless RF thruster:

1. Ignition:
   a. Set gas flow into liner
   b. Apply power to RF antenna, can ramp to operational power as fast as 100 ms

To ignite a Hall thruster [1]:

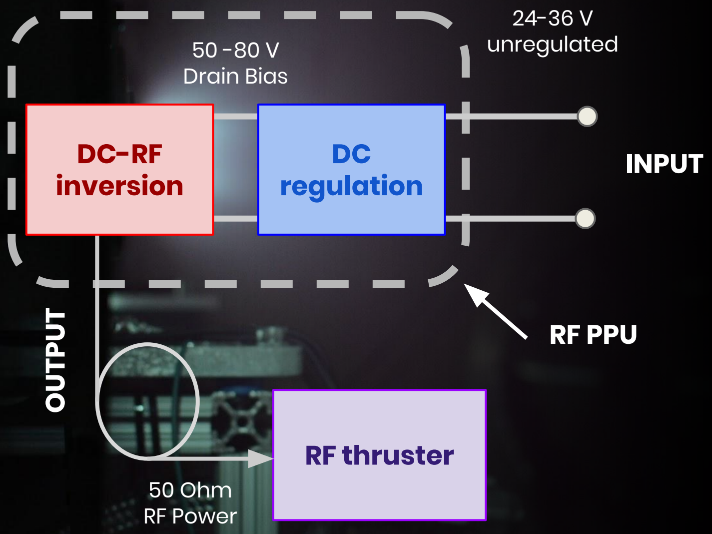
1. Conditioning:
   a. Gradually ramp up cathode heater current, typ. 35 minutes
   b. Typ. cathode temperature 900-1100 deg C
   c. This process can be shortened modestly for subsequent ignitions
2. Ignition:
   a. Set cathode & anode gas flow
   b. Set cathode & anode bias voltages
   c. Operate high voltage igniter circuit to initiate discharge

[1] Rubin & Williams, Journal of Applied Physics, Vol 104, No. 053302 (2008).

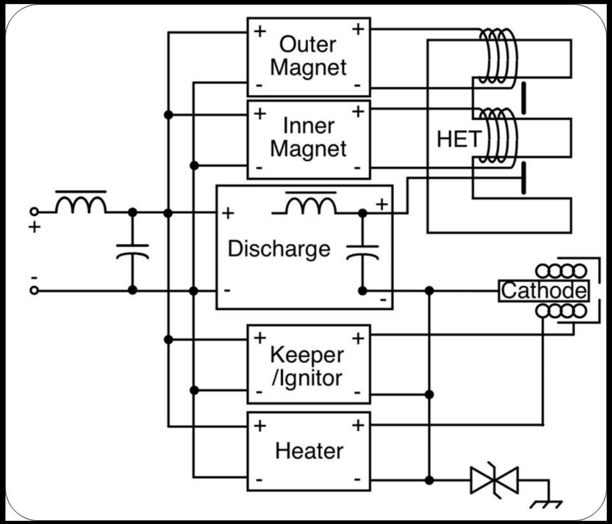
Lessons learned - Technology enablers

RF electronics are small & efficient - driven by the wireless power industry [1]

Phase Four PPU High Level Architecture



HET PPU High Level Architecture [2]



[1] Yates et al., "A 100-W 94% Efficient 6-MHz SiC Class E Inverter with a Sub 2-W GaN Resonant Gate Drive for IPT", Wireless Power Transfer Conference, IEEE (2016).
[2] Pinero et al., "High Input Voltage Discharge Supply for High Power Hall Thrusters Using Silicon Carbide Devices," IEPC-2013-388 (2013)

Lessons learned - Technology enablers

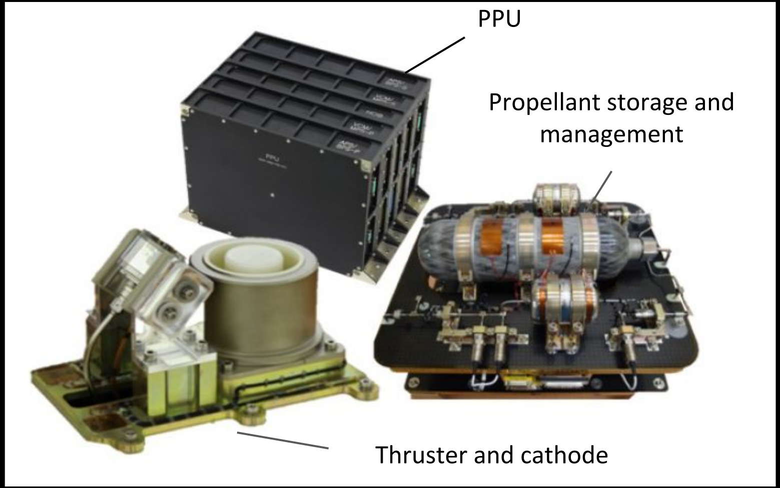
RF electronics are small & efficient - driven by the wireless power industry [1]

<u>Phase Four PPU Installation into Maxwell</u>

Installation of 500 W PPU into Maxwell chassis
Proprietary details blurred out of focus

PPU Mass: 0.65 kg

<u>HET Subsystems [2]</u>



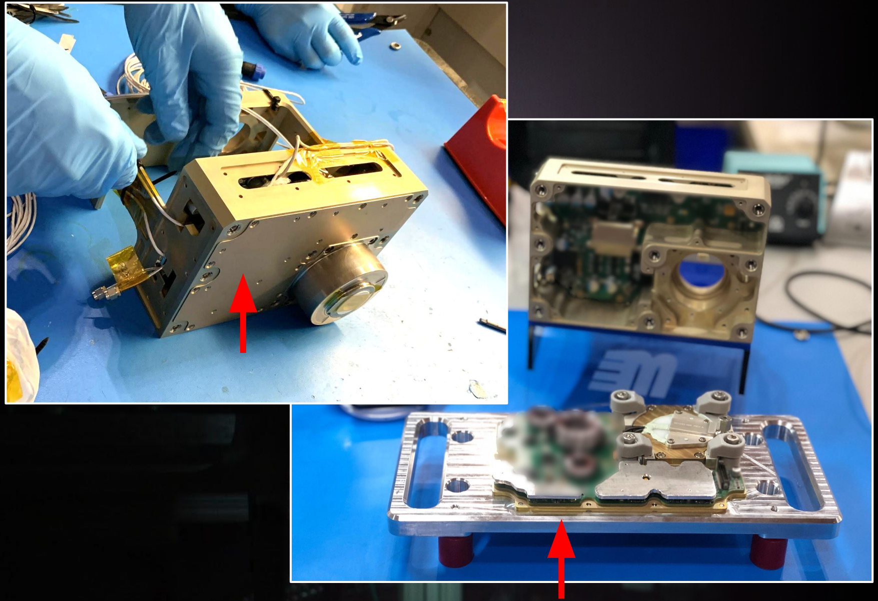
Example 300 W HET

PPU Mass: 10 kg

[1] Yates et al., "A 100-W 94% Efficient 6-MHz SiC Class E Inverter with a Sub 2-W GaN Resonant Gate Drive for IPT", Wireless Power Transfer Conference, IEEE (2016).
[2] Lee et al., "Development of Low Power Hall Effect Propulsion System with Improved System Efficiency for Small Satellite Applications," SP2018-00181 (2018)

Lessons learned - Technology challenges

Thermal engineering requires strict definitions and close interfaces



Background:

- Traditional plasma propulsion designed for long duration operations
- Thermal load on spacecraft necessitates that thrusters are outboard and radiate their heat away, relaxing constraints on the bus [1]
- Small satellite applications require
    - shorter, more frequent thrust operations
    - compact, integrated form factor

Approach:

- Treat Maxwell as an RF electronic system
- Mount PPU power electronics to baseplate
- Baseplate compresses to spacecraft thermal structure when propulsion system is mounted
- Baseplate carries heat from thruster + PPU onto the spacecraft thermal structure
- Spacecraft thermal management system determines power, and thrusting duty cycle

[1] Myers et al., "Hall Thruster Thermal Modeling and Test Data Correlation", AIAA Propulsion and Energy Forum (2016).

Lessons learned - Technology challenges

How to minimize residual dipole moment with magnet assemblies

The problem:

- Permanent magnets on board small plasma thrusters create permanent dipole moments on the spacecraft that are torqued by LEO magnetic fields

The solution:

- All permanent magnets have a cancellation pair mounted no closer than critical distance to primary magnet, forming a quadrupolar assembly
- +80% of residual dipole moment comes from magnet piece variability in magnetization strength
- Phase Four worked directly with the magnet manufacturer to deliver flight magnets in controlled batches, with individually measured dipole moments

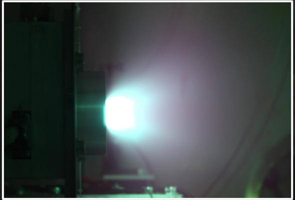
Where next with electrodeless propulsion?

Enable new capabilities by advancing development on new propellants

2017

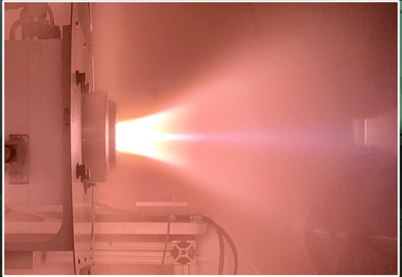
100 W, Xe

2018



500 W, Xe

TODAY



Gen 2 Design

Xe | Kr | I_2 | O_2 & N_2

TOMORROW

Unpressurized propellants

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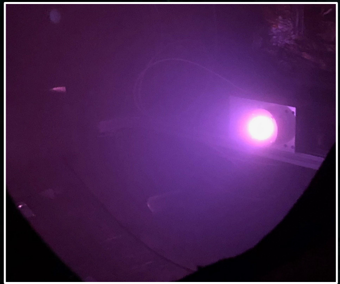
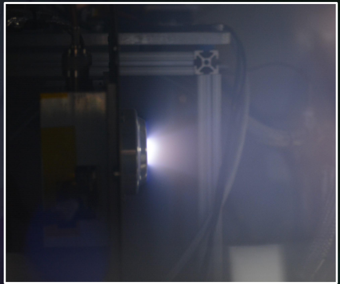
Xe, 400 W

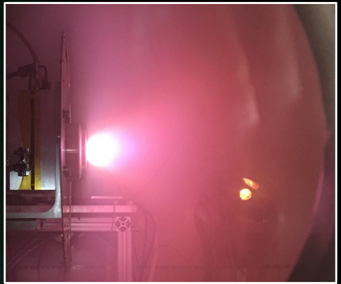


Kr, 200 W

H2O, 200 W



IPA, 100 W



Air, 100 W