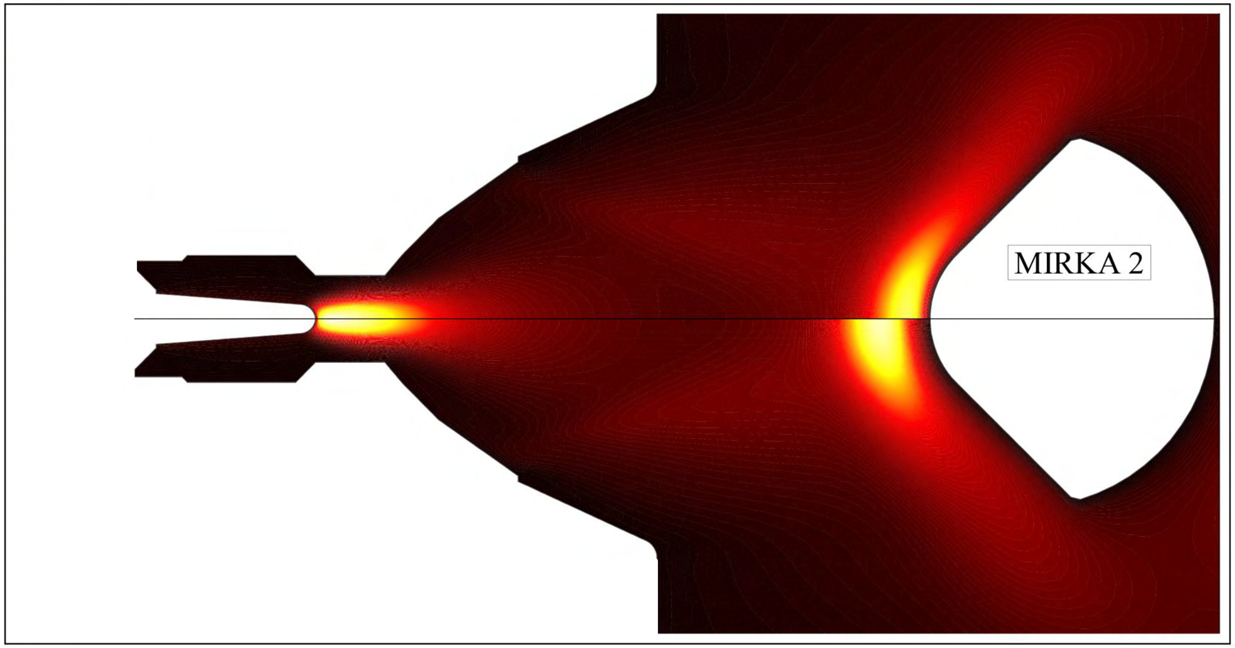
Numerical Assessment of Magnetohydrodynamic (MHD) impact on the surface heat flux of the MIRKA2-Capsule



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15th International Planetary Probe Workshop
IPPW-2018, University of Colorado, Boulder

Smead Aerospace
UNIVERSITY OF COLORADO BOULDER

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Germany

Motivation

- Development of secondary *thermal protection systems* (TPS) in order to reduce heat loads and system mass
- Hyperbolic re-entry: significant ionization levels

→ Opportunity to deflect charged particles with applied magnetic fields

- Numerical assessment of applied magnetic fields and MHD-effects as a secondary TPS

Ref.: ESA. Re-entry Demonstrator - artist's impression.

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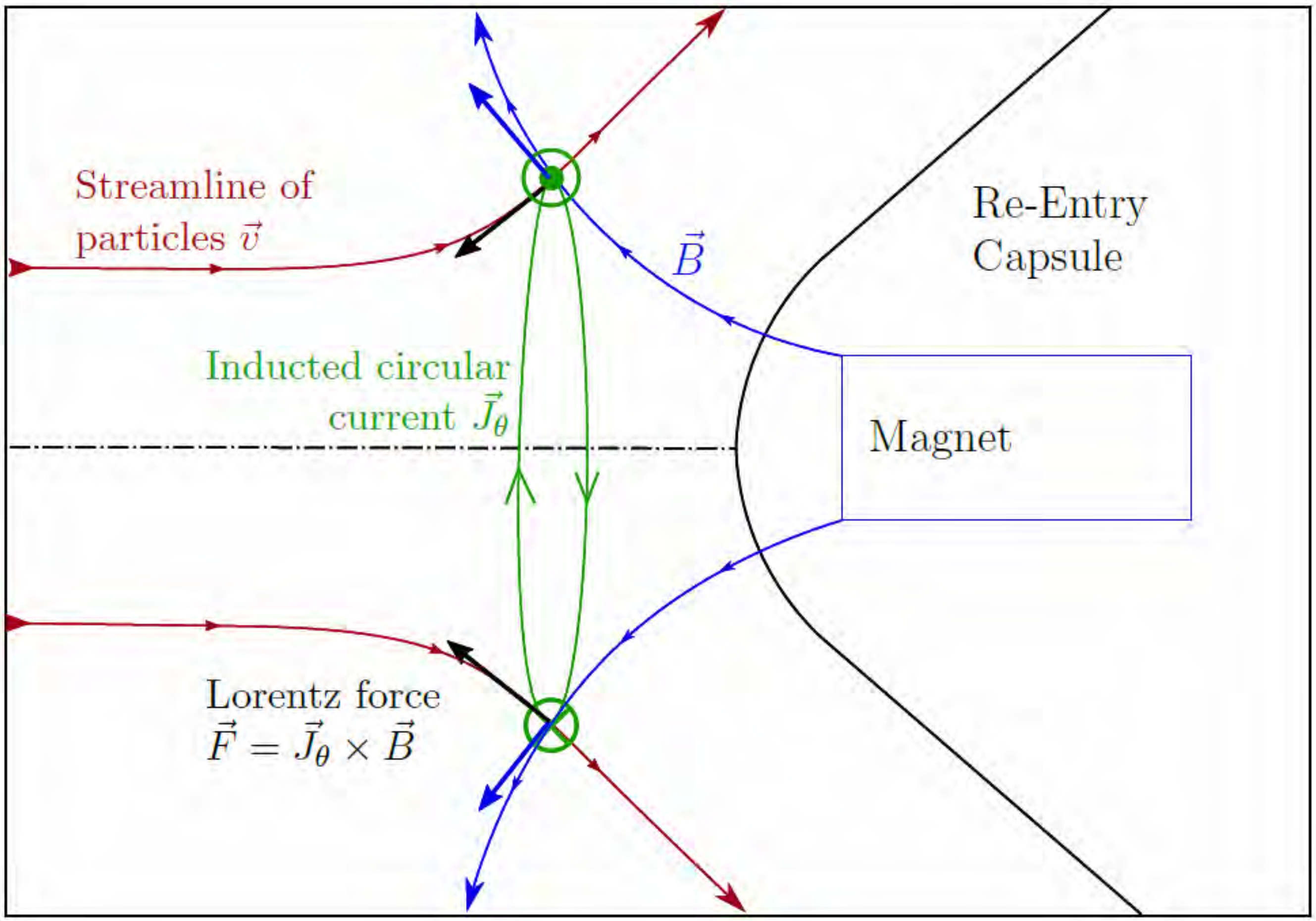
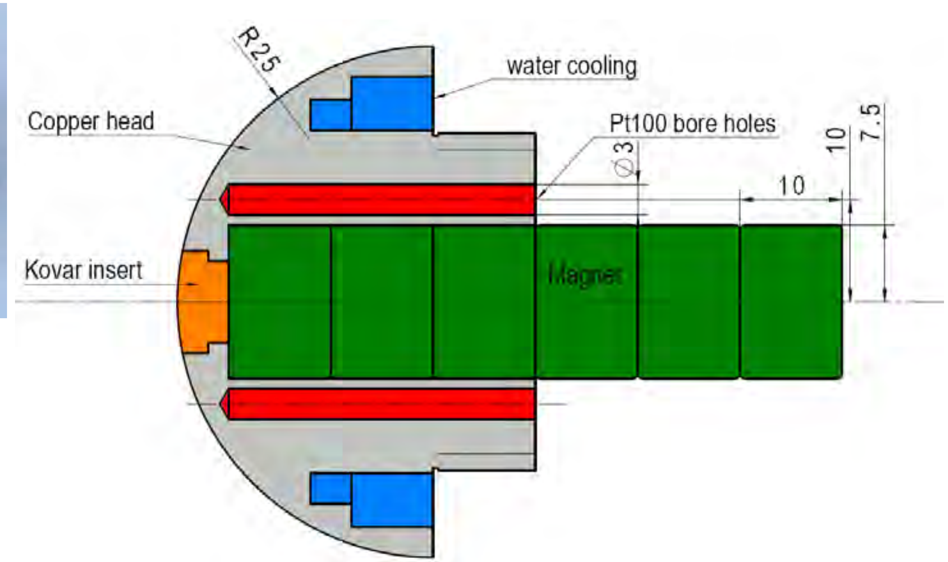
Fundamentals of Magnetohydrodynamics (MHD)



- Lorentz force decelerates charged particles and pushes them towards capsule‘s axis → funnel effect / θ-Pinch
- Reduce heat flux and decrease bending of bow shock

Background: MHD-experiments



- Extensive experimental work
- Use of NdFeB (Neodymium) permanent magnets
- Argon as working gas

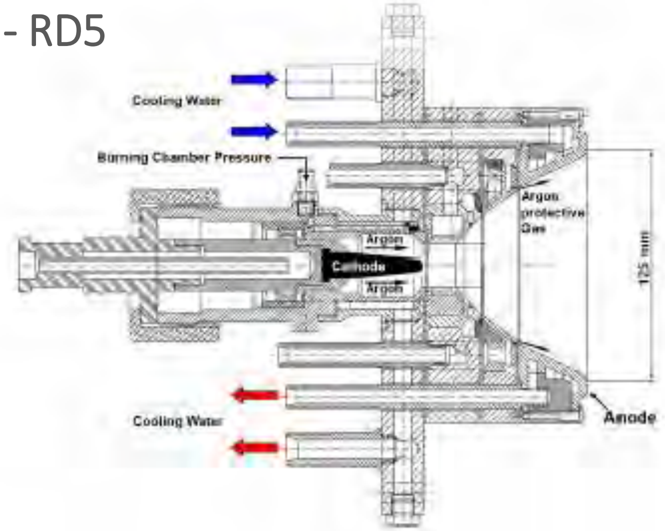
Magnet Properties	
Diameter	15 mm
Length	10 mm
Material	NeFeB
Material Grade	N35EH
Max. operating temperature	200 °C

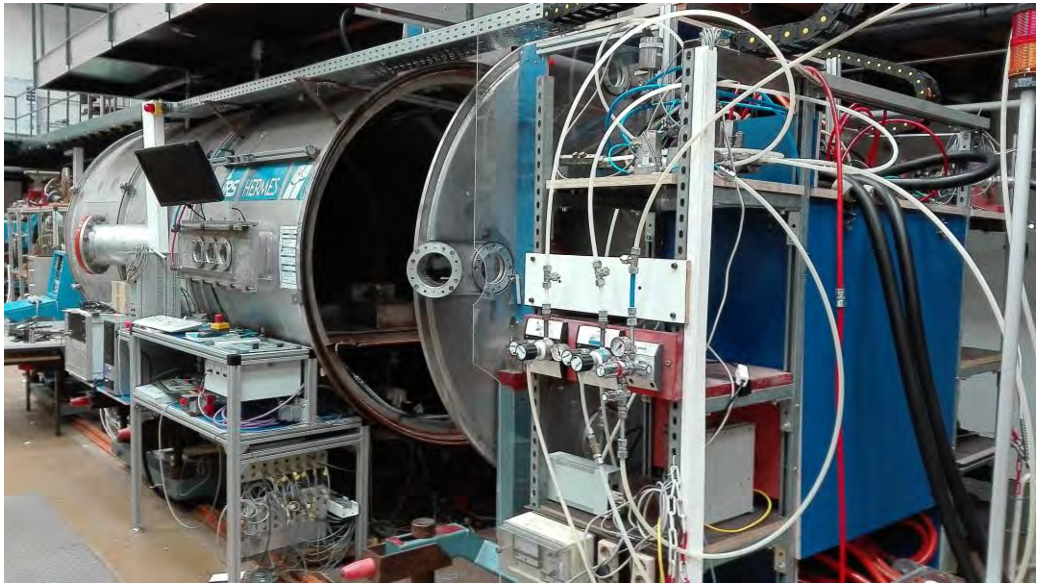
Ref.: A. J. Knapp, „Investigation of MHD Impact on Argon Plasma Flows by Variation of Magnetic Flux Density”, The Open Plasma Physics Journal, 5, 11-22, 2012.

Background: MHD-experiments

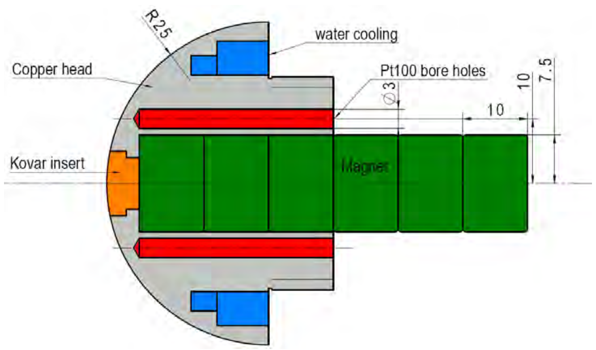
Plasma Wind Tunnel

MPG (plasma generator)
- RD5



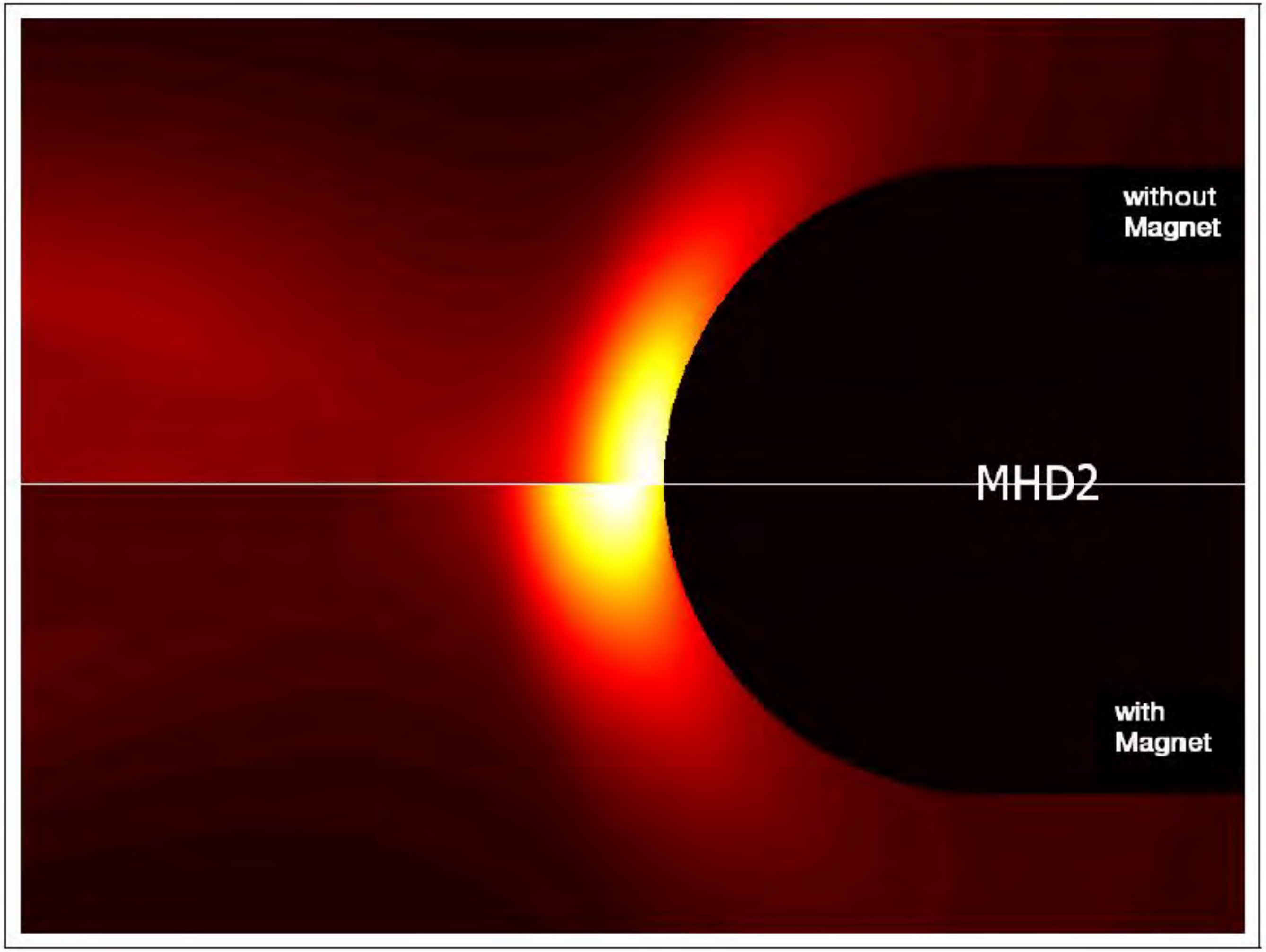


Parameter	Value	Unit
Gas flow rate	1.5 + 0.5	g/s
Ambient pressure	30	Pa
Current	1040	A
Voltage	35	V
Power	36.4	kW



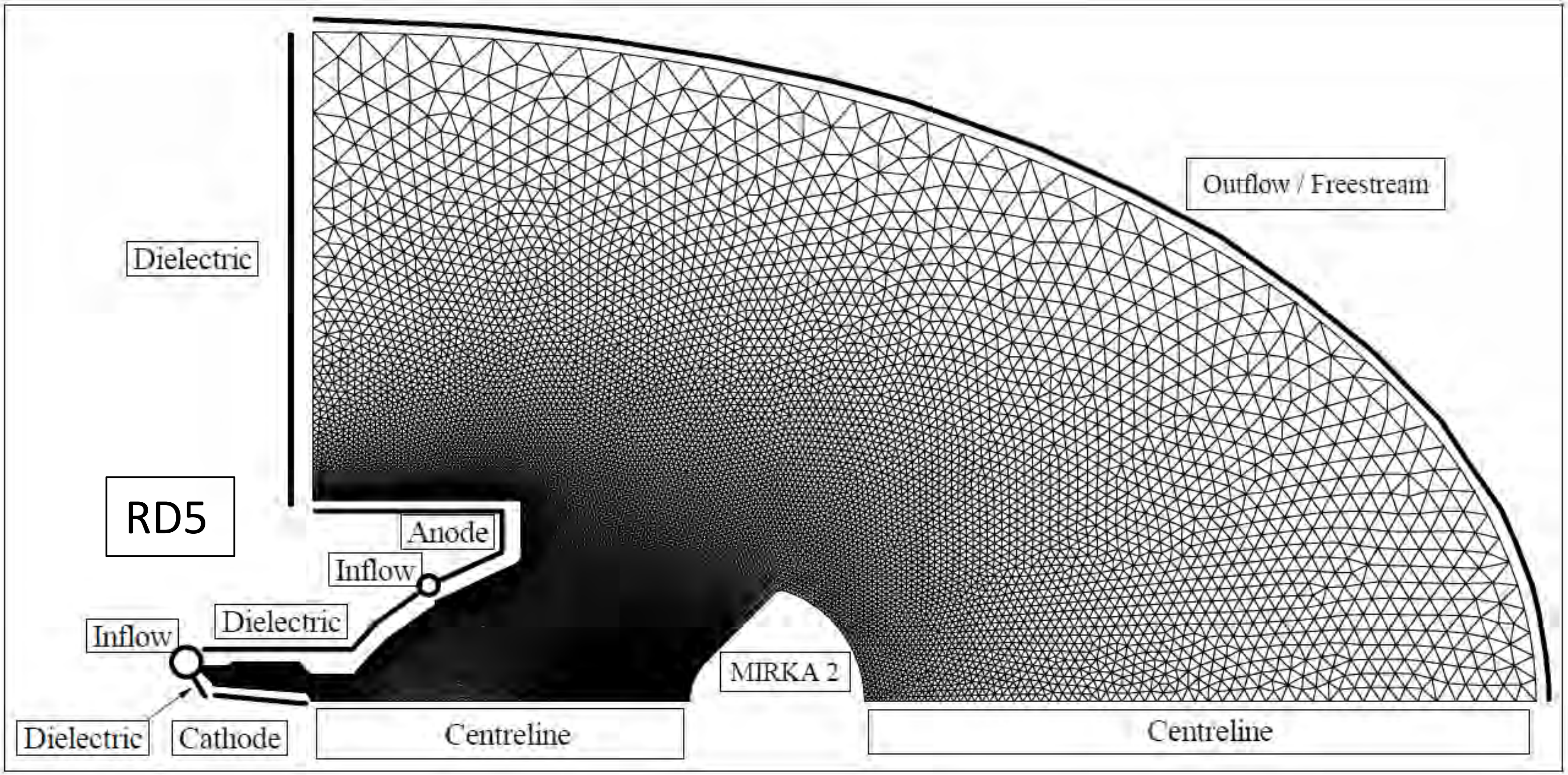
Experimental Result

Plasma Wind Tunnel



- Highly ionized argon flow with 30 % ionization degree
- Despite seemingly higher intensity : measured temperature reduction

SAMSA



- Employs finite-volume method on an unstructured adaptive grid
- Axisymmetric calculation domain
- Validated by successful numerical rebuild of MHD-experiments (previous slides)
- Very suitable for MPD-thruster problems, adaptation to simulate re-entry problems with applied magnetic fields
- Three gas models: Argon / Xenon / Helium

Ref.: P.P. Upadhyay, R. Tietz, G. Herdrich, „Numerical Simulation Accompanied with Shock stand-off prediction for heat-flux mitigation by MHD flow control on Re-entry Vehicles", 31st ISTS Matsuyama-Ehime Japan, 2017.

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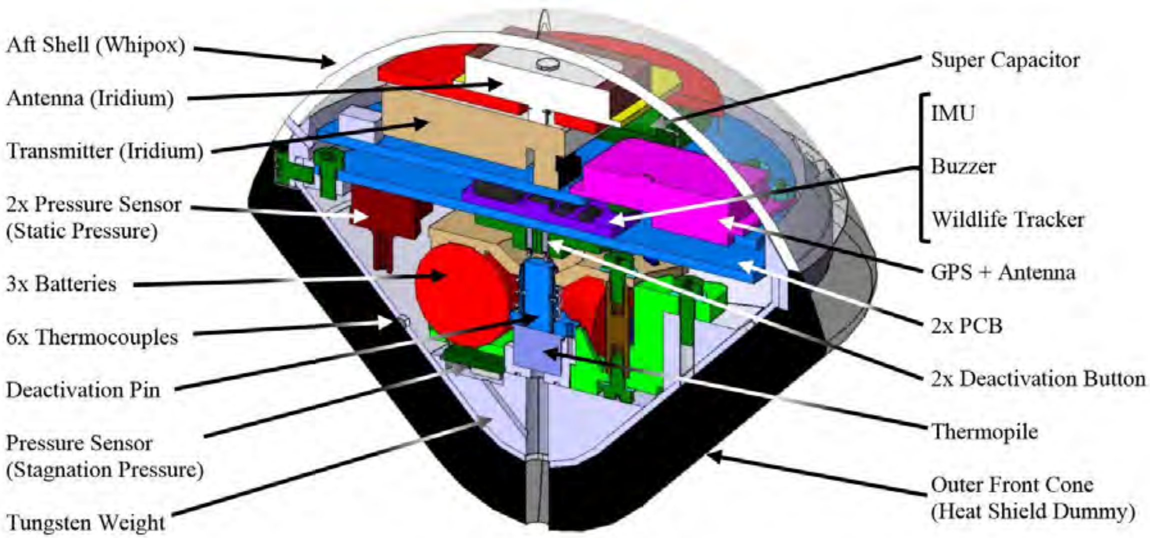
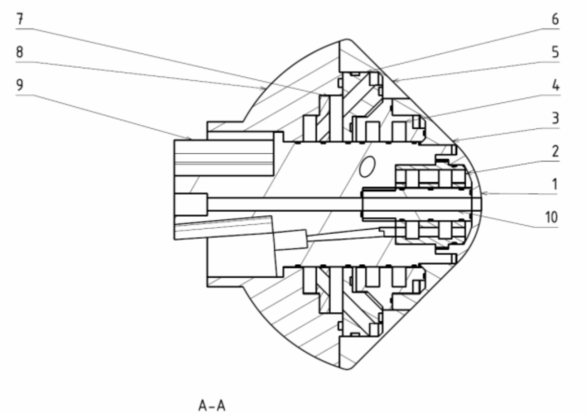
MIRKA2 Capsule



CAD-model of MIRKA2-Capsule

Retrieved MIRKA2-RX capsule

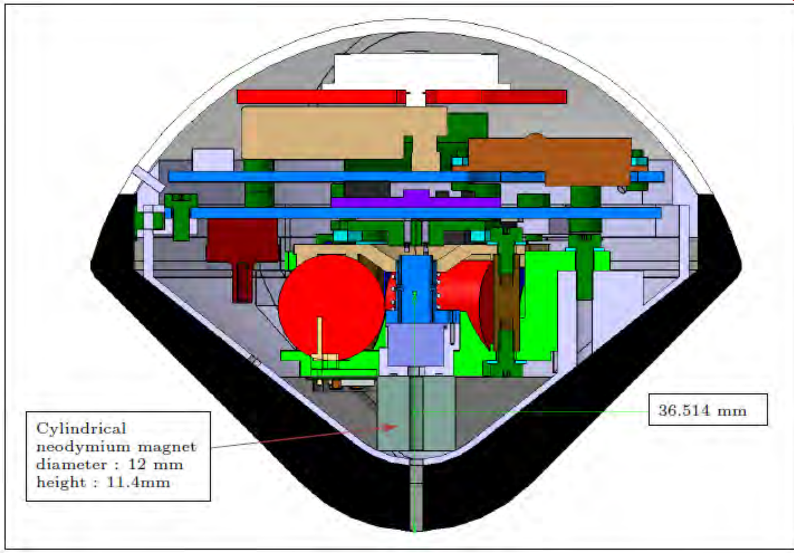
- MIRKA2 or MikroRückkehrKapsel 2 capsule built by students association KSat
- Part of the CAPE project (*CubeSat Atmospheric Probe for Education*)
- CubeSat compatible: MIRKA2 diameter: 100 mm ; CubeSat size (1U): 135x100x100mm



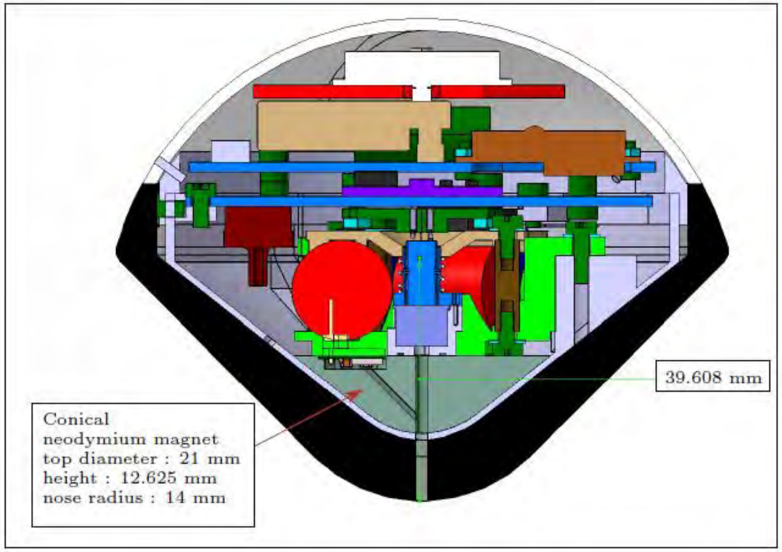
MIRKA2 probe (copper) drawing

Ref.: J.Gauger: Design of an Atmospheric Entry Capsule Geometry Plasma Probe

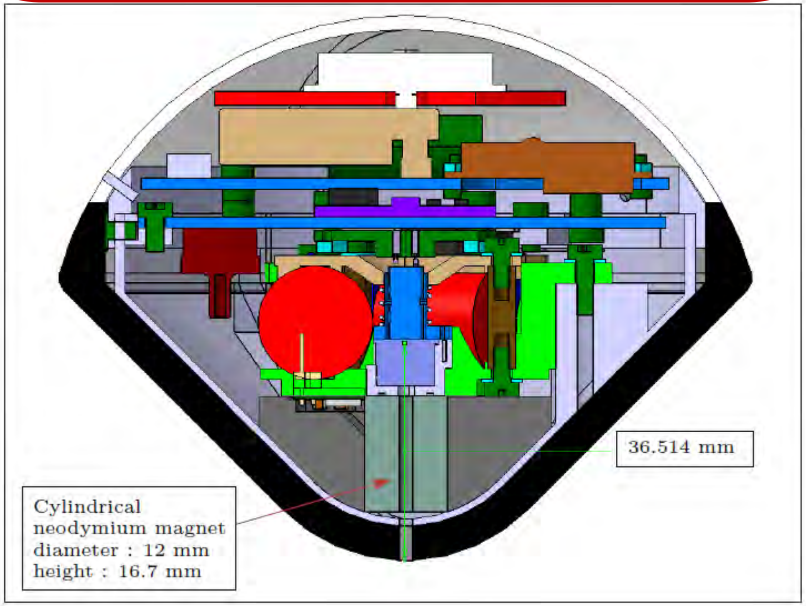
CAD adaptation of MIRKA2 - Capsule



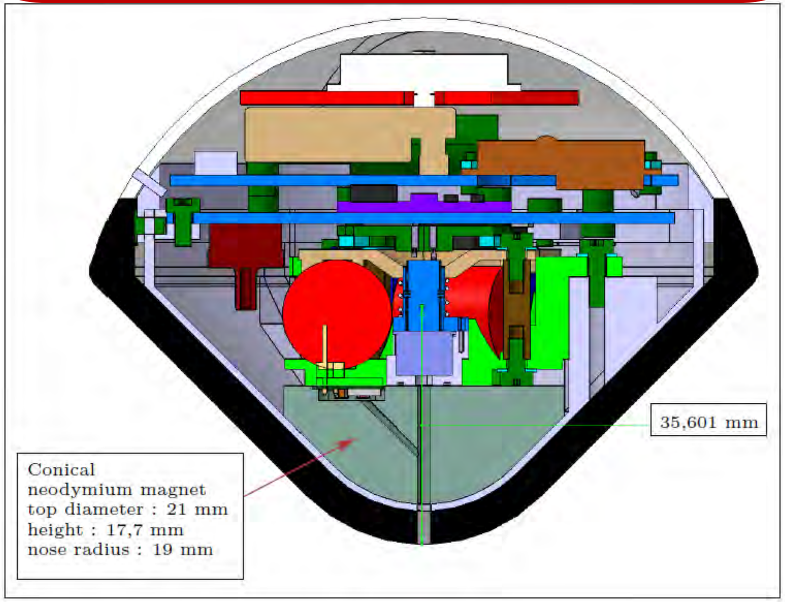
10 mm TPS at tip, cylindrical Magnet



10 mm TPS at tip, conical magnet



5 mm TPS at tip, cylindrical Magnet

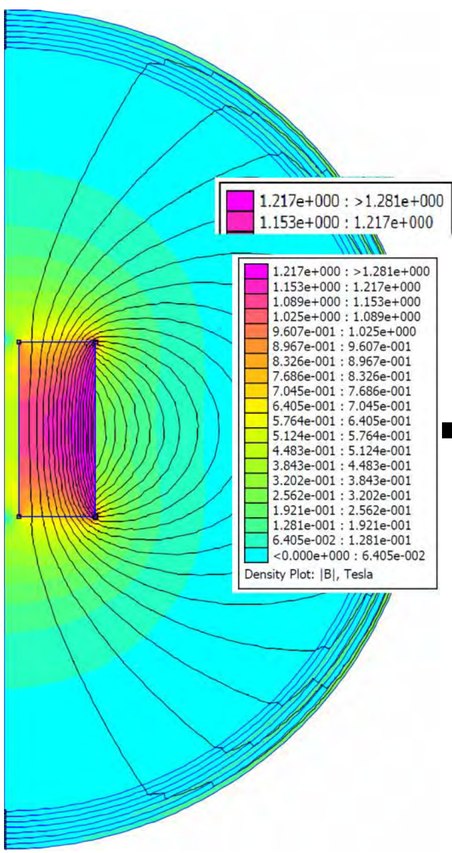


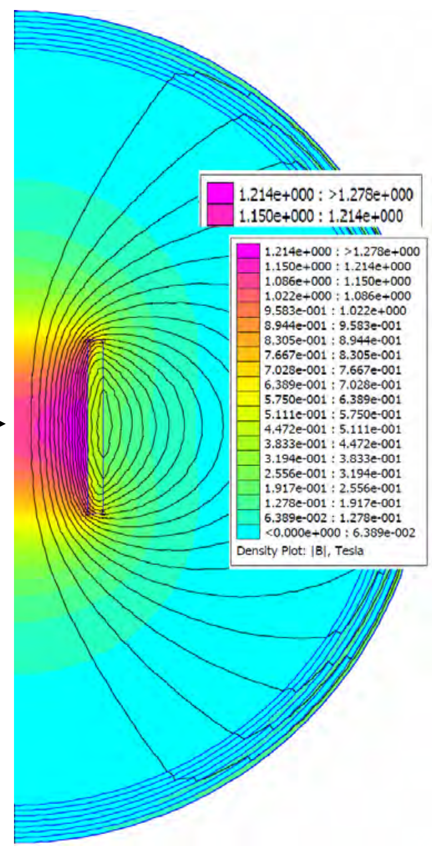
5 mm TPS at tip, conical Magnet

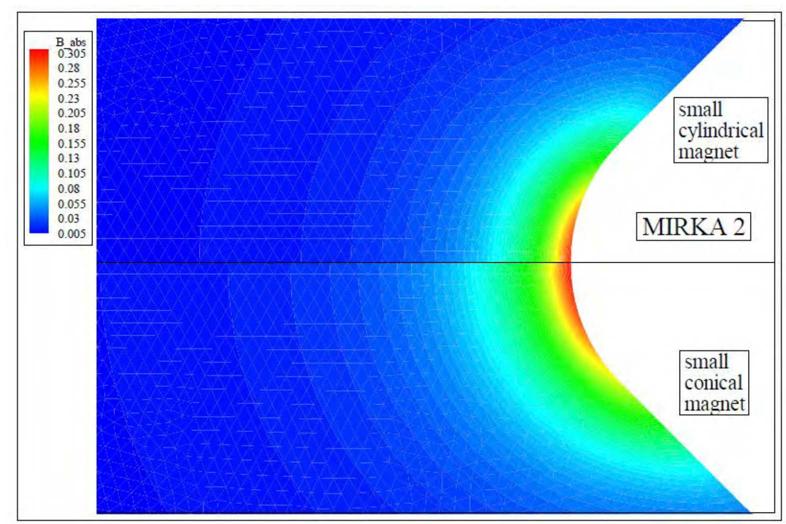
SAMSA: Magnetic Field geometry

- Standardized magnetic field strength at tip of the capsule
- Eleven RD5 simulation cases

Small cylindrical magnet [T]		Small conical magnet [T]
	0	
0.1		0.1
0.2	Freestream cases	0.2
0.3		0.3
0.6		0.6
1.0		1.0

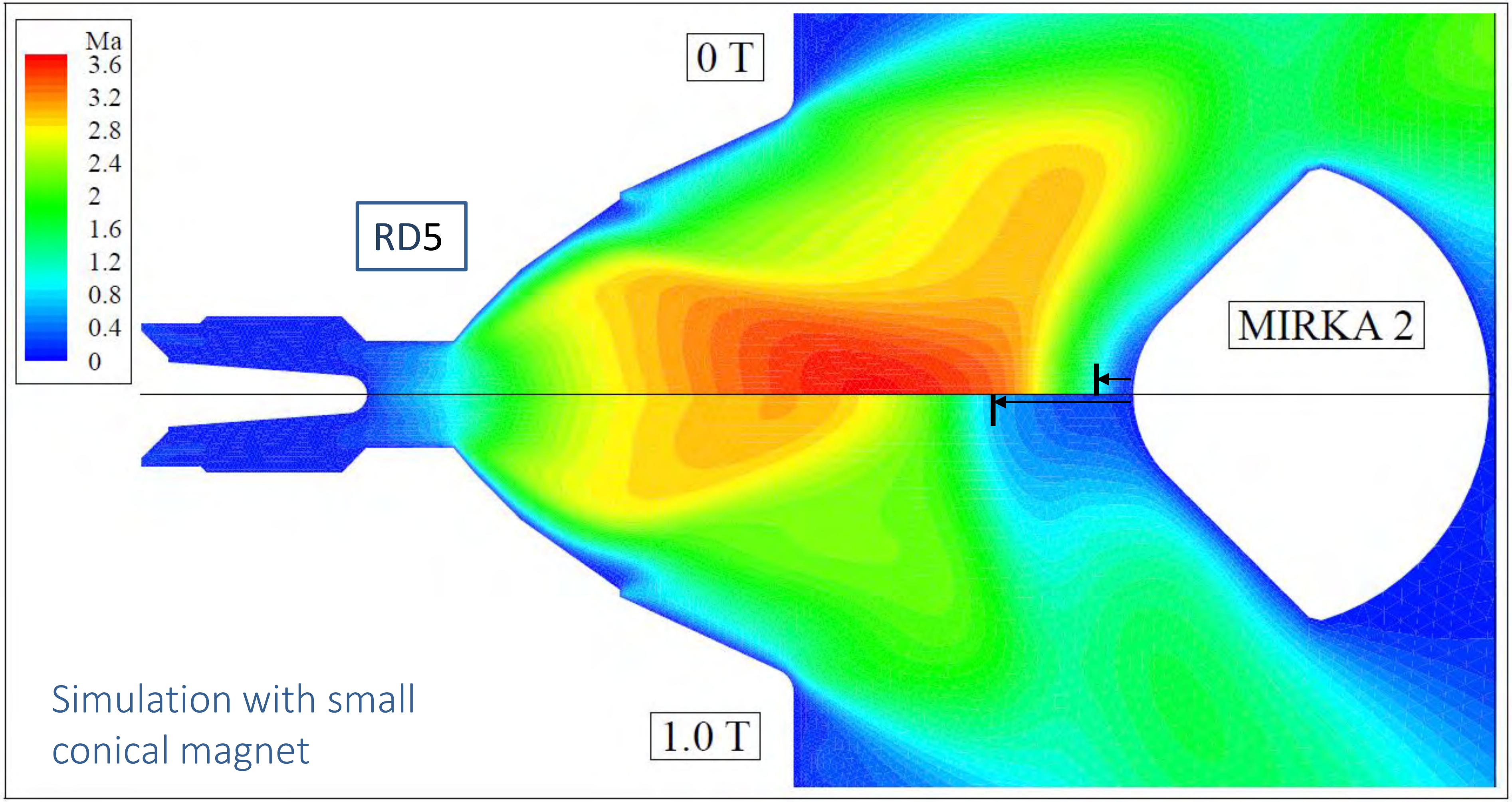






- Using FEMM (Finite Element Method Magnetics) to create Coil-Setup

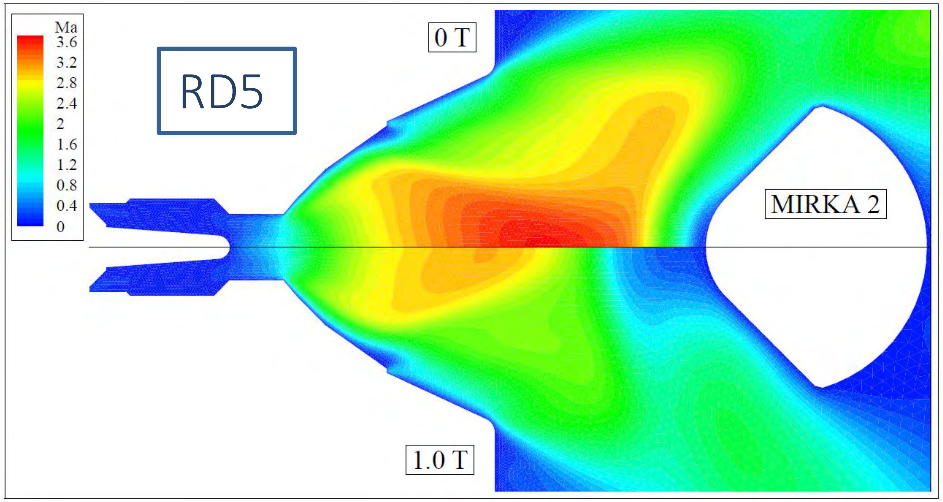
RD5 simulation – Mach Number



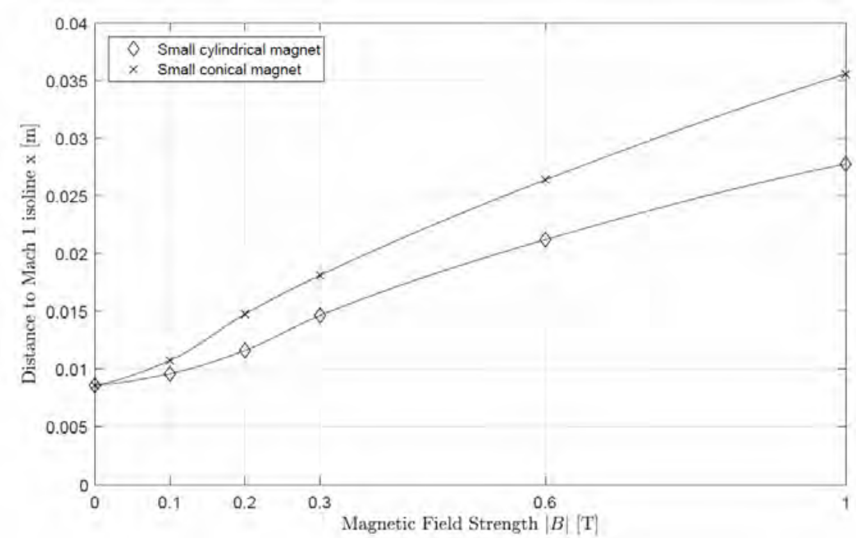
Simulation with small conical magnet

- Boundary layer significantly wider
- Fluid flow decelerated significantly
- Distance to Mach 1 isoline as a reference for analysis

RD5 simulation – Mach Number



Simulation with small conical magnet

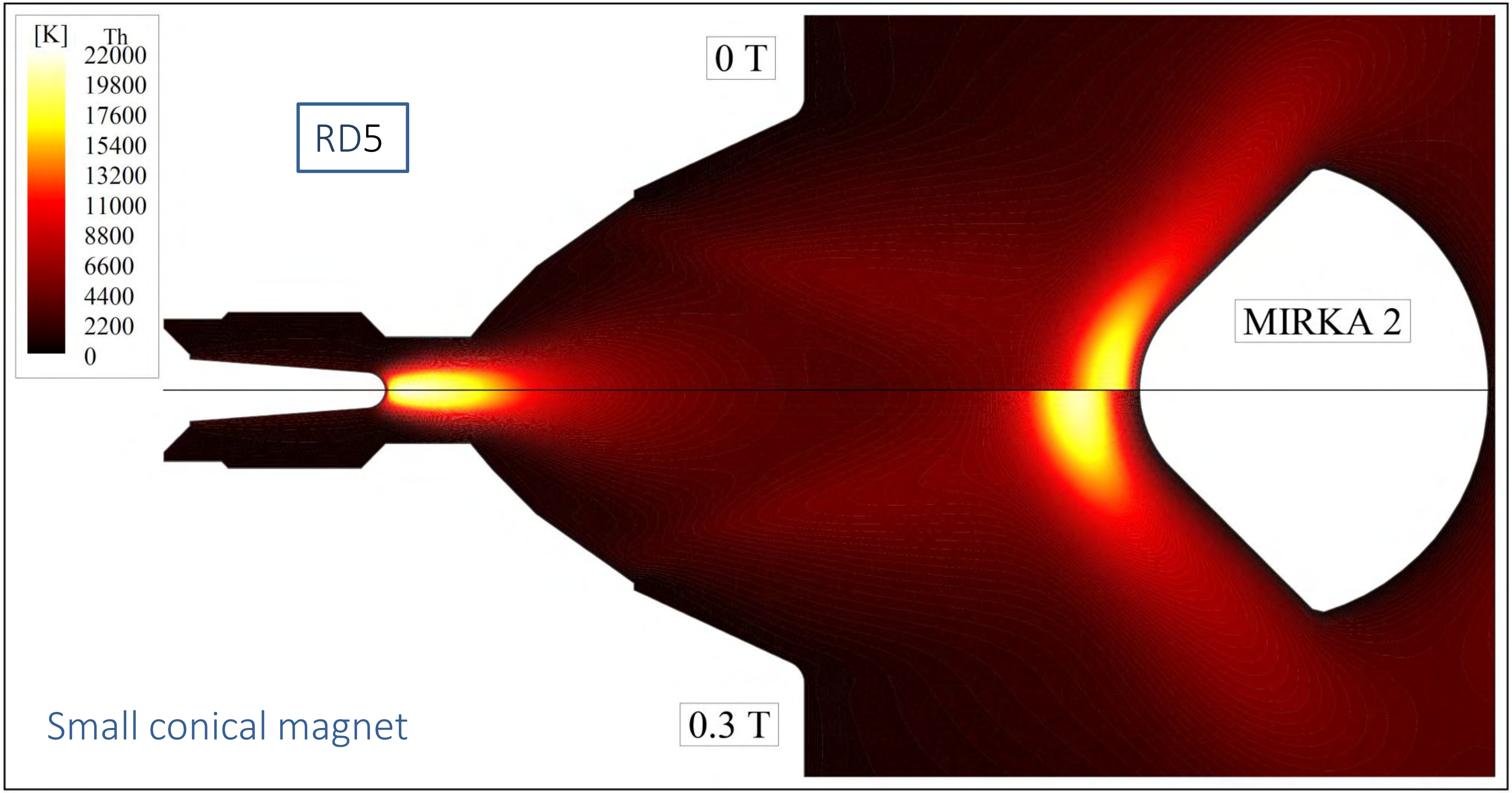


Distance of Mach 1 isoline to stagnation point plotted over magnetic field strength

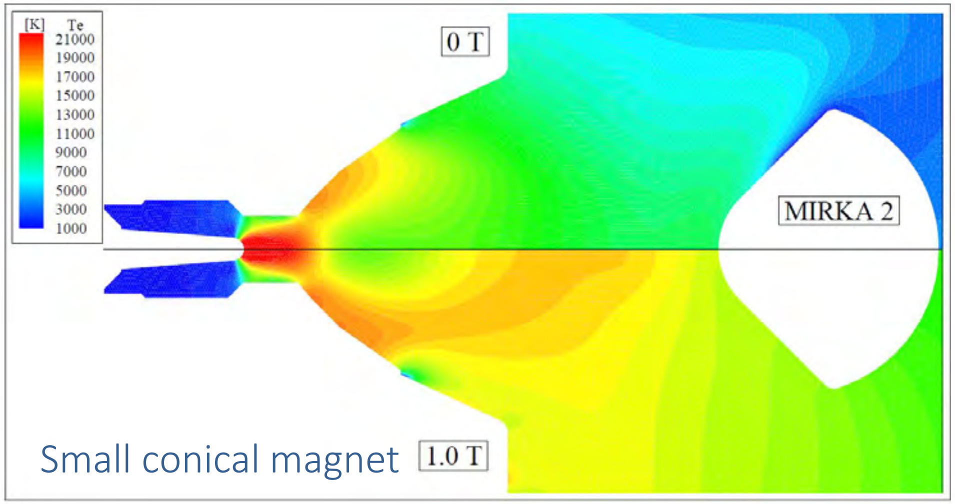
- Boundary layer significantly wider
- Fluid flow decelerated significantly
- Distance to Mach 1 isoline again as a reference for analysis

Magnetic field strength [T]	Small cylindrical case distance [mm]		Small conical case distance [mm]	
0	8.59		8.60	
0.1	9.60	[+11.8 %]	10.70	[+25.0%]
0.2	11.60	[+35.3 %]	14.80	[+72 %]
0.3	14.70	[+70.6 %]	18.10	[+111.0 %]
0.6	21.20	[+147.0 %]	26.40	[+207.3 %]
1.0	27.80	[+223.4 %]	35.60	[+314.1 %]

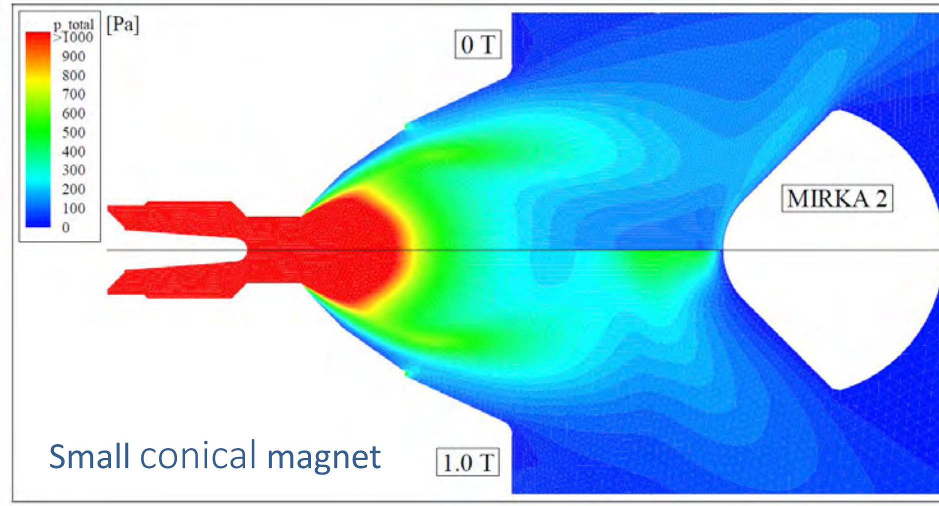
RD5 simulation – Heavy particle temperature



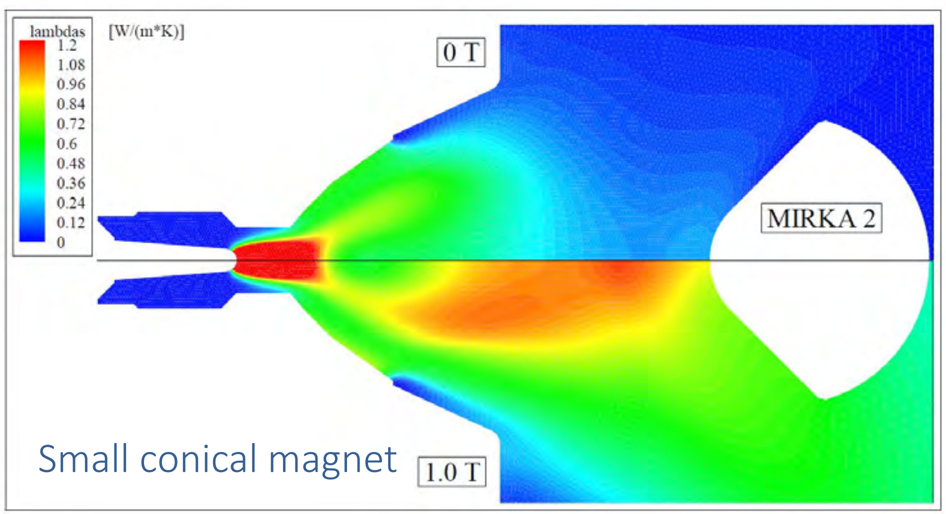
RD5 simulation – Other parameters



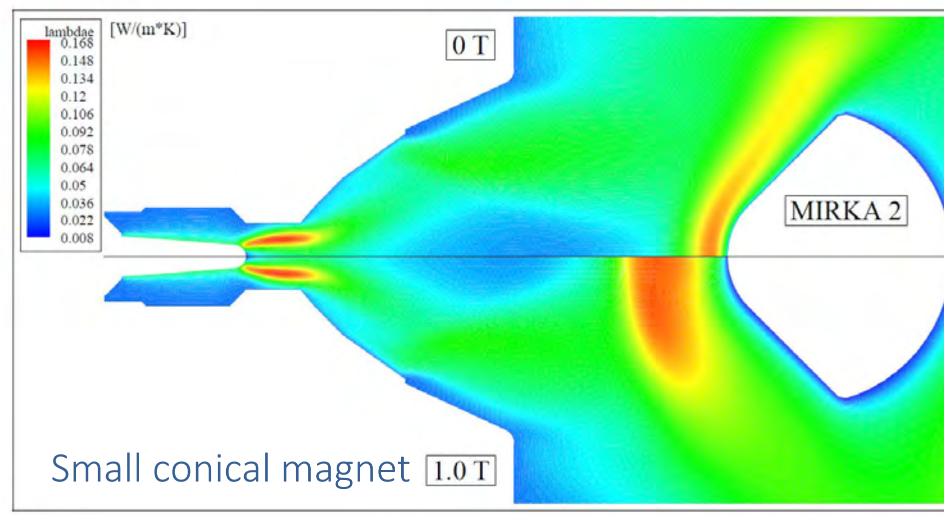
Electron temperature



Heavy particle total pressure



Heavy particle thermal conductivity



Electron thermal conductivity

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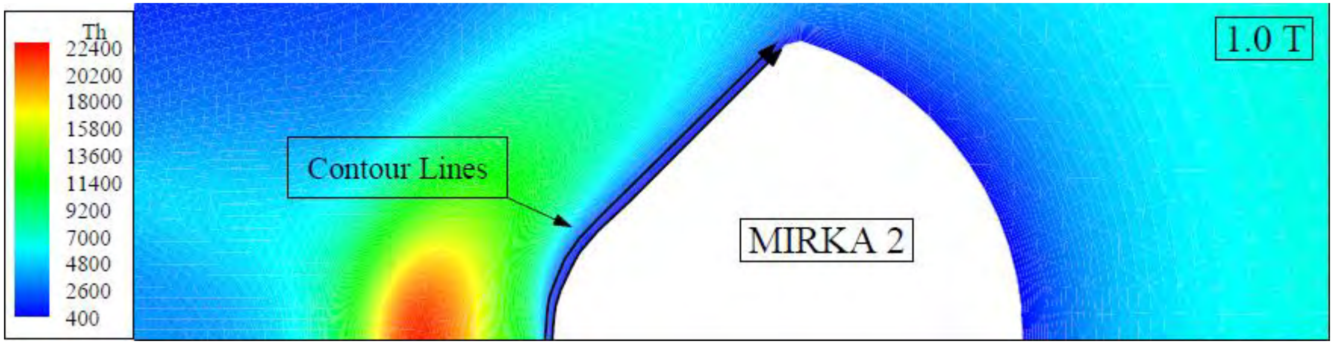
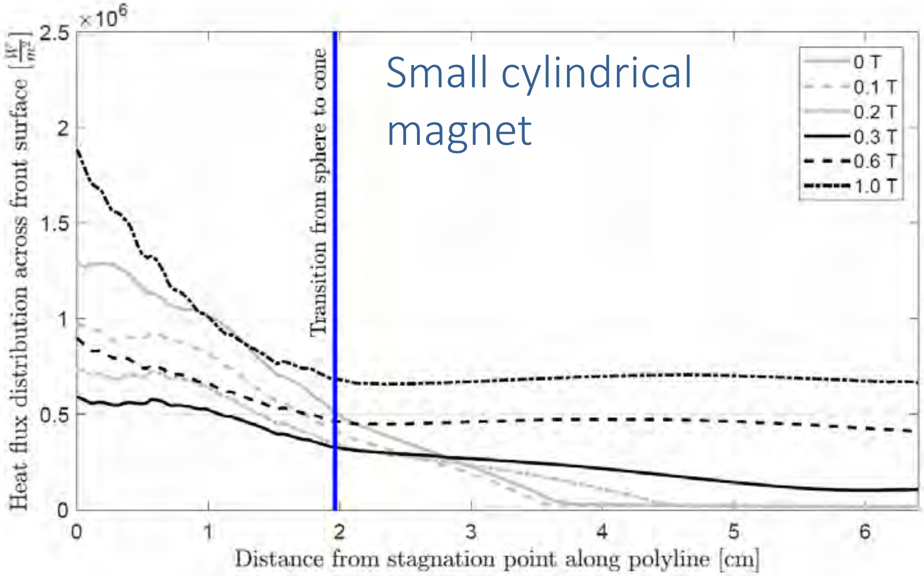
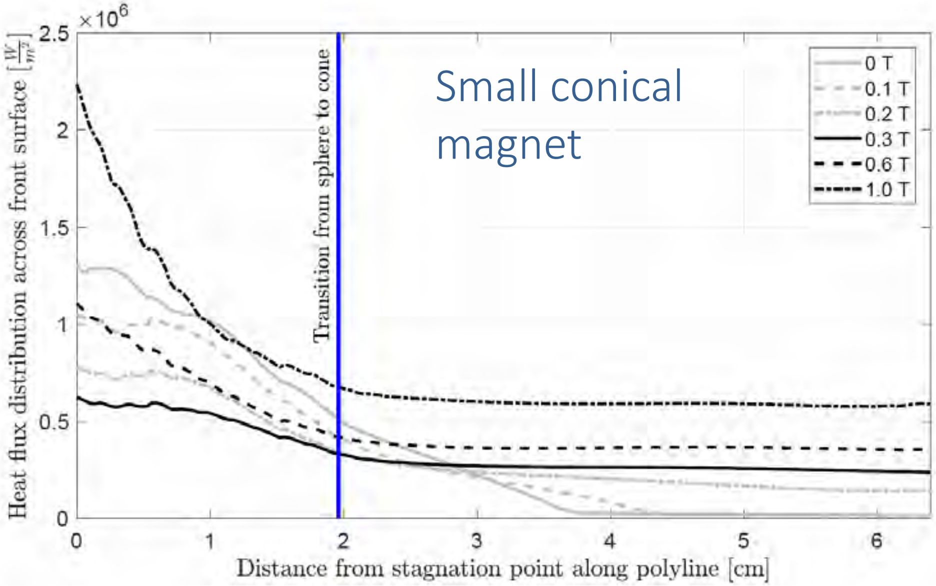
RD5 simulation – Heat flux distribution across front surface

Fourier's Law:
One-dimensional case

$$q = -\lambda_s \frac{dT}{dx}$$







- Flatter heat flux distribution for lower magnetic field strengths

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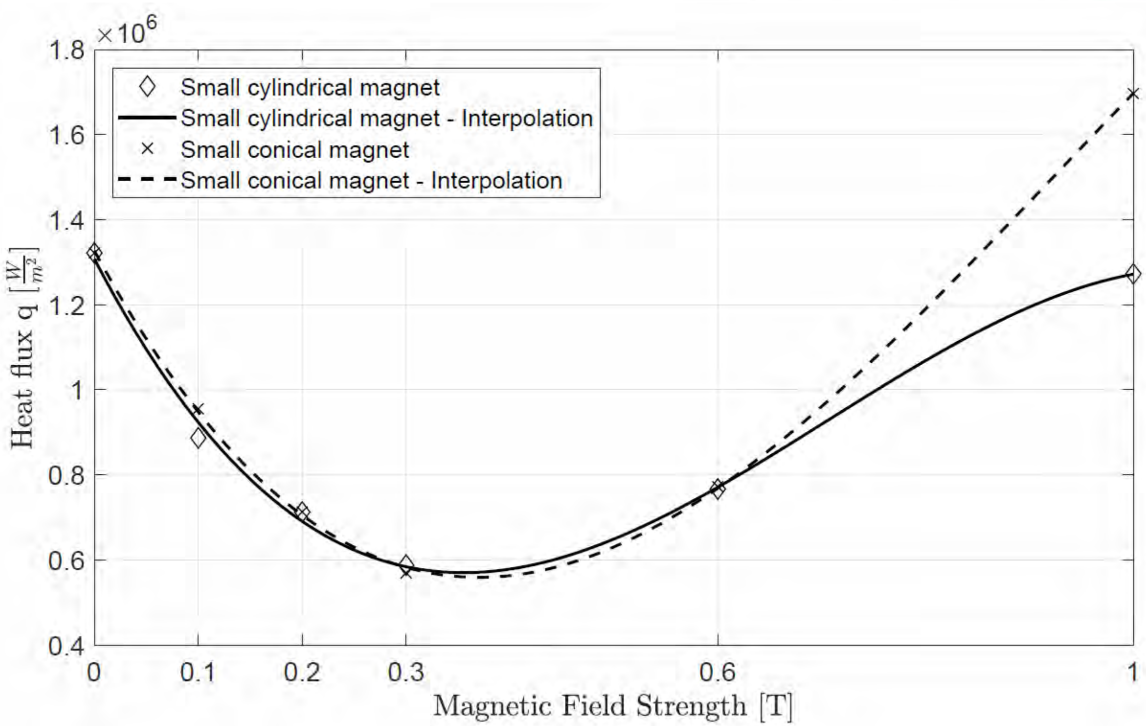
RD5 simulation – Convective Heat Flux at stagnation pont

Fourier's Law:
One-dimensional case

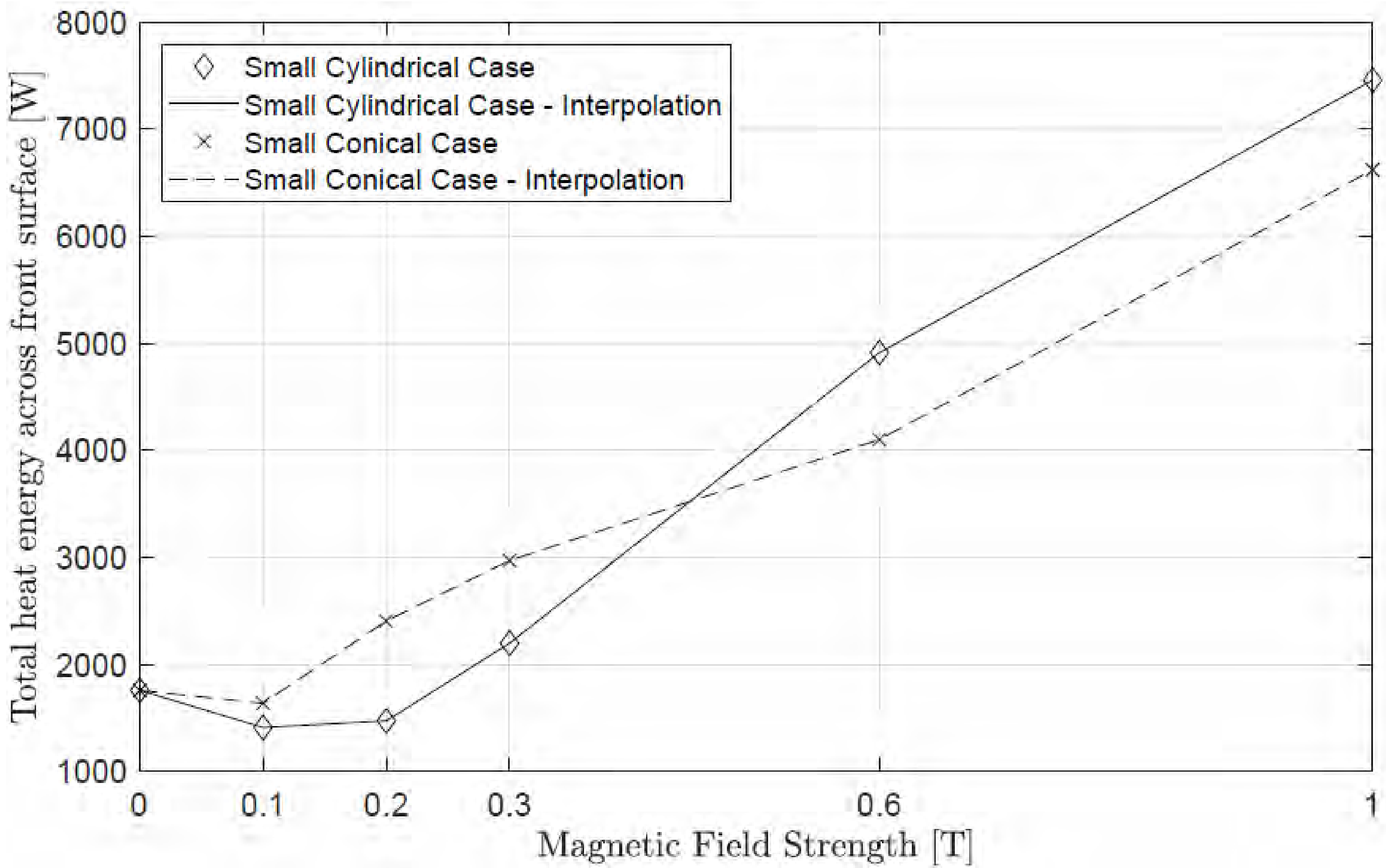
$$q = -\lambda_s \frac{dT}{dx}$$

Magnetic field strength [T]	Convective heat flux $[MW/m^2]$	
	Small Cylindrical magnet	Small Conical magnet
0	1.320	1.320
0.1	0.887 [−32.8 %]	0.955 [−27.7 %]
0.2	0.712 [−46.0 %]	0.713 [−46 %]
0.3	0.588 [−55.5 %]	0.569 [−56.9 %]
0.6	0.767 [−41.9 %]	0.772 [−41.2 %]
1.0	1.272 [−0.4 %]	1.697 [+28.6 %]



- Geometry does not have a notable influence on heat flux except for 1.0 T case

RD5 simulation – Total heat flow across front surface



- Numerical integration of heat flux distribution over discretized geometry to calculate heat energy

Conclusion

1. Funnel effect / θ-Pinch in front of the capsule: particles pushed towards axis and away from stagnation point

2. Energy redistribution in plasma :
High magnetic strengths can also lead to locally increased convective heat flux

3. Most important insight:
Optimal point with highest convective heat flux reduction is not at the highest magnetic field strength

4. Reduction of maximum heat loads (at stagnation point) might be more effective than reduction of total heat flow

5. Flatter heat flux profile along front surface for lower magnetic field strengths

Outlook

- Experimental tests with other gases and lower ionization degrees, e.g. air , oxygen, carbon-dioxide

- *Direct Simulation Monte Carlo* (DSMC) simulations
  - Comparison of SAMSA and DSMC results
  - Problem: DSMC needs to be adapted to simulate applied magnetic fields

- System and mission analysis for deployment of permanent magnets or electromagnets as a secondary TPS in re-entry vehicles

Thank you

Backup Slides

Supplemental Information

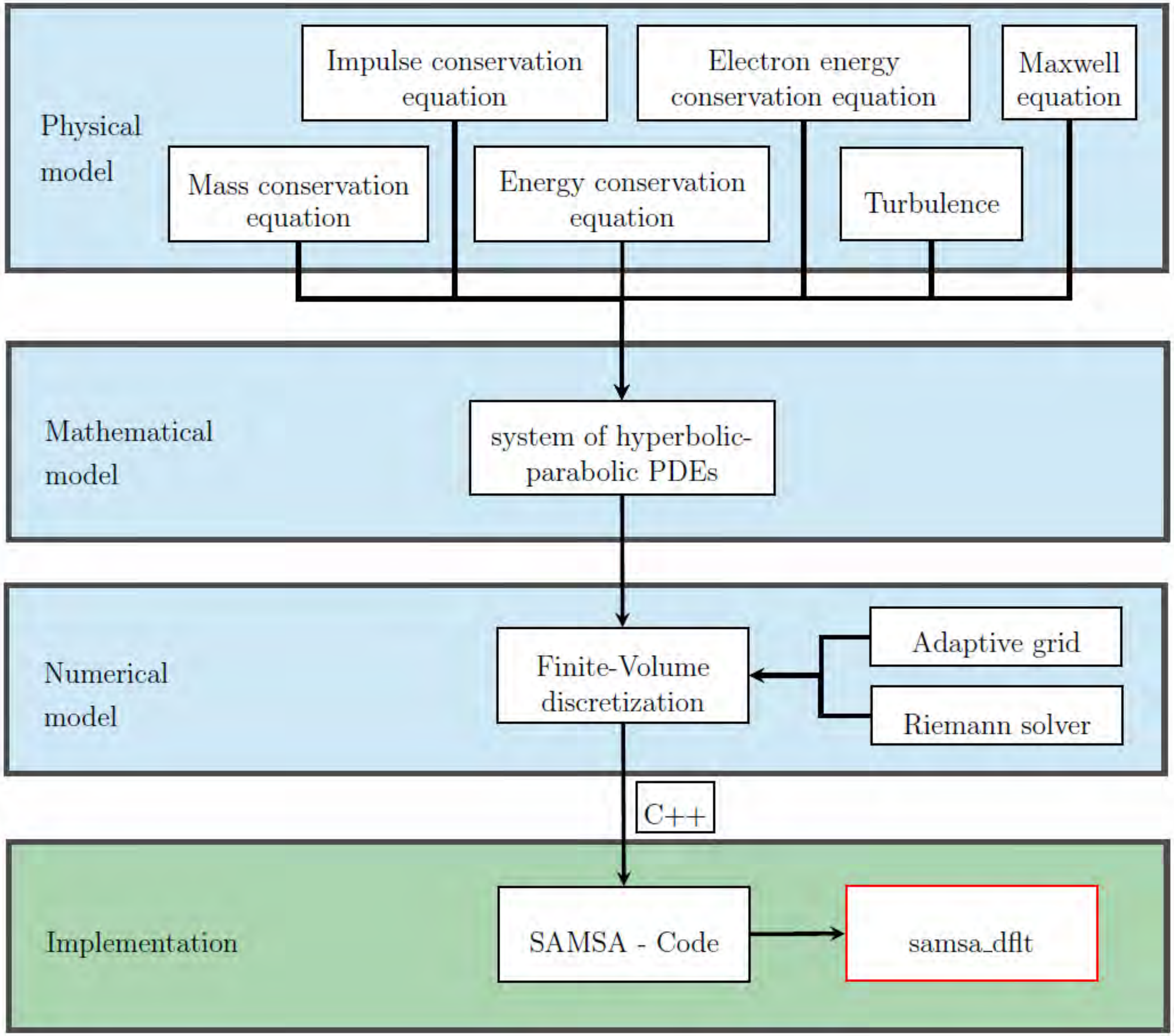
Why Argon instead of air ?

- Argon is a mono atomic gas which enables a simplified (yet still complex) modelling with ionization reaction rates. It is possible to simulate with one-fold ionized to six-fold ionized plasma
- Argon was used as a working gas in experimental work on MHD, ionization is reached more easily (up to 30 % for experiments)
- Extent of MHD-effects can be tested on different gases
- 11 species in air:

$$N_2,\ O_2,\ NO,\ N,\ O,\ N^+, O^+\ O_2^+,\ N_2^+,\ NO^+ \text{ and } e^-$$

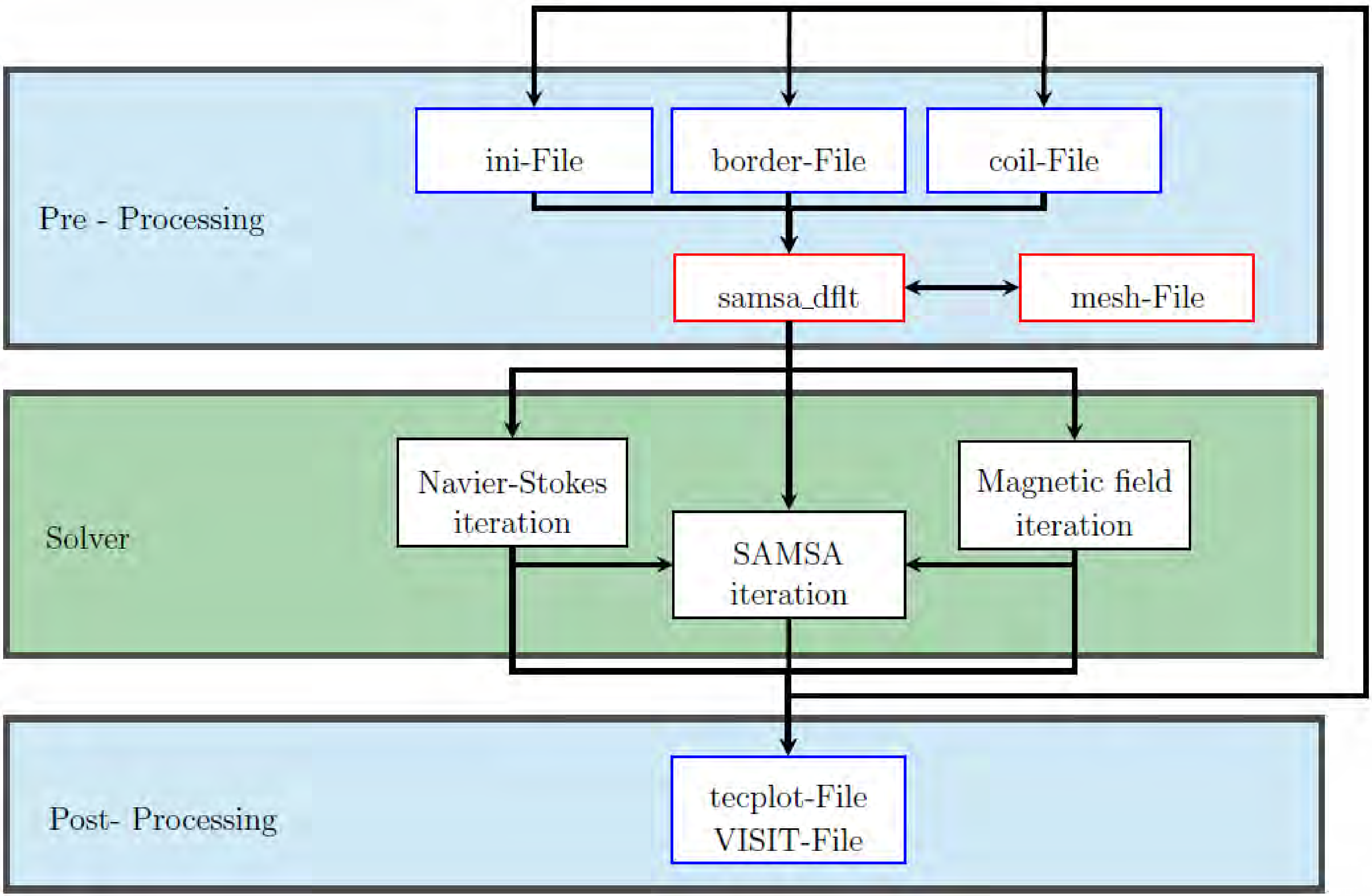
  - High numbers of species
  - various chemical reactions (excitation/relaxation)
  - very high complexity
  - no air model implemented in SAMSA yet
- Next step : experimental investigation with air

Supplemental Information



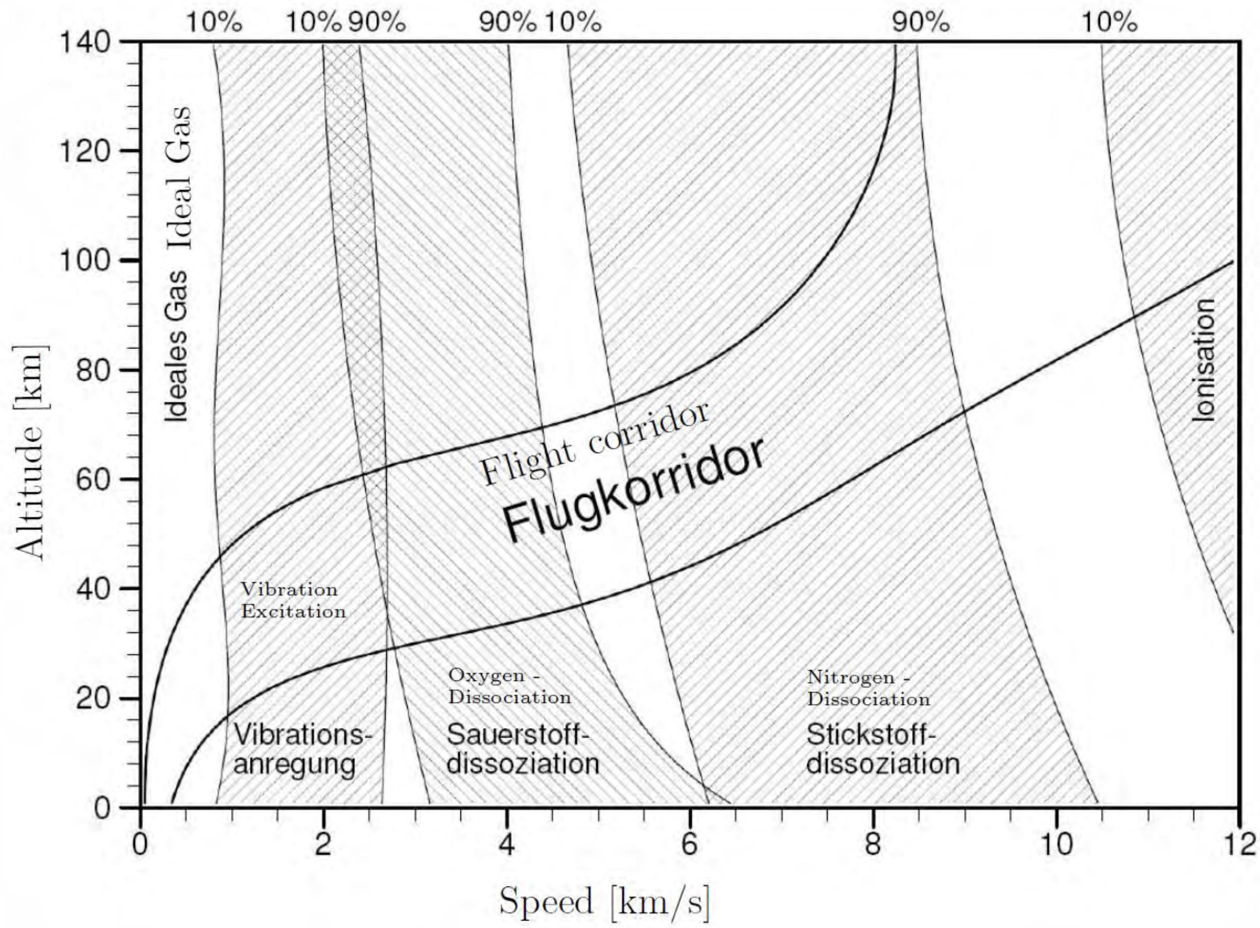
SAMSA modelling sequence

Supplemental Information



SAMSA modelling sequence

Aerothermochemistry

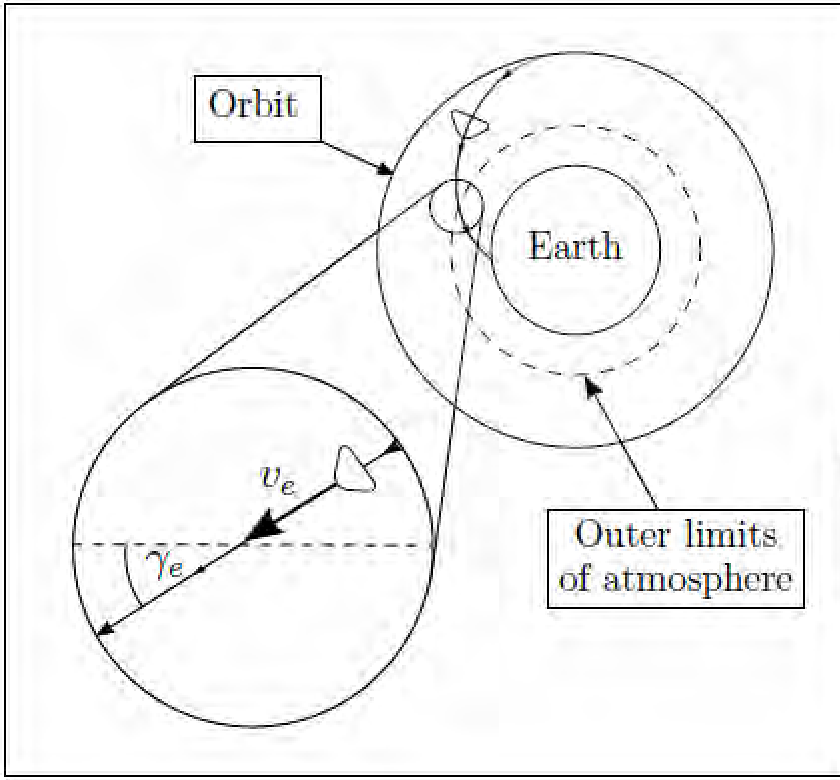


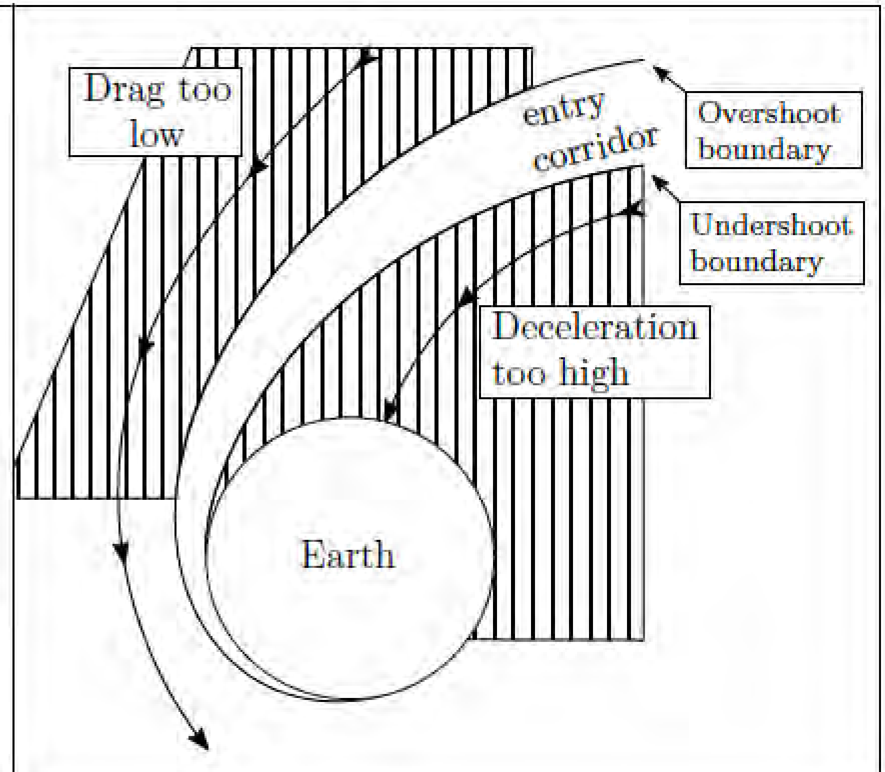
- Hyperbolic re-entry: notable ionization levels
- Opportunity: Deflect charged particles with applied magnetic fields as a secondary TPS

Ref :Koppenwallner, G.: Aerothermodynamik – Ein Schlüssel zu neuen Transportgeräten der Luft- und Raumfahrt

Supplemental Information

Re-entry missions





Re-entry from orbit

Re-entry from orbital trajectory

Low re-entry velocity and ionization

Possibly high re-entry velocity and ionization

Supplemental Information

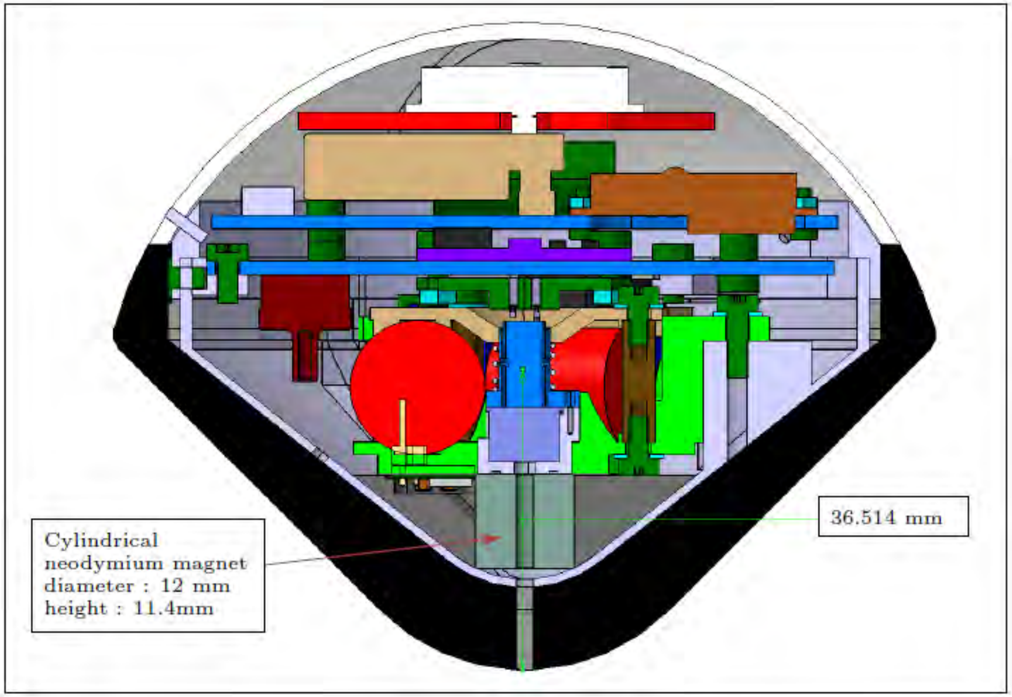
Permanent Magnet:Feasibility and Potential

Problems:

1. Center of Gravity:
   Nutation of Capsule
   if CoG is not low enough

2. Limited Space

3. Curie temperature:
   Does the permanent magnet
   lose ist remanence during
   re-entry , cooling needed?



4. Maximum of attainable field:
   0.1 to 0.2 Tesla at tip for neodymium magnets.
   Higher field strengths required for noticable effect on weakly ionized flows?

Right now, many problems that limit feasibility

Supplemental Information

Plasma parameters

Knudsen number:

$$Kn = \frac{\lambda}{L}$$

$10 \leq Kn$: Molecular flow

$Kn \leq 0.01$: Continuum flow

Stuart number: -Ratio of electromagnetic to inertial forces.
-Needed for characterisation of experiments

$$S = \frac{\sigma B^2 L}{(1 + \Omega_e \Omega_i)\rho v} = \frac{\sigma B^2 L}{\rho v}$$

Debye length: - Distance of microscopic charge seperation in plasma
- Characteristic value for plasma flows
- Can be used to assess quality of experimental data

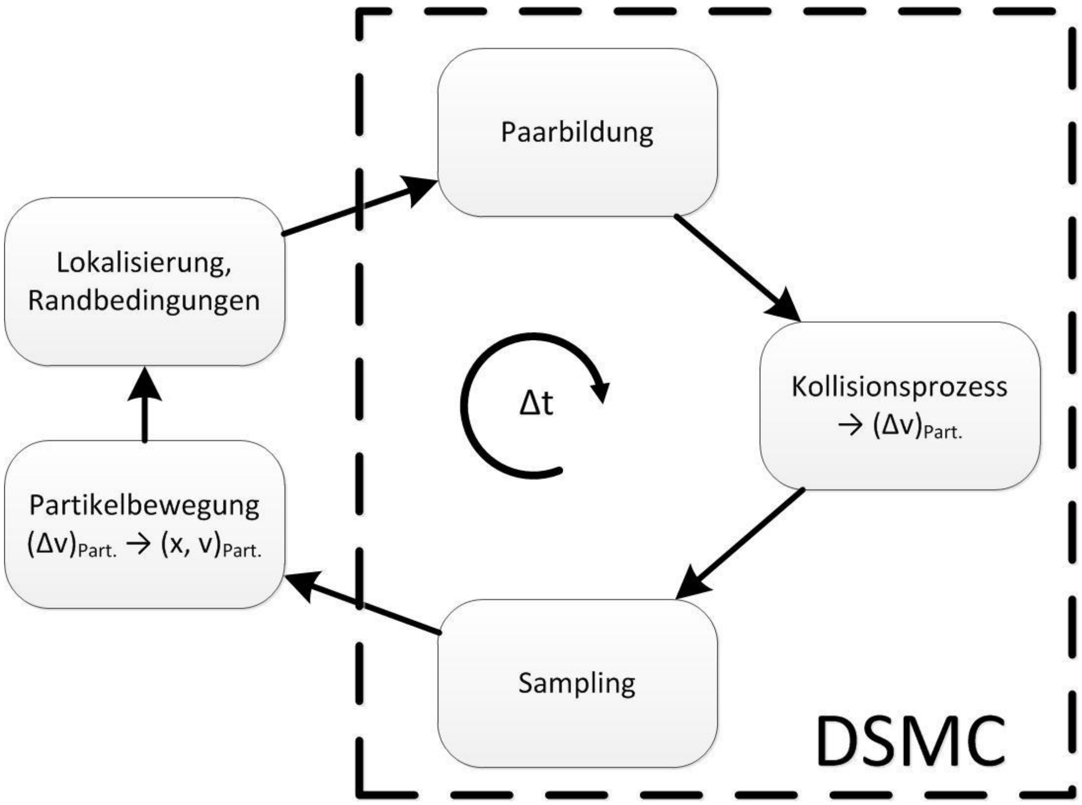
$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{e^2 n_e}}$$

Hall parameter: - Important to characterise MPD-thrusters

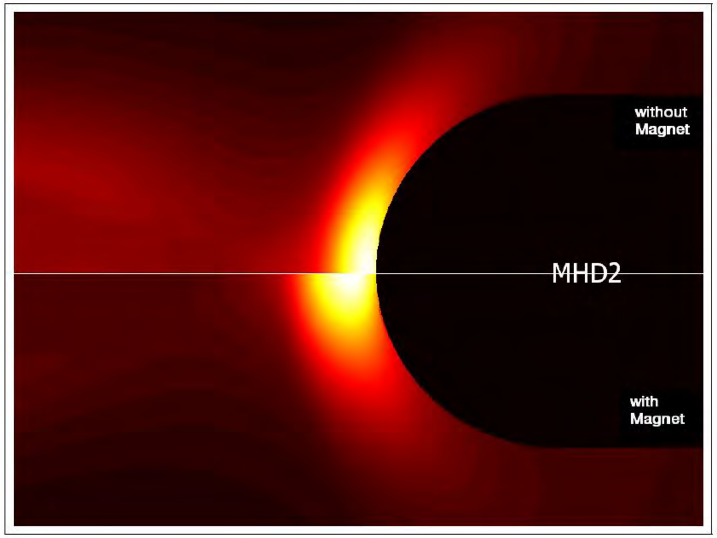
Supplemental Information

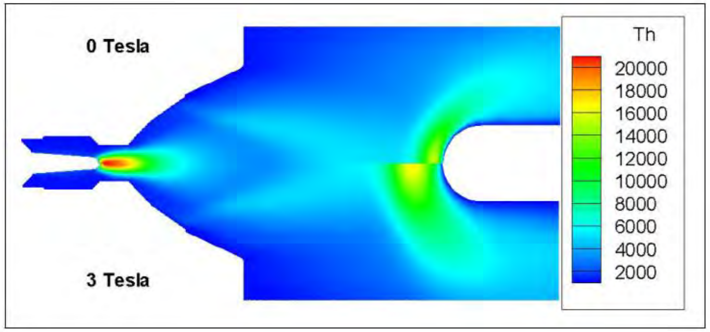
DSMC (*Direct Simulation Monte Carlo*)

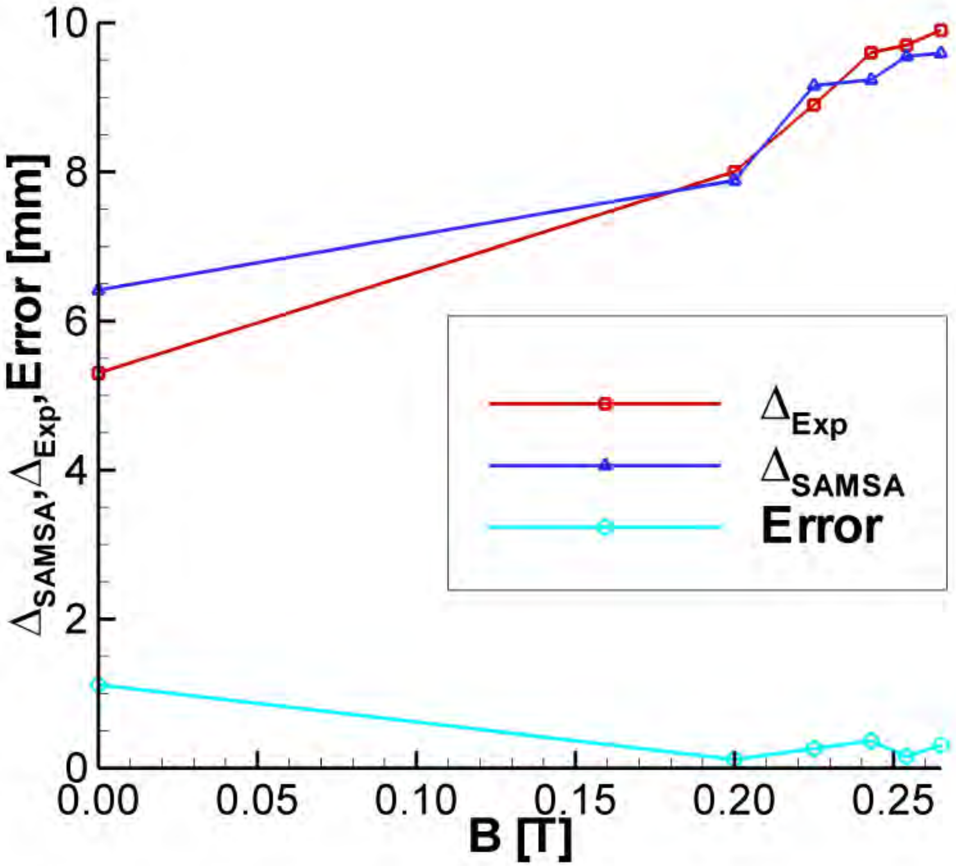
- Propabilistic approach
- Particles as a representative number of particles instead of continuum
- Solving the Boltzman equation, which describes the statistical behaviour of particles



SAMSA: PWK1 validation





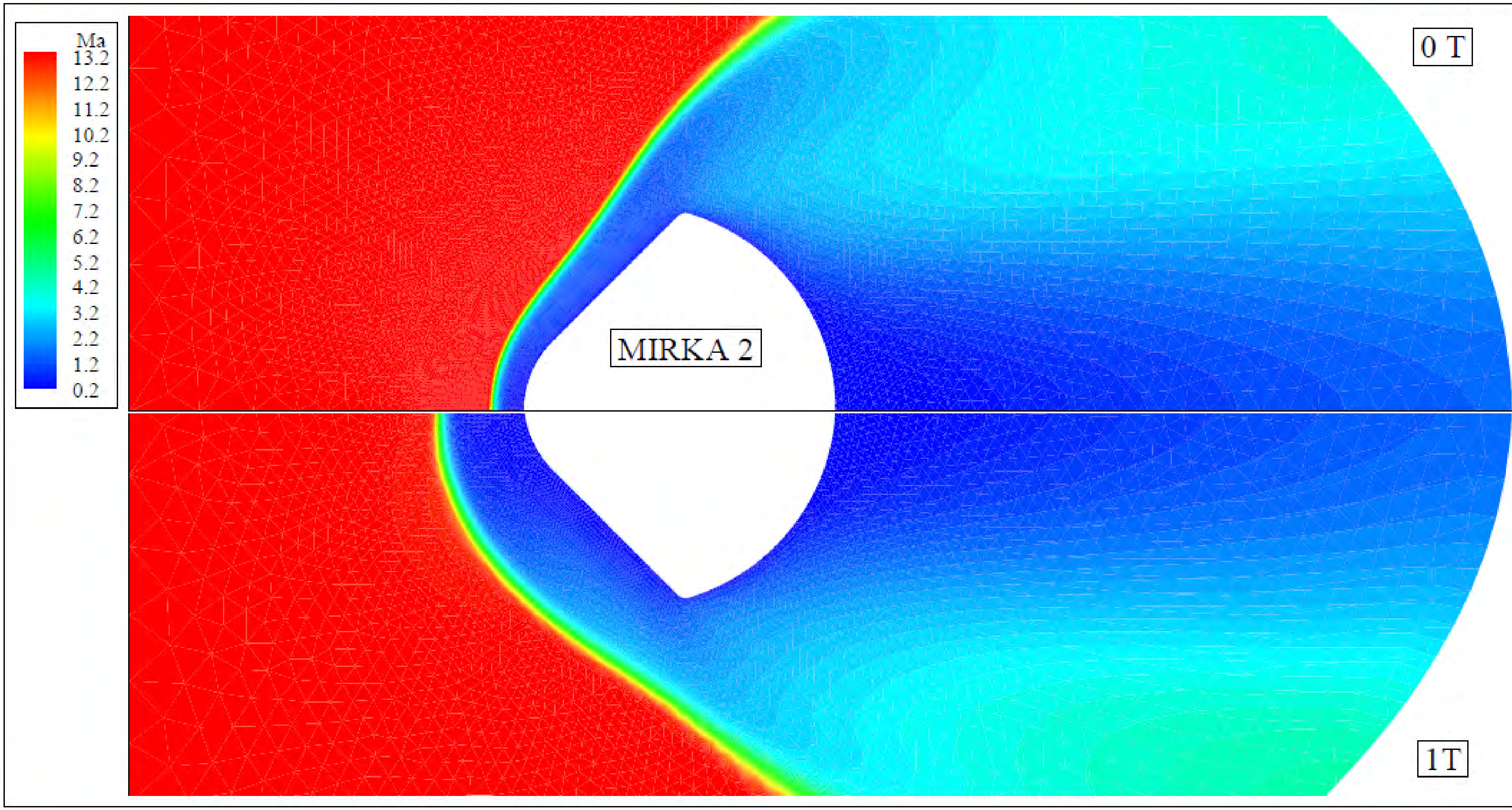


- SAMSA capability to simulate PWK1 conditions was validated by R. Tietz and P.P. Upadhyay

Ref.: R.Tietz : Simulation of Re-entry Problems Coupled with MHD Effect in Argon Plasma Flows

Freestream simulation: Mach number

Altitude	v_e	ρ_∞	p_∞	T_W	T_i



1.0 18.3 [+240 %]

Mach number

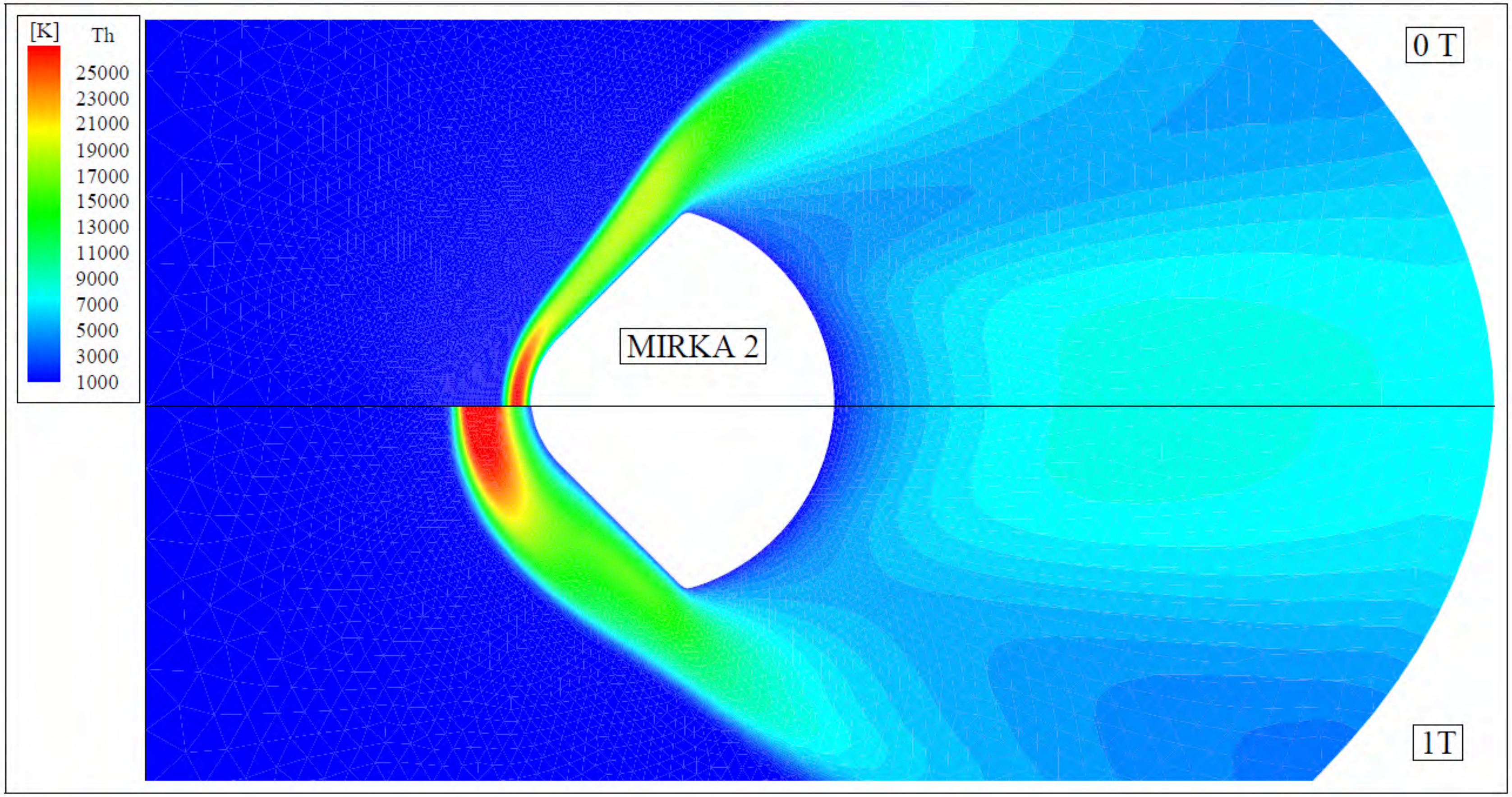
temperatures increased

- Lower temperature gradient

Distance to Mach 1 isoline

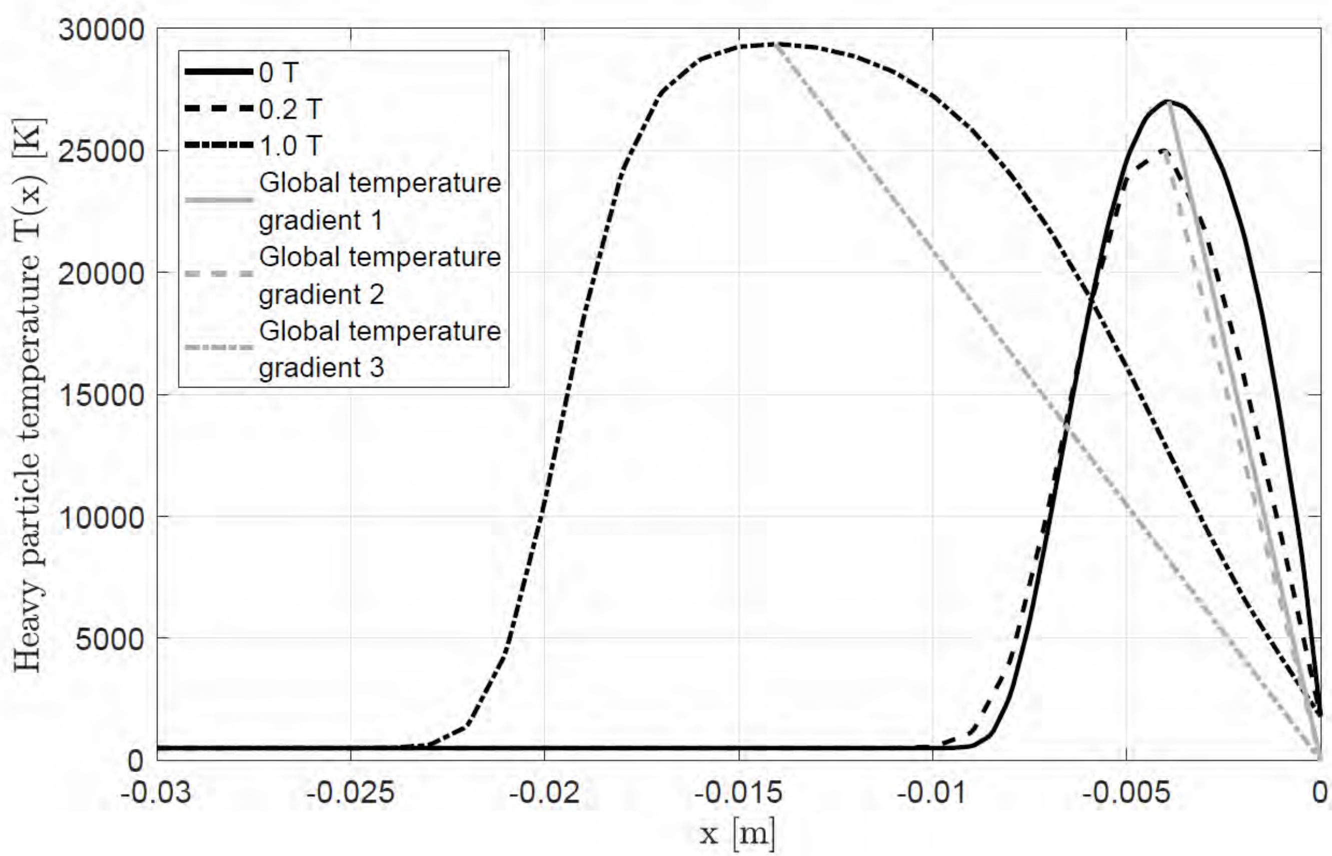
Ref.: J.Baumann: Aerothermodynamic re-entry analysis of the CubeSat-sized entry vehicle MIRKA2

Freestream simulation
Heavy particle temperature



- Boundary layer significantly wider
- Distance of area with high temperatures increased
- Lower temperature gradient

Freestream simulation
Temperature gradient

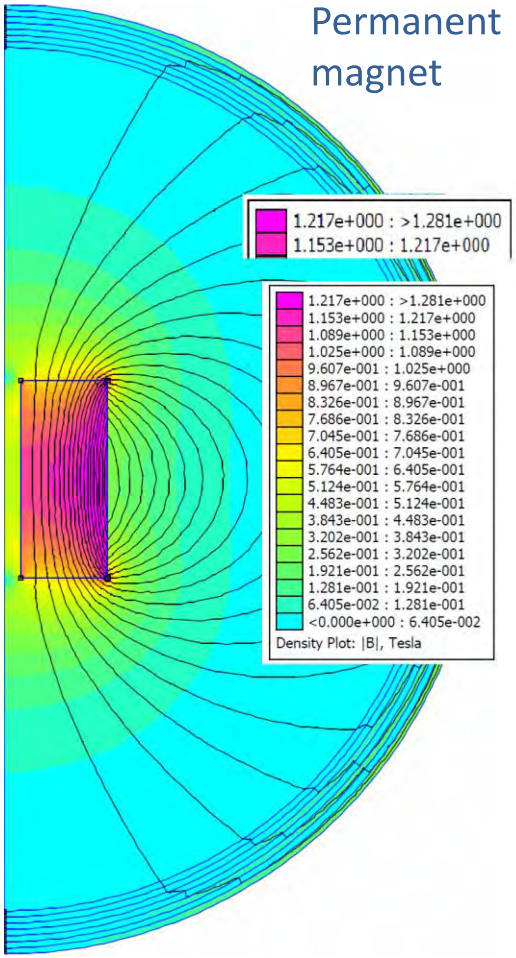


Magnetic Field Strength [T]	Temperature gradient [K/mm]	
0	6899.5	
0.2	6226.4	[−10.8 %]
1.0	2089.8	[−69.7 %]

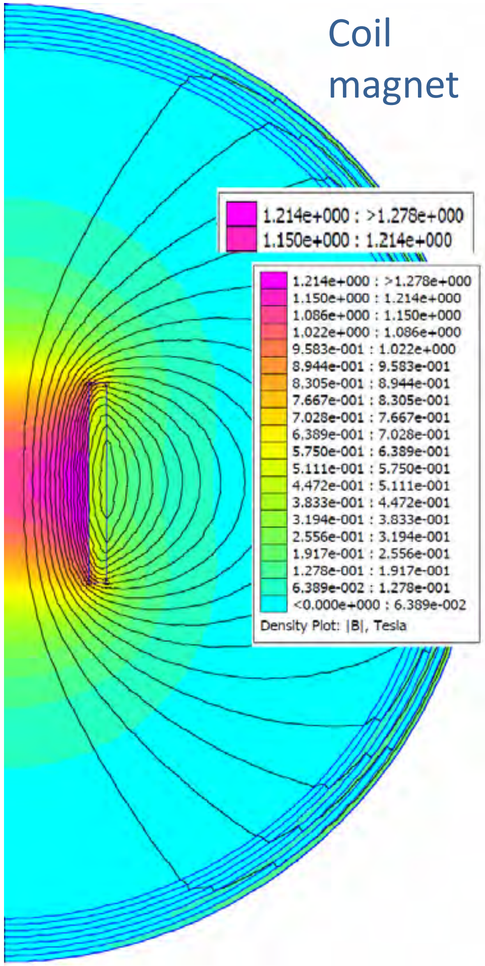
- Heavy particle temperature plot 3 cm in front of the tip
- Temperature gradient reduced significantly

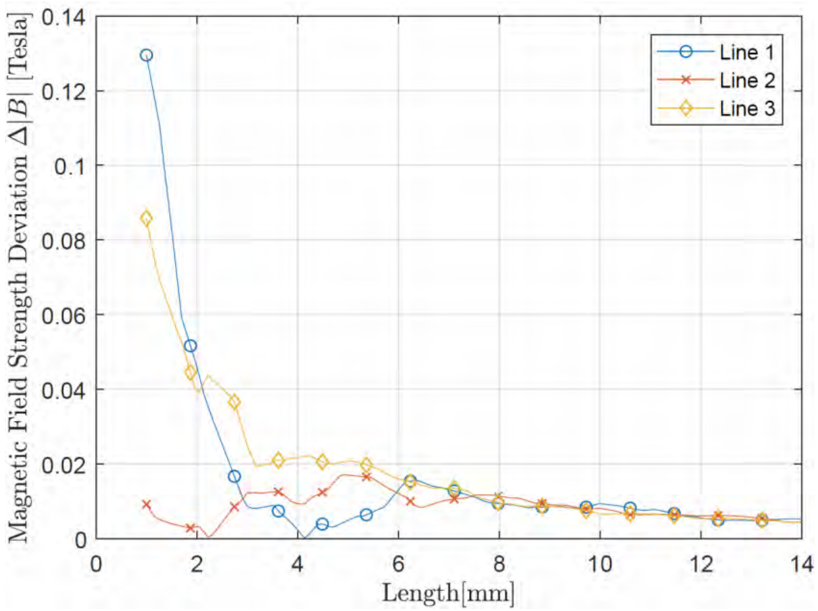
FEMM: Magnetic Field Modelling

Permanent magnet



Coil magnet

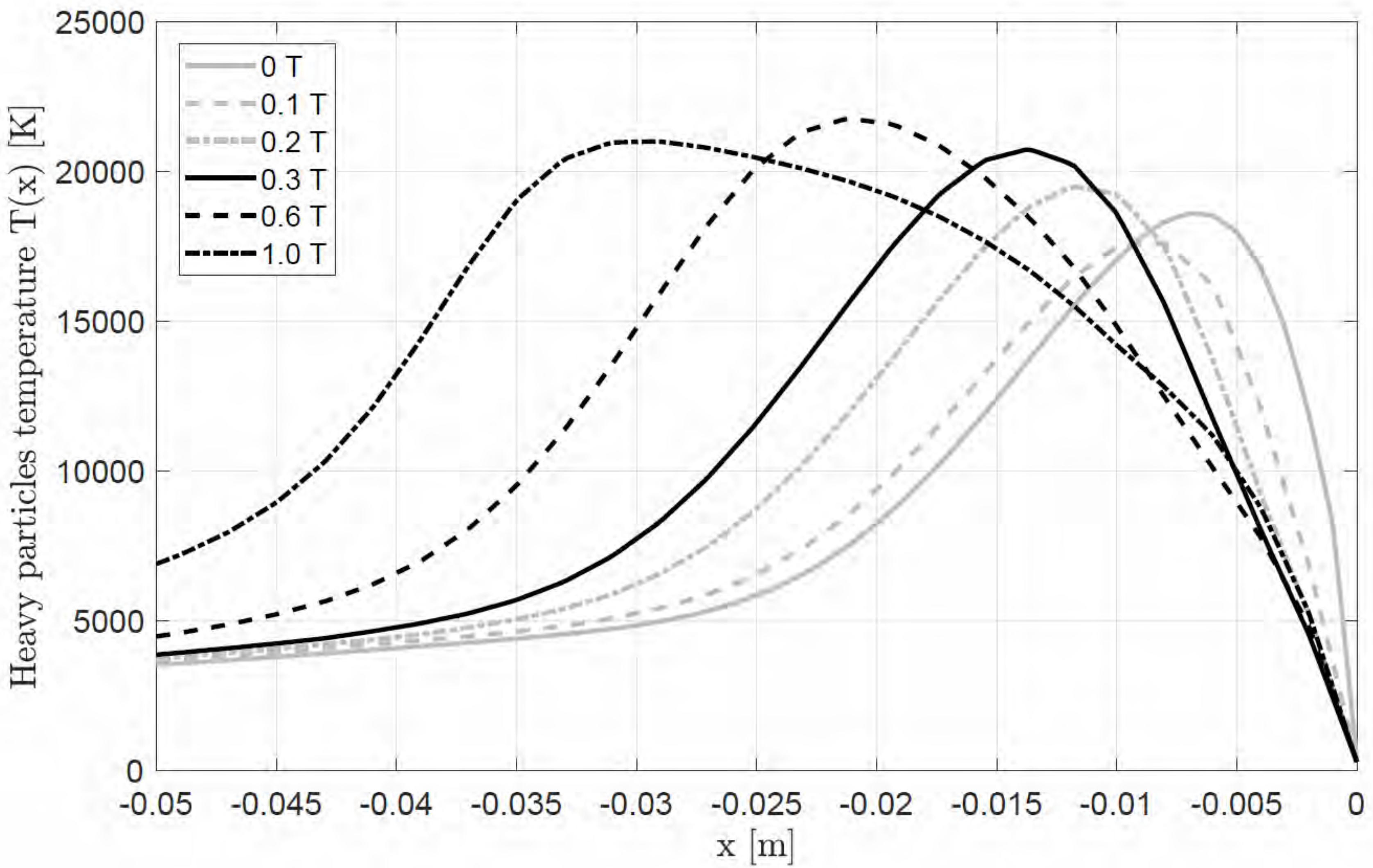




Deviation between coil field and permanent magnetc field

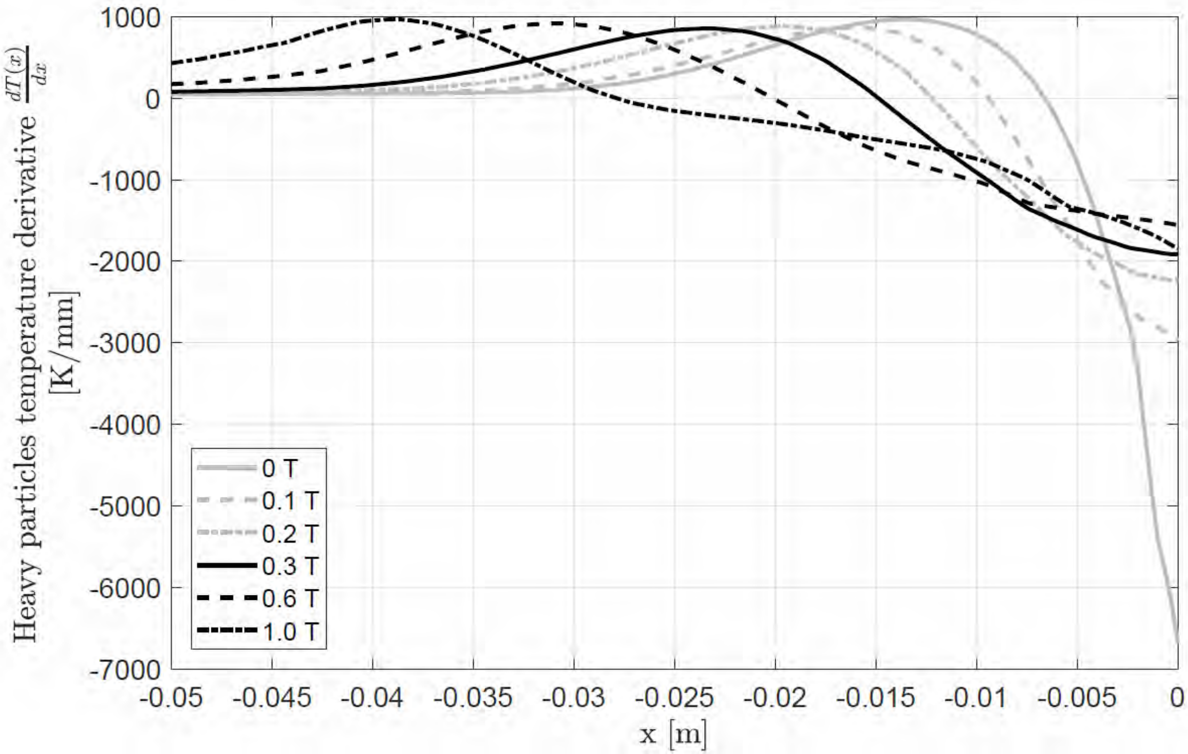
- SAMSA only simulates solenoids
- FEMM is used to design preliminary magnetic setup: geometry, coil turn and current variation to reach desired coil-setup

RD5 simulation – Heavy particle temperature



Heavy particle temperature at stagnation point 5cm in front of the tip

RD5 simulation – Heavy particle gradient



Magnetic field strength [T]	Small cylindrical temperature gradient $[K/mm]$		Small conical temperature gradient $[K/mm]$	
0	2370		2370	
0.1	1858	[−21.6 %]	1973	[−16.8 %]
0.2	1579	[−33.4 %]	1447	[−39.0 %]
0.3	1404	[−40.8 %]	1286	[−45.7 %]
0.6	1164	[−50.9 %]	916	[−61.4 %]
1.0	810	[−65.8 %]	661	[−72.1 %]

- Significant reduction
- Needed for heat flux calculation