Thrust Stand Measurements of an RMF-FRC Thruster with Continuous Power System

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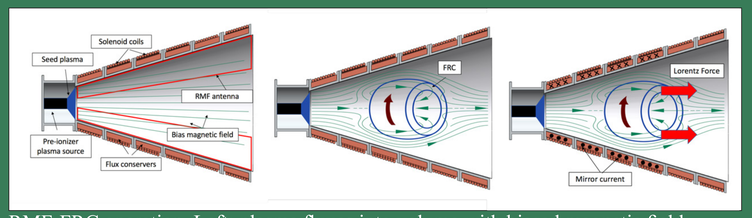
EAGLE HARBOR TECHNOLOGIES

Introduction

Eagle Harbor Technologies, Inc. (EHT) developed a continuously-operating repetitively-pulsed power system for the University of Michigan (UM) Rotating Magnetic Field (RMF) – Field-Reversed Configuration (FRC) Thruster. EHT leveraged a previously designed resonant full bridge in single-burst mode to develop a continuously-operating repetitively-pulsed system at 4 kW of average power. The EHT solid-state power system can drive peak currents of ±2 kA at 500 kHz in the inductive RMF coils. UM integrated the power system with the thruster and conducted performance measurements in their Large Vacuum Test Facility. With the EHT power system they demonstrated parametrical control of the thruster performance (thrust, specific impulse, and efficiency) by varying the plasma input energy, neutral flow rate, and applied magnetic field. The new EHT power system and UM thruster upgrades improved the coupling efficiencies from ~3% to more than 50% and active specific impulses approaching 1000 s, while allowing for a direct thrust measurement. This is the first direct performance measurement of a continuously operating RMF–FRC Thruster using a standard inverted-pendulum thrust stand in space-like conditions.

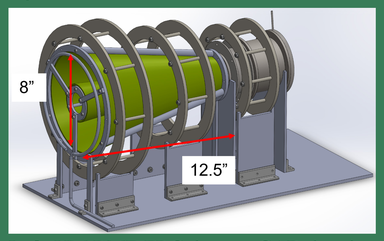
RMF-FRC Thruster Concept

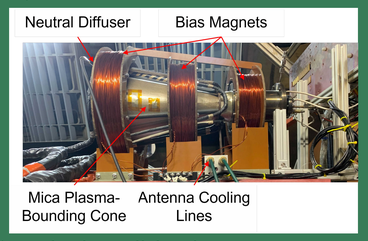


RMF-FRC operation. Left: plasma fluxes into volume with biased magnetic field. Middle: RMF antenna generates azimuthal current in plasma giving rise to field reversal. Right: Lorentz force interaction with background magnetic field and induced field in flux conservers drives acceleration.

UM RMF-FRC Thruster (V2)

UM constructed a second generation thruster out of G10/FRP to minimize conduction and used a scaffold structure to simplified fab. The plasma was bounded by mica sheets formed into cones, and an optional dielectric cone to better diffuse gas (not used in test). From the exit, neutral gas could be injected back into the conical thruster body.



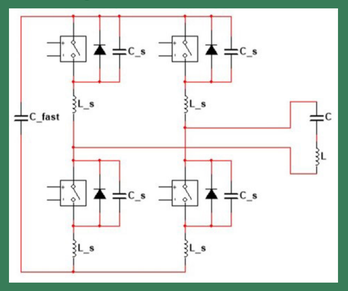


Left: UM RMF-FRC thruster CAD drawing (note that inner dielectric cone was not used). Right: Constructed thruster on bench prior to installation in the vacuum chamber.

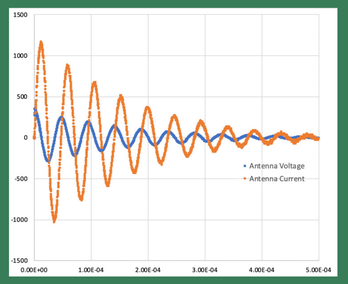
RMF-FRC Thruster Power System

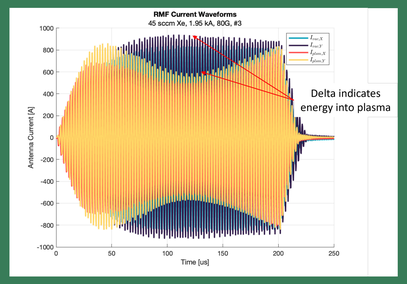
The Gen 1 thruster power system was a charged capacitor and switched that was closed into the inductive antenna. The current and voltage waveforms in the antenna were an underdamped LCR circuit. This circuit was capable of delivering 2 J/pulse and could operate continuously at up to 1.2 kW.

EHT developed solid-state full bridge to drive a resonant LC network at the resonant frequency. The primary inductance is the RMF antenna and a tuning capacitor was added for an operational frequency of 400 kHz. EHT had previously built similar systems and the new work focused on building a continuously-operating repetitively pulsed system that could operate at 4 kW. Ultimately, this system output 4 kA_{pk-pk} in 200 µs bursts of 400 kHz RF. When operated at half current, it delivered 20 J/pulse at 2 kW.



Left: Circuit diagram of full bridge (with stray capacitance) driving a LC circuit. The bridge was operate at the load’s resonant frequency. Right: Thermal testing one RMF power system prior to installing in a rack.





Left: Current and voltage waveforms from Gen 1 underdamped LCR circuit power system. Right: Current waveforms from EHT driven resonant circuit. Blue waveforms are a vacuum shot of both antennas. Orange waveforms show the plasma loading the antennas.

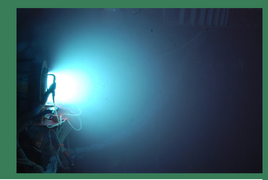
UM Large Vacuum Test Facility

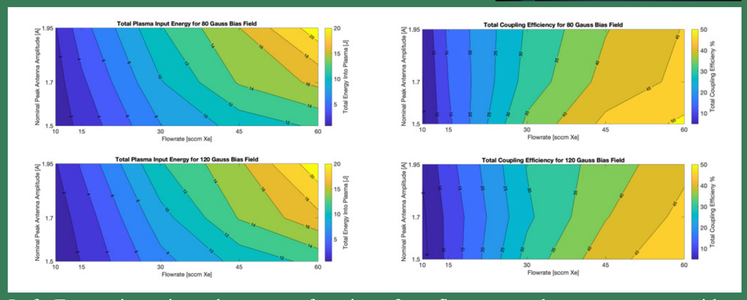
The vacuum chamber (6 m x 9 m) is cryogenically pumped (13 TM1200i Cryopumps and 6 PHPK Cryomech pumps) with measured speeds up to 520 kL/sec Xe. The facility can process up to 100 kW continuous power and contains an inverted-pendulum thrust stand that was operated in null mode.

UM Large Vacuum Chamber

Thruster Measurements

The thruster was operated at 75 Hz for 1-5 minutes. Max energy delivered to plasma is 20 J, which is likely to increase at higher currents. Coupling efficiency near 50%. Major driver is the flow rate (gas density).





Left: Energy input into plasma as a function of gas flow rate and antenna current with 80 G (top) and 120 G (bottom) bias field. Right: Total coupling efficiency as a function of gas flow rate and antenna current with 80 G (top) and 120 G (bottom) bias field.

	PEPL RMF V1	PEPL RMF V2
Waveform	Underdamped LC circuit	Driven LC circuit
RMF Frequency [kHz]	20 or 125	400
Max Antenna Current [kA_{pk-pk}]	2	4
Energy per Pulse [J]	2	20*
Average Power [kW]	1.2	4
Coupling Efficiency	1-3%	50%
Thrust [mN]	0	8 (543 ‘active’)

* Operated at 2 kA_{pk-pk} max. Higher energy per pulse is expected at higher current.

Conclusion

UM conducted first thrust stand measurement of CW RMF-FRC thruster in space-like conditions using an EHT RMF power system. The EHT power system was operated up to 4 kW continuous with repetitive 200 µs bursts of 4 kA_{pk-pk} with up to 500 kHz RF. UM characterized thruster performance with the damped LC circuit and EHT power system and showed improved coupling from 3% to 50% and improved thrust from unmeasurable to 8 mN (543 mN ‘active’).

In future work, EHT plans to implement water cooling to increase the average power which should increases gas efficiency, specific impulse and average thrust. UM plans to optimize the magnetic field and gas injection schemes. For more info: http://www.eagleharbortech.com/

Acknowledgment

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