New Magnetohydrodynamic (MHD) Lift Concept

for More Efficient Missions to Mars and Neptune

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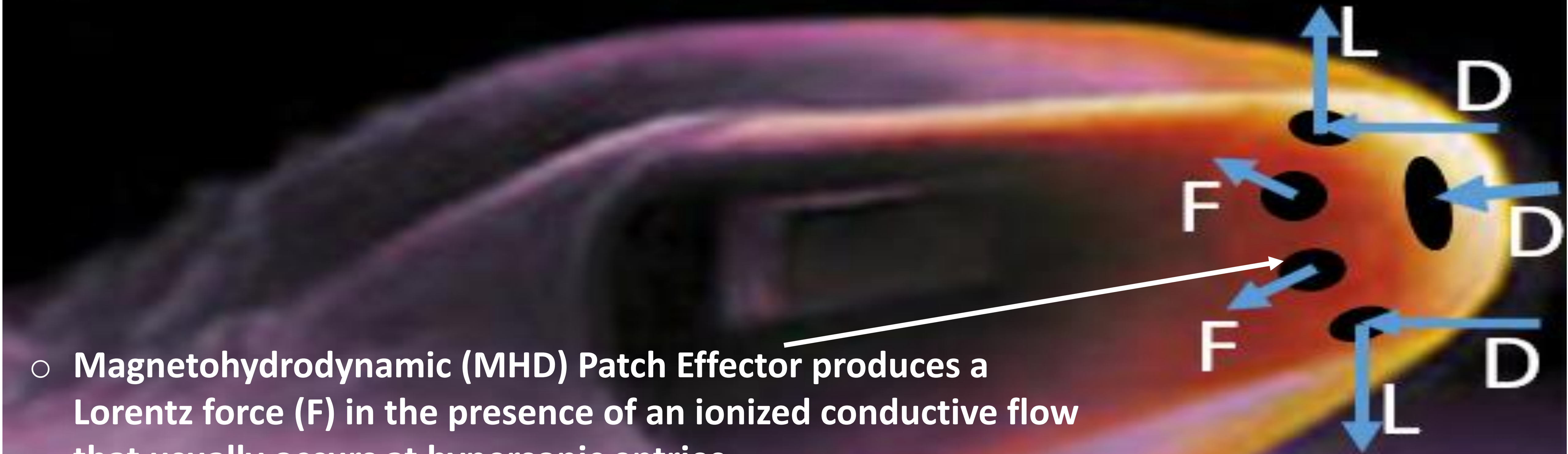
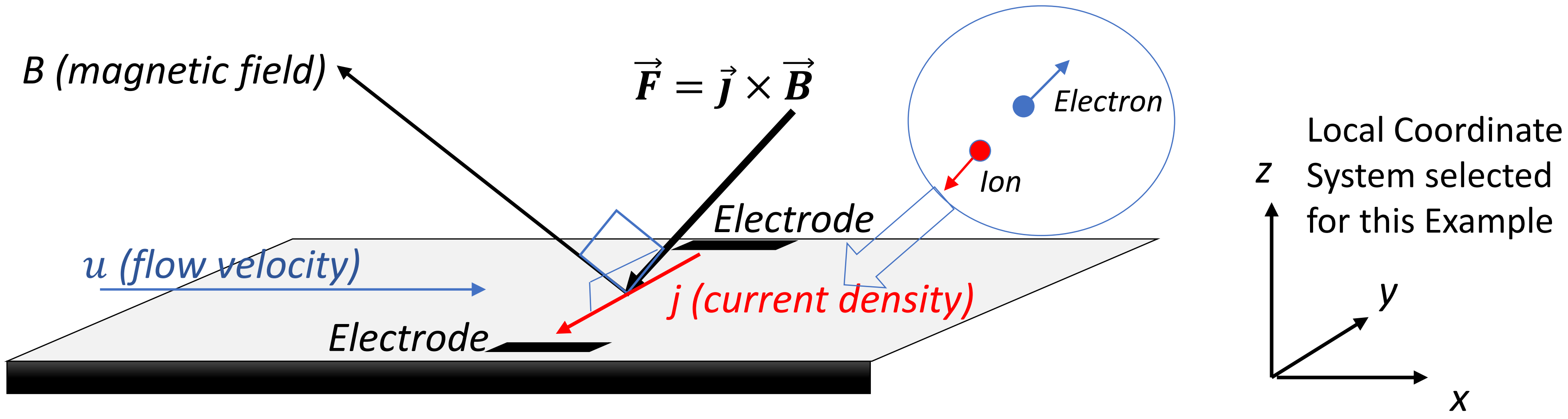


- Magnetohydrodynamic (MHD) Patch Effector produces a Lorentz force (F) in the presence of an ionized conductive flow that usually occurs at hypersonic entries.
- Placement of the Effector allows alignment of the force vector to produce drag (D) or lift (L) for steering the spacecraft.
- These forces augment the aerodynamic lift and drag and typically occur at higher altitudes.
- Entries at Neptune and Mars are presented herein to illustrate the creation of force by a single Effector.

“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 $\boldsymbol{q}$ 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 $\boldsymbol{\sigma}$ is the electrical conductivity, and $\boldsymbol{K}$ is the load factor (load resistance vs plasma resistance). Interaction of the induced current with the **B** field creates body force per unit area:

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

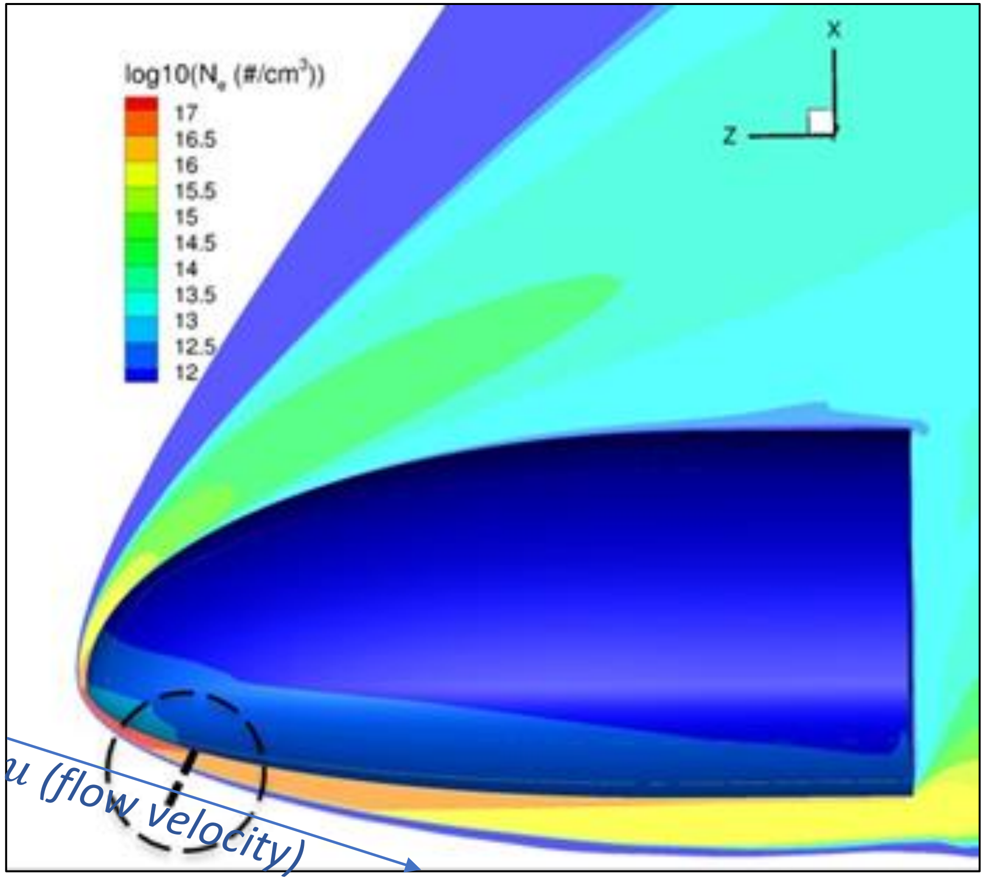
If the B field is inclined with respect to the surface, the force would have both decelerating(drag) and normal (lift) components*****:

***Depends on orientation of the spacecraft’s velocity vector**

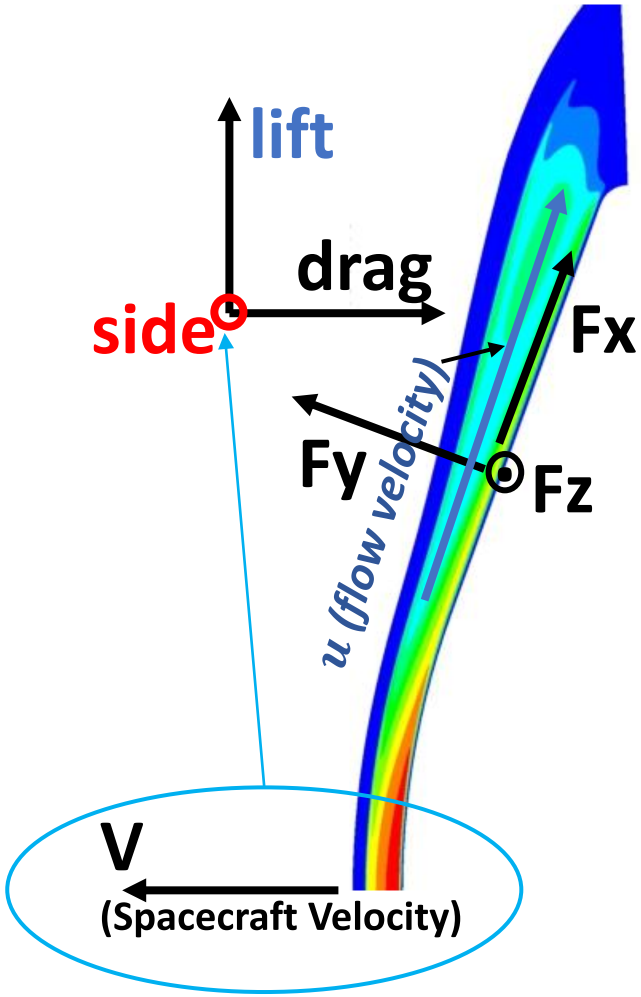
$$F_x = -(1 - K)\sigma u {B_z}^2$$
$$F_z = (1 - K)\sigma u B_z B_x$$

Alignment of Forces with respect to Spacecraft Velocity Vector

Mid L/D Aeroshell

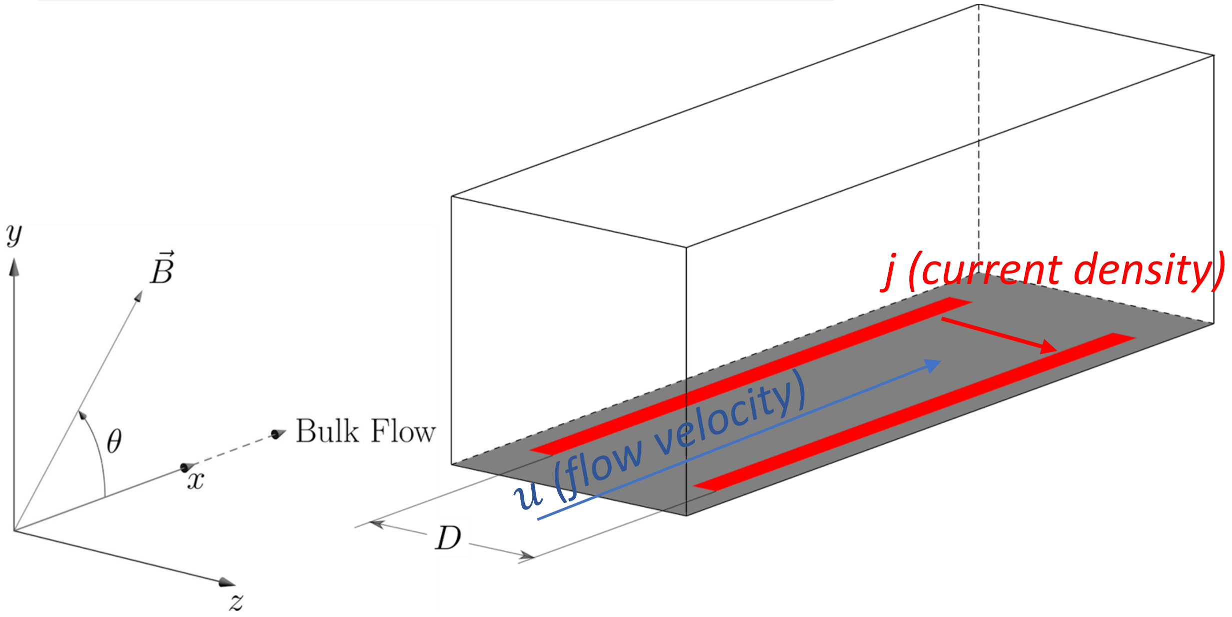


Blunt-body Aeroshell



Combined CFD + MHD Analysis

CFDWARP[1] Problem Setup



Example:

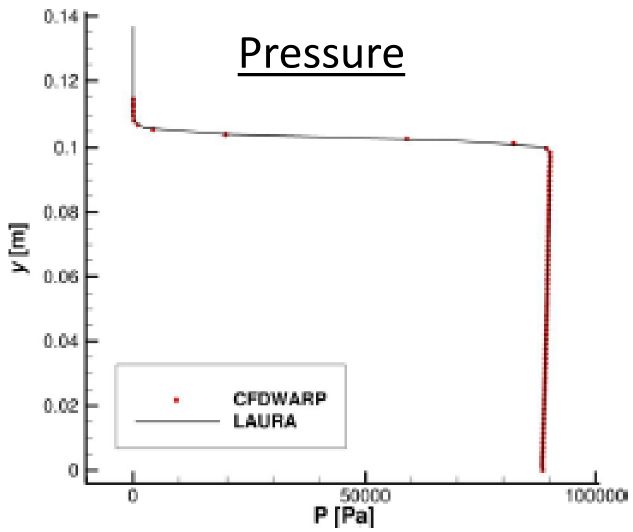
theta=90 degrees
|B|=0.1 - 3 Tesla
D=0.97 m

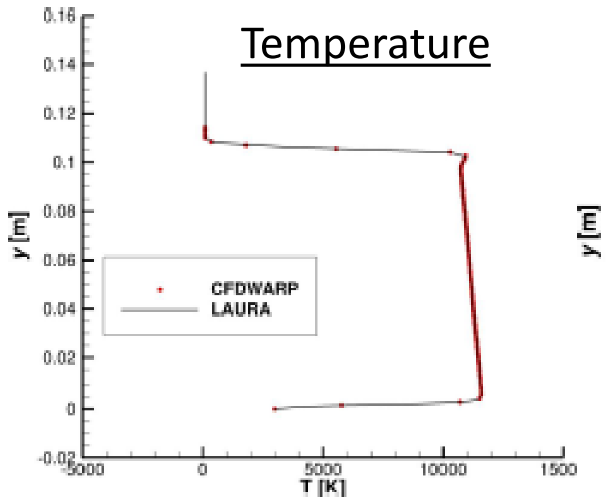
Bx=|B|*cos(theta)
By=|B|*sin(theta)
Bz=0

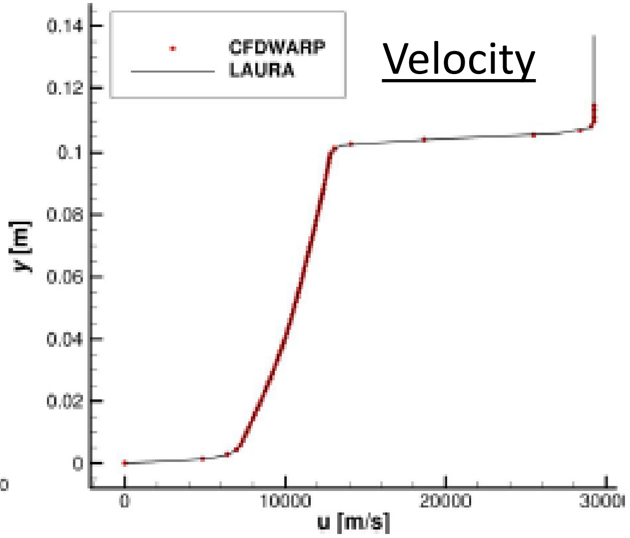
Outline shown is the computational domain. Dimensions of domain: 1.0 m along x, 1.0 m along y, 1.0 m along z. Electrodes are in red. Wall of capsule is in dark gray. **Flow properties taken from LAURA on the flank of the capsule.** Zero current boundary conditions are imposed everywhere except at the 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.

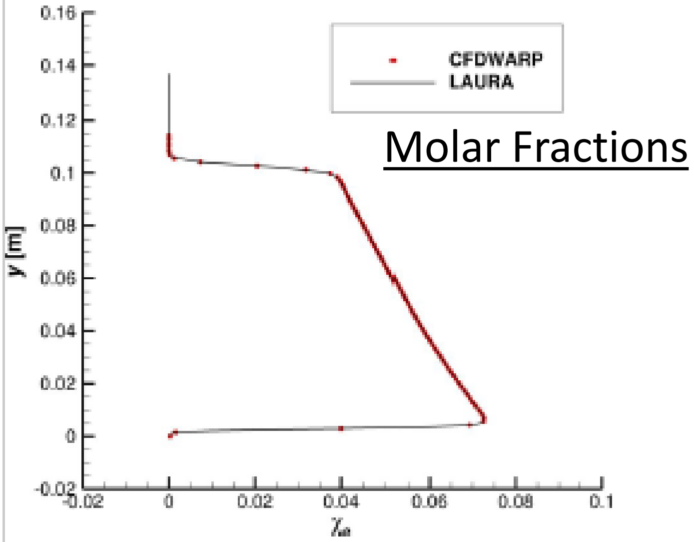
[1] CFDWARP is a combined CFD/MHD/plasma-sheath open-source code for hypersonic and planetary entry flows by Bernard Parent that can compute results in coupled or uncoupled modes

Bulk Flow Properties in CFDWARP Interpolated from LAURA


Pressure

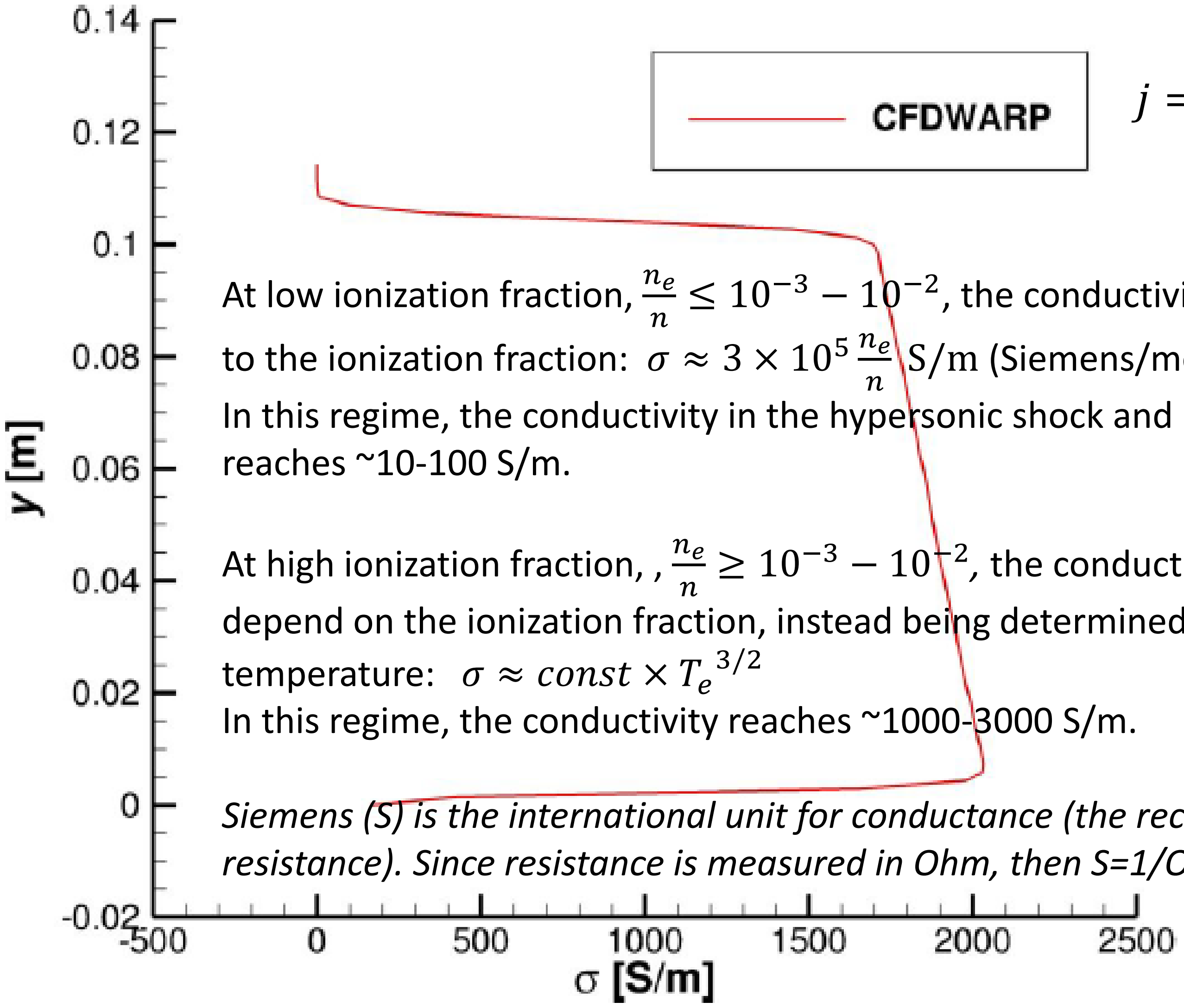

Temperature


Velocity


Molar Fractions

- 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



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

At low ionization fraction, $\frac{n_e}{n} \leq 10^{-3} - 10^{-2}$, the conductivity is proportional to the ionization fraction: $\sigma \approx 3 \times 10^5 \frac{n_e}{n}\,\mathrm{S/m}$ (Siemens/meter).
In this regime, the conductivity in the hypersonic shock and boundary layers reaches ~10-100 S/m.

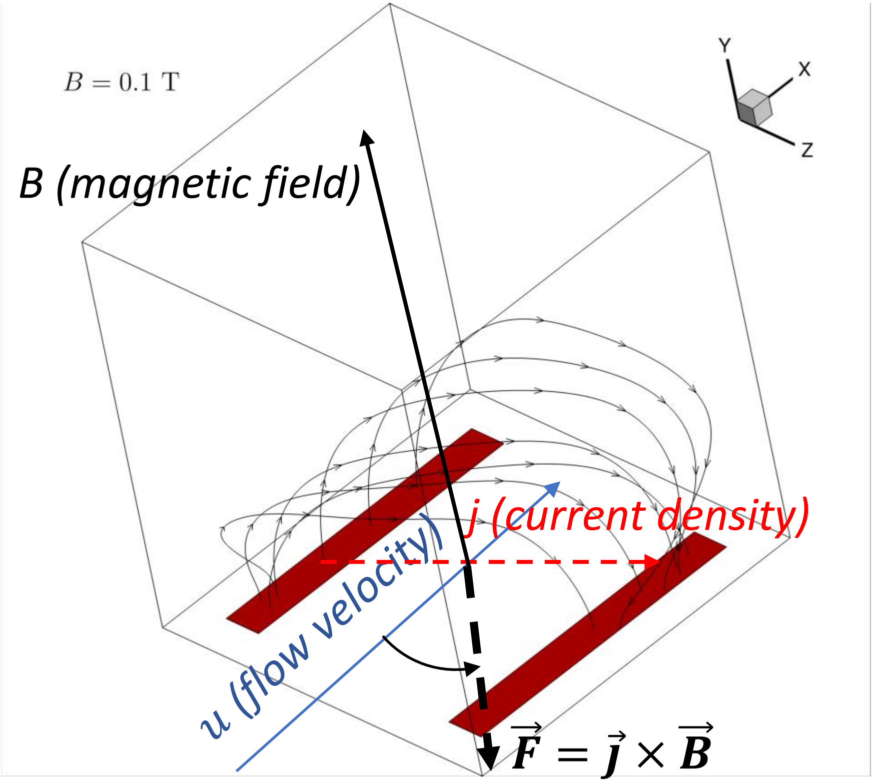
At high ionization fraction, , $\frac{n_e}{n} \geq 10^{-3} - 10^{-2}$, the conductivity does not depend on the ionization fraction, instead being determined by the electron temperature: $\sigma \approx const \times {T_e}^{3/2}$
In this regime, the conductivity reaches ~1000-3000 S/m.

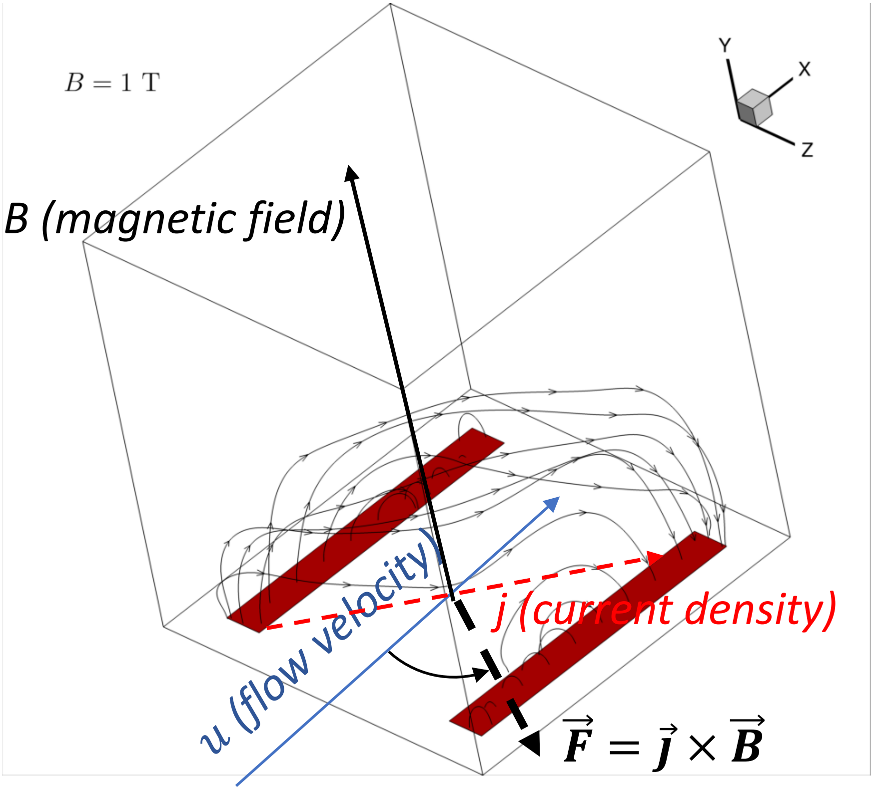
Siemens (S) is the international unit for conductance (the reciprocal of resistance). Since resistance is measured in Ohm, then S=1/Ohm.

CFDWARP: Mars 9 km/s Case

Current Density Streamlines

Hall and ion slip effects are present due to the rarefied atmosphere





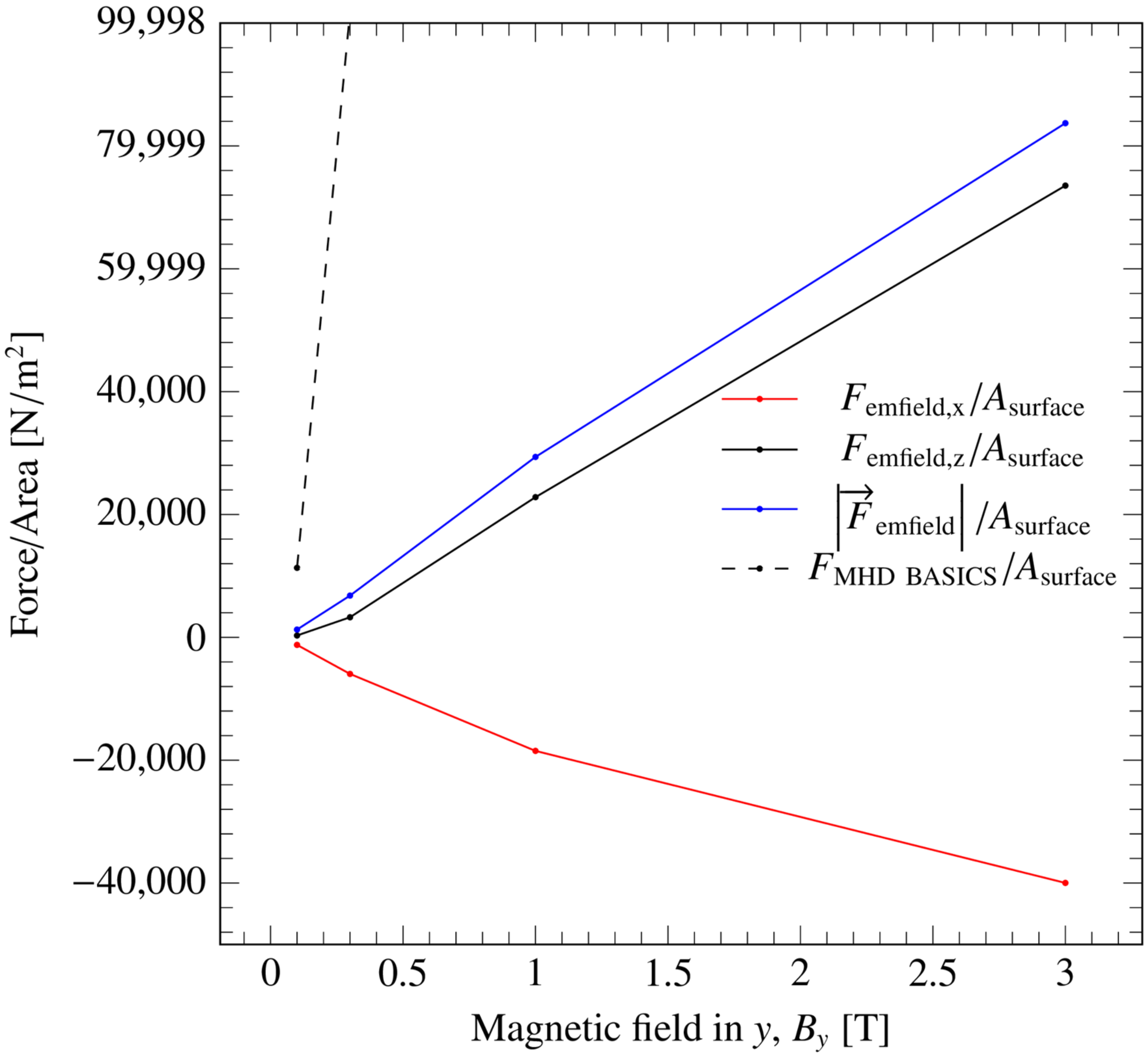
At **B=0.1 T**, the current is affected by the Hall effect and flows at an off angle of 10-30 degrees leading to reduced performance.

At **B=1.0 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



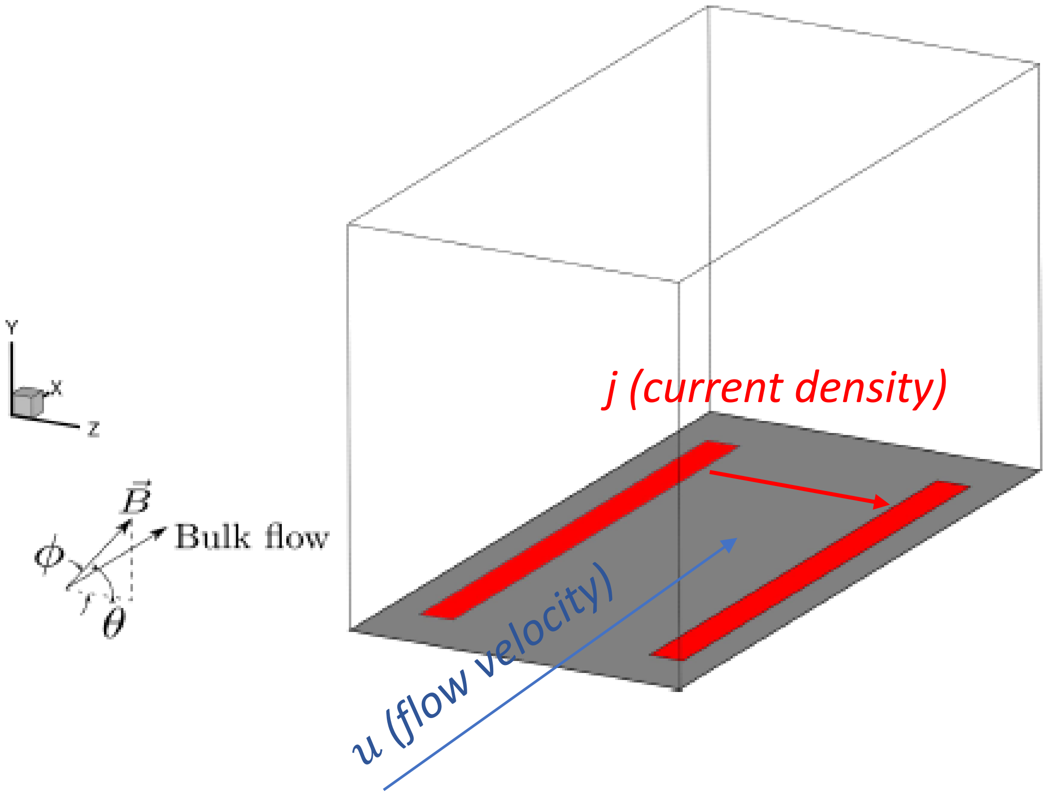
- Force increases more or less linearly with B
- Force measured is 10-100 times less than predicted through “MHD Basics” theory
- **Force per unit area is several times greater than the dynamic pressure (3 kPa)**

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
    - **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



Bx=|B|*cos(theta)*sin(phi)
By=|B|*sin(theta)*sin(phi)
Bz=|B|*cos(phi)

phi=45 degrees
theta=90 degrees

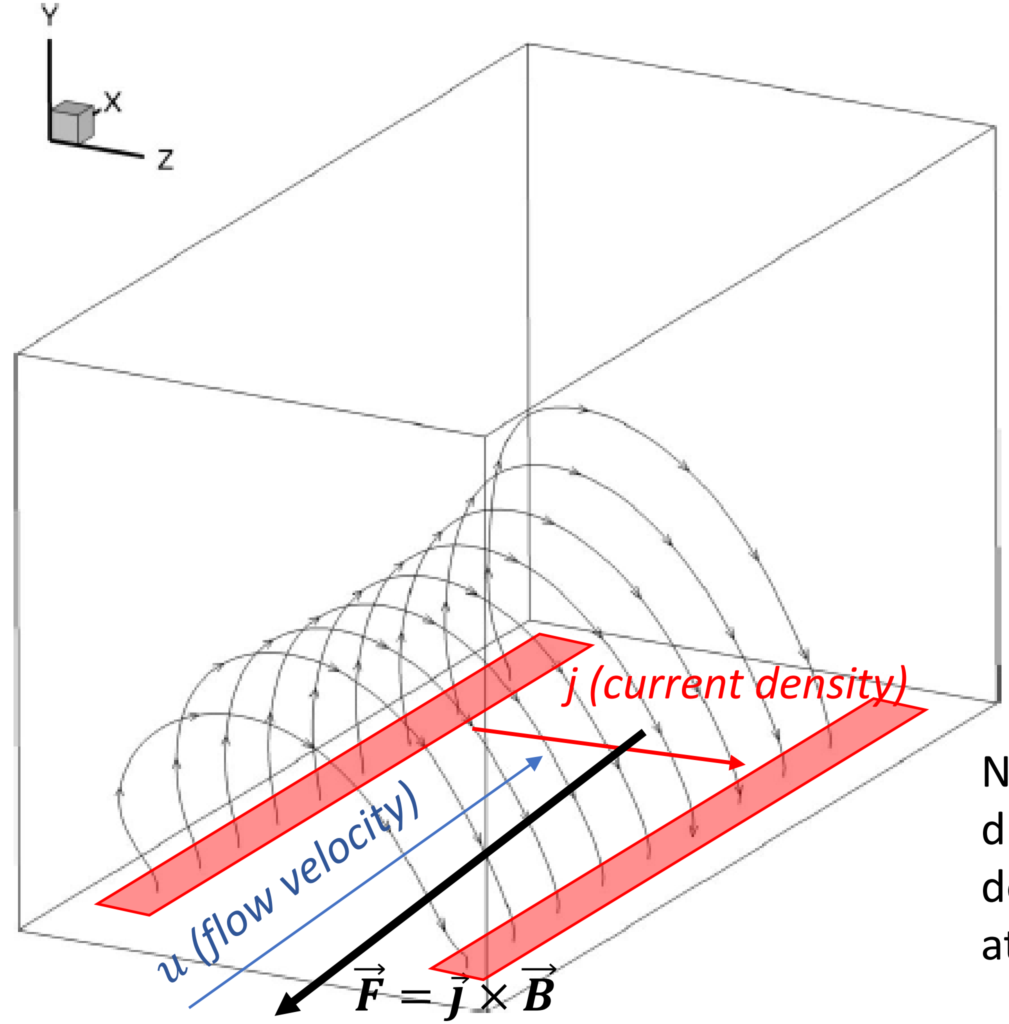
|B|=1 Tesla

Bx=0
By=0.71 T
Bz=0.71 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.

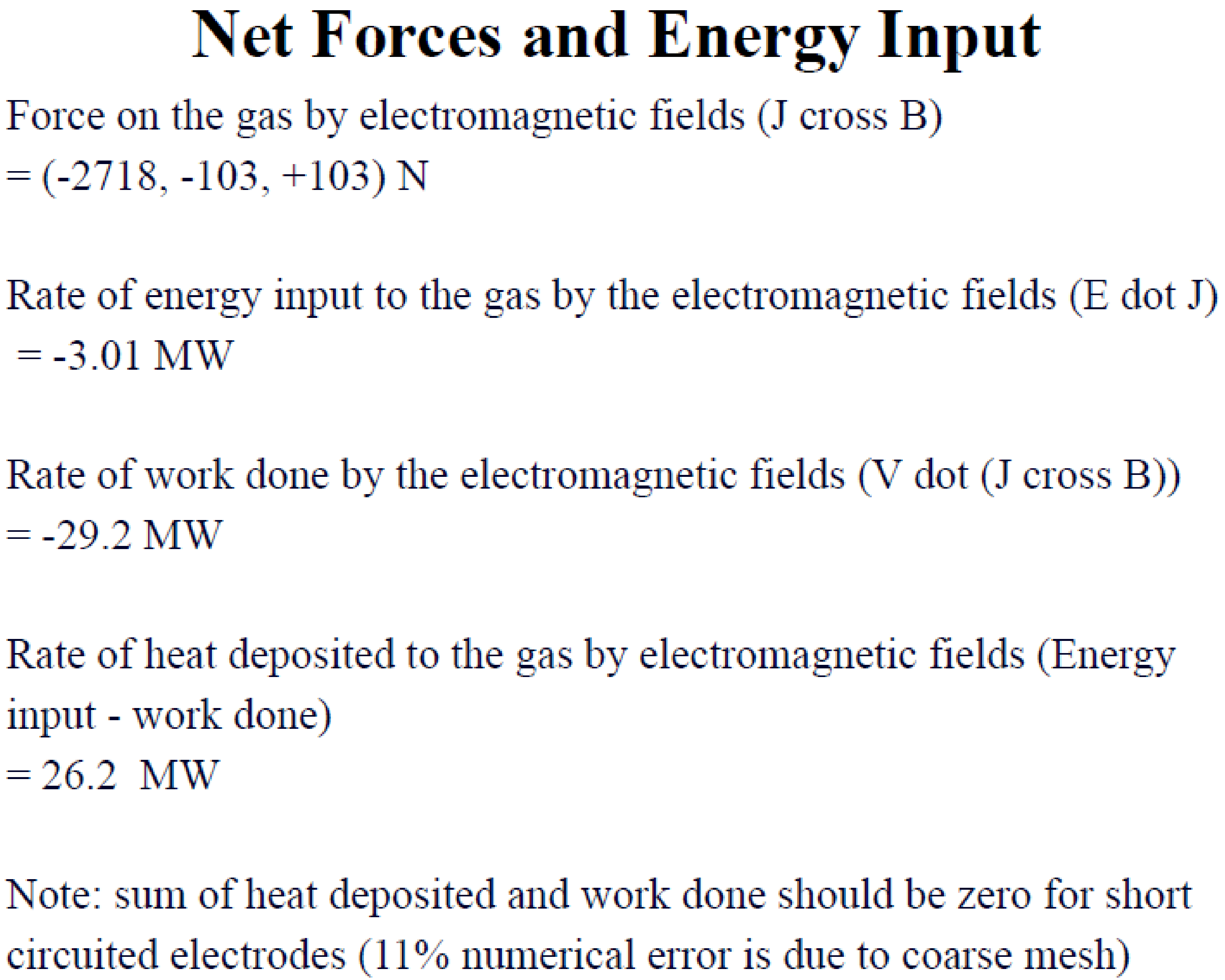
CFDWARP Neptune 29 km/s Case

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 (J cross B)
= (-2718, -103, +103) N

Rate of energy input to the gas by the electromagnetic fields (E dot J)
= -3.01 MW

Rate of work done by the electromagnetic fields (V dot (J cross B))
= -29.2 MW

Rate of heat deposited to the gas by electromagnetic fields (Energy input - work done)
= 26.2 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 2.0e+5 N.
- **This is comparable to the "whole body" drag and lift forces computed by LAURA for the Neptune entry velocity and atmospheric density.**
- Creates 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

- The results of the Phase I Study illustrate that strong Lorentz Forces are present during entries at Neptune and Mars and that the system mass to capitalize on that opportunity to produce additional lift and/or drag is on the order of the ballast mass used for recent lander missions at Mars.
- Study indicates 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

- Continue our analysis for Neptune and Mars to
  - conduct trajectory and thermal analysis and compare with aerodynamic only cases found in the literature
  - conduct 3-D fully coupled analysis necessary for sizing system components
  - further study the Hall and Ion slip effects at Mars
  - validate analysis results via ground-based testing
  - look for flight test opportunities for Earth Return Entries

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