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

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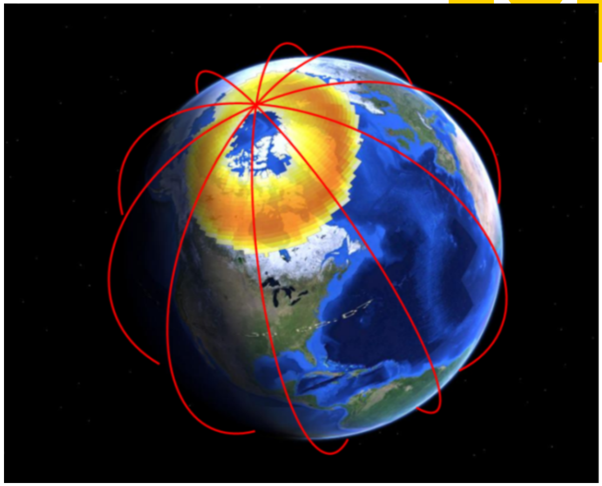
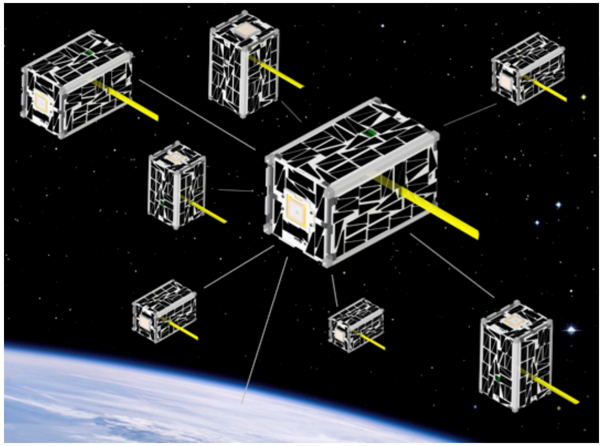
Outline

- 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

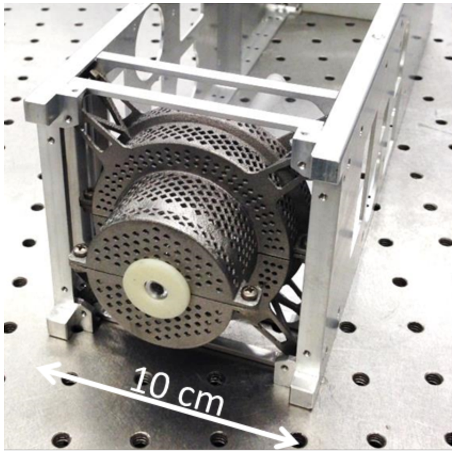
- Previously inaccessible orbits
  - Orbits that are not accessed by launch vehicle
  - Highly elliptical orbits
  - Geostationary orbits
  - Polar orbits
  - Earth-Moon, Earth-Sun Lagrange points
- Cluster formation flying
- Long-lived low altitude orbits



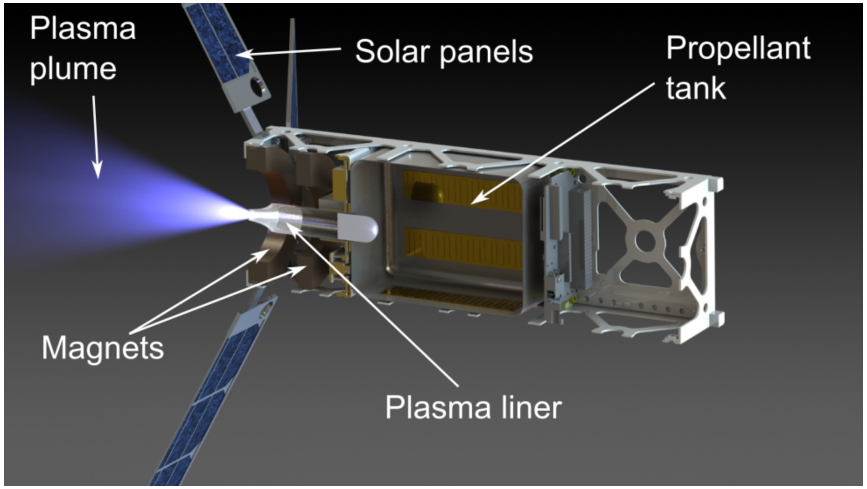


Credit: NASA

CubeSat Ambipolar Thruster (CAT)



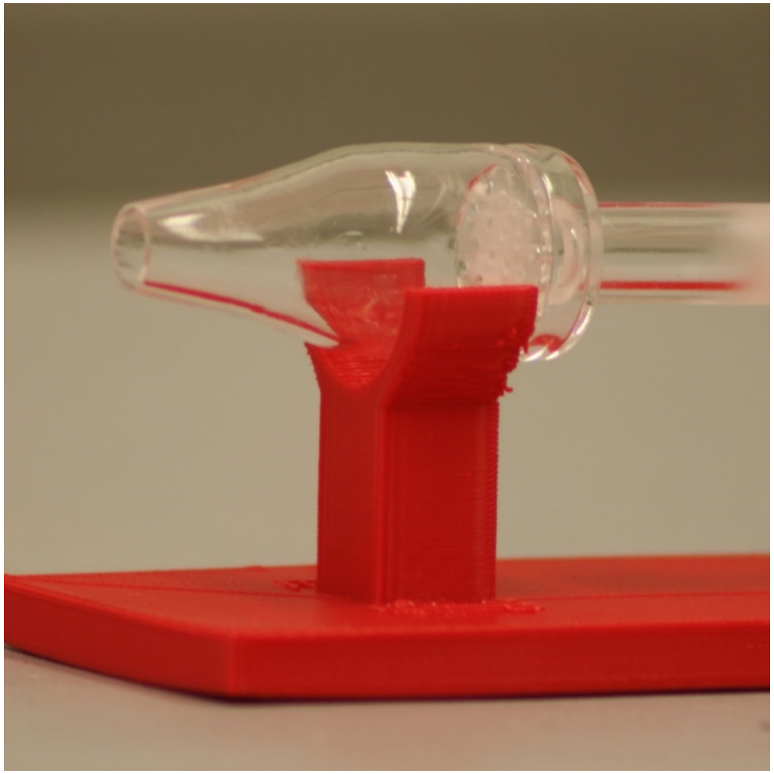
- ~0.6U for thruster
- Mass: <1 kg
- 0.4U – 0.9U for propellant tank
- Uses “free” spring space



- ~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

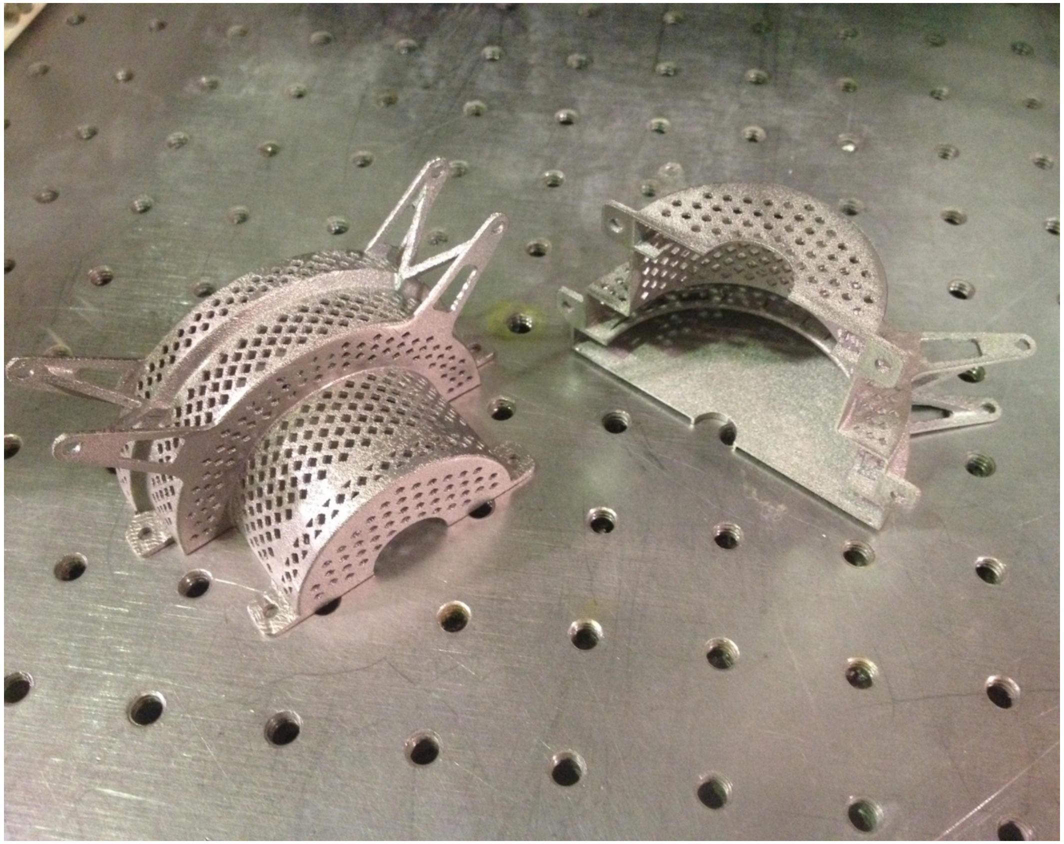


Antenna generates plasma, heats electrons

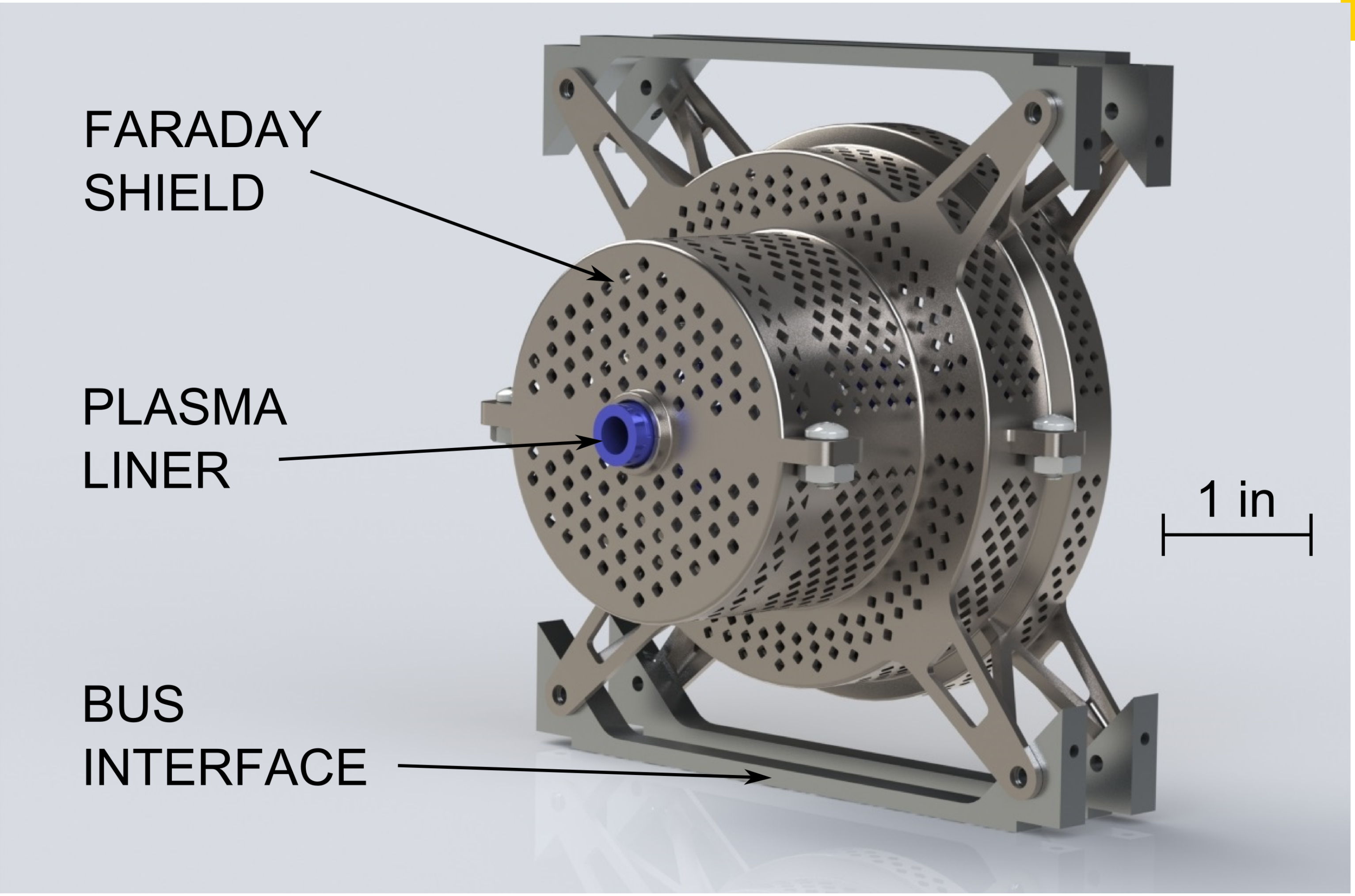
- 3D printed
  - Complex geometries possible
- Solid silver to maximize conductivity
- Helical half-twist
  - Ideal for launching helicon
- Power leads connect to RF source
- Couples RF energy into electrons via helicon plasma wave

Faraday shield contains RF, encases thruster

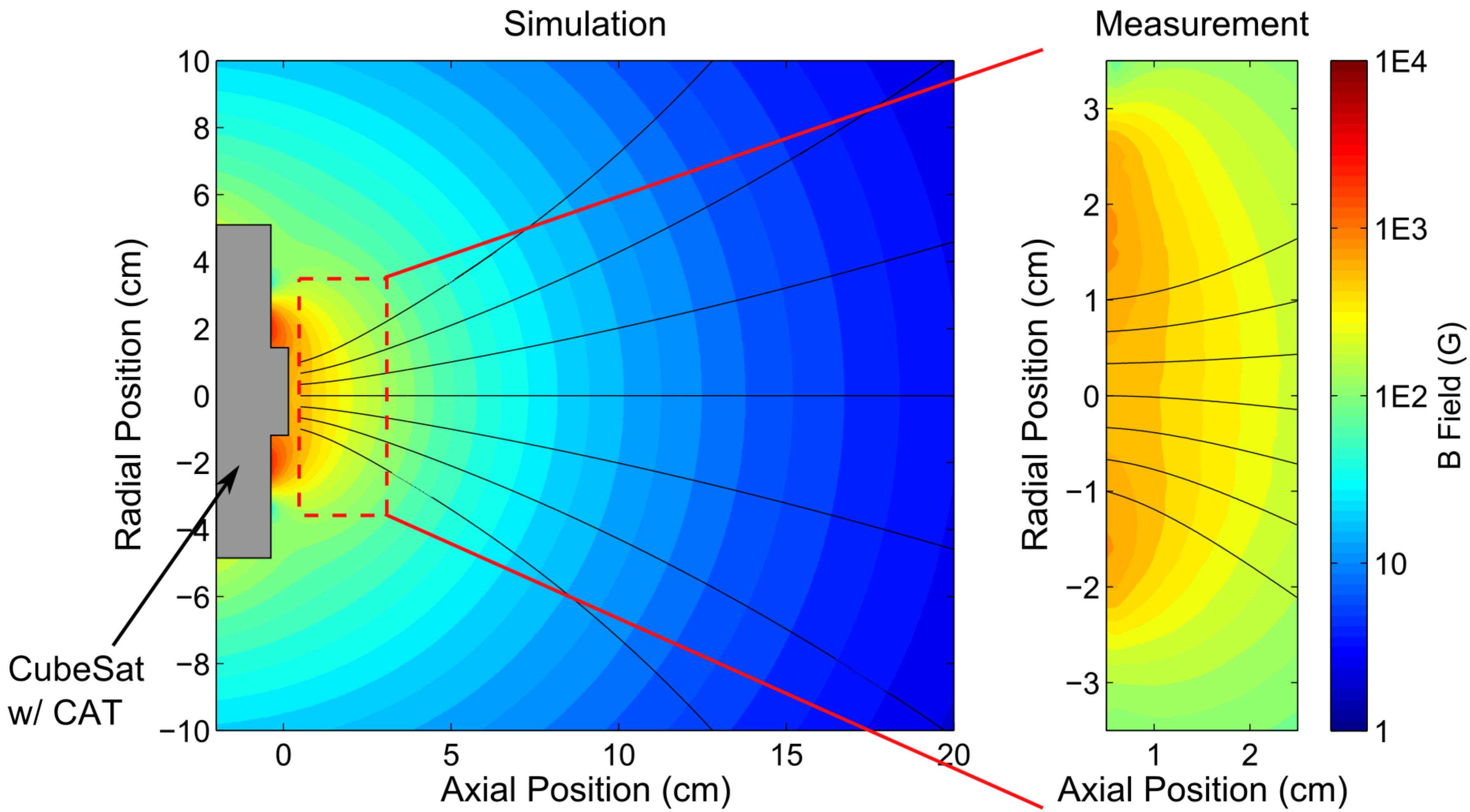
- 3D printed
  - Low cost
  - Rapid iteration
- Titanium
- Contains RF within thruster
- Structural support for liner, magnets



Fully assembled CAT engine

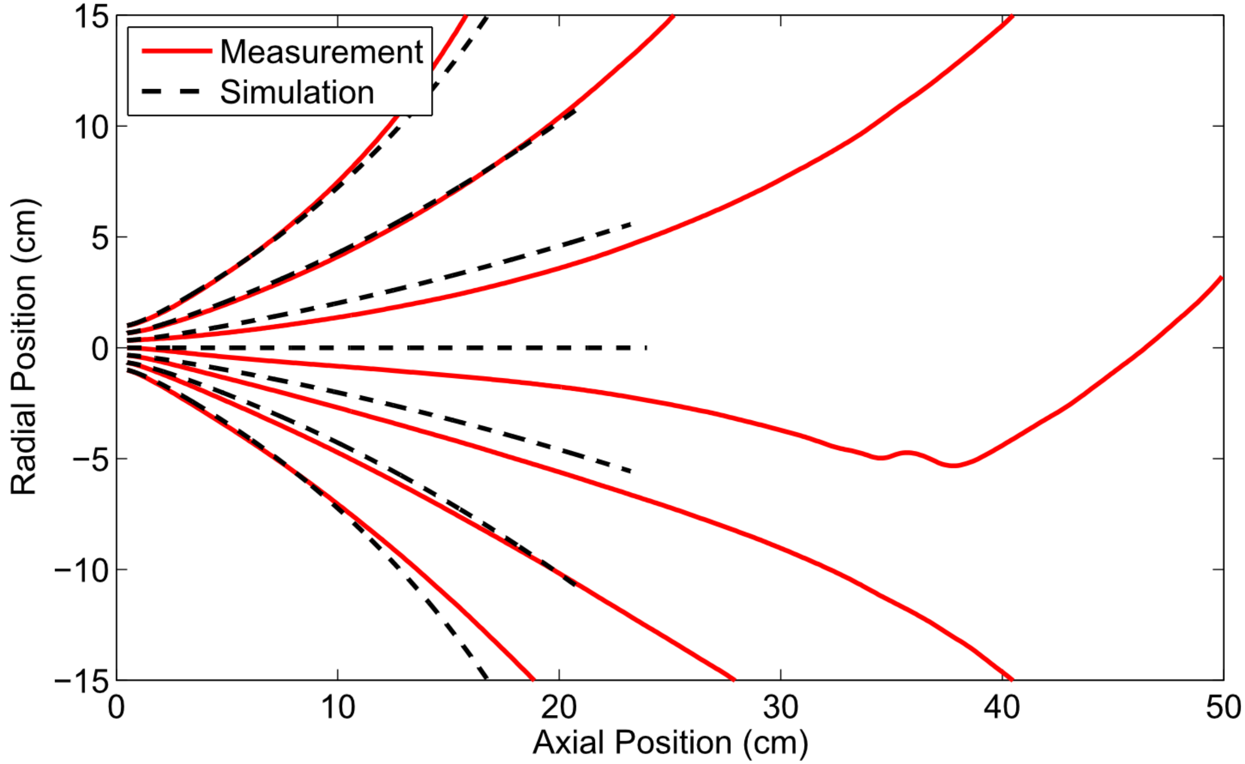


Magnetic nozzle replaces physical rocket nozzle

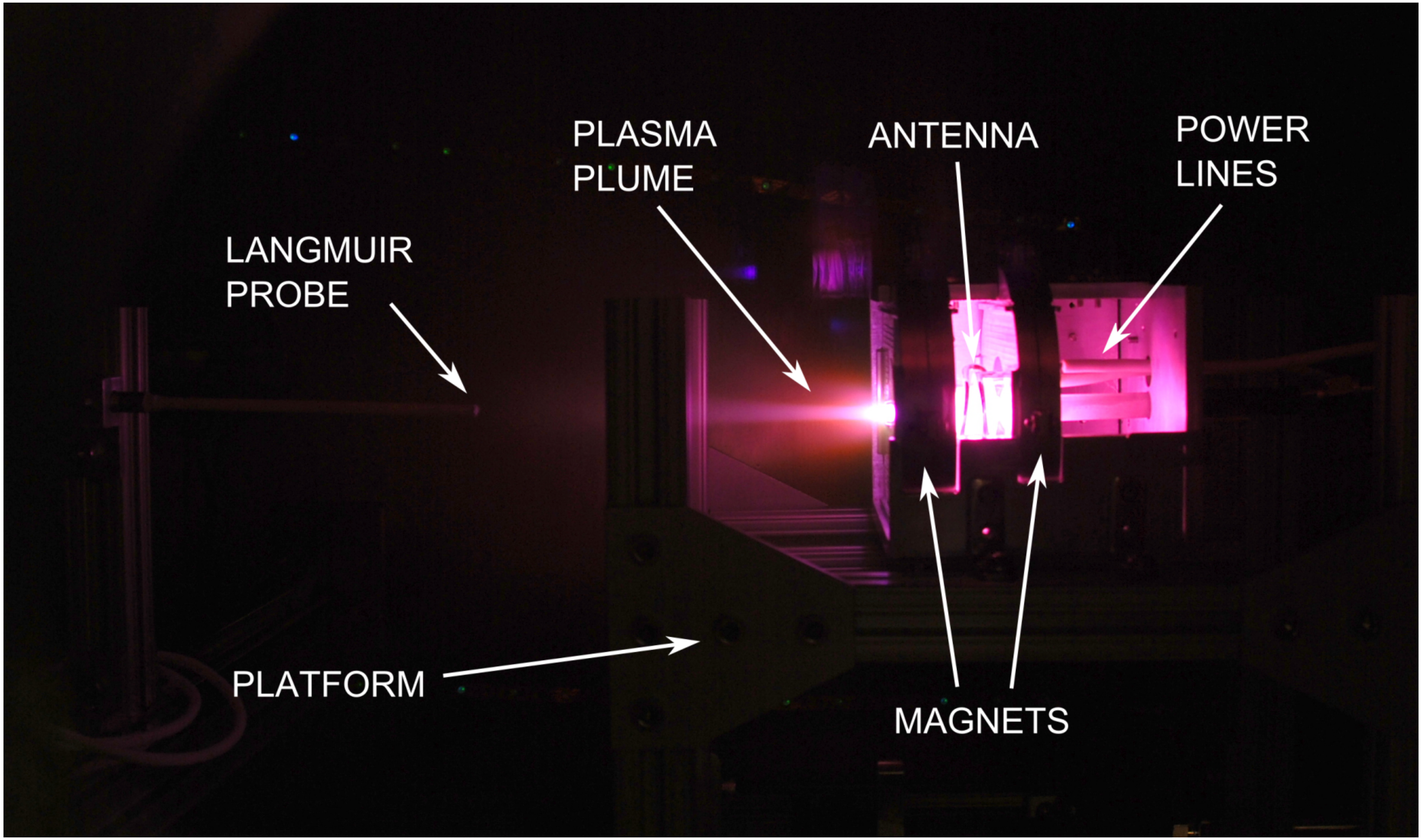


Measurements match simulations to within 10%

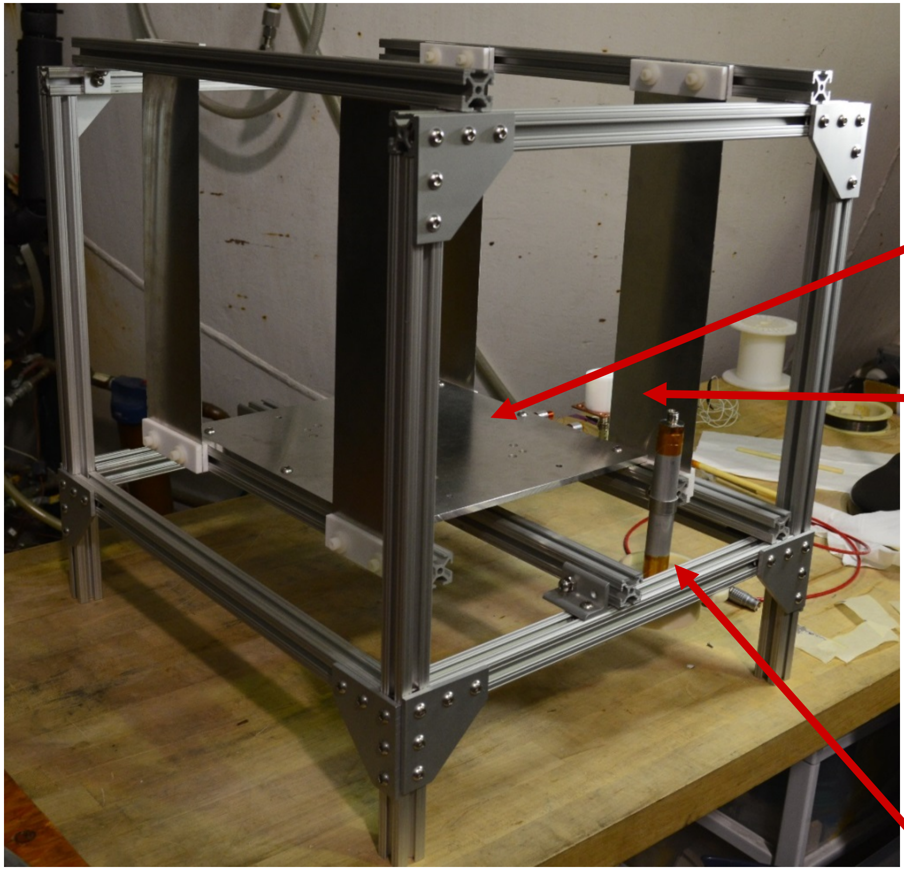
- Permanent magnets
  - No power requirements
  - Currently NdFeB
  - SmCo for higher Curi temperature
- Maximum strength in device of 800 G
- Net dipole moment of 55 A·m^2
  - Dipole cancelation designs
- Earth's gravity takes over at ~40 cm



Xenon testing: plasma follows magnetic field lines



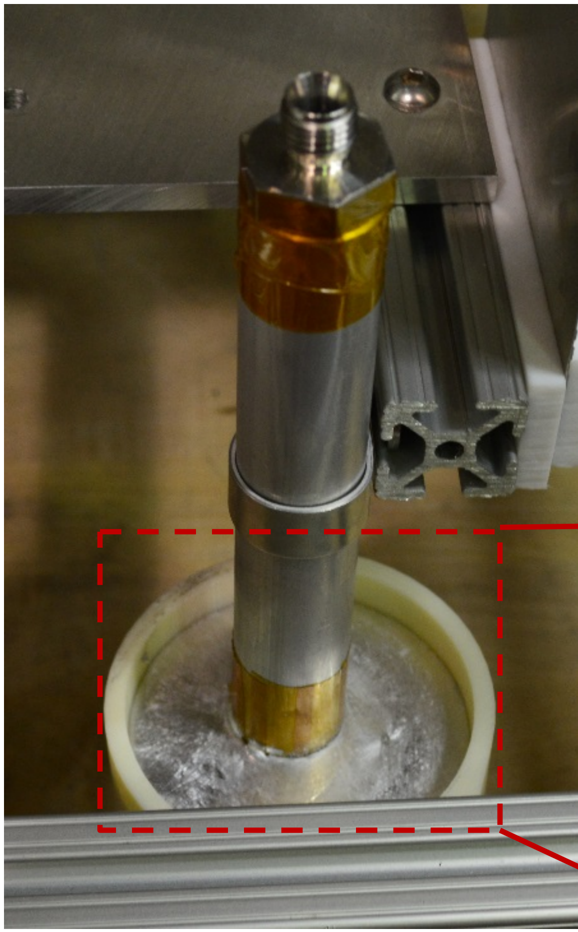
Beam-deflection micronewton thrust stand

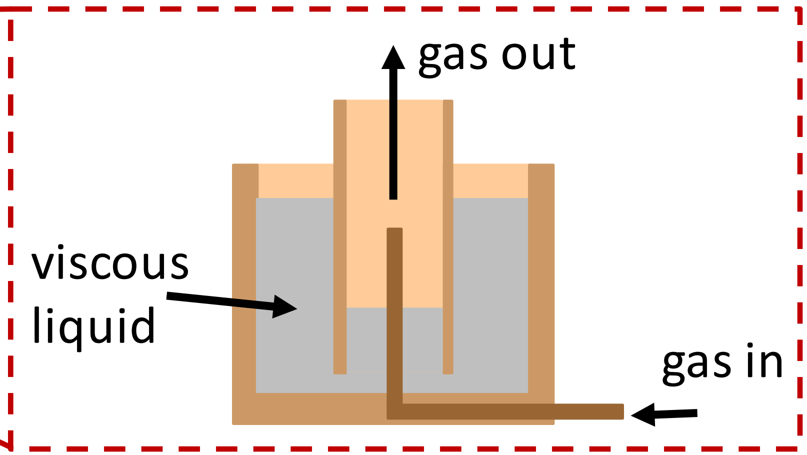


- Measure 10s mN, resolution 10s μN
- Thruster supported on mount plate
- Thrust moves plate, deflects thin beams
  - Euler-Bernoulli beam theory
- Deflection measured by optical displacement sensor (obscured)
- Tensionless gas feed system

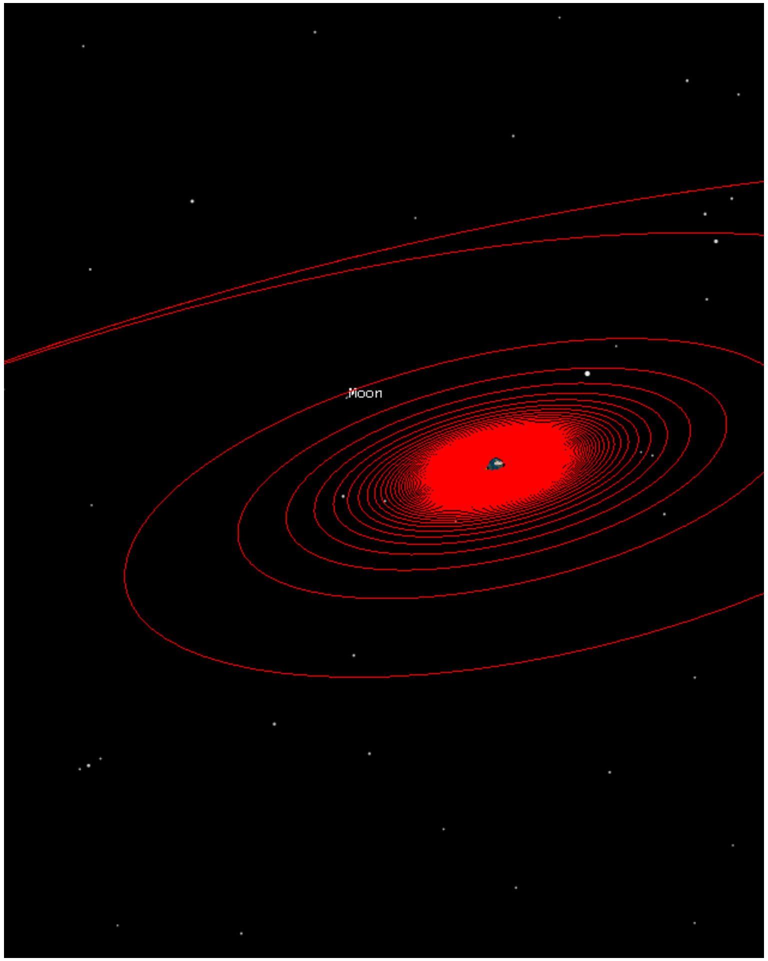
Tensionless gas connector

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





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

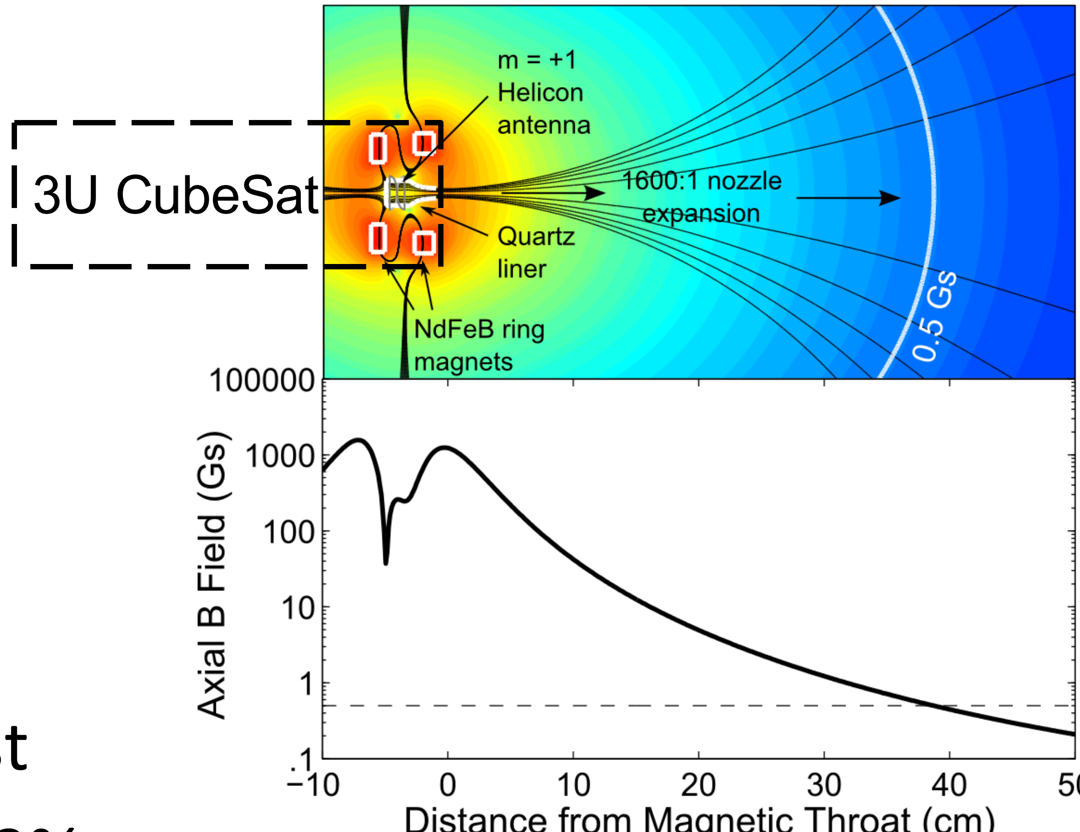
Design procedure and parameters

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

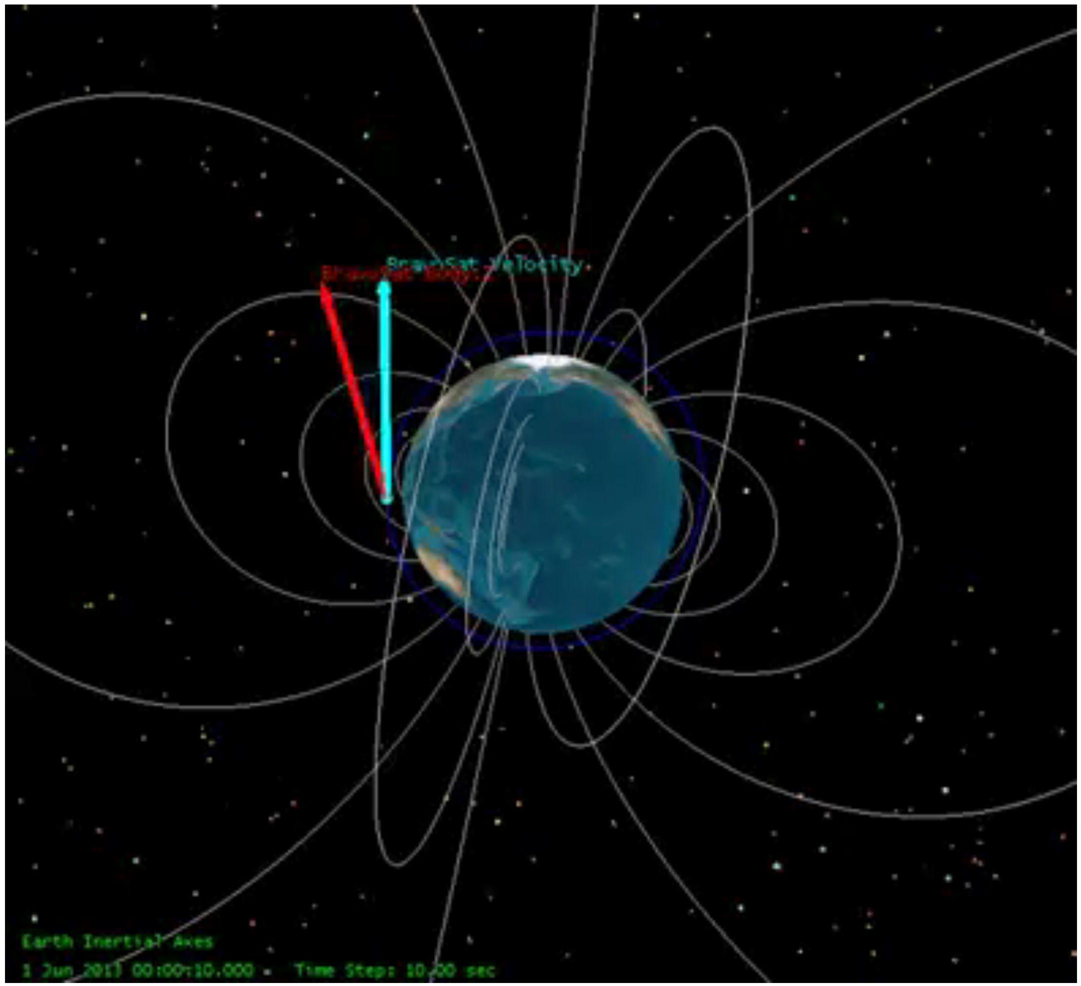
Magnets create converging-diverging magnetic field

- 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%

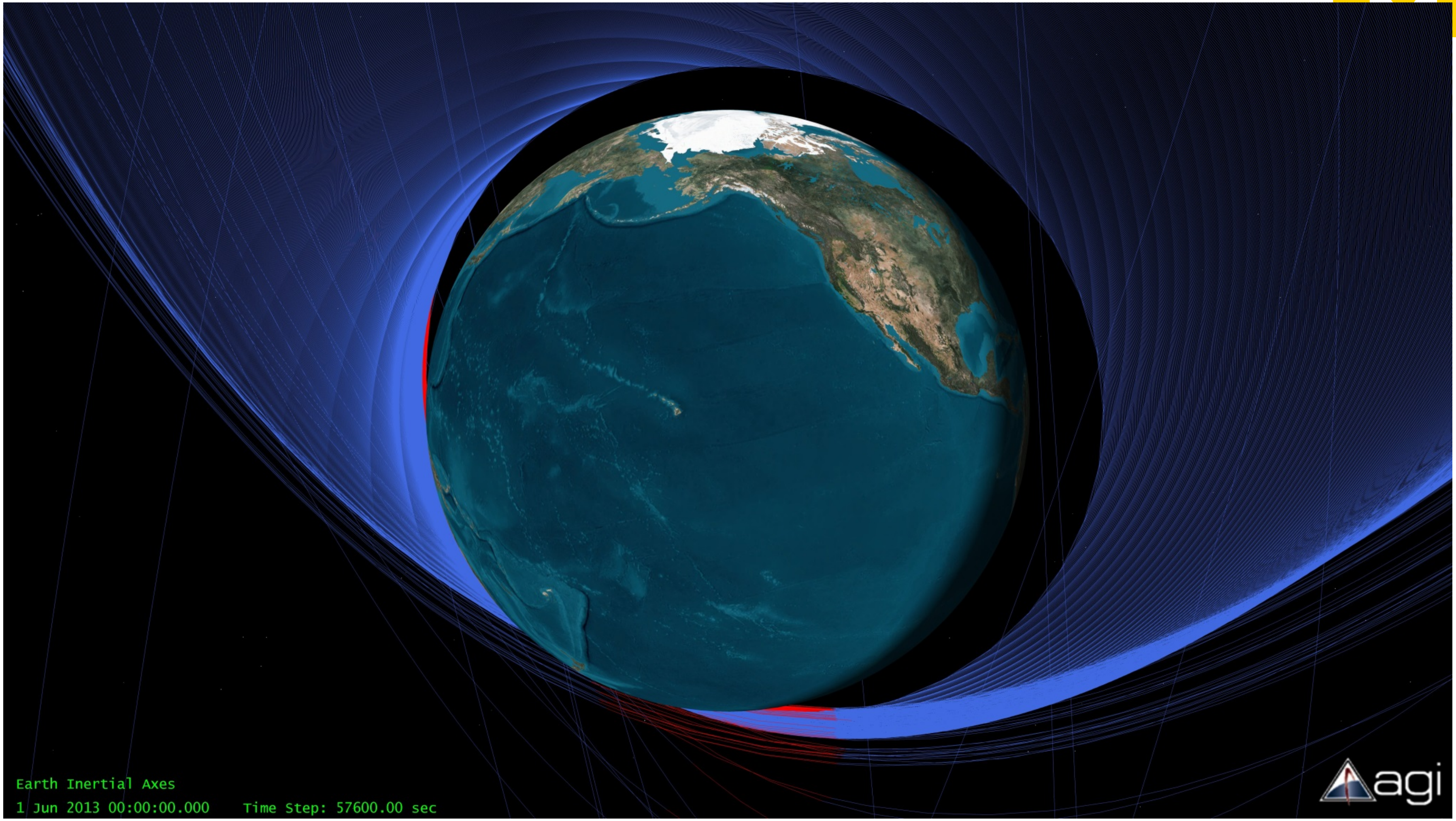


Note: figure does not represent final magnet design

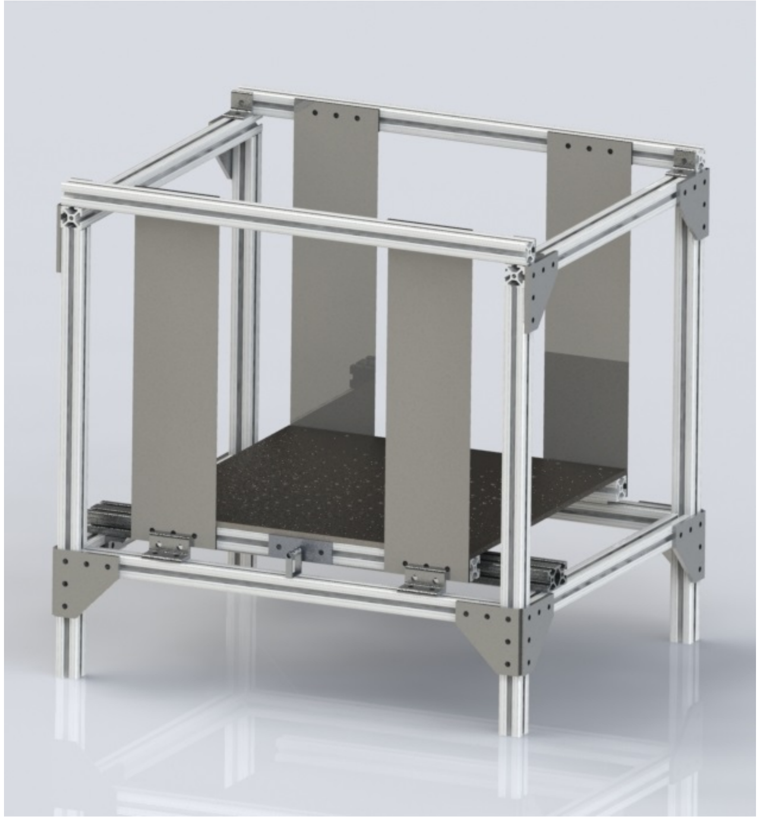
Passive magnetic stabilization

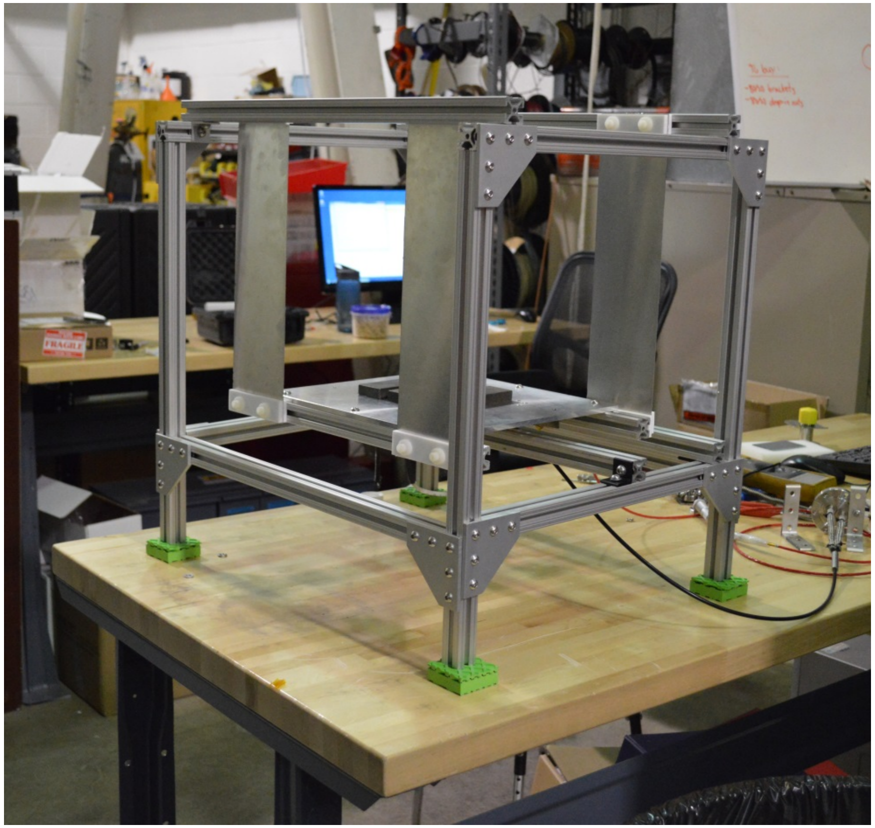


Earth escape from LEO firing from perigee



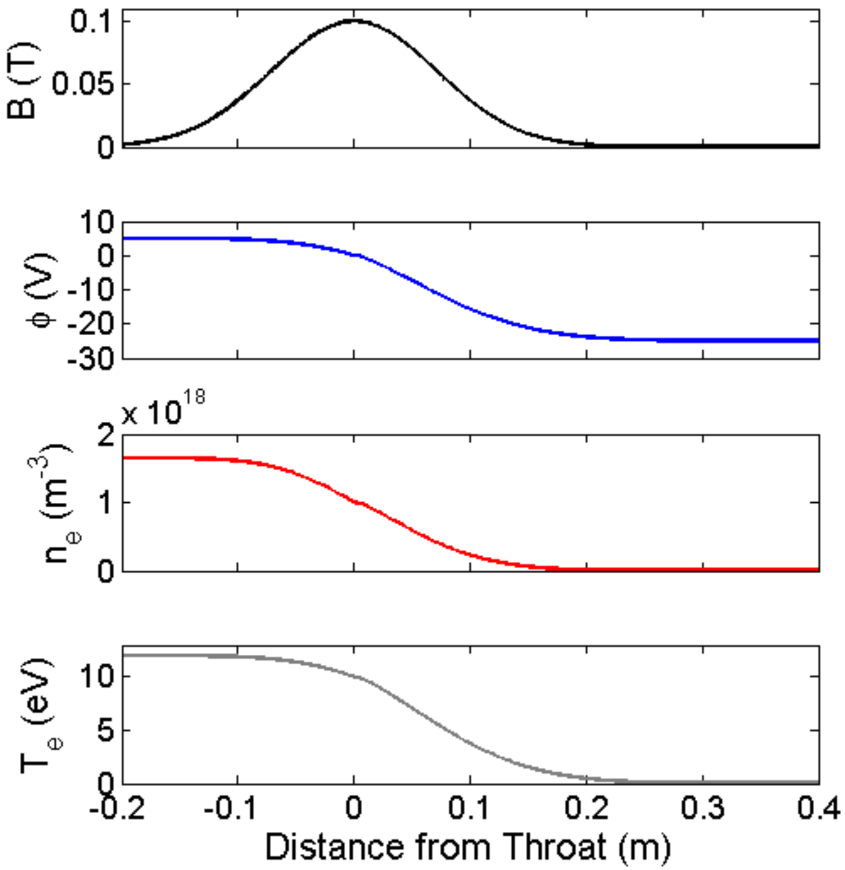
Thrust stand for micronewton force measurements





Mission to Europa: 6U CubeSat, double CATs

Ambipolar ion acceleration mechanism



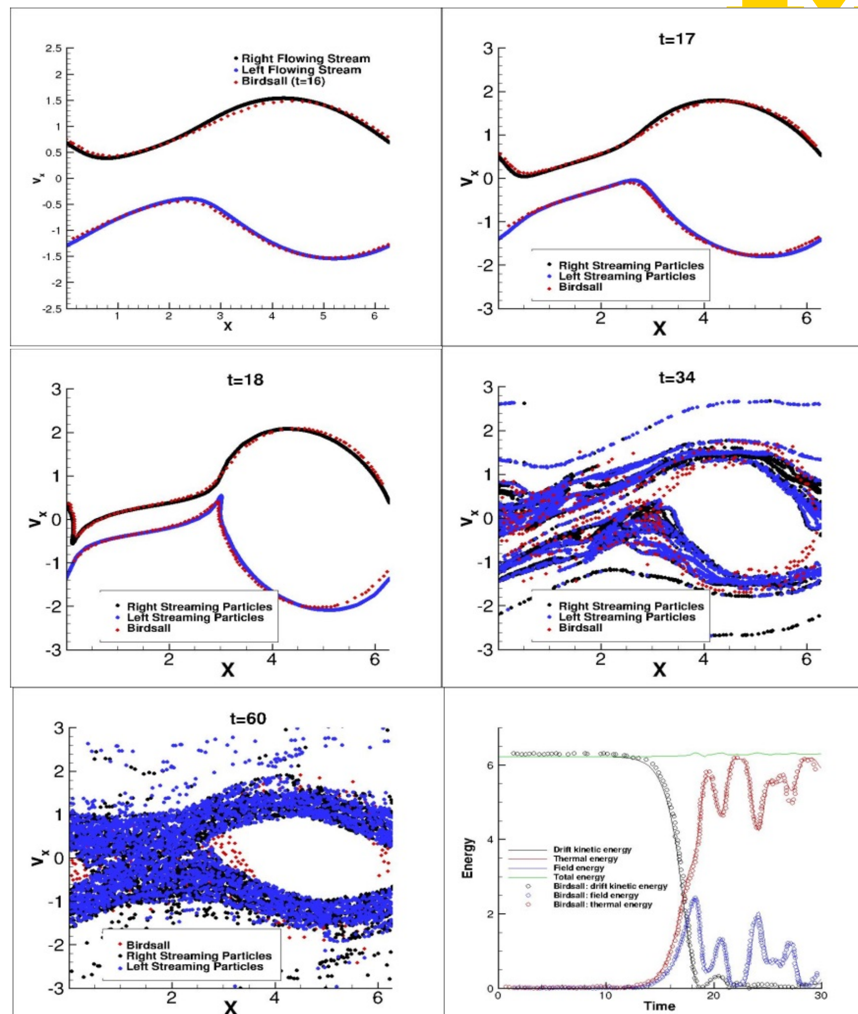
- Electrons heated by helicon wave
- Electrons rush out of nozzle
- Slow ions dragged along by E field
- Electrons lose thermal energy to ion kinetic energy
- Higher electron temperature → higher ion velocity
- $E_{ion} = 2T_e$
- Mechanism is critical for thrust, performance models

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