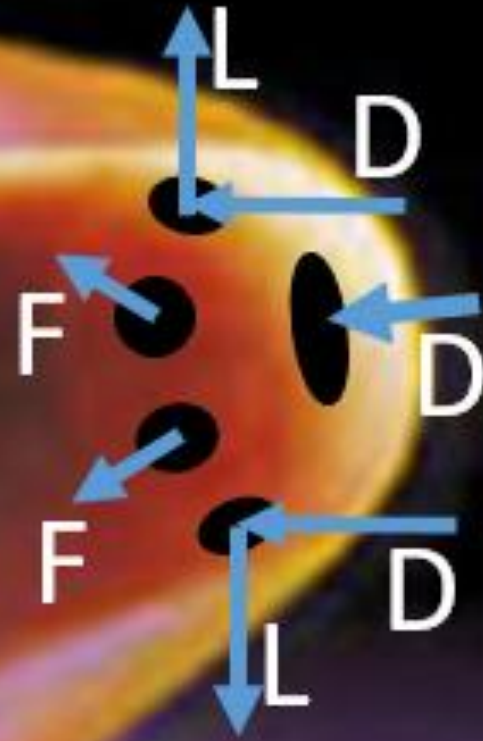


Advanced Aerocapture System

*For Enabling Faster-Larger
Planetary Science &
Human Exploration Missions
to Worlds with Atmospheres*



Dr. Robert W. Moses
NASA Langley Research Center

2021 International Planetary Probe Workshop

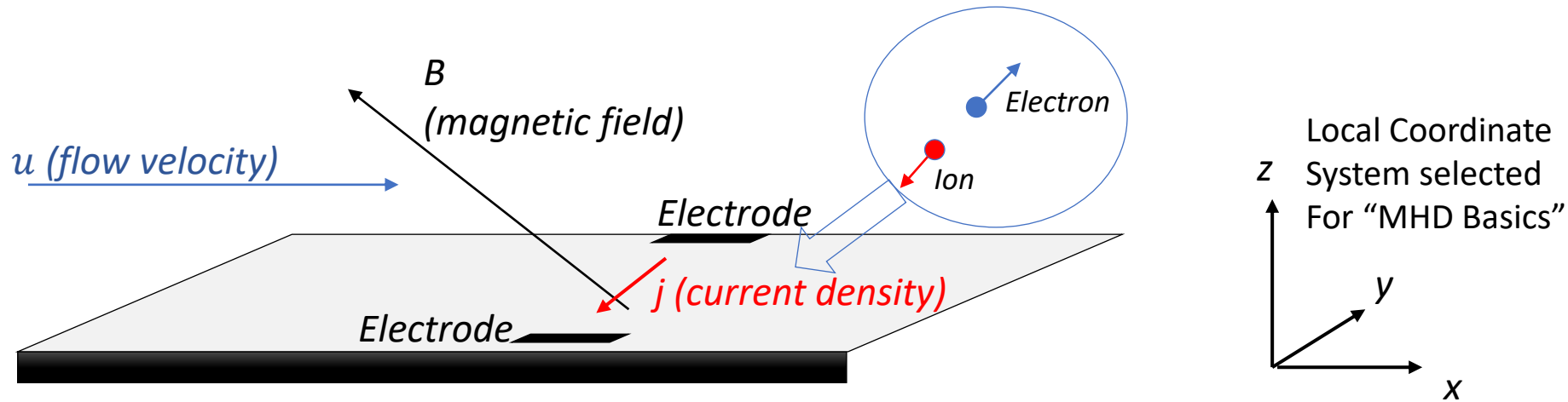
Future Missions Session

10 August 2021

Executive Summary

- Applied well-known principles of Magnetohydrodynamic (MHD) Power Generation to create electromagnetic (Lorentz) forces
- Forces are intended to steer the spacecraft during aerocapture maneuvers at Neptune, Mars, Earth, and other worlds with an atmosphere
- The magnitude of the Lorentz forces using a small “MHD Patch” effector away from the spacecraft’s centerline are “substantial” and in some cases as high as the whole-body aerodynamic drag force
- Mass of “MHD Patch” effector including magnet is on the order of the ballast mass ejected during previous Mars entries
- Electrical power is also generated during the aerocapture maneuver
- Much additional work is envisioned
- Additional funding was approved recently for continuing the subsystem design necessary for proceeding with a wind-tunnel experiment to validate the analysis

“MHD Basics”



When electrically conducting fluid crosses magnetic field lines, charged particles experience Lorentz forces $\vec{F}_L = q\vec{u} \times \vec{B}$, and since the charges q of electrons and ions are of opposite signs, the electrons and ions are pulled apart, which creates a Faraday electromotive force (emf). If the circuit is closed, current flows:

$$j = (1 - K)\sigma u B_z$$

Here σ is the electrical conductivity, and K is the load factor (load resistance vs plasma resistance). Interaction of the induced current with the B field creates body force per unit area:

$$\vec{F} = \vec{j} \times \vec{B}$$

If the B field is inclined with respect to the surface, the force would have both decelerating (drag) and normal (lift) components*:

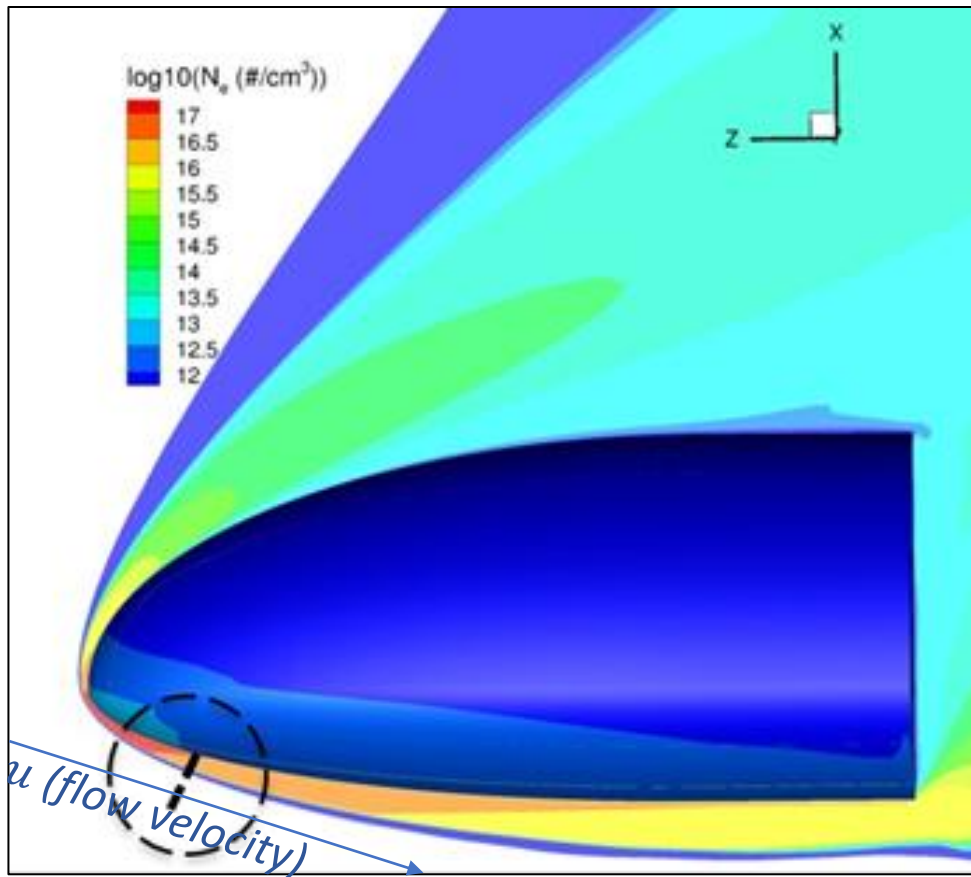
*Depends on orientation of the spacecraft's velocity vector

$$F_x = -(1 - K)\sigma u B_z^2$$

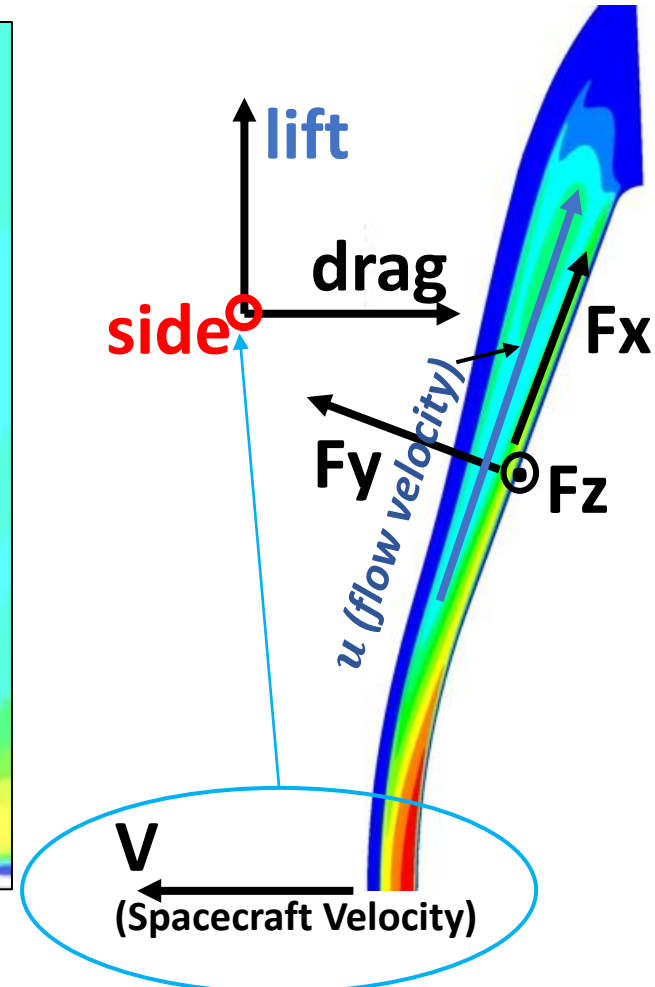
$$F_z = (1 - K)\sigma u B_z B_x$$

Alignment of Forces with respect to Spacecraft Velocity Vector

Mid L/D Aeroshell

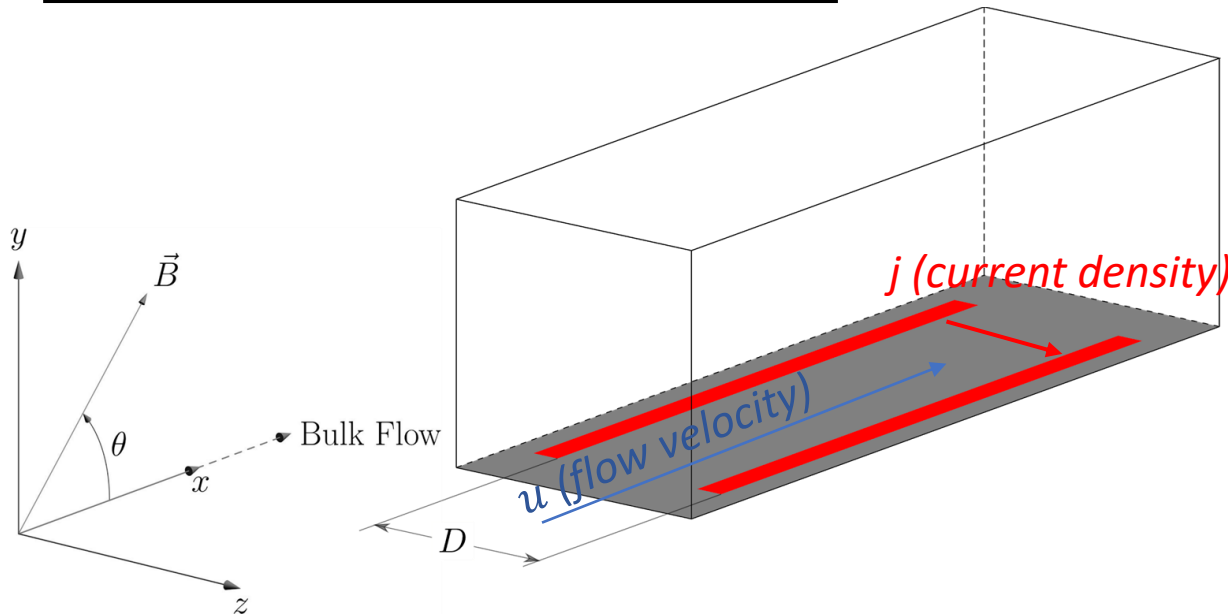


Blunt-body Aeroshell



Combined CFD + MHD Analysis

CFDWARP¹ Problem Setup



Example:

$\theta = 90$ degrees

$|B| = 0.1 - 3$ Tesla

$D = 0.97$ m

$B_x = |B| \cdot \cos(\theta)$

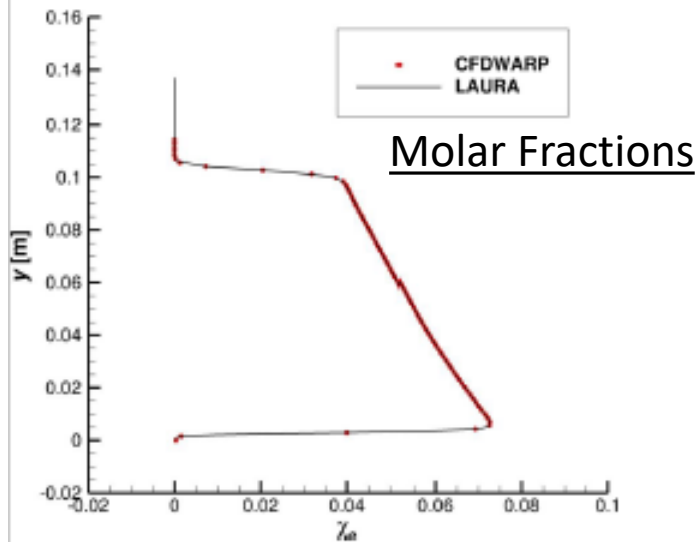
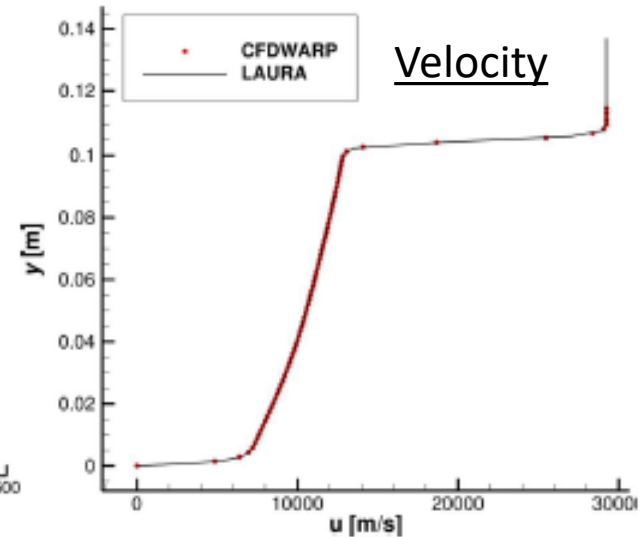
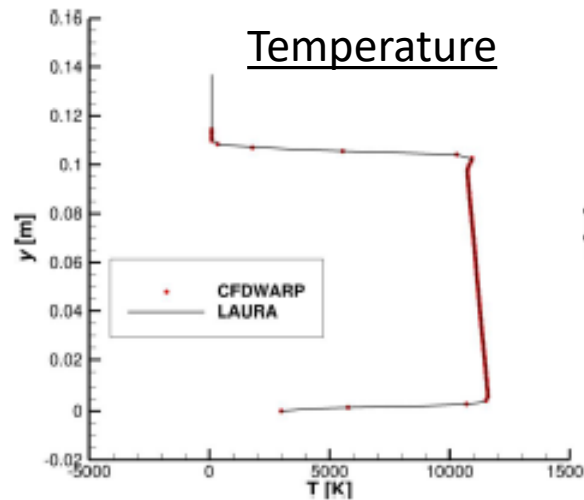
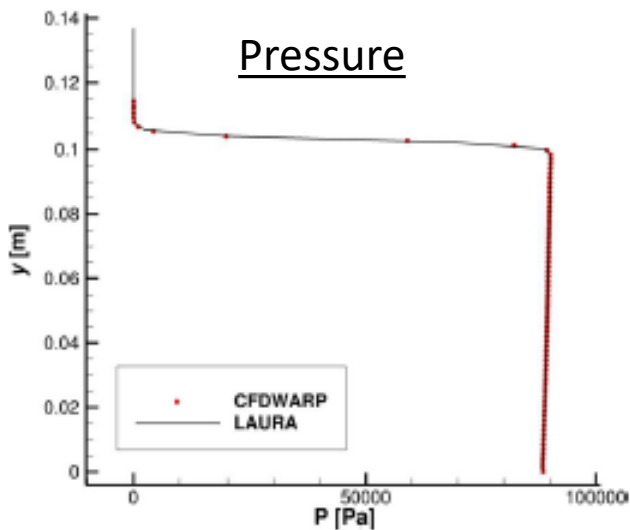
$B_y = |B| \cdot \sin(\theta)$

$B_z = 0$

Outline shown is the computational domain. Dimensions of domain: 1.0 m along x, 1.0 m along y, 1.0 m along z. Electrodes are in red. Wall of capsule is in dark gray. **Flow properties taken from LAURA on the flank of the capsule.** Zero current boundary conditions are imposed everywhere except at the electrodes. Both electrodes are given the same voltage (short circuit). Flow properties are frozen (no coupling). Hall effect and ion slip effects are taken into consideration.

¹CFDWARP is a combined CFD/MHD/plasma-sheath open-source code for hypersonic and planetary entry flows by Bernard Parent that can compute results in coupled or uncoupled modes

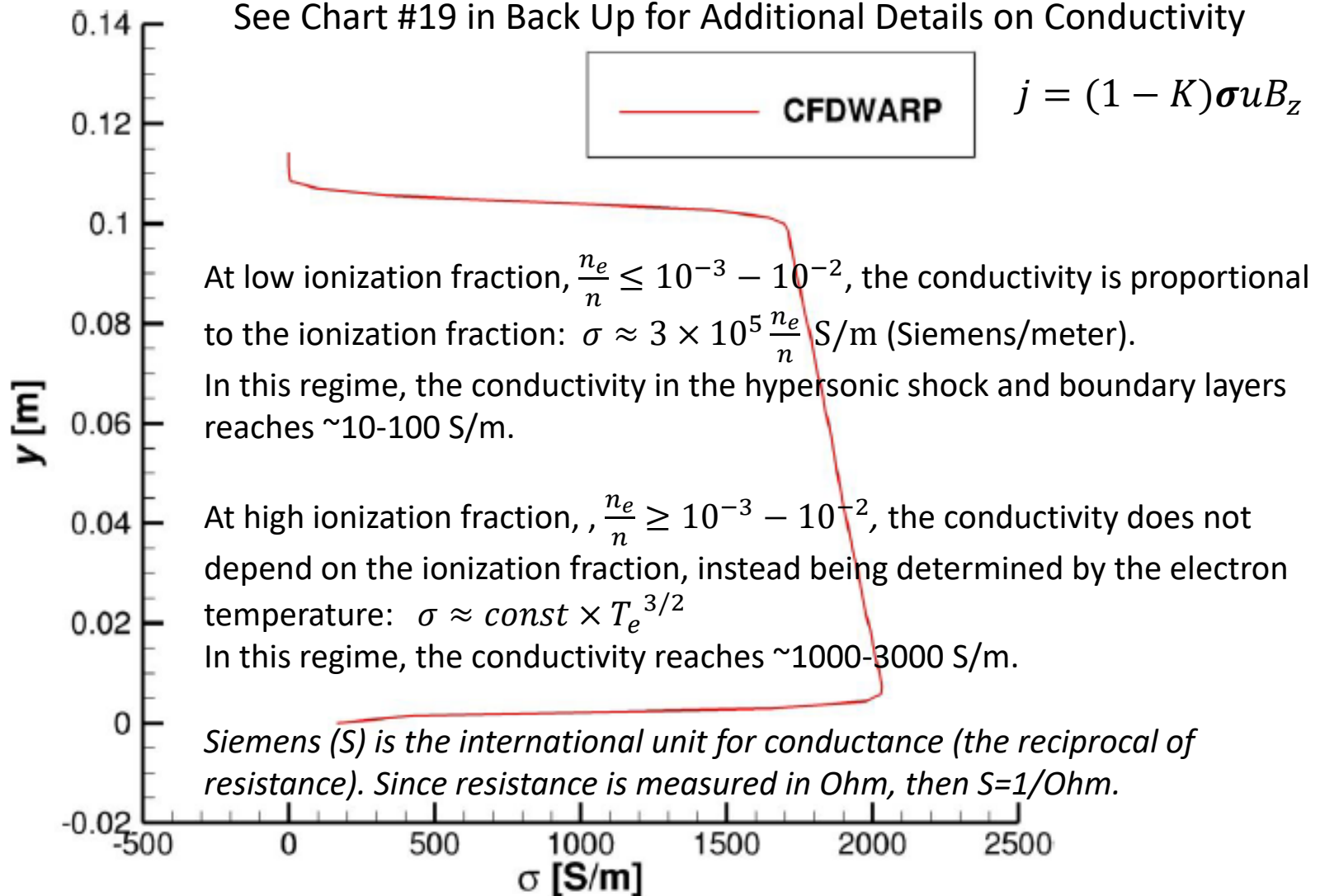
Bulk Flow Properties in CFDWARP Interpolated from LAURA



- Pressure, temperatures, and streamwise velocity (velocity component along x) are interpolated from LAURA
- All species molar fractions are interpolated from LAURA
- Interpolation done using splines

Resulting Electrical Conductivity in CFDWARP

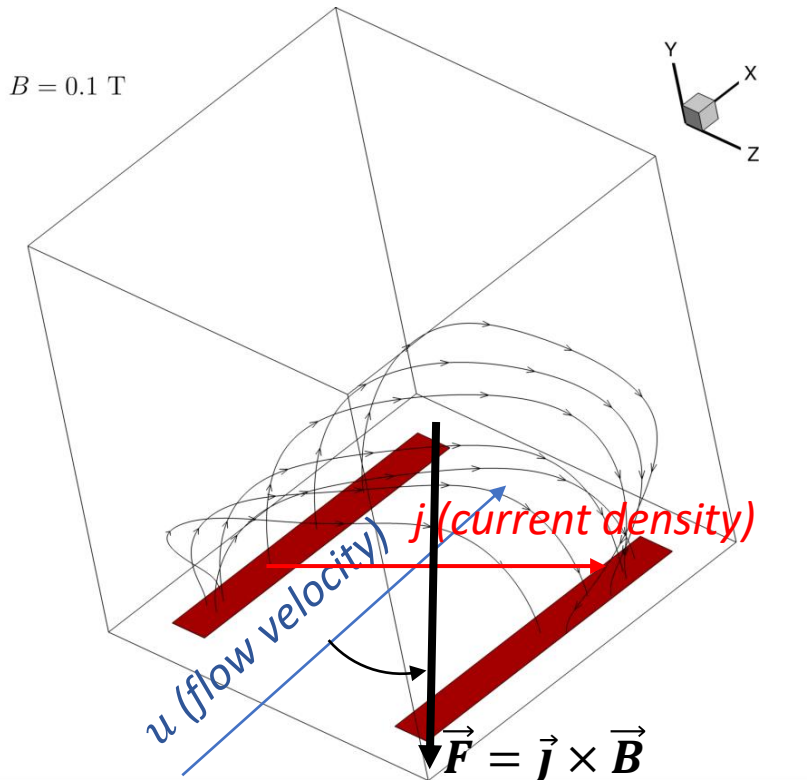
See Chart #19 in Back Up for Additional Details on Conductivity



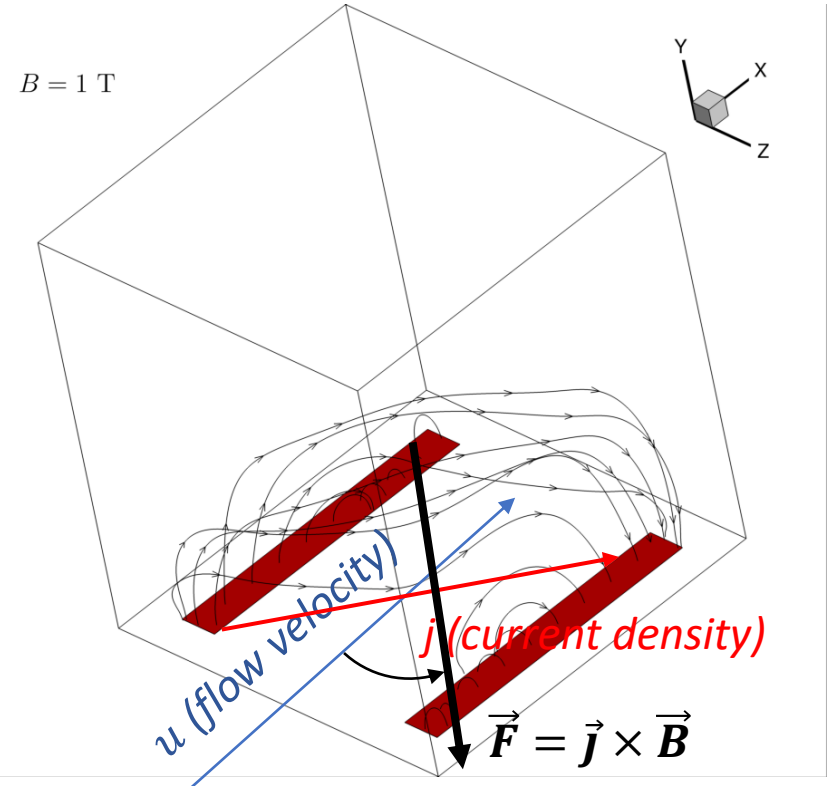
CFDWARP: Mars 9 km/s Case

Current Density Streamlines

Hall and ion slip effects are present due to the rarefied atmosphere (see Chart #20 in Back Up for More Details)



At $B=0.1 \text{ T}$, the current is affected by the Hall effect and flows at an off angle of 10-30 degrees leading to reduced performance.

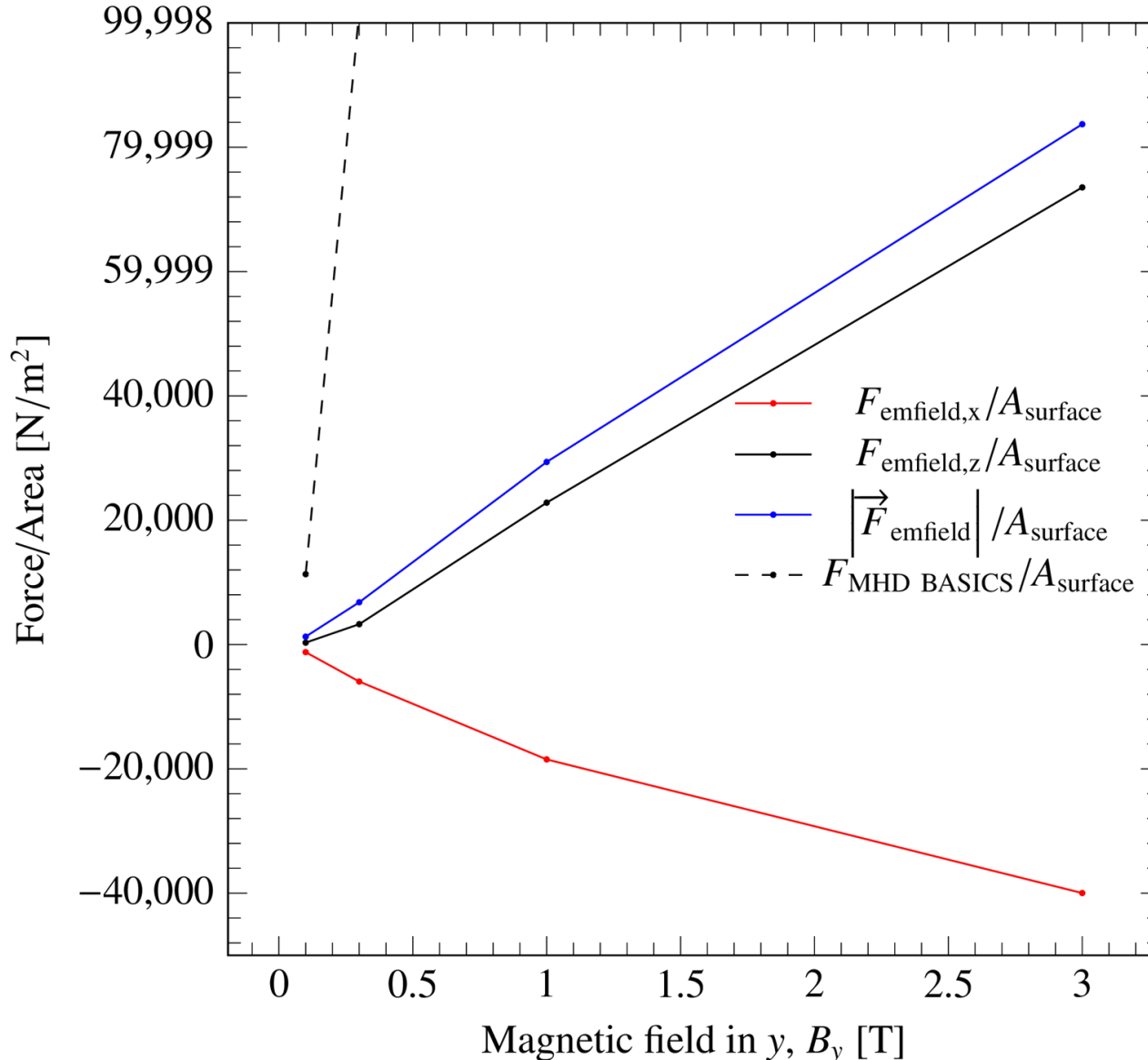


At $B=1.0 \text{ T}$, the Hall parameter is about 30, leading to severe distortion of the current streamlines and much reduced performance.

CFDWARP: Mars 9 km/s Case

Impact of B on EM Force acting on the flow

Hall and ion slip effects are present due to the rarefied atmosphere (see Chart #20)



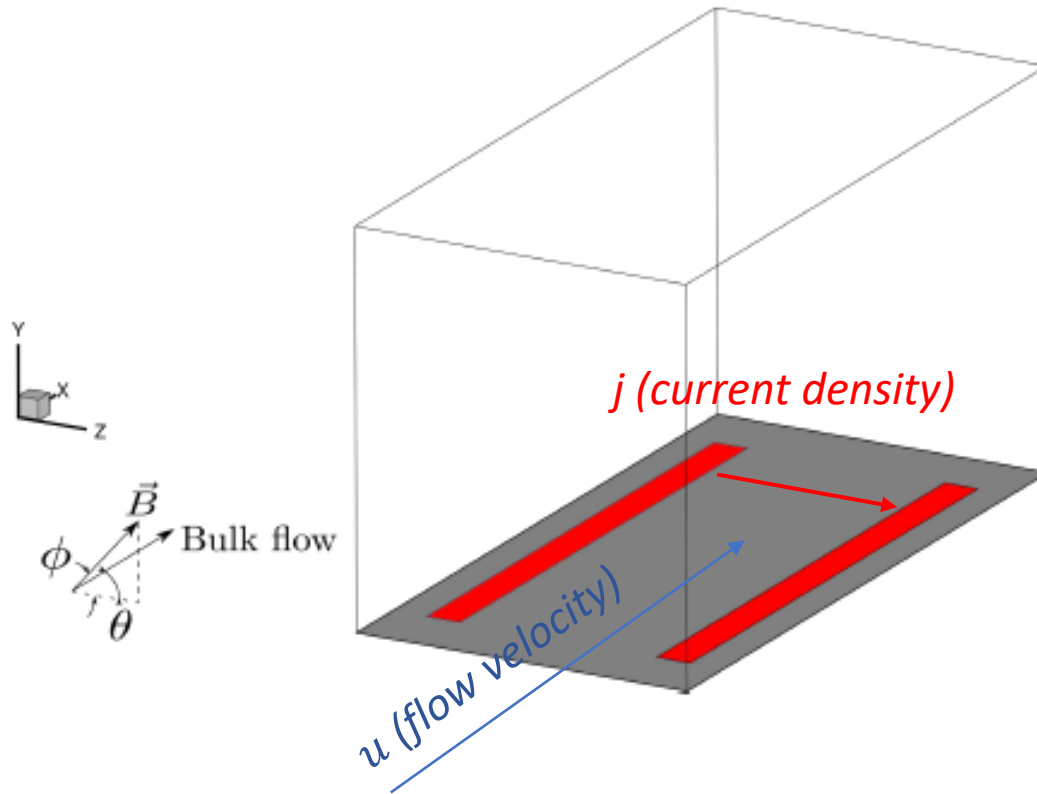
- Force increases more or less linearly with B
- Force measured is 10-100 times less than predicted through “MHD Basics” theory
- **Force per unit area is several times greater than the dynamic pressure (3 kPa)**

Options for Mars

- Hall and ion slip effects are present due to the rarefied atmosphere, and **these effects produce a side force that is lateral** to the spacecraft surface while also orthogonal to the flow (see Chart #20 in the Back Up for More Details)
 - **This yields an opportunity for rolling moments and roll control and additional opportunities to implement direct force control in 3 axes**
- Seeding the flow may also offer improved opportunities to modulate the forces in the light atmosphere of Mars
 - Seeding boosts the density and the conductivity of the flow in the MHD patch region leading to opportunities for increased control
 - Seeding extends the Mach range for which this approach can be used, such as for EDL to the surface
- These are areas of future work

Neptune 29 km/s Case

CFDWARP Problem Setup



$$B_x = |B| \cdot \cos(\theta) \cdot \sin(\phi)$$
$$B_y = |B| \cdot \sin(\theta) \cdot \sin(\phi)$$
$$B_z = |B| \cdot \cos(\phi)$$

$$\phi = 45 \text{ degrees}$$
$$\theta = 90 \text{ degrees}$$

$$|B| = 1 \text{ Tesla}$$

$$B_x = 0$$

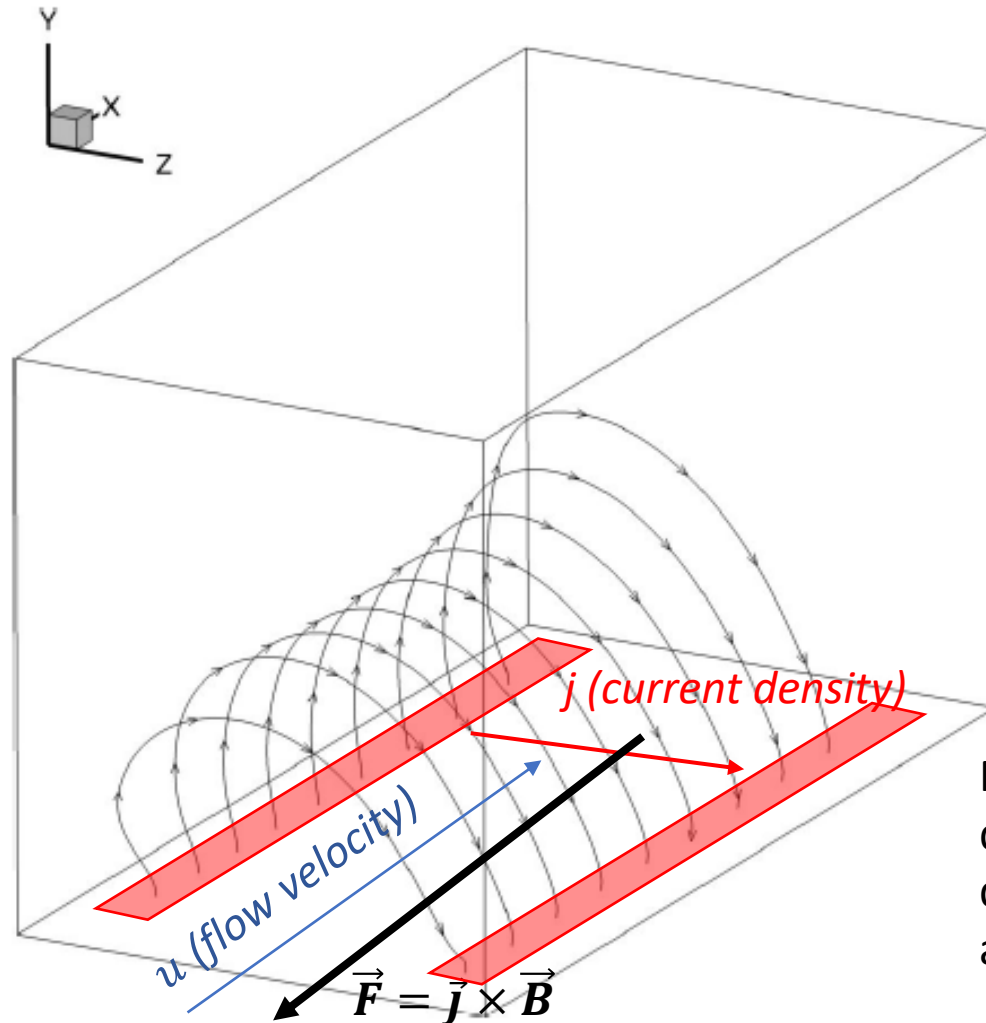
$$B_y = 0.71 \text{ T}$$

$$B_z = 0.71 \text{ T}$$

Outline is the computational domain. Dimensions of domain: 0.2m along x, 0.118m along y, 0.1m along z. Electrodes are in red. Wall of capsule is in dark gray. Zero current boundary conditions are imposed everywhere except at the electrodes. Both electrodes are given the same voltage (short circuit). Flow properties are frozen (no coupling). Hall effect and ion slip effects are taken into consideration.

CFDWARP Neptune 29 km/s Case

Current Density Streamlines Between the Two Electrodes



No significant Hall effect
due to relatively high
density of the
atmosphere

CFDWARP Neptune 29 km/s Case

Net Forces and Energy Input

Force on the gas by electromagnetic fields ($\mathbf{J} \text{ cross } \mathbf{B}$)

$$= (-2718, -103, +103) \text{ N}$$

Rate of energy input to the gas by the electromagnetic fields ($\mathbf{E} \text{ dot } \mathbf{J}$)

$$= -3.01 \text{ MW}$$

Rate of work done by the electromagnetic fields ($\mathbf{V} \text{ dot } (\mathbf{J} \text{ cross } \mathbf{B}))$)

$$= -29.2 \text{ MW}$$

Rate of heat deposited to the gas by electromagnetic fields (Energy input - work done)

$$= 26.2 \text{ MW}$$

Note: sum of heat deposited and work done should be zero for short circuited electrodes (11% numerical error is due to coarse mesh)

Placing the Forces in Perspective -

Neptune & Earth:

- An MHD patch effector having an area of 1 m^2 would produce a force of $2.0 \times 10^5 \text{ N}$.
- **This is comparable to the “whole body” drag and lift forces computed by LAURA for the Neptune entry velocity and atmospheric density.**
- Opportunity for sizing and orientation of the magnetic field to produce the desired drag and lift vectors for controlling the entry body.
- This approach seems applicable to a range of entry shapes, blunt or slender.

Conclusions

- Study results reveal the ground-breaking potential of this MHD approach to aerocapture at Neptune and Mars
- Produces large forces up to, or higher than, whole body drag for investigated conditions
- For Mars, low-density atmosphere is challenging—degrades performance of lift and drag. However, it offers opportunity for side force and control in 3 axes
- For Neptune, forces and power generation are ground-breaking, creating new opportunities for capsule design, increased payload sizes, and faster trip times.
- Relevant MHD conditions for Neptune should be achievable in a flight test at Earth

Future Work

- Initial run of fully coupled (CFD + MHD) mode showed good agreement with uncoupled results shown herein
- Next steps are to
 - conduct 3-D fully coupled analysis for additional configurations and possibly other missions
 - further study the Hall and Ion slip effects at Mars
 - further explore seeding the flow at Mars to extend the operational range to include EDL in addition to Aerocapture
 - validate analysis results via ground-based testing
 - look for flight test opportunities for Earth Return Entries
- Funding has been approved for continuing with a preliminary design leading to subsequent validation testing in a wind tunnel

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Backup Slides

Electrical Conductivity of the Flow

The scalar electrical conductivity is proportional to the number density n_e of principal charge carriers (electrons) and inversely proportional to the rate, or frequency, of their collisions with ions (ν_{ei}) and neutral molecules (ν_{en}):

$$\sigma = \frac{e^2 n_e}{m(\nu_{ei} + \nu_{en})}$$

Here e and m are the electron charge and mass, respectively.

At low ionization fraction, $\frac{n_e}{n} \leq 10^{-3} - 10^{-2}$ (n is the number density of gas), electrons collide mostly with neutral molecules, and the conductivity is proportional to the ionization fraction:

$$\sigma \approx 3 \times 10^5 \frac{n_e}{n} \text{ S/m}$$

In this regime, the conductivity in hypersonic shock and boundary layers reaches ~ 10 - 100 S/m (Siemens per meter).

At high ionization fraction, $\frac{n_e}{n} \geq 10^{-3} - 10^{-2}$, electrons collide mostly with ions, and the conductivity does not depend on the ionization fraction, instead being determined by the electron temperature:

$$\sigma \approx \text{const} \times T_e^{3/2}$$

In this regime, the conductivity reaches ~ 1000 - 3000 S/m (Siemens per meter).

Siemens (S) is the international unit for conductance (the reciprocal of resistance). Since resistance is measured in Ohm, then $S=1/\text{Ohm}$.

Hall and Ion Slip Effects in Rarefied Flow

Hall effect

With the induced electric field \vec{E} perpendicular to the B field, electrons and ions have $\vec{E} \times \vec{B}$ drift motion along the flow, which effectively diverts their cross-flow motion and thus reduces MHD body forces. This can be expressed as an effective conductivity lower than the scalar one.

Ion slip effect

MHD effects increase with flow velocity. However, as B field increases, the motion of electrons and ions is retarded so much that the ion-electron fluid starts to slip against the bulk neutral gas, and the lower ion-electron velocity reduces the MHD effects (including body forces). This ion slip effect can also be expressed as a reduction in the effective conductivity.

$$\sigma_{eff} = \frac{\tilde{\sigma}}{1 + \tilde{\Omega}^2}$$

Here the conductivity $\tilde{\sigma}$ and the Hall parameter $\tilde{\Omega}$ corrected for ion slip are:

$$\tilde{\sigma} = \frac{\sigma}{1 + \Omega_e \Omega_i}; \quad \tilde{\Omega} = \frac{\Omega_e}{1 + \Omega_e \Omega_i}$$

Here σ is the scalar conductivity (see previous slide), and the electron and ion Hall parameters are:

$$\Omega_e = \frac{eB}{m(\nu_{ei} + \nu_{en})}; \quad \Omega_i = \frac{eB}{M\nu_{in}}$$

(M and ν_{in} are the ion mass and ion-neutral collision frequency, respectively).

The performance-reducing Hall and ion slip effects become dominant at low gas density.