# MHD supersonic flow control simulation in OpenFOAM

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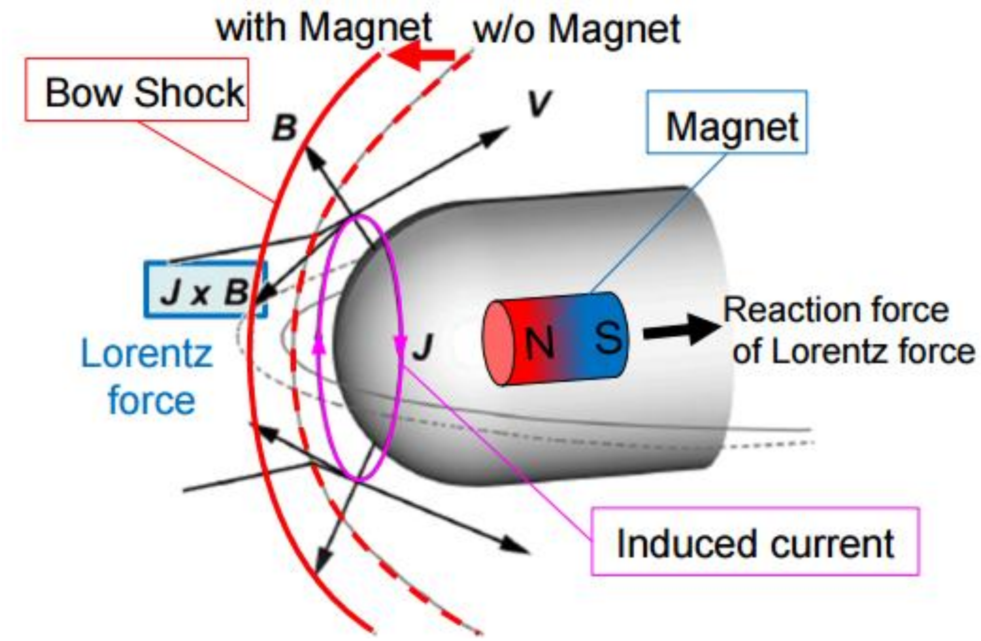
# MHD flow control concept

Magnetic field interacts with weakly ionized plasma between the bow shock and the body:

- *Lorentz force*
- *Joule heating*

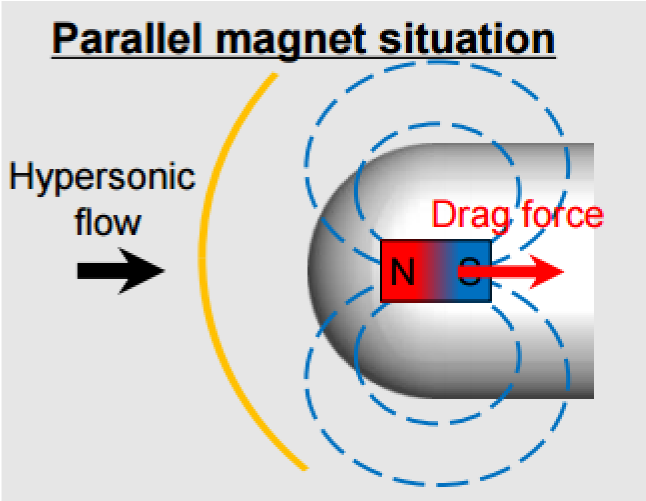
Effects:

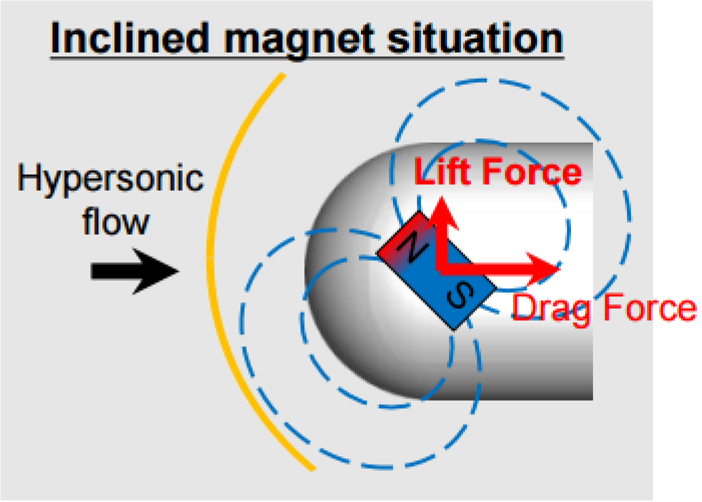
- *Reduction of aerodynamic heating*
- *Enhancement of drag force*
- *Widening of shock layer*




*Y Nagata, K Yamada, T Abe

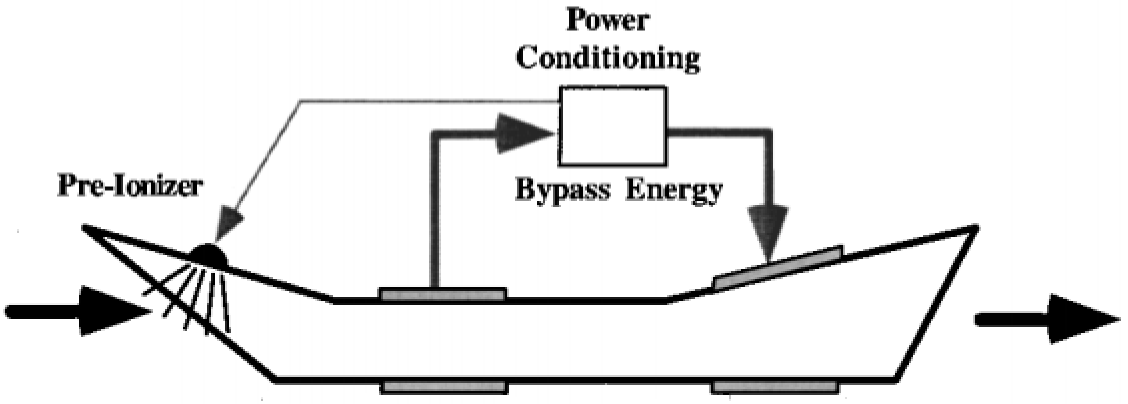
Controlling reentry flight trajectory

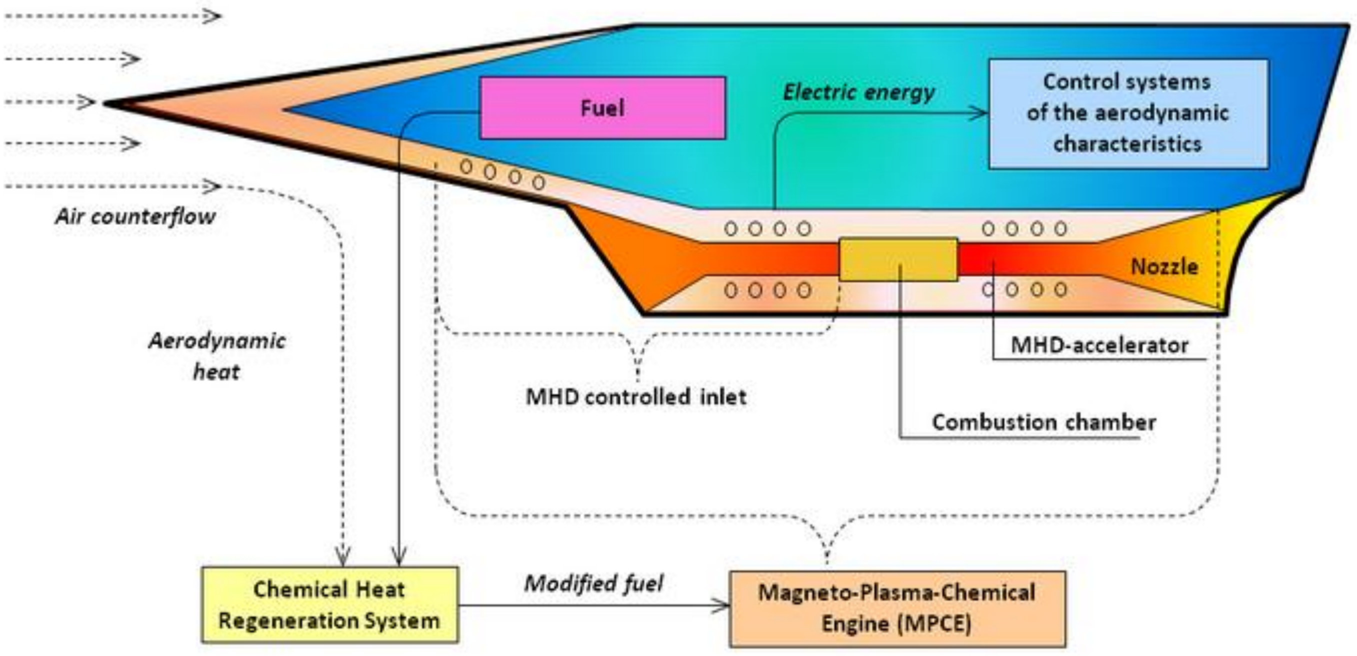


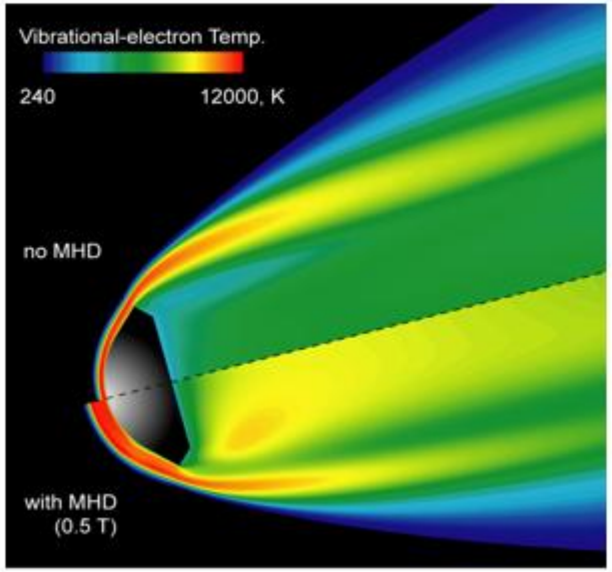



# MHD control applications

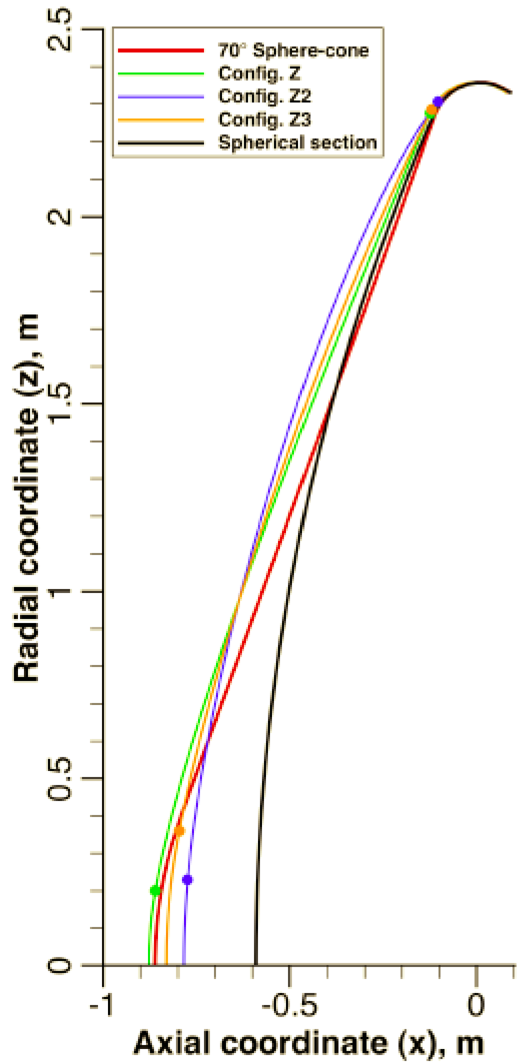
- ***Hypersonic scramjet aerodynamics***
- ***Atmospheric entry vehicles***
- ***MHD energy bypass engine***



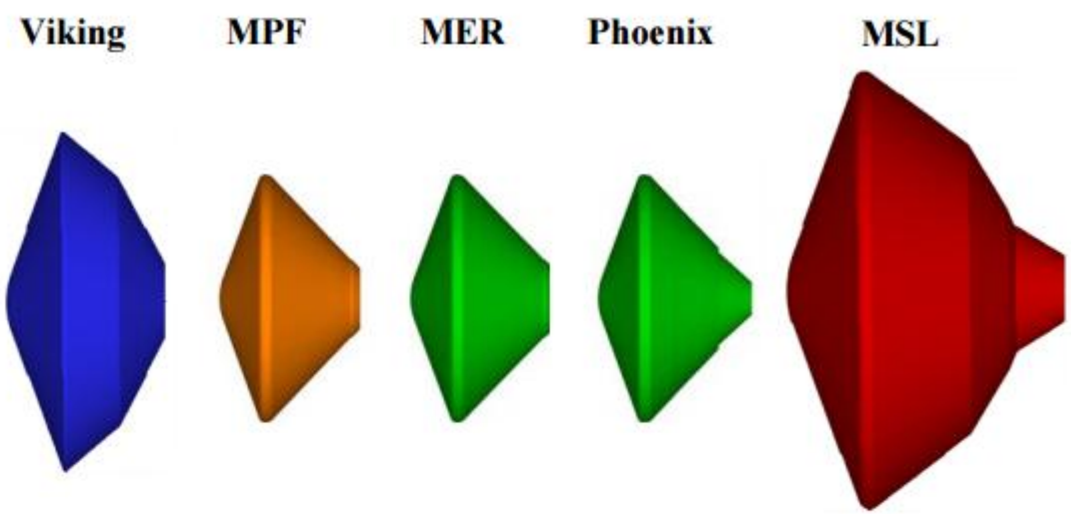



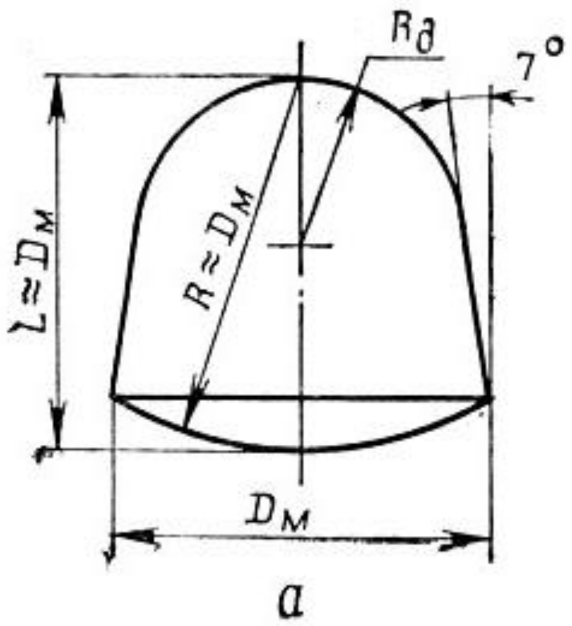
# Case geometries



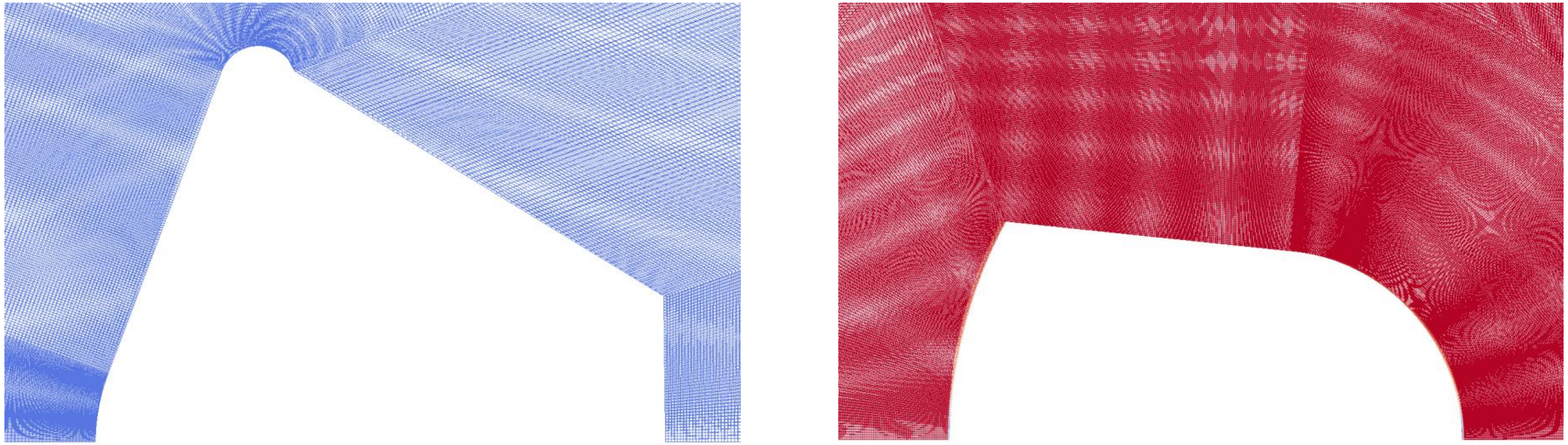

Generatrices




NASA Mars descent capsules shapes




Soyuz capsule schematics



Corresponding meshes

# OpenFOAM supersonic and MHD capabilities

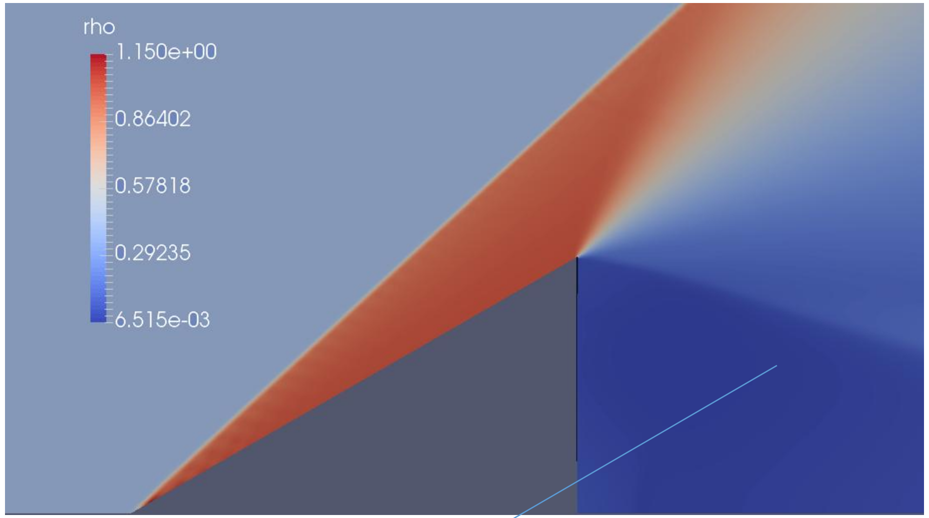
## Supersonic solvers

| Solver | Source | Application | Comments |
|---|---|---|---|
| sonicFoam | OpenFOAM | Transient, trans-sonic/supersonic | Pressure-based |
| rhoCentralFoam | OpenFOAM | Supersonic | Density-based, Kurganov-Tadmor |
| dbnsTurbFoam | foam-extend | Supersonic | Roe-type |
| pisoCentralFoam | Kraposhin, Strijhak | Subsonic/Supersonic | Hybrid KT-PISO |

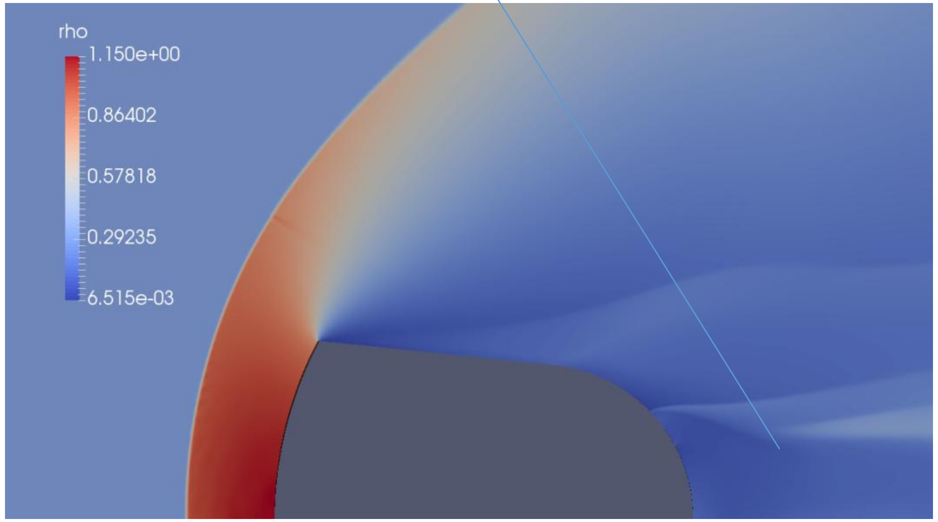
## MHD solvers

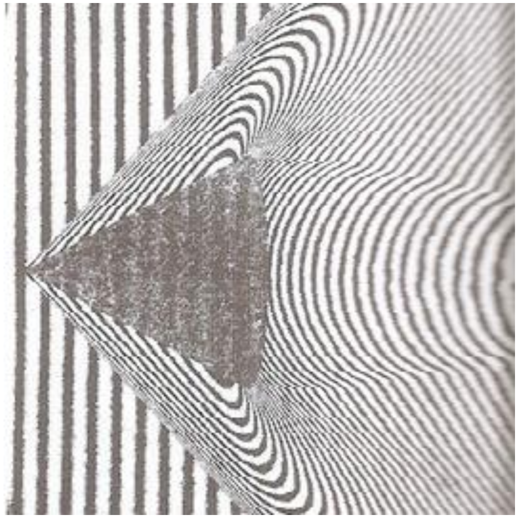
| Solver | Source | Application | Comments |
|---|---|---|---|
| mhdFoam | OpenFOAM | Incompressible MHD | Incompressible Induction form |
| rhoPisoFoam (MHD) | Xisto, et. al. | Compressible resistive MHD | Pressure-based |

# Supersonic flow experimental data

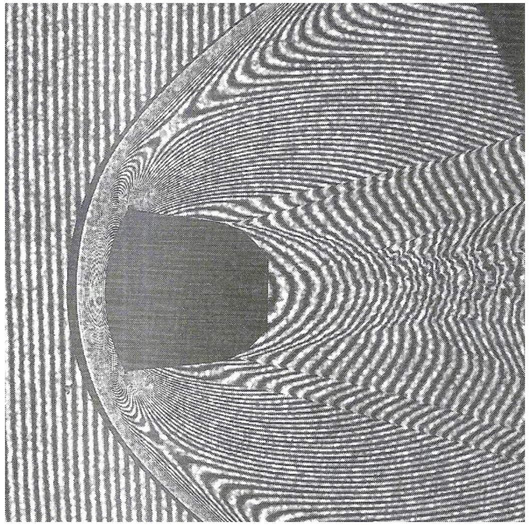



Subsonic flow region

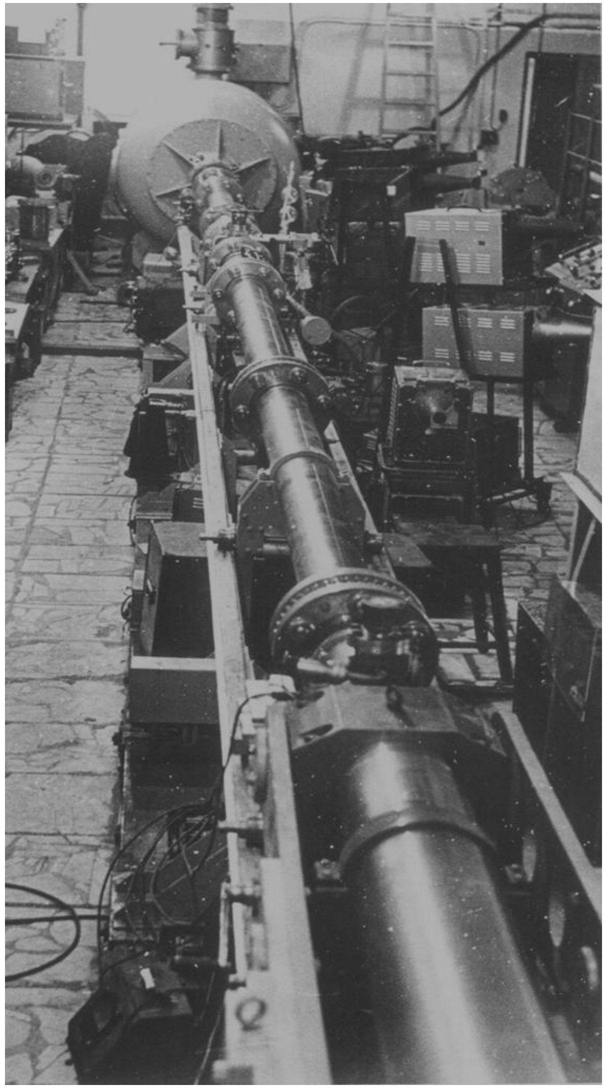


Cone, middle diameter: 19 mm, Mach = 2



“Soyuz” model, middle diameter: 17.4 mm, Mach = 2.4



Ioffe Institute shock tube

# Flow parameters and MHD equations

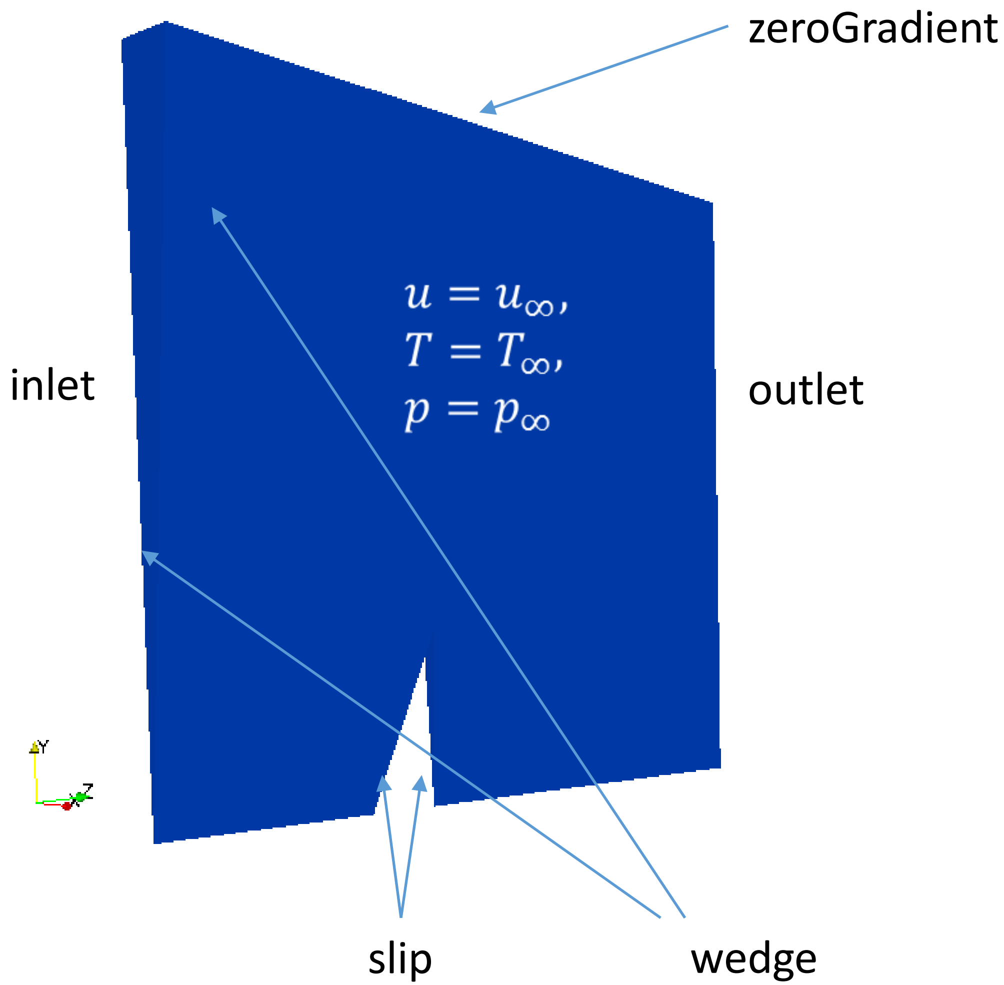
| Parameter | Formula | Value |
|---|---|---|
| Reynolds number ($R$) | $\frac{\rho v L_c}{\eta}$ | $10^5 - 10^6$ |
| Stuart number ($S$) | $\frac{\sigma L_c B^2}{\rho v}$ | $0 - 1$ |
| Magnetic Reynolds number | $\frac{uL}{\eta_m}$ | $\ll 1$ |
| Knudsen number | $\frac{k_B T}{\sqrt{2}\pi d^2 p l}$ | $\sim 10^{-3} - 10^{-5}$ |
| Mach number | $\frac{u}{\sqrt{\frac{\gamma R T}{M}}}$ | $2 - 4$ |

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \qquad \frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(p + \frac{1}{2}B^2\right) I_{3\times 3} - \mathbf{B}\mathbf{B}\right] = 0,$$

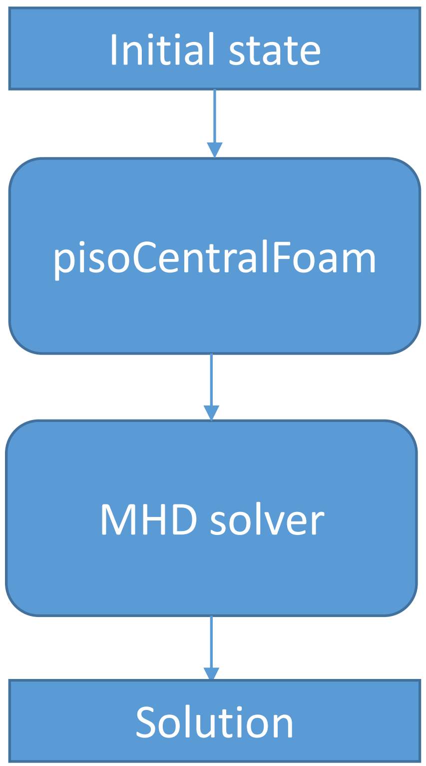
$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \rho e + \frac{1}{2}B^2\right) + \nabla \cdot \left[\left(\frac{1}{2}\rho v^2 + \rho e + p + B^2\right)\mathbf{v} - \mathbf{v} \cdot \mathbf{B}\mathbf{B}\right] = 0.$$

$$B = B_0(x, y, z)$$

# Initial and boundary conditions



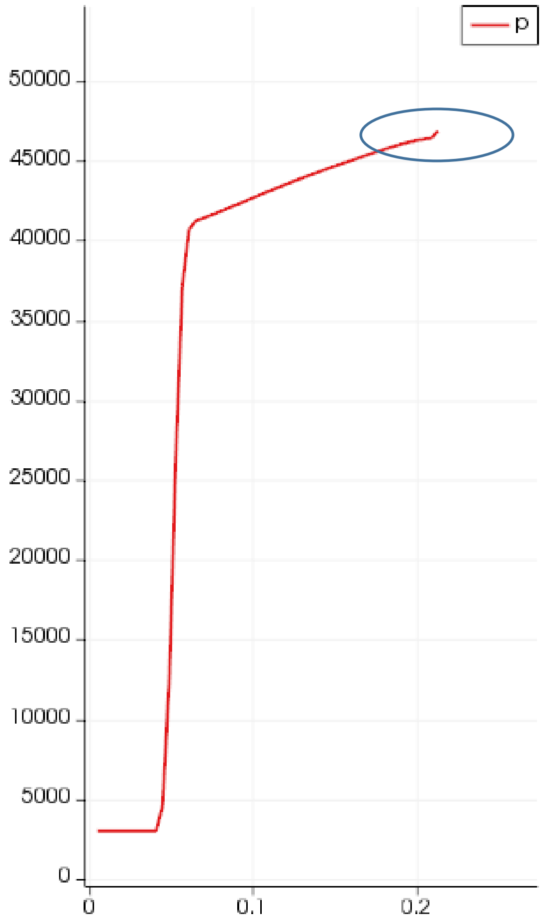

Solution flowchart



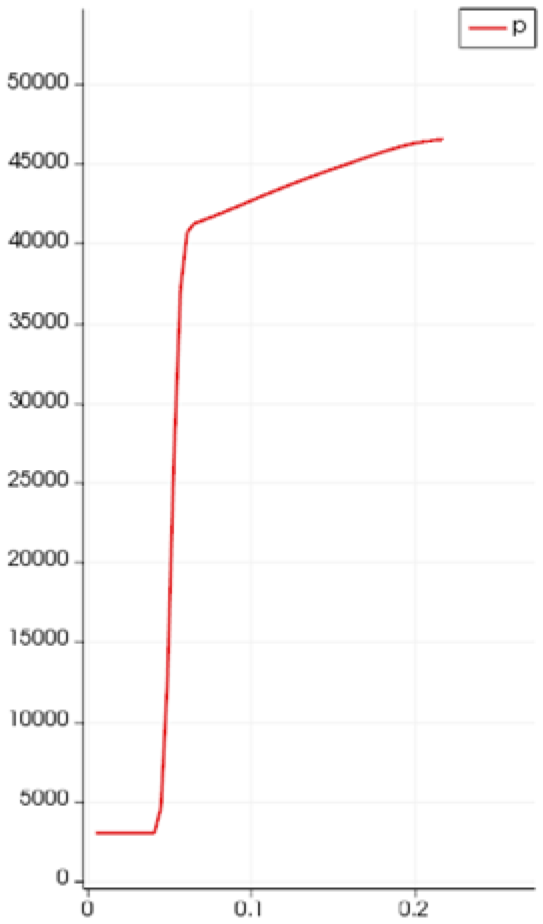
# Numerical algorithms

1. **B-T schemes** *(Balbás J., Tadmor E., Wu C. C. Non-oscillatory central schemes for one- and two-dimensional MHD equations)*
2. **HLL-Roe scheme**. *(Janhunen P., A positive conservative method for magnetohydrodynamics based on HLL and Roe methods)*

Balbas-Tadmor




HLL-Roe




Pressure profiles on the axis

# MHD interactions experiment

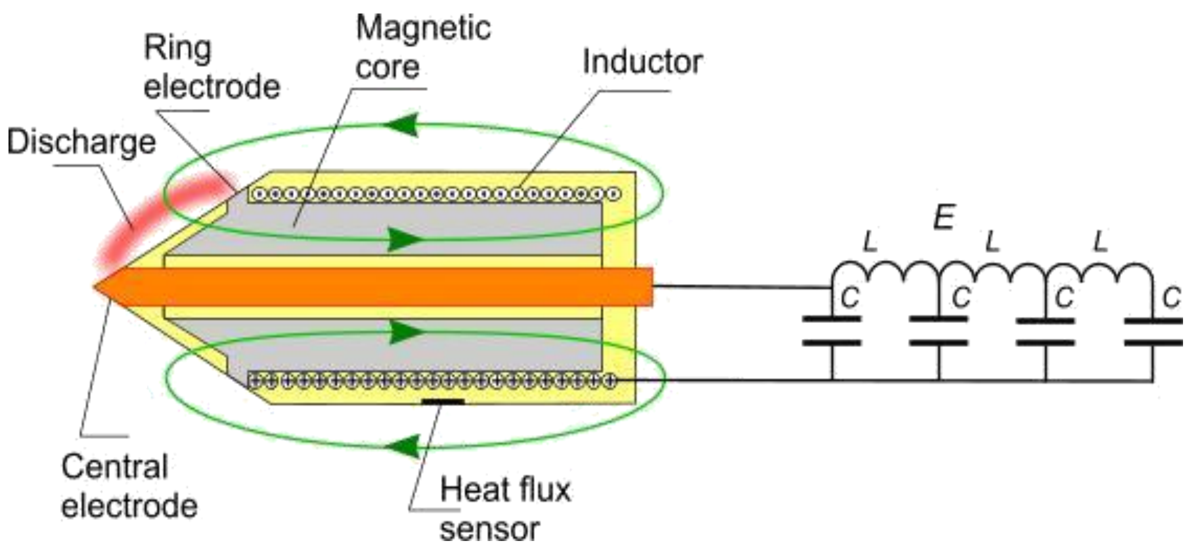
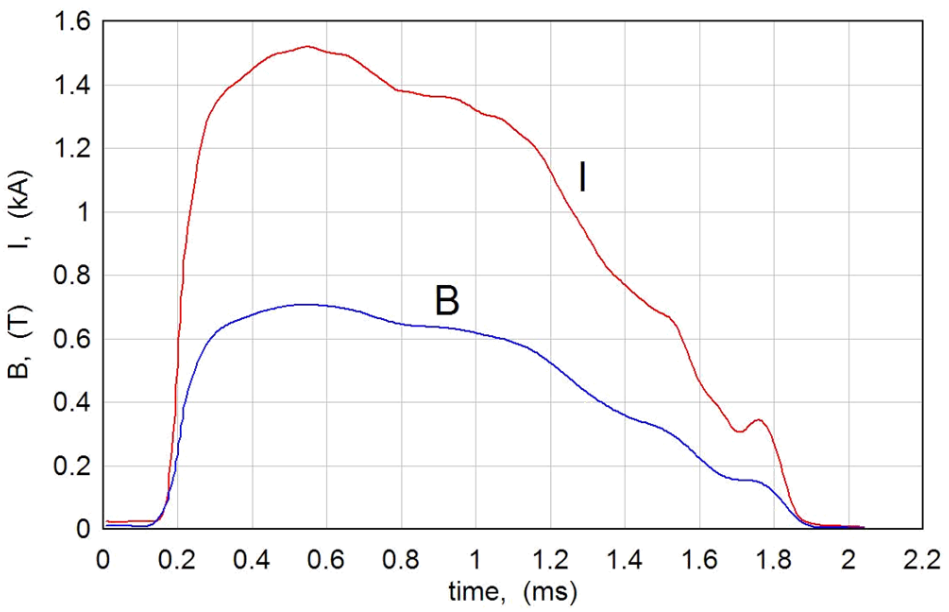
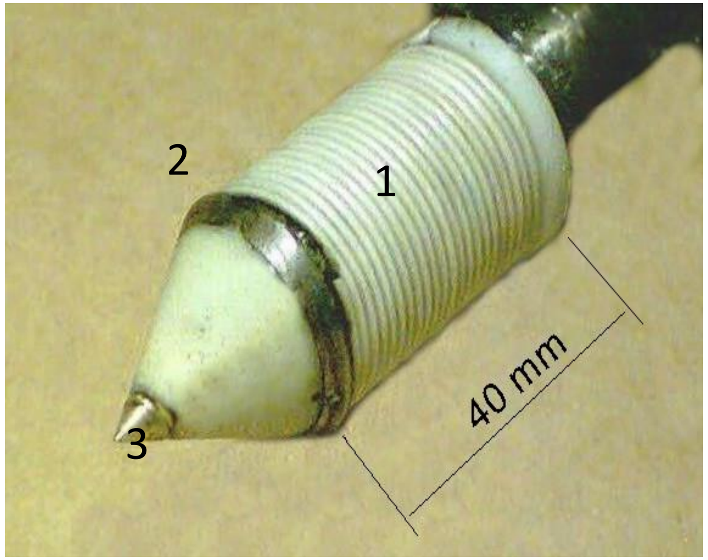
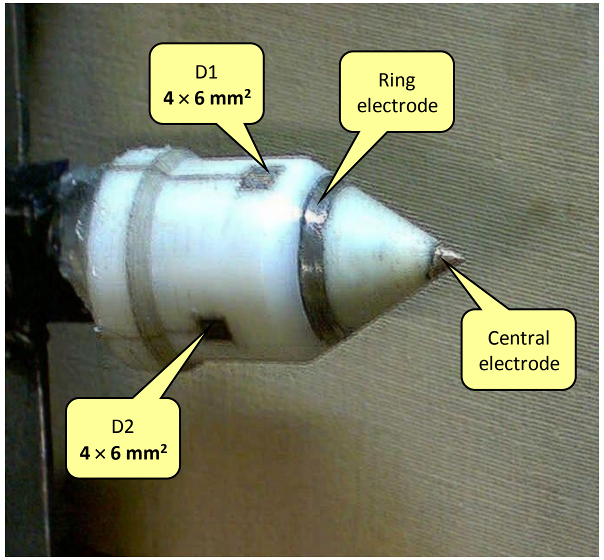



*Fig. Model schematics*




1. Solenoid
2. Ring electrode
3. Central electrode

D1, D2 – Hear sensors

*from the materials of Fundamental Research session of RAS presidium "Fundamental problems in mechanics and related sciences" Saint-Petersburg, July 5-6, 2014

# Conductivity mechanisms

## Passive (Thermal)

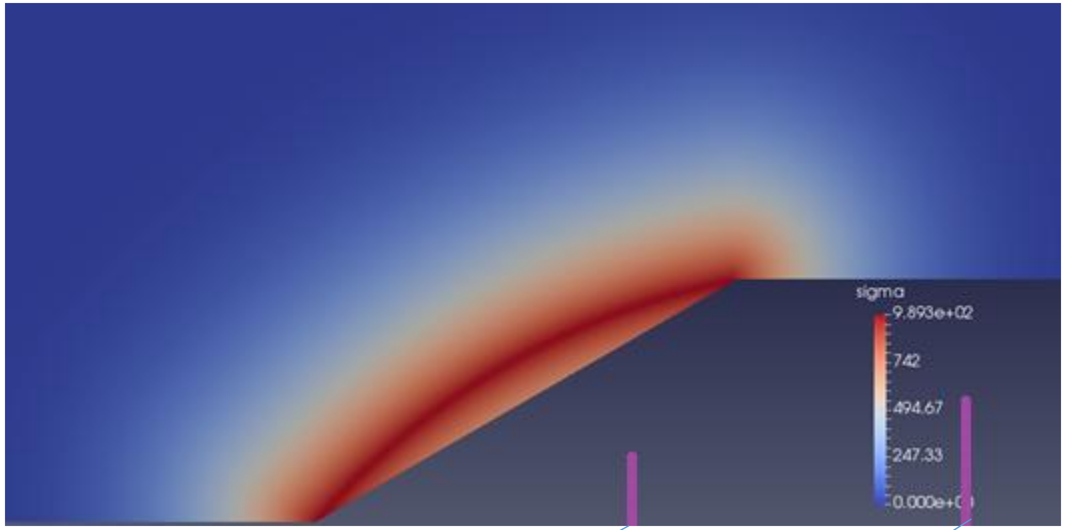
*Spitzer – Harm conductivity formula*

$$\sigma = 1.53 \times 10^{-2} \frac{T^{\frac{3}{2}}}{\ln\Lambda};$$

$$\ln \Lambda = \ln\left(\frac{12\sqrt{2}\pi(k_B \epsilon_0 T)^{\frac{3}{2}}}{q^3 n^{\frac{1}{2}}}\right).$$

$$T = \frac{1}{c_v}\left[e_t - \frac{1}{2}\left(U^2 + \frac{B^2}{\rho\mu_0}\right)\right].$$

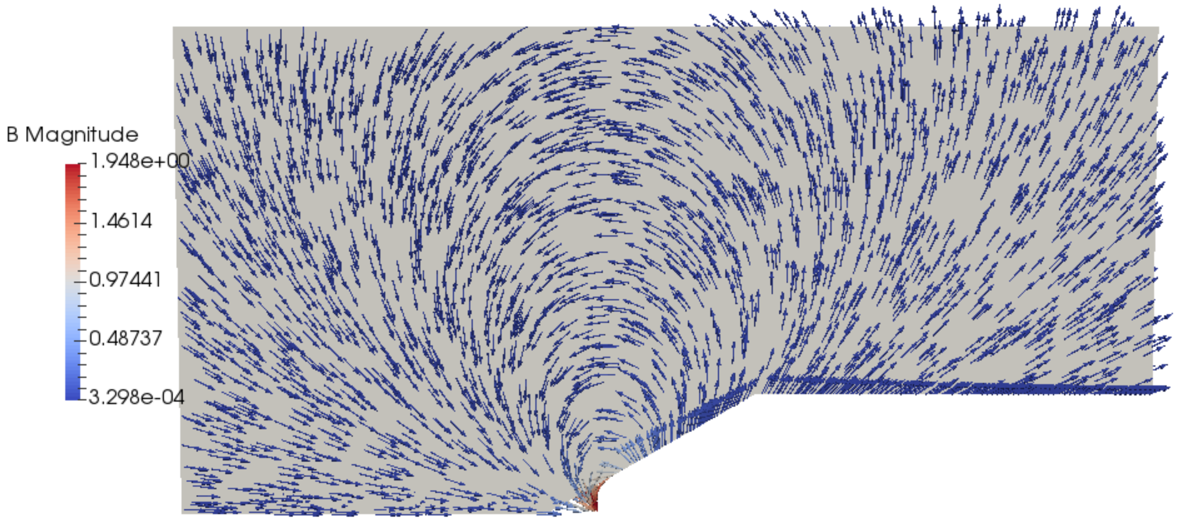
## Active (Discharge)



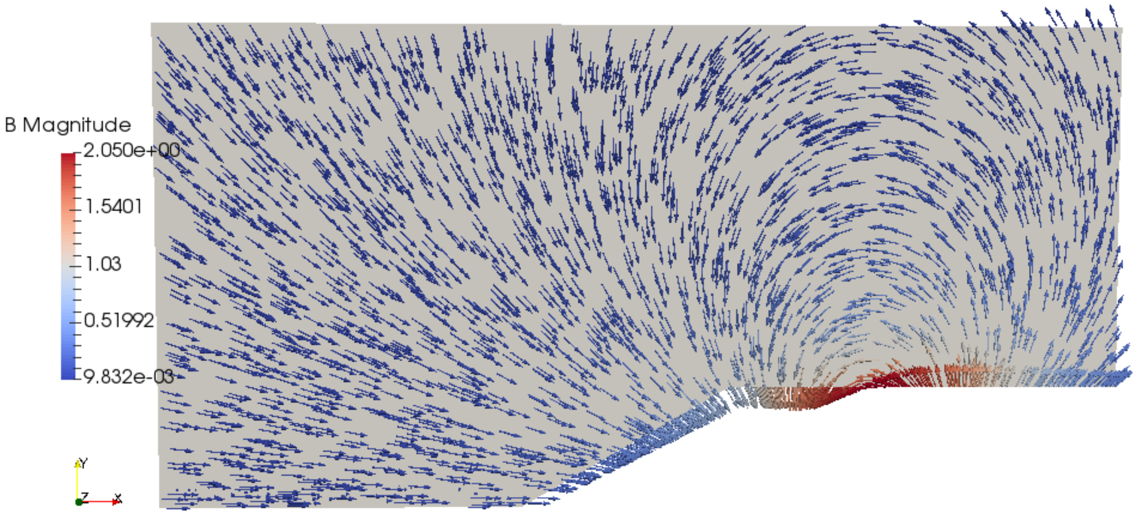

Position 2 Position 1

Gas in front of the body is ionized by the electrical discharge between the vertex and the base of the cone. Coil, that generates the magnetic field was placed in 2 different positions.

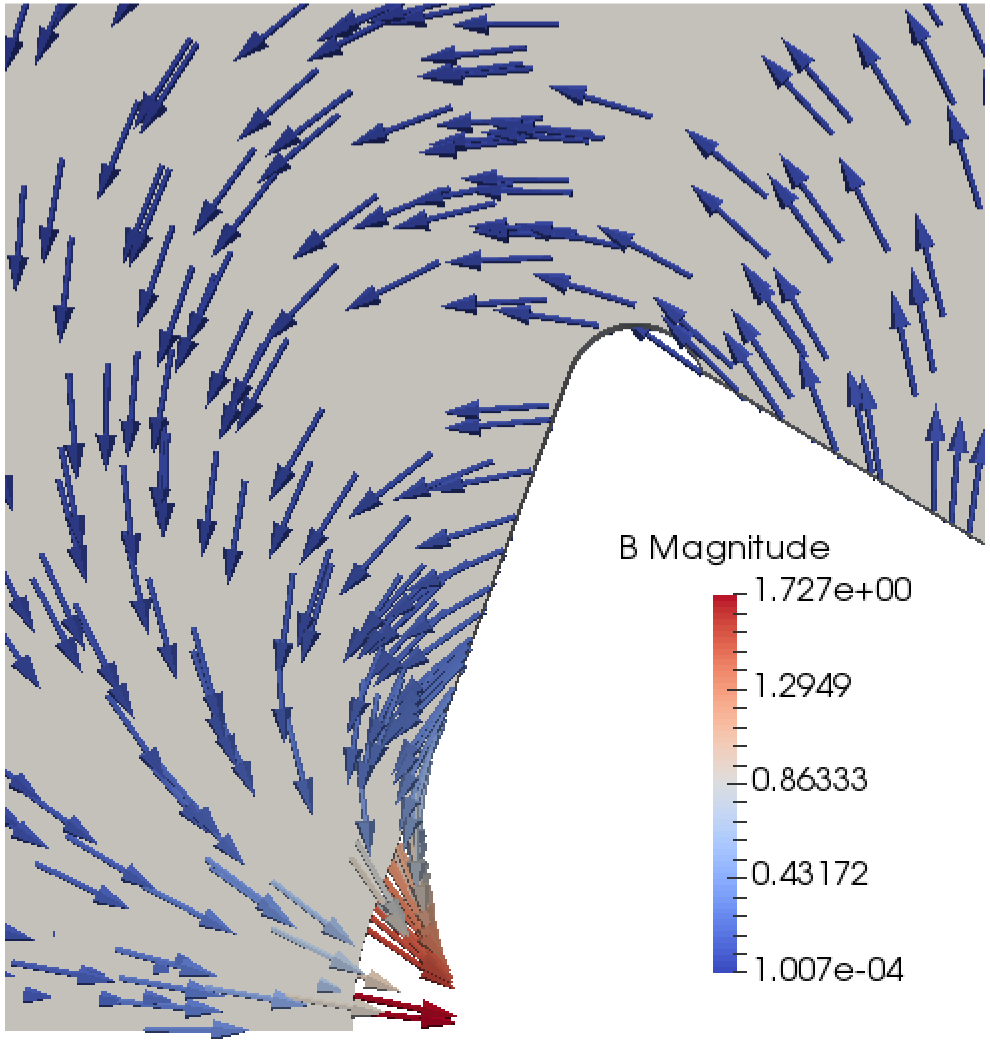
# Magnetic field distribution




Cone-cylinder case 1



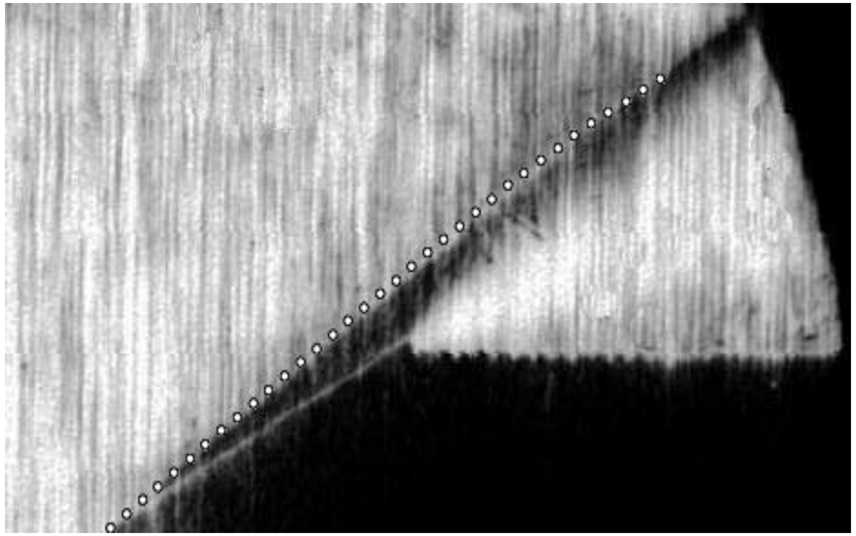

Cone-cylinder case 2

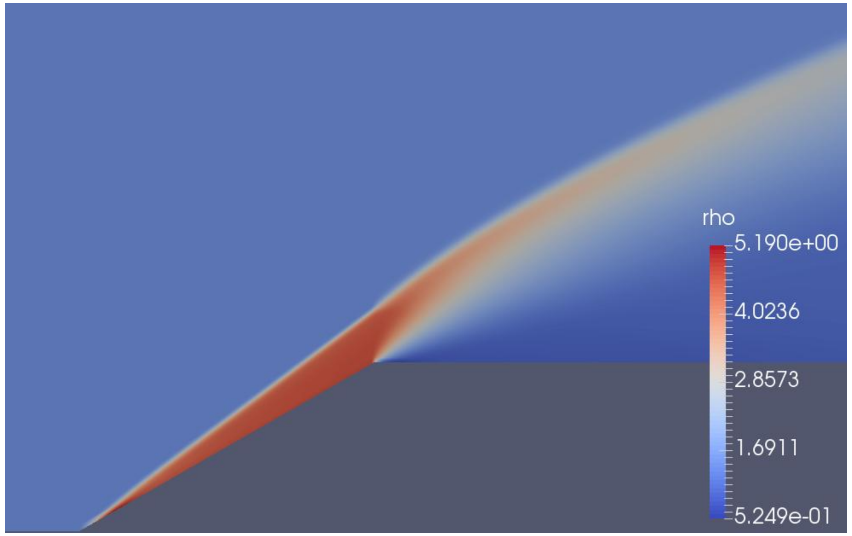



Frustum case

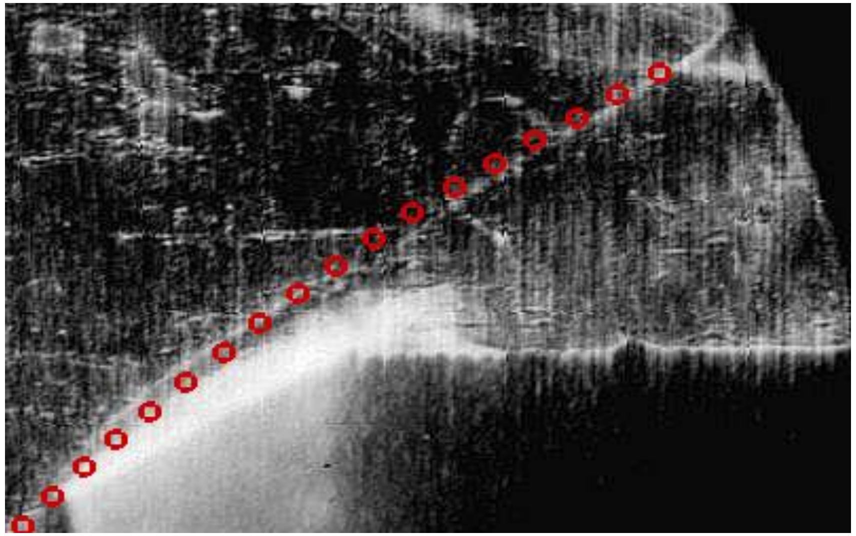
# Wave front shape comparison

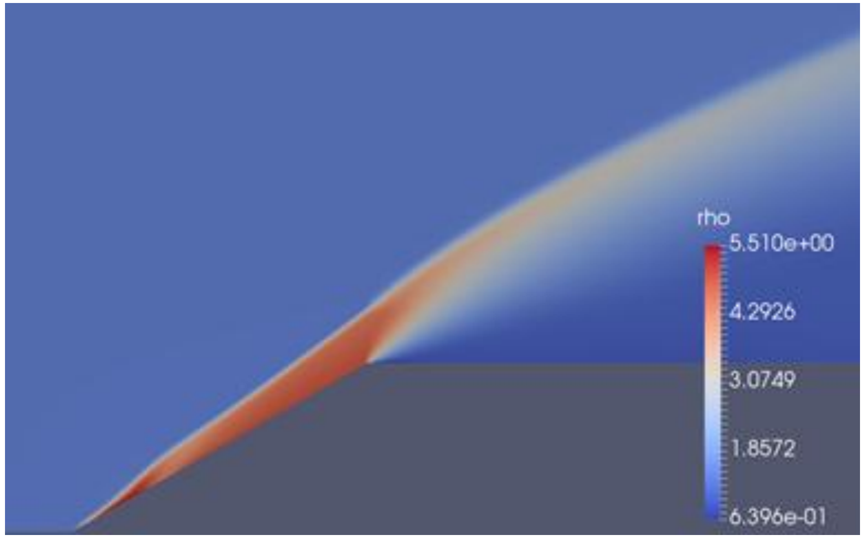
a.)





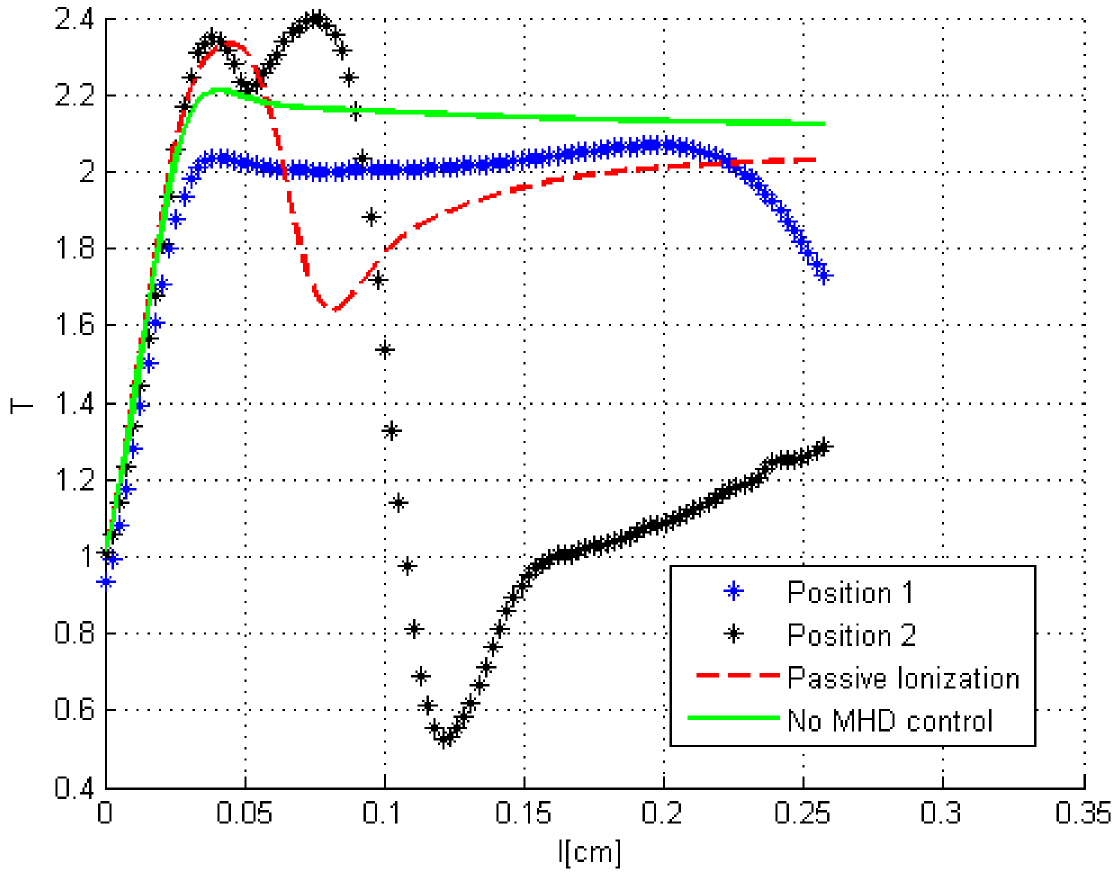

b.)



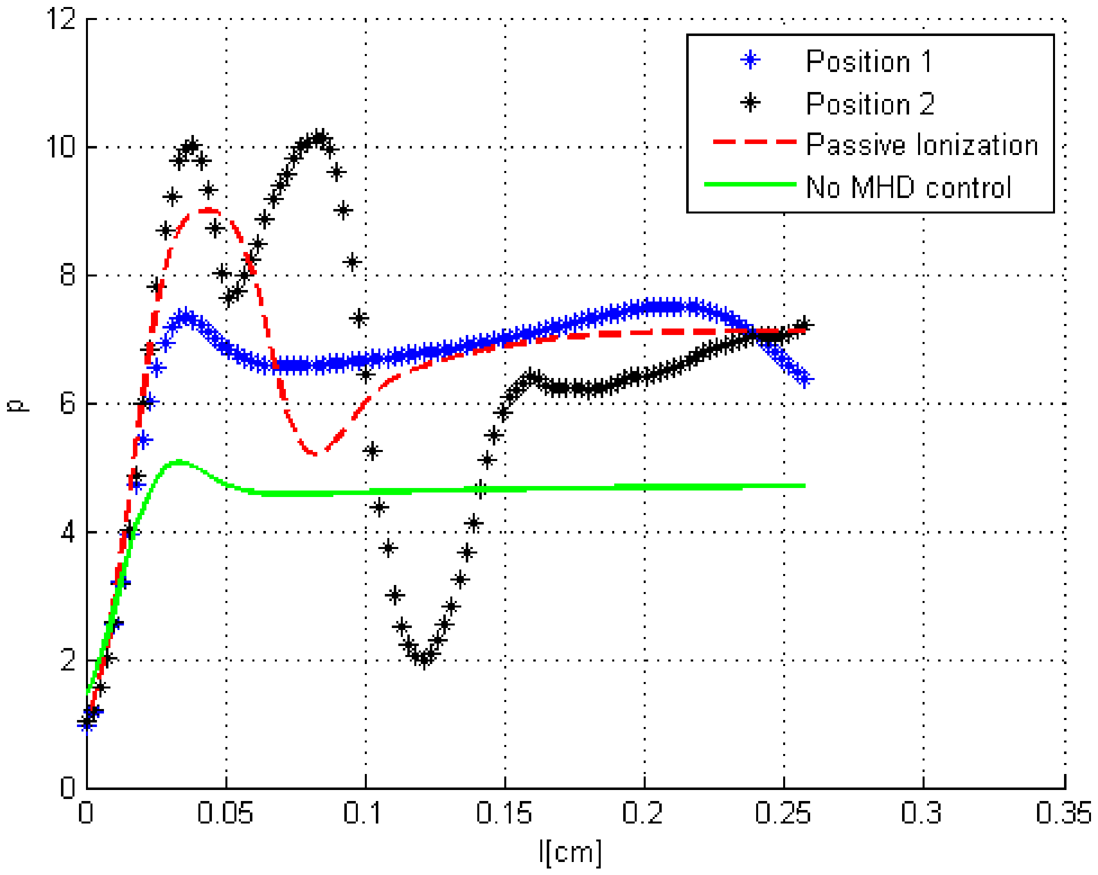



Shadowgrams of the flow (on the left) a.) without a magnetic field b.) with a magnetic field compared to the numerical results (on the right)

# Numerical results: cone-cylinder




Temperature profiles
on the generatrix of a cone-cylinder

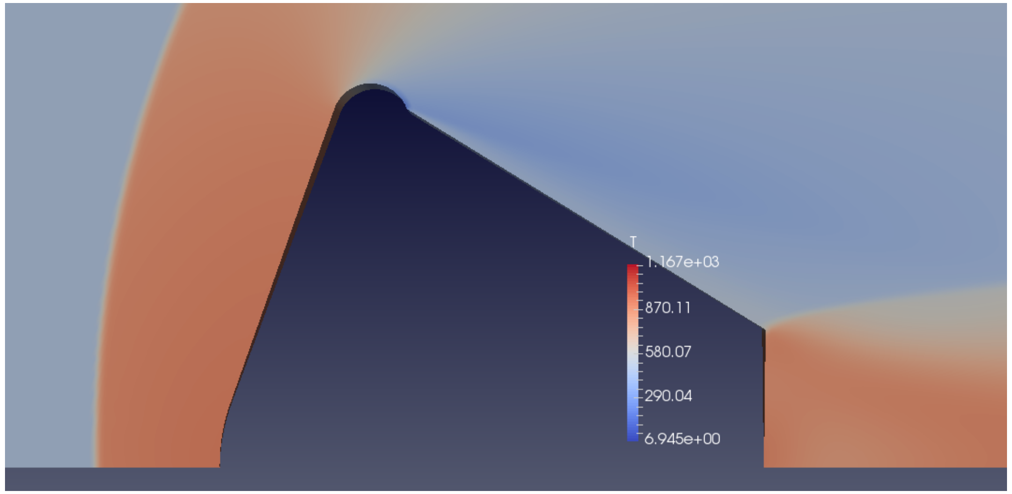


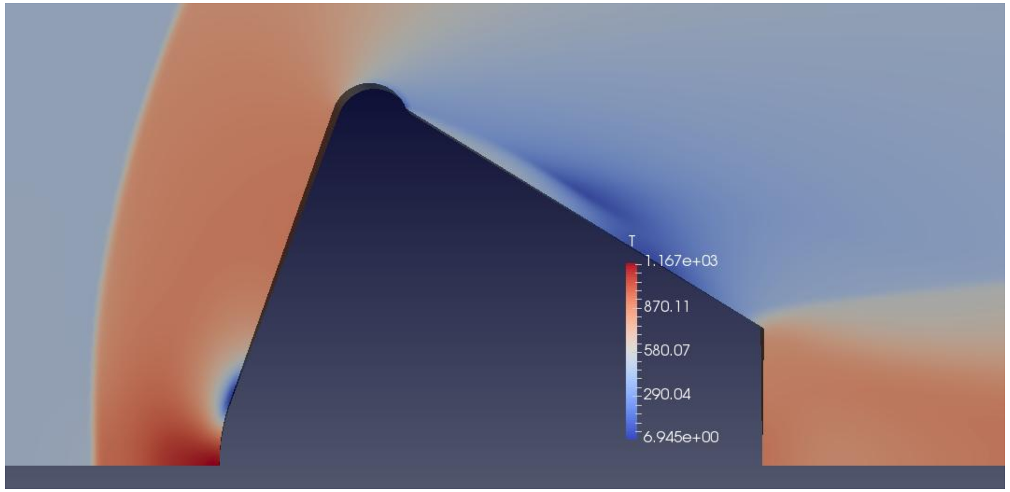

Pressure profiles
on the generatrix of a cone-cylinder

# Numerical results: flow around sphere-cone

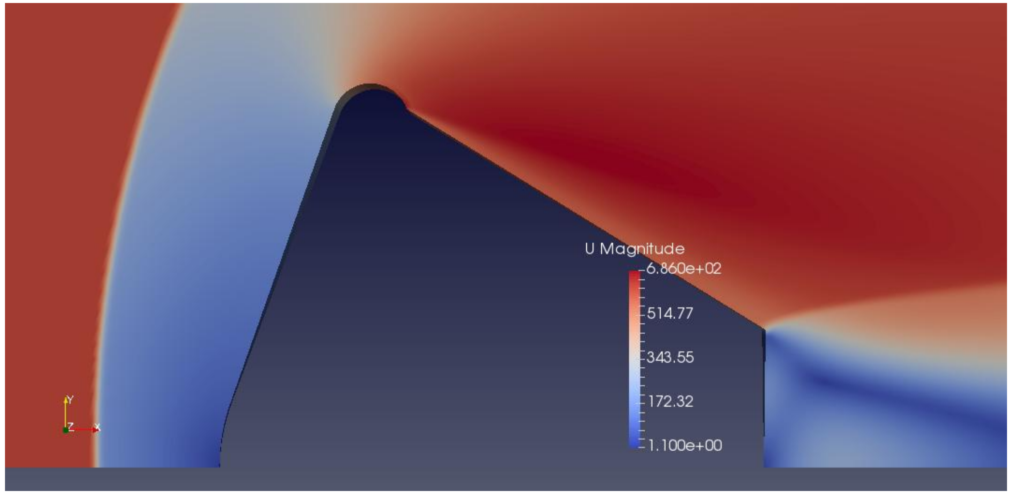
no MHD

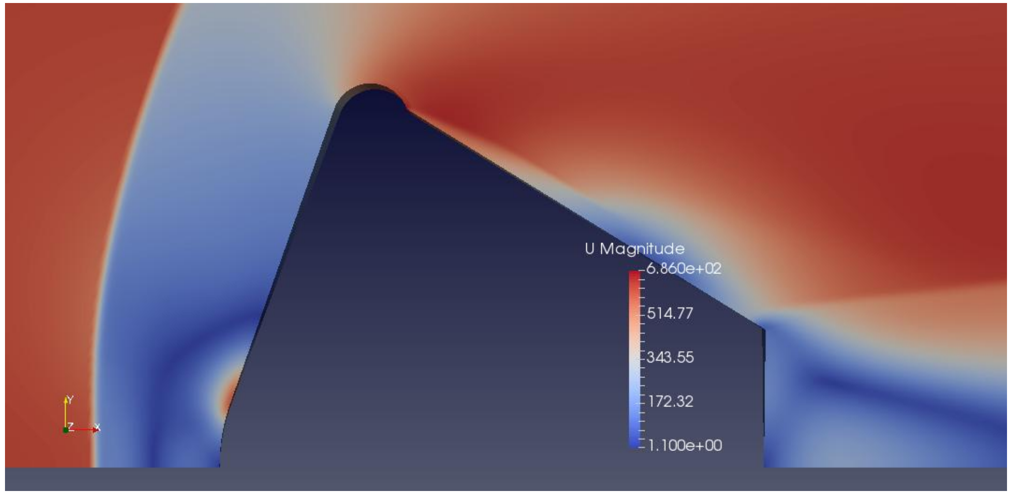
MHD




Temperature

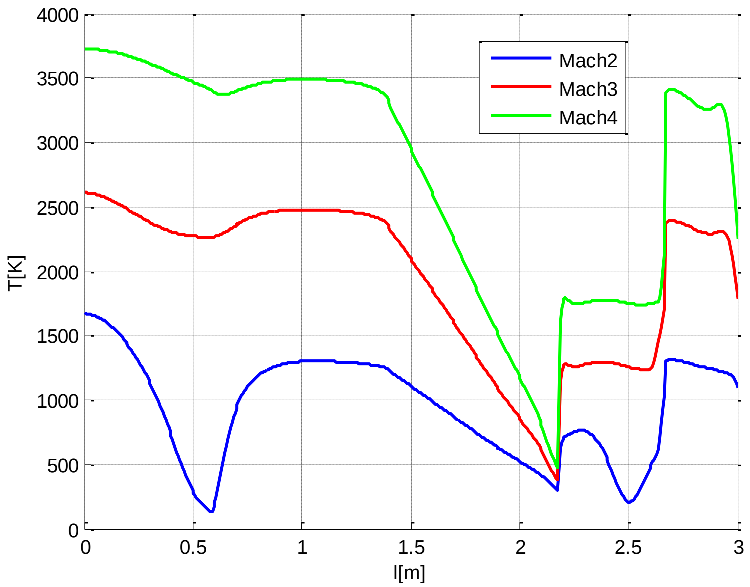


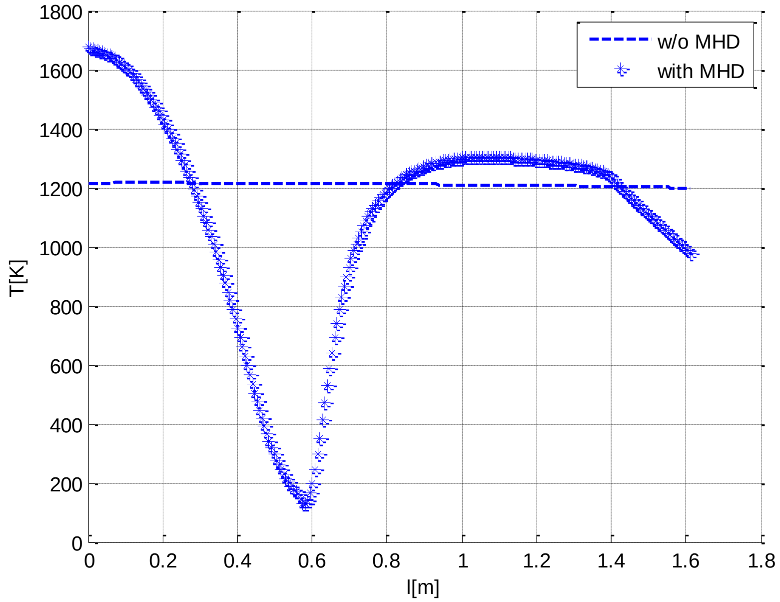

Velocity magnitude

# Numerical results: flow around sphere-cone

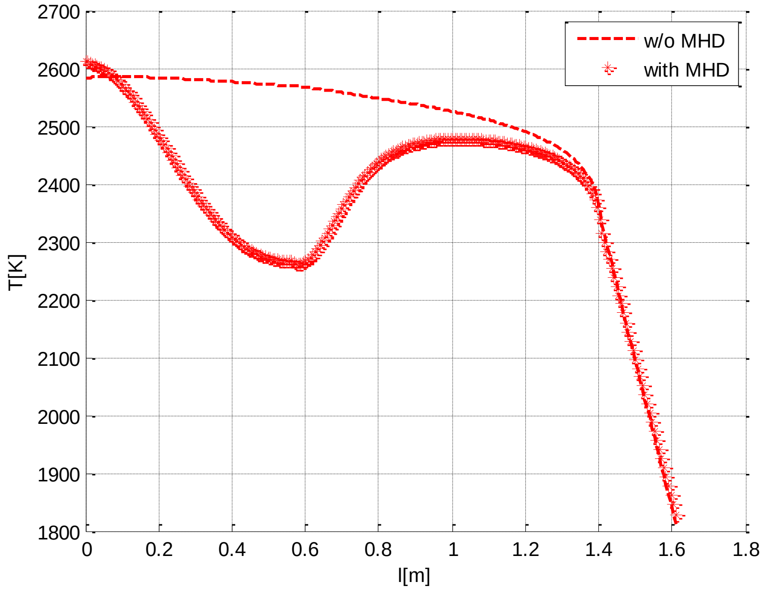
Temperature profiles over the whole body:



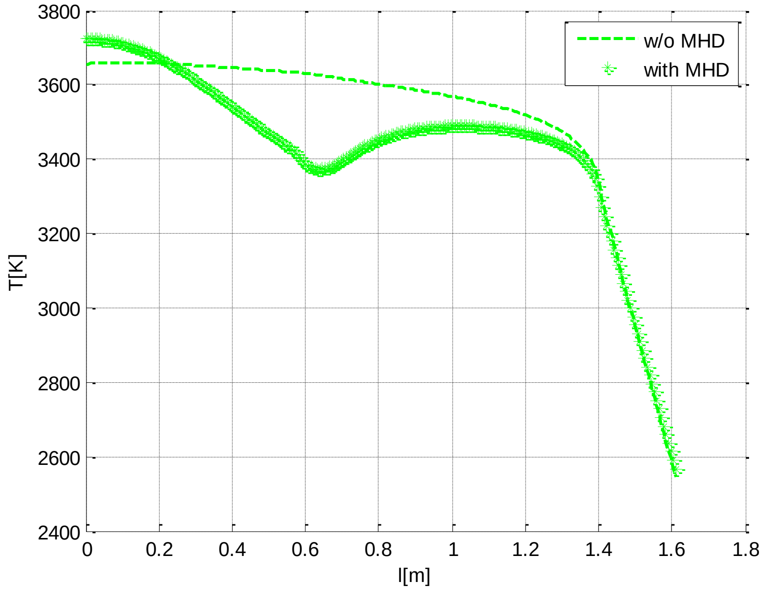

T on the front, Mach 2




T on the front, Mach 3




T on the front, Mach 4



# Further research prospects

## Physical phenomenon investigation

- Determining the feasibility of the concept
- Designing a flexible control system
- Figuring the energy cost

## Mathematical model enhancement

- Transition to 3D, angle of attack
- Taking into account real gas effects
- Surface radiation
- Laminar-turbulent transition
- Introducing comprehensive thermochemical model, Ionization model

## Solver development

- Increasing stability and accuracy
- Dealing with low-density effects