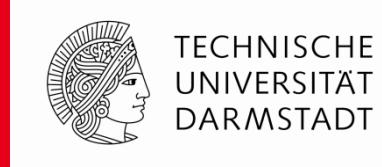


Simulation of the Thermal Heating based on Eigenmode Excitations



W. Ackermann, H. De Gersem, W. F. O. Müller

Institute for Accelerator Science and Electromagnetic Fields (TEMF), TU Darmstadt

6th Collaboration Workshop SMART
Online Meeting
January 14, 2022



Overview



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- Motivation
- Quadrupole Resonator
 - 3D Eigenmode calculations
 - Thermal steady state calculations
 - Material modeling and heat sources
 - Application to different probe geometries
- Quadrupole Resonator with Tilted Rods
 - 2D Eigenmode calculations in the coaxial gap
- Summary and Outlook

Overview

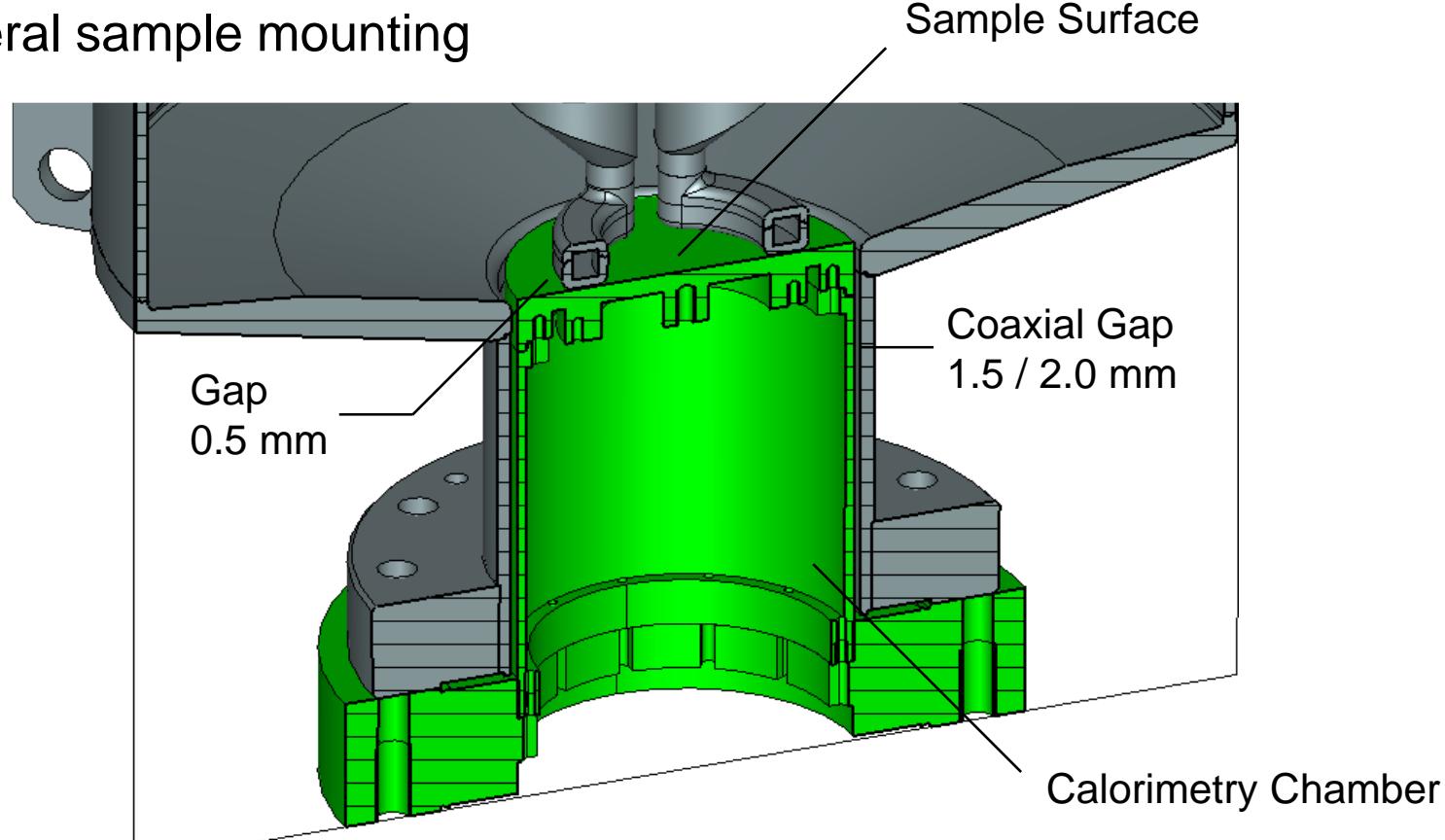


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Motivation



- Geometry Information
 - General sample mounting



Overview

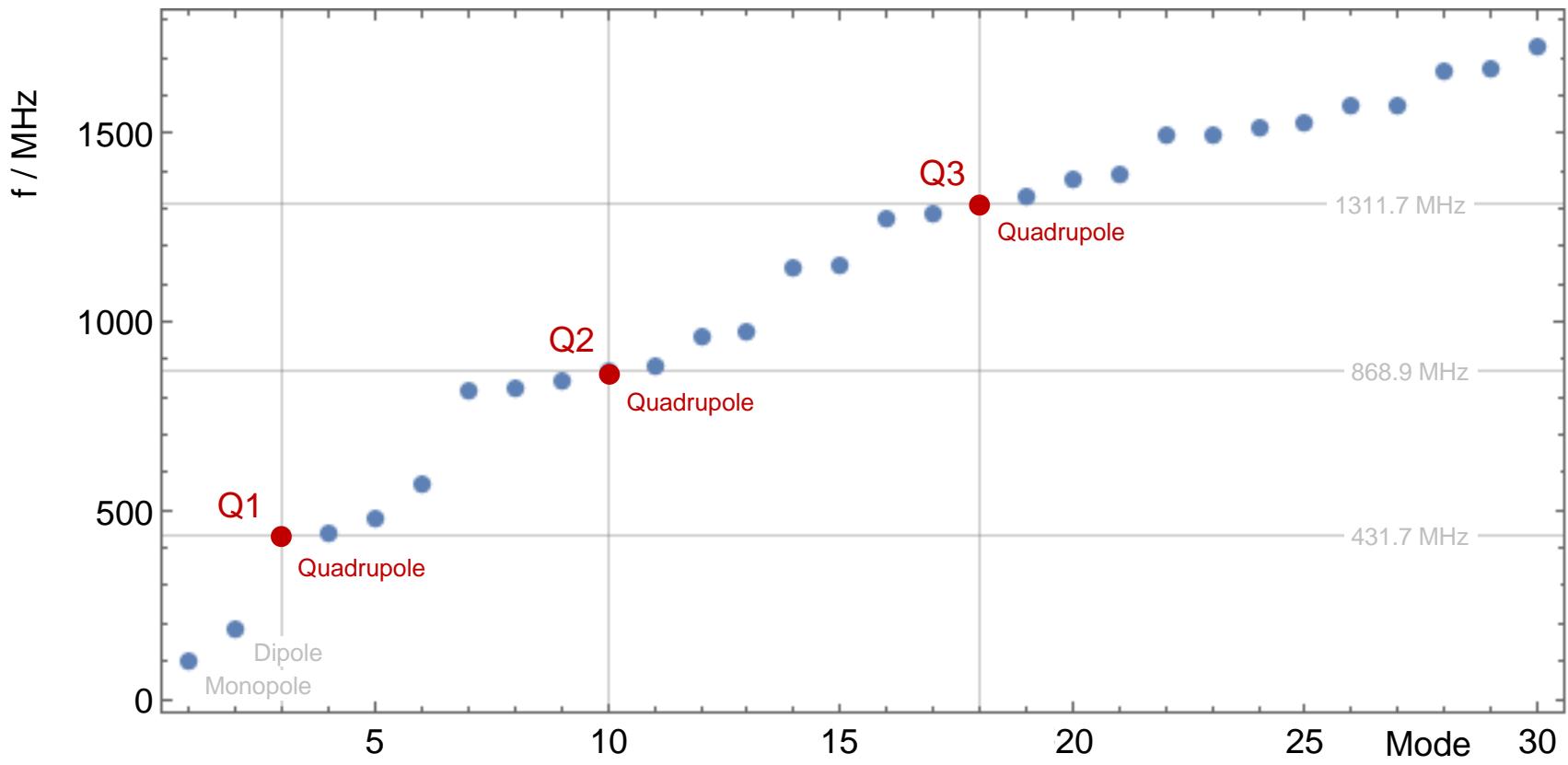


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Quadrupole Resonator

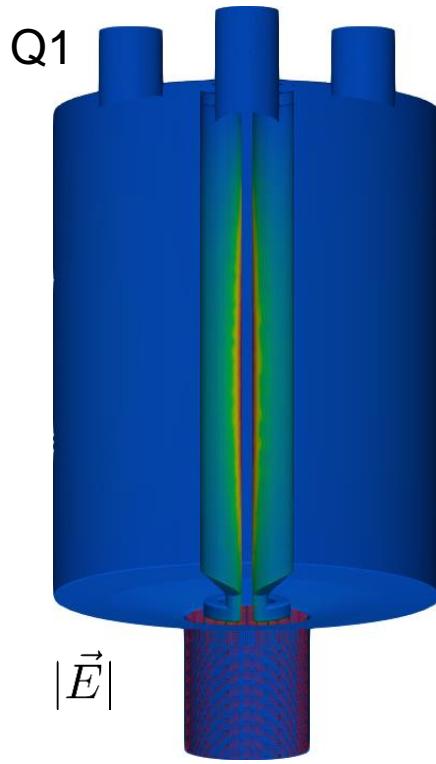
- Eigenmode Calculations
 - Selection of eigenmodes



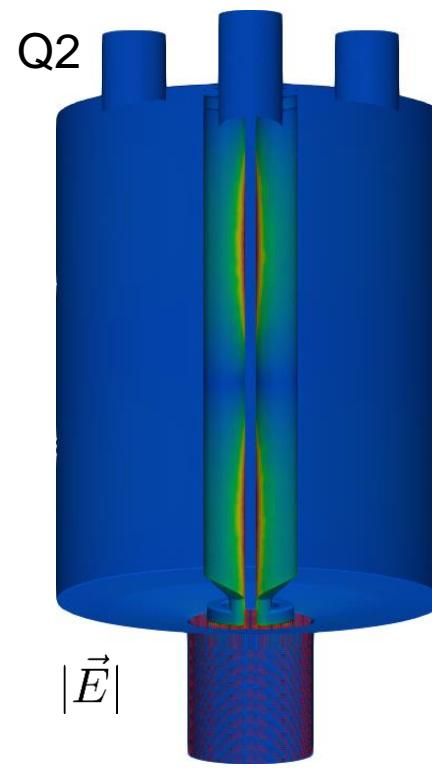
Quadrupole Resonator



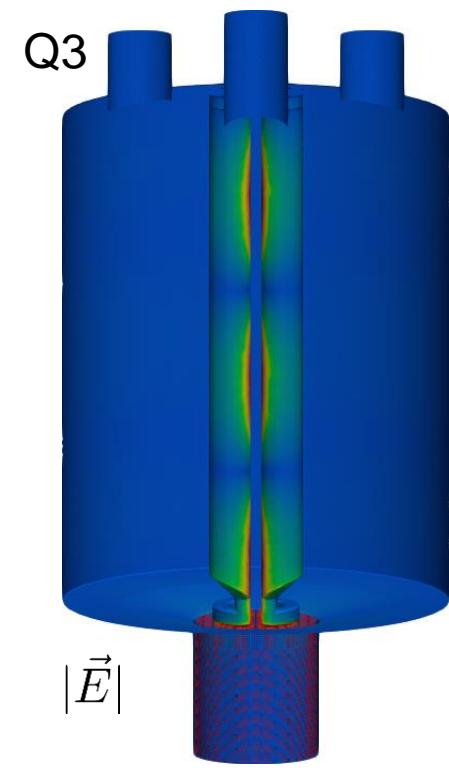
- Eigenmode Calculations
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$$f_{\text{res}} = 431.7 \text{ MHz}$$



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

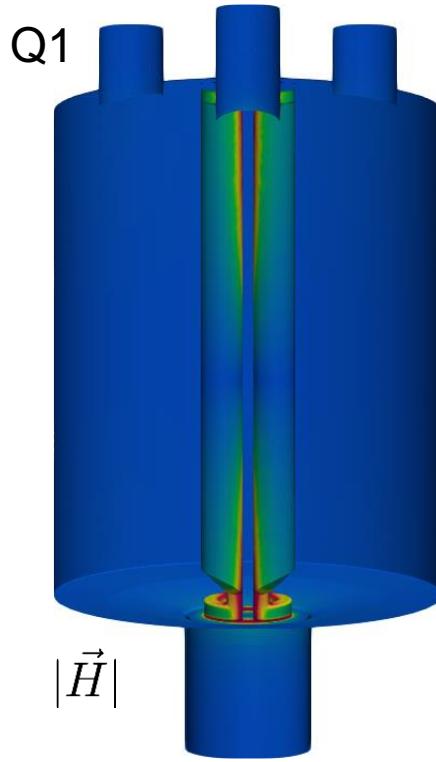


$$f_{\text{res}} = 1311.7 \text{ MHz}$$

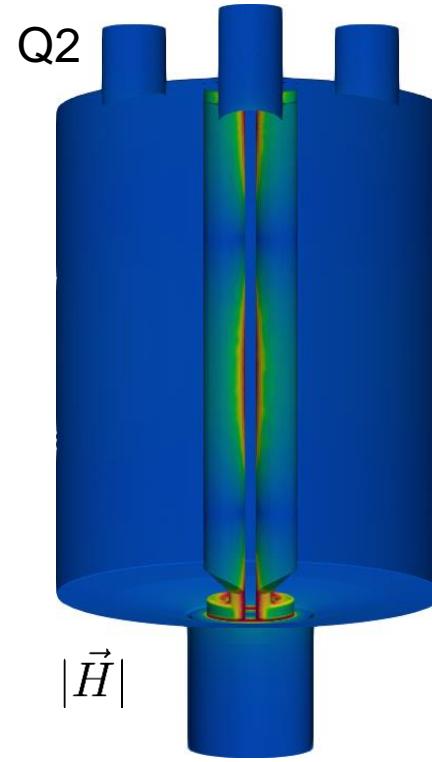
Quadrupole Resonator



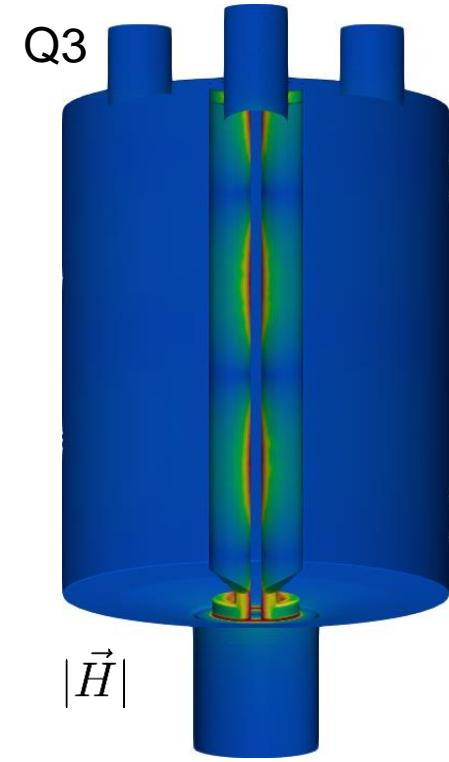
- Eigenmode Calculations
 - Selection of eigenmodes



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



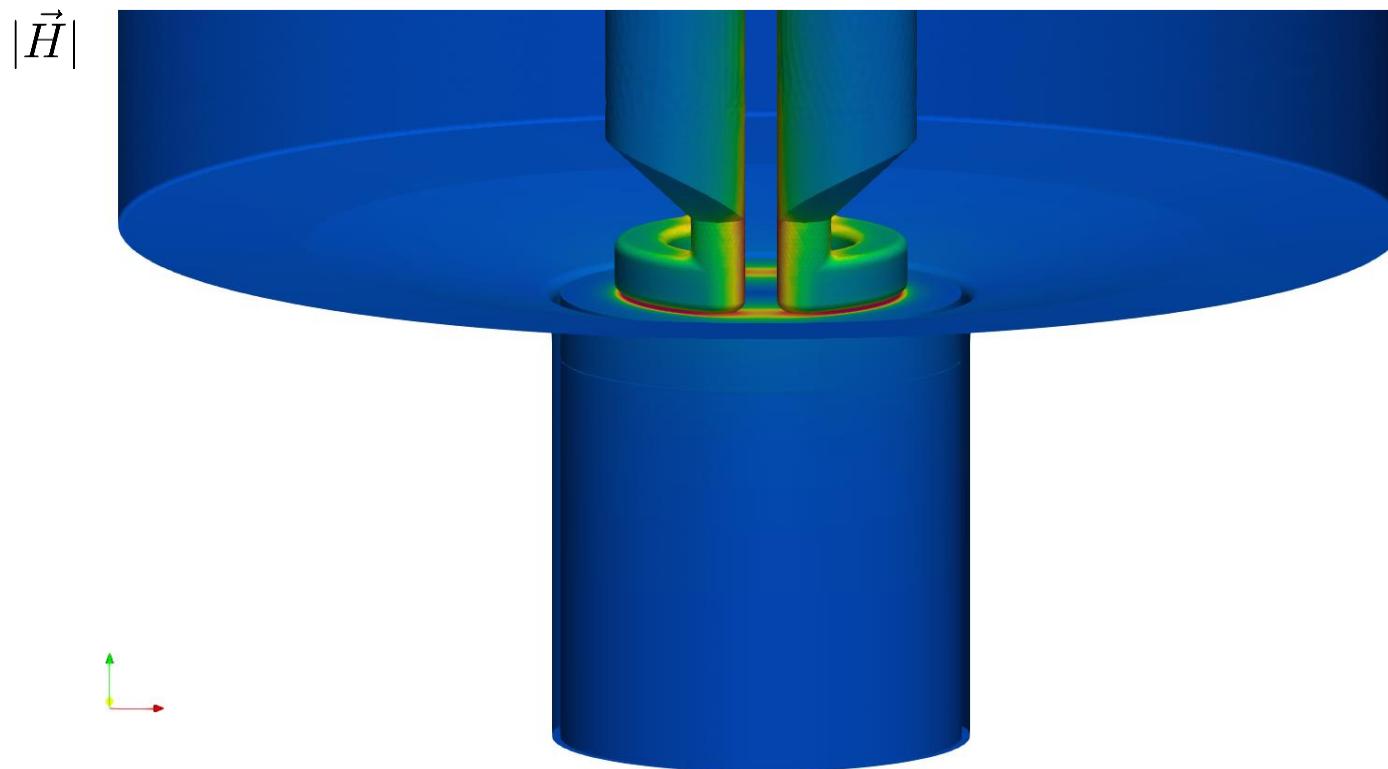
$$f_{\text{res}} = 868.9 \text{ MHz}$$



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

Quadrupole Resonator

- Eigenmode Calculations
 - Distribution of the magnetic field strength



Overview

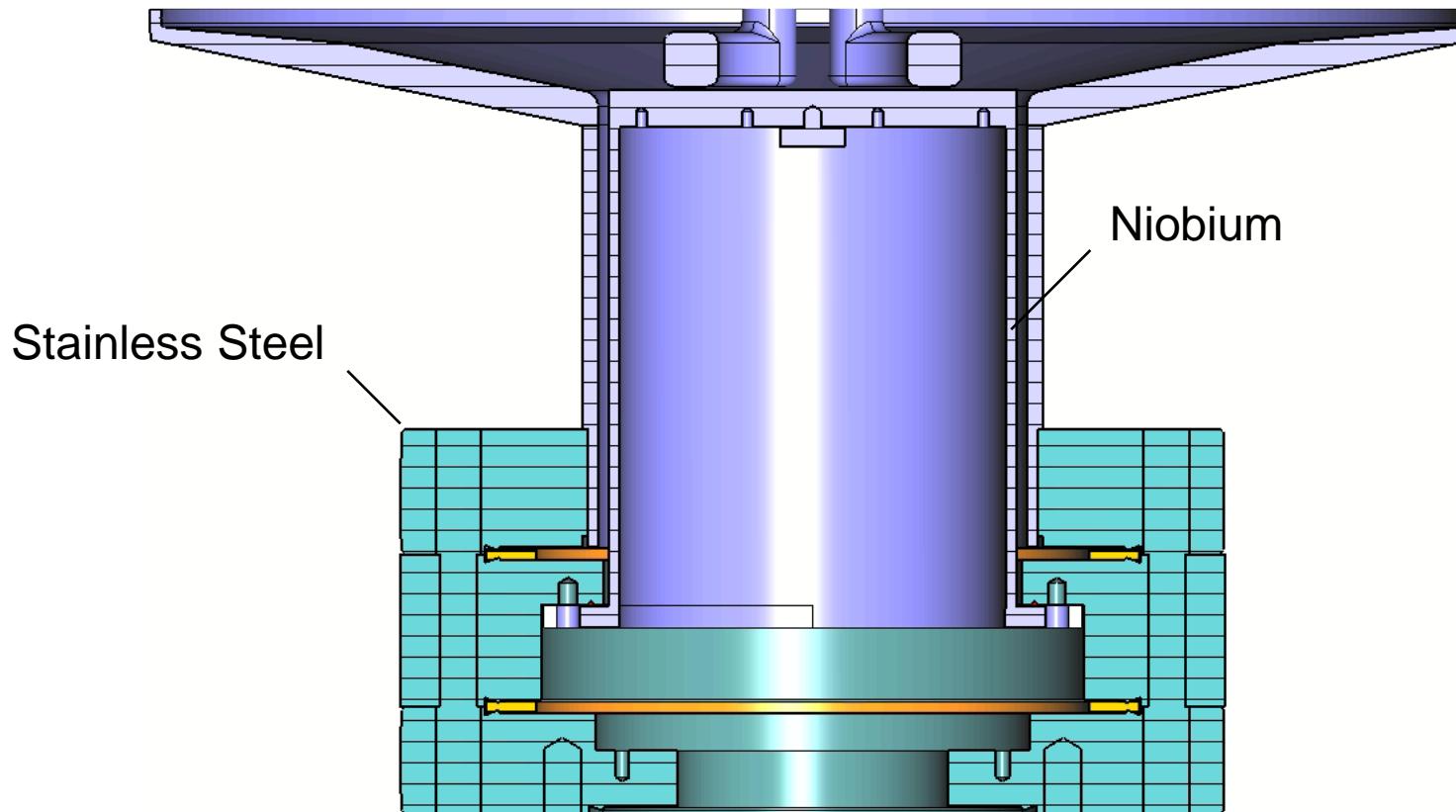


- Motivation
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Thermal Steady State



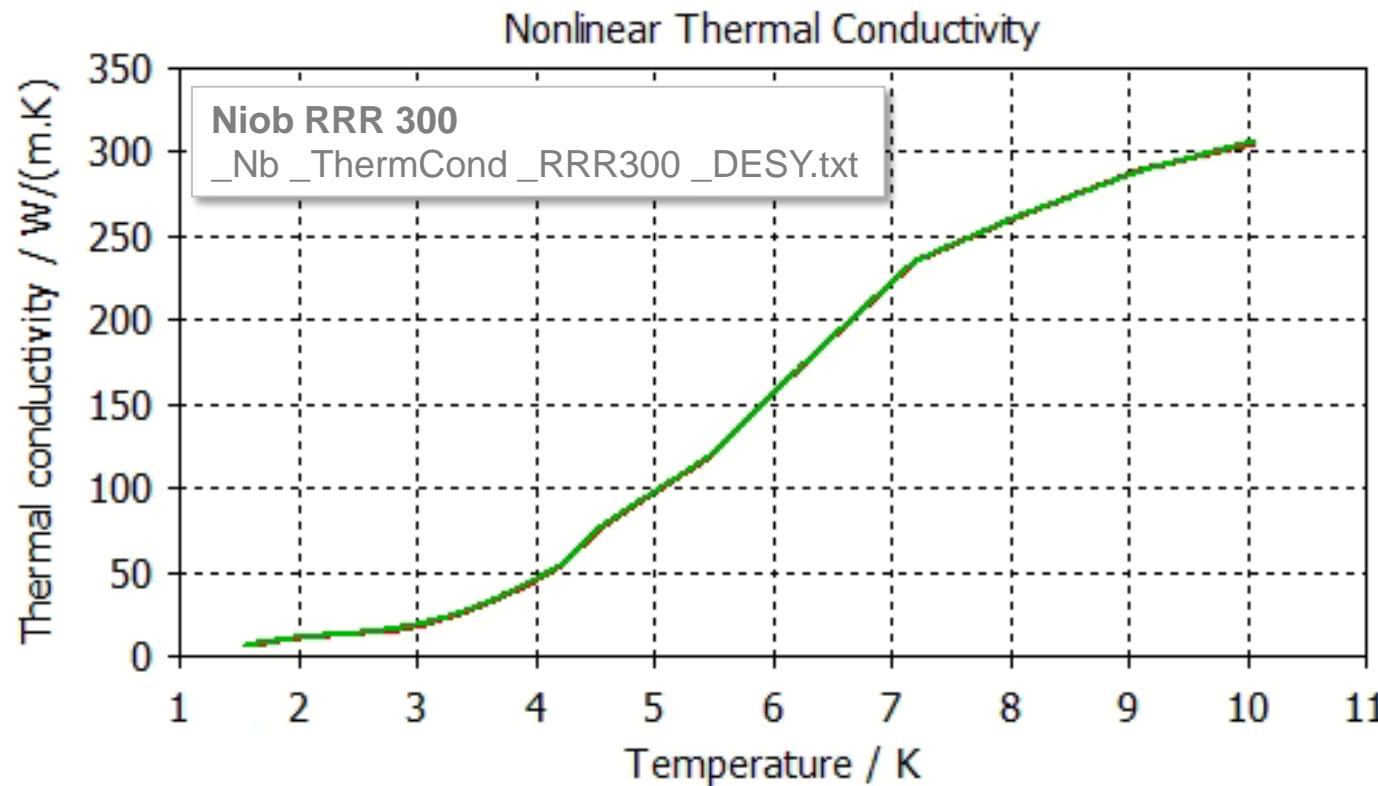
- Material Modeling for the Thermal Solver



Thermal Steady State



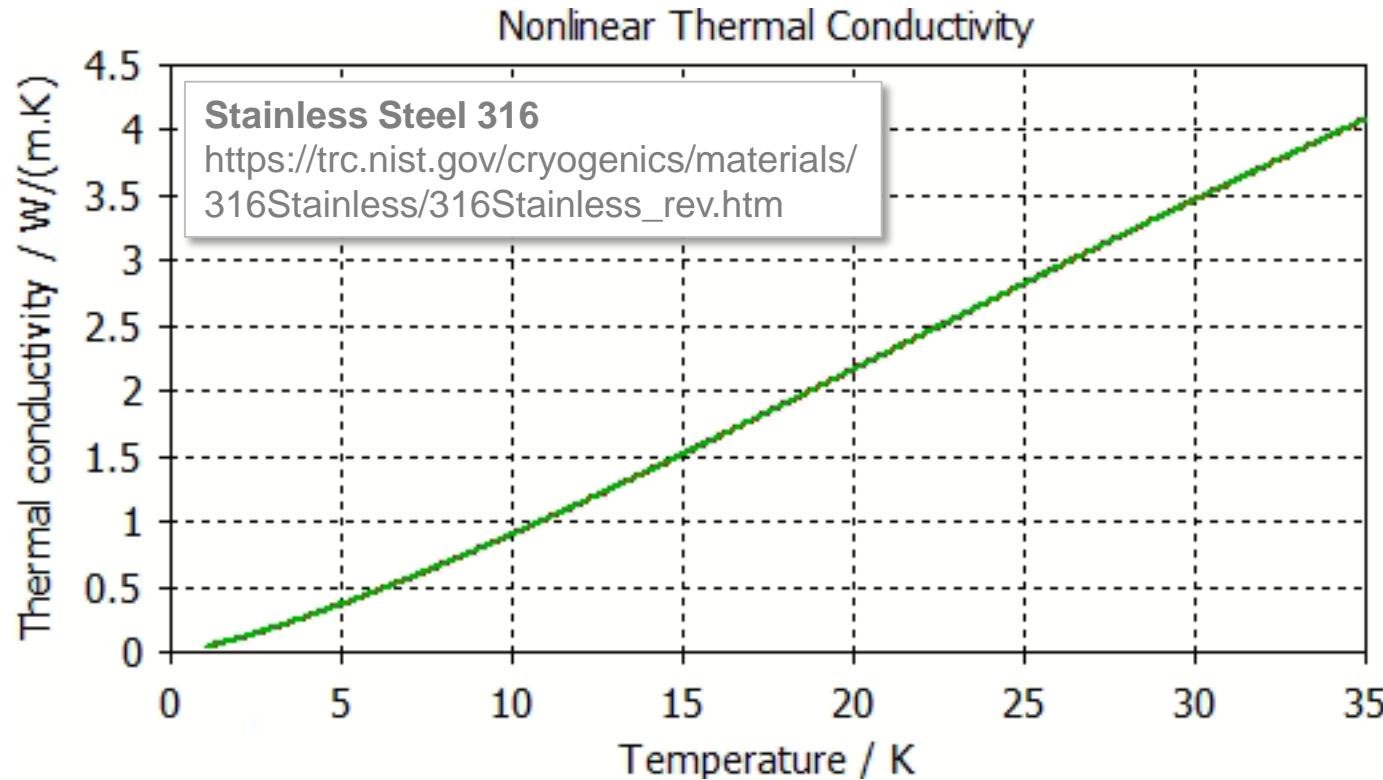
- Thermal Conductivity at Cryogenic Temperature
 - Niobium



Thermal Steady State



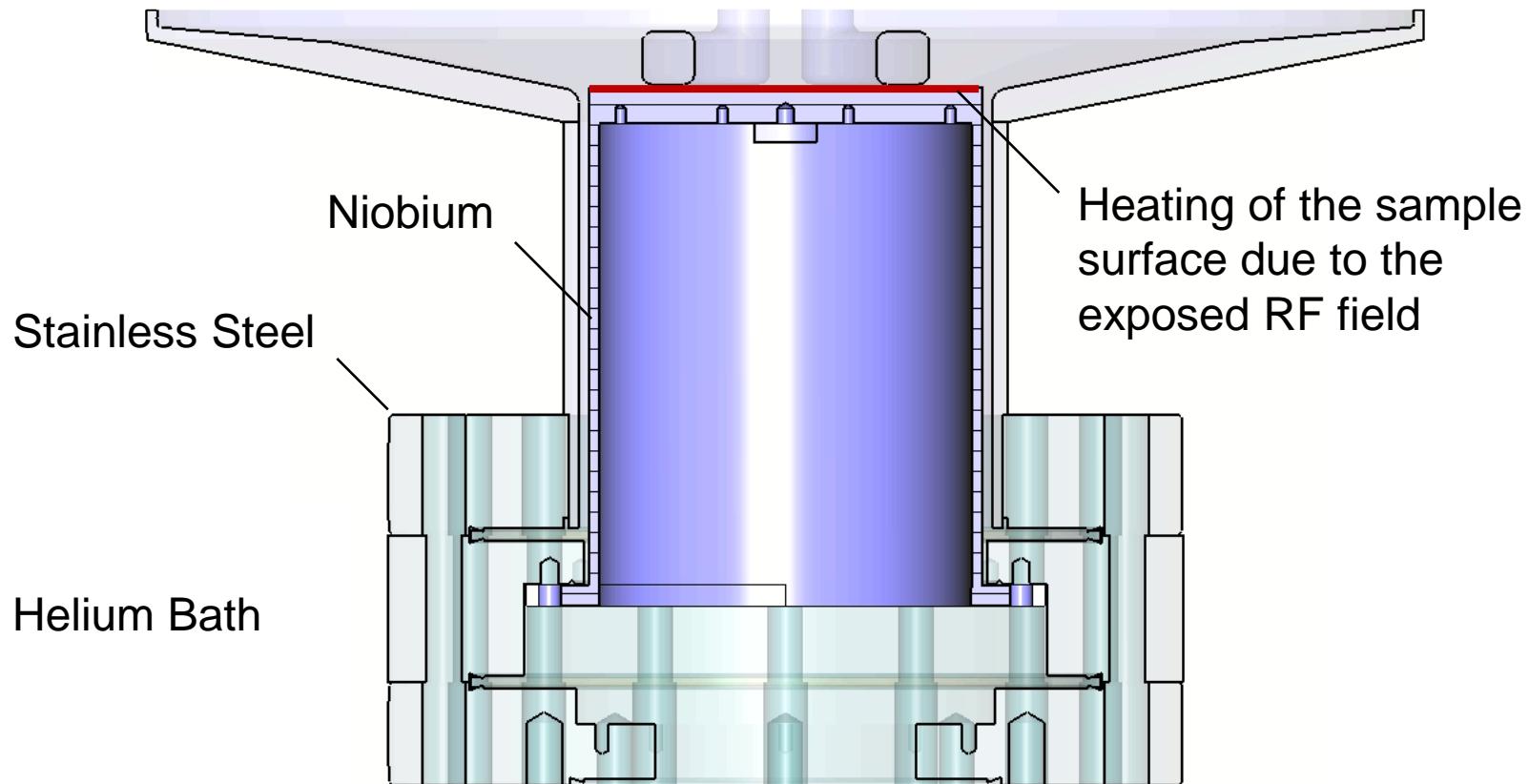
- Thermal Conductivity at Cryogenic Temperature
 - Stainless Steel



Thermal Steady State



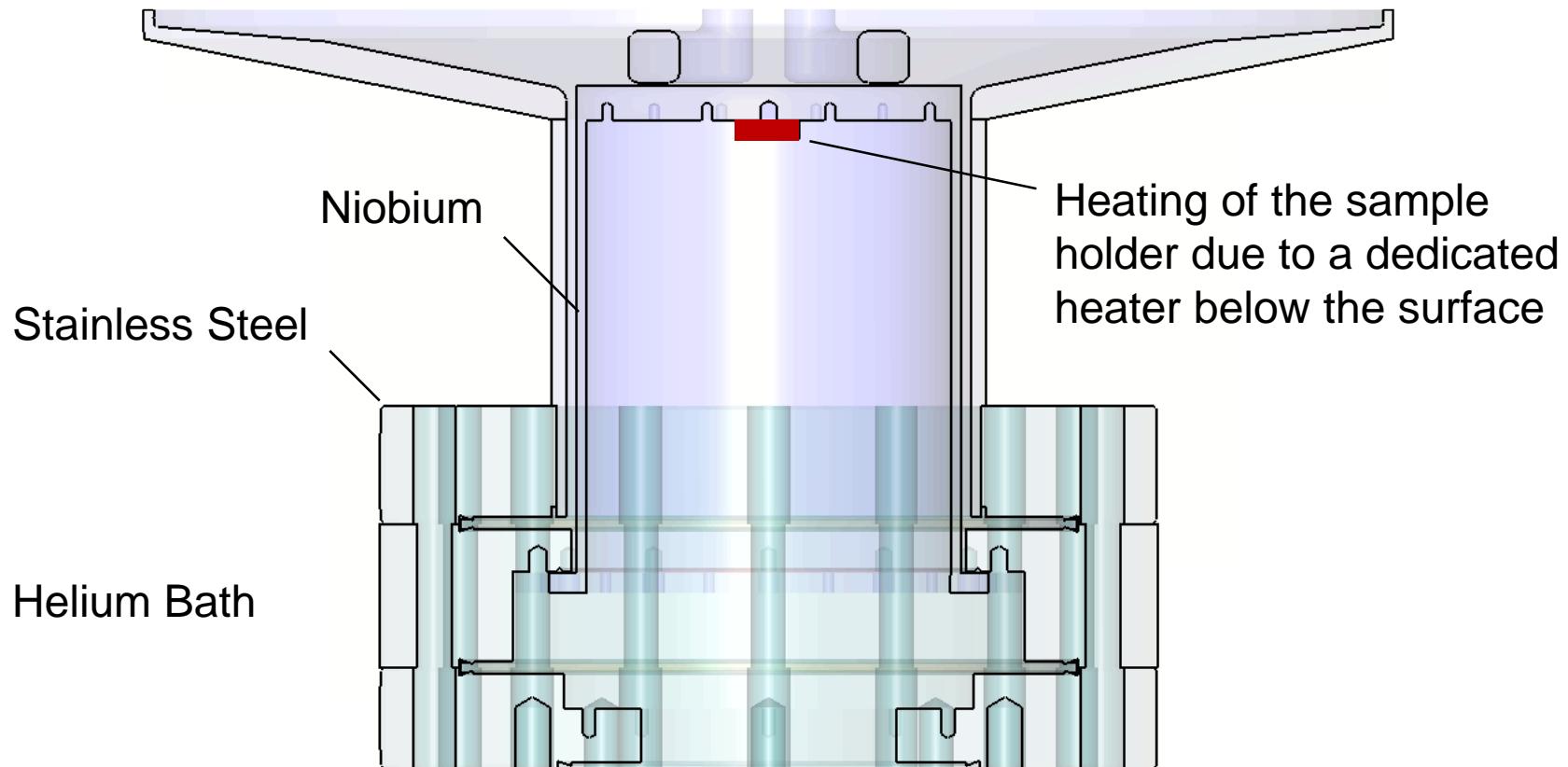
- Heat Source used for the Thermal Solver



Thermal Steady State



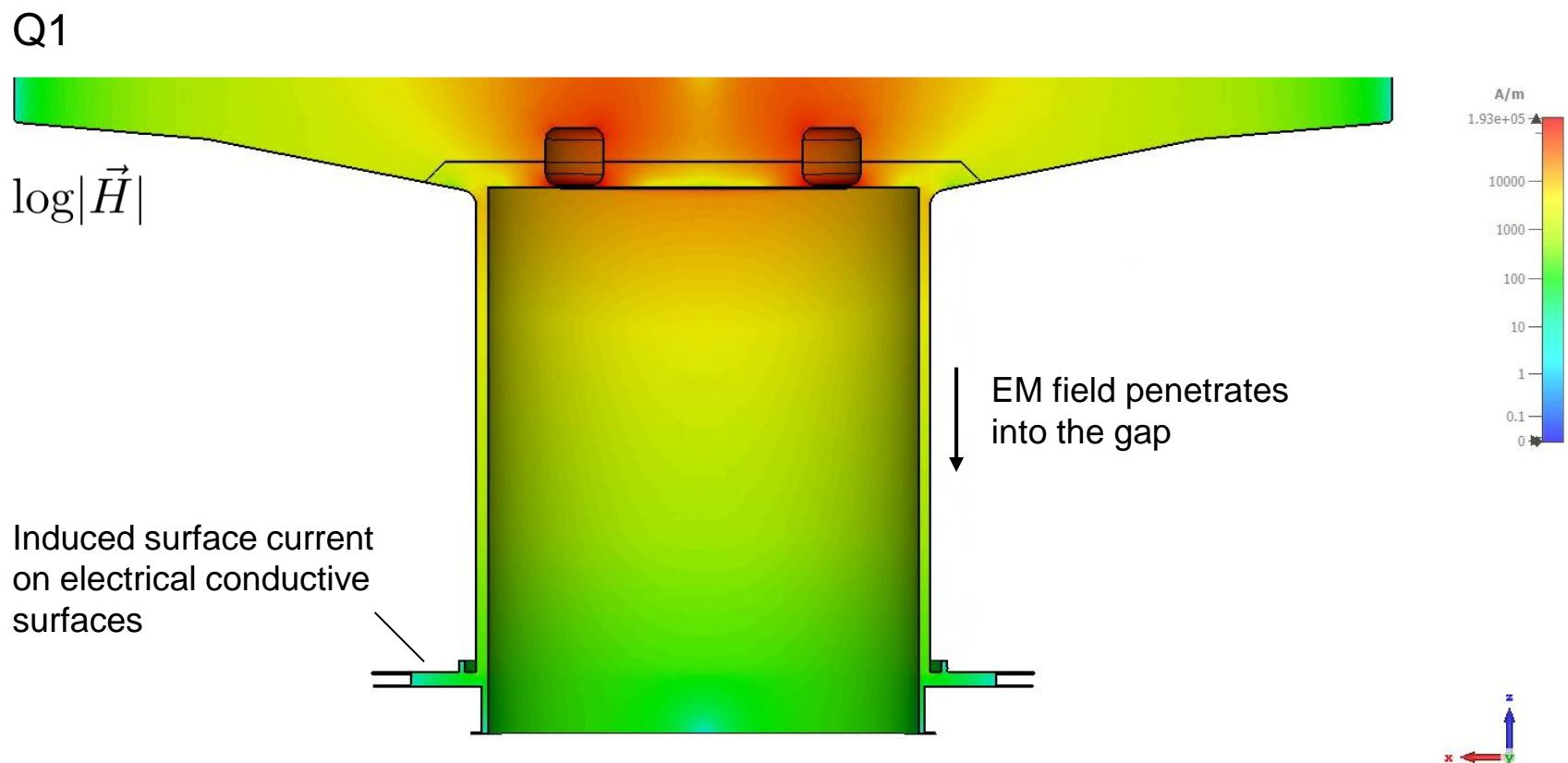
- Heat Source used for the Thermal Solver



Thermal Steady State

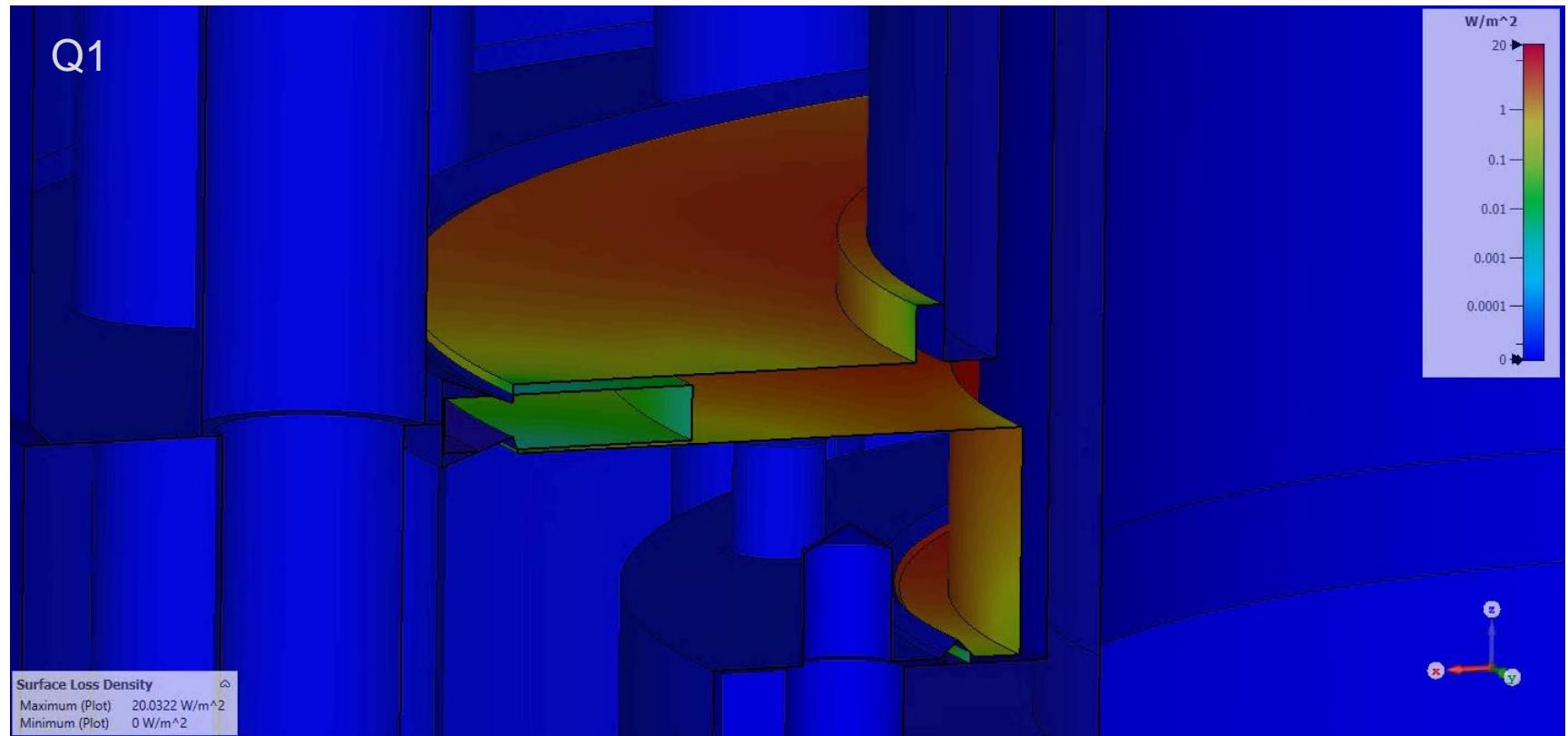


- Distribution of the Magnetic Field Strength



Thermal Steady State

- Distribution of the Surface Loss Density



Thermal Steady State



- Distribution of the Heat Flow Density

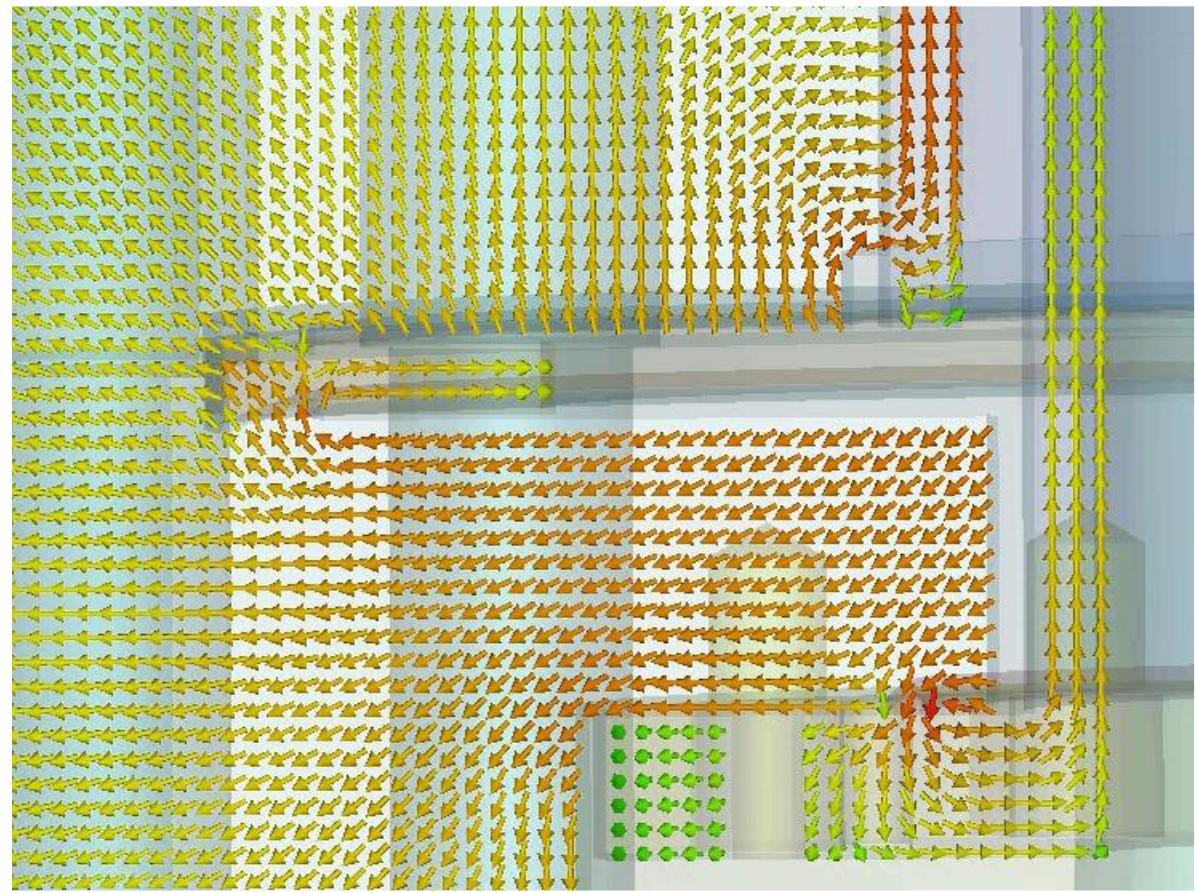
Q1

- Heat Sources

- StSt Flange Cavity
- StSt Flange Probe
- Copper Seal
- Indium Seal

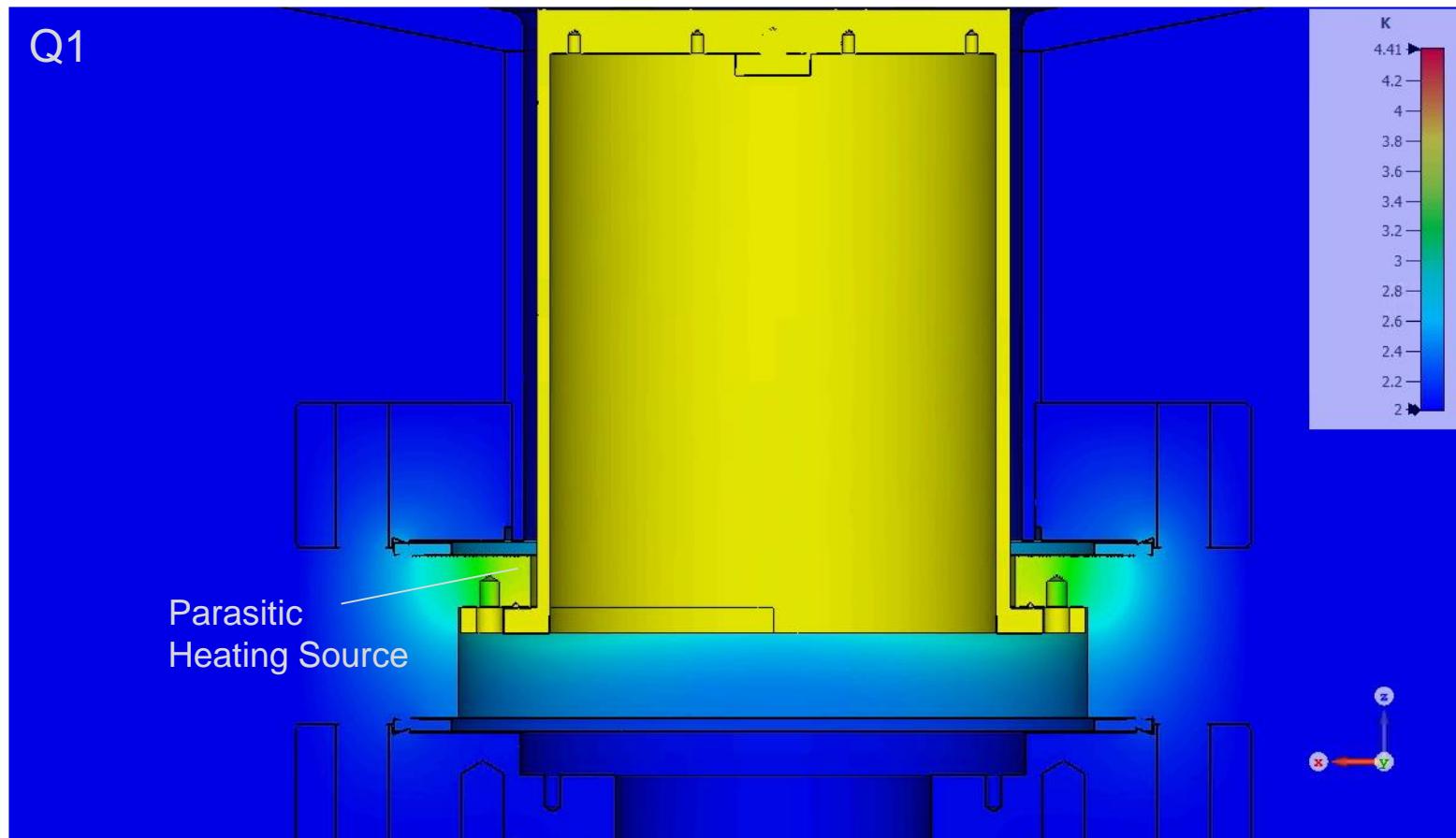
- Heat Sink

- Helium Bath



Thermal Steady State

- Distribution of the Steady State Temperature



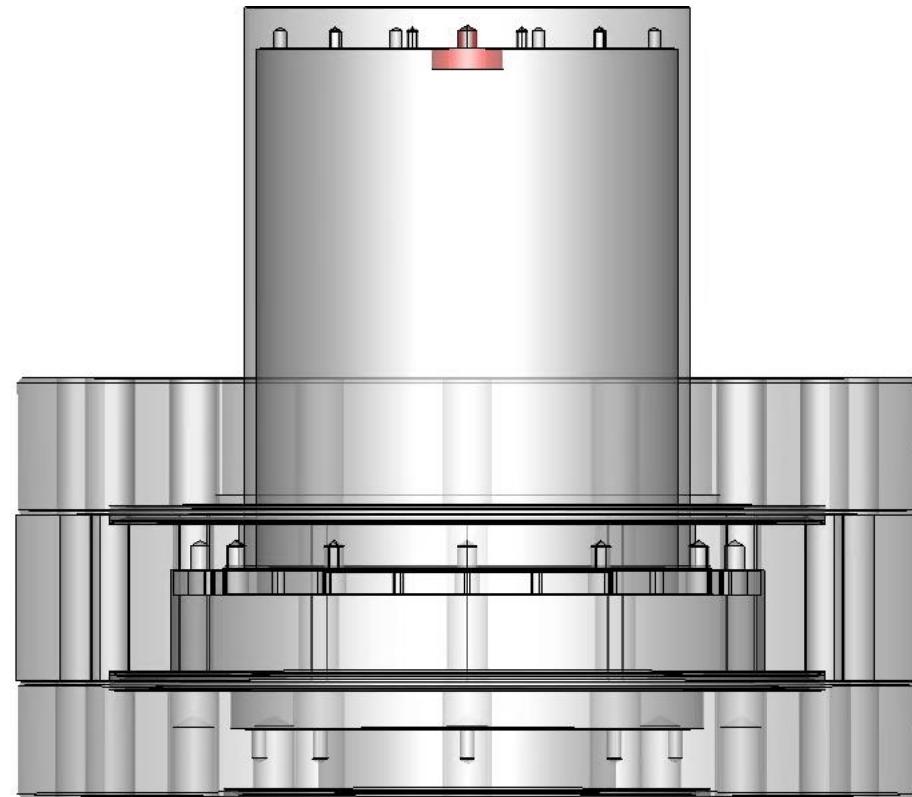
Thermal Steady State

- Volume Heat Source Excitation

Variation of power
excitation



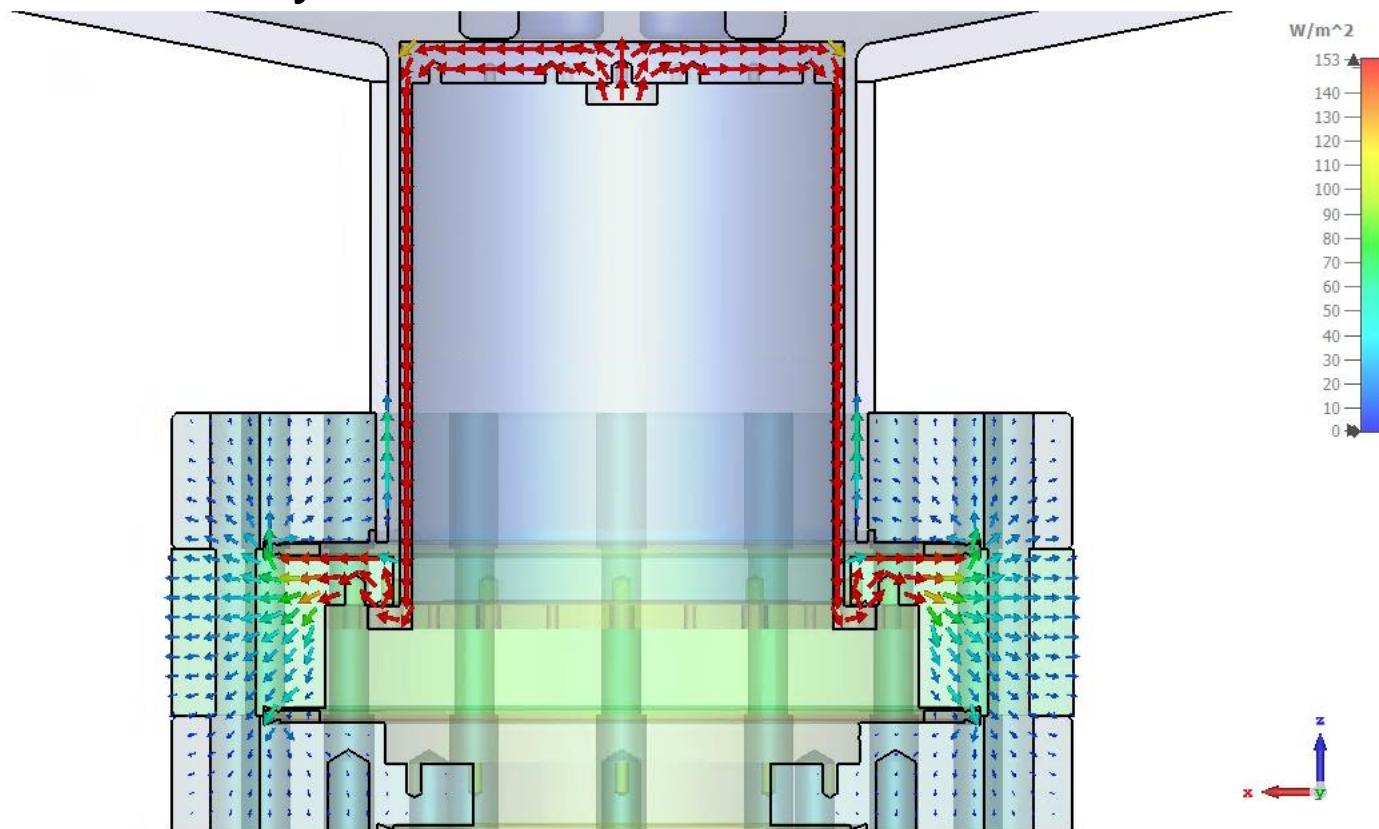
Enables comparison of
steady state temperature





Thermal Steady State

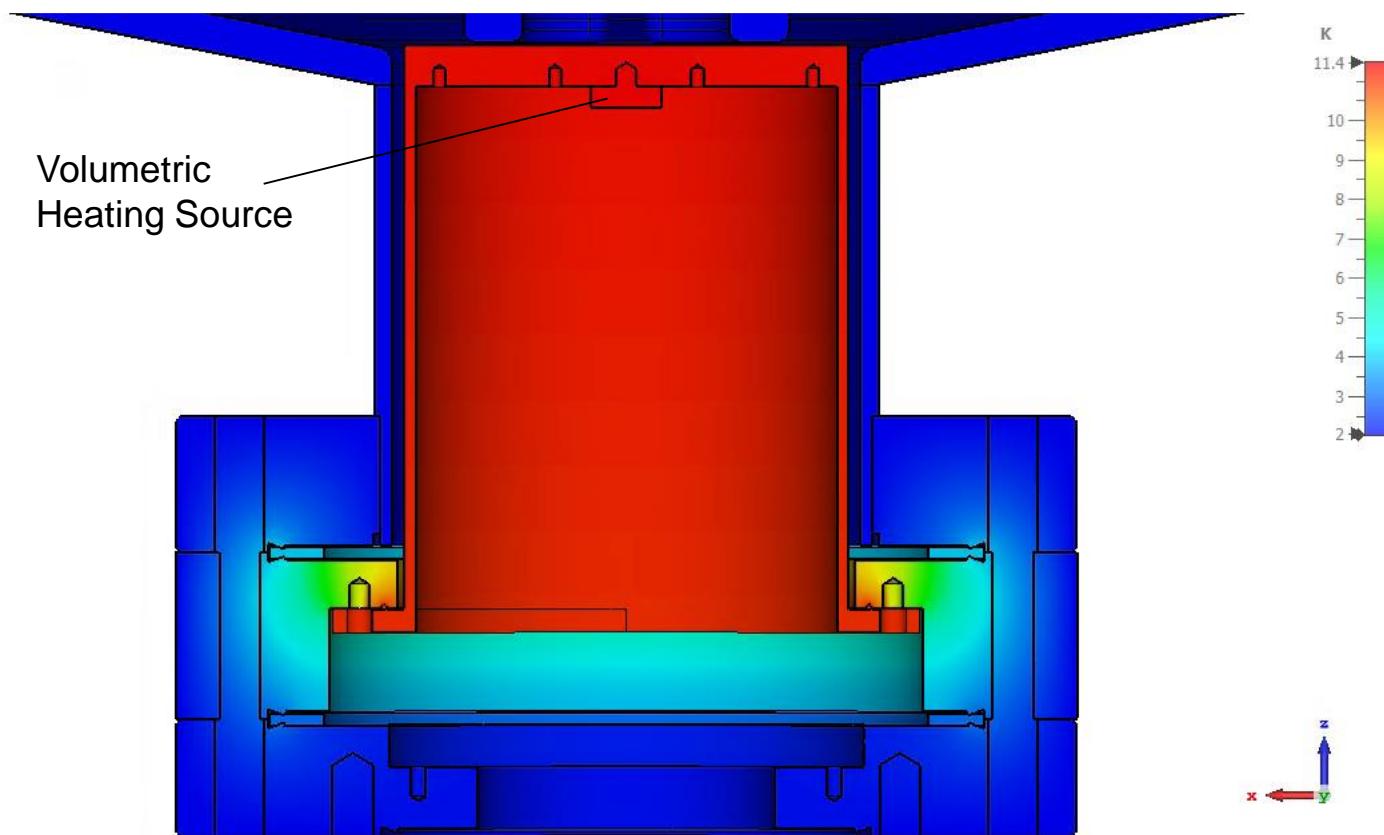
- Volume Heat Source Excitation
 - Heat Flow Density



Thermal Steady State



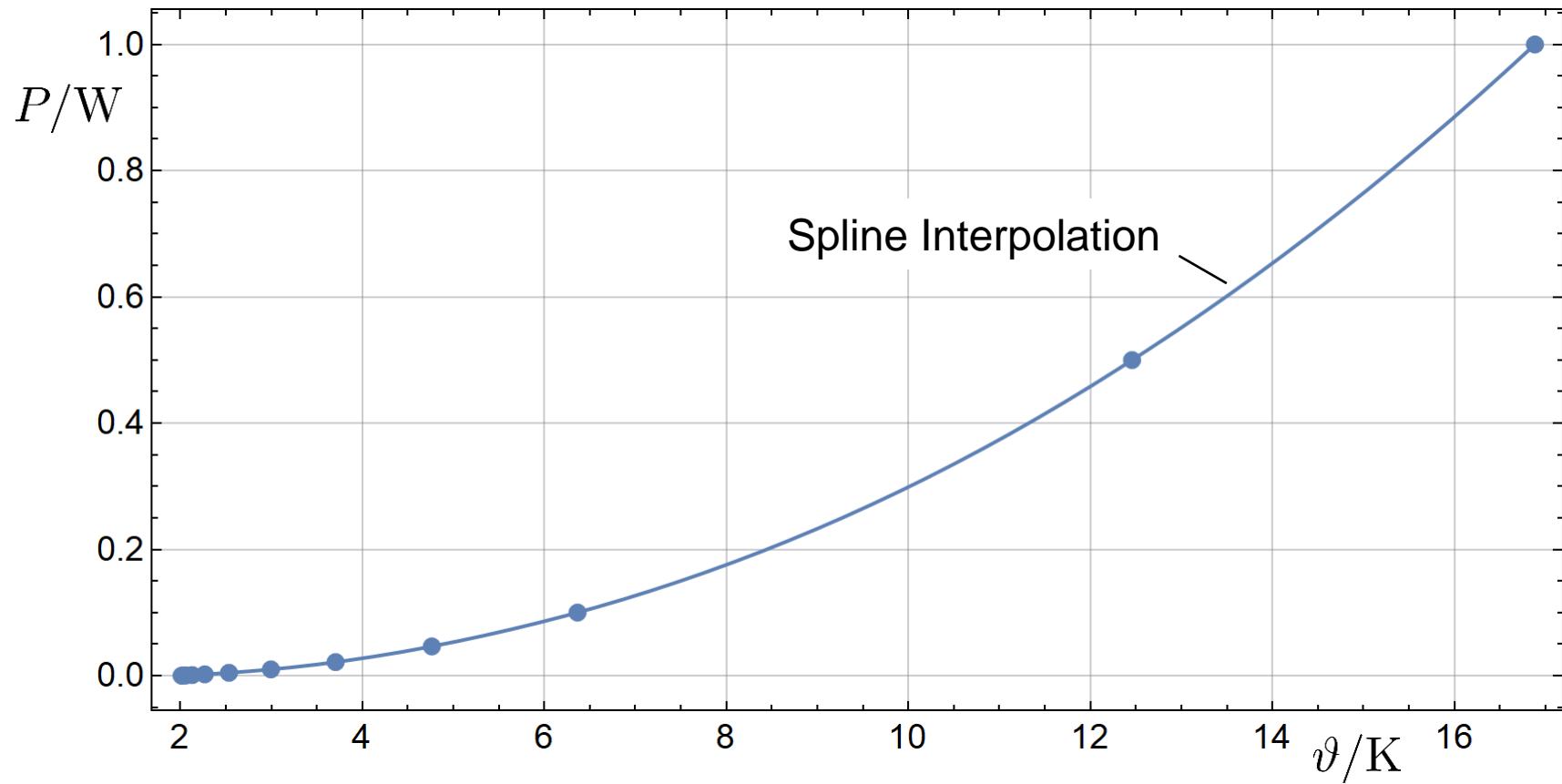
- Volume Heat Source Excitation
 - Temperature Distribution



Thermal Steady State



- Volume Heat Source Excitation



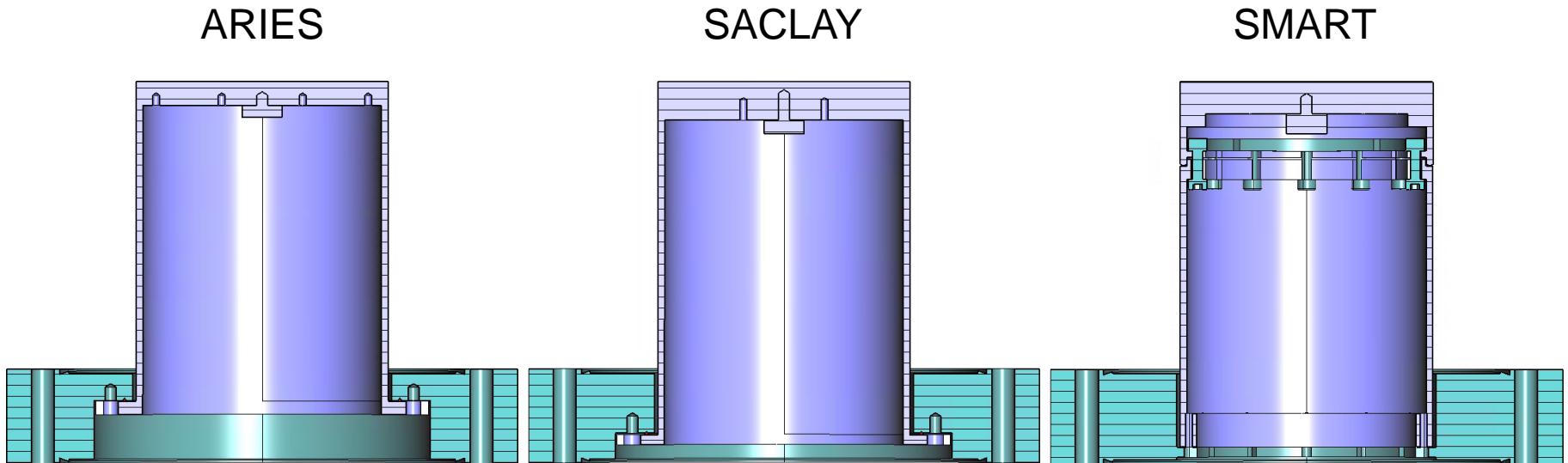
Overview



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Thermal Steady State

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



→ Comparison of different designs (using identical material properties)

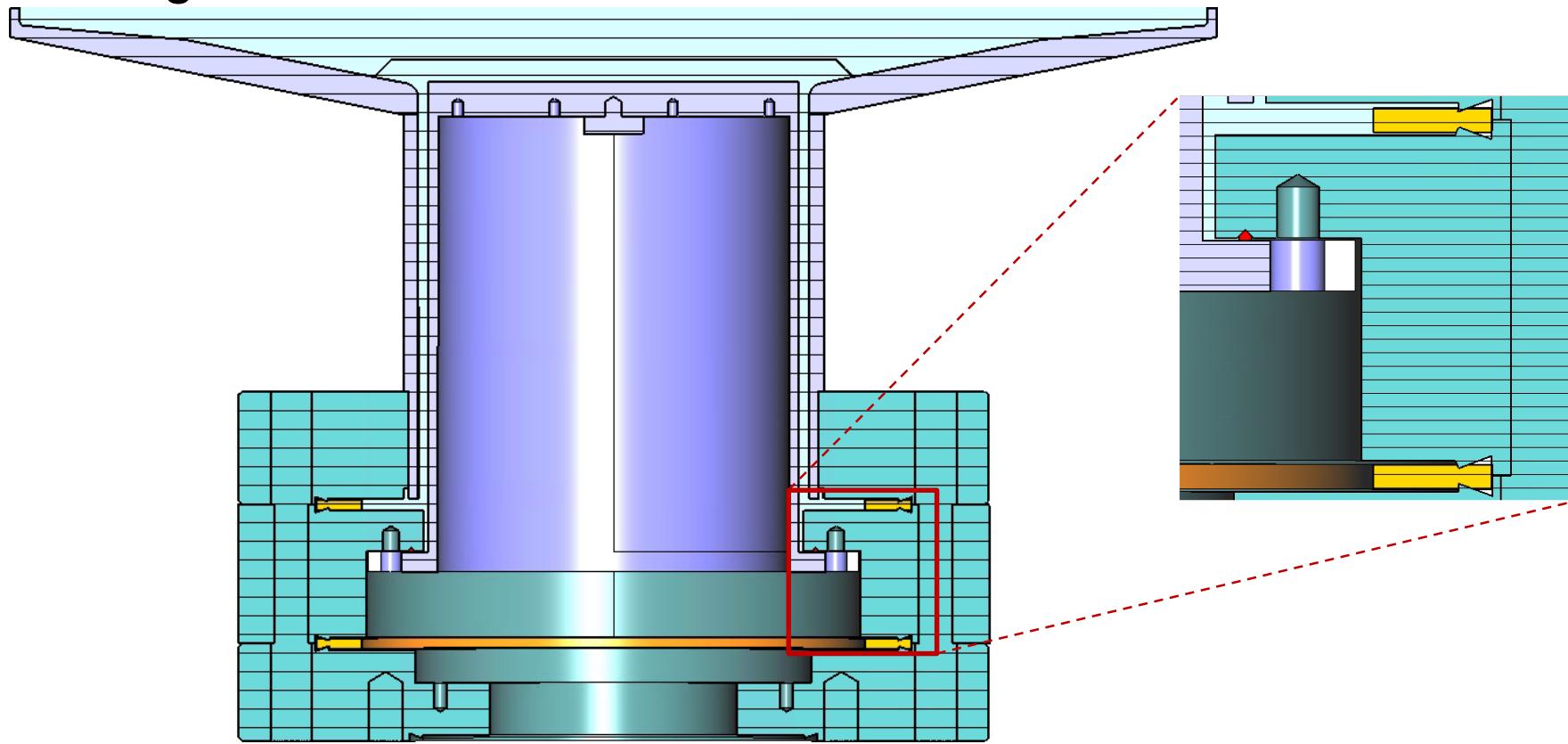
CAD data kindly provided by Sebastian Keckert

Thermal Steady State



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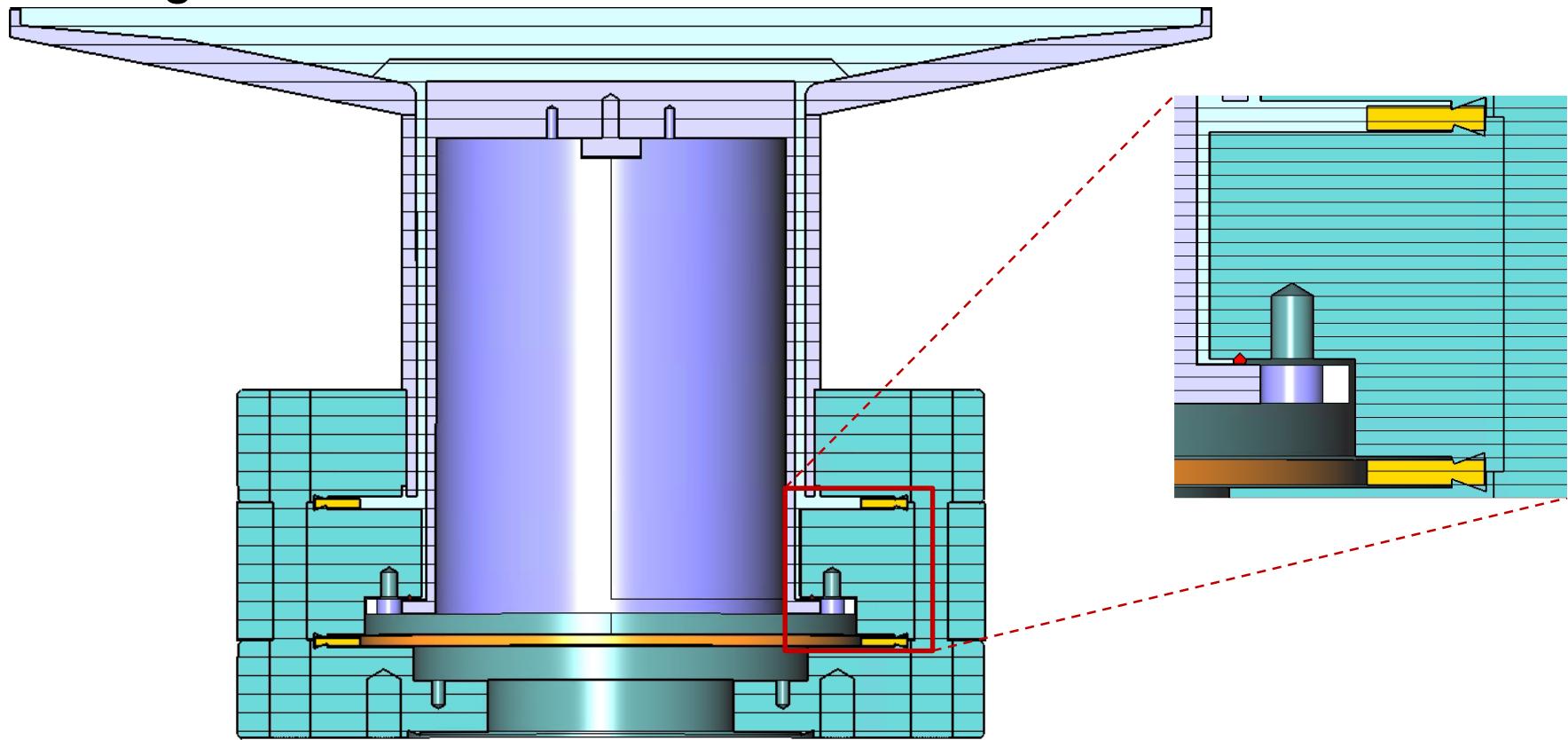
- Geometric Modeling
 - Design: ARIES



Thermal Steady State

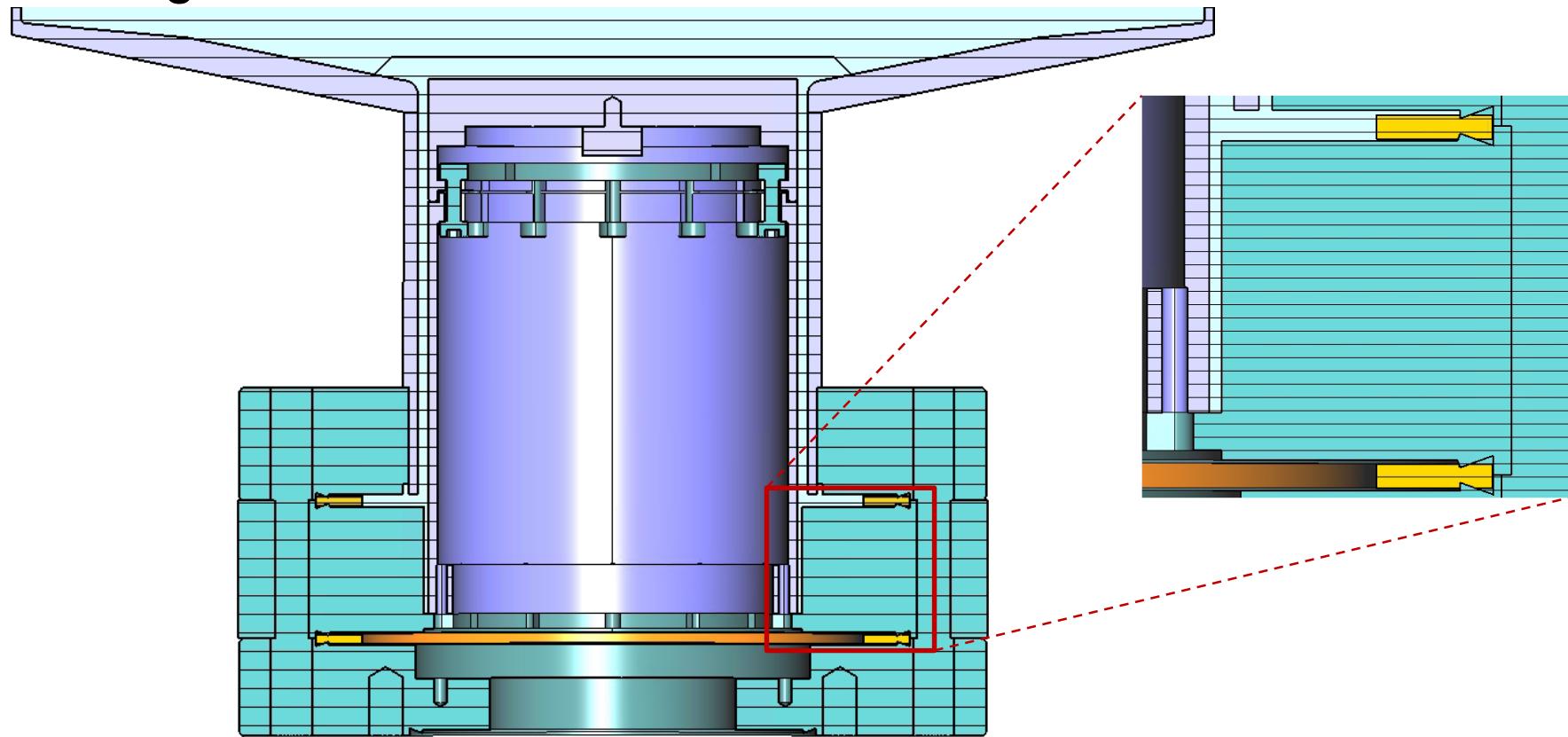


- Geometric Modeling
 - Design: SACLAY



Thermal Steady State

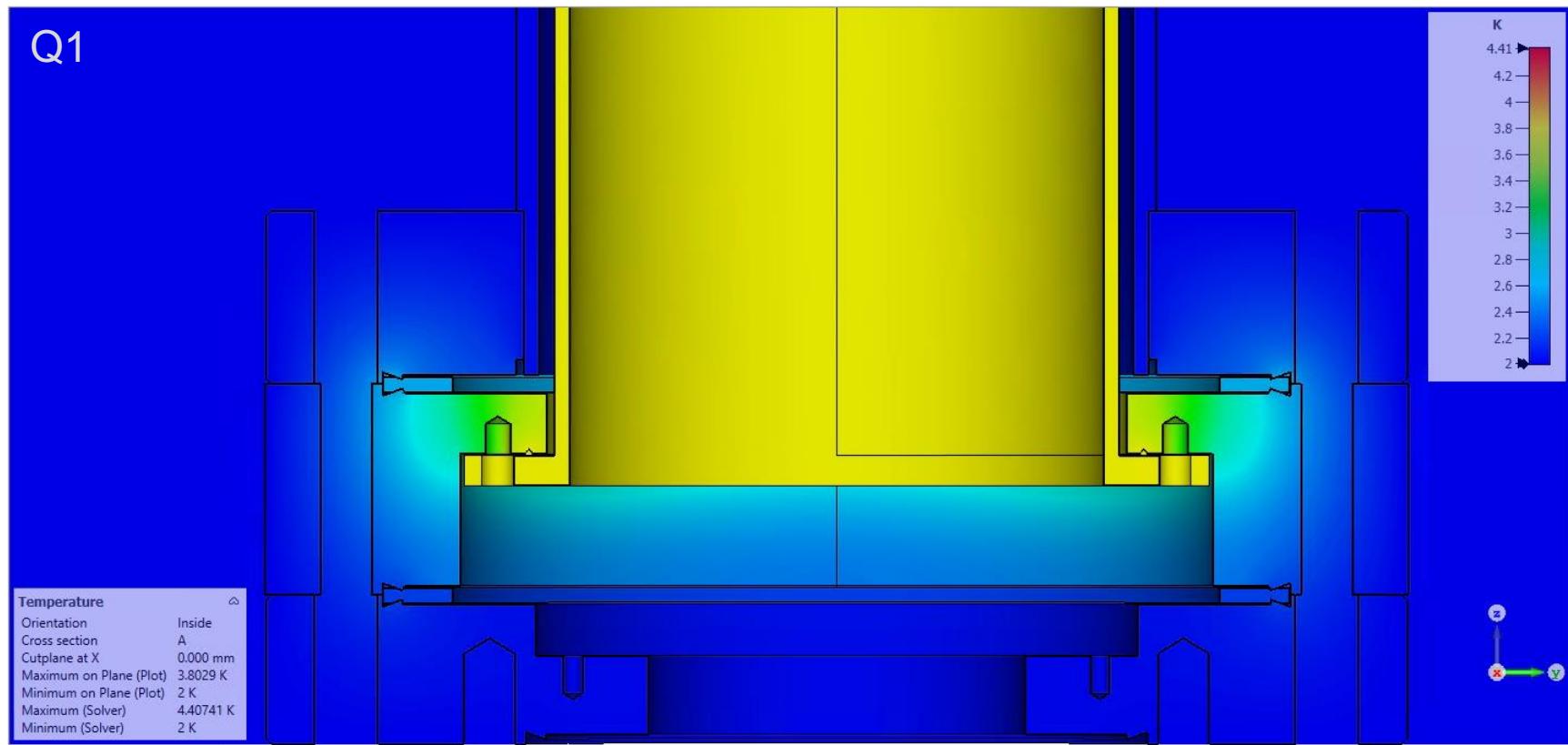
- Geometric Modeling
 - Design: SMART





Thermal Steady State

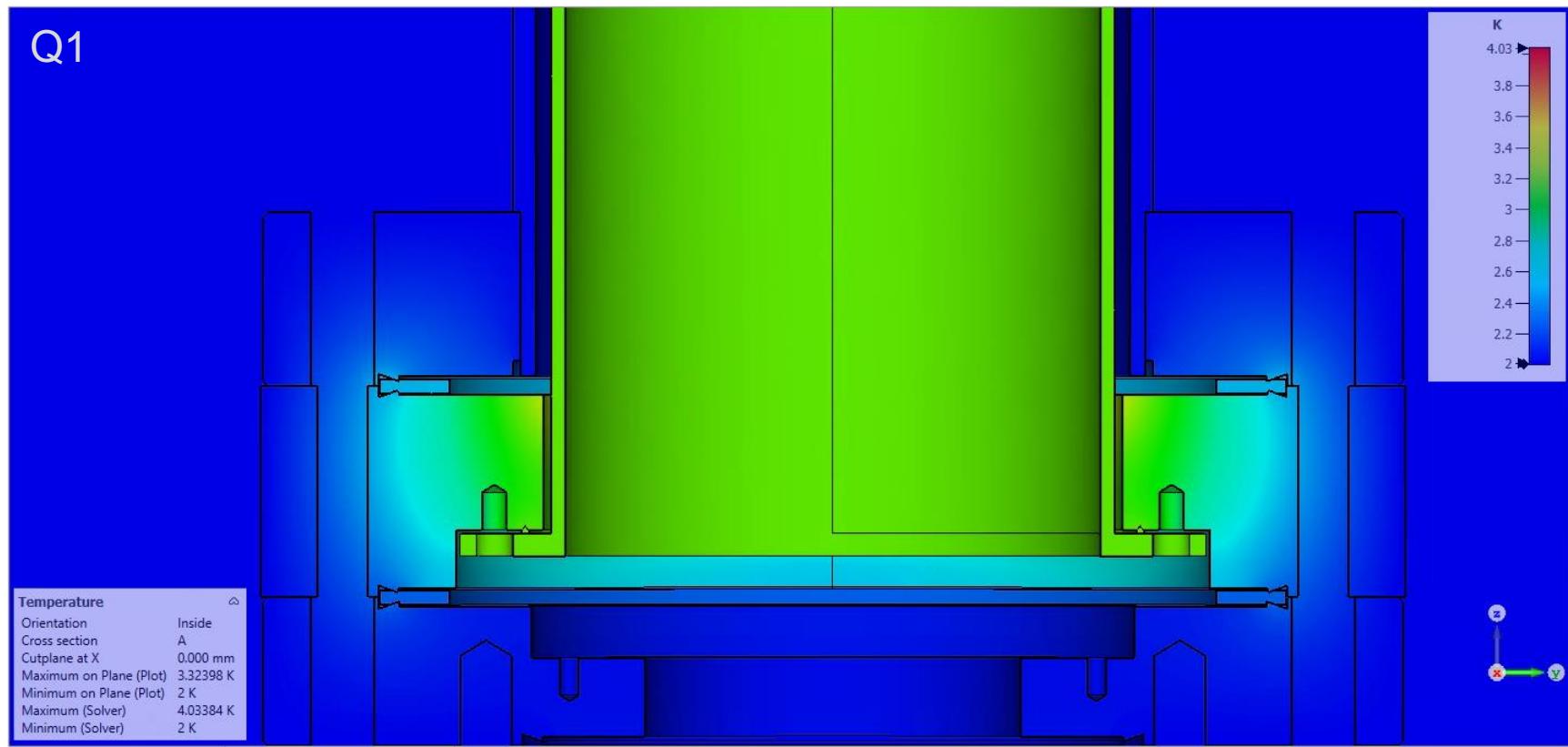
- ARIES Design



Thermal Steady State



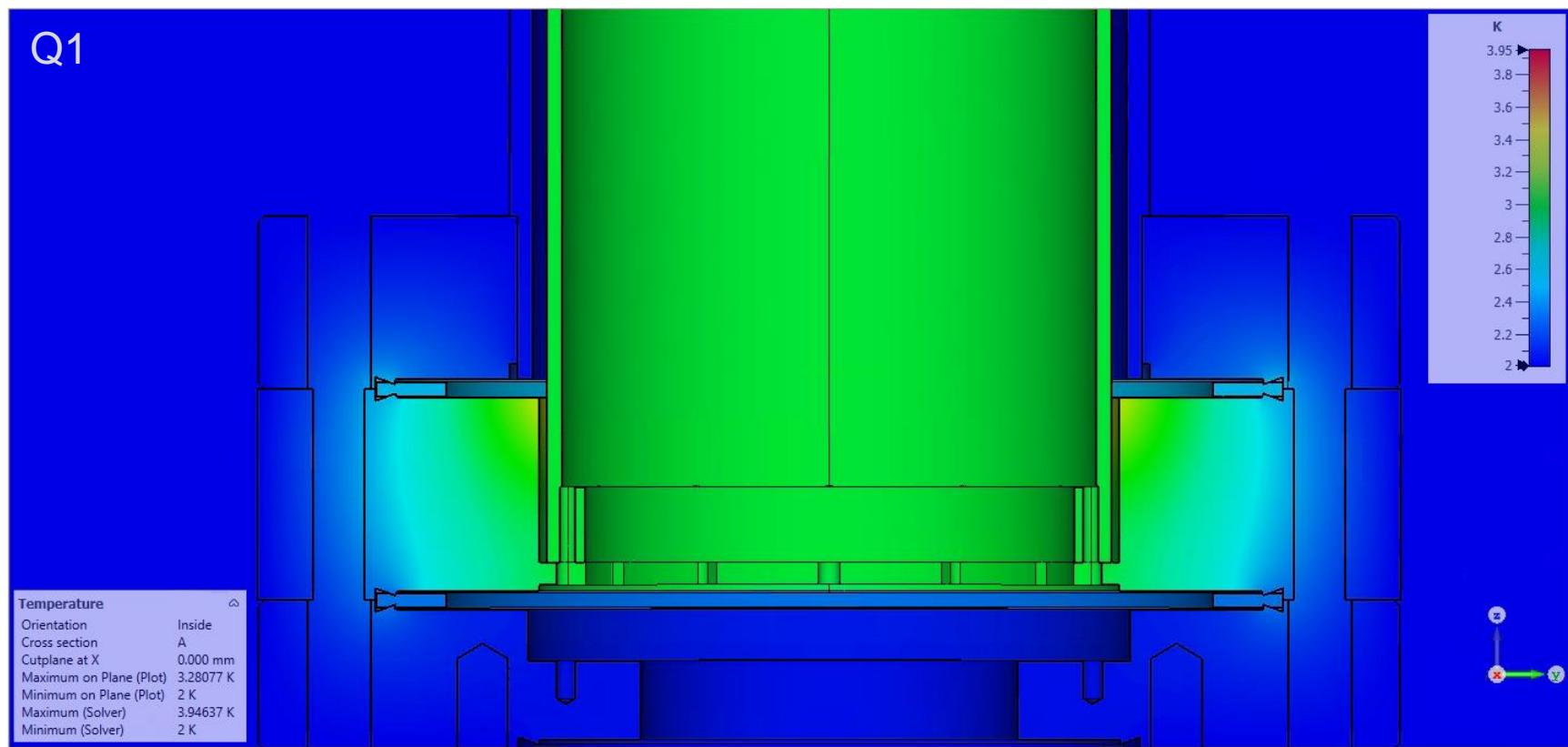
- SACLAY Design



Thermal Steady State



- SMART Design





Thermal Steady State

▪ Summary ARIES Design

(no additional flange cooling measures)

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	2,008	0,067	12,6	2,015	0,129	26.0	2,032	0,282	63,1
10	2,030	0,266	12,6	2,058	0,515	26,0	2,124	1,127	63,0
20	2,117	1,062	12,6	2,219	2,050	25,9	2,446	4,449	62,1
50	2,621	6,527	12,4	3,059	12,839	25,9	3,879	30,083	67,3
100	3,803	28,171	13,4	4,801	58,558	29,5	6,513	131,641	73,6



Thermal Steady State

▪ Summary SACLAY Design

(no additional flange cooling measures)

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	2,004	0,043	8,2	2,008	0,085	17,2	2,019	0,197	43,9
10	2,017	0,172	8,2	2,033	0,340	17,2	2,075	0,786	43,9
20	2,066	0,689	8,2	2,127	1,360	17,1	2,280	3,122	43,6
50	2,371	4,252	8,1	2,669	8,342	16,8	3,293	19,999	44,7
100	3,171	17,325	8,2	3,917	36,636	18,5	5,306	91,944	51,3



Thermal Steady State

▪ Summary SMART Design

(no additional flange cooling measures)

Sample temperature, effective power and parasitic surface resistance

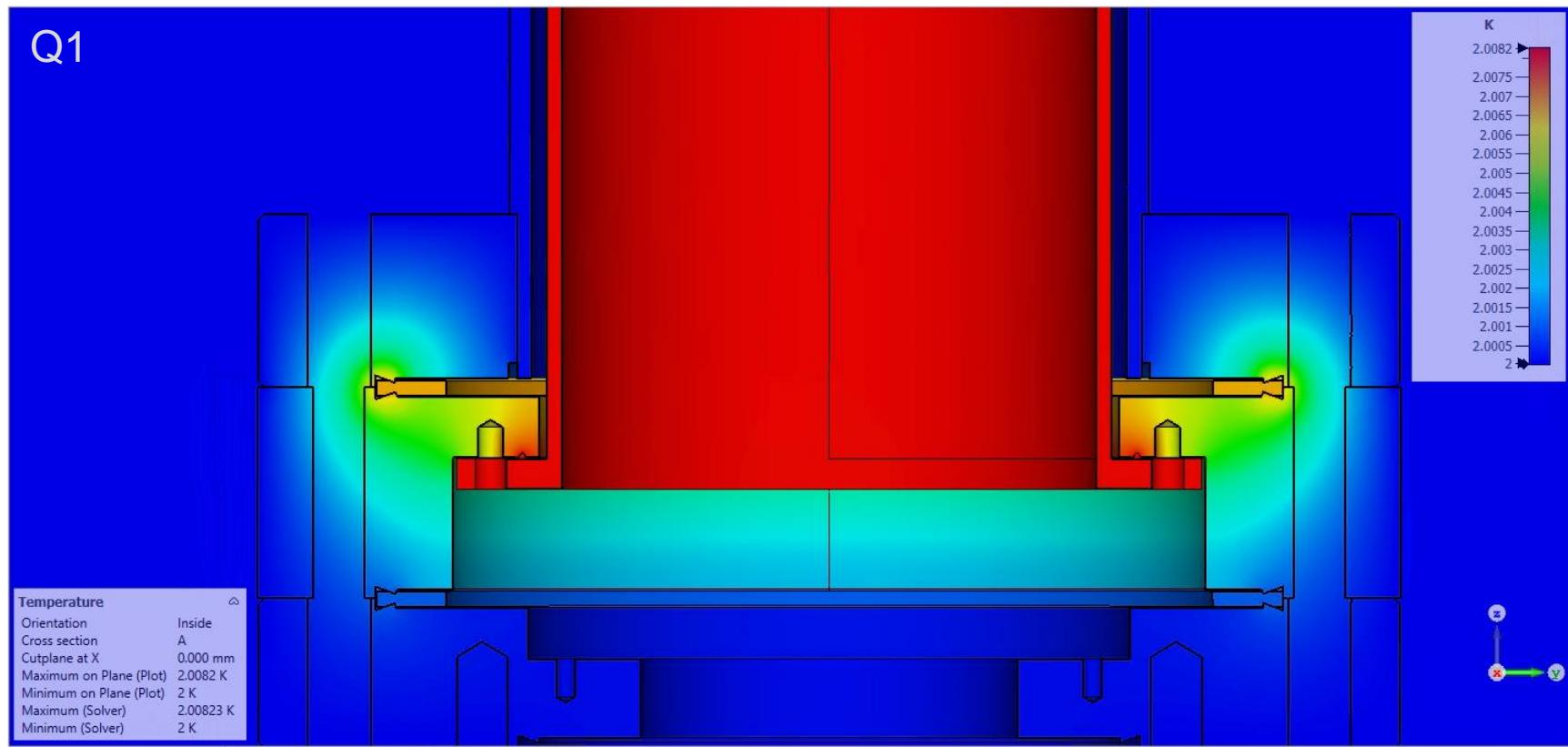
	Q1			Q2			Q3		
B / mT	T / K	P / mW	R / nΩ	T / K	P / mW	R / nΩ	T / K	P / mW	R / nΩ
5	2,003	0,025	4,7	2,006	0,050	10,0	2,014	0,116	25,8
10	2,012	0,100	4,7	2,024	0,200	10,0	2,054	0,463	25,8
20	2,047	0.401	4,7	2,092	0,797	10,0	2,206	1,844	25,7
50	2,273	2,490	4,7	2,504	4,909	9,9	3,008	11.516	25,6
100	2,900	9,924	4,7	3,515	20,591	10,4	4,689	51,851	28,9

Thermal Steady State



▪ ARIED Design

Stainless Steel Flanges coated with Niobium

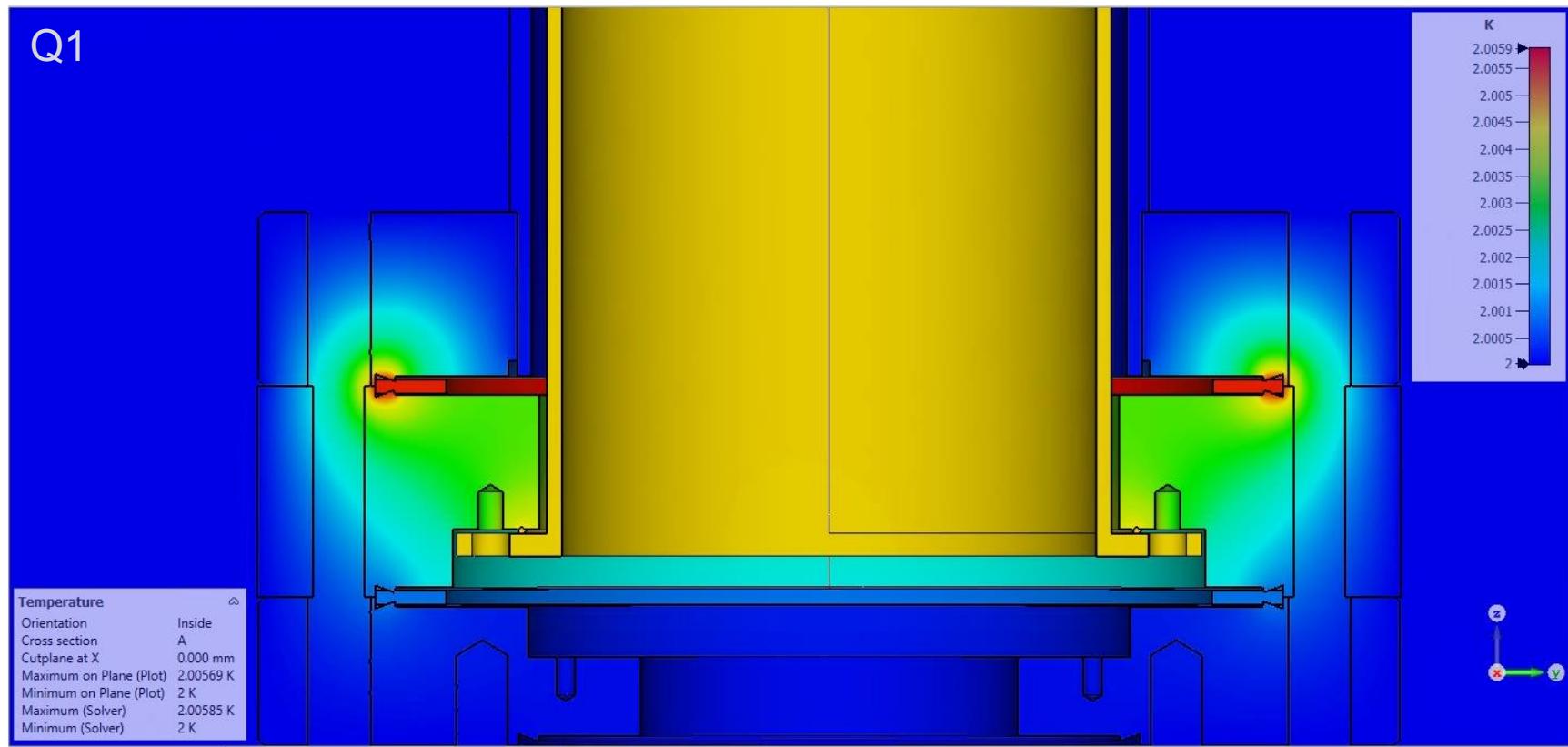


Thermal Steady State



▪ SACLAY Design

Stainless Steel Flanges coated with Niobium

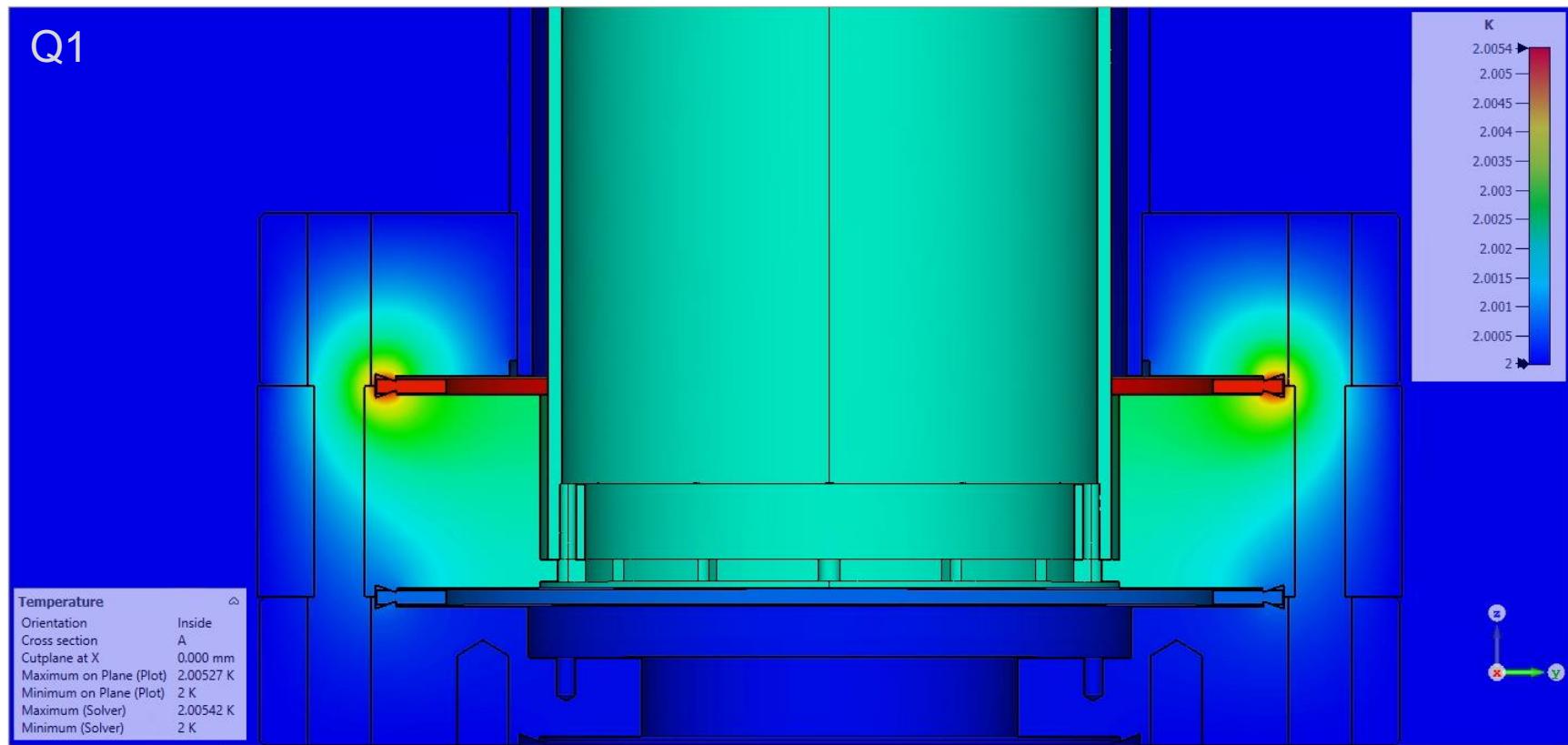


Thermal Steady State



▪ SMART Design

Stainless Steel Flanges coated with Niobium

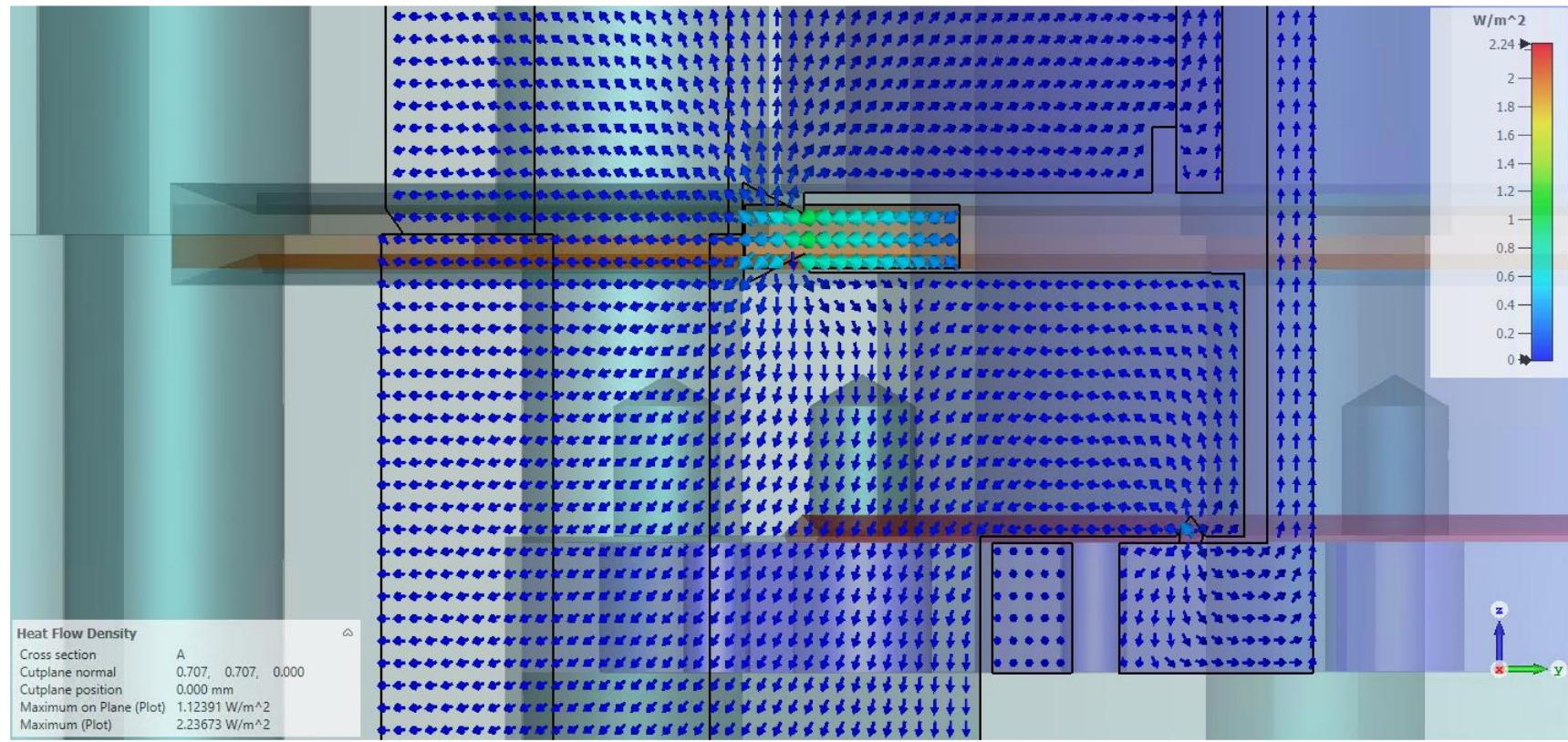


Thermal Steady State



▪ ARIED Design

Stainless Steel Flanges coated with Niobium





Thermal Steady State

▪ 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

▪ 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



▪ Summary SMART Design

(Stainless Steel Flanges coated with Niobium)

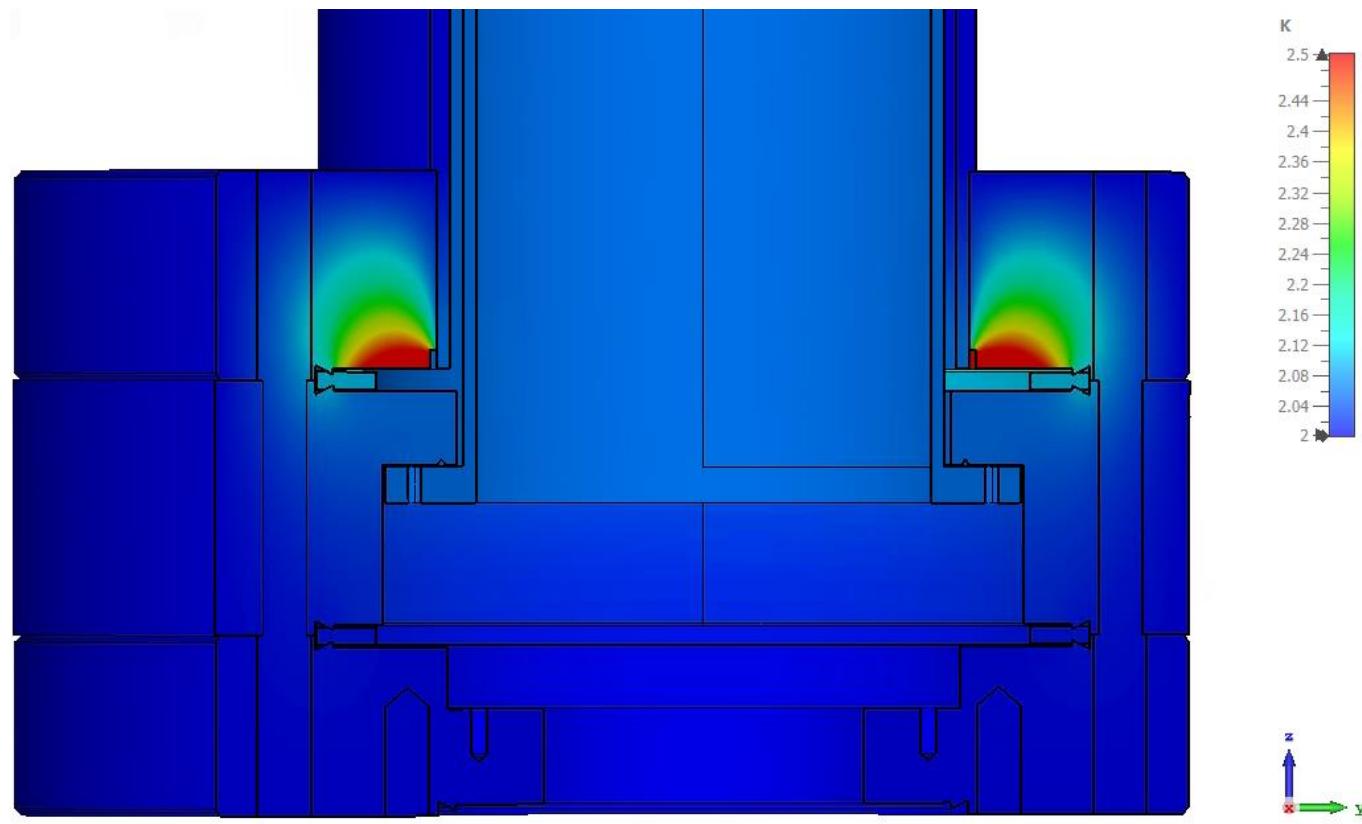
Sample temperature, effective power and parasitic surface resistance

	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

Thermal Steady State

- ARIED Design

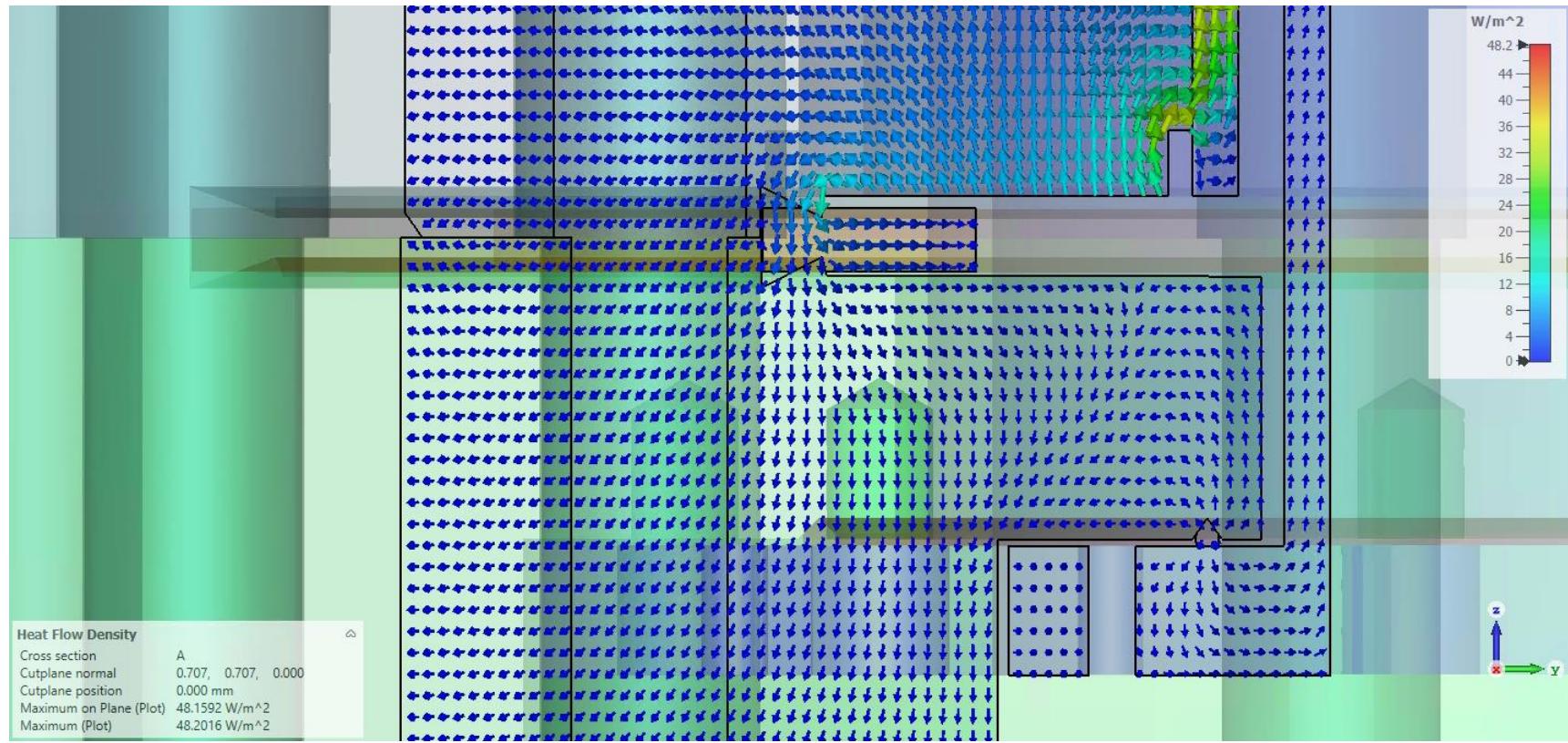
Stainless Steel Flange coated with Niobium



Thermal Steady State

▪ ARIED Design

Stainless Steel Flange coated with Niobium





Thermal Steady State

▪ Summary ARIES Design

(Stainless Steel Flange 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	0,001	0,258	2,000	0,003	0,542	2,001	0,006	1,356
10	2,001	0,005	0,258	2,001	0,011	0,542	2,003	0,024	1,356
20	2,002	0,022	0,258	2,005	0,043	0,542	2,011	0,097	1,356
50	2,016	0,136	0,258	2,030	0,268	0,542	2,068	0,606	1,354
100	2,061	0,544	0,258	2,118	1,071	0,540	2,255	2,408	1,346



Thermal Steady State

▪ Summary SACLAY Design

(Stainless Steel Flange 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	0,001	0,192	2,000	0,402	0.048	2,000	0,005	1,020
10	2,000	0,004	0,192	2,001	0,402	0.048	2,002	0,018	1,020
20	2,002	0,016	0,192	2,003	0,402	0.048	2,007	0,073	1,020
50	2,010	0,101	0,192	2,019	0,402	0.048	2,044	0,457	1,020
100	2,039	0,404	0,192	2,076	0,402	0.048	2,169	1,823	1,017



Thermal Steady State

▪ Summary SMART Design

(Stainless Steel Flange 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	0,001	0,118	2,000	0,001	0,247	2,000	0,003	0,620
10	2,000	0,003	0,118	2,001	0,005	0,247	2,001	0,011	0,620
20	2,001	0,010	0,118	2,002	0,020	0,247	2,005	0,045	0,620
50	2,007	0,063	0,118	2,015	0,123	0,247	2,033	0,278	0,619
100	2,030	0,250	0,118	2,058	0,491	0,247	2,127	1,109	0,617

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Eigenmode Solver



- ARIES Design
 - Waveguide magnitudes

Modes Q1,Q2,Q3

$z = 2 \text{ mm}$

$z = 42 \text{ mm}$

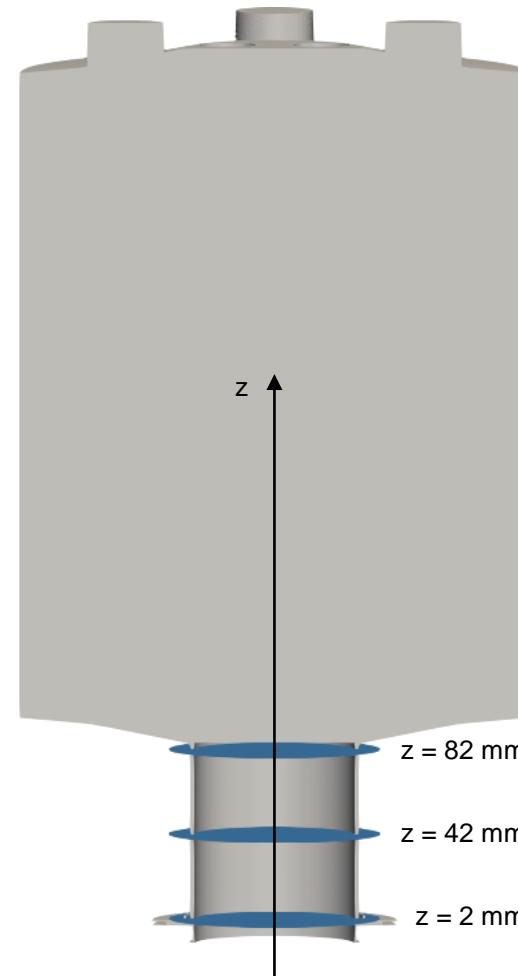
$z = 82 \text{ mm}$

$n_{\text{Rad}} = 10$

$n_{\Phi} = 1.210$

$n_Z = 3$

$n_{\text{Points}} = 36.300$



Eigenmode Solver



- ARIES Design
 - Waveguide magnitudes

Modes Q1,Q2,Q3

$z = 2 \text{ mm}$

$z = 42 \text{ mm}$

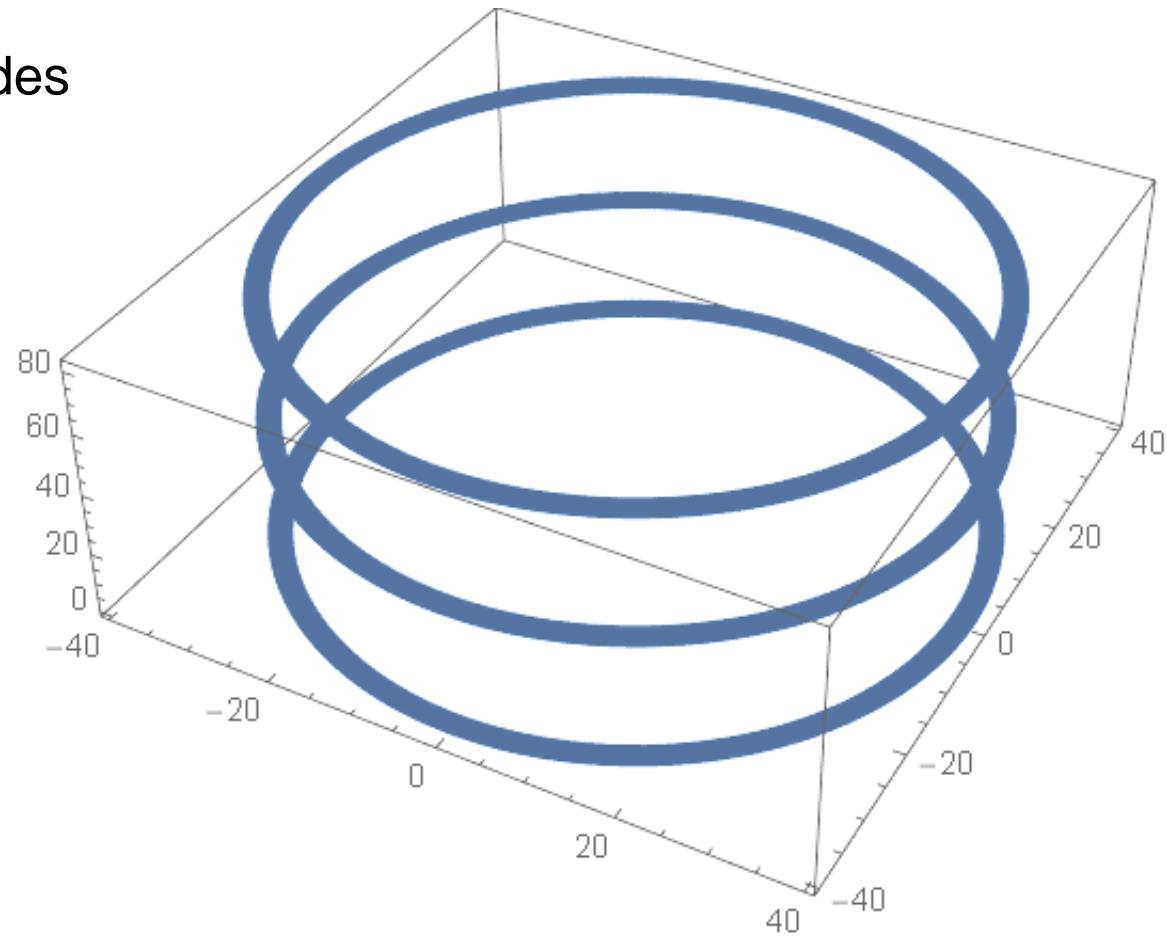
$z = 82 \text{ mm}$

$n_{\text{Rad}} = 10$

$n_{\Phi} = 1.210$

$n_Z = 3$

$n_{\text{Points}} = 36.300$

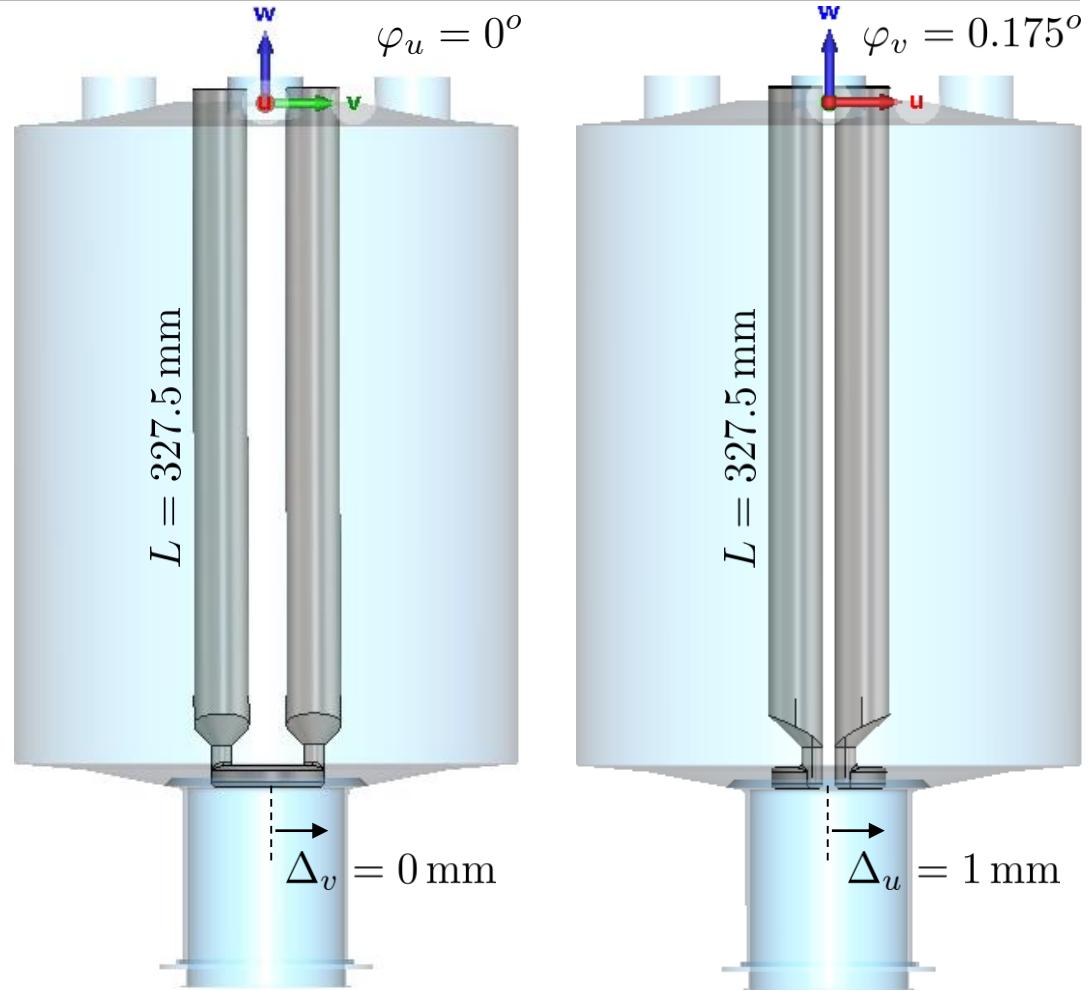


Eigenmode Solver



▪ ARIES Design

- Artificial tilt of the rods
- Cavity and probe unchanged
- Excitation of asymmetric fields in the vicinity of the probe
- Calculation of the 3D field for the modes Q1,Q2,Q3
- Extraction of the modal field amplitudes in the coaxial gap



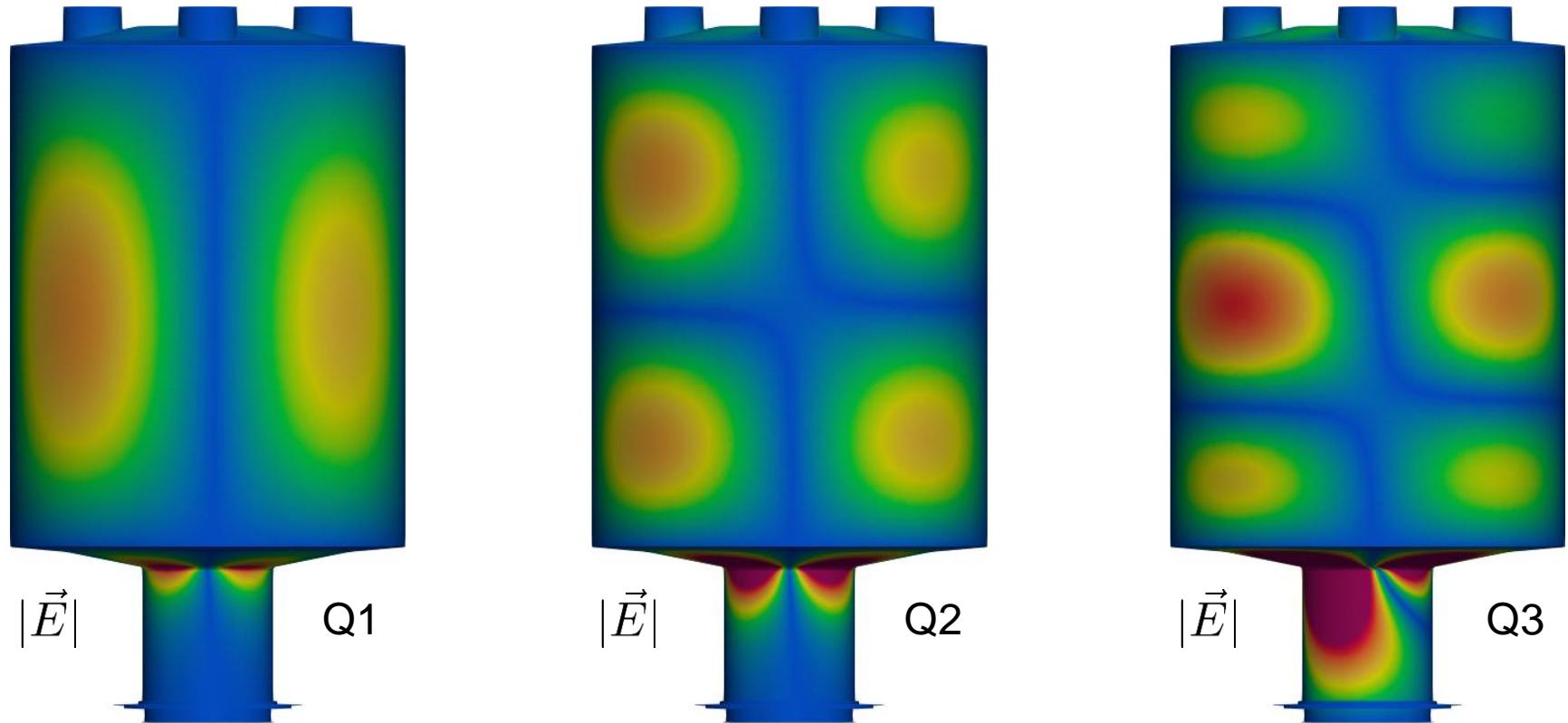
Eigenmode Solver



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- ARIES Design
 - Field distribution

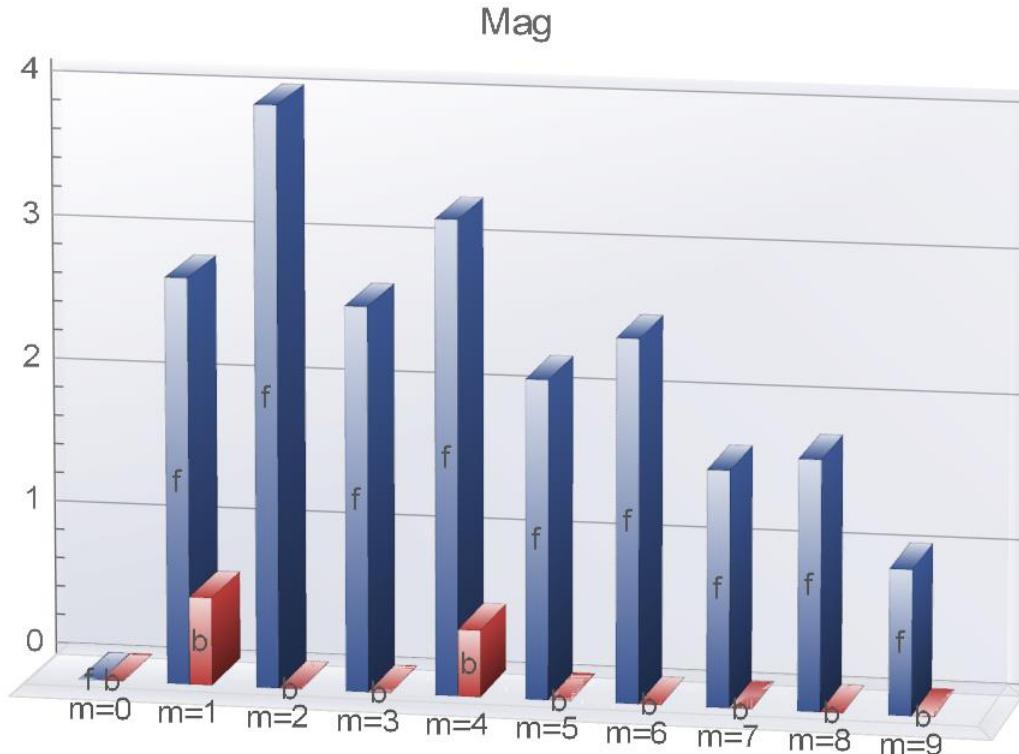
$$\begin{aligned}\varphi_u &= 0^\circ \\ \varphi_v &= 0.175^\circ\end{aligned}$$



Eigenmode Solver

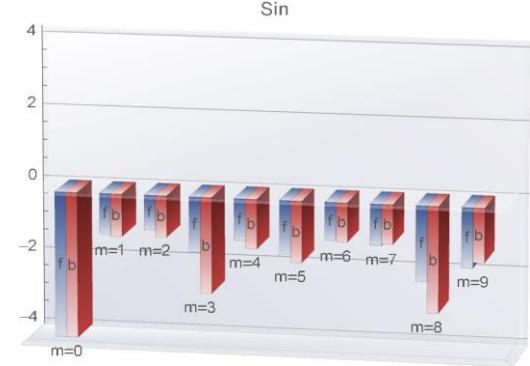
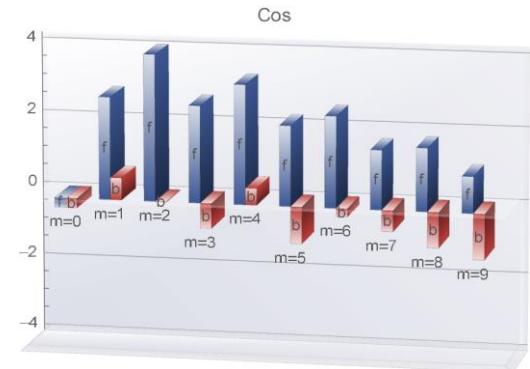


- Waveguide Magnitudes
 - Mode Q1 @ z=82mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

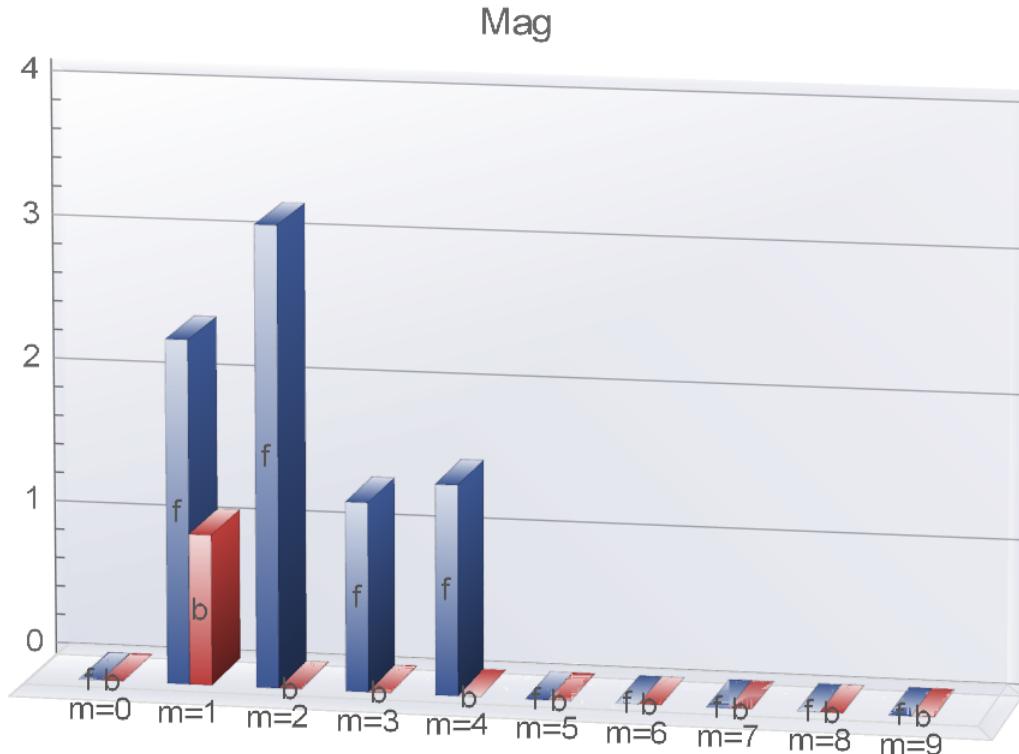
$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Eigenmode Solver

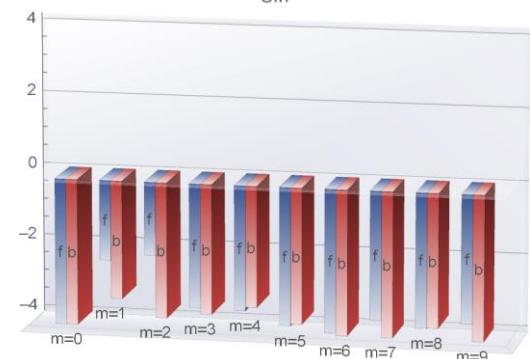
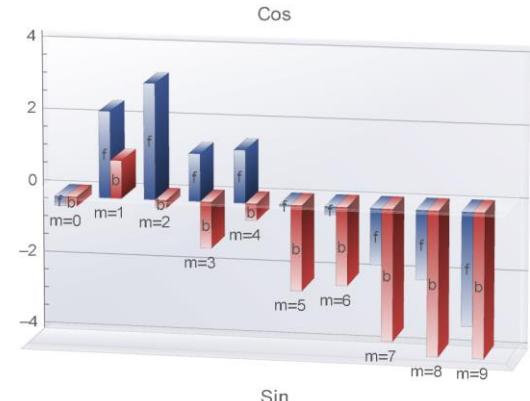


- Waveguide Magnitudes
 - Mode Q1 @ z=42mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

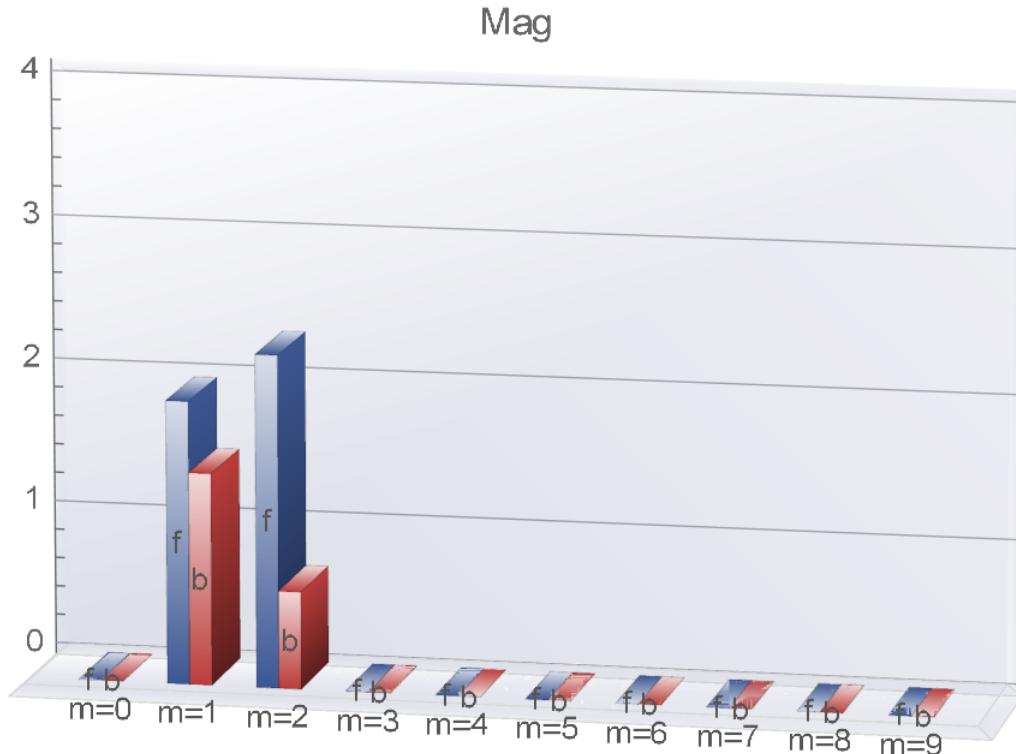
$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Eigenmode Solver

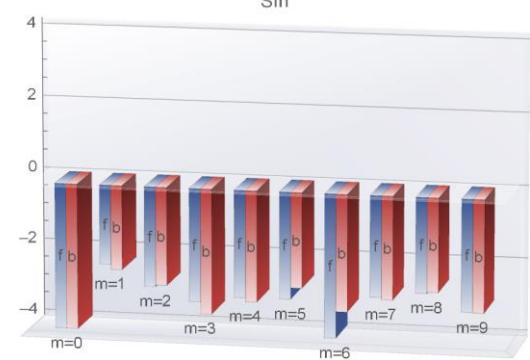
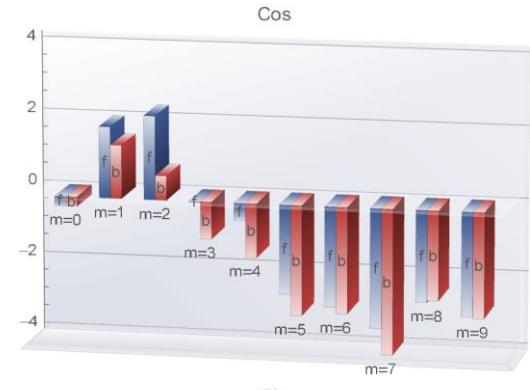


- Waveguide Magnitudes
 - Mode Q1 @ z=2mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

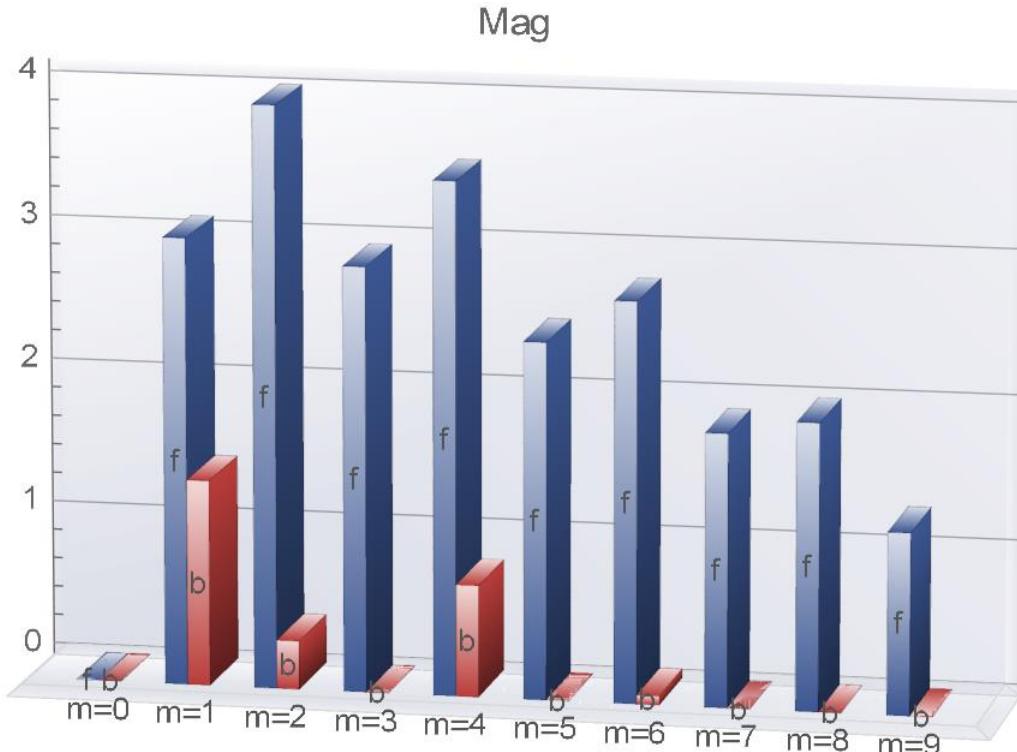
$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Eigenmode Solver

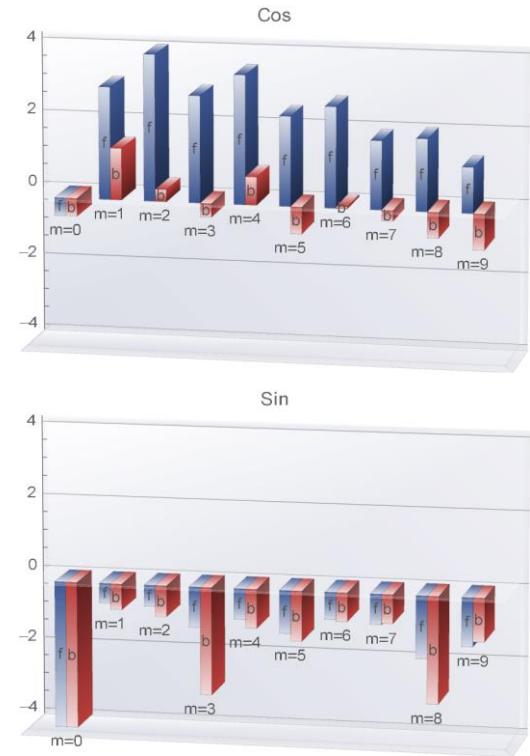


- Waveguide Magnitudes
 - Mode Q2 @ z=82mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

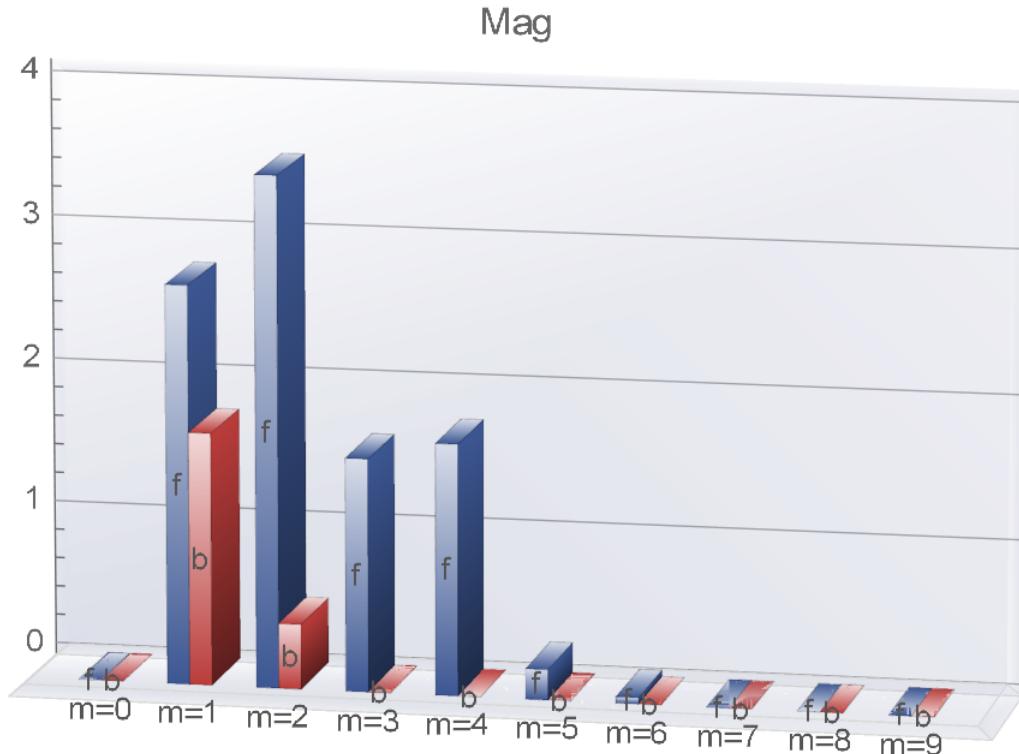
$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Eigenmode Solver

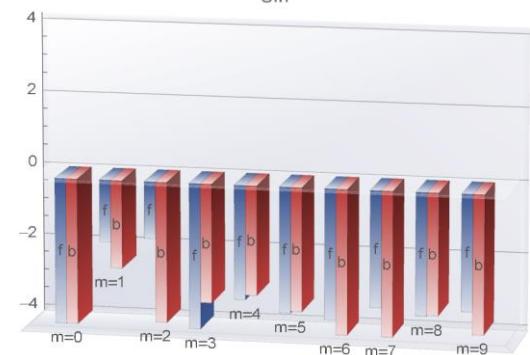
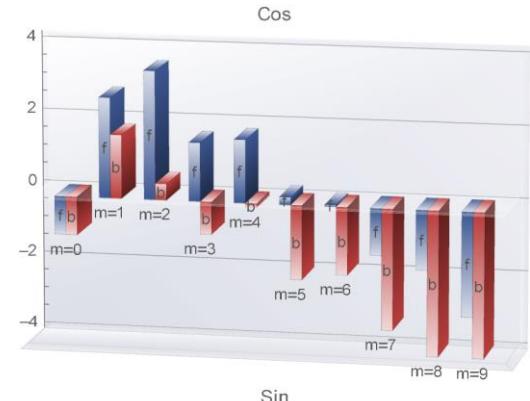


- Waveguide Magnitudes
 - Mode Q2 @ z=42mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

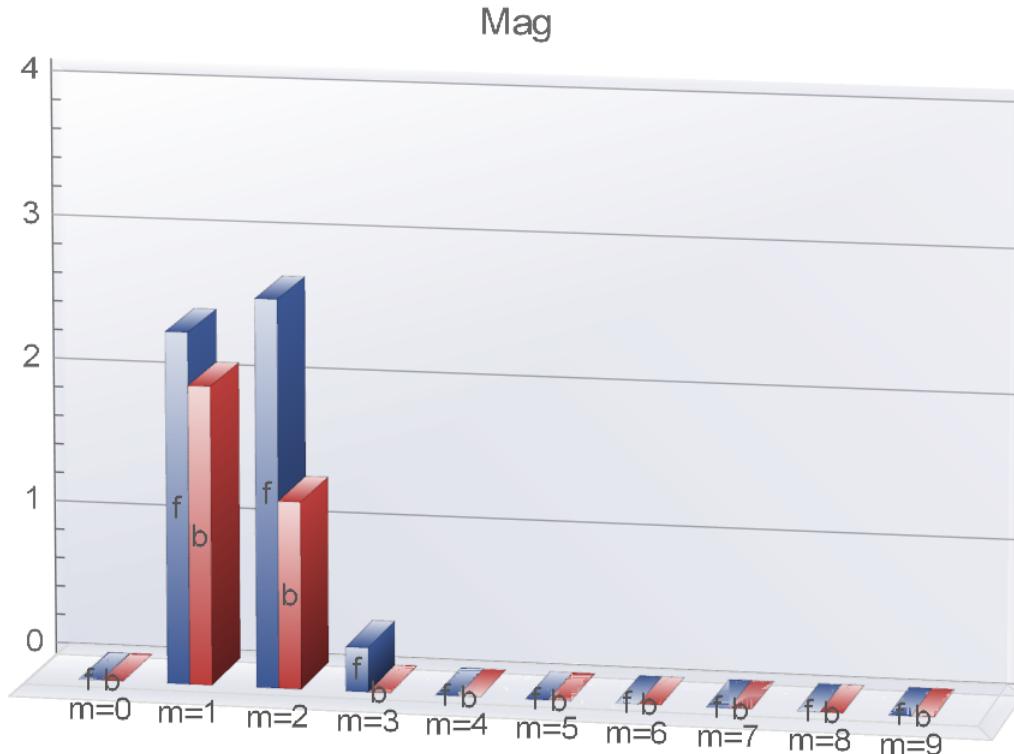
$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Eigenmode Solver



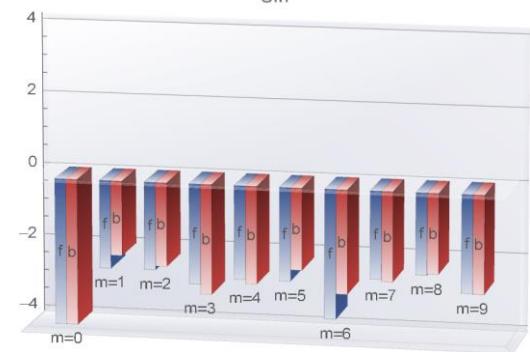
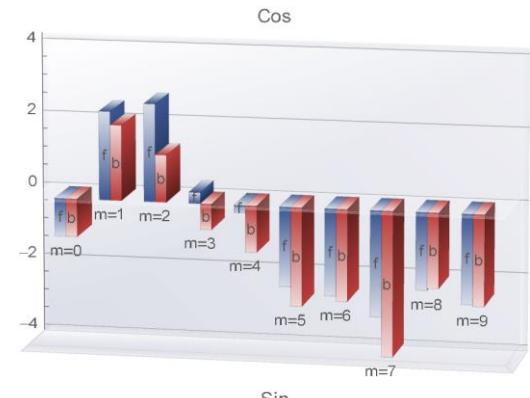
- Waveguide Magnitudes
 - Mode Q2 @ z=2mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$

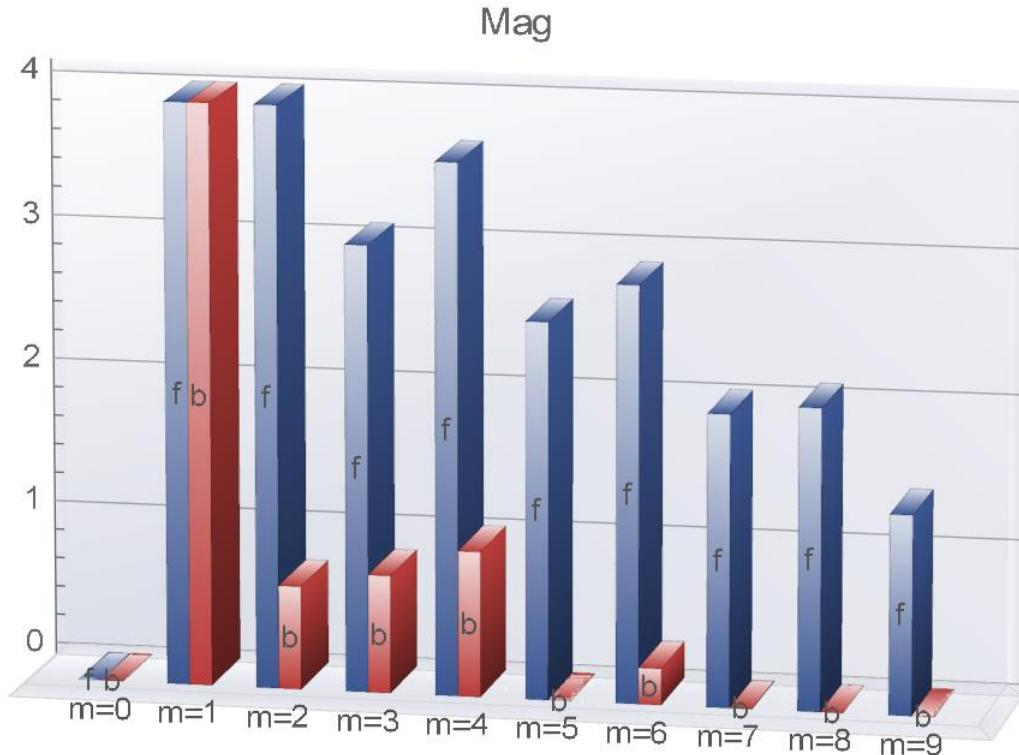
forward
backward



Eigenmode Solver



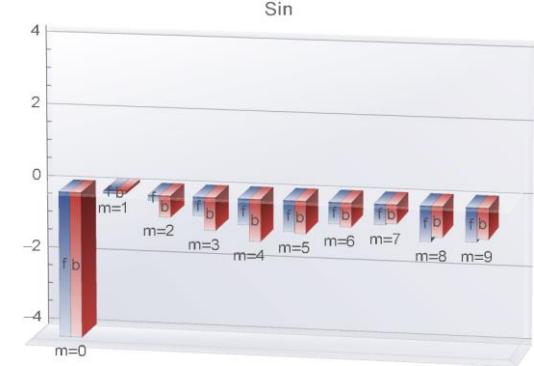
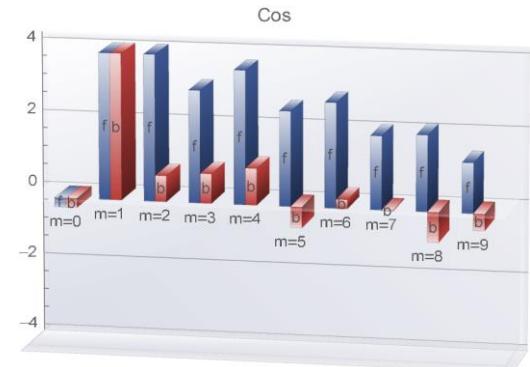
- Waveguide Magnitudes
 - Mode Q3 @ z=82mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

$$f_{c,\text{dipole}} = 1239.4 \text{ MHz}$$

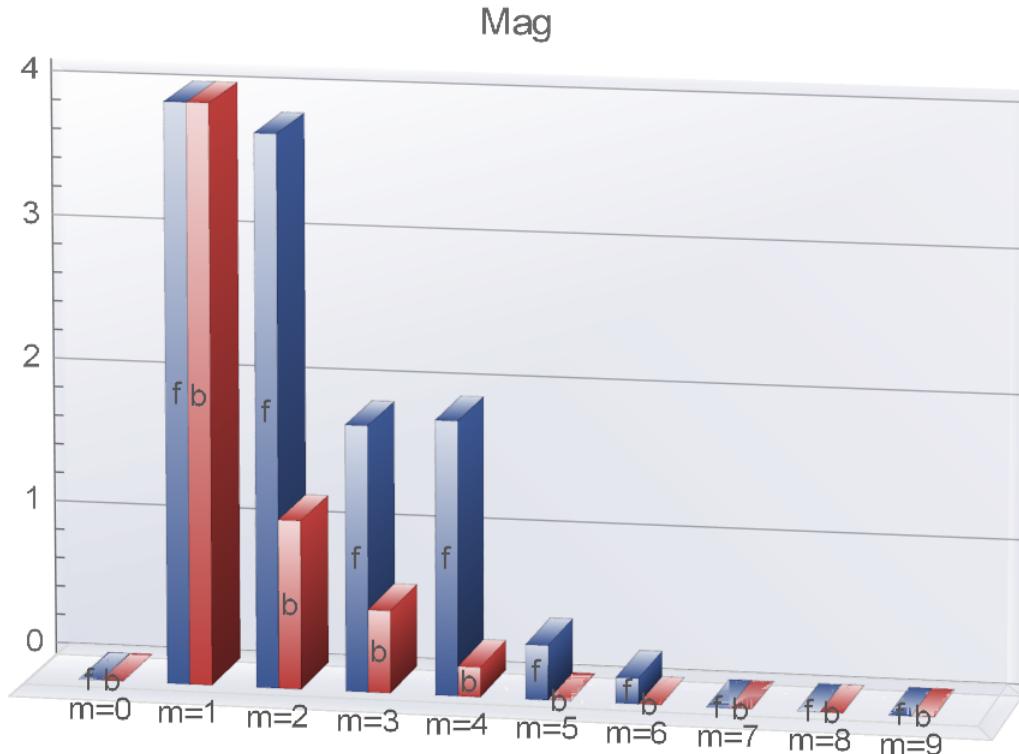
$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Eigenmode Solver

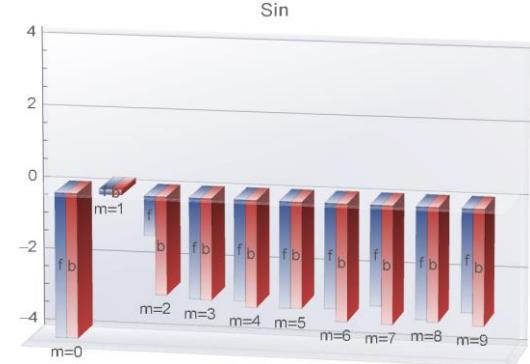
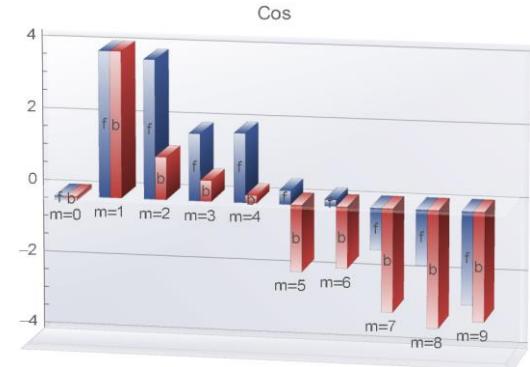


- Waveguide Magnitudes
 - Mode Q3 @ z=42mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$

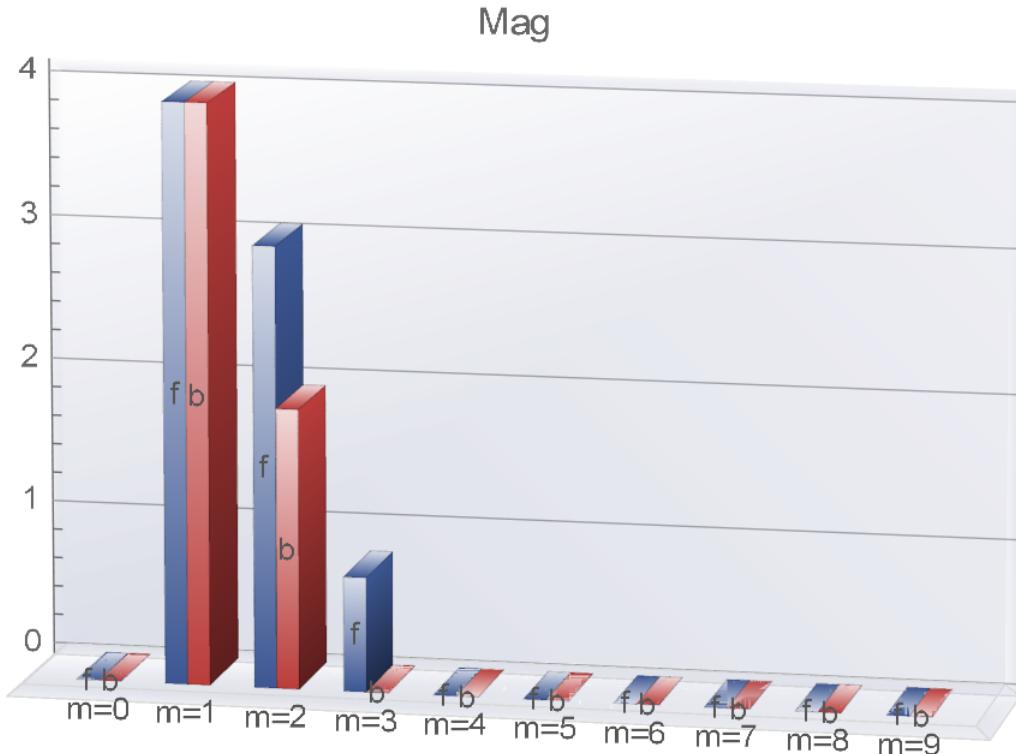


$$f_{c,\text{dipole}} = 1239.4 \text{ MHz}$$

Eigenmode Solver



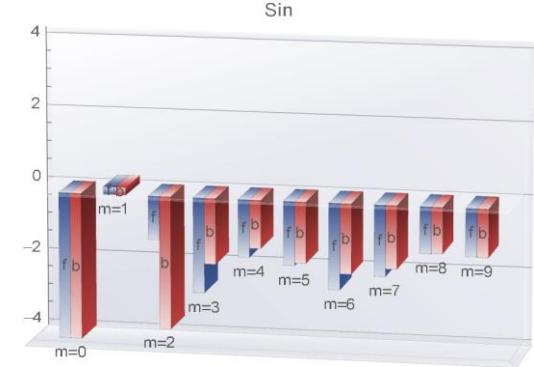
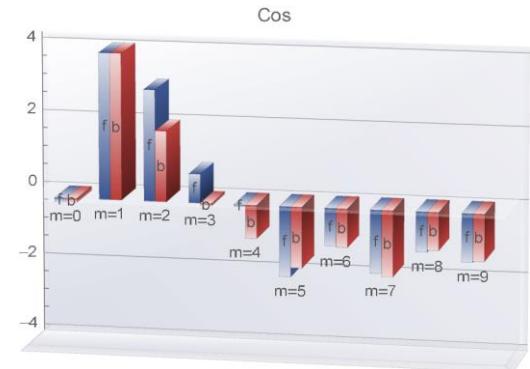
- Waveguide Magnitudes
 - Mode Q3 @ z=2mm (logarithmic scaling)



Azimuthal order $m = 0$: monopole, $m = 1$: dipole, $m = 2$: quadrupole, ...

$$f_{c,\text{dipole}} = 1239.4 \text{ MHz}$$

$$\varphi_u = 0^\circ$$
$$\varphi_v = 0.175^\circ$$



Overview



- Motivation
- Quadrupole Resonator
 - 3D Eigenmode calculations
 - Thermal steady state calculations
 - Material modeling and heat sources
 - Application to different probe geometries
- Quadrupole Resonator with Tilted Rods
 - 2D Eigenmode calculations in the coaxial gap
- Summary and Outlook

Summary and Outlook



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- Summary
 - QPR: Precise geometry model
 - Eigenmodes
 - Surface heat source
 - Temperature distribution
 - Determination of the parasitic surface resistance
- Outlook
 - Modeling of coated niobium as a multilayer structure

End