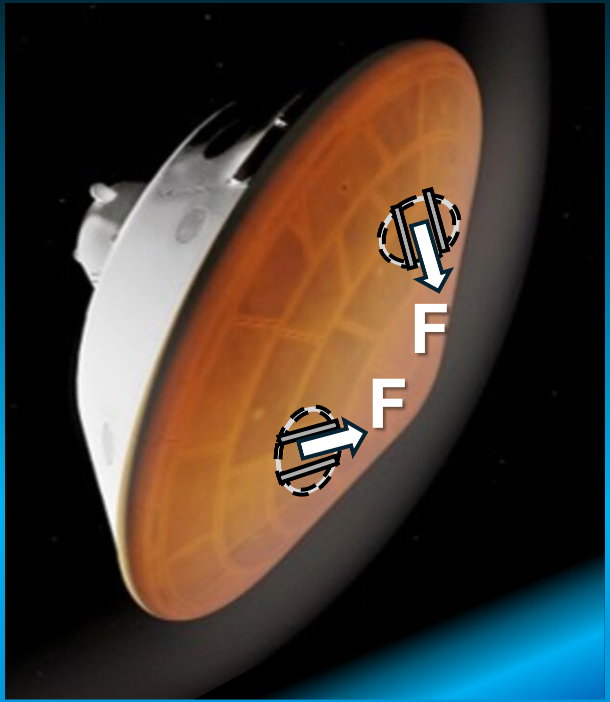
Magnetohydrodynamics (MHD) Aerocapture System for Enabling Faster-Larger Planetary Science & Human Exploration Missions



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Background: Aerocapture

- What is aerocapture?

  Aerocapture is the use of a planet's atmosphere to slow down and transfer into an orbit around the planet

- Why use aerocapture?

  Aerocapture reduces the **propulsive** ΔV required to reach a target orbit, which allows for less propellant and thus less mass

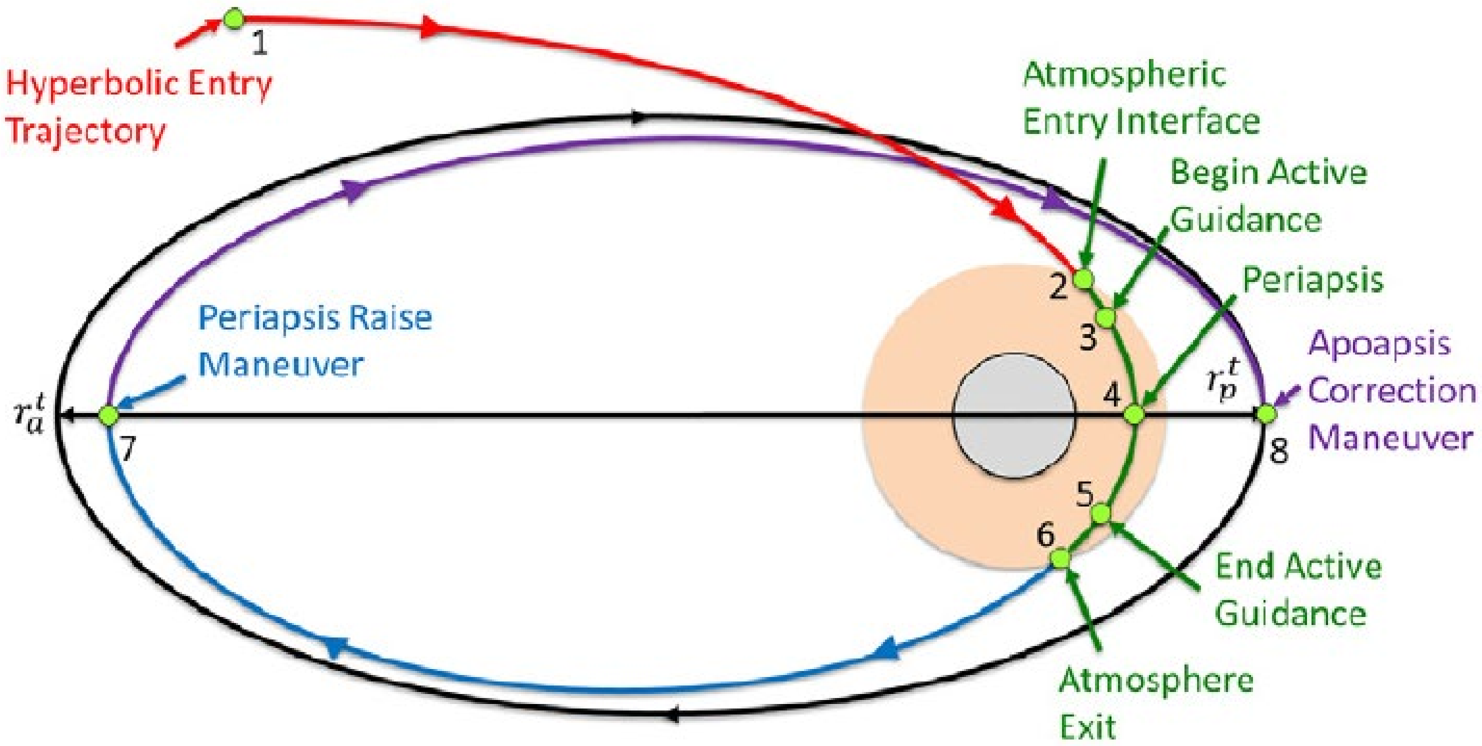


Image From [2]

- Requires precision atmospheric guidance and control

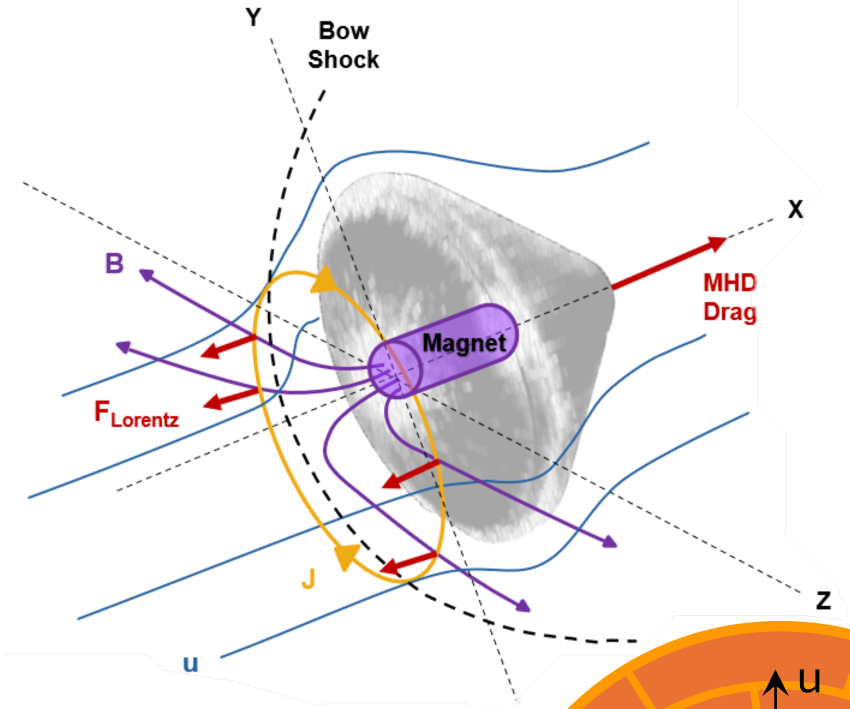
  Previously, aerodynamic only control mechanisms have been investigated

Background: Magnetohydrodynamic (MHD) Control

- Hypersonic entry produces an ionized plasma surrounding the spacecraft
- With an onboard magnet, a magnetic field, $\vec{B}$, can be applied on the plasma create an electron current, $\vec{J}$, and induce a Lorentz force:

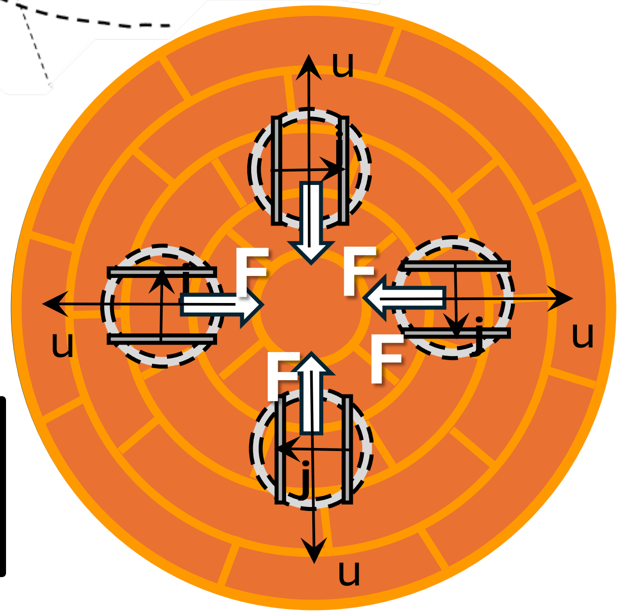
$$\vec{F}_{Lorentz} = \vec{J} \times \vec{B}$$

$$F_{Lorentz} \propto MHD\ Drag$$



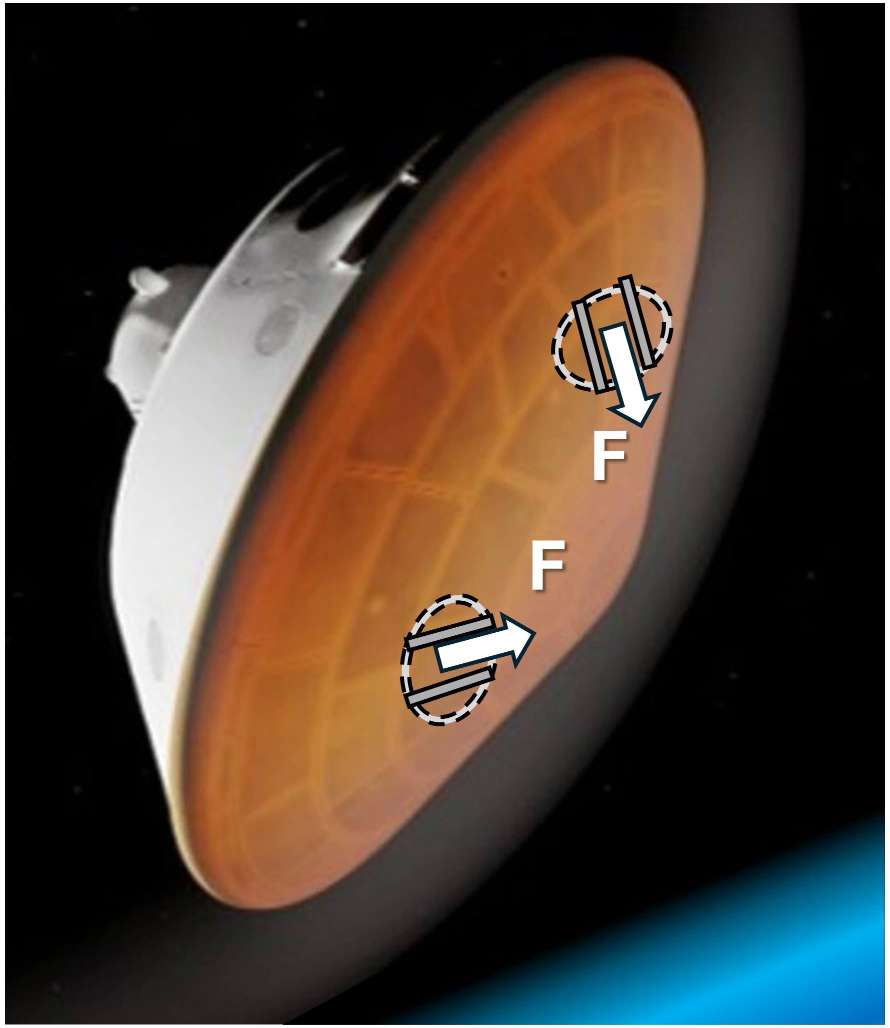
- **This MHD force is in addition to aerodynamic forces**
- Assuming a uniform magnetic field, the Lorentz forces will sum and act equally and oppositely on the vehicle in only the drag direction
- With multiple patches and a non-uniform magnetic field, **the current for each patch can be commanded individually to produce Drag, Lift, or Side forces on the spacecraft**

$$\vec{j} \propto \vec{B}$$
$$\vec{F}_{Lorentz} \propto \vec{j} \propto \vec{B}^2$$



Potential Advantages of MHD Control

- **Higher atmospheric activation → Enables faster hyperbolic inertial entry velocities → Faster interplanetary transit times**
- **Lower the aerodynamic heating → Decreasing requirements on the Thermal Protection System**
- **Increase the useful mission timeline → Improve vehicle controllability**
- **Decelerate more mass → Increase scientific payload capacity**
- Does not require mass ballasts, aerodynamic flaps, jettisons, or a complex size-changing aeroshell



Goal & Challenge

Goal

Create a vehicle design that quantifies the configuration and mass benefits compared to the current state-of-the-art, which rely on propulsive and aerodynamic forces only.

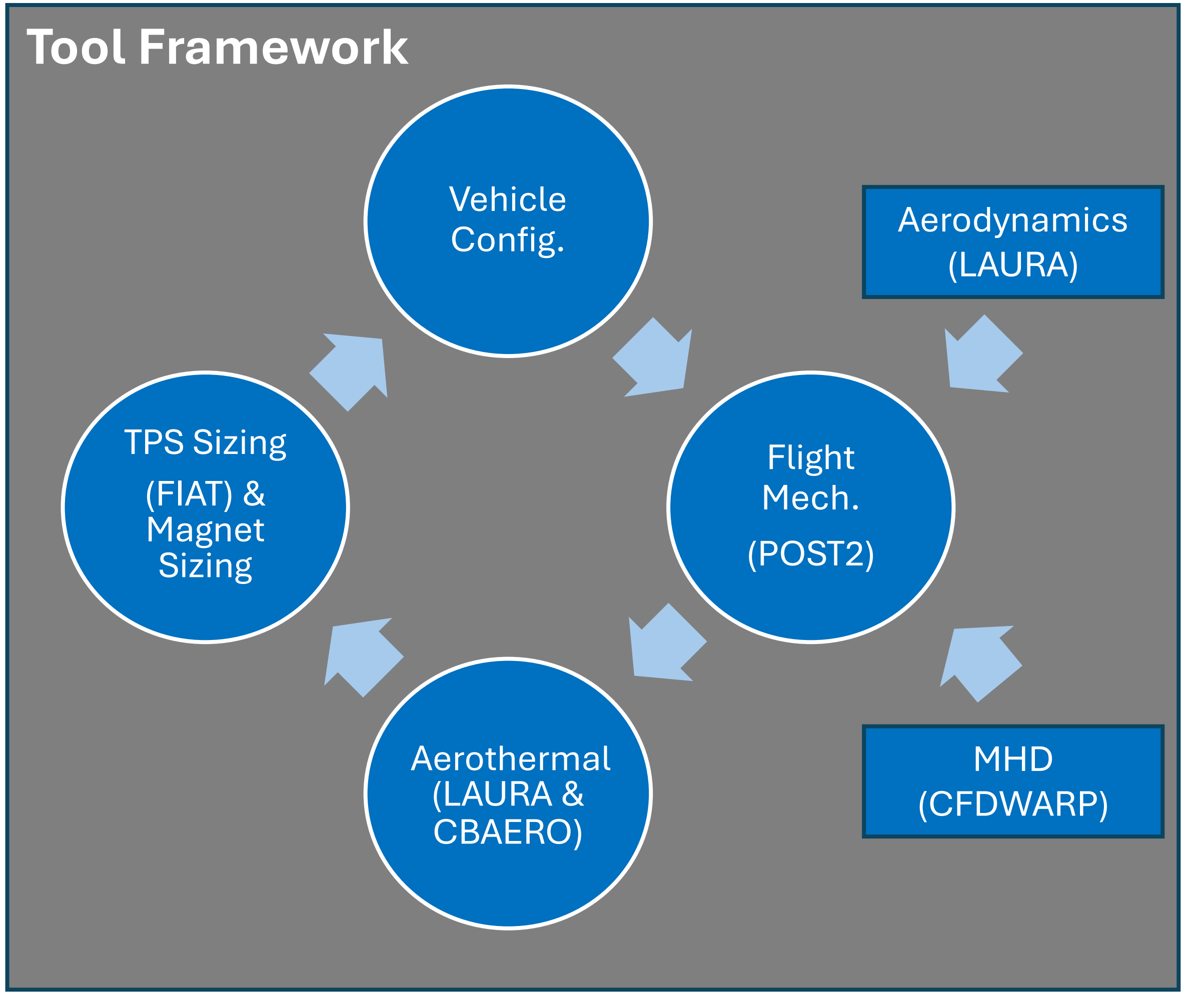
Challenge

Link different computer analysis systems into a common database to conduct MHD system sizing and vehicle design trades

- **Flight Mechanics**: Program to Optimize Simulated Trajectories – II (POST2)
- **Aerodynamics**: Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA)
- **Aerothermodynamics**: Fully Implicit Ablation and Thermal Analysis Program (FIAT)
- **Magnetohydrodynamics**: CFDWARP

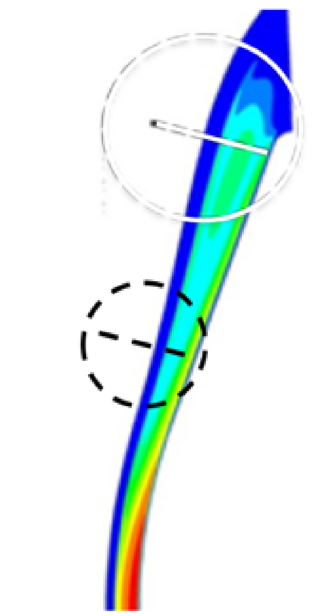
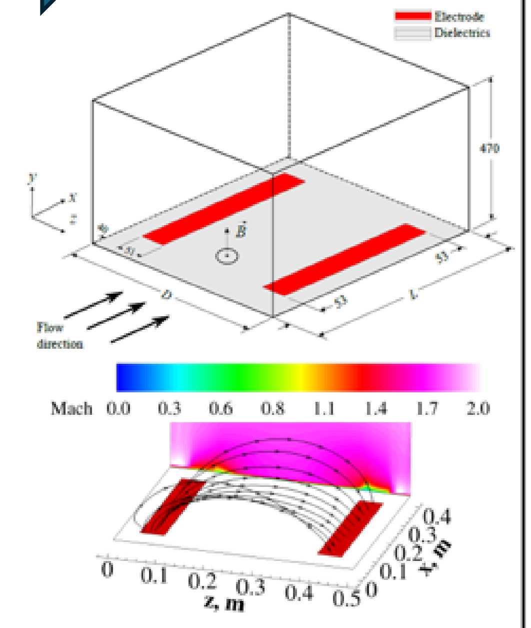
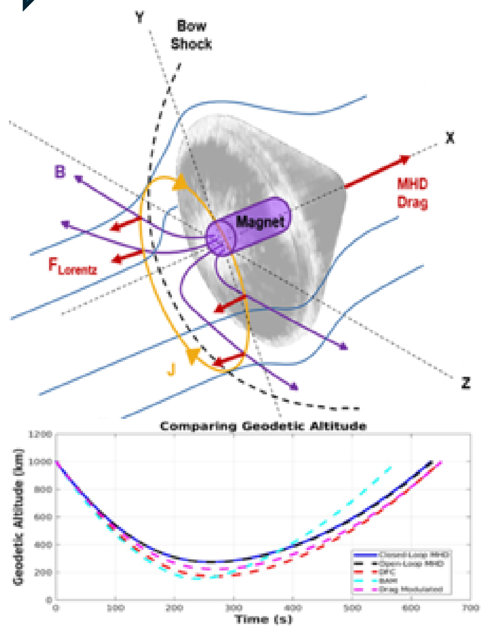
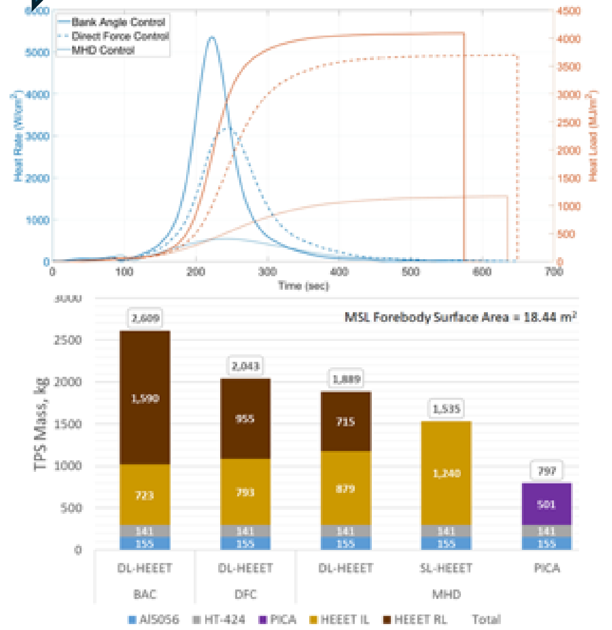
Why is it hard?

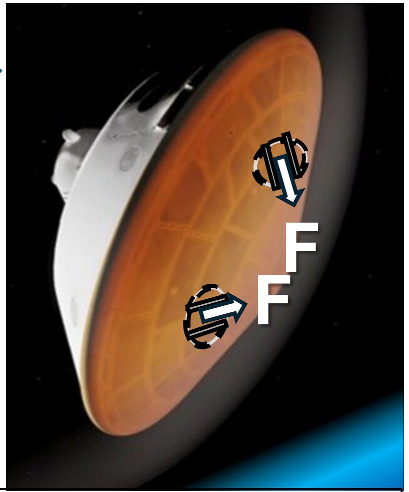
- Relatively large multi-disciplinary problem



Analysis Framework & Performance Estimates

Data Flows to the Right

LAURA	CFDWARP	POST2	FIAT
			
Conduct aero-heating analysis to select places of ionization and flow velocity for MHD system analysis	Port LAURA results into CFDWARP to calculate electrical and thermal conductivities of ionized flow for sizing MHD patch system and calculating Lorentz forces needed for controls analysis	Port results from LAURA and CFDWARP into POST2 for calculating entry trajectories and comparing MHD control results with other aerodynamic control strategies	Utilize trajectory information from POST2 to calculate heat rates and heat loads on the spacecraft and size the Thermal Protection System based on known properties of materials such as HEEET and PICA



Estimates:

- MHD System mass penalty (i.e., magnets)
- TPS mass savings
- Generated Power vs. Power Consumed (i.e., by electromagnets)

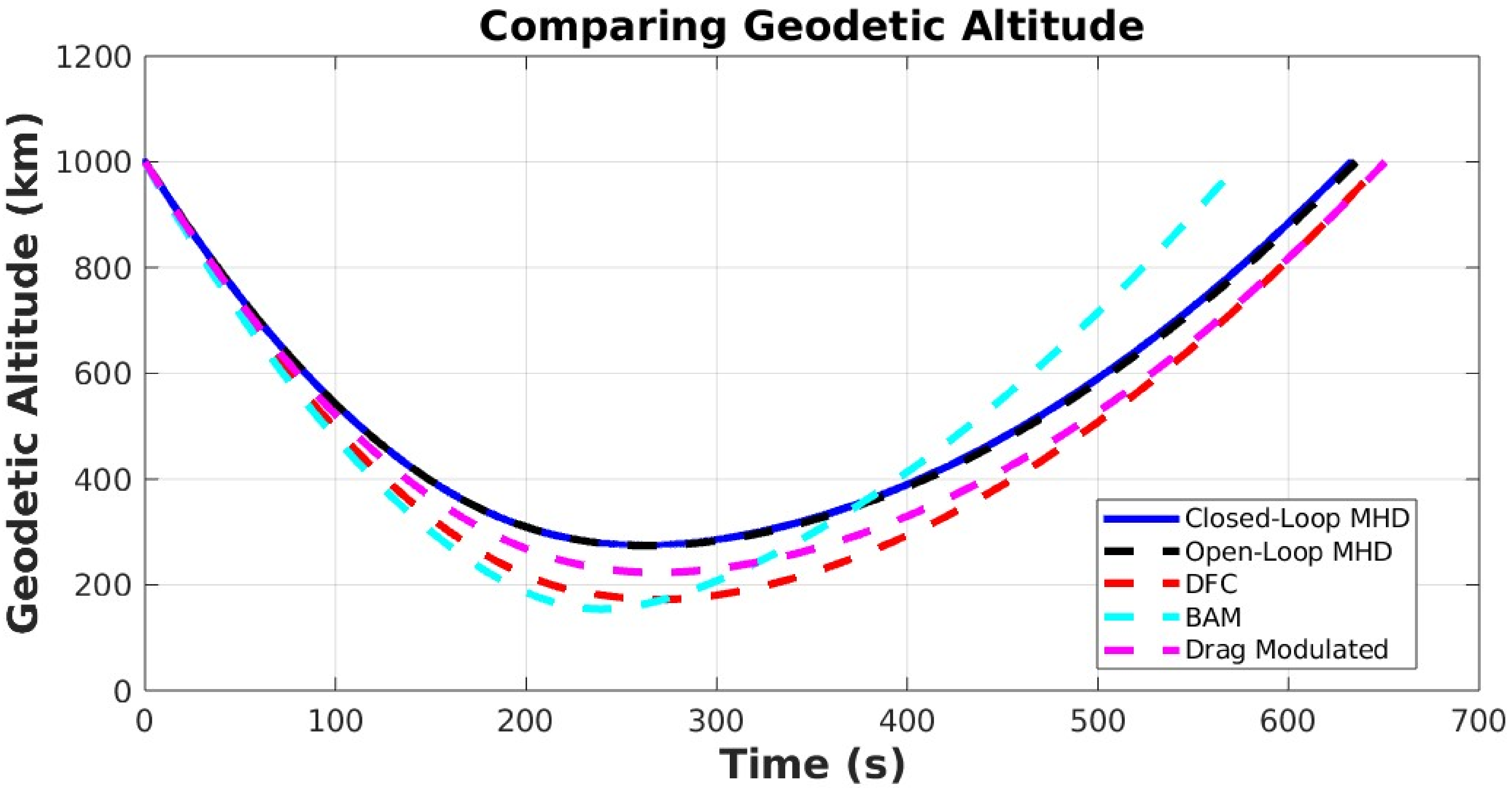
Case Study

- Aerocapture targeting a 430,000 x 3,986 km Neptune orbit with Titan flybys [1, 2]
- 70^{0} sphere cone Mars Science Laboratory (MSL) class vehicle
  - Vehicle Mass: 2000 kg
  - Vehicle Diameter: XXm
- Comparing following implementations:
  - MHD Enabled: MHD drag modulated
  - Aerodynamic only:
    - Bank Angle Modulated (BAM)
    - Direct Force Control (DFC)
    - Drag Modulated

Image Credit [3]

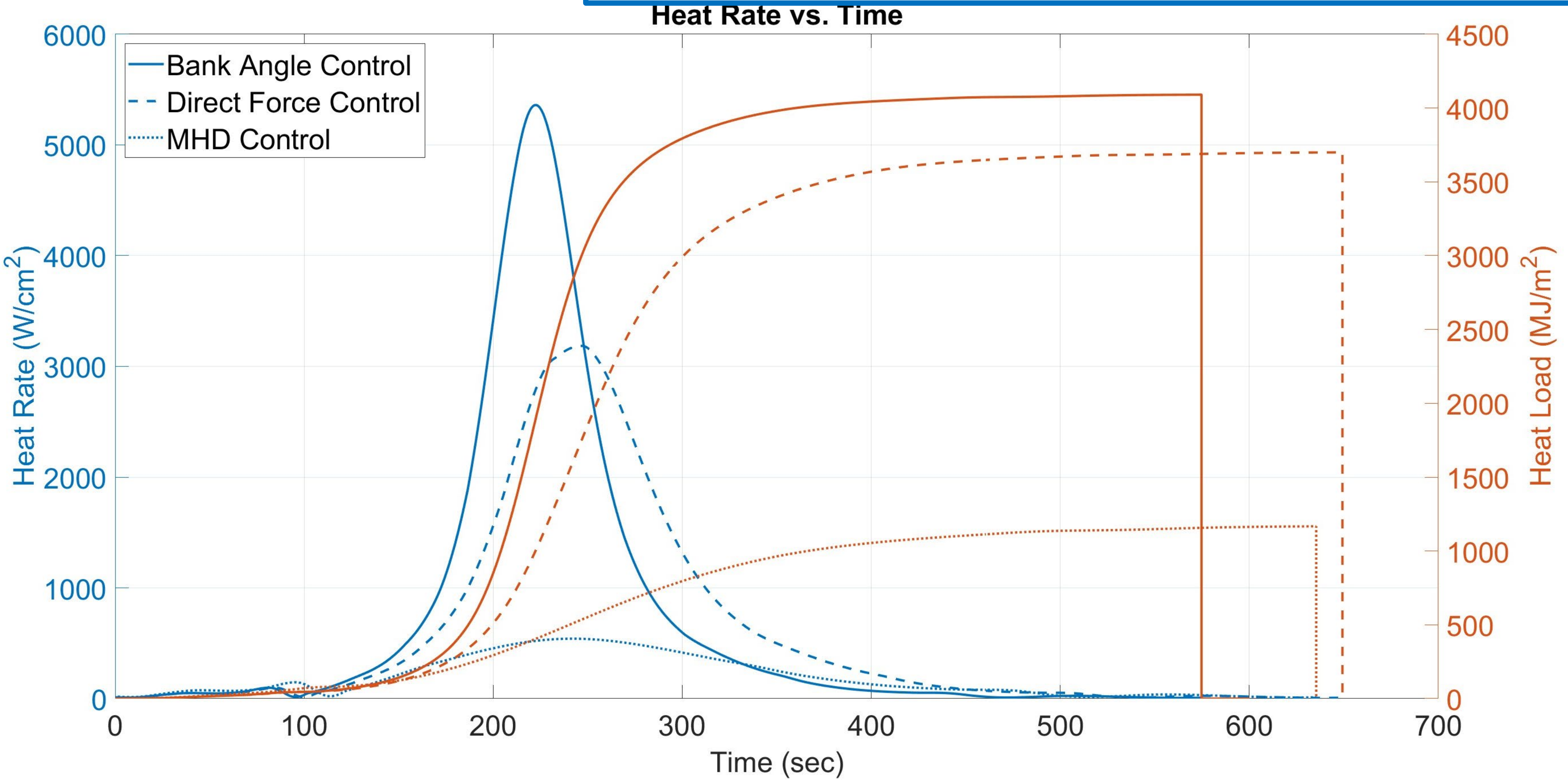
Results: Trajectory

2 MHD Control Cases do not enter as deep into the atmosphere as the 3 Aerodynamic Approaches

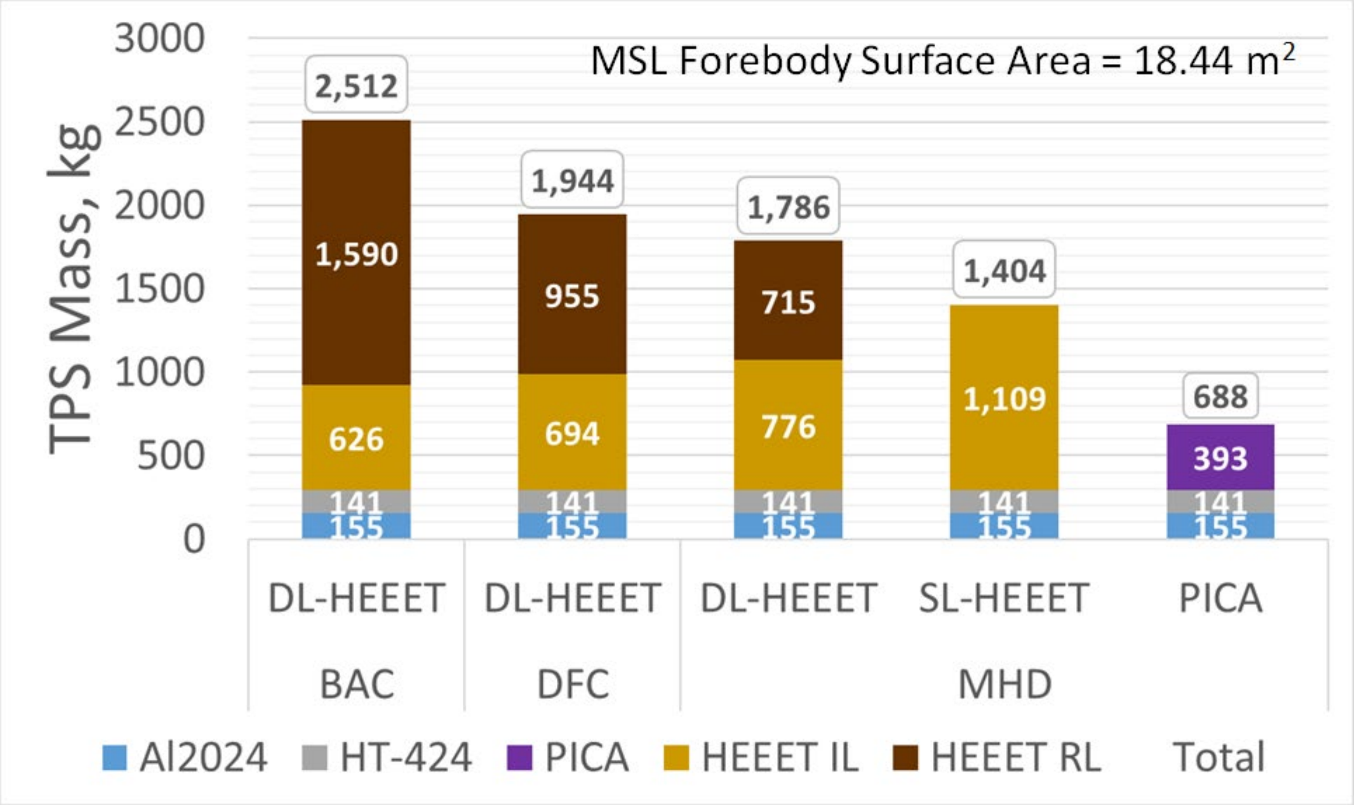


Results: Heating

Heat Rate and Heat Load on the spacecraft for the MHD Control Case are less than for the Aerodynamic Aerocapture Cases



Metrics of Performance: TPS and Magnet Sizing



Using 10 distributed magnets, the total power consumed and magnetic field:

- **Total power consumed: 5.521 kW**
- **Total magnetic field: 1.056 T**

System Impact:

- Est. MHD System mass penalty: $\approx \mathbf{167}$ kg
- Est. TPS mass savings: $\approx \mathbf{1824}$ kg

References

1. M. K. Lockwood, K. T. Edquist, B. R. Starr, B. R. Hollis, G. A. Hrinda, R. W. Bailey, J. L. Hall, T. R. Spilker, M. A. Noca, N. O'Kongo, R. J. Haw, C. G. Justus, A. L. Duvall, V. W. Keller, J. P. Masciarelli, D. A. Hoffman, J. R. Rae, C. H. Westhelle, C. A. Graves, N. Takashima, K. Sutten, J. Olejniczak, Y. K. Chen, M. J. Wright, B. Laub, D. Prabhu, R. E. Dyke and R. K. Prabhu, "Aerocapture Systems Analysis for a Neptune Mission," NASA/TM-2006-214300, 2006.

2. R. Deshmukh, D. A. Spencer and S. Dutta, "Investigation of Direct Force Control for Planetary Aerocapture at Neptune," in AAS 19-212, 29th Space Flight Mechanics Meeting, Maui, 2019.

3. J. Carter, "Will NASA's Next Flagship Mission Be To 'Ice Giant' Neptune And Its Mad Moon Triton?," Forbes, 9 April 2022. [Online]. Available: https://www.forbes.com/sites/jamiecartereurope/2022/04/09/will-nasas-next-flagship-mission-be-to-ice-giant-neptune-and-its-peculiar-moon-triton/?sh=33aba8c57b1f.

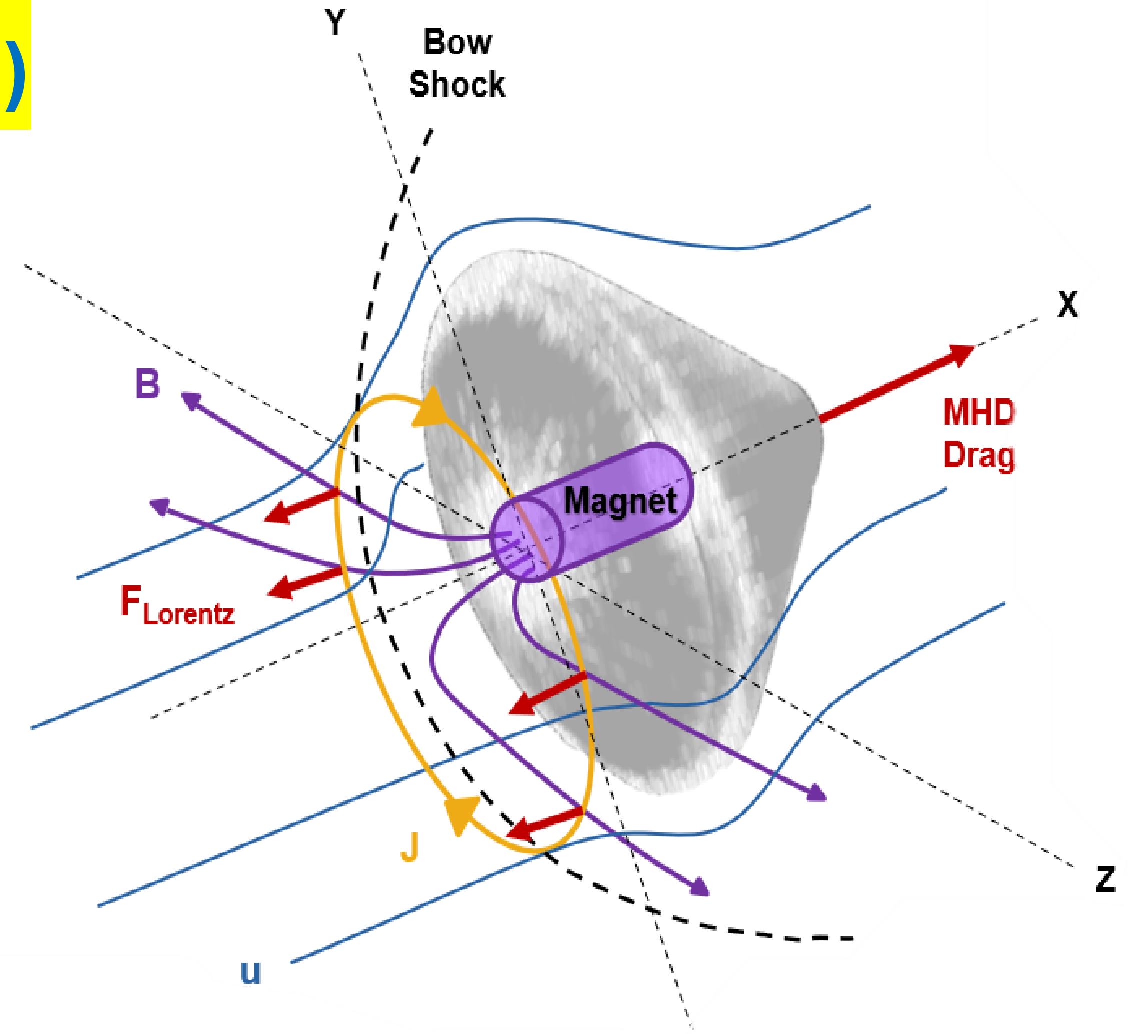
Prior Versions & Backup (delete in final version)

Background: Magnetohydrodynamic (MHD) Control (electrodeless case)

- Hypersonic entry produces an ionized plasma surrounding the spacecraft
- With an onboard magnet, a magnetic field, $\vec{B}$, can be applied on the plasma create an electron current, $\vec{J}$, and induce a Lorentz force:

$$\vec{F}_{Lorentz} = \vec{J} \times \vec{B}$$

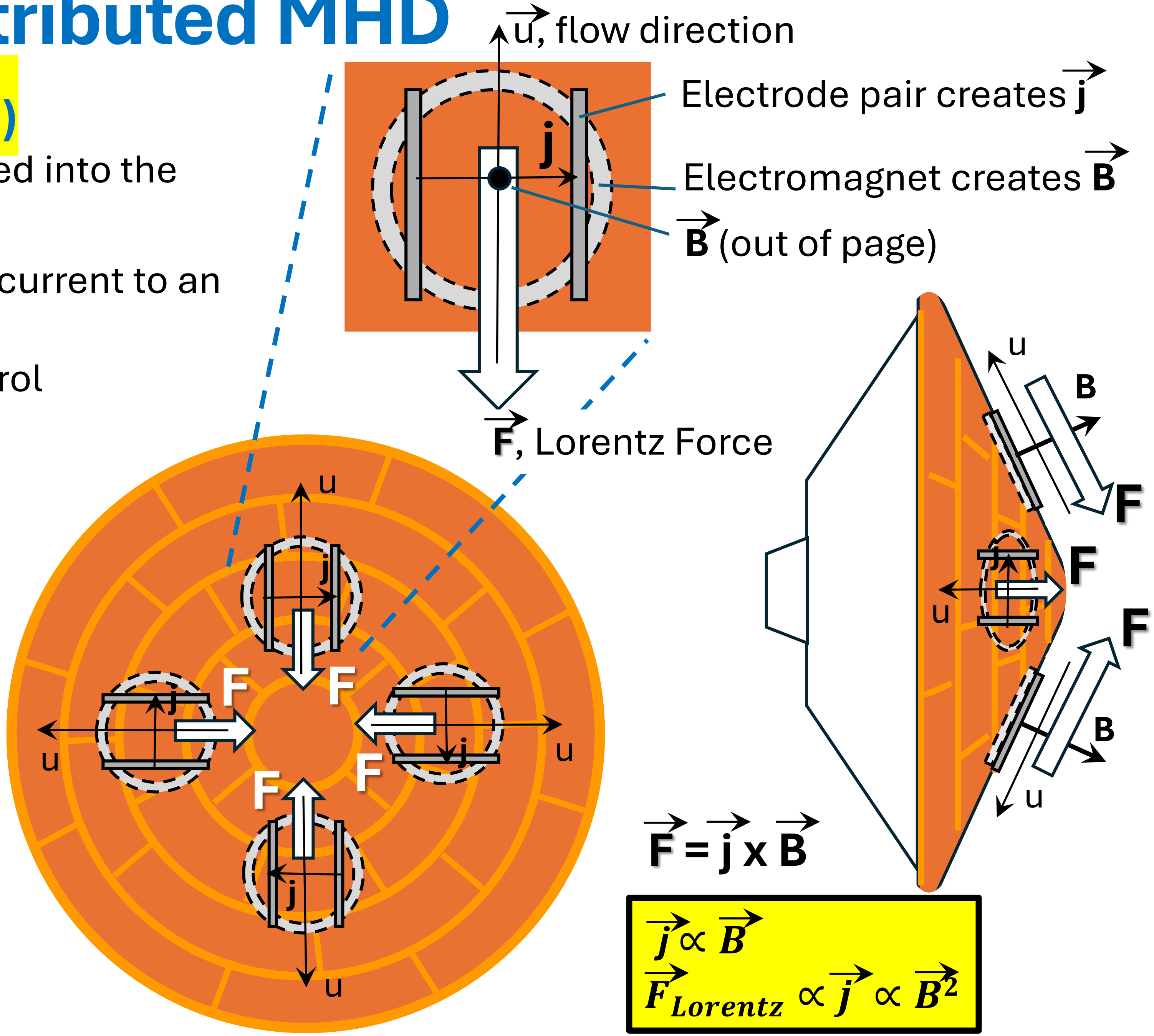
- **This force is in addition to aerodynamic forces**
- Assuming a uniform magnetic field, the Lorentz forces will sum and act equally and oppositely on the vehicle in only the drag direction



$$F_{Lorentz} \propto MHD\ Drag$$

Our Approach: Distributed MHD Patches (with electrodes)

- The magnetic field B can be integrated into the forebody as individual patches
- When using surface electrodes, the current to an electromagnet configuration can be manipulated to allow for active control
- With electrodes, the Lorentz force is proportional to the square of the magnetic field because the current is proportional to the magnetic field (Faraday EMF principle) and the Lorentz force is proportional to the current times the magnetic field.
- **The current for each patch can be commanded individually to produce Drag, Lift, or Side forces on the spacecraft**



$$\vec{j} \propto \vec{B}$$
$$\vec{F}_{Lorentz} \propto \vec{j} \propto \vec{B}^2$$

State of the Art

- First vehicle configuration assessment of MHD enabled aerocapture system
- First demonstration of a closed-loop guidance and controlled MHD enabled aerocapture

Accomplishments

- Completed and submitted a NIAC Phase II Proposal
- Completed aerothermal analysis bounding cases for use in trades
- Completed model developments:
- Flight Mechanics (POST2)
- TPS Sizing (FIAT)
- Completed an initial trade (on a nominal trajectory) comparing aerodynamic only Neptune aerocapture with MHD drag modulated