Numerical Analysis of a QPR Resonator

TECHNISCHE UNIVERSITÄT DARMSTADT

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DESY-TEMF-CANDLE
Summer Meeting on Video
21st September 2021

Overview

- Motivation
- Quadrupole Resonator
  - Simulation Model
  - Eigenmode Calculations
  - Postprocessing
- Thermal Steady State
  - Material Modeling
  - Heat Sources
  - Simulation Results
- Summary and Outlook

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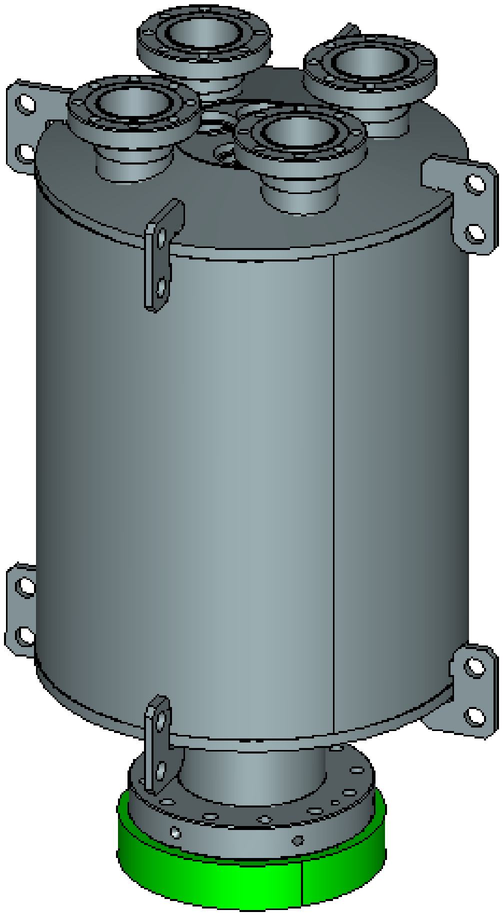
- Summary and Outlook

Motivation

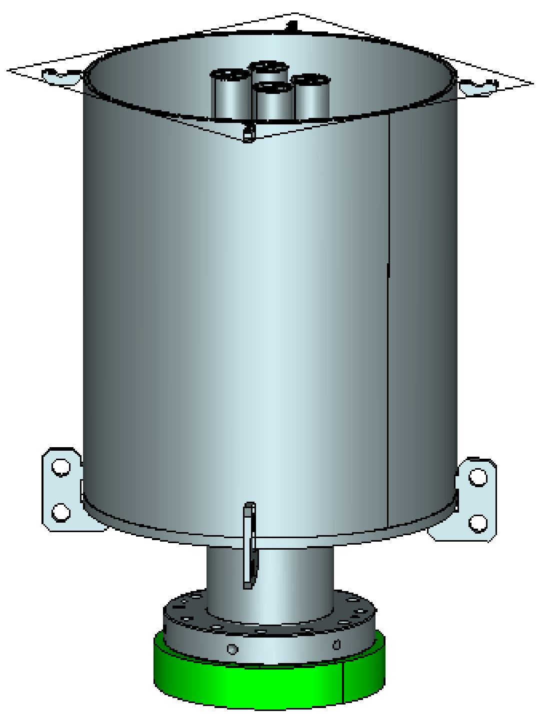
- Quadrupole Resonator
  - Radio frequency characterization of superconductor materials used for particle accelerators
  - Geometry models kindly provided by DESY and HZB
  - Eigenmode calculation based on the FEM using curved tetrahedral elements and a robust JD eigenvalue solver



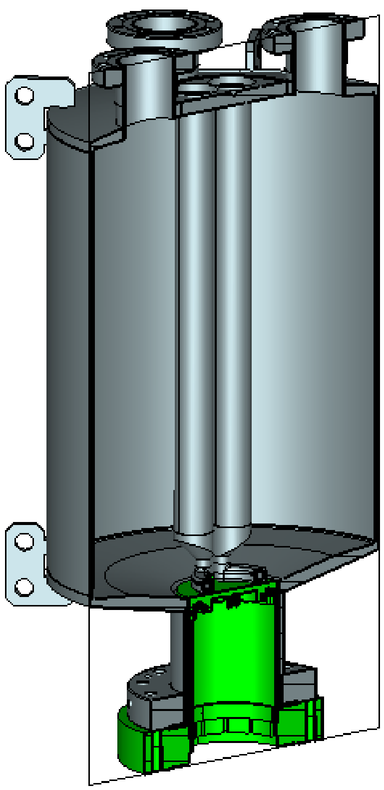
→ Determination of the surface resistance for niobium at various temperatures and fields

Motivation

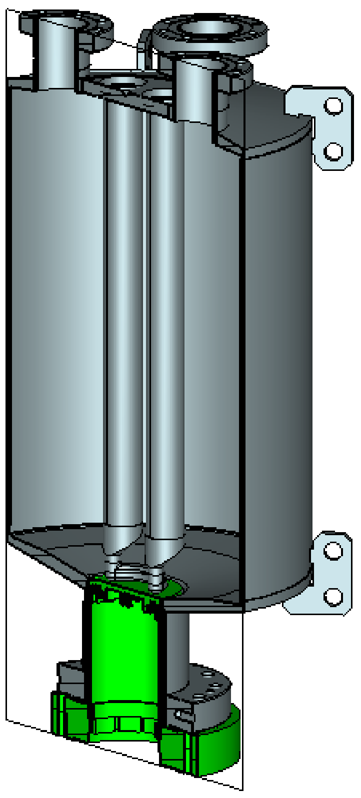
- Geometry Information
  - Cut views



xy plane



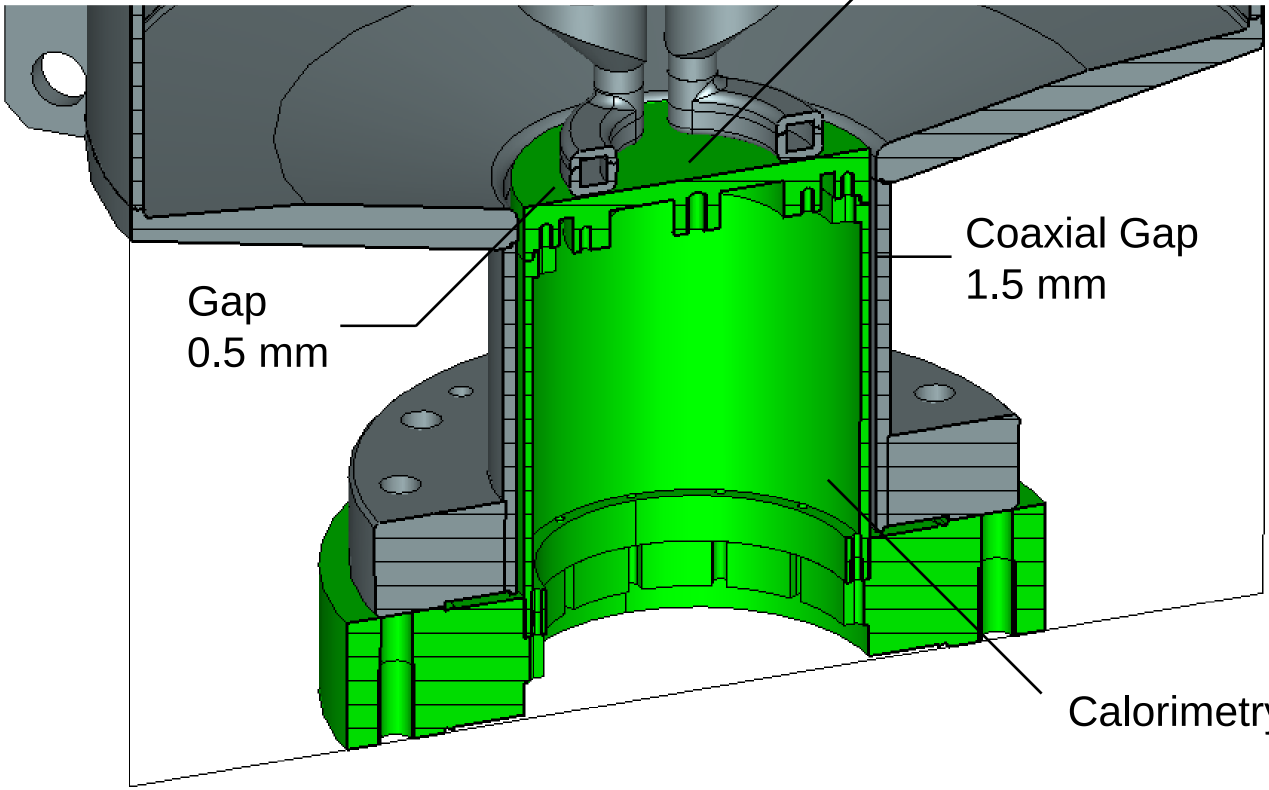
xz plane



yz plane

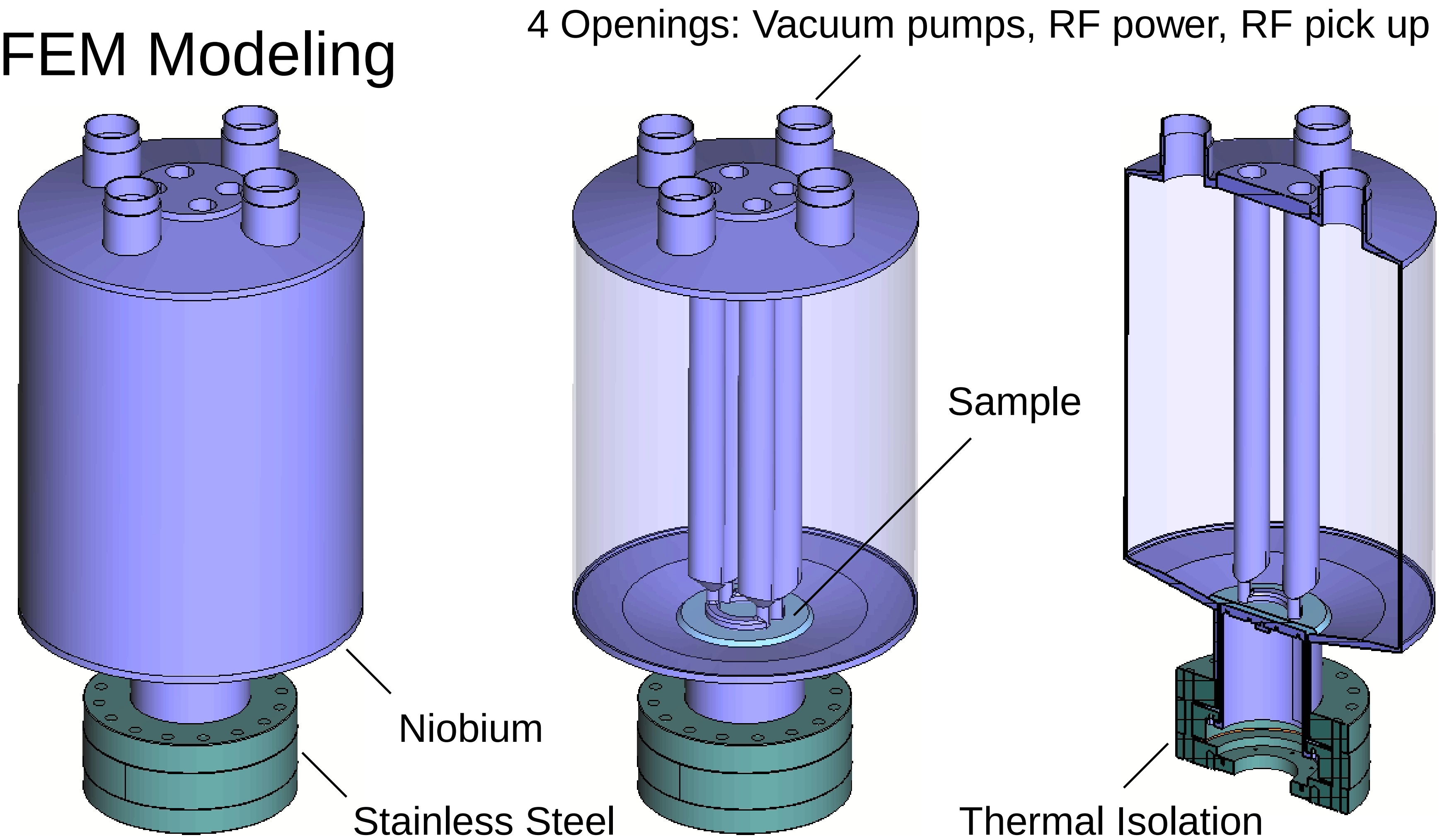
Motivation

- Geometry Information
  - Interchangeable sample fixture



Motivation

- FEM Modeling



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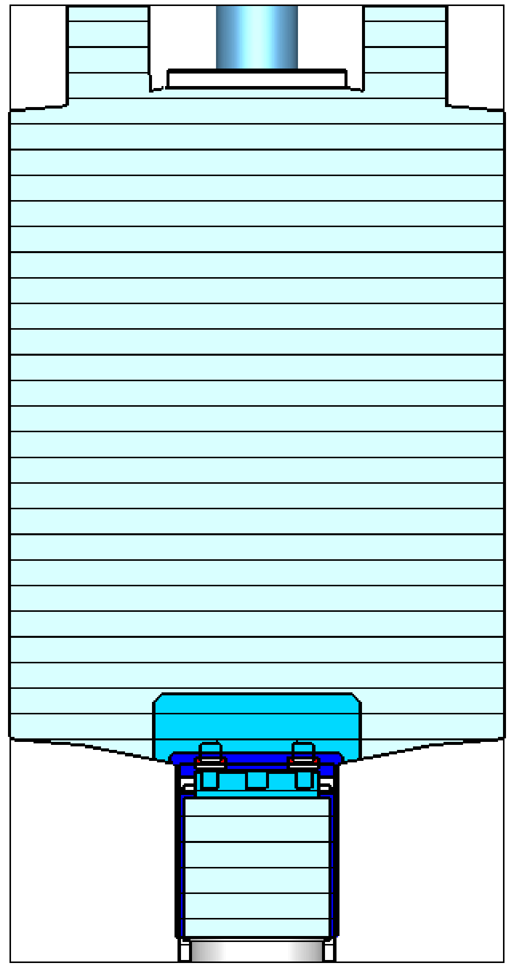
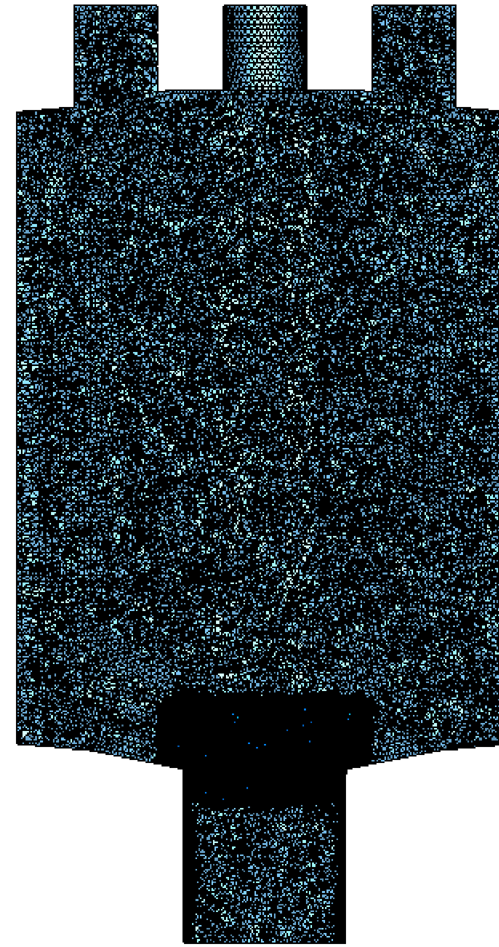
Quadrupole Resonator

- Simulation Model
  - Numerical approach
    - Eigenmode calculation
    - Second order finite element method (FEM) on curved tetrahedral elements
    - Parallel Jacobi-Davidson eigenvalue solver
    - Grid refinement using four levels (artificially change of material properties)
  - Field evaluation on the surface of the probe
    - Enforce local fine grid resolution in high field regions





$N_{\text{tet}} = 17.737.075$

Quadrupole Resonator

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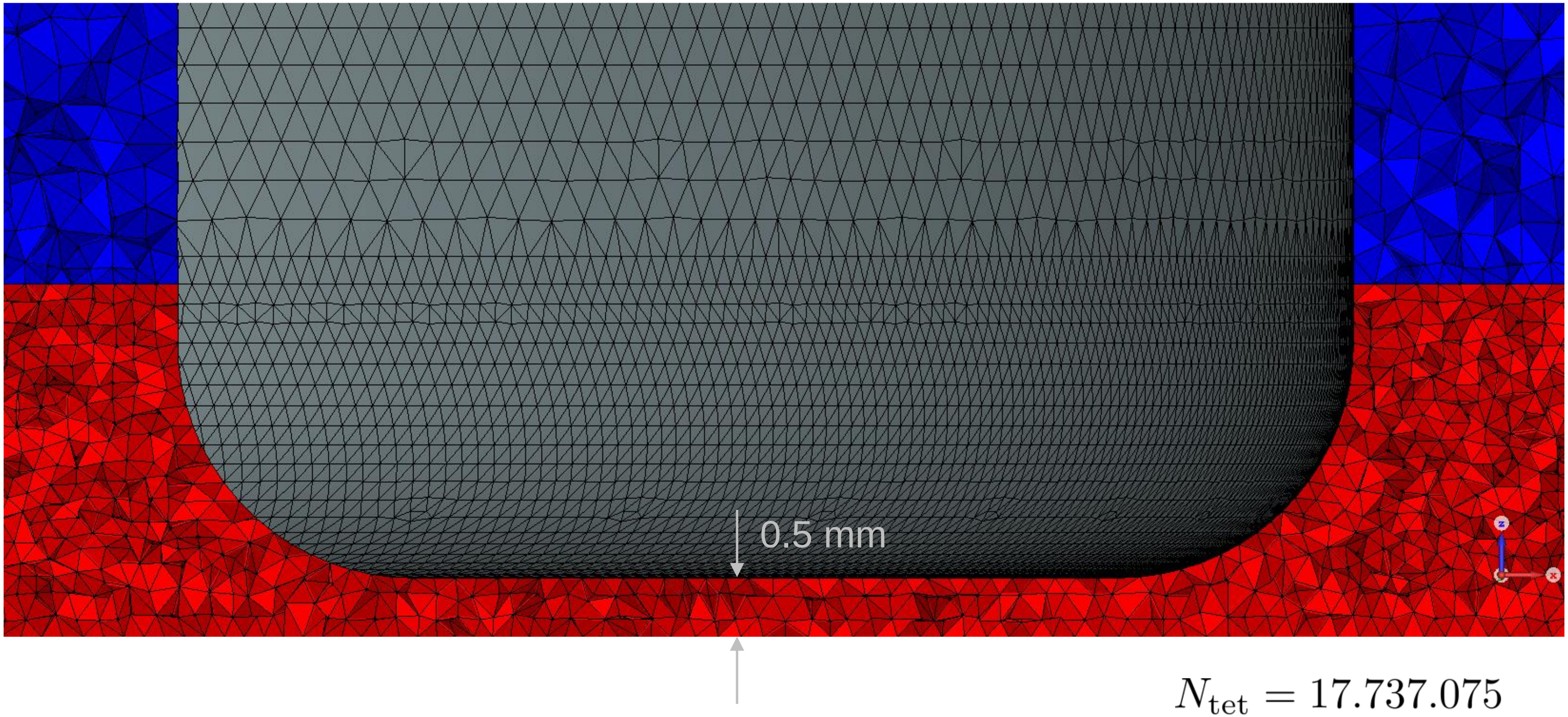
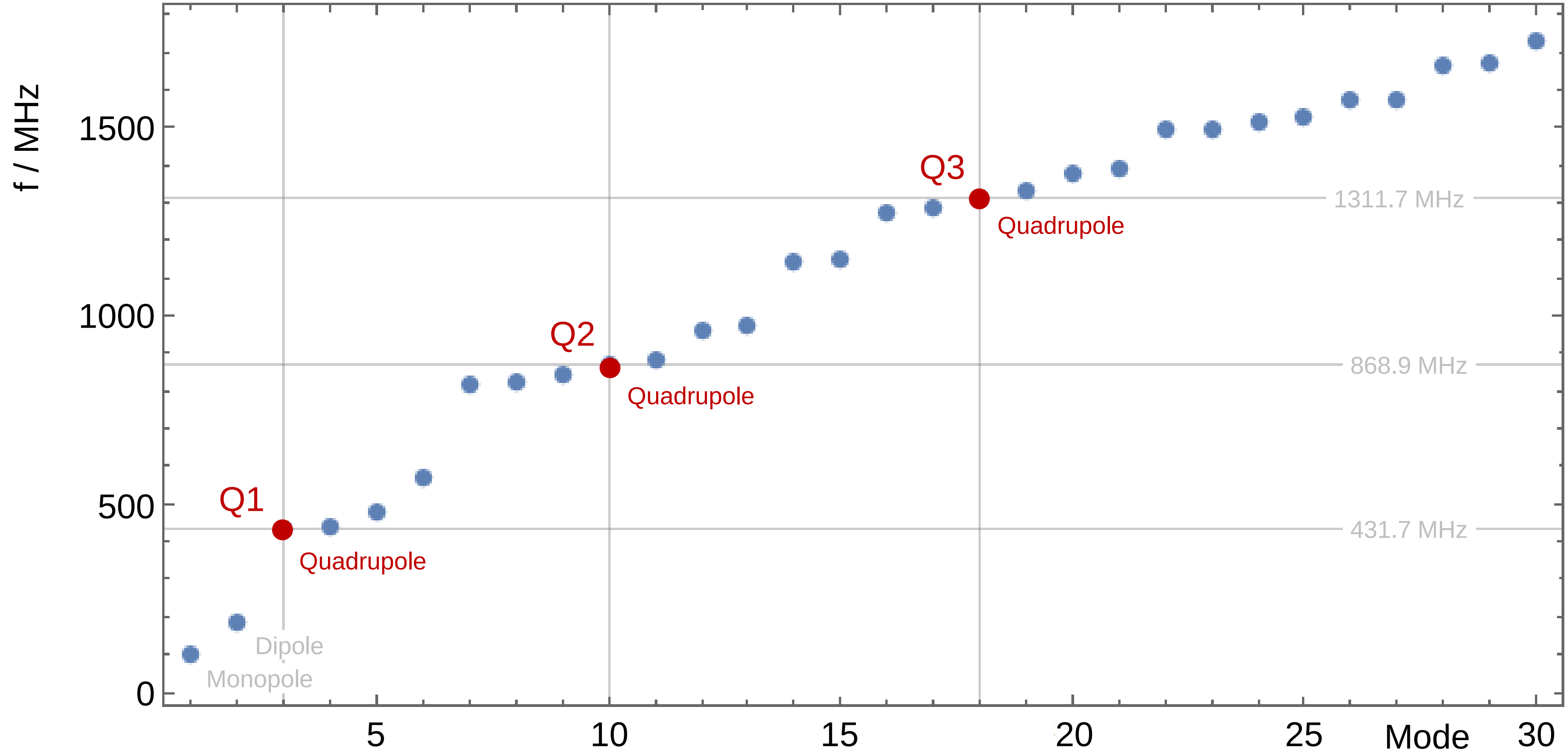
- Simulation Model
  - Tetrahedral element distribution around the horseshoe region



$N_{\text{tet}} = 17.737.075$

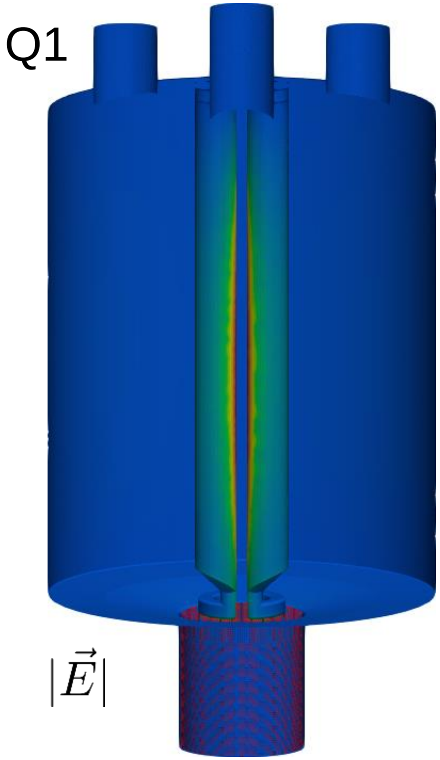
Quadrupole Resonator

- Eigenmode Calculations
  - Selection of eigenmodes

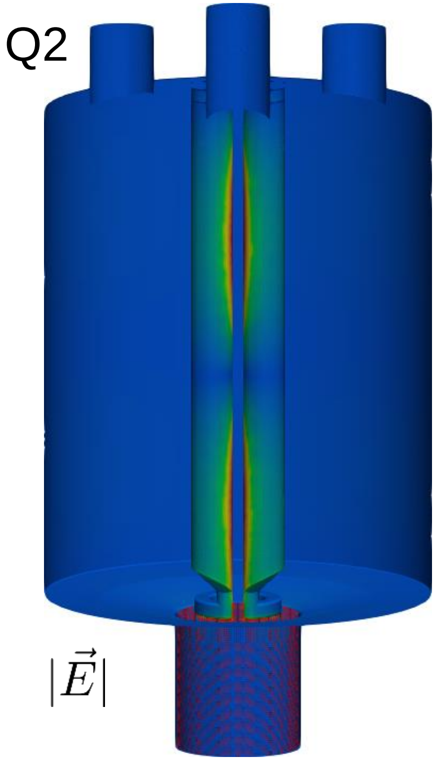


Quadrupole Resonator

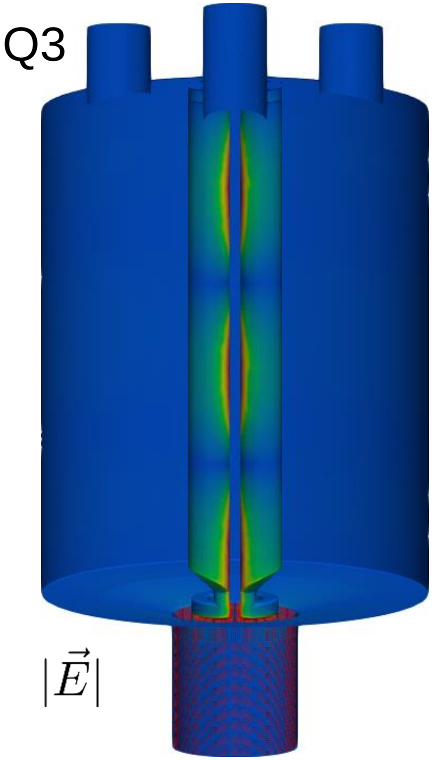
- Eigenmode Calculations
  - Selection of eigenmodes



$f_{\mathrm{res}} = 431.7\ \mathrm{MHz}$



$f_{\mathrm{res}} = 868.9\ \mathrm{MHz}$

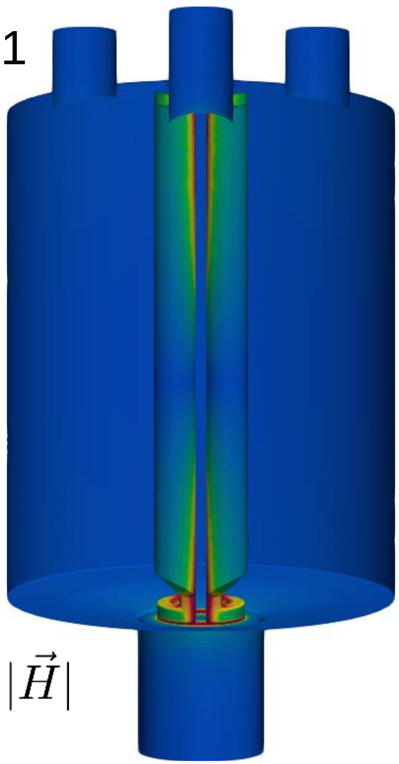


$f_{\mathrm{res}} = 1311.7\ \mathrm{MHz}$

Quadrupole Resonator

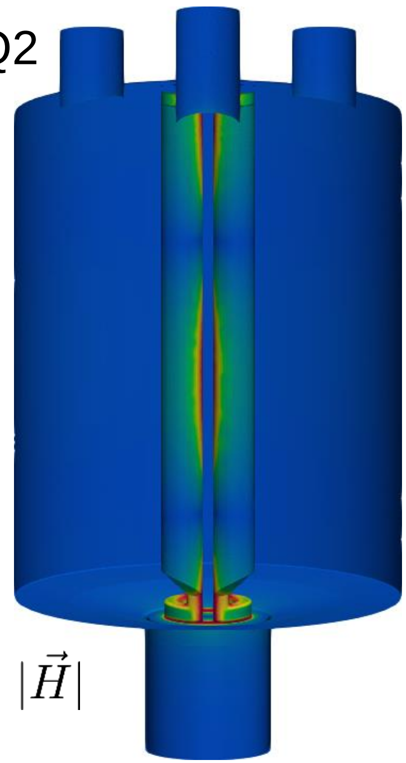
- Eigenmode Calculations
  - Selection of eigenmodes

Q1



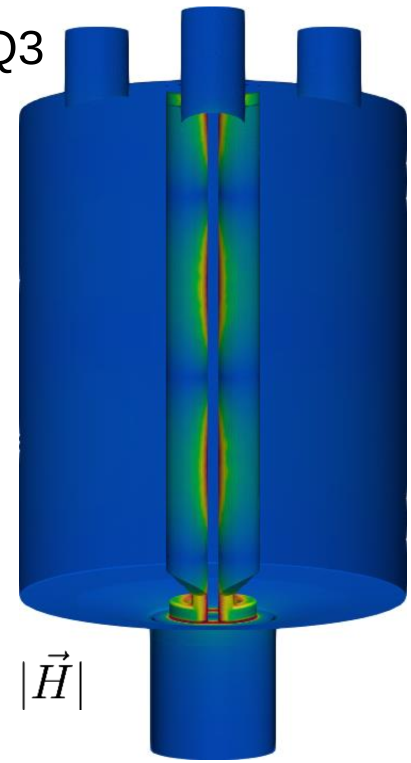
$f_{\mathrm{res}} = 431.7\ \mathrm{MHz}$

Q2



$f_{\mathrm{res}} = 868.9\ \mathrm{MHz}$

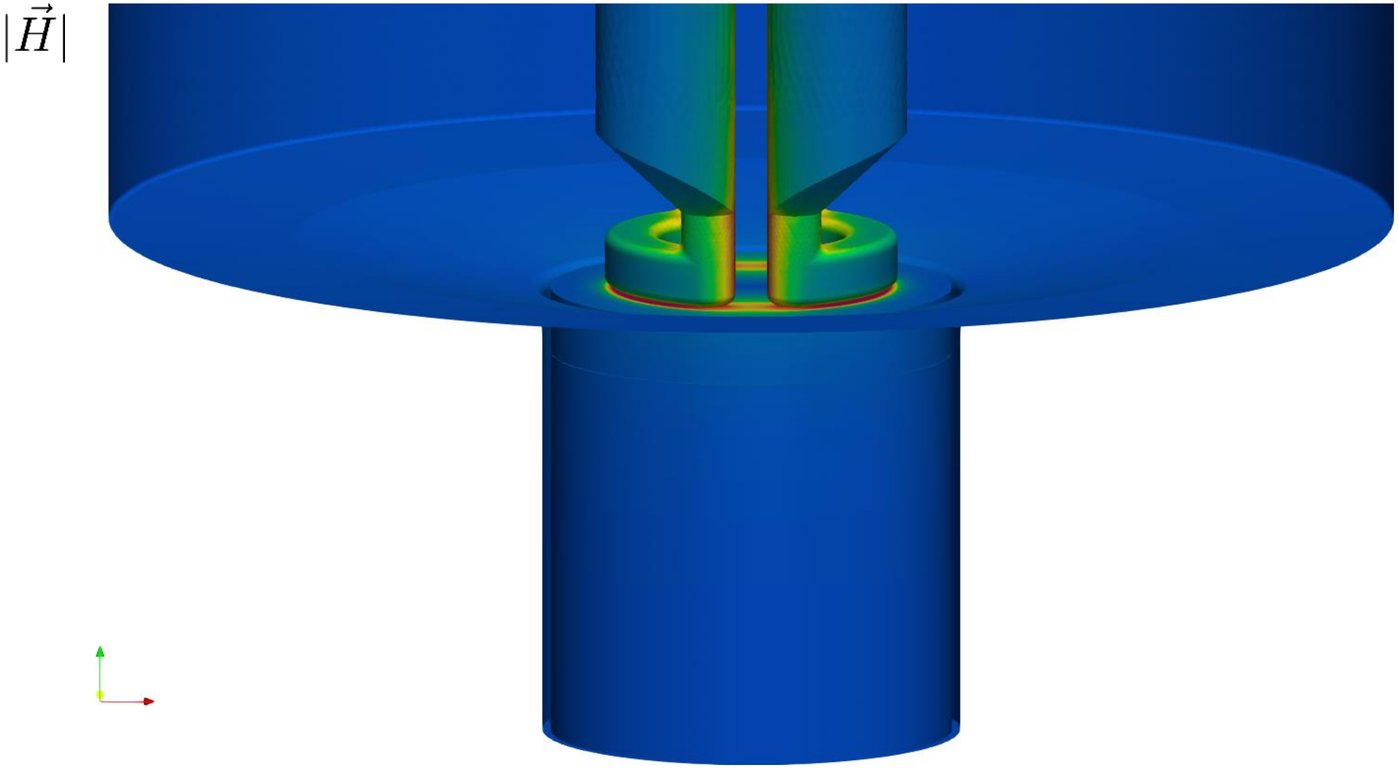
Q3



$f_{\mathrm{res}} = 1311.7\ \mathrm{MHz}$

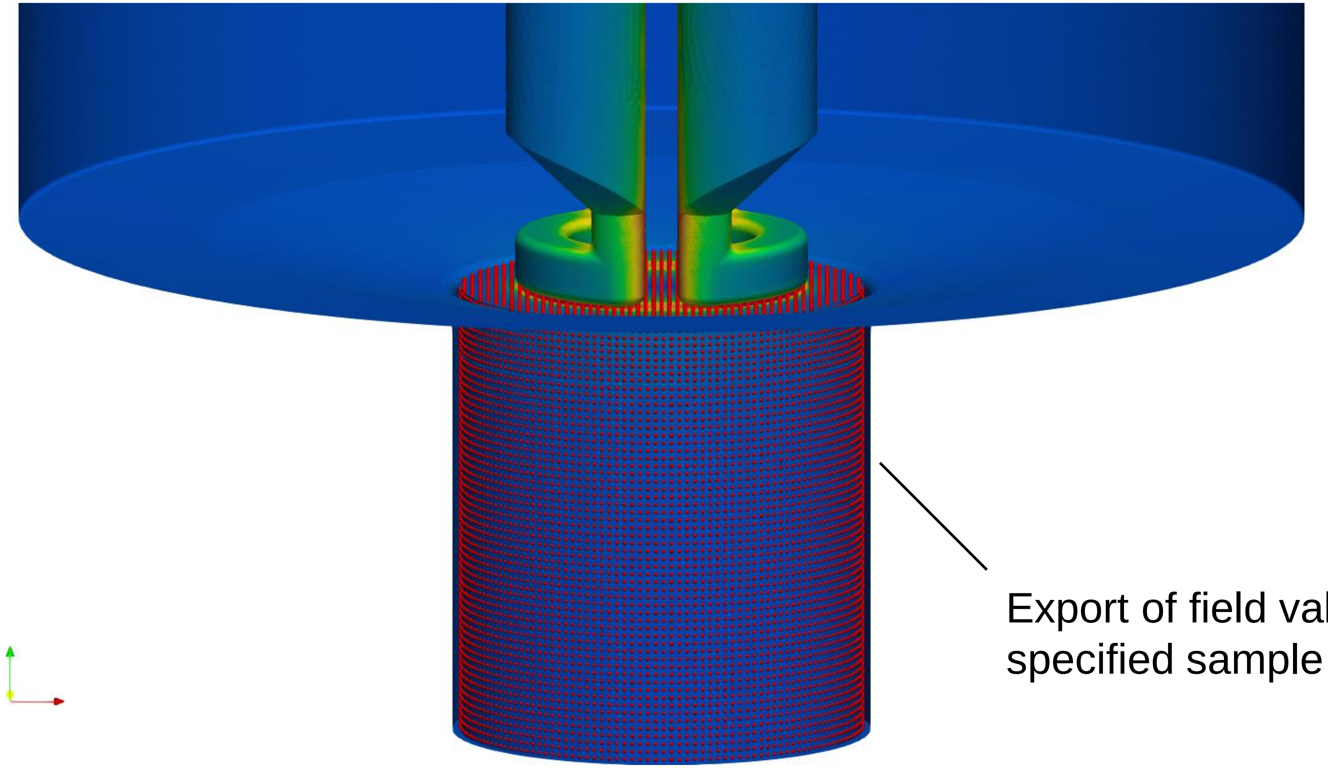
Quadrupole Resonator

- Eigenmode Calculations
  - Distribution of the magnetic field strength



Quadrupole Resonator

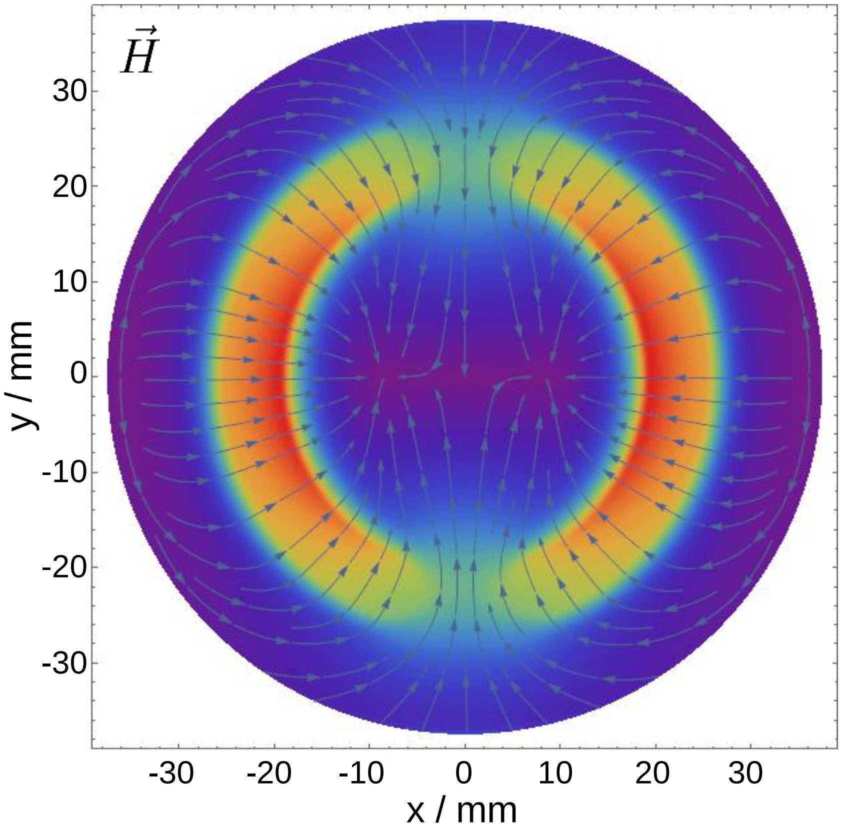
- Eigenmode Calculations
  - Distribution of the magnetic field strength

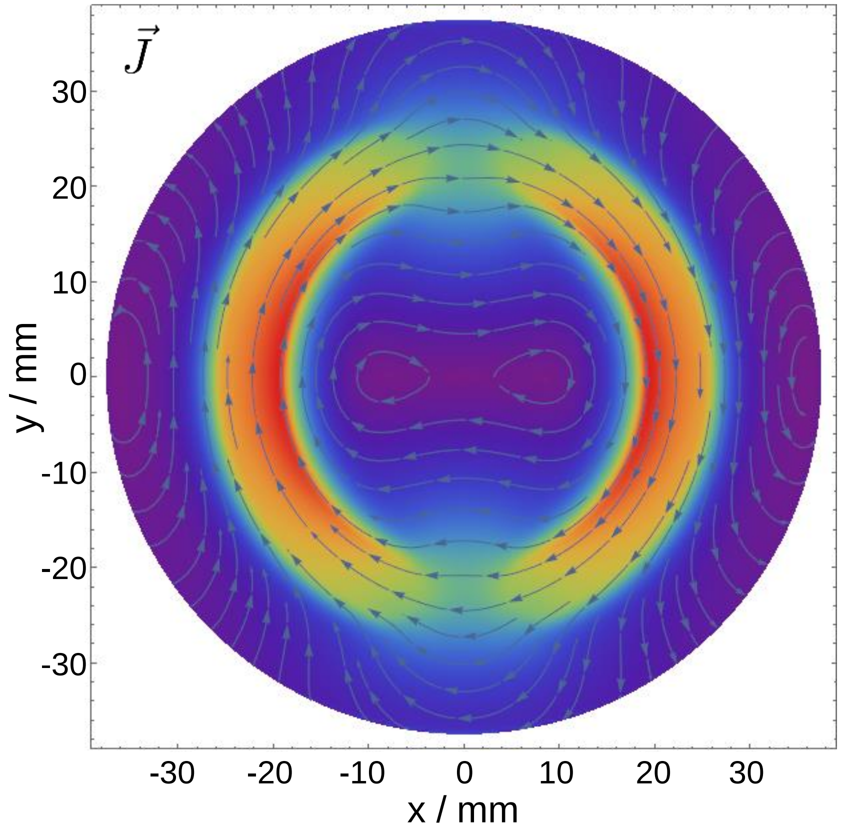


Export of field values at specified sample points

Quadrupole Resonator

- Postprocessing
  - Visualization of the field distribution on the sample surface



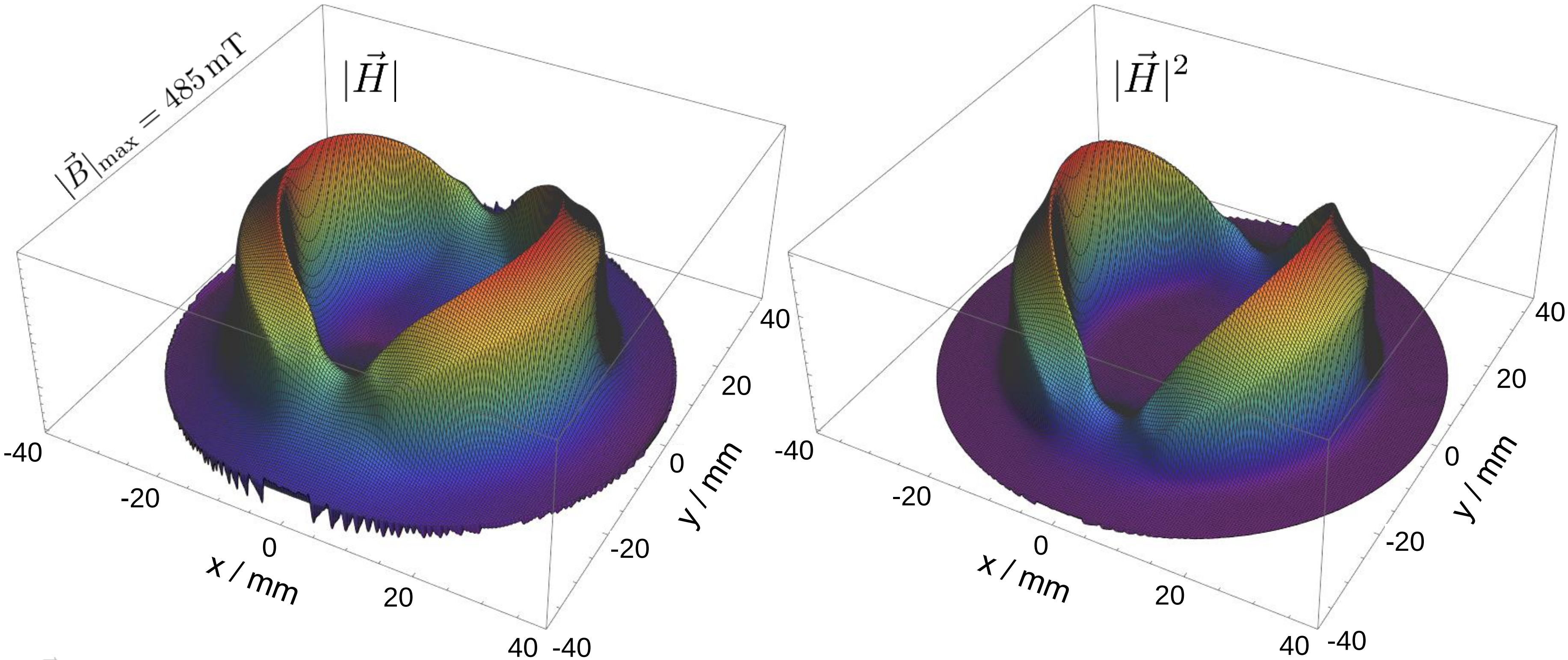


Quadrupole Resonator

- Postprocessing

$$I_\nu = \iint_{A_\nu} \vec{H} \cdot \vec{H} \, \mathrm{d}A$$

  - Visualization of the field distribution on the sample surface



$|\vec{B}|_{\mathrm{max}} = \{485, 497, 552\}\,\mathrm{mT}$

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  - Material Modeling
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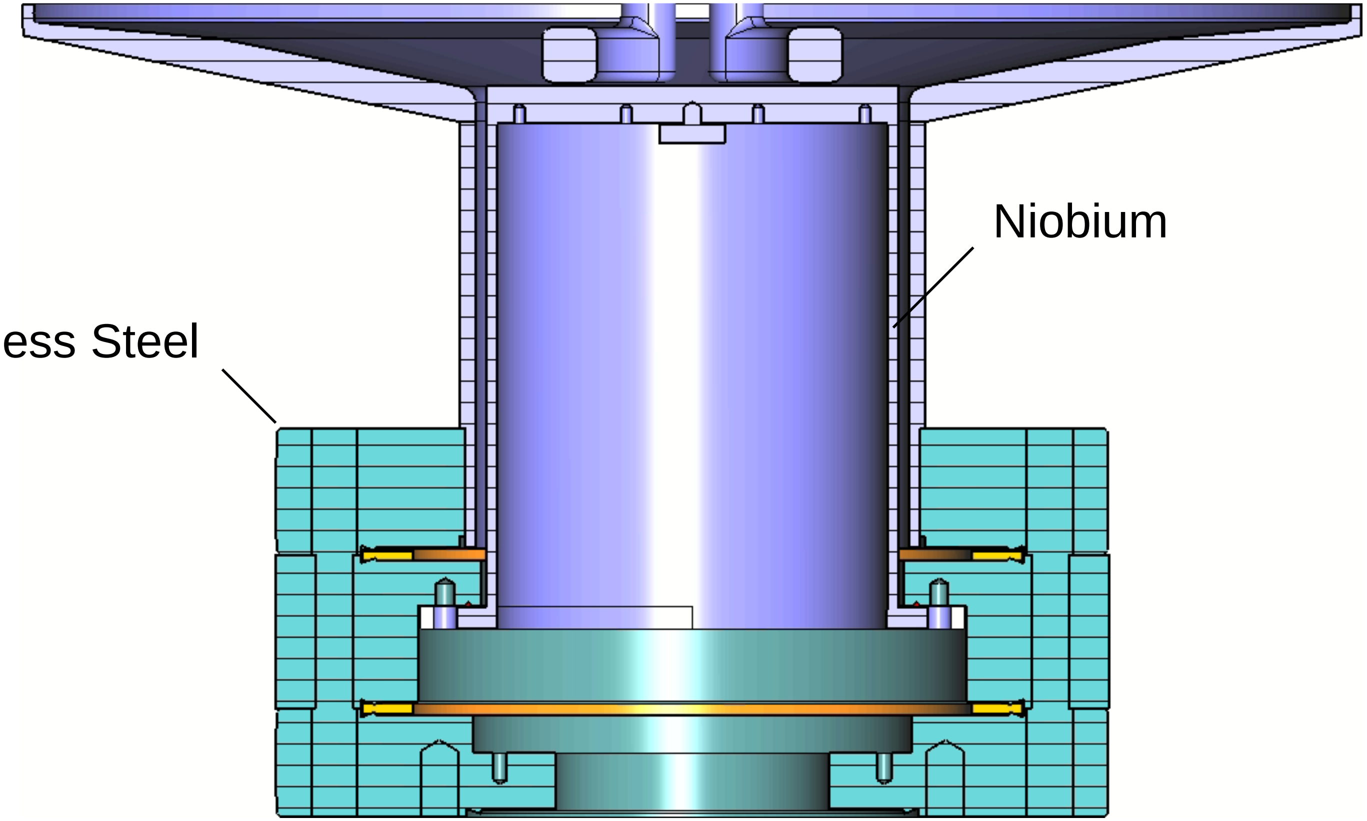
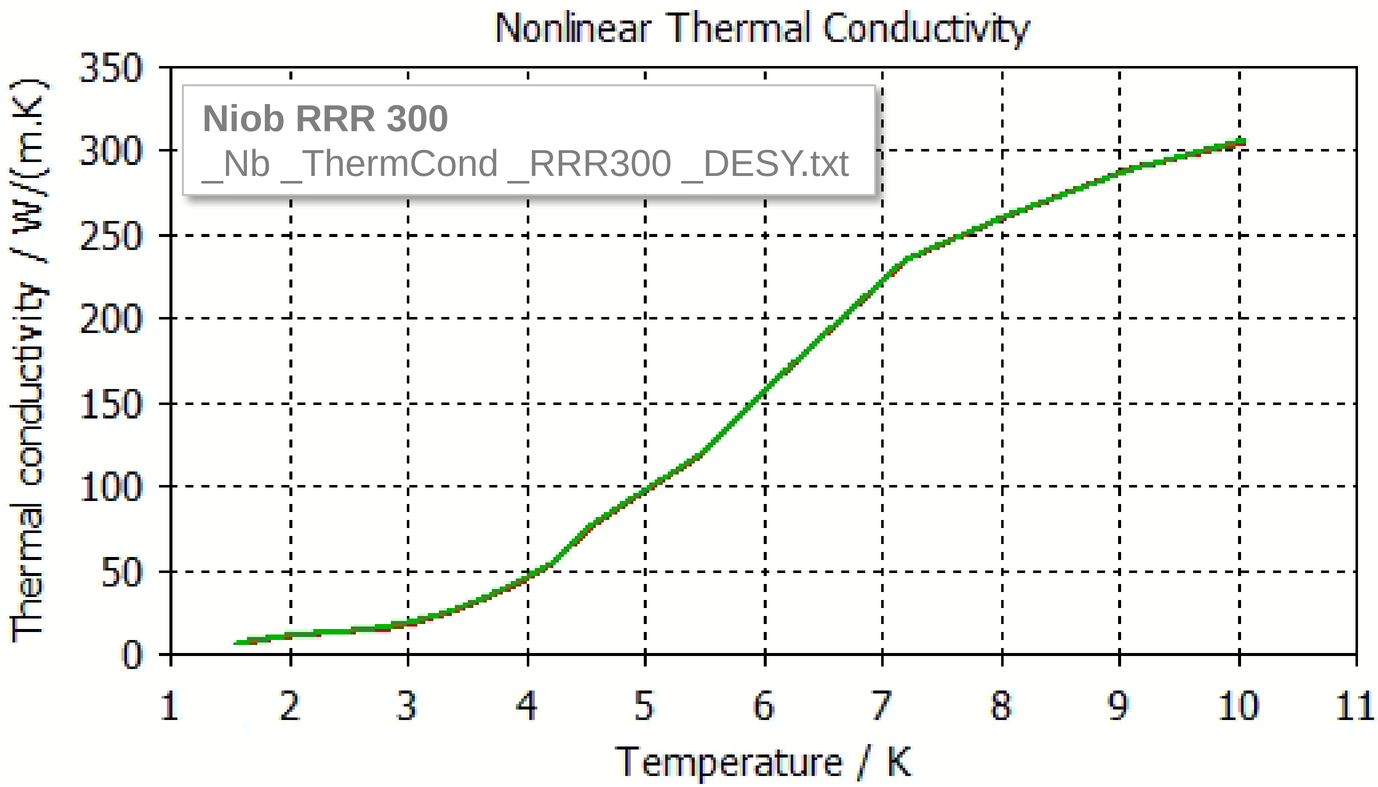
Thermal Steady State

- Material Modeling for the Thermal Solver



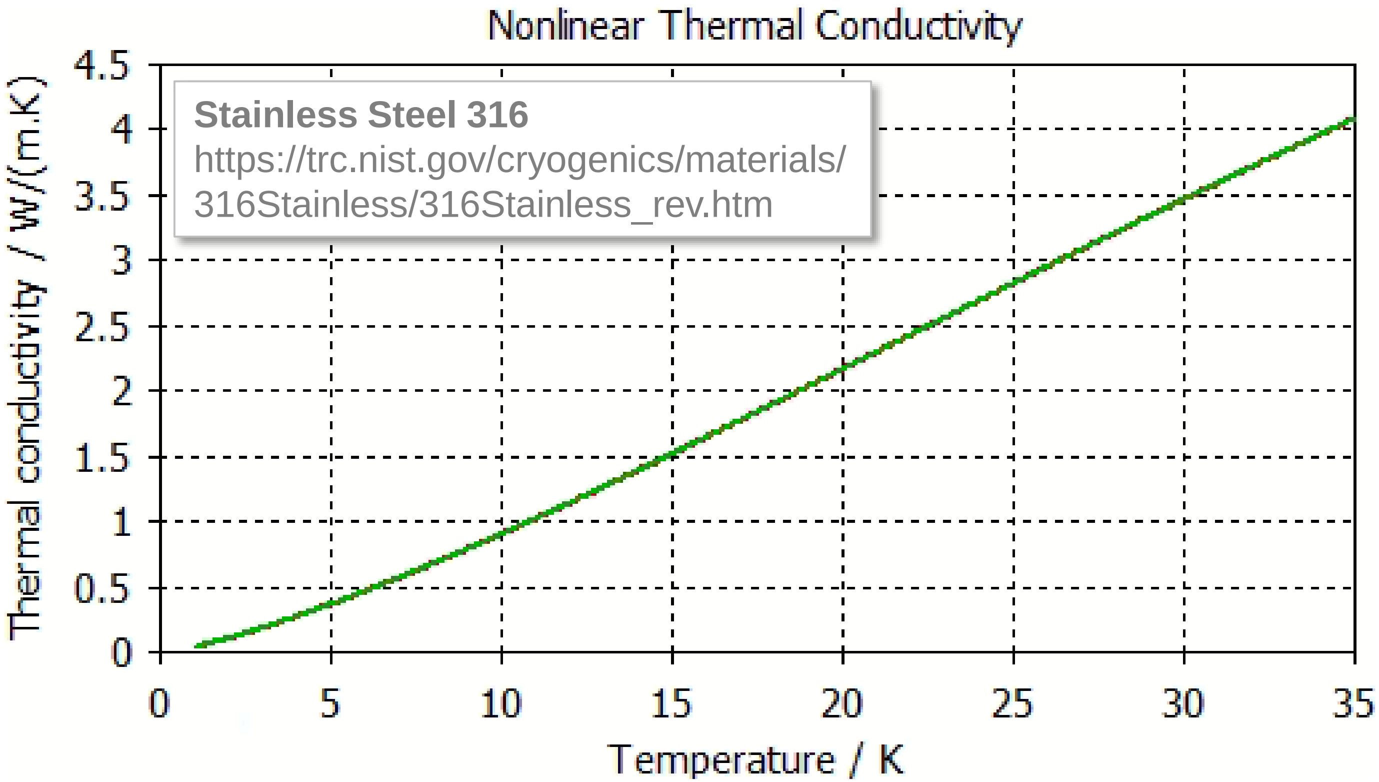
Thermal Steady State

- Thermal Conductivity at Cryogenic Temperature
  - Niobium



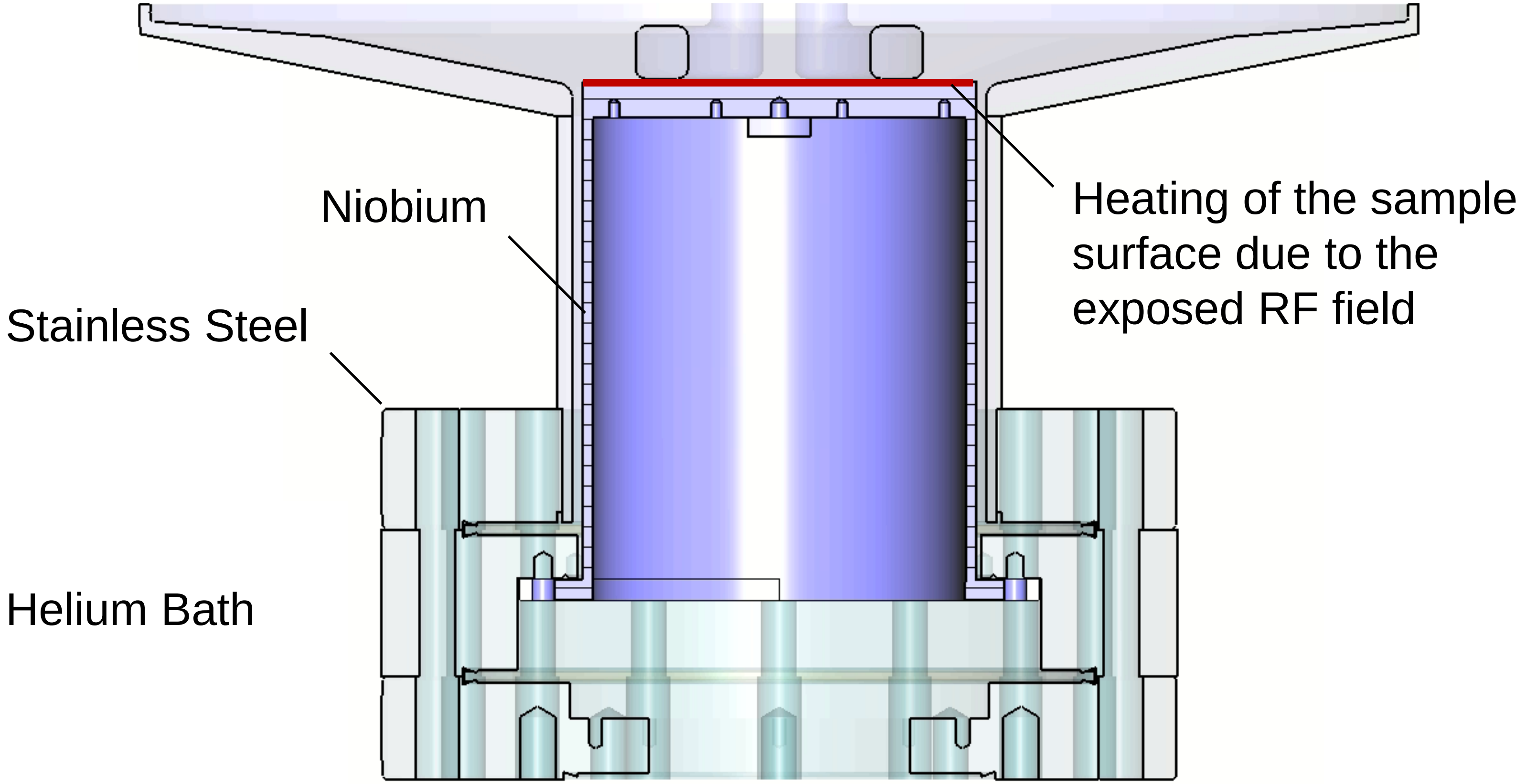
Thermal Steady State

- Thermal Conductivity at Cryogenic Temperature
  - Stainless Steel



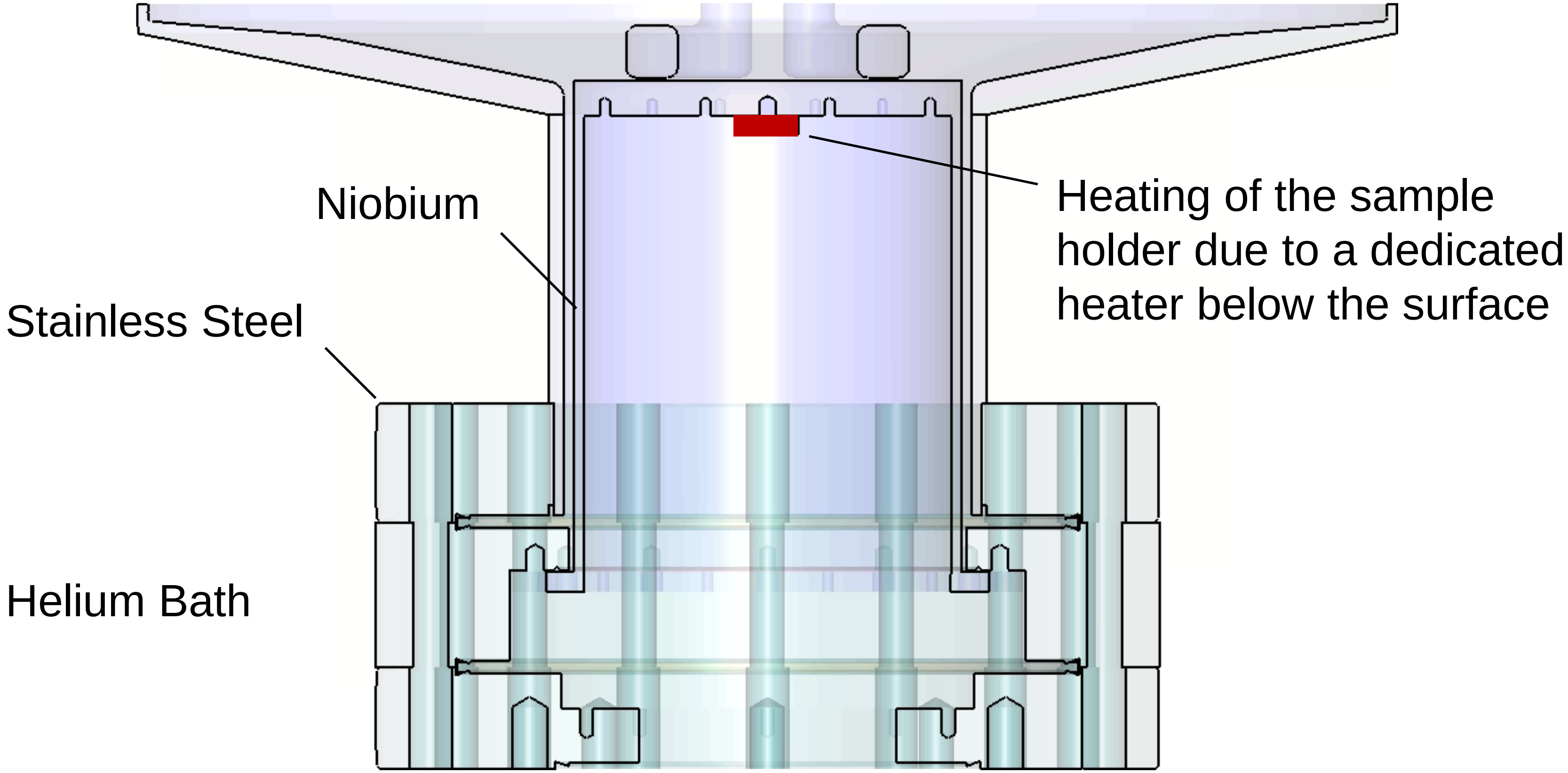
Thermal Steady State

- Heat Source used for the Thermal Solver



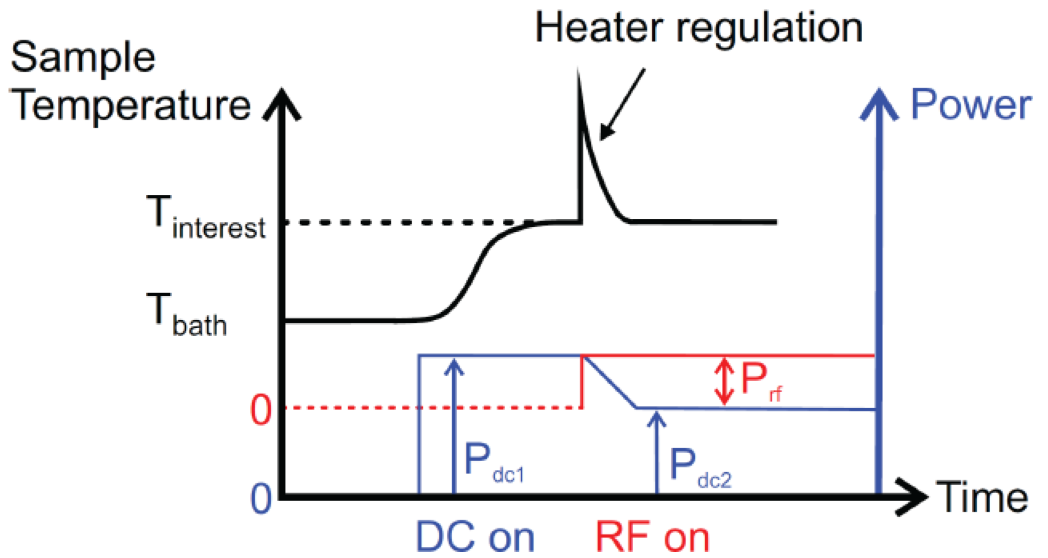
Thermal Steady State

- Heat Source used for the Thermal Solver



Thermal Steady State

- Calorimetric Measurement Principle
  - Position of the heat source is less important due to the high thermal conductivity of niobium compared to stainless steel
  - Determination of the exposed power



$$P_{\mathrm{rf}} = \frac{1}{2} R_{\mathrm{s}} \, I_{\mathrm{rf}}$$

$$I_{\mathrm{rf}} = \iint_A \vec{H} \cdot \vec{H} \, \mathrm{d}A$$

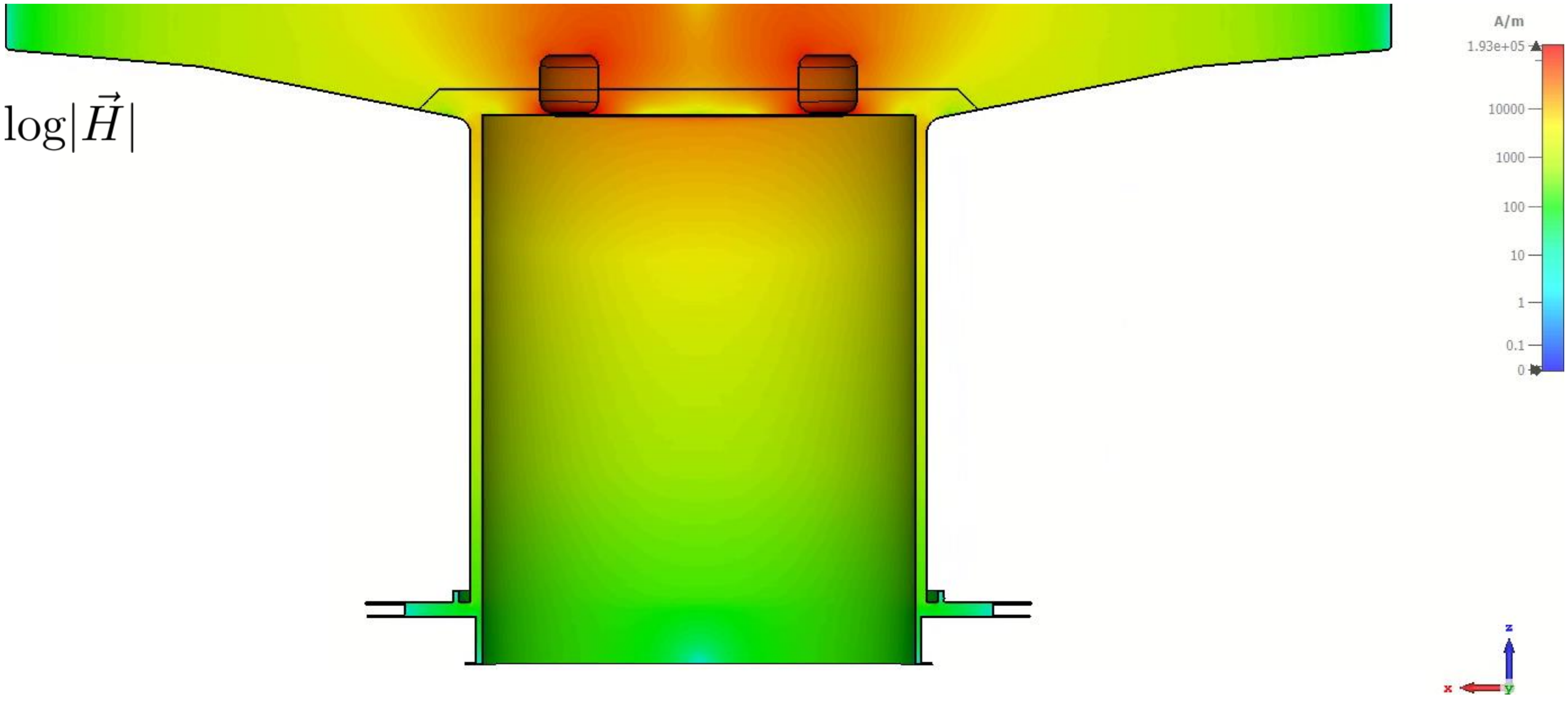
CERN-THESIS-2015-339, Sebastian Keckert, July 2015

Thermal Steady State

- Distribution of the Magnetic Field Strength

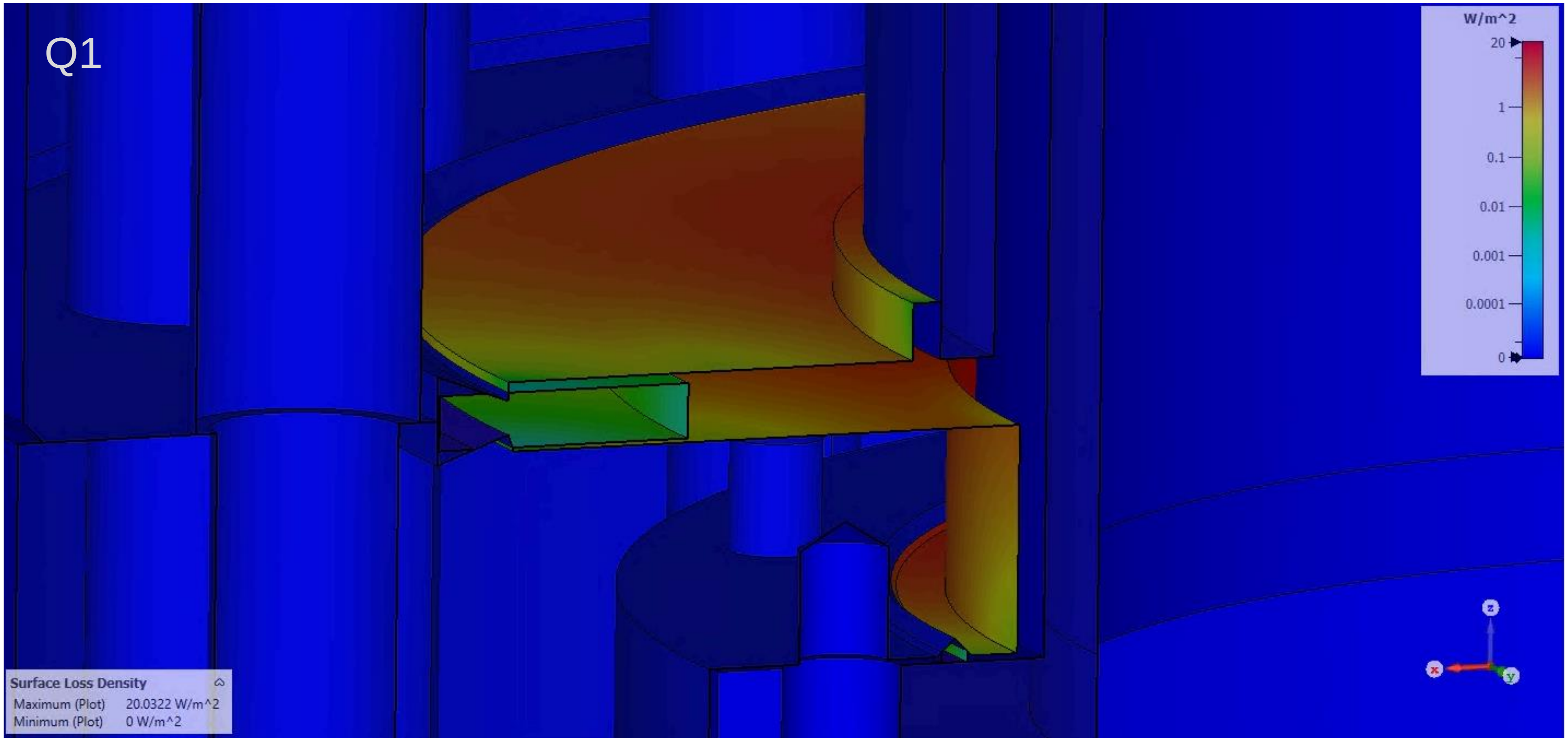
Q1

$\log|\vec{H}|$



Thermal Steady State

- Distribution of the Surface Loss Density

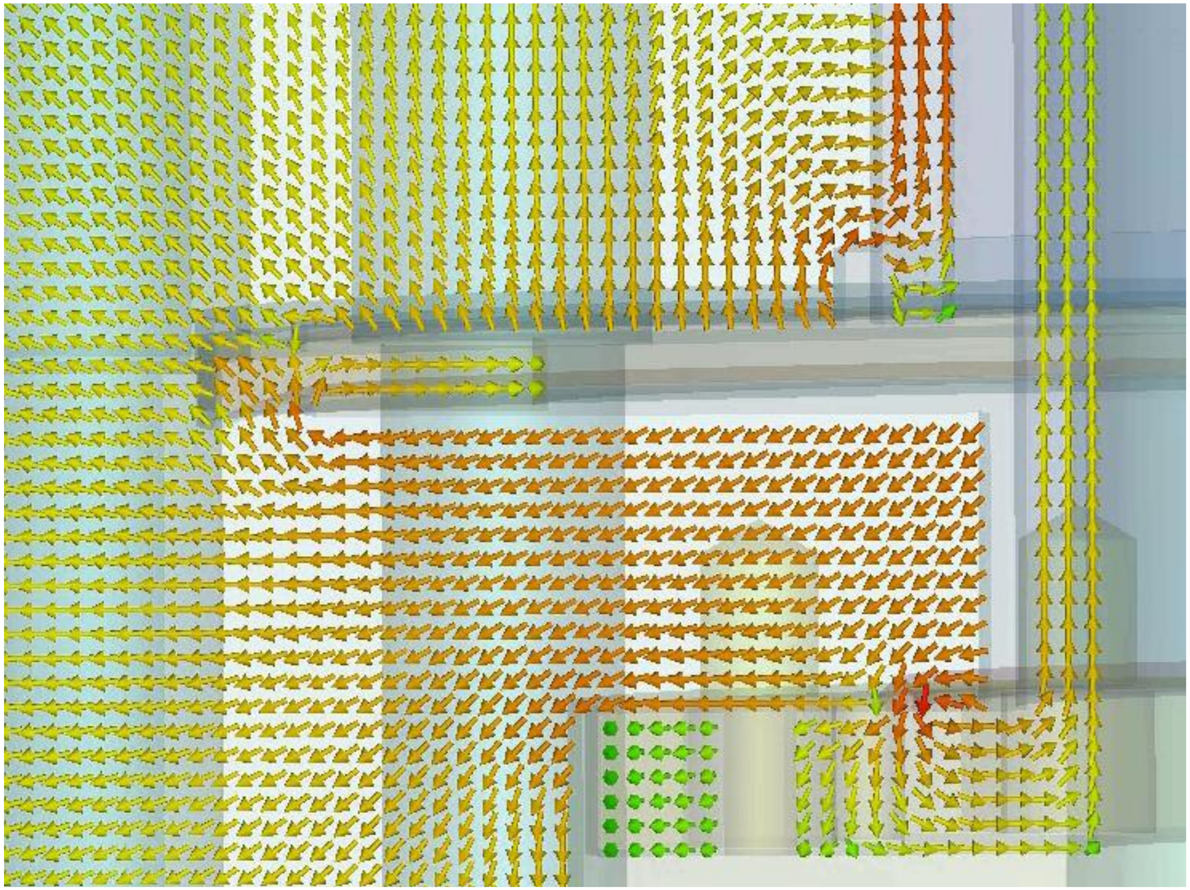


Thermal Steady State

- Distribution of the Heat Flow Density

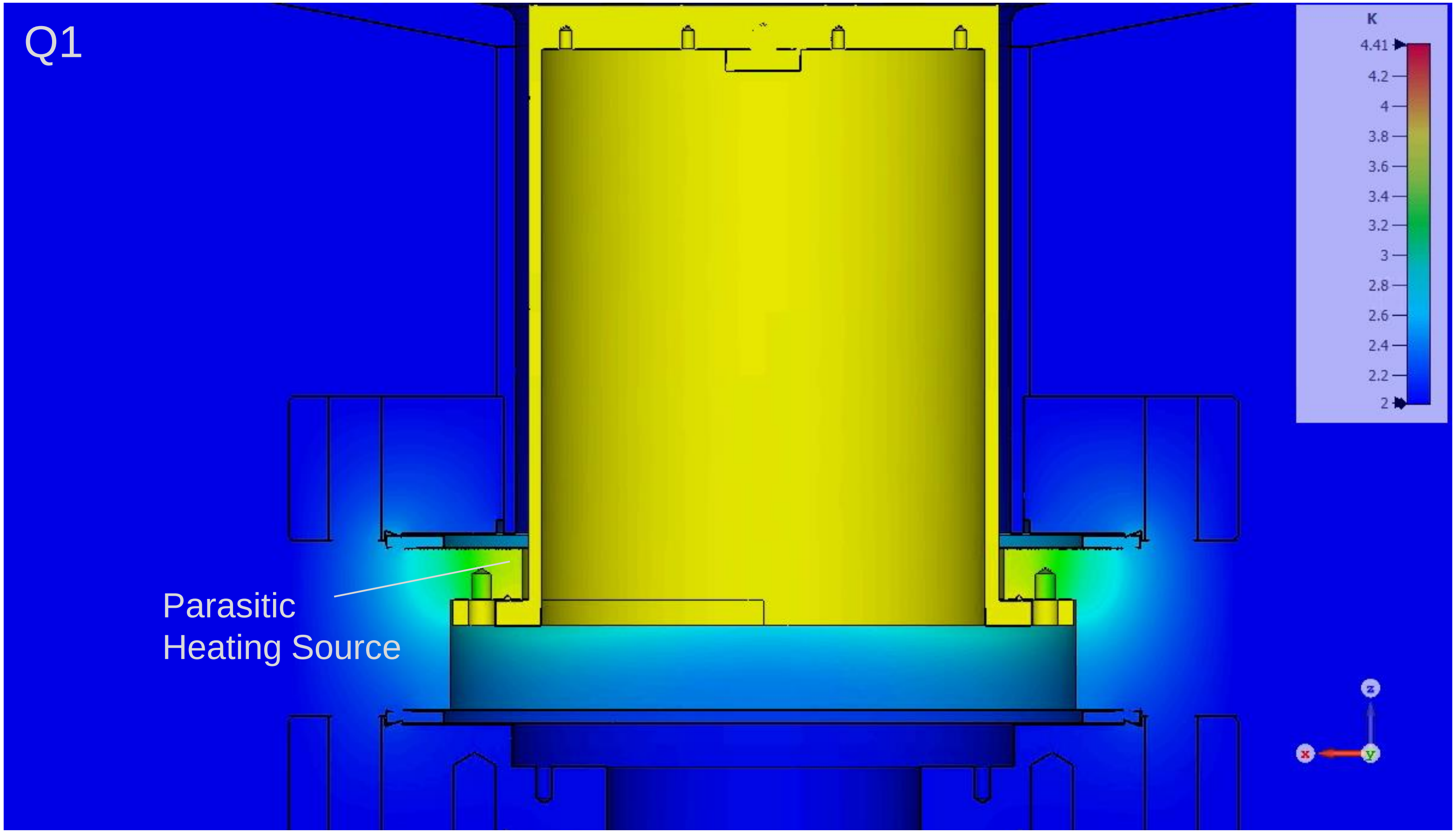
  - Heat Sources
    - StSt Flange Cavity
    - StSt Flange Probe
    - Copper Seal
    - Indium Seal
  - Heat Sink
    - Helium Bath

Q1



Thermal Steady State

- Distribution of the Steady State Temperature



Thermal Steady State

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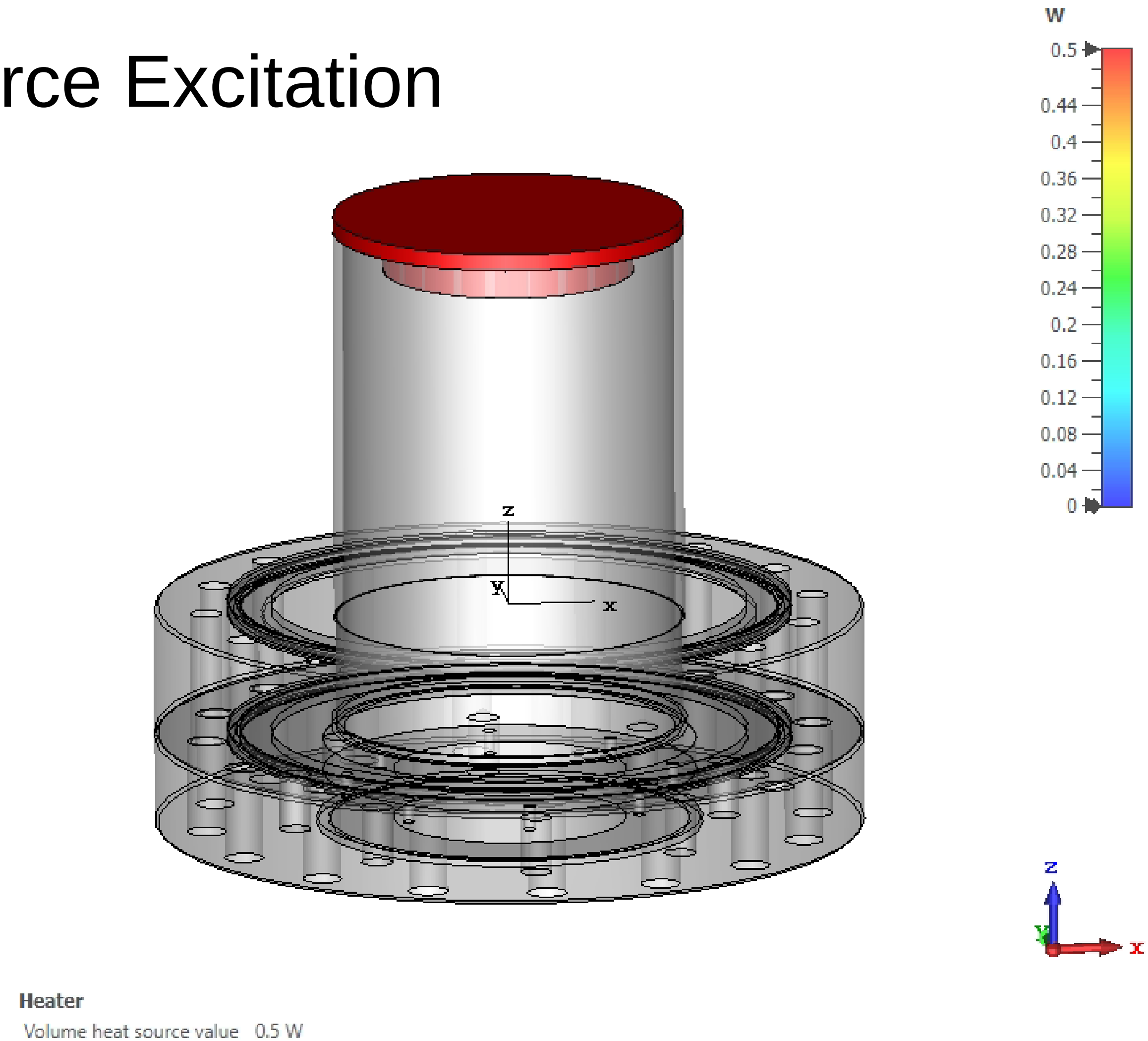
- Volume Heat Source Excitation

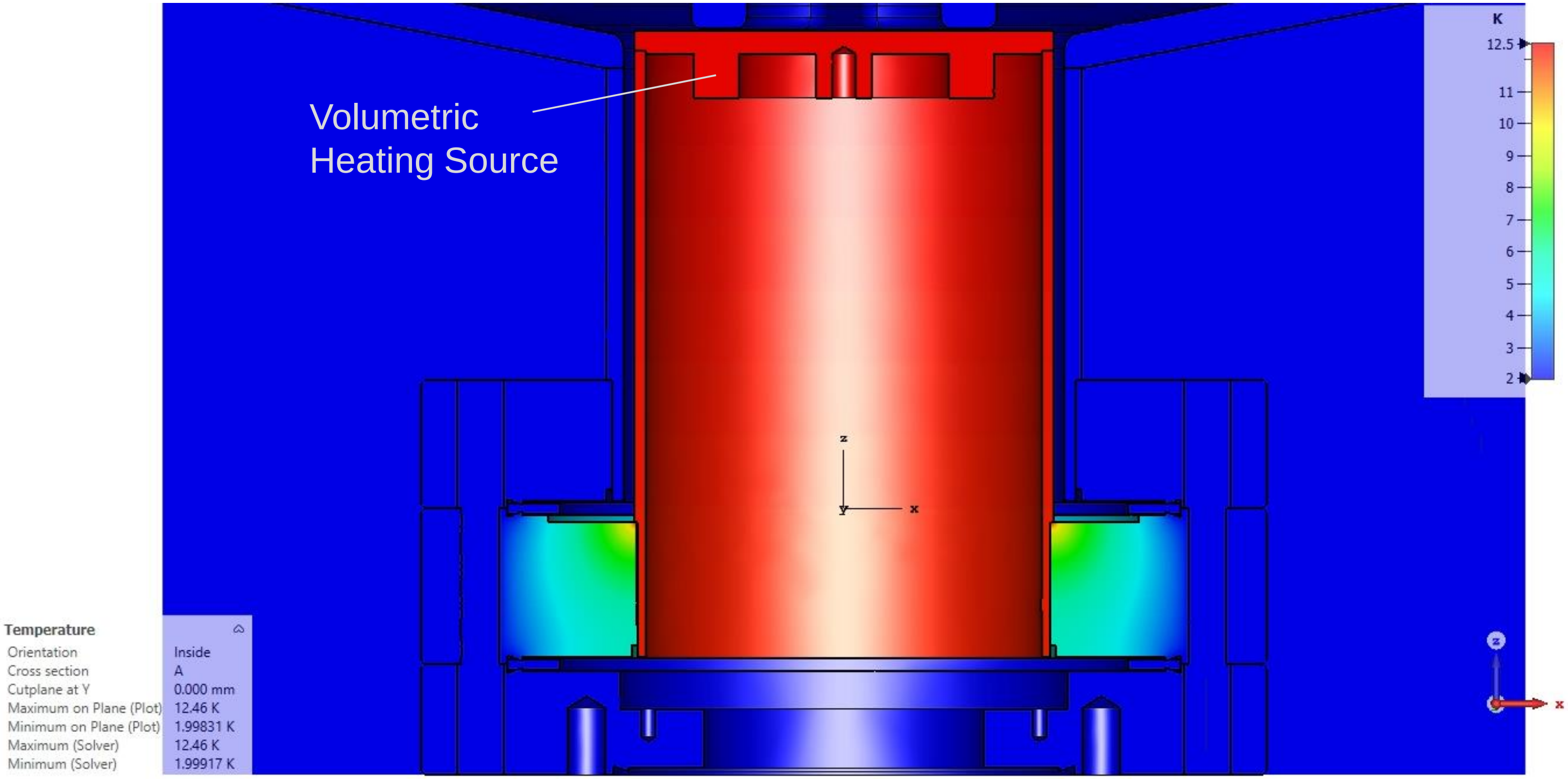
Variation of power excitation

Enables comparison of steady state temperatute



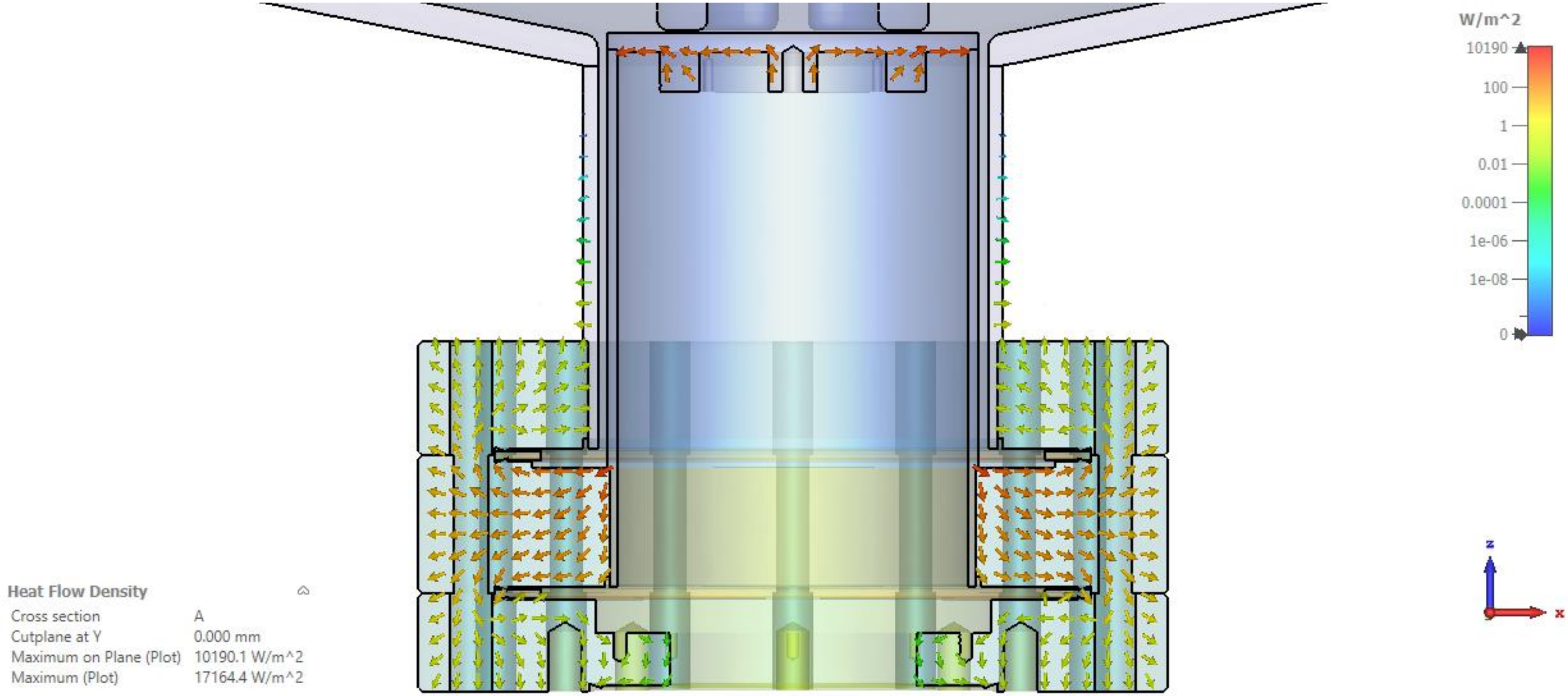
Thermal Steady State

- Volume Heat Source Excitation
  - Temperature Distribution



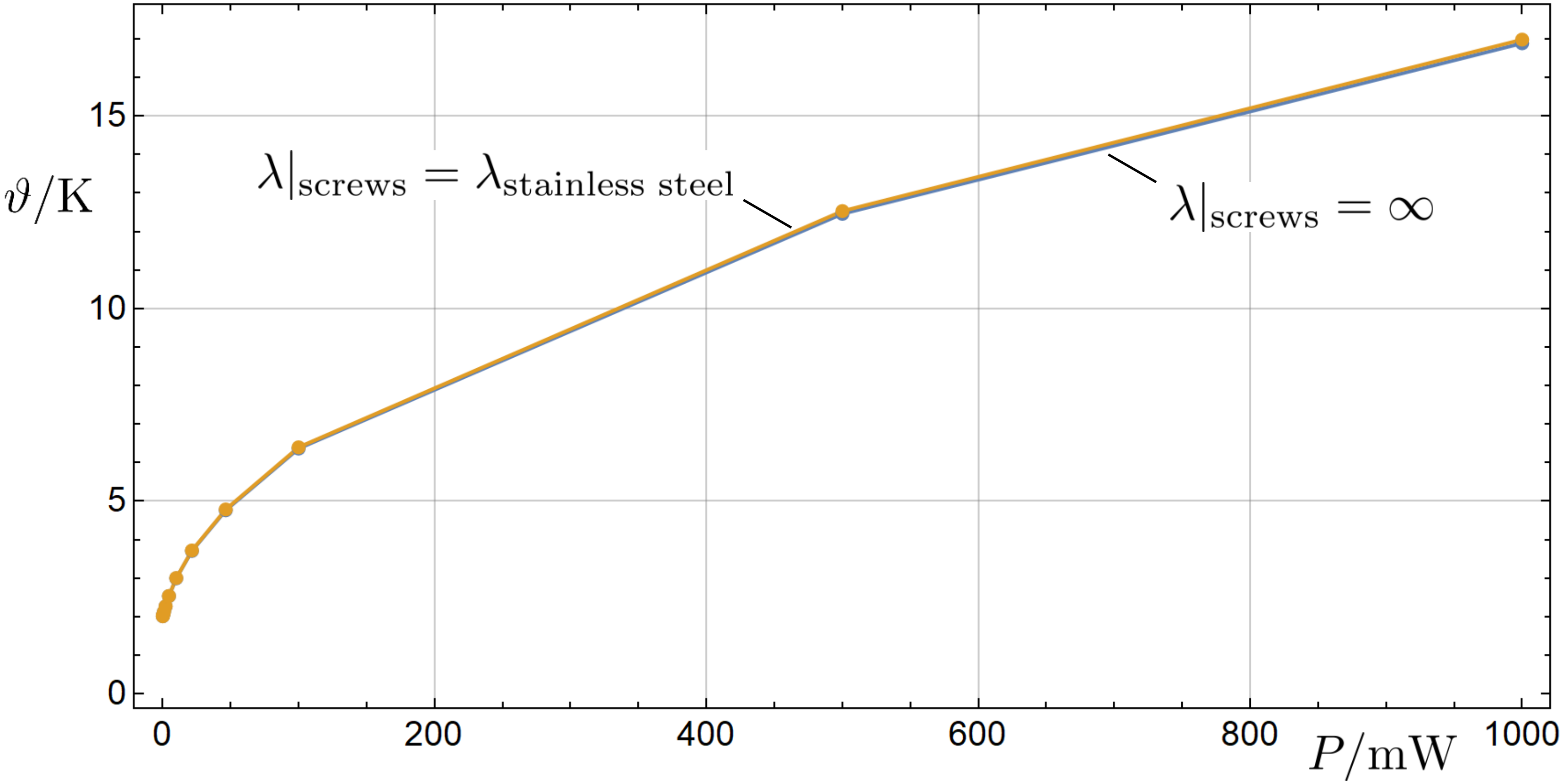
Thermal Steady State

- Volume Heat Source Excitation
  - Heat Flow Density



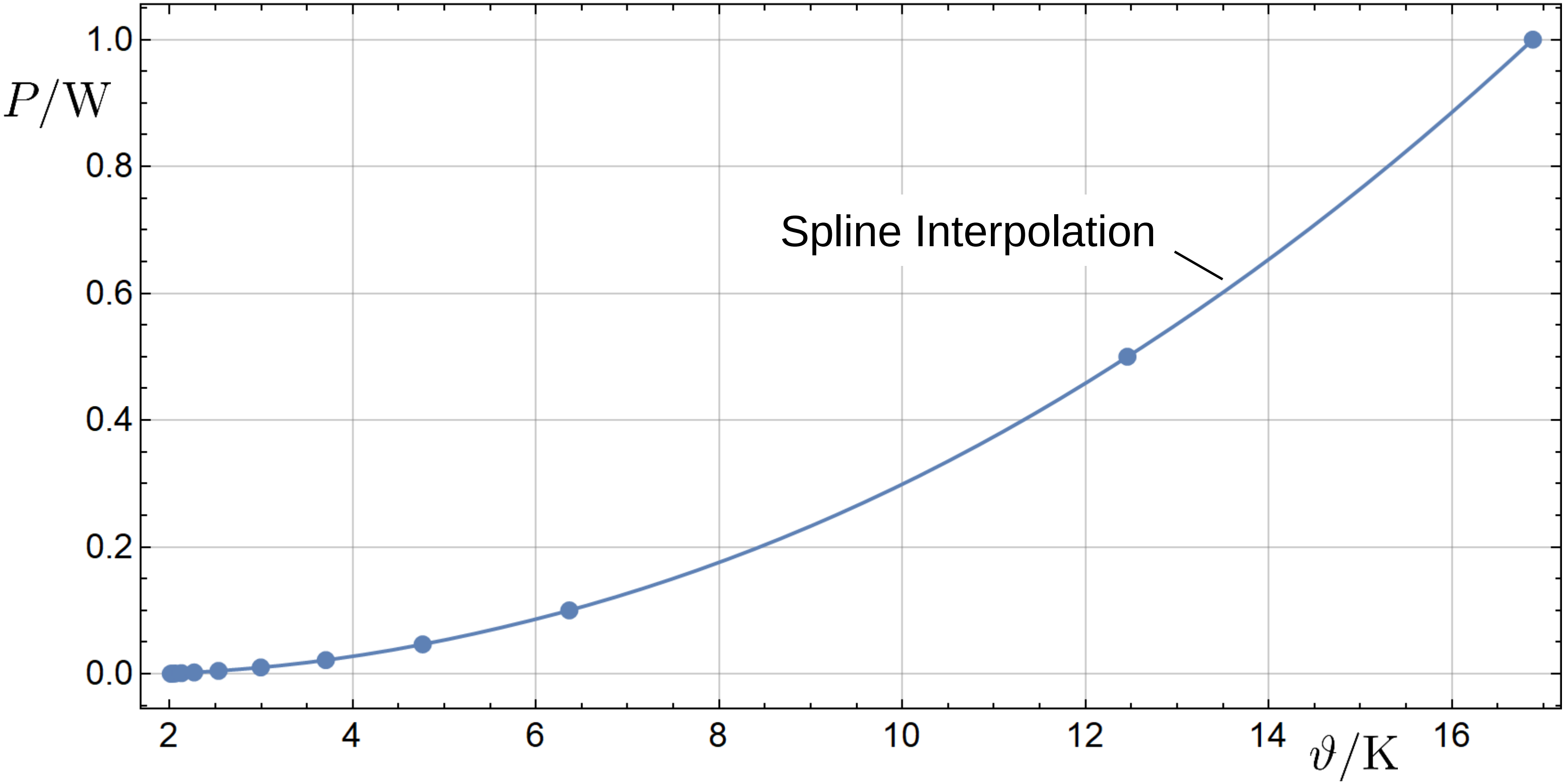
Thermal Steady State

- Volume Heat Source Excitation



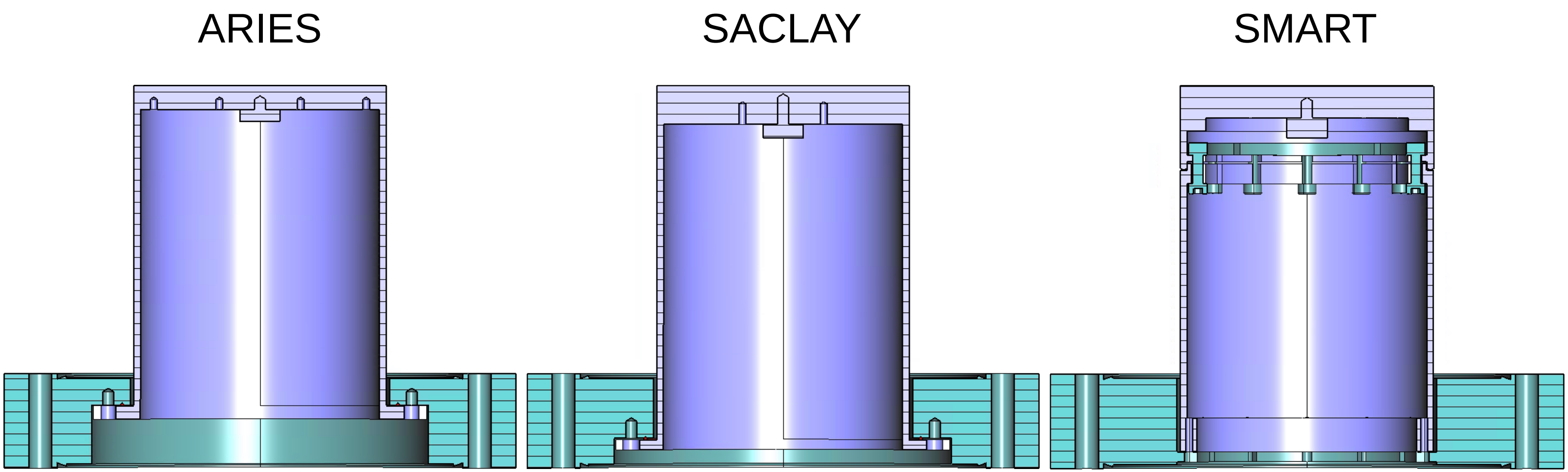
Thermal Steady State

- Volume Heat Source Excitation



Thermal Steady State

- Numerical Modeling of QPR with Different Probes
  - Eigensolutions and Temperature Distribution

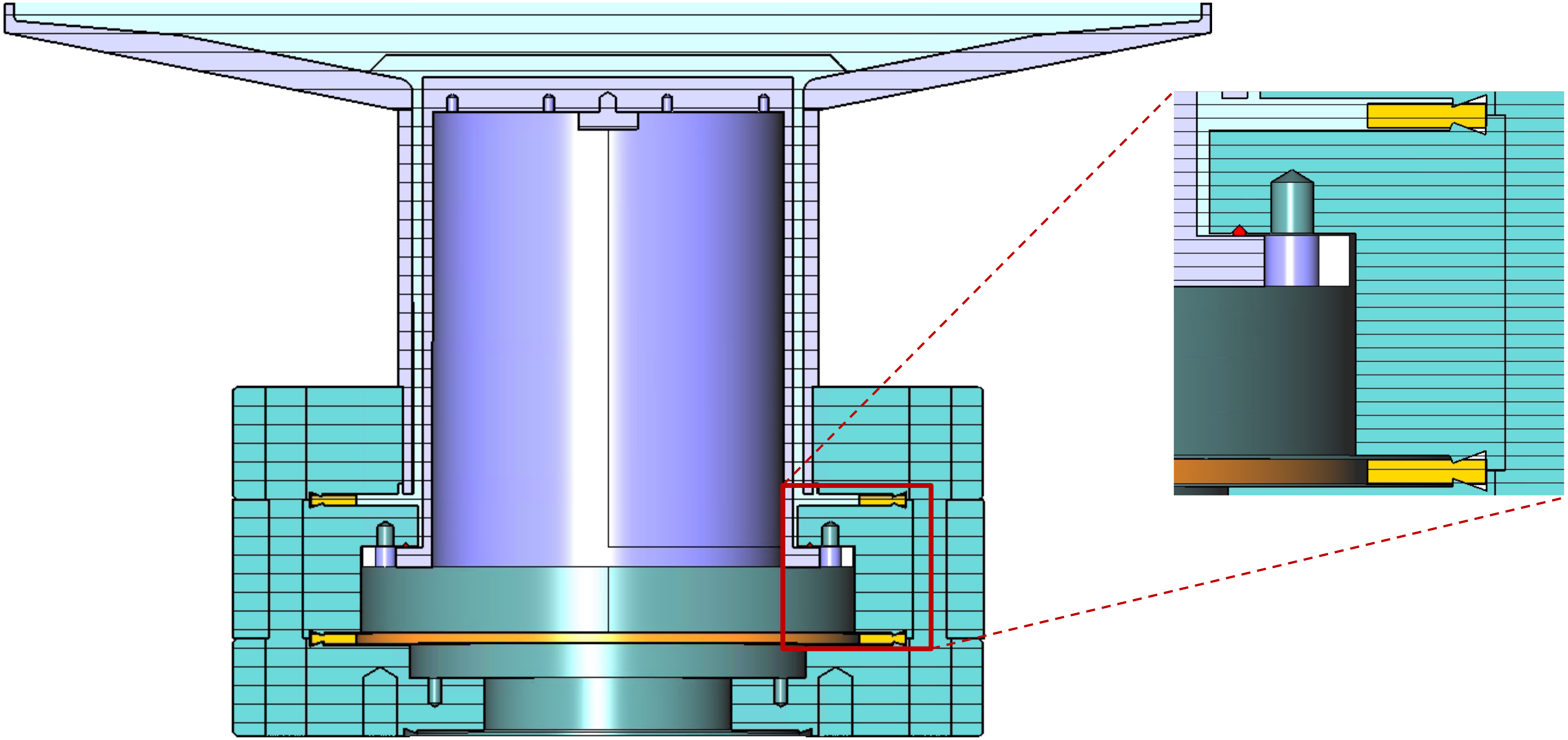


➡ Comparison of different designs (using identical material properties)

CAD data kindly provided by Sebastian Keckert

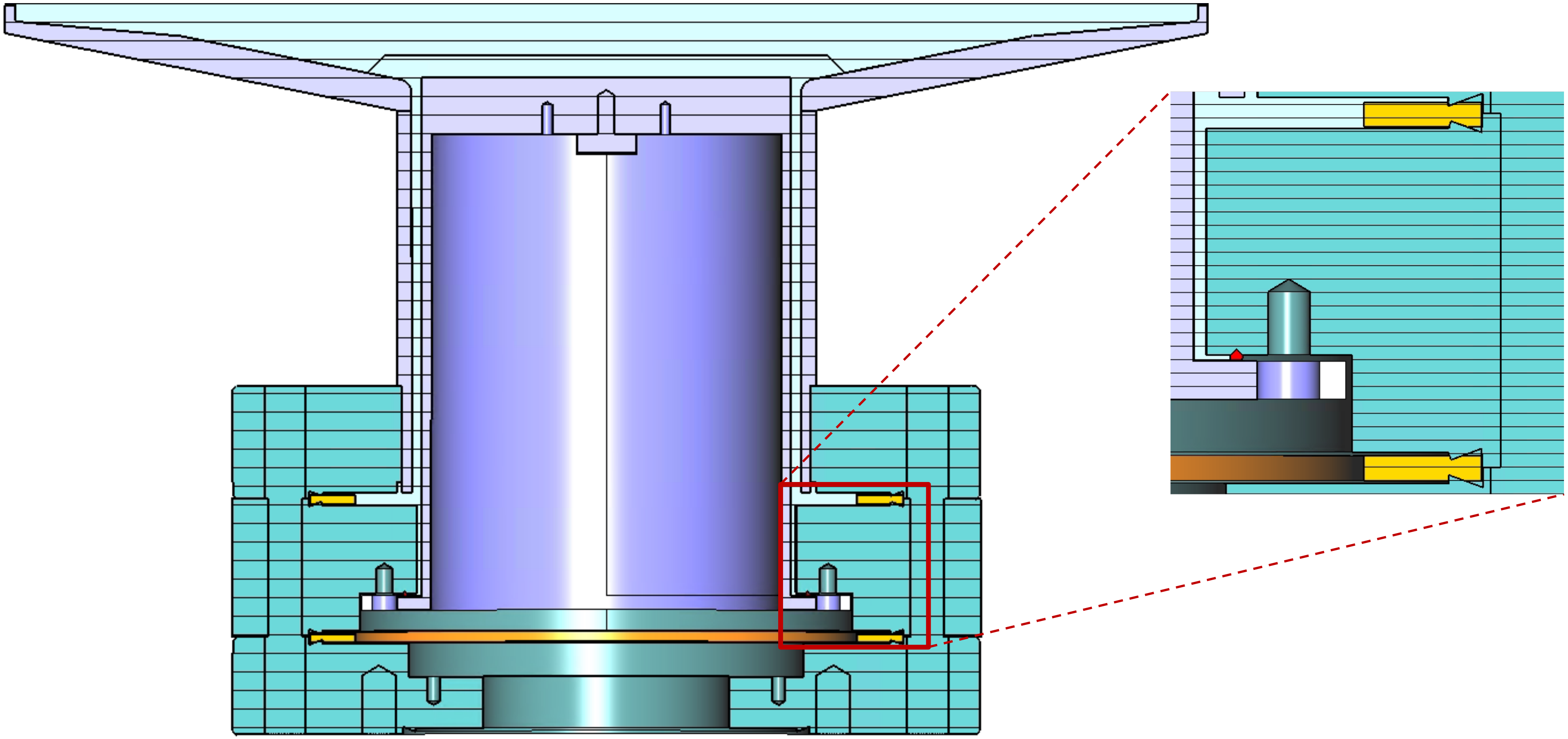
Thermal Steady State

- Geometric Modeling
  - Design: ARIES



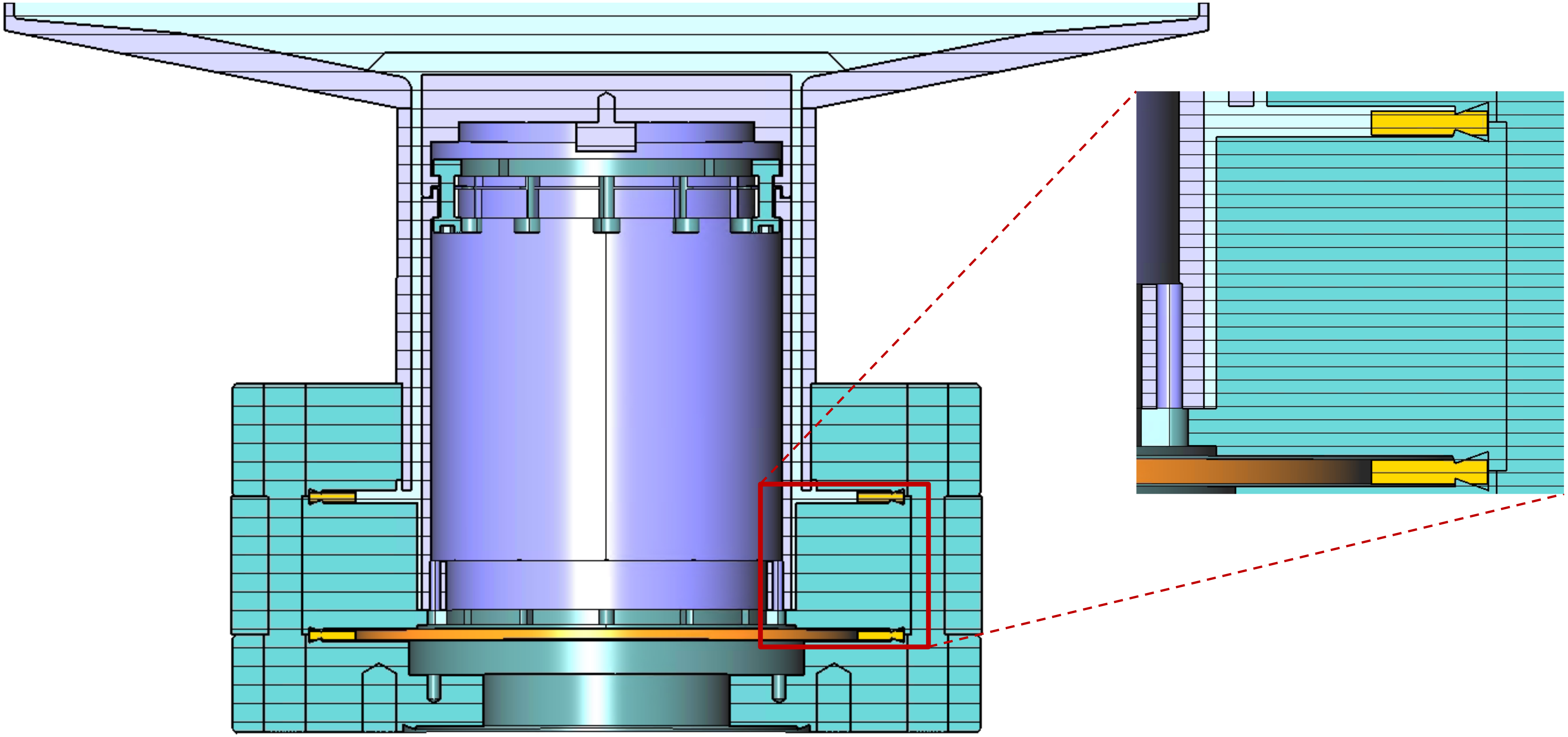
Thermal Steady State

- Geometric Modeling
  - Design: SACLAY



Thermal Steady State

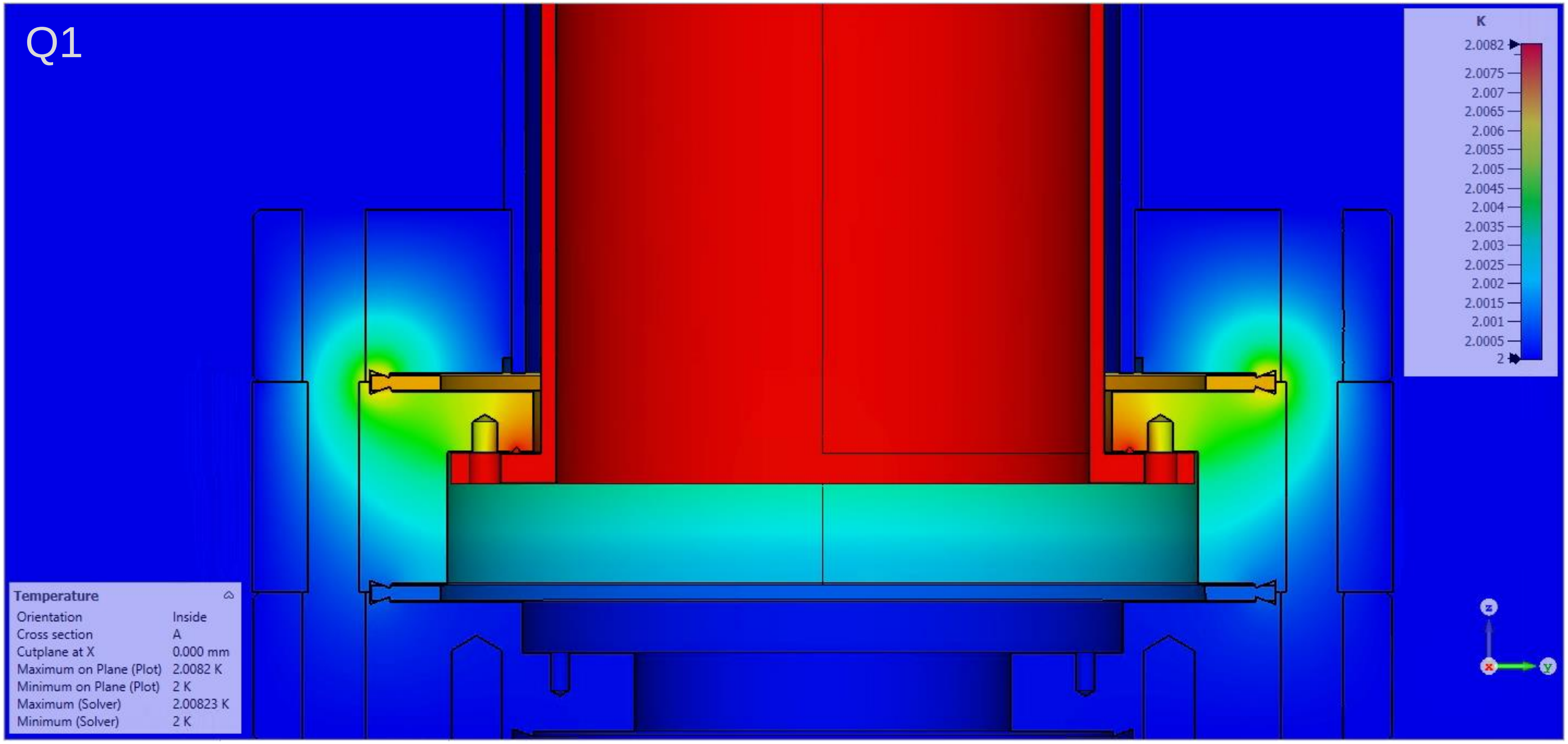
- Geometric Modeling
  - Design: SMART



Thermal Steady State

- ARIED Design

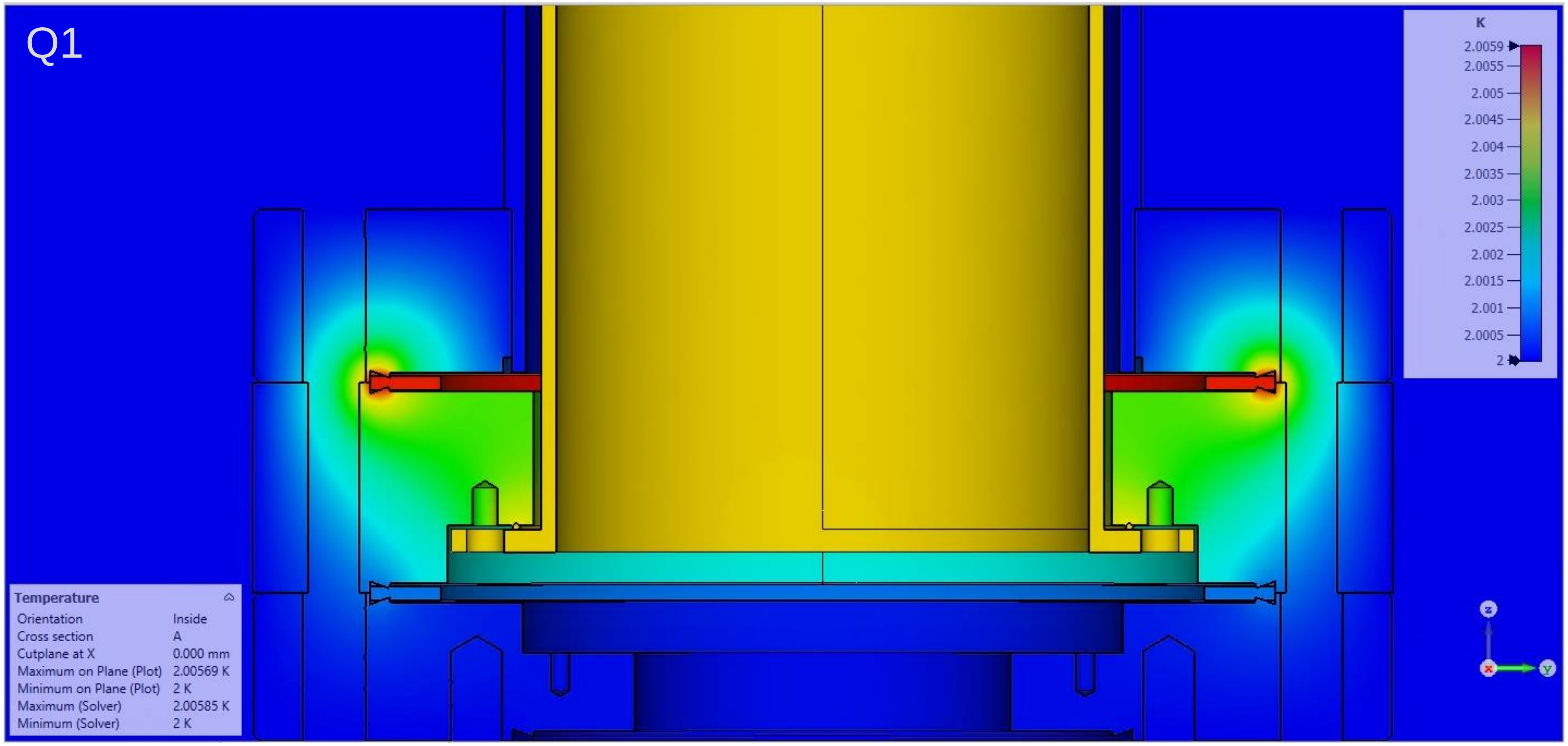
  Stainless Steel Flanges coated with Niobium



Thermal Steady State

- SACLAY Design

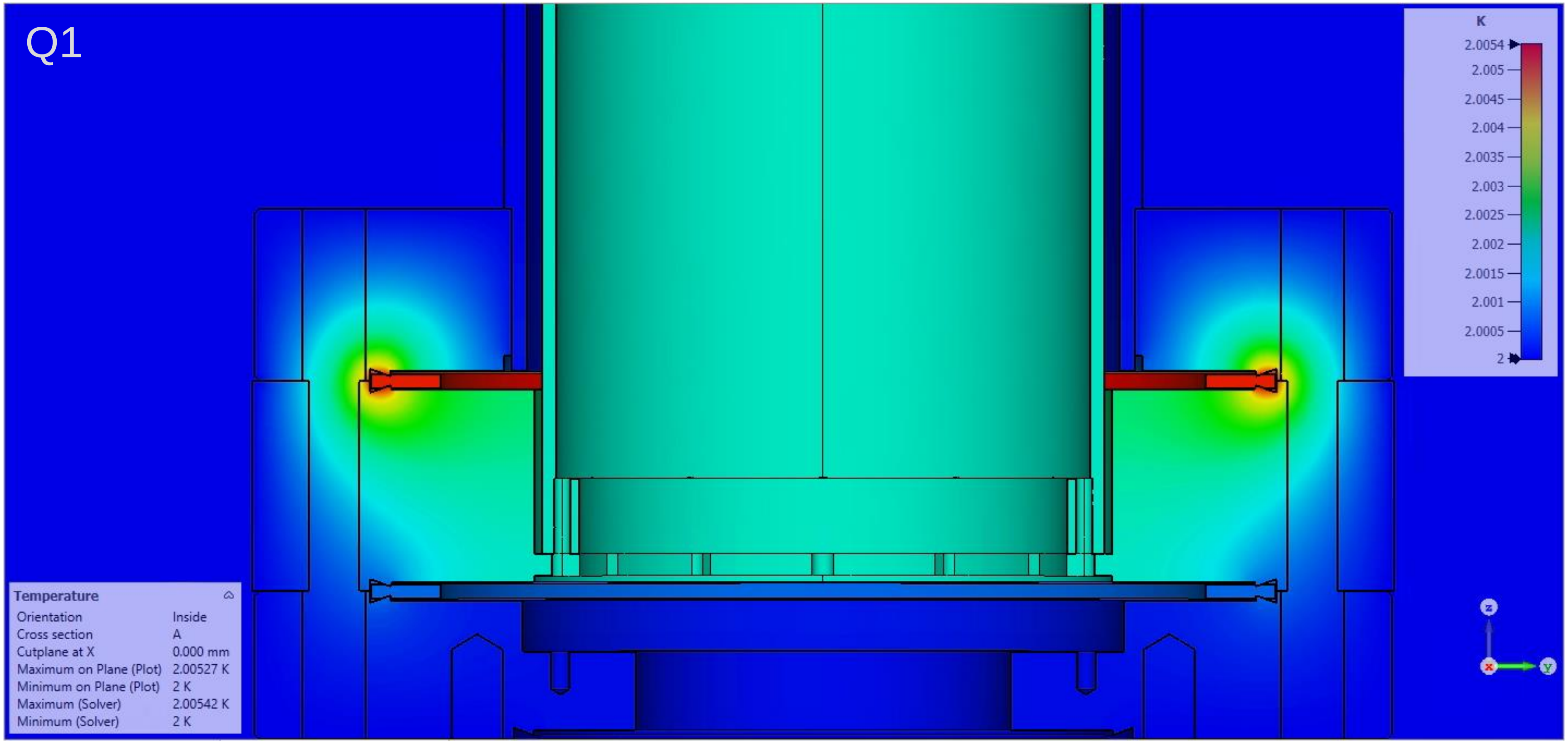
Stainless Steel Flanges coated with Niobium



Thermal Steady State

- SMART Design

  Stainless Steel Flanges coated with Niobium



Thermal Steady State

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- Summary ARIES Design (Stainless Steel Flanges coated with Niobium)

Sample temperature, effective power and parasitic surface resistance

	Q1			Q2			Q3		
B / mT	**T / K**	**P / mW**	**R / nΩ**	**T / K**	**P / mW**	**R / nΩ**	**T / K**	**P / mW**	**R / nΩ**
5	2,000	0,000	0,034	2,000	0,000	0.071	2,000	0,001	0,176
10	2,000	0,001	0,034	2,000	0,001	0.071	2,000	0,003	0,176
20	2,000	0,003	0,034	2,001	0,006	0.071	2,001	0,013	0,176
50	2,002	0,018	0,034	2,004	0,035	0.071	2,009	0,079	0,176
100	2,008	0,072	0,034	2,016	0,141	0.071	2,036	0,314	0,176

Thermal Steady State

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- Summary SACLAY Design (Stainless Steel Flanges coated with Niobium)

Sample temperature, effective power and parasitic surface resistance

	Q1			Q2			Q3		
B / mT	**T / K**	**P / mW**	**R / nΩ**	**T / K**	**P / mW**	**R / nΩ**	**T / K**	**P / mW**	**R / nΩ**
5	2,000	0,000	0,022	2,000	0,000	0.048	2,000	0,000	0,126
10	2,000	0,000	0,022	2,000	0,001	0.048	2,000	0,002	0,126
20	2,000	0,002	0,022	2,000	0,004	0.048	2,001	0,009	0,126
50	2,001	0,012	0,022	2,002	0,024	0.048	2,006	0,056	0,126
100	2,005	0,047	0,022	2,009	0,094	0.048	2,022	0,225	0,126

Thermal Steady State

TECHNISCHE UNIVERSITÄT DARMSTADT

- Summary SMART Design (Stainless Steel Flanges coated with Niobium)

Sample temperature, effective power and parasitic surface resistance

	Q1			Q2			Q3		
B / mT	**T / K**	**P / mW**	**R / nΩ**	**T / K**	**P / mW**	**R / nΩ**	**T / K**	**P / mW**	**R / nΩ**
5	2,000	0,000	0,007	2,000	0,000	0.014	2,000	0,000	0,036
10	2,000	0,000	0,007	2,000	0,000	0.014	2,000	0,001	0,036
20	2,000	0,001	0,007	2,000	0,001	0.014	2,000	0,003	0,036
50	2,000	0,004	0,007	2,001	0,007	0.014	2,002	0,016	0,036
100	2,002	0,014	0,007	2,003	0,029	0.014	2,008	0,065	0,036

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Summary and Outlook

- Summary
  - QPR Precise Geometry Model
  - Eigenmodes
  - Surface Heat Source
  - Temperature Distribution
  - Determination of the Parasitic Surface Resistance

- Outlook
  - Examination of a Detachable Probe Design
  - Modeling of Coated Niobium as a Multilayer Structure