

The Plasma Ambipolar Thruster for Responsive In-Orbit Transfers (PATRIOT) Mission

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Outline

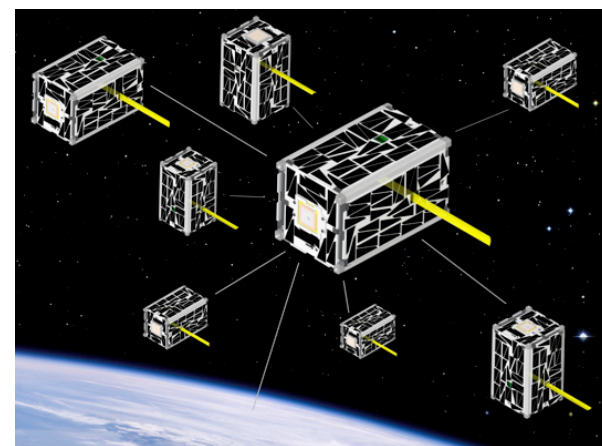
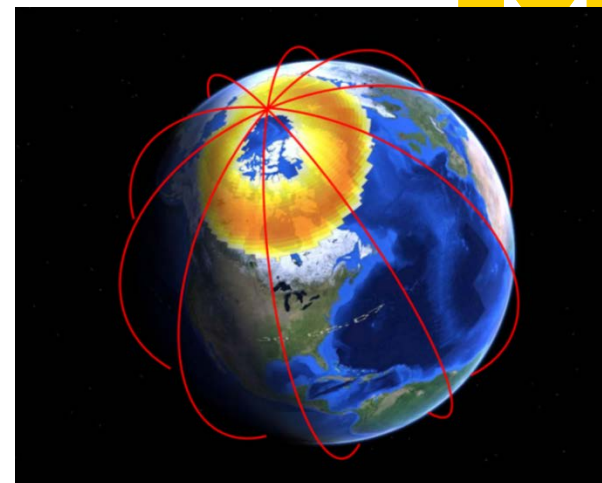


- Propelled nanosatellite missions
- The CubeSat Ambipolar Thruster (CAT)
 - Design
 - Magnetic field
 - Initial firing
- Micronewton thrust stand
- PATRIOT mission goals

Maneuverable CubeSats could enable many new missions

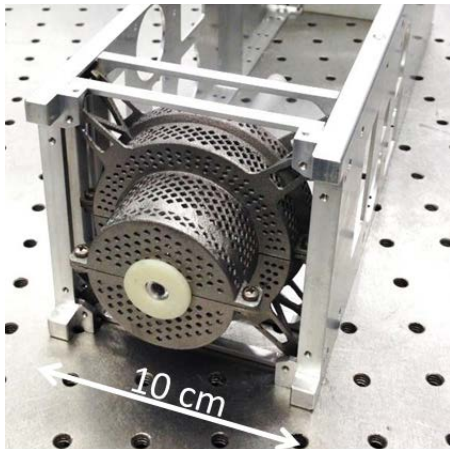


- Previously inaccessible orbits
 - Orbits that are not accessed by launch vehicle
 - Highly elliptical orbits
 - Geostationary orbits
 - Polar orbits
 - Earth-Moon, Earth-Sun Lagrange points
- Cluster formation flying
- Long-lived low altitude orbits

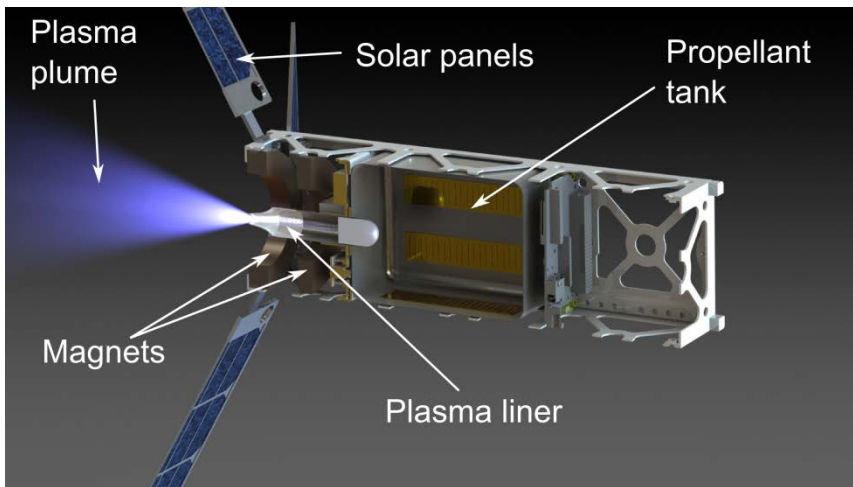


Credit: NASA

CubeSat Ambipolar Thruster (CAT)



- $\sim 0.6U$ for thruster
- Mass: < 1 kg
- $0.4U - 0.9U$ for propellant tank
- Uses “free” spring space

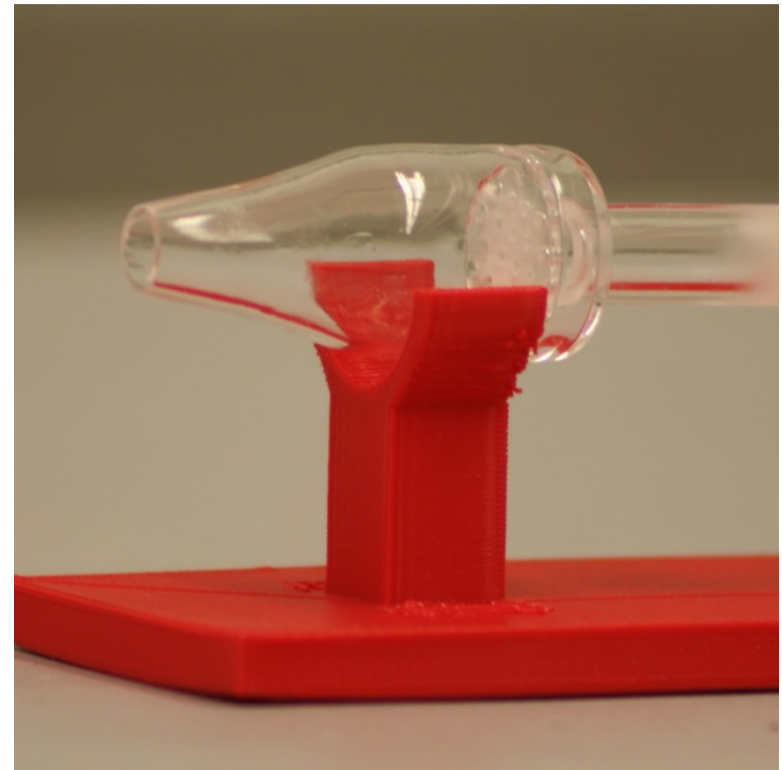


- $\sim 1U$ for spacecraft controls
- $0.5U - 1.0U$ for instruments
- Powered by 10s of V
- 10 – 50 W, assisted by batteries

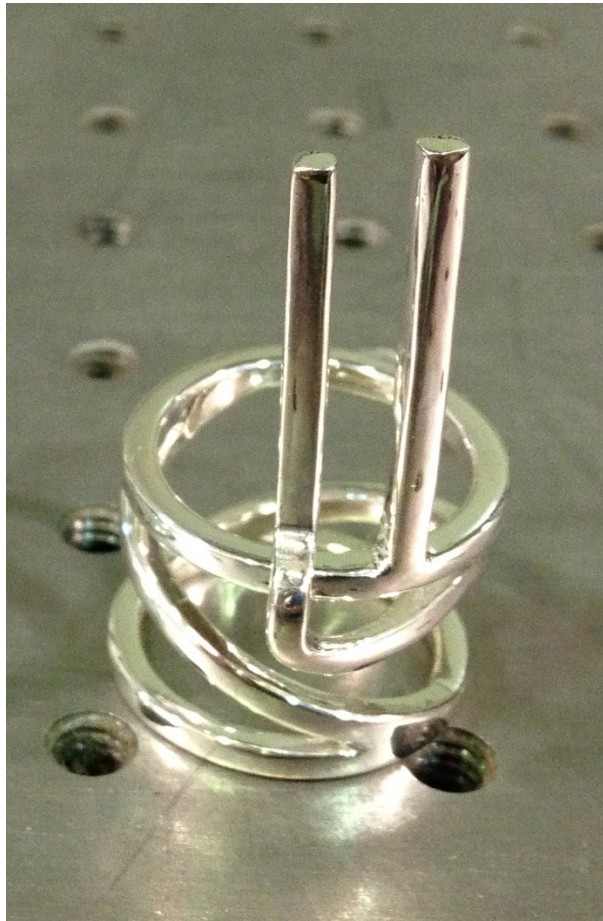
Plasma liner contains plasma, directs flow of gas



- Quartz tolerates high temperatures
- Showerhead disperses gas, protects downstream elements from plasma
- Physical nozzle follows magnetic nozzle



Antenna generates plasma, heats electrons

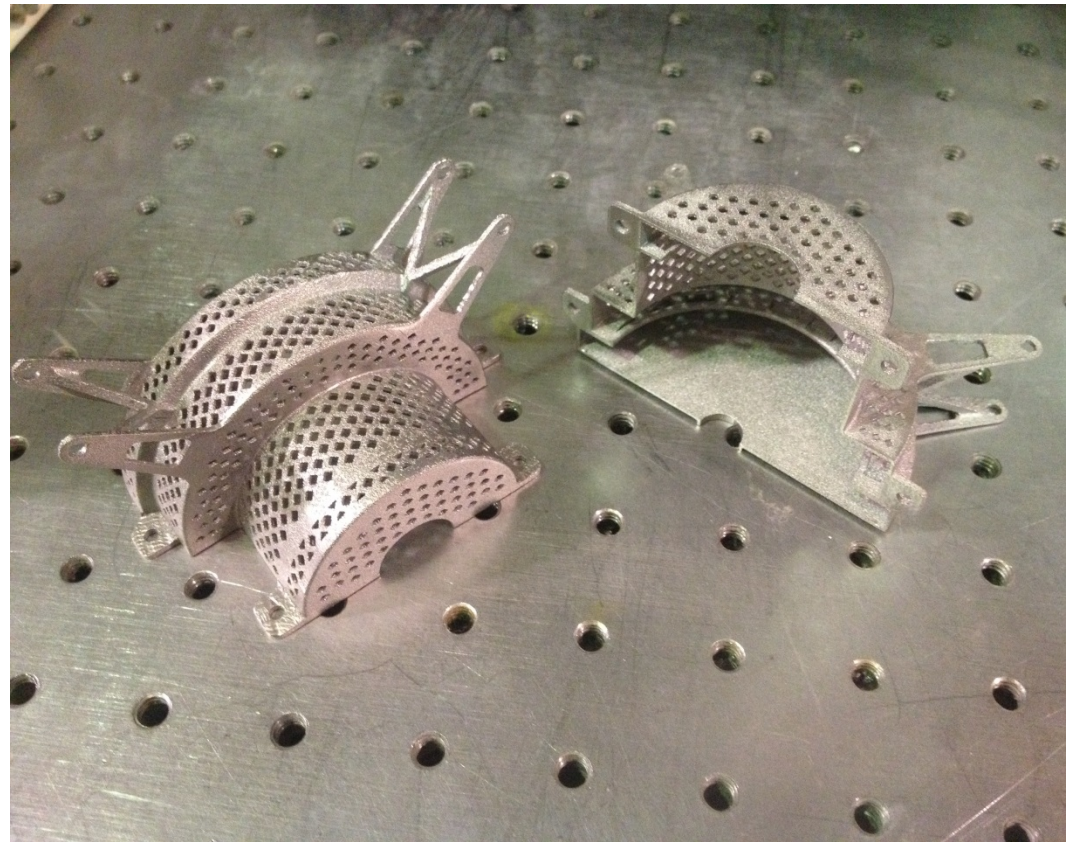


- 3D printed
 - Complex geometries possible
- Solid silver to maximize conductivity
- Helical half-twist
 - Ideal for launching helicon
- Power leads connect to RF source
- Couples RF energy into electrons via helicon plasma wave

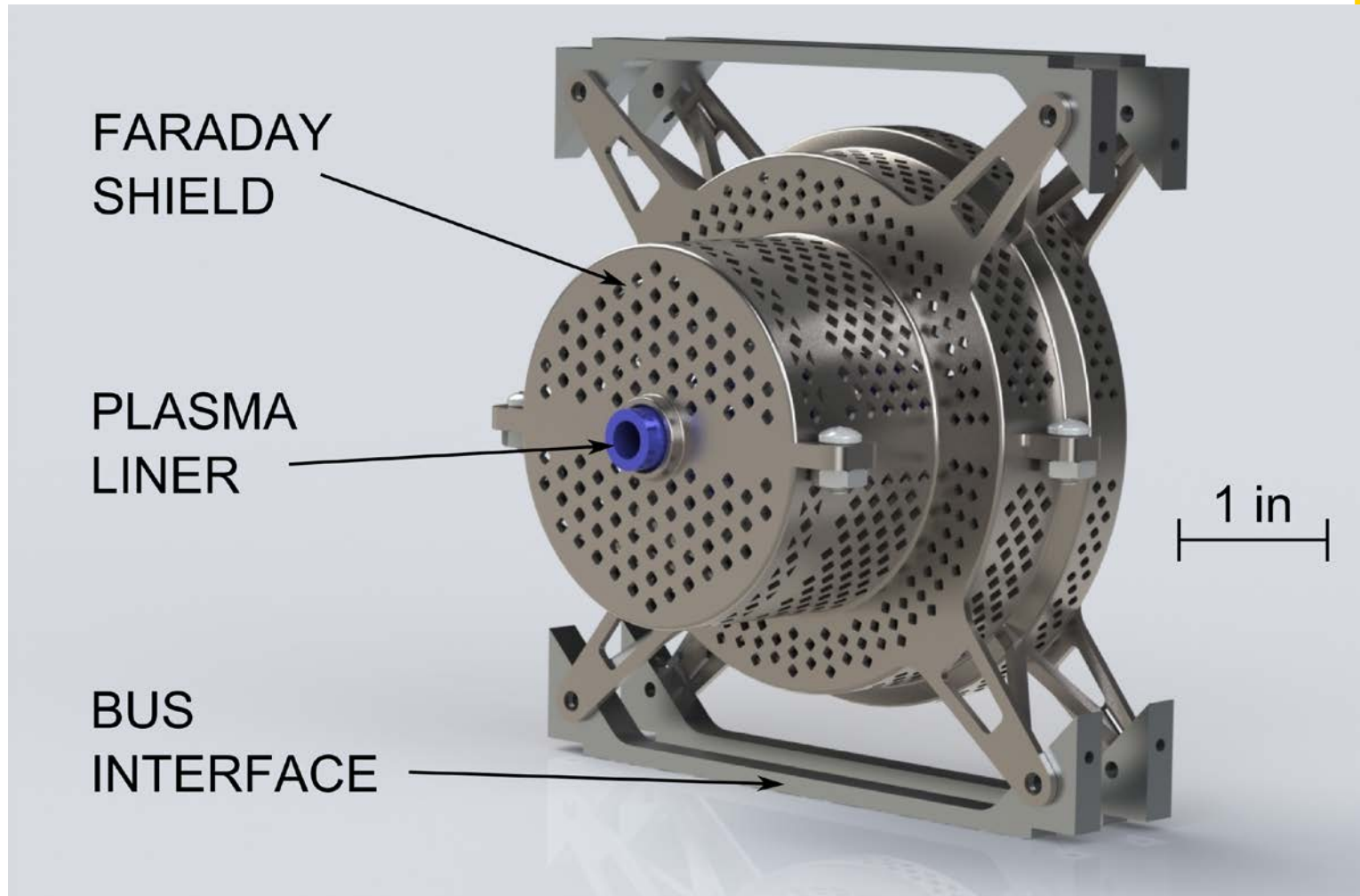
Faraday shield contains RF, encases thruster



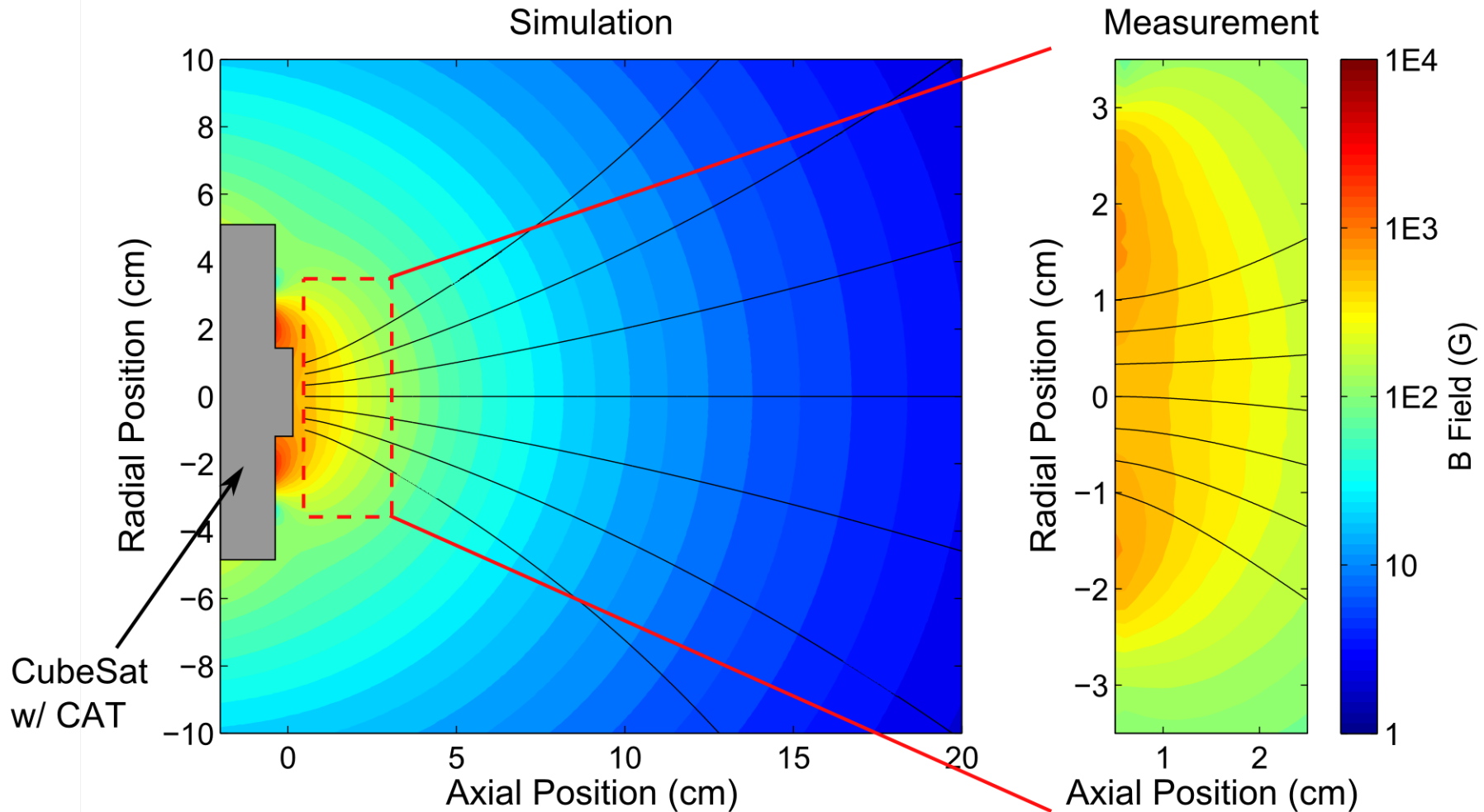
- 3D printed
 - Low cost
 - Rapid iteration
- Titanium
- Contains RF within thruster
- Structural support for liner, magnets



Fully assembled CAT engine



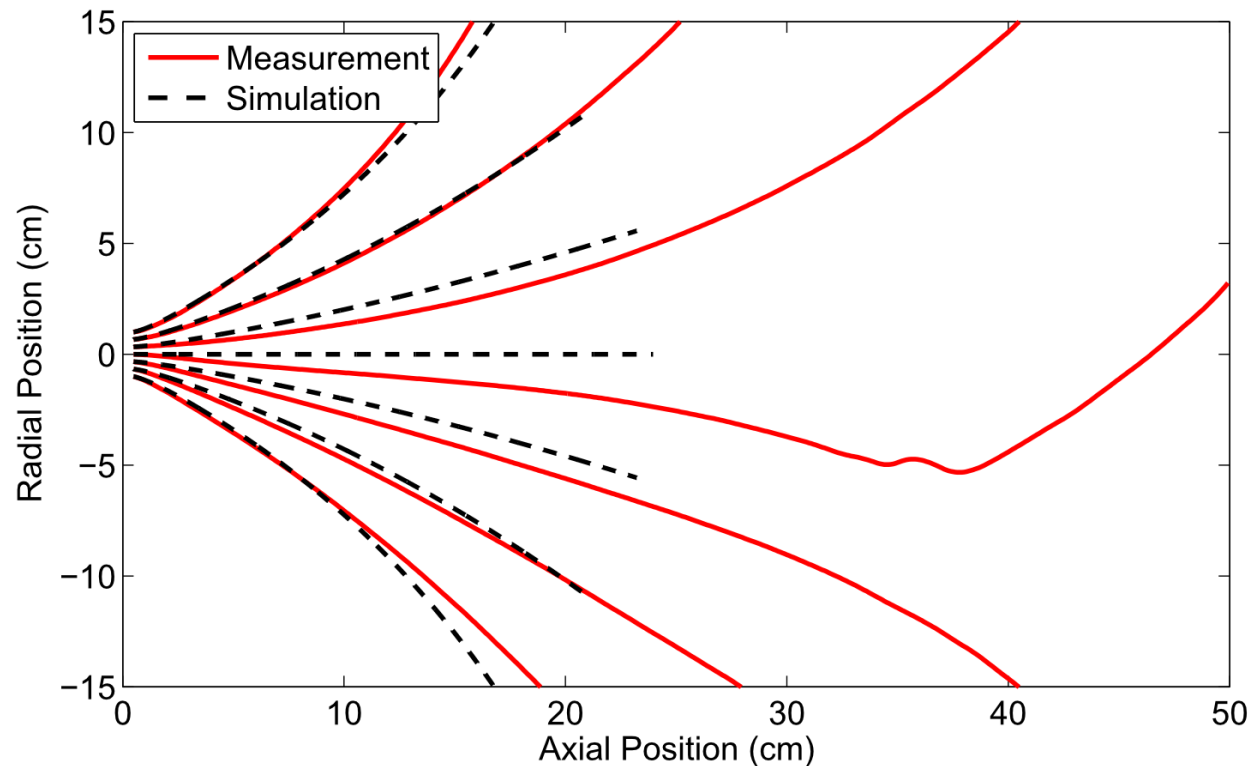
Magnetic nozzle replaces physical rocket nozzle



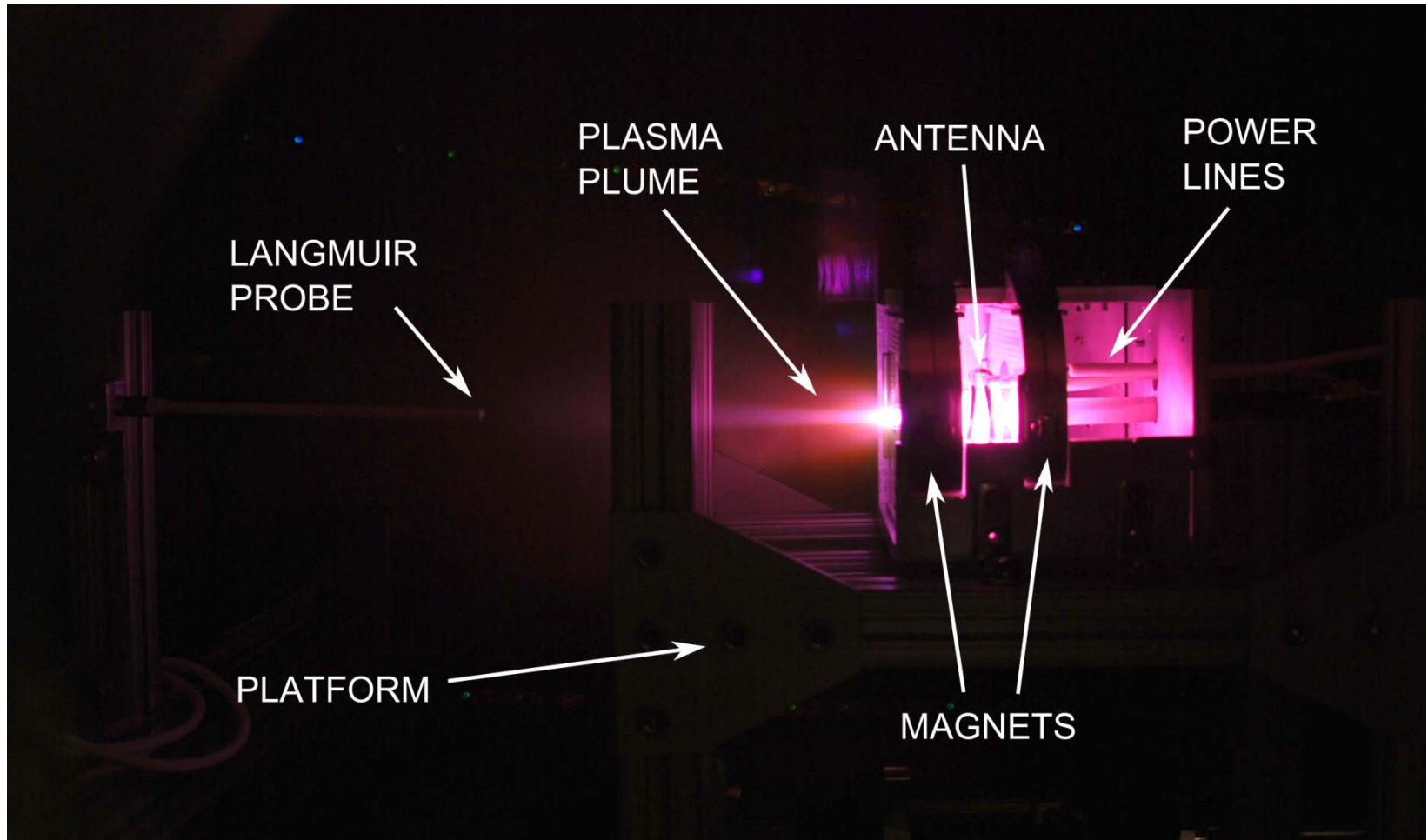
Measurements match simulations to within 10%



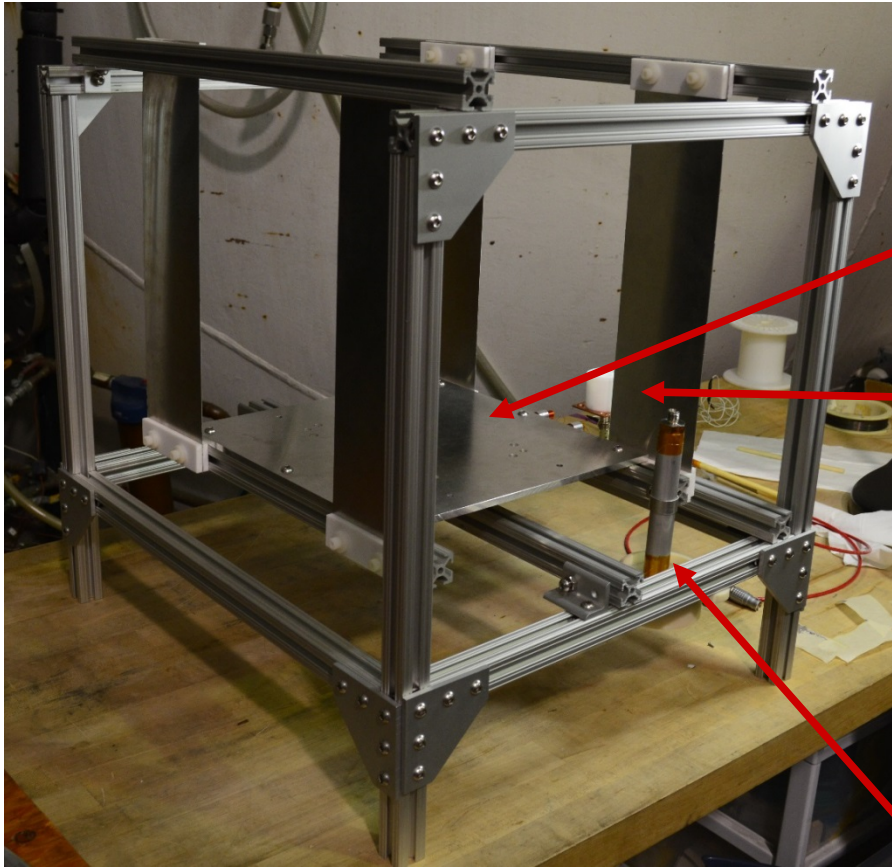
- Permanent magnets
 - No power requirements
 - Currently NdFeB
 - SmCo for higher Curie temperature
- Maximum strength in device of 800 G
- Net dipole moment of $55 \text{ A}\cdot\text{m}^2$
 - Dipole cancellation designs
- Earth's gravity takes over at $\sim 40 \text{ cm}$



Xenon testing: plasma follows magnetic field lines

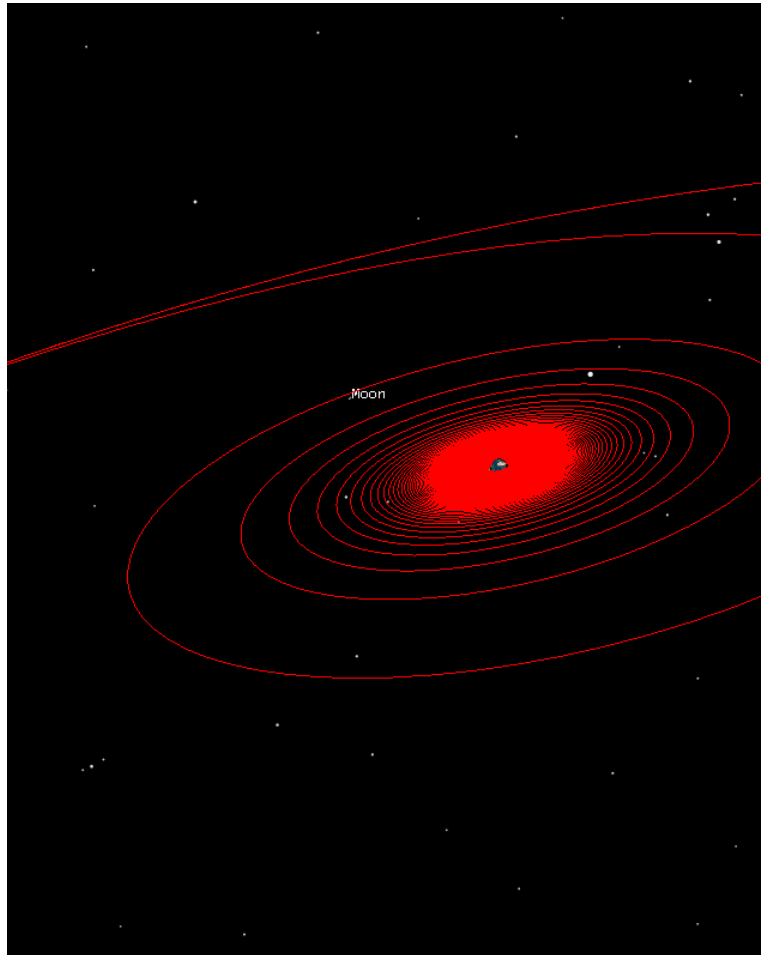


Beam-deflection micronewton thrust stand



- Measure 10s mN, resolution 10s μ N
- Thruster supported on mount plate
- Thrust moves plate, deflects thin beams
 - Euler-Bernoulli beam theory
- Deflection measured by optical displacement sensor (obscured)
- Tensionless gas feed system

PATRIOT mission will test CAT on orbit



- Objectives
 - Turn CAT on
 - Thrust measurement
 - Observable orbit change
 - Earth escape
- Multiple flights
- Non-propulsion requirements
 - Long range communications
 - Power systems
 - Attitude control
 - RF shielding

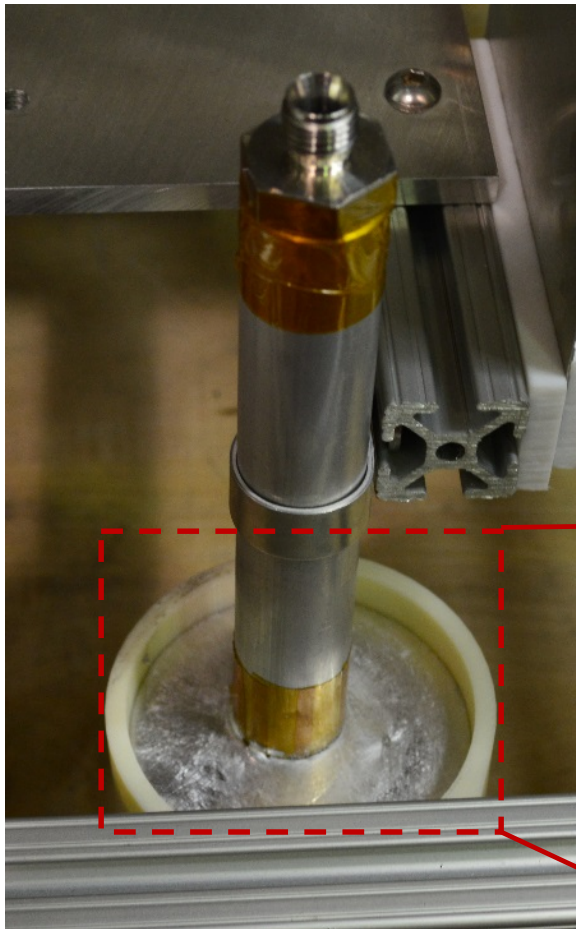
Conclusions



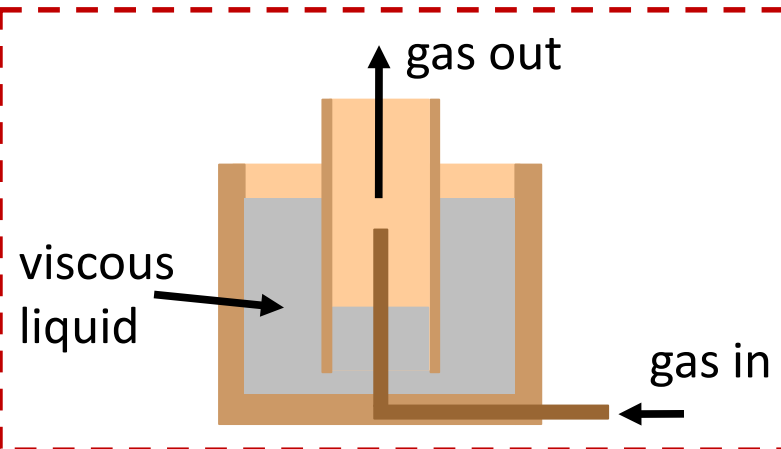
- CAT's magnetic field is consistent with predictions to within 10%
- Inductive discharge achieved in prototype device
- Novel thrust stand in development
- Wide variety of propellants being explored



Tensionless gas connector



- Deliver gas without restricting motion
- Coaxial feed design
- Viscous, non-volatile liquid
 - Galinstan: eutectic metal
- Liquid damps oscillations
- Similar design in development for RF



Design procedure and parameters



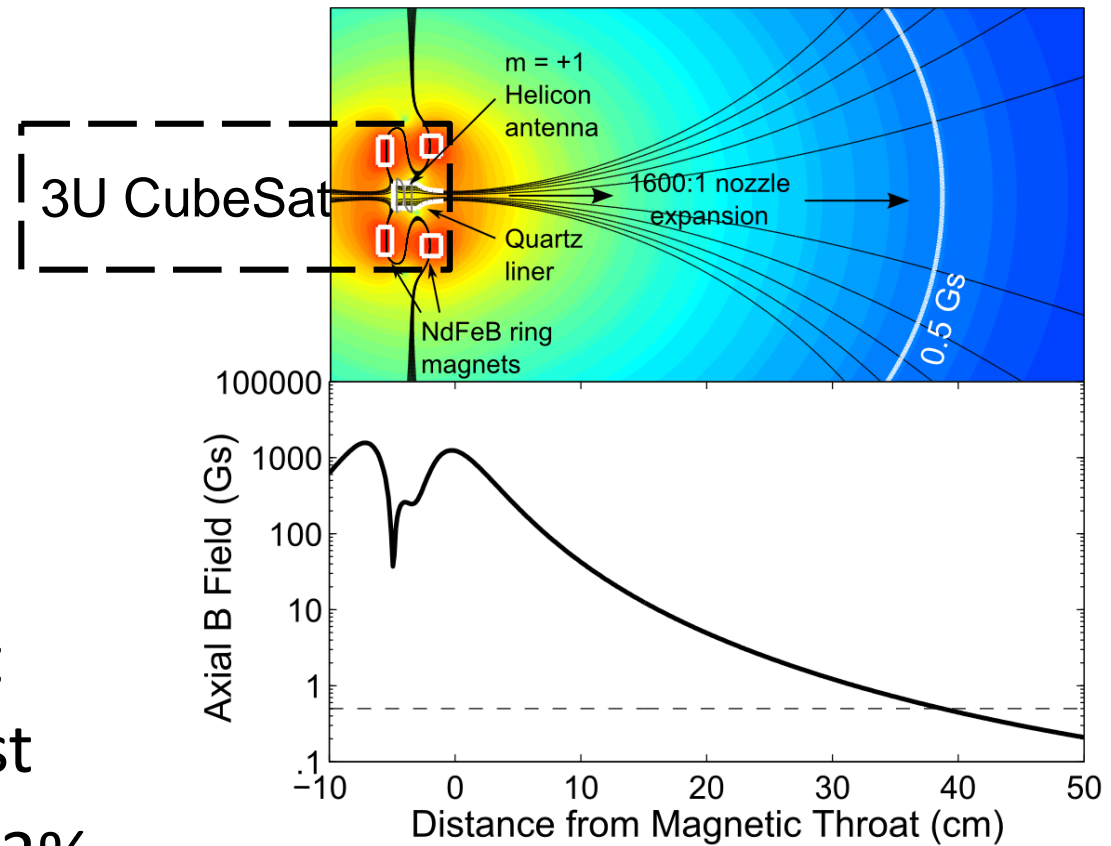
Power	10 - 50 W
Flow Rate	5 - 15 sccm
Density (max)	10^{14} cm^{-3}
B Field (max)	800 G
I_{sp}	400 - 800 s
Efficiency	10% - 40%
Thrust	0.5 - 4 mN
ΔV	1 - 2 km/s

- Design begins from power requirements
- Plasma density, B field driven by helicon dispersion relation
- Approximate performance parameters for 3U CubeSat, xenon propellant

Magnets create converging-diverging magnetic field

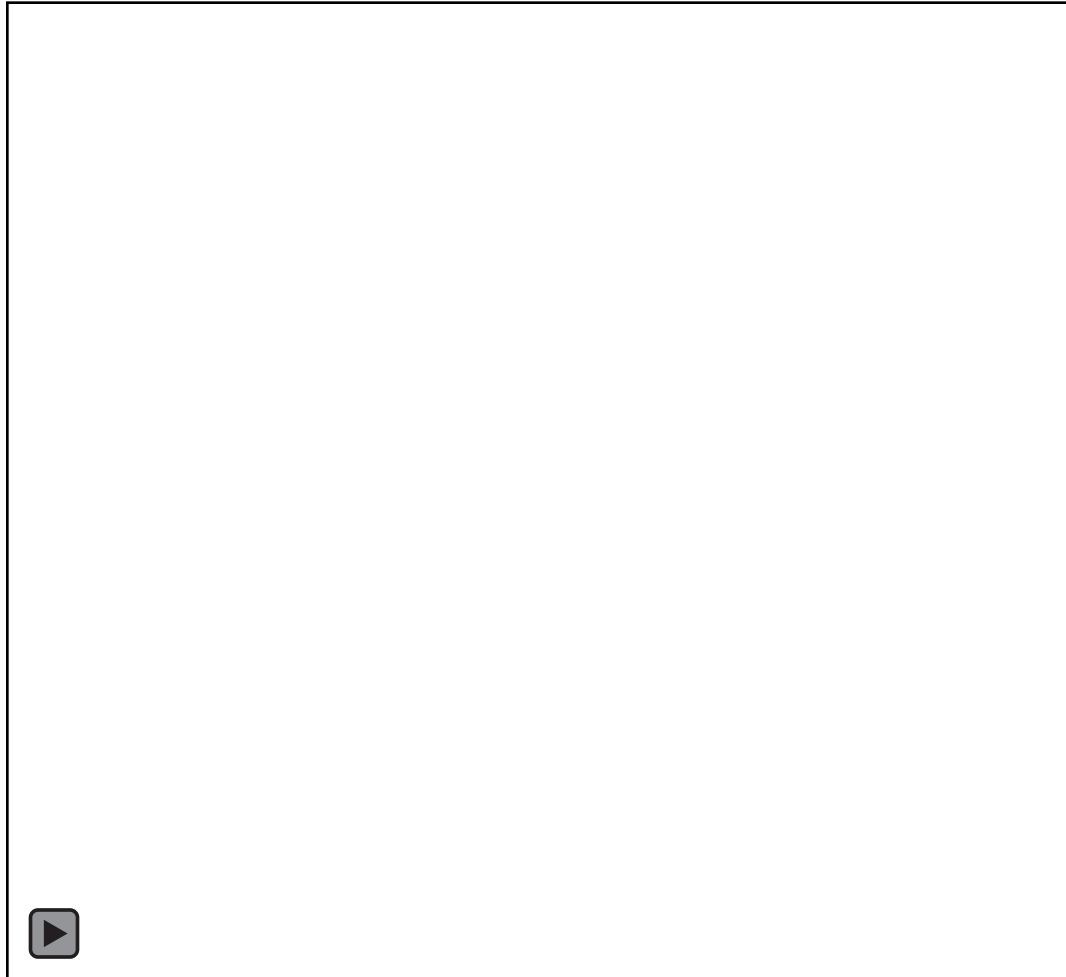


- NdFeB permanent ring magnets
- Magnetic field at throat: 800G
- Decays to Earth's magnetic field in 40 cm
- Plasma detaches at 0.5 G at the furthest
- Nozzle efficiency: 83%

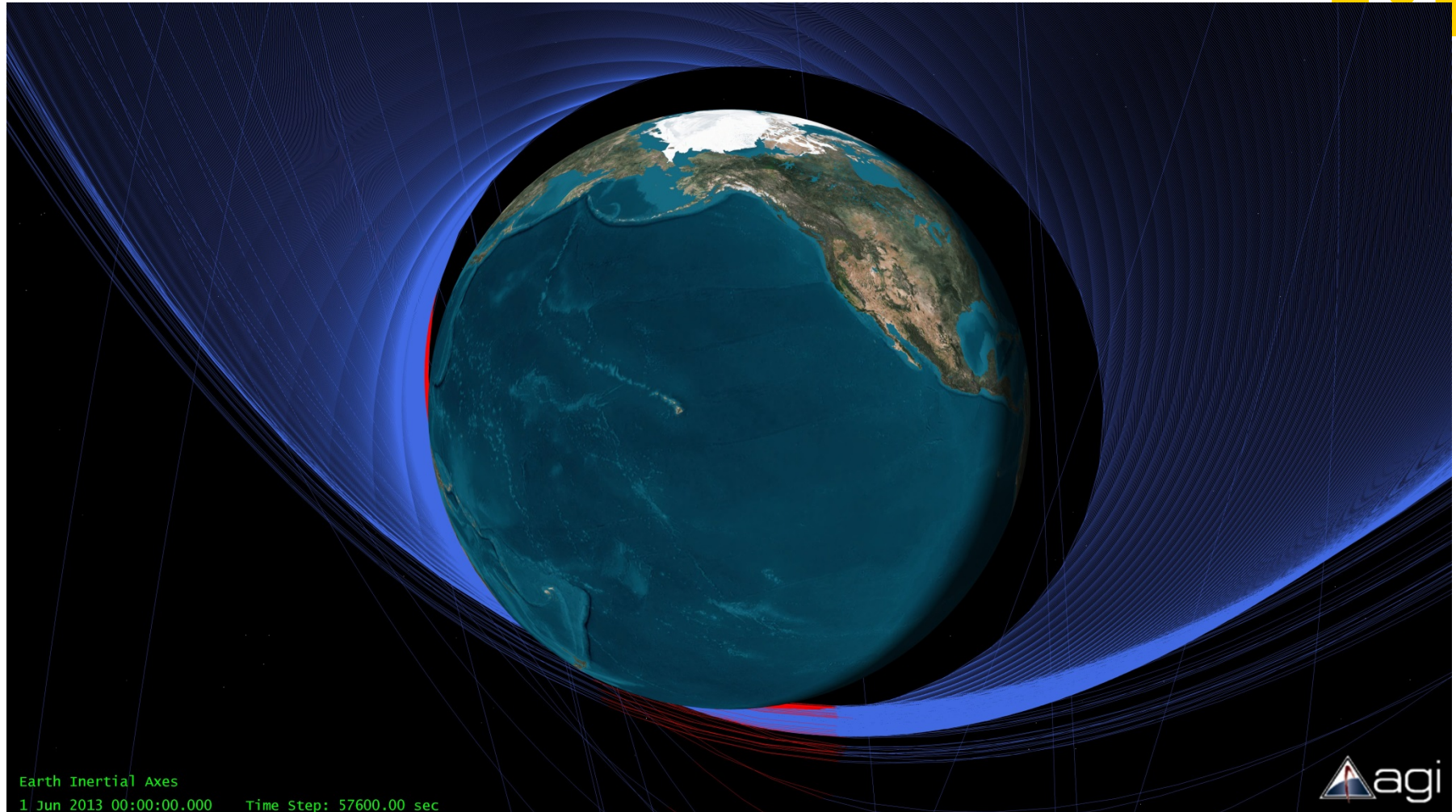


Note: figure does not represent final magnet design

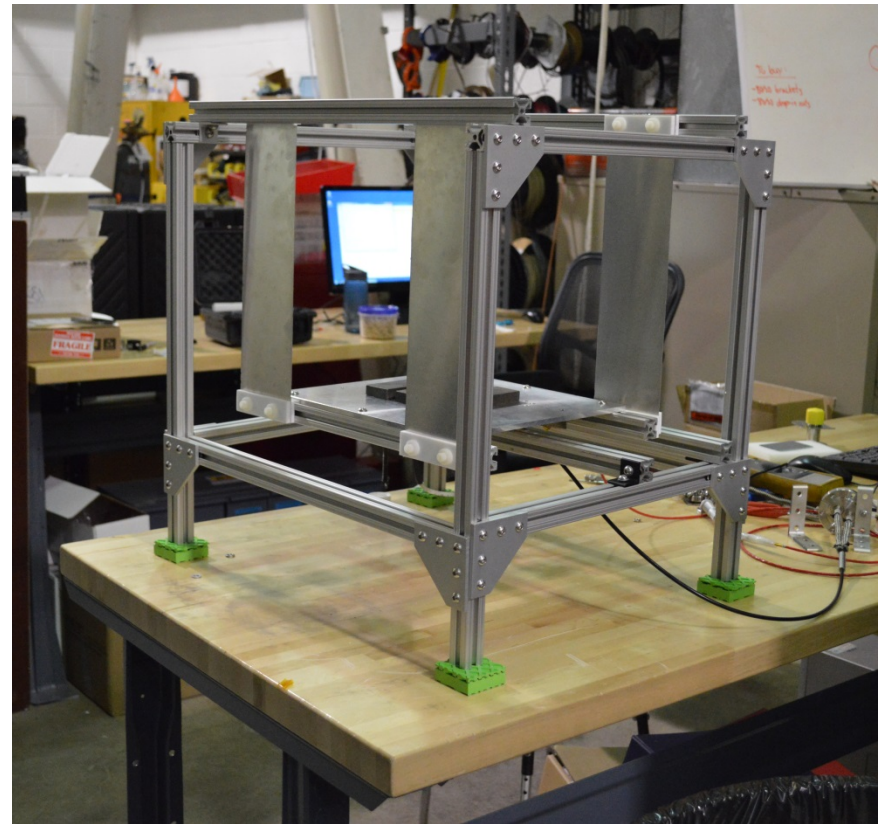
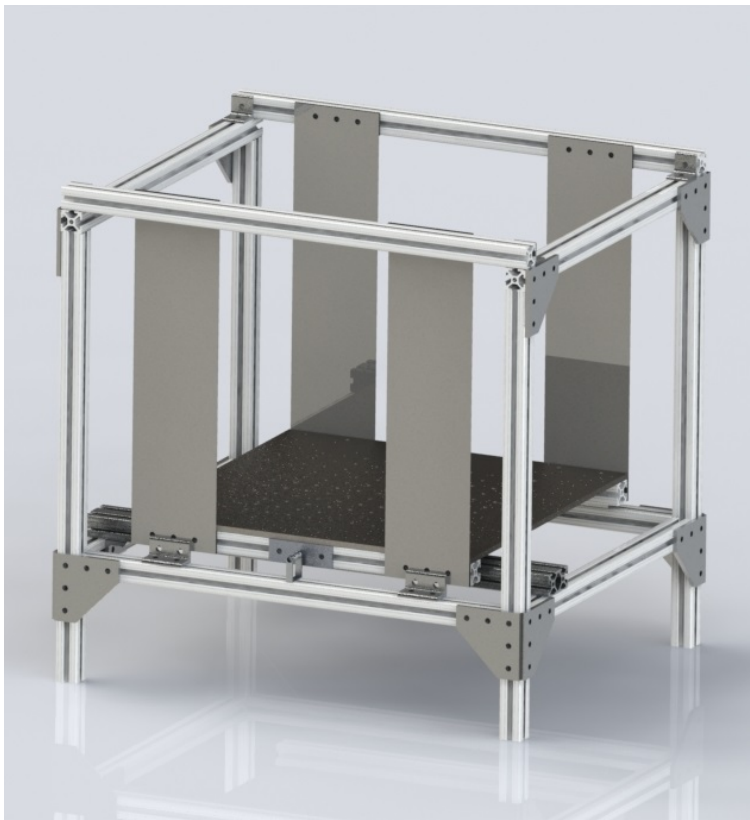
Passive magnetic stabilization



Earth escape from LEO firing from perigee



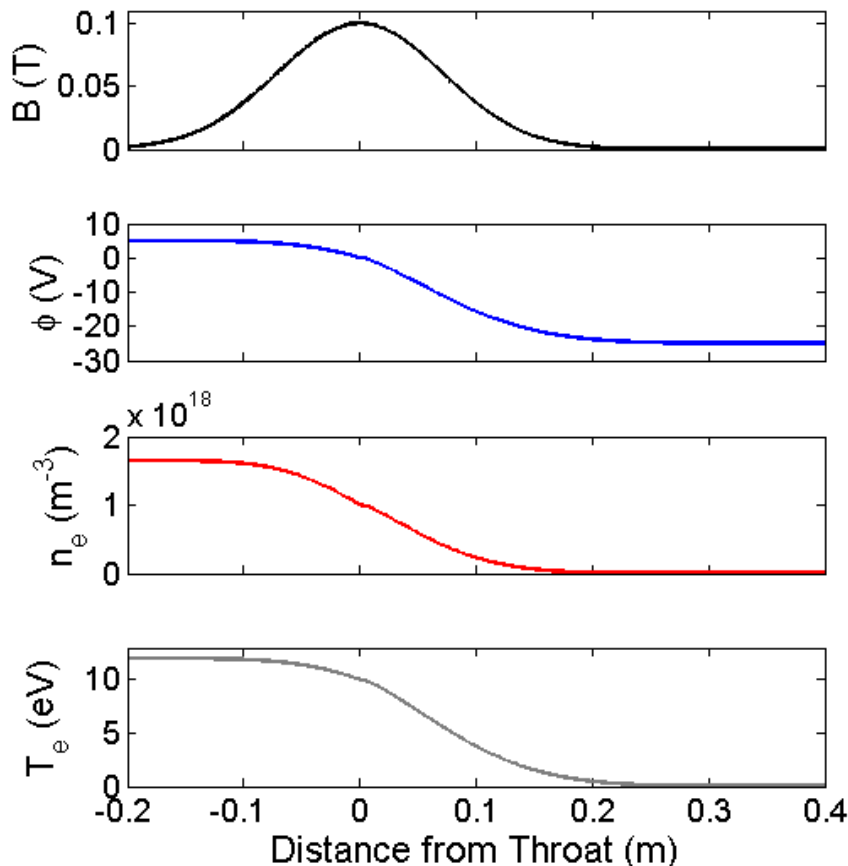
Thrust stand for micronewton force measurements



Mission to Europa: 6U CubeSat, double CATs



Ambipolar ion acceleration mechanism



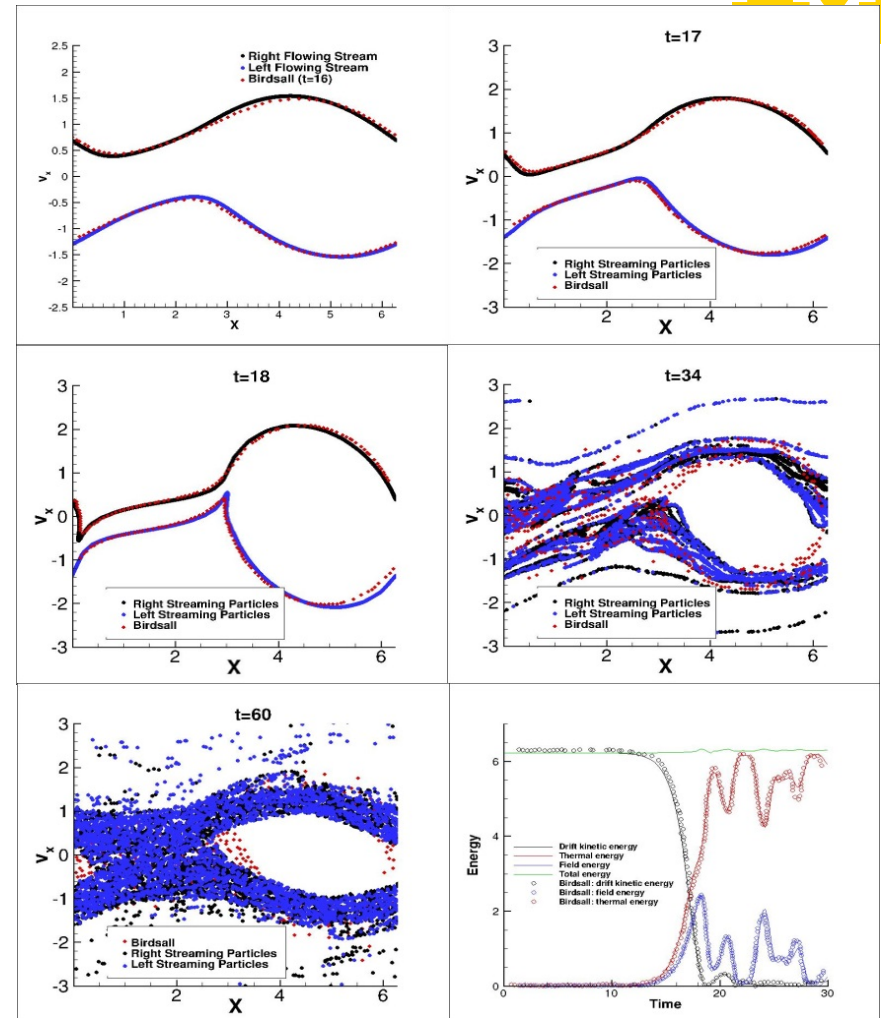
- Electrons heated by helicon wave
- Electrons rush out of nozzle
- Slow ions dragged along by E field
- Electrons lose thermal energy to ion kinetic energy
- Higher electron temperature \rightarrow higher ion velocity
- $E_{\text{ion}} = 2T_e$
- Mechanism is critical for thrust, performance models

Quasi-1d3v particle-in-cell simulations in development



- Axial spatial dimension
- Axisymmetric
- Magnetic mirror forces accounted for

$$B_r = -\frac{r_L}{2} \frac{\partial B_z}{\partial z}$$
- Modified semi-implicit Boris algorithm particle mover
- Verification campaign nearly completed
 - Two-stream instability (right)
 - Sheath
 - Magnetic mirror



Solid storable propellants greatly reduce volume requirements



- Gases: xenon, krypton, argon
 - Benchmark testing
 - Flight certified hardware
 - Miniature flow systems
- Solids and liquids: no pressure vessel
- Solid/liquid propellants
 - Water
 - Galinstan
 - ~~Mercury~~
 - Iodine
- Iodine propellant system
 - Solid storable
 - Heat to control vapor pressure/mass flow rate

