Local Loss Estimations based on Eigenvalue Calculations

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2nd Quadrupole Resonator Workshop
Zoom Meeting
November 23, 2020

Outline

- Motivation
- Numerical Solver Development
  - Superconducting Billards (lossless)
  - TESLA Resonators (lossy)
- Quadrupole Resonator
  - Mounting Cylinder (short/long slit)
  - Mounting Cylinder (connected/isolated sample)
  - Mounting Cylinder (straight/zigzag slit)
- Summary

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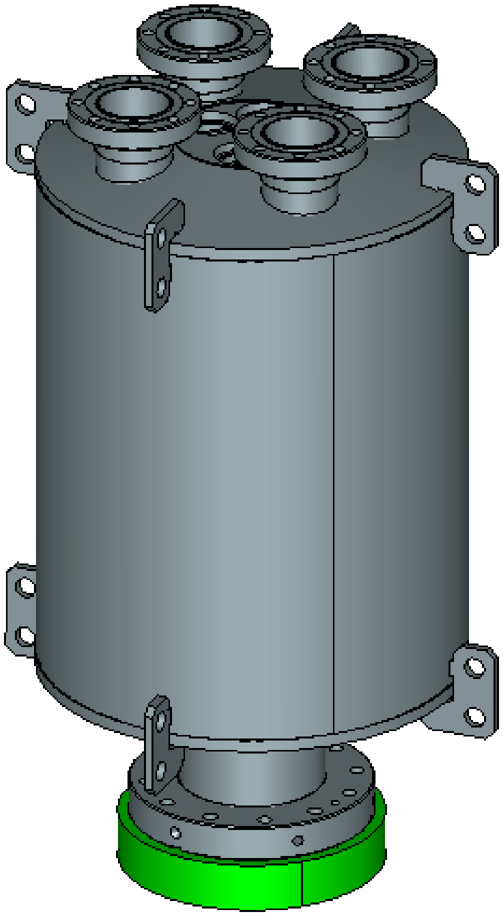
Motivation

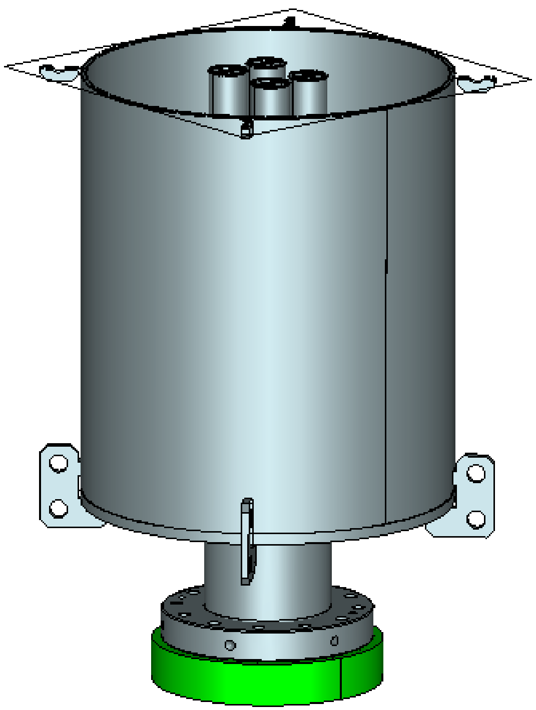
- Quadrupole Resonator
  - Radio frequency characterization of superconductor materials used for particle accelerators
  - Geometry models from Marc Wenskat, Oliver Kugeler and Sebastian Keckert
  - Eigenmode calculation based on the FEM using curved tetrahedral elements and a robust JD eigenvalue solver

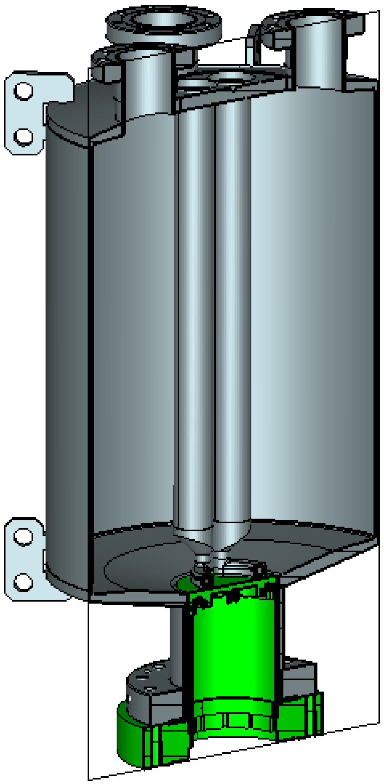


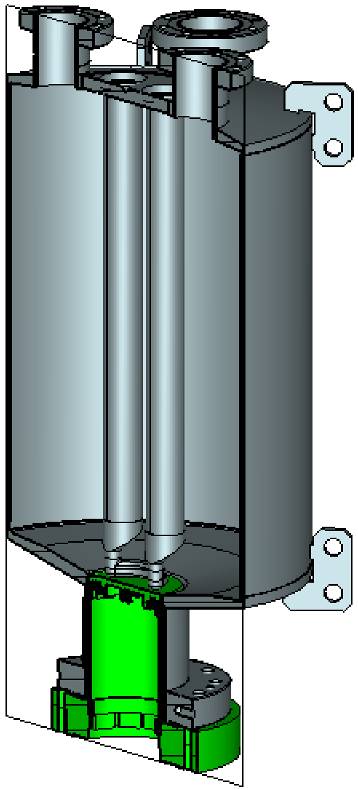
→ Determination of the electric and magnetic field distribution in the entire computational domain

Quadrupole Resonator

- Geometry Information
  - Cut views


xy plane


xz plane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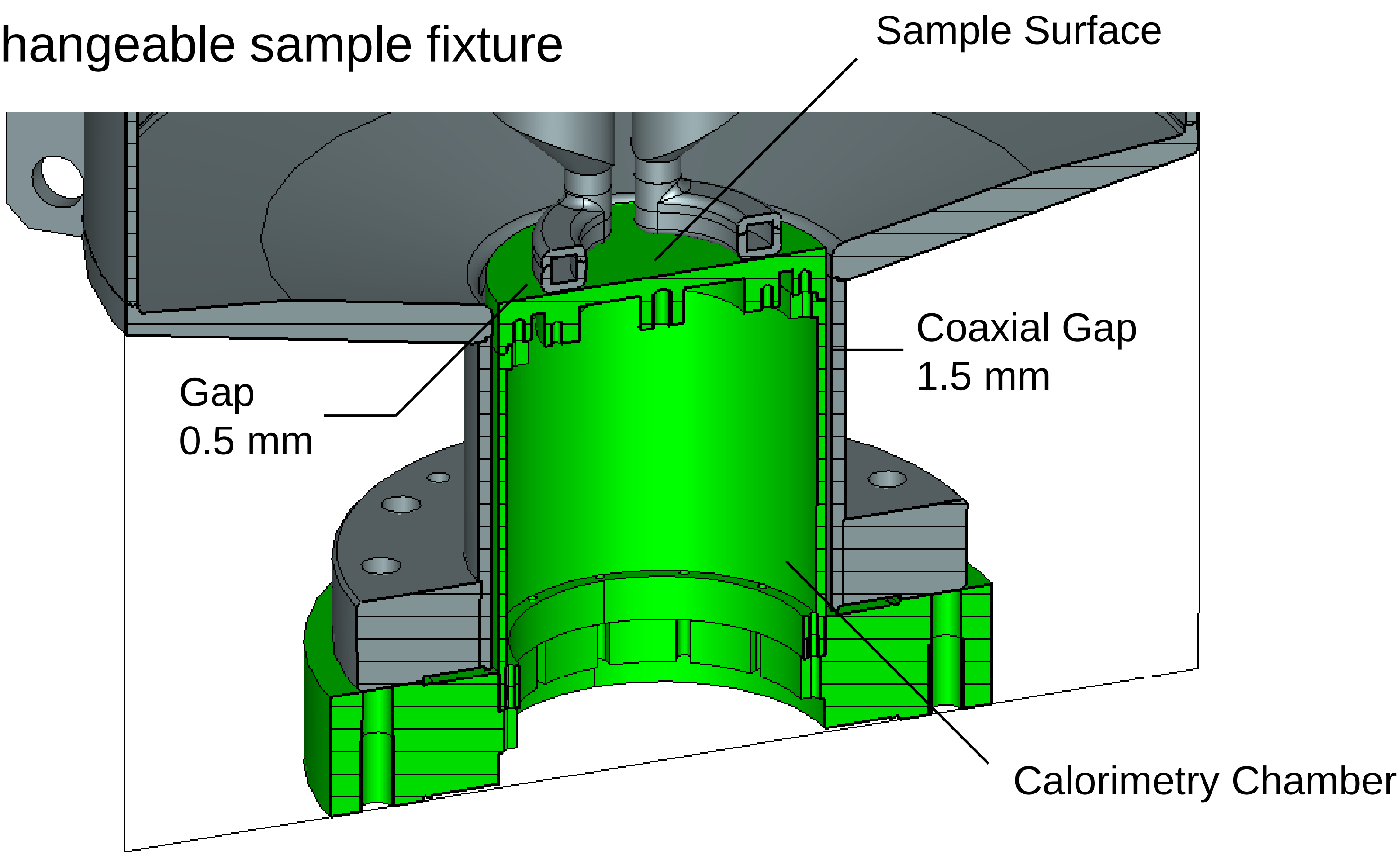
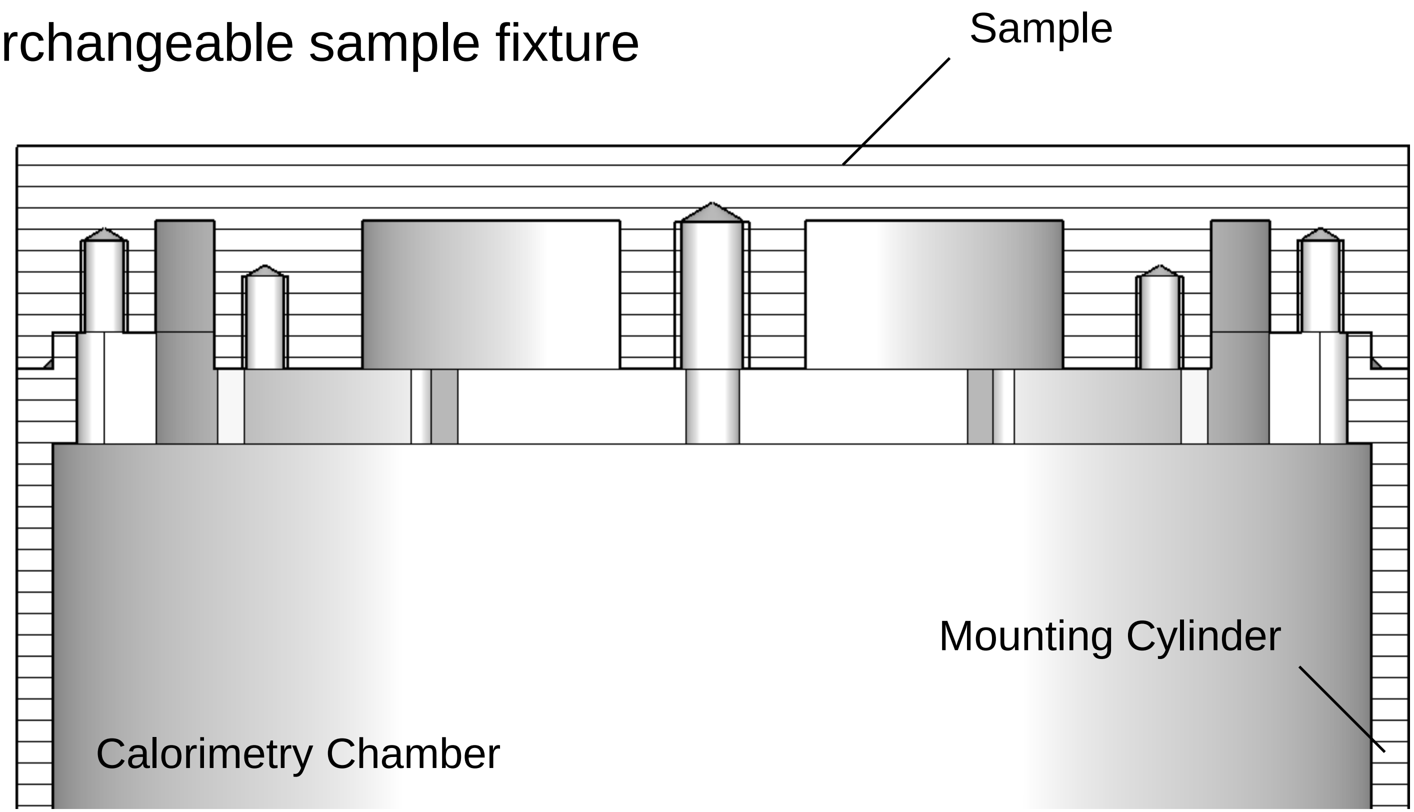
Quadrupole Resonator

- Geometry Information
  - Interchangeable sample fixture



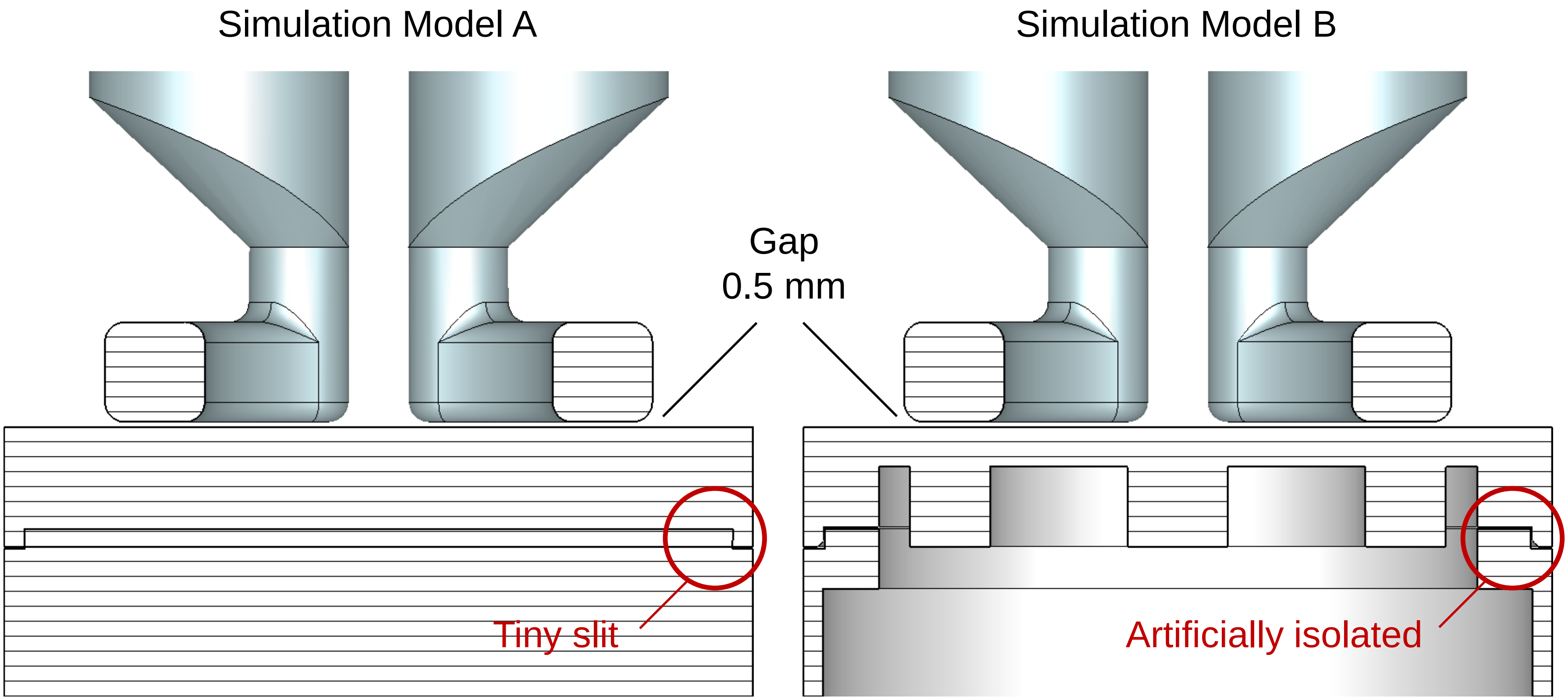
Quadrupole Resonator

- Geometry Information
  - Interchangeable sample fixture



Quadrupole Resonator

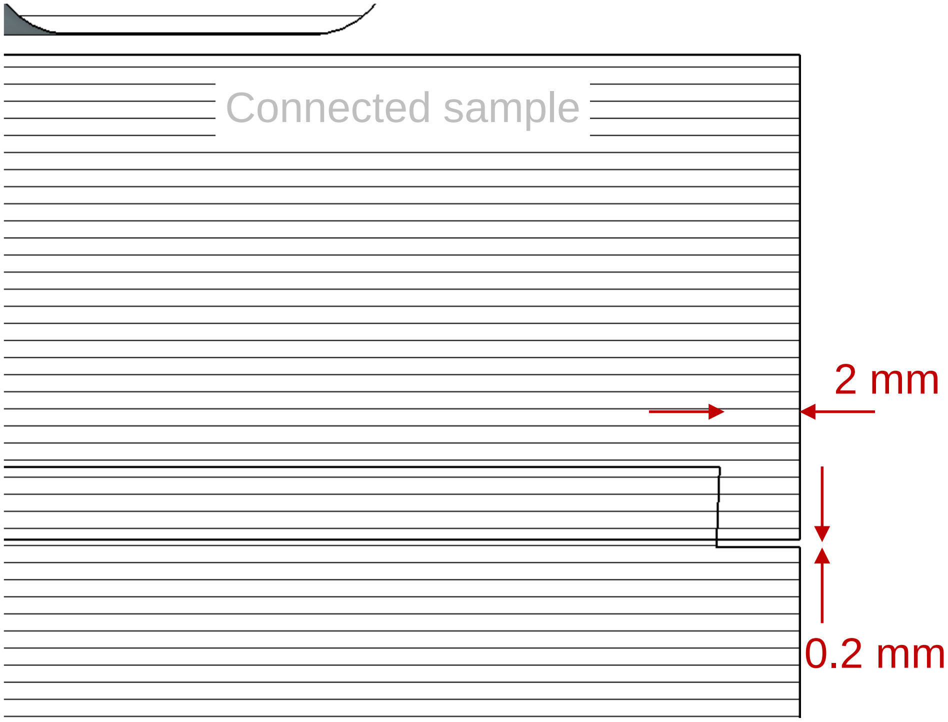
- Geometry Information
  - Model simplifications



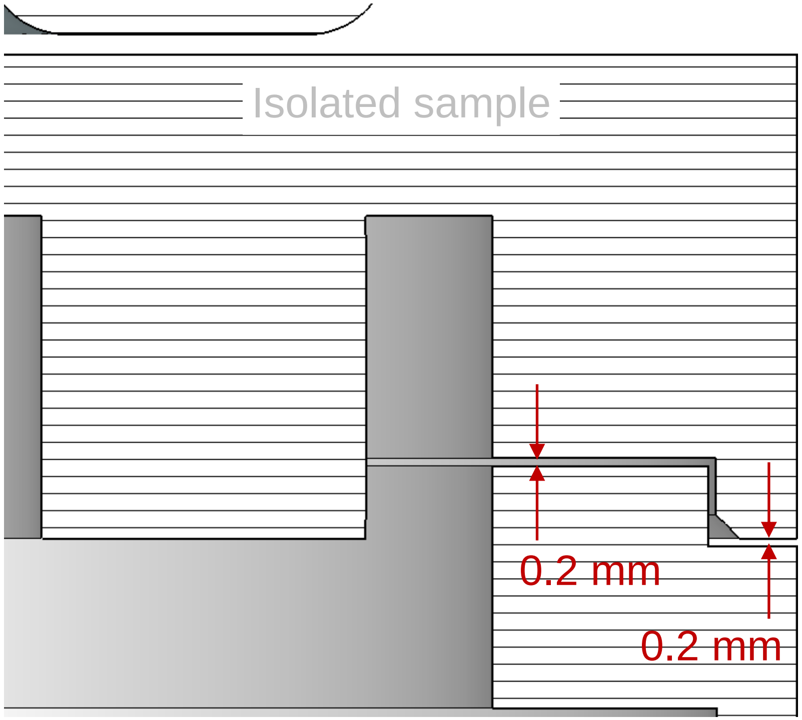
Quadrupole Resonator

- Geometry Information
  - Model simplifications

Simulation Model A



Simulation Model B



Quadrupole Resonator

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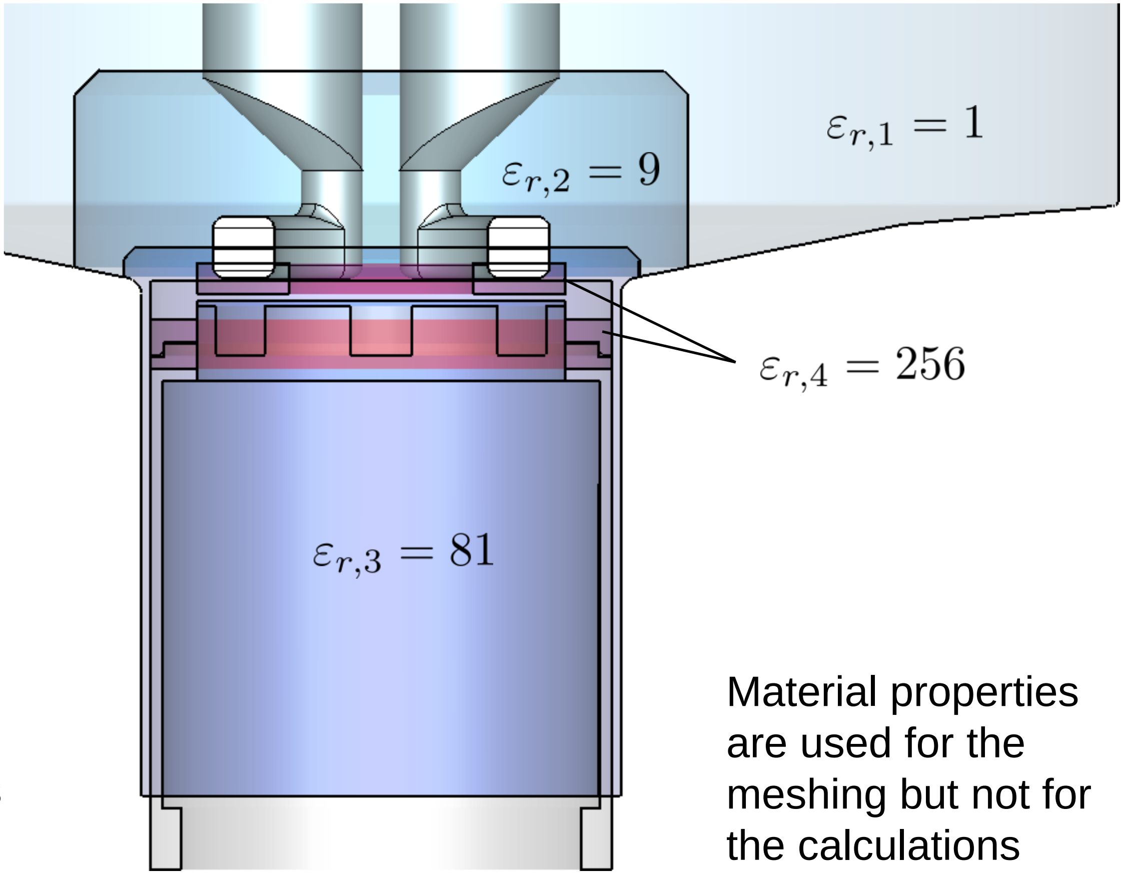
- Simulation Model
  - Numerical approach
    - Eigenmode calculation
    - Second order finite element method (FEM) on curved tetrahedral elements
    - Parallel Jacobi-Davidson eigenvalue solver
    - Grid refinement using four levels (artificially change of material properties)
  - Field evaluation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



Material properties are used for the meshing but not for the calculations

Quadrupole Resonator

- **Simulation Model**
  - Numerical approach
    - Eigenmode calculation
    - Second order finite element method (FEM) on curved tetrahedral elements
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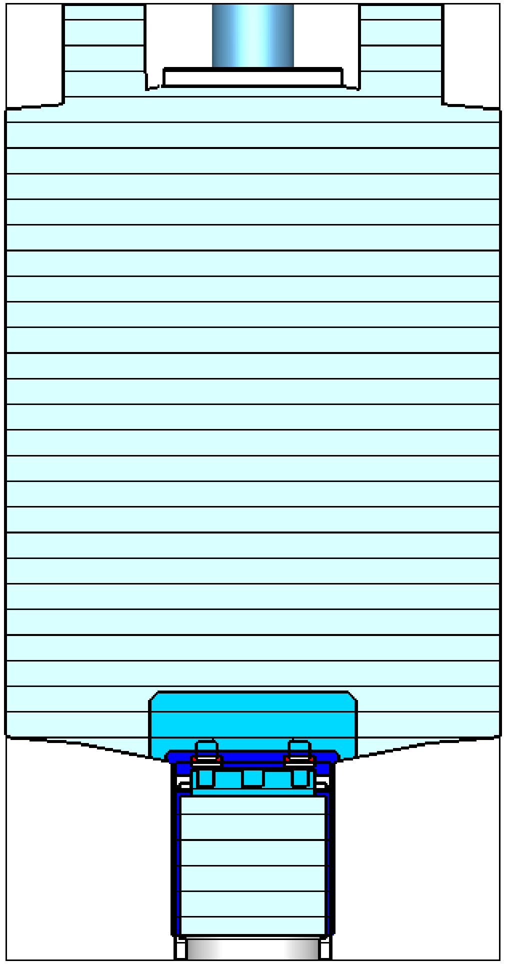
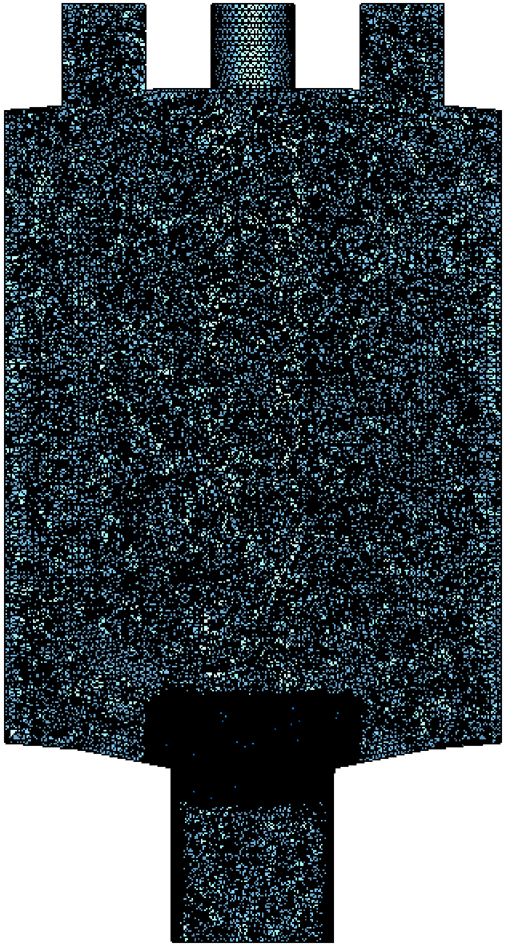
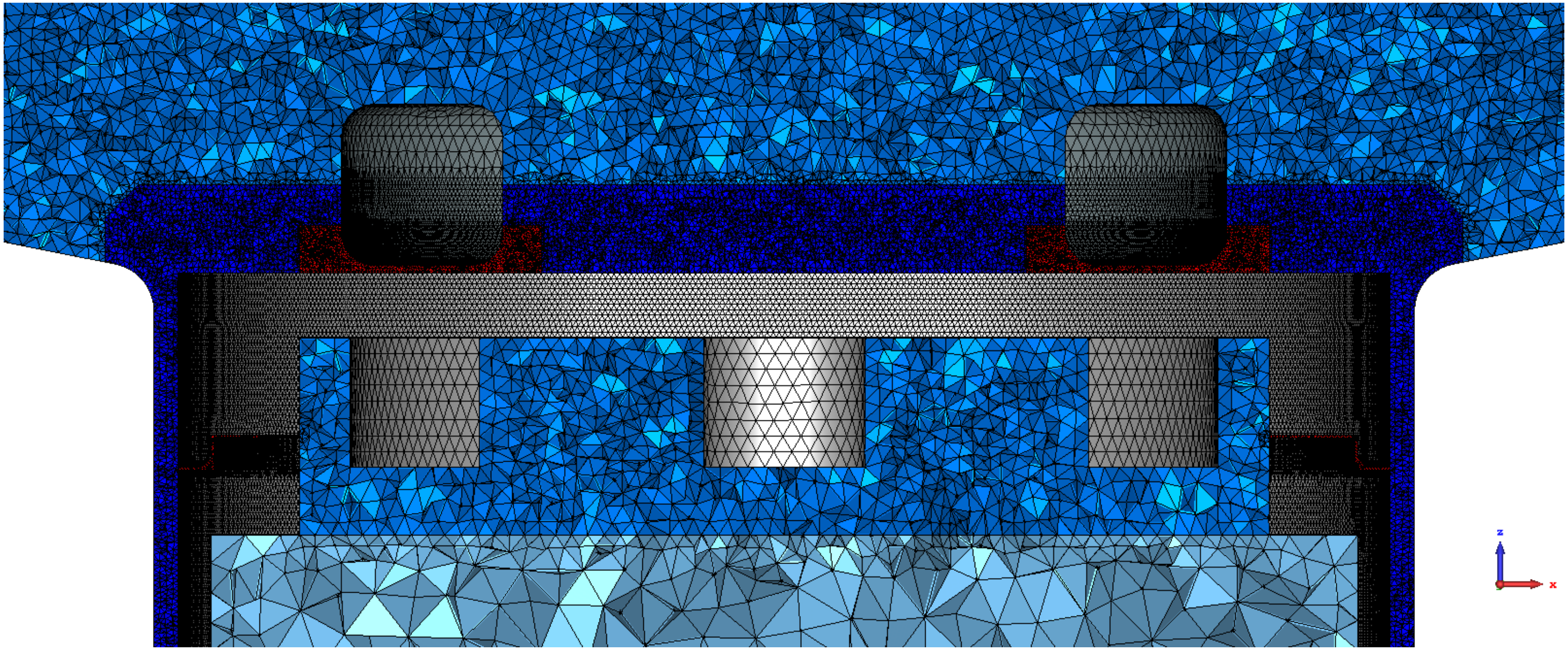




$N_{\text{tet}} = 17.737.075$

Quadrupole Resonator

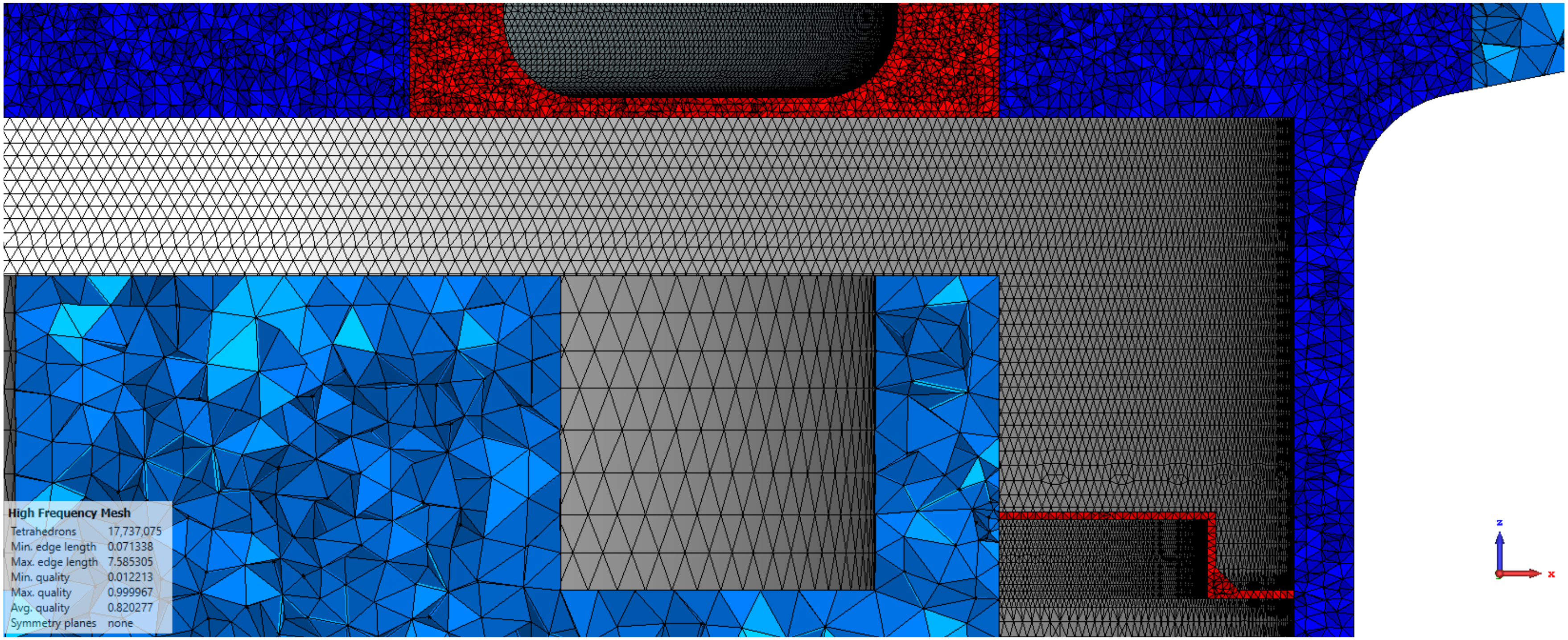
- Simulation Model
  - Tetrahedral element distribution



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

Quadrupole Resonator

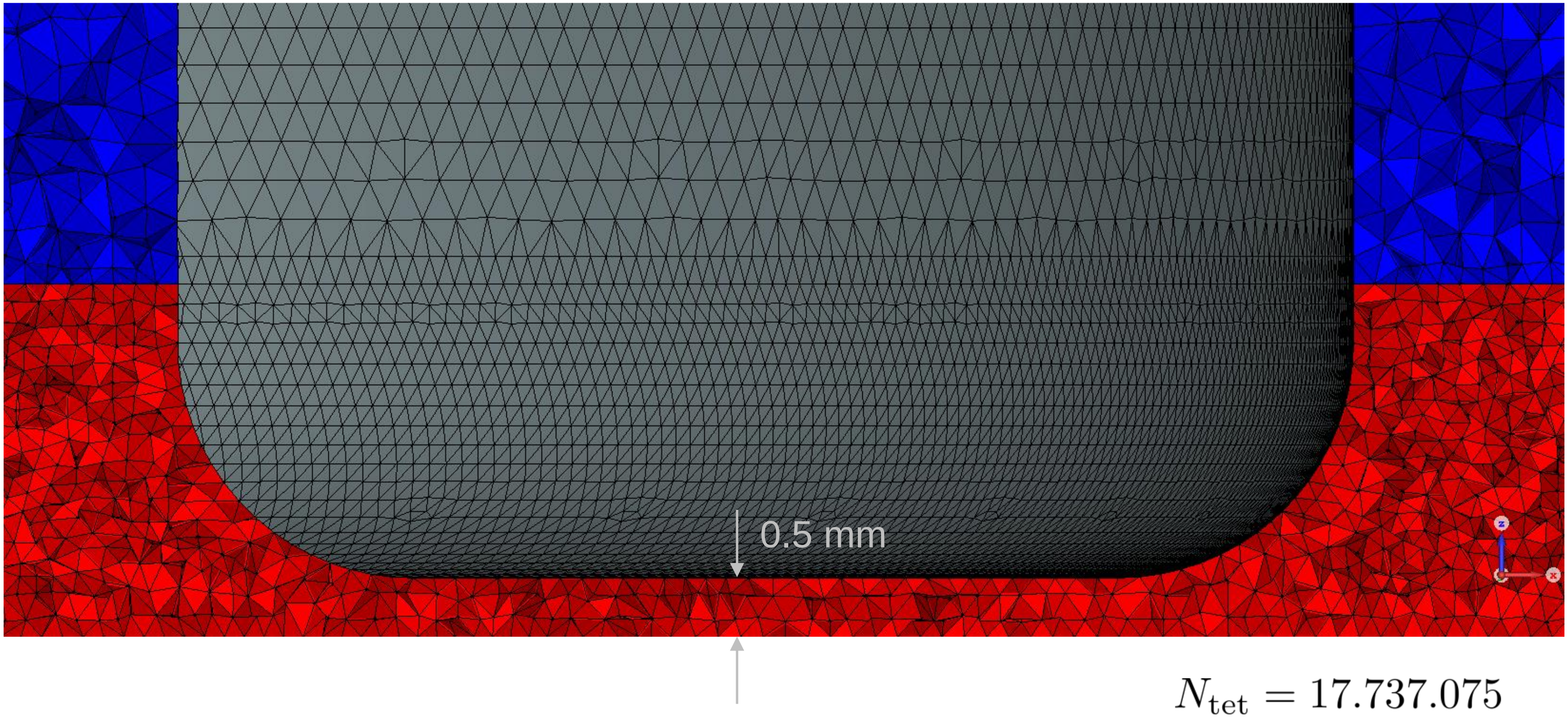
- Simulation Model
  - Tetrahedral element distribution



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

Quadrupole Resonator

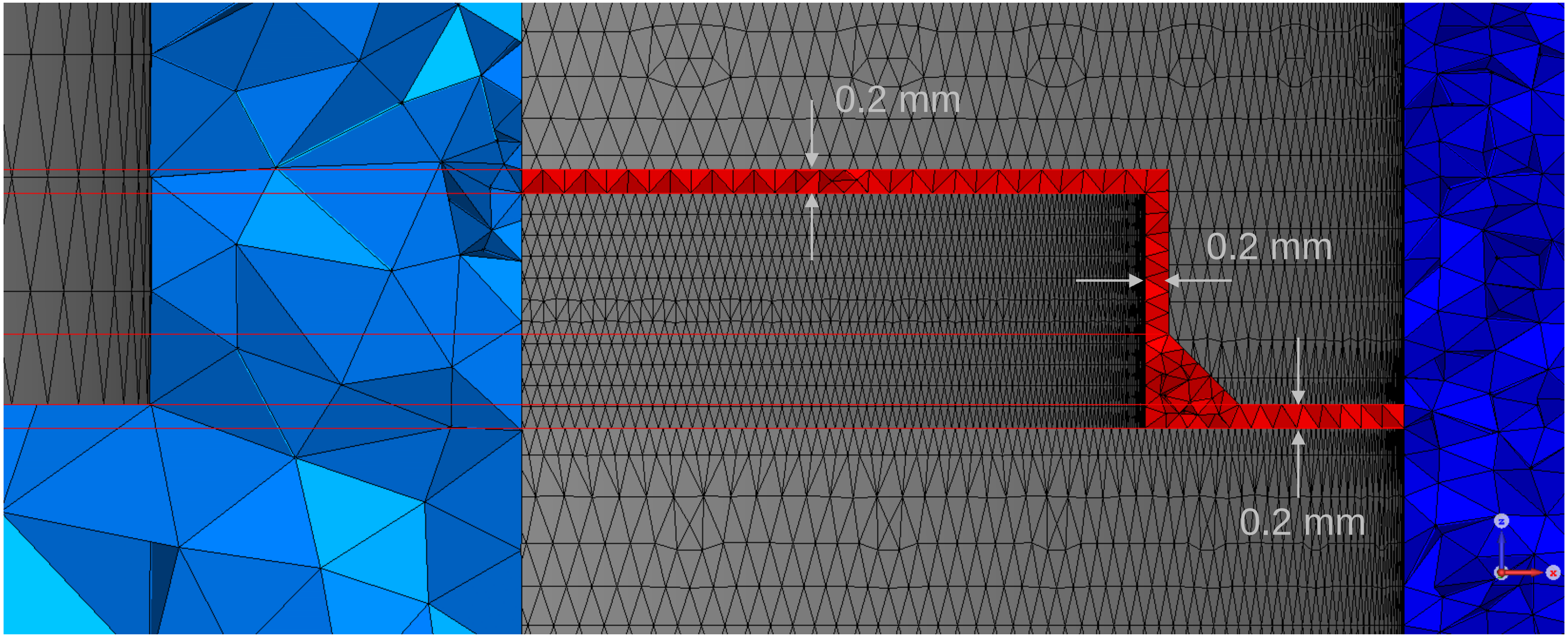
- Simulation Model
  - Tetrahedral element distribution around the horseshoe region



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

Quadrupole Resonator

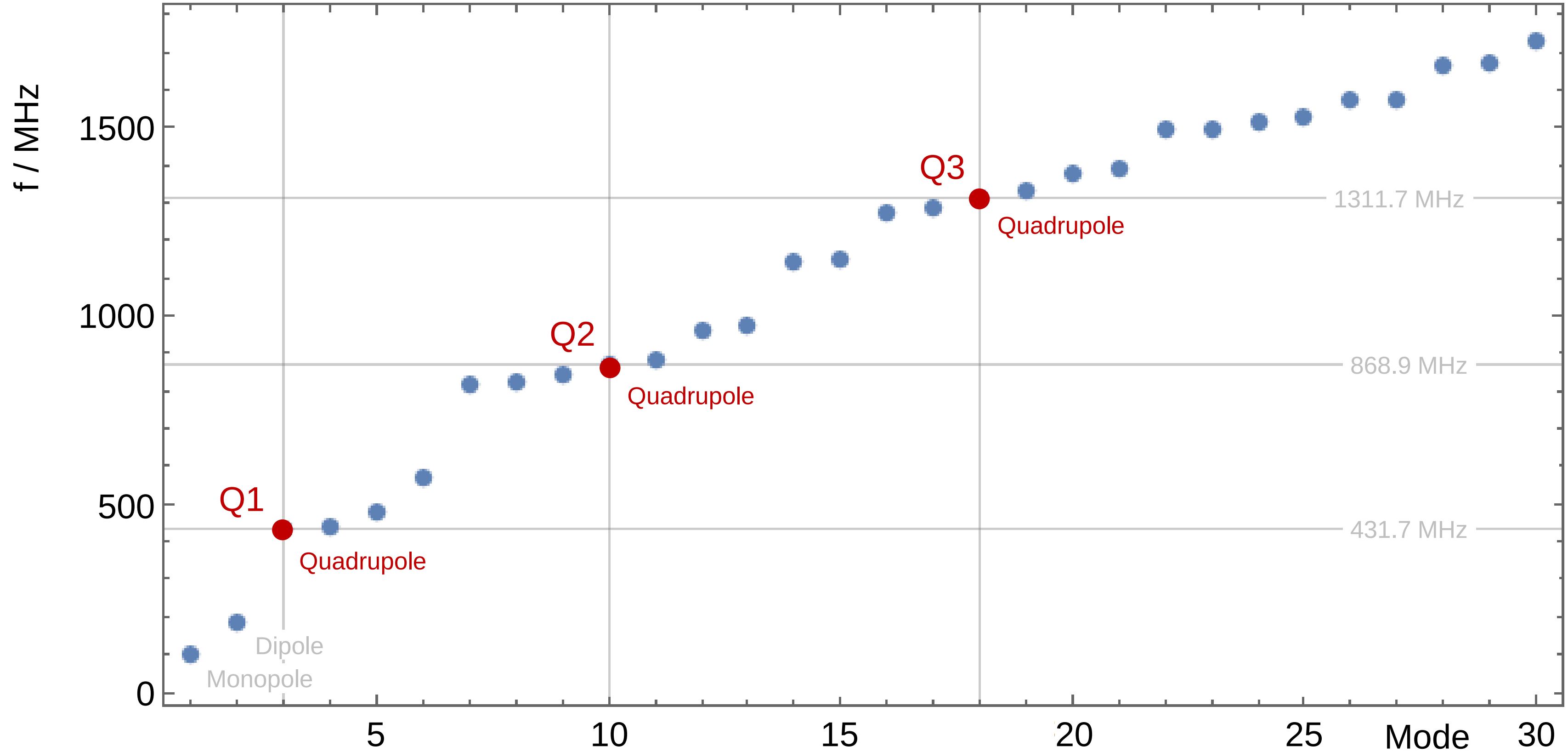
- Simulation Model
  - Tetrahedral element distribution around the isolation gap



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

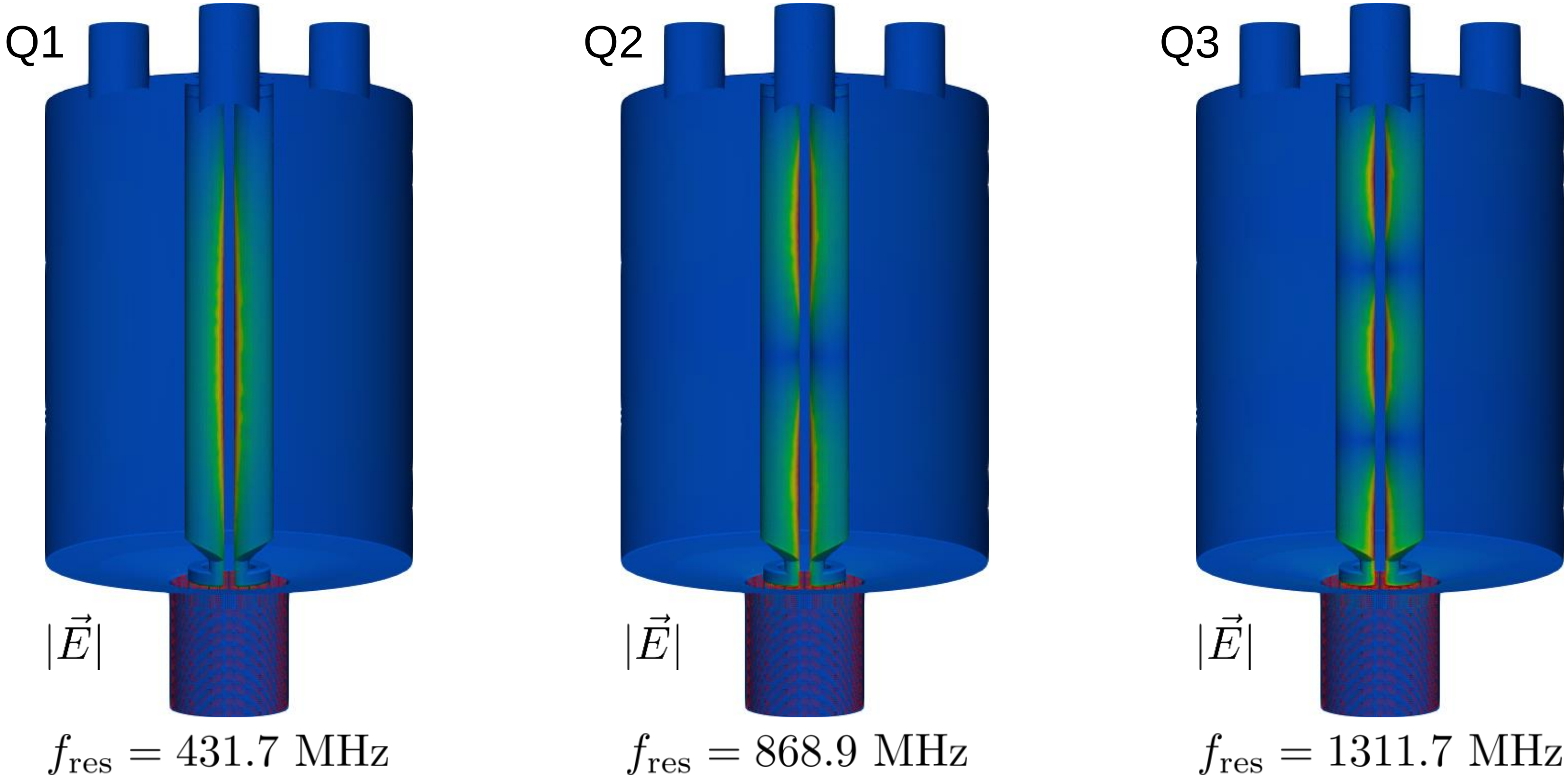
Quadrupole Resonator

- Eigenmode Calculations
  - Selection of eigenmodes



Quadrupole Resonator

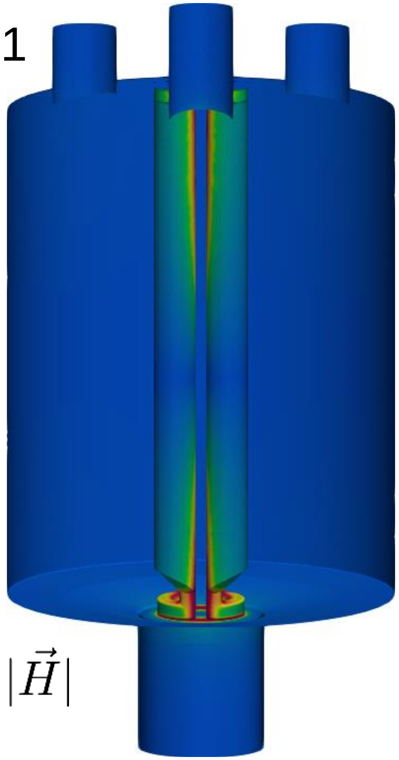
- Eigenmode Calculations
  - Selection of eigenmodes



Quadrupole Resonator

- Eigenmode Calculations
  - Selection of eigenmodes

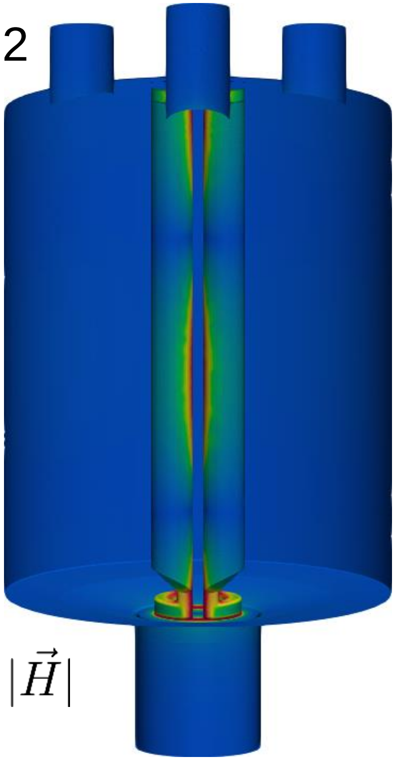
Q1



$|\vec{H}|$

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

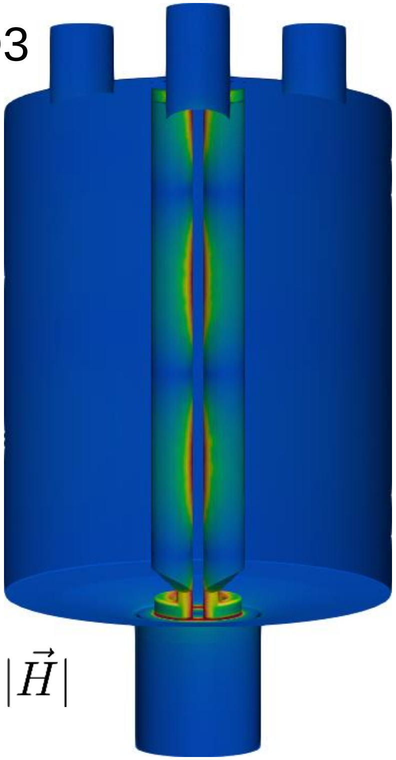
Q2



$|\vec{H}|$

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

Q3

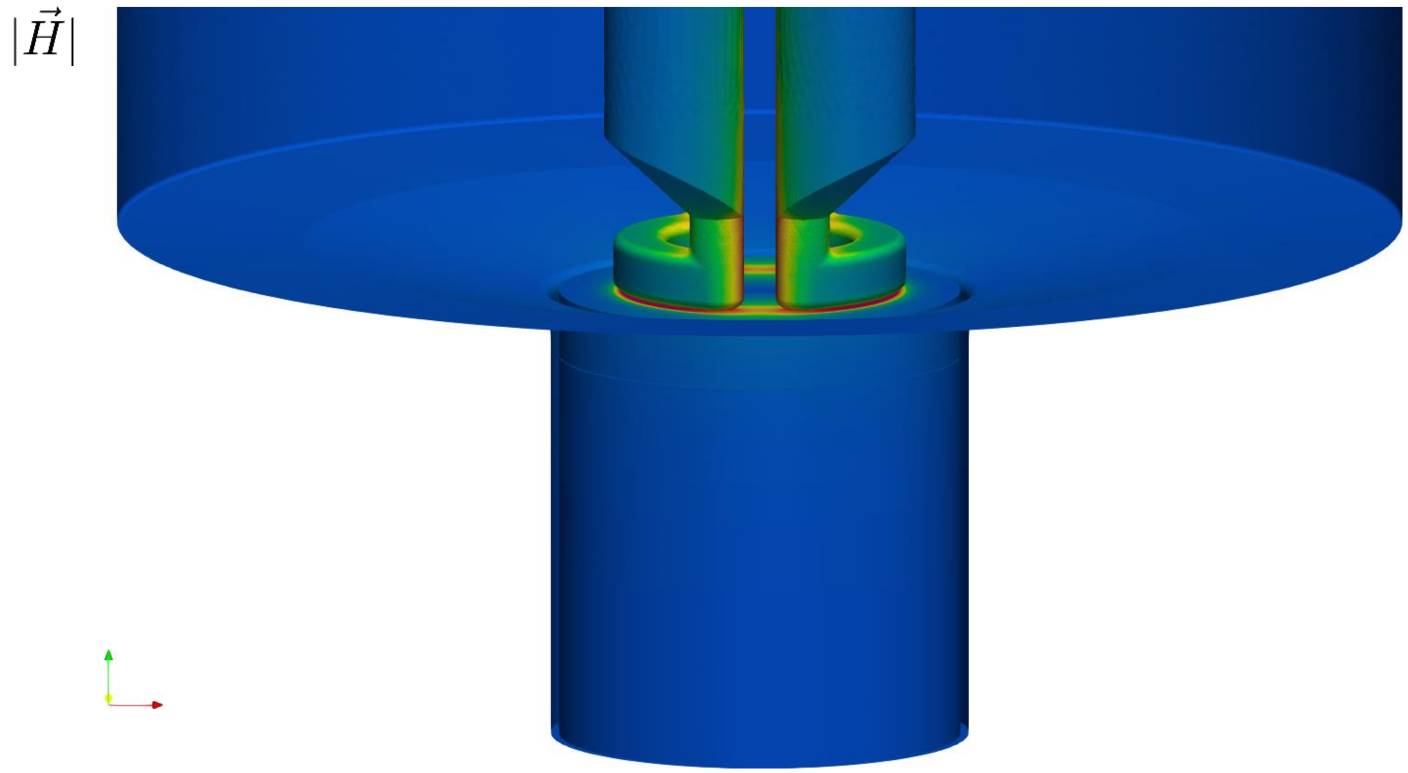


$|\vec{H}|$

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

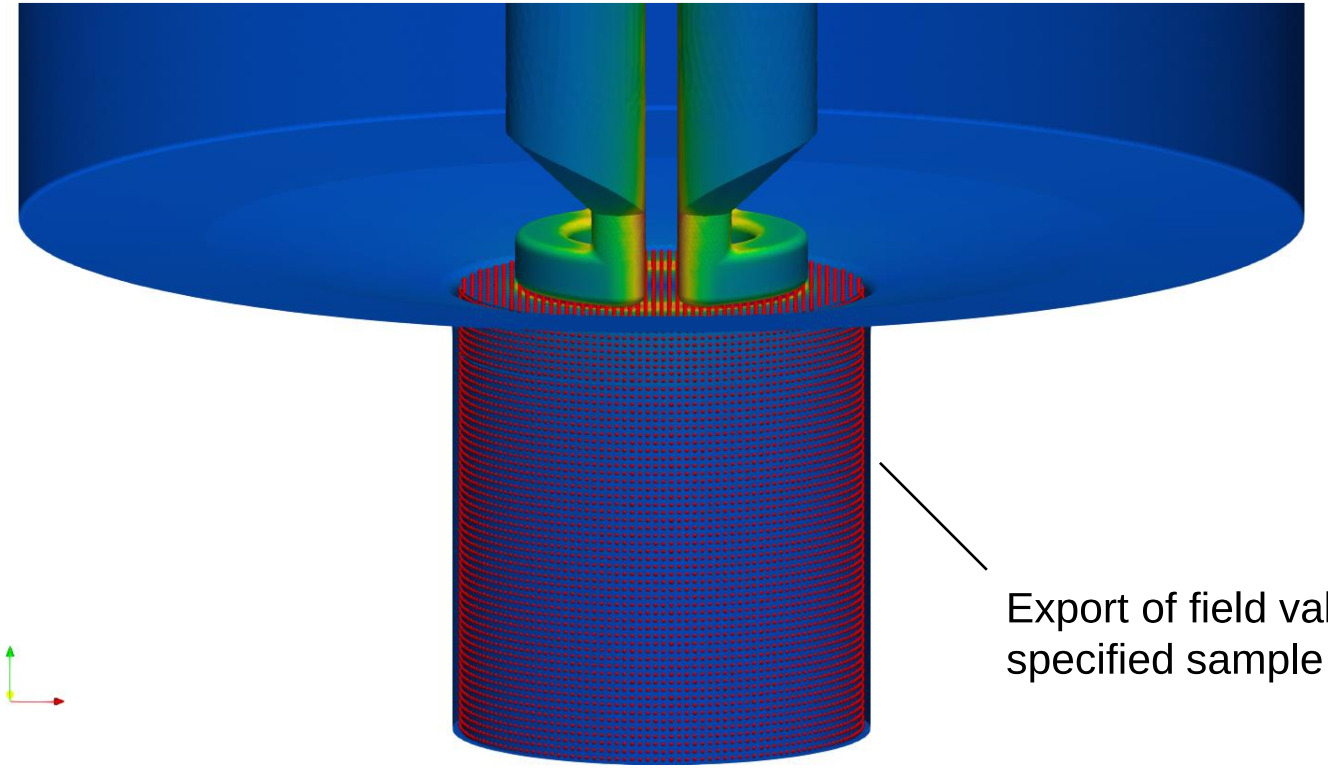
Quadrupole Resonator

- Eigenmode Calculations
  - Distribution of the magnetic field strength



Quadrupole Resonator

- Eigenmode Calculations
  - Distribution of the magnetic field strength

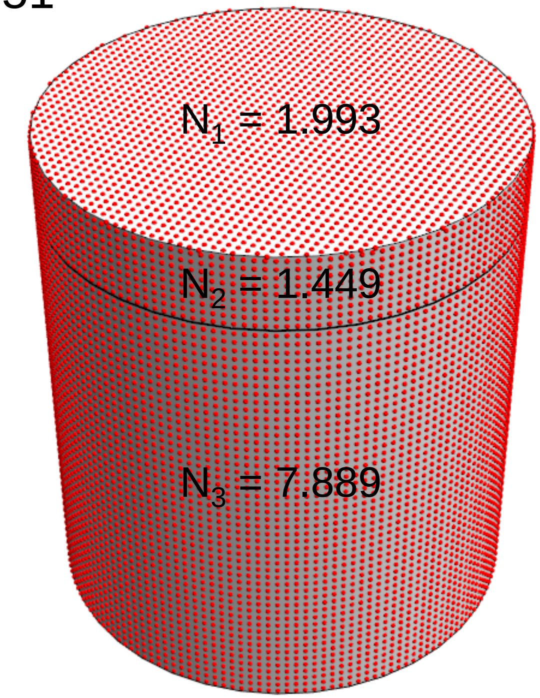


Export of field values at specified sample points

Quadrupole Resonator

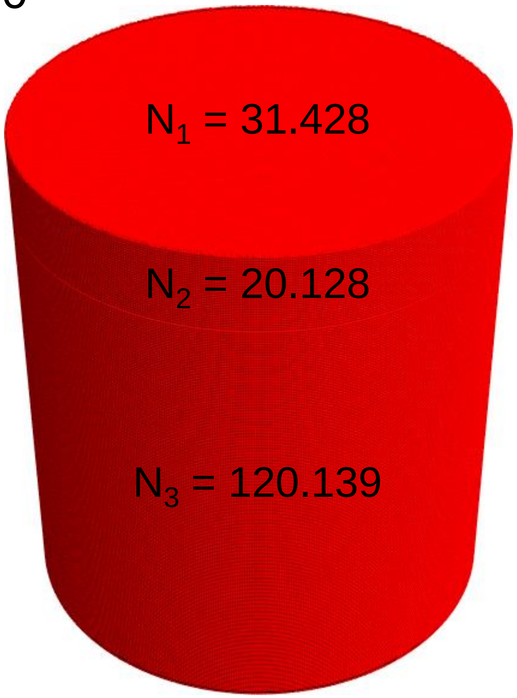
- Postprocessing
  - Example for the distribution of specified sample points

N_{sub} = 51



N_{total} = 11.331

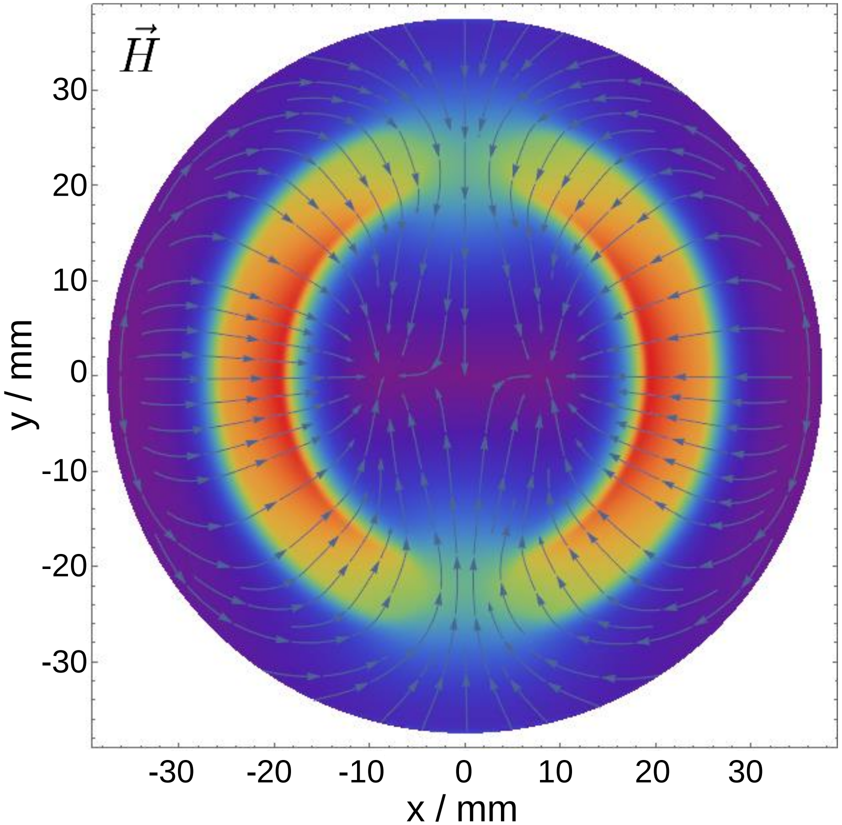
N_{sub} = 200

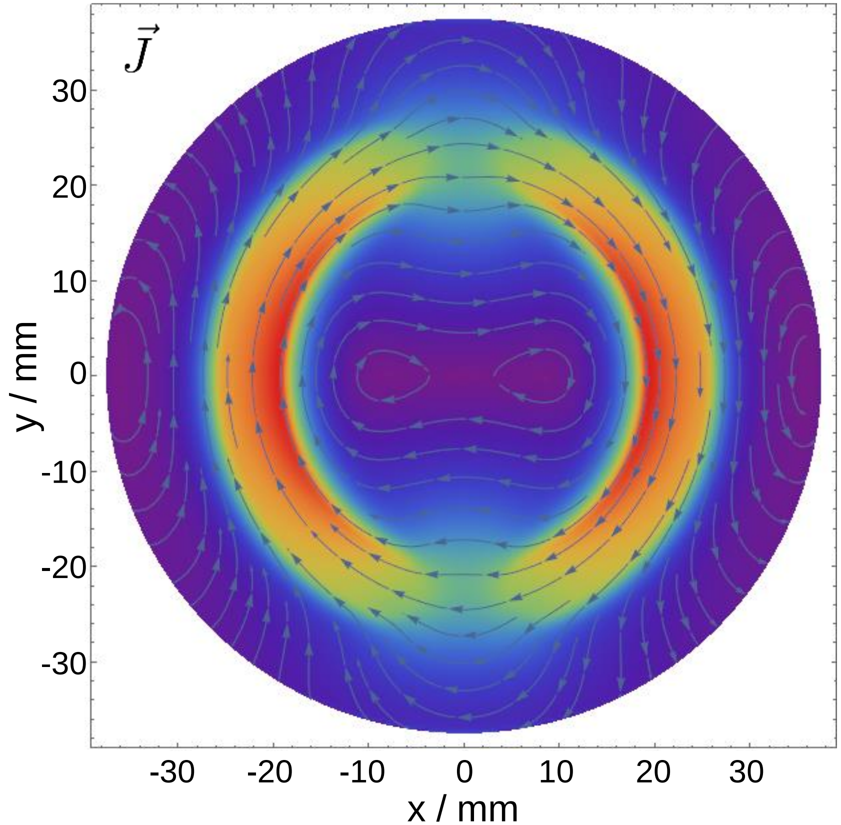


N_{total} = 171.695

Quadrupole Resonator

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





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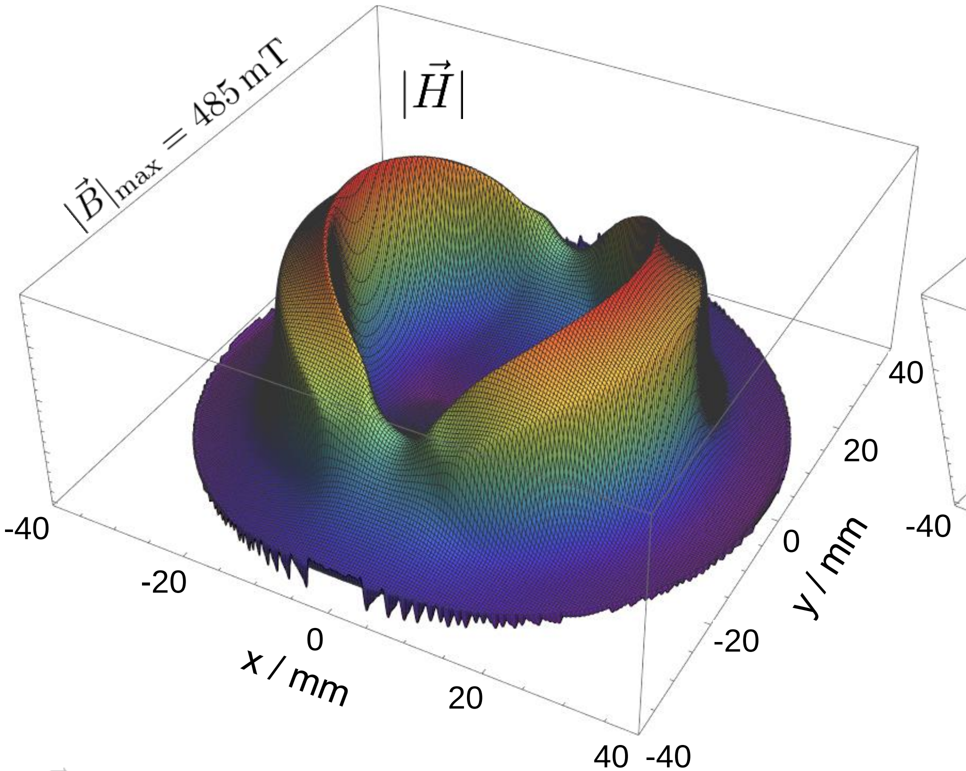
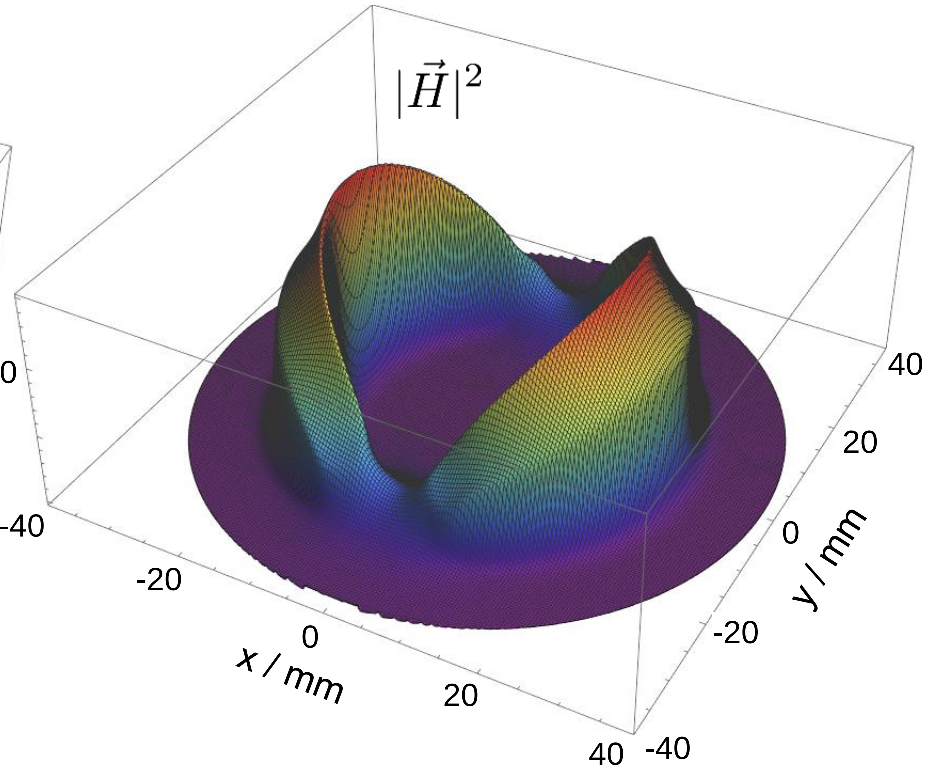
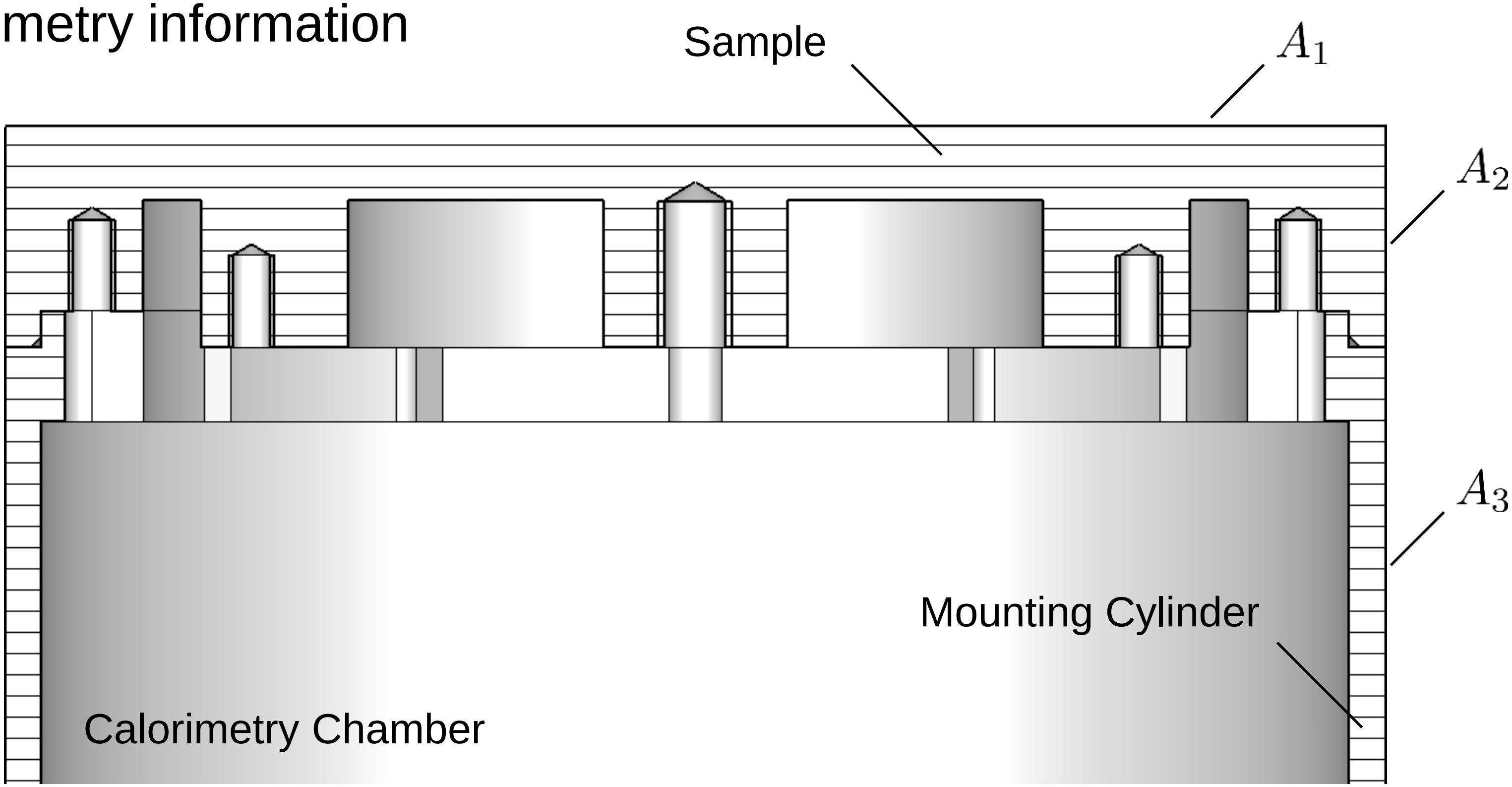




$|\vec{B}|_{\max} = \{485, 497, 552\}\,\mathrm{mT}$

Quadrupole Resonator

- Postprocessing
  - Geometry information



Quadrupole Resonator

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- Postprocessing
  - Simulation results

$$P_\nu = \frac{1}{4}\,\mu\,\omega\,\delta\,I_\nu \qquad I_\nu = \iint_{A_\nu} \vec{H}\cdot\vec{H}\,\mathrm{d}A$$

N_{DOF}=18.830.148 N_{DOF}=19.870.254

Mode	Parameter	Model A	3.119.892 tets	Model B	3.314.581 tets
Quadrupole 1	f_{res} / MHz	431.694		431.687	
	I_1 / kA²	102.220	99.43 %	102.216	99.43 %
	I_2 / kA²	0.432	0.42 %	0.460	0.45 %
	I_3 / kA²	0.153	0.15 %	0.125	0.12 %
Quadrupole 2	f_{res} / MHz	868.820		868.805	
	I_1 / kA²	100.869	99.45 %	100.855	99.45 %
	I_2 / kA²	0.402	0.40 %	0.433	0.43 %
	I_3 / kA²	0.158	0.16 %	0.129	0.13 %
Quadrupole 3	f_{res} / MHz	1311.578		1311.545	
	I_1 / kA²	112.824	99.47 %	112.775	99.47 %
	I_2 / kA²	0.405	0.36 %	0.448	0.40 %
	I_3 / kA²	0.194	0.17 %	0.159	0.14 %

Quadrupole Resonator

- Postprocessing
  - Simulation results

$$P_\nu = \frac{1}{4}\,\mu\,\omega\,\delta\,I_\nu \qquad I_\nu = \iint_{A_\nu} \vec{H}\cdot\vec{H}\,\mathrm{d}A$$

N_{DOF}=104.994.928 N_{DOF}=108.944.262

Mode	Parameter	Model A	17.022.210 tets	Model B	17.737.075 tets
Quadrupole 1	f_{res} / MHz	431.750		431.742	
	I_1 / kA²	102.248	99.43 %	102.237	99.43 %
	I_2 / kA²	0.437	0.42 %	0.463	0.45 %
	I_3 / kA²	0.153	0.15 %	0.125	0.12 %
Quadrupole 2	f_{res} / MHz	868.926		868.912	
	I_1 / kA²	100.917	99.44 %	100.897	99.44 %
	I_2 / kA²	0.406	0.40 %	0.436	0.43 %
	I_3 / kA²	0.158	0.16 %	0.129	0.13 %
Quadrupole 3	f_{res} / MHz	1311.708		1311.682	
	I_1 / kA²	112.879	99.47 %	112.833	99.46 %
	I_2 / kA²	0.408	0.36 %	0.450	0.40 %
	I_3 / kA²	0.194	0.17 %	0.159	0.14 %

Quadrupole Resonator

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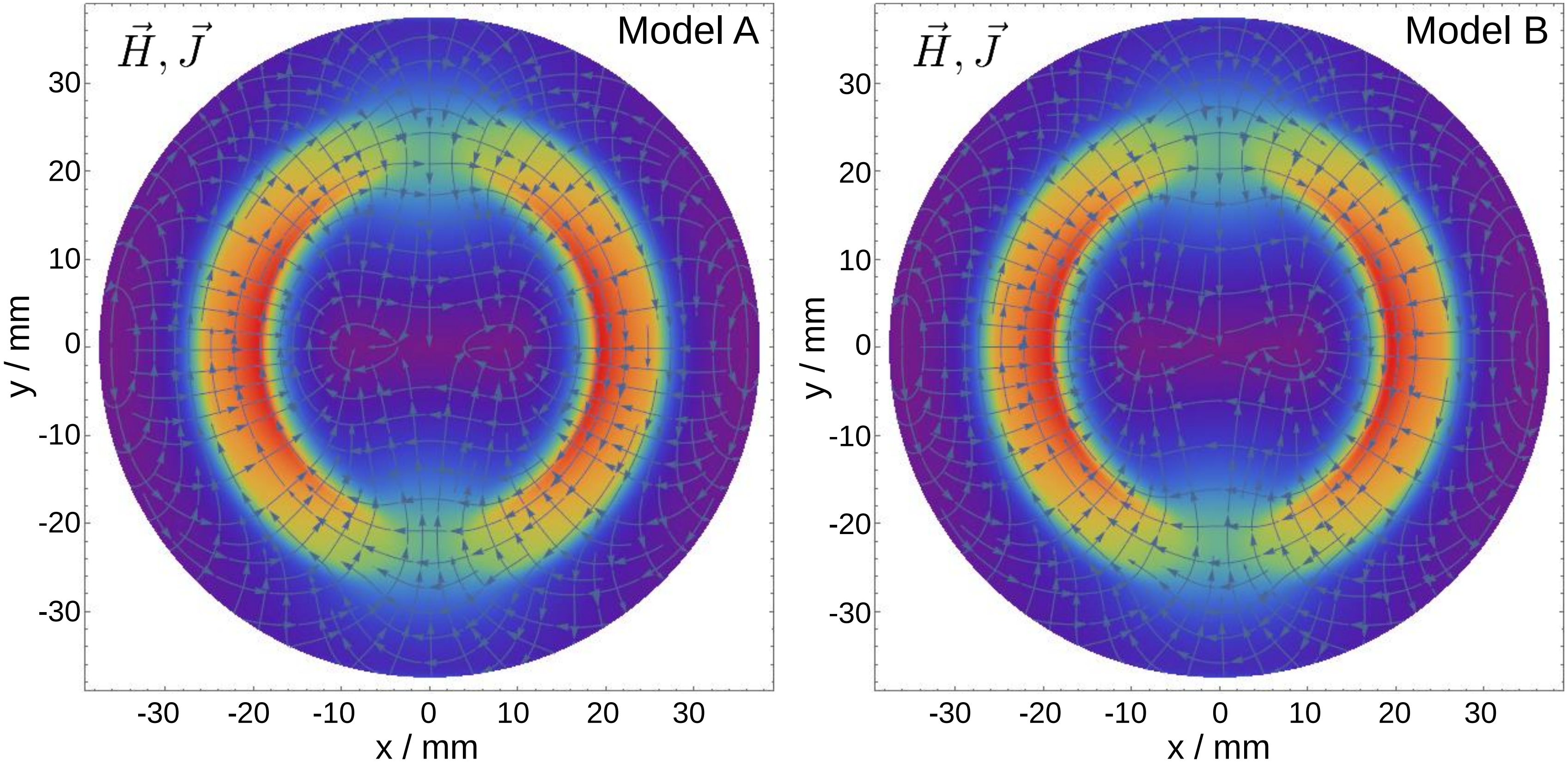
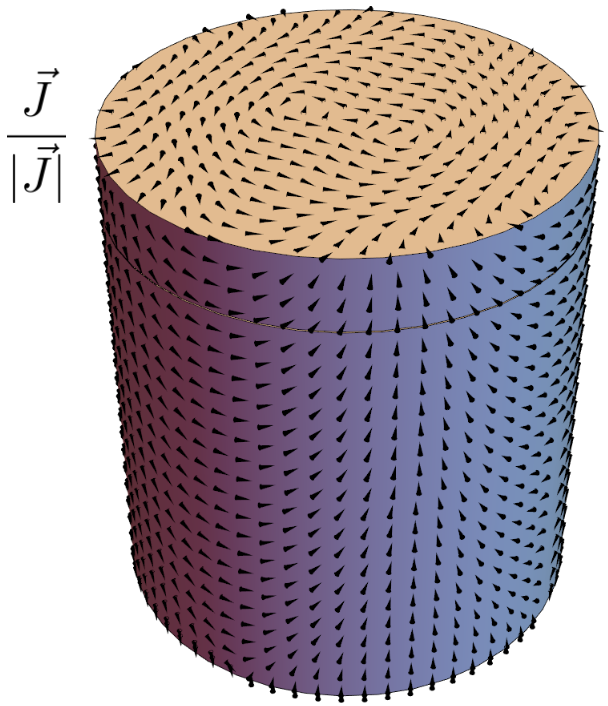
- Postprocessing
  - Visualization of the field distribution on the sample surface



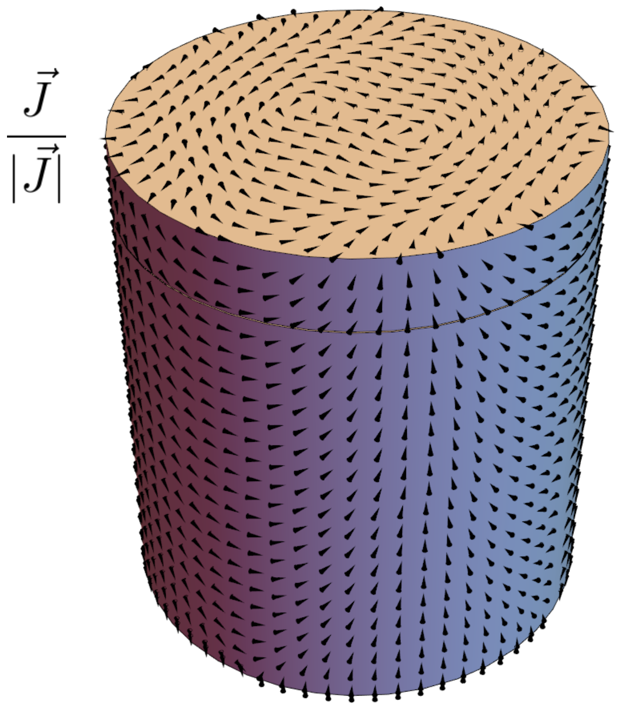
Quadrupole Resonator

- Postprocessing
  - Induced current direction for the first quadrupole mode

Model A

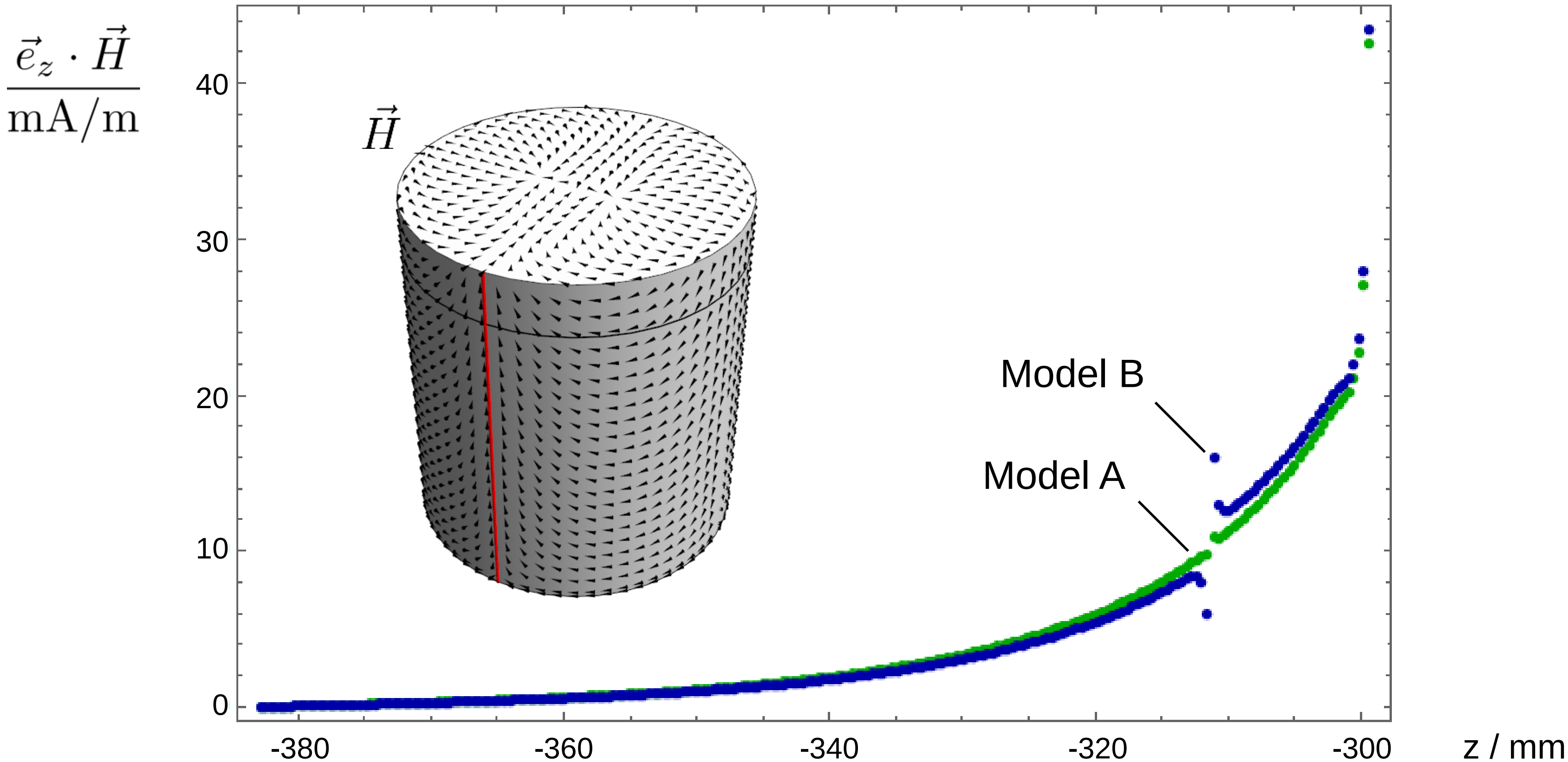


Model B



Quadrupole Resonator

- Postprocessing
  - Evaluate field along a line



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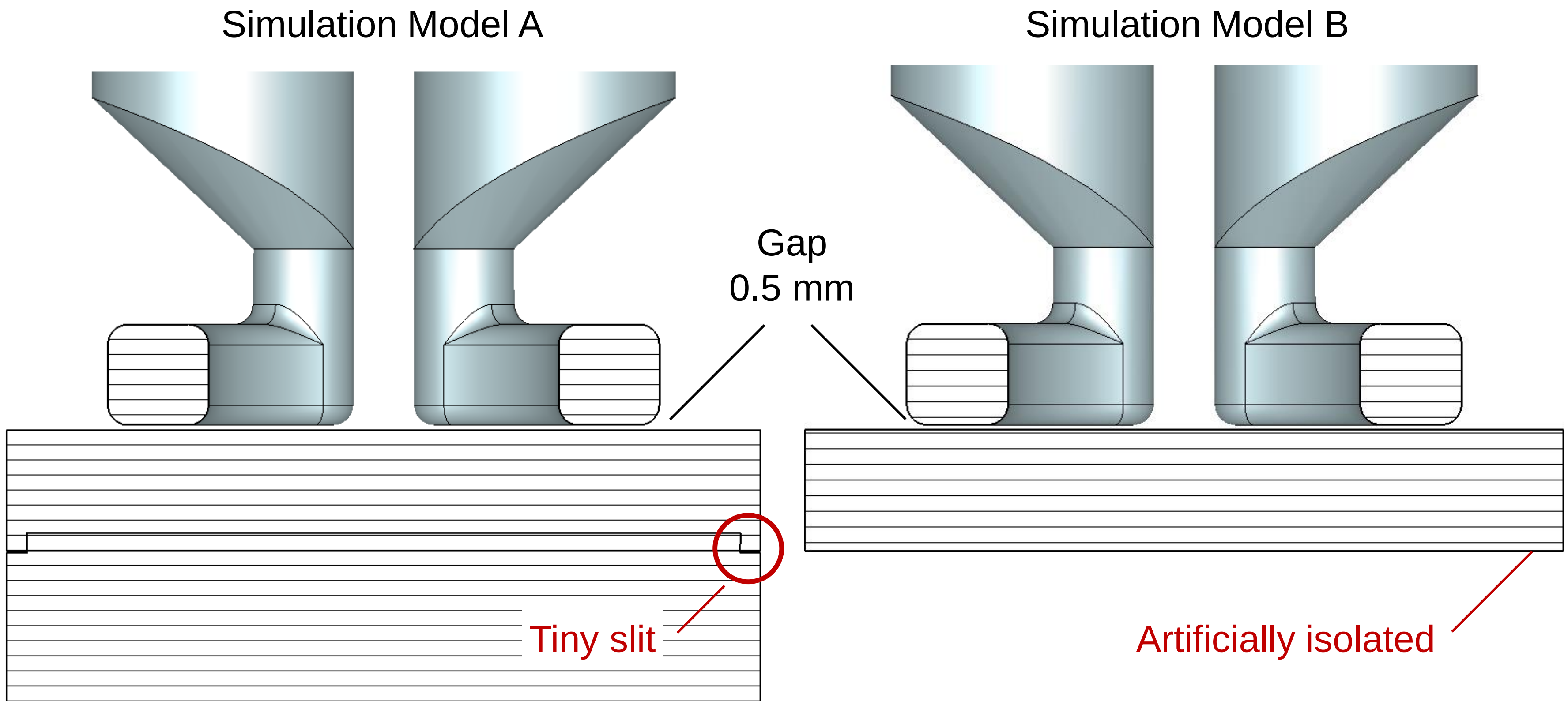
Quadrupole Resonator

- Geometry Information
  - Model simplifications



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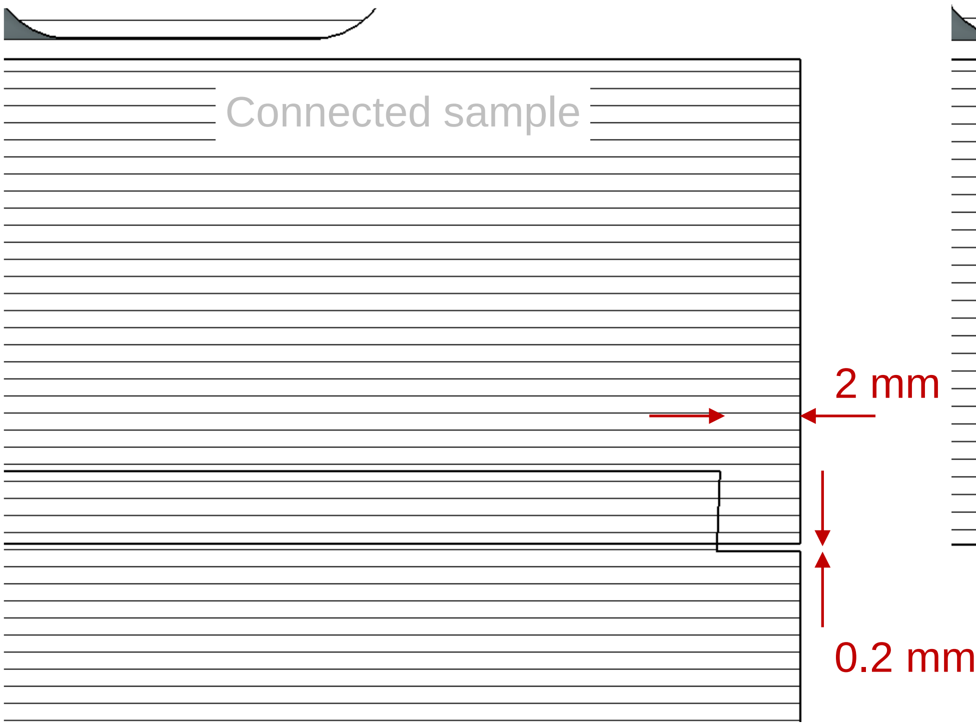
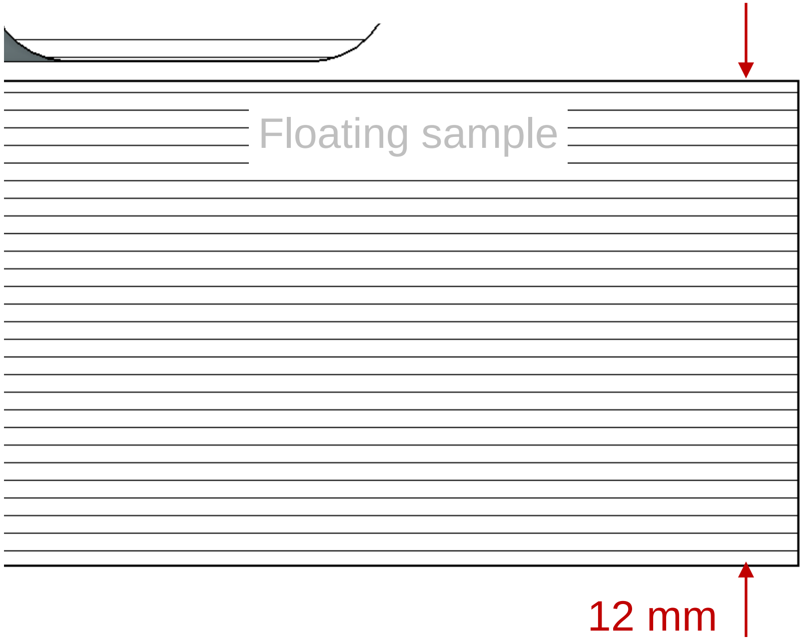
Simulation Model A



Simulation Model B



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- Geometry Information
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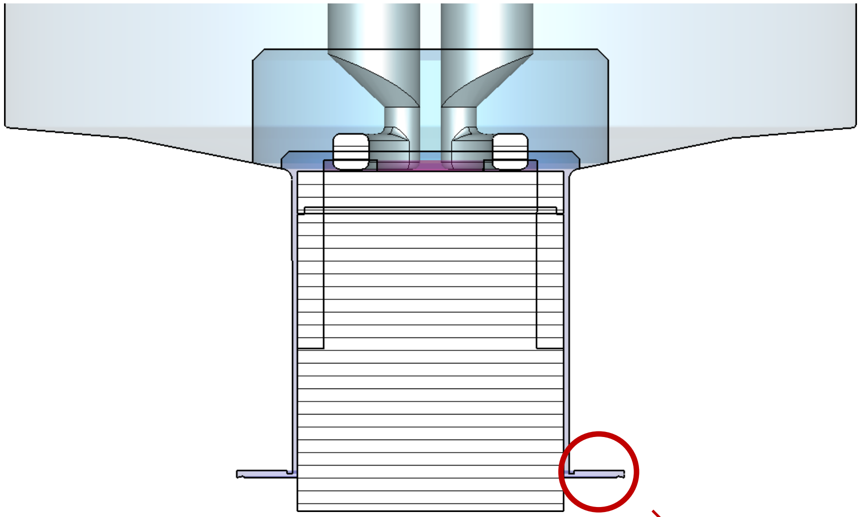
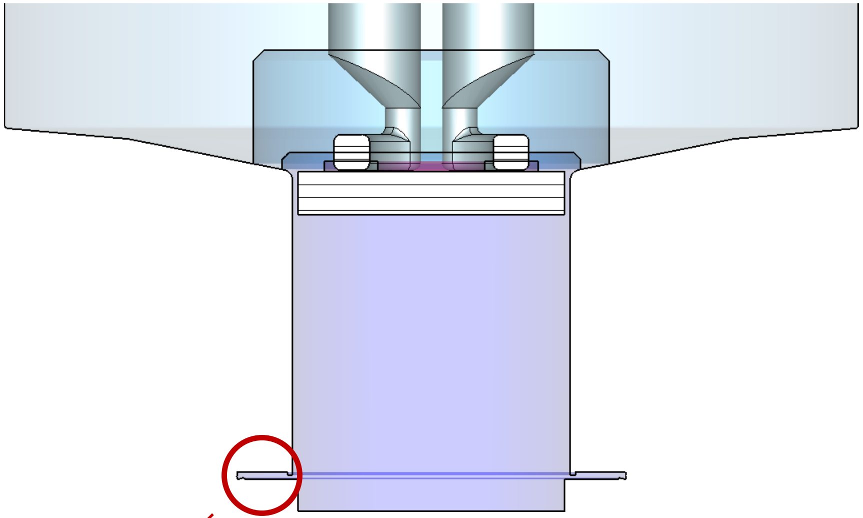
Simulation Model A



Simulation Model B



No seal used here

Quadrupole Resonator

- Simulation Models
  - Numerical approach
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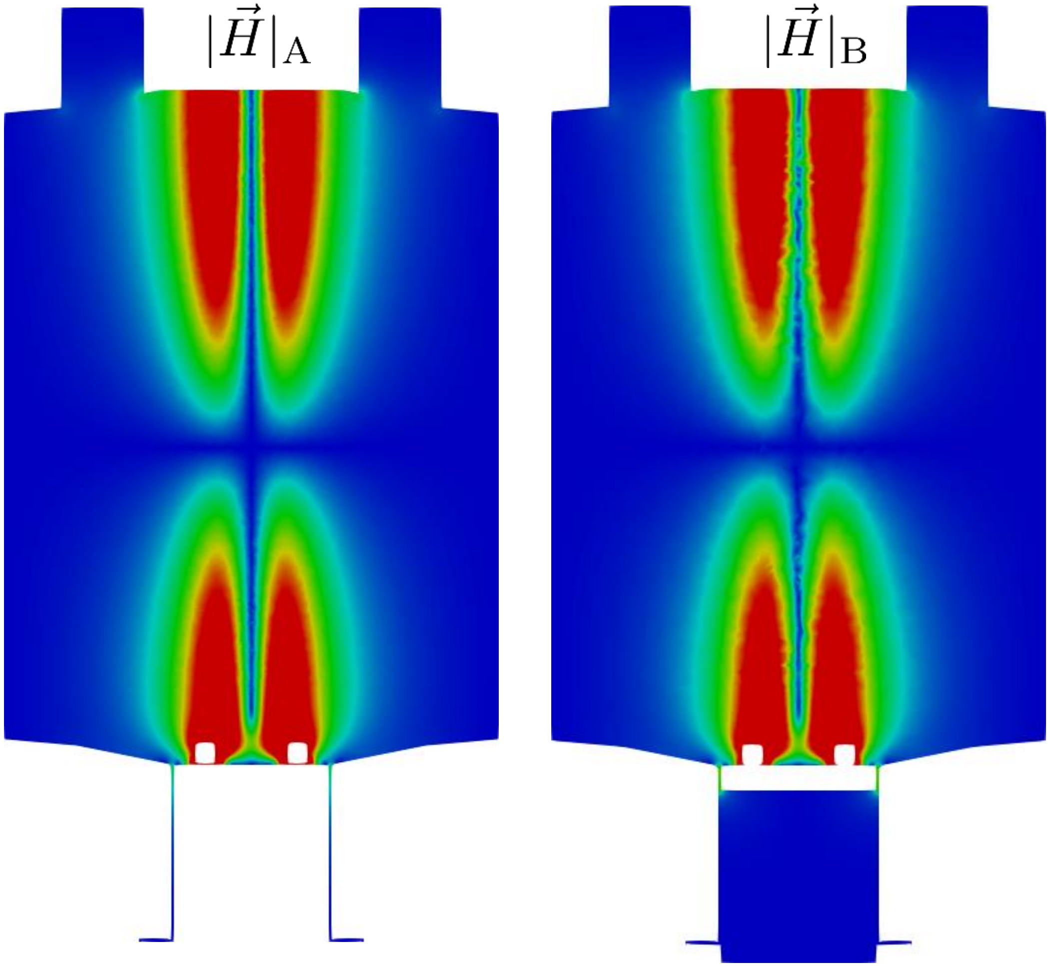

Quadrupole Resonator

- Geometry Information
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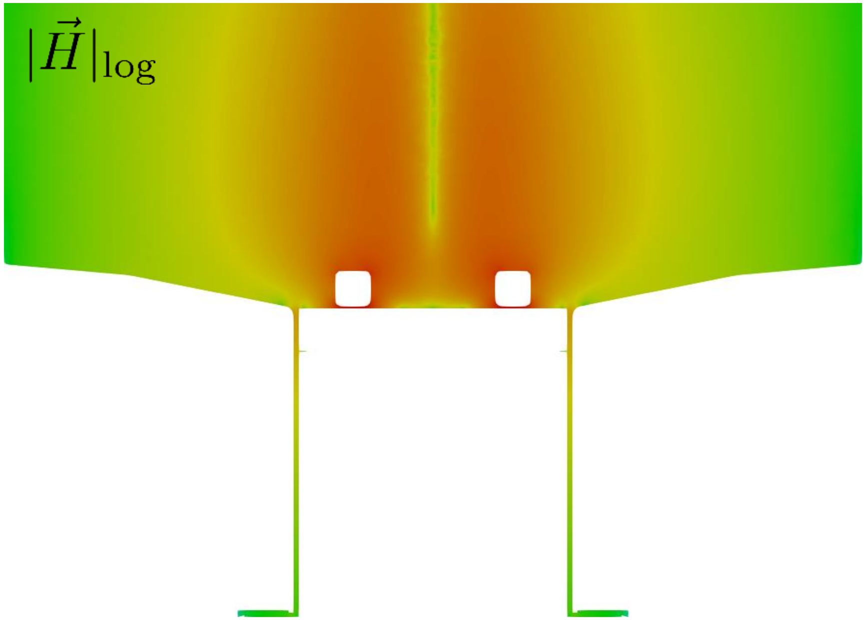
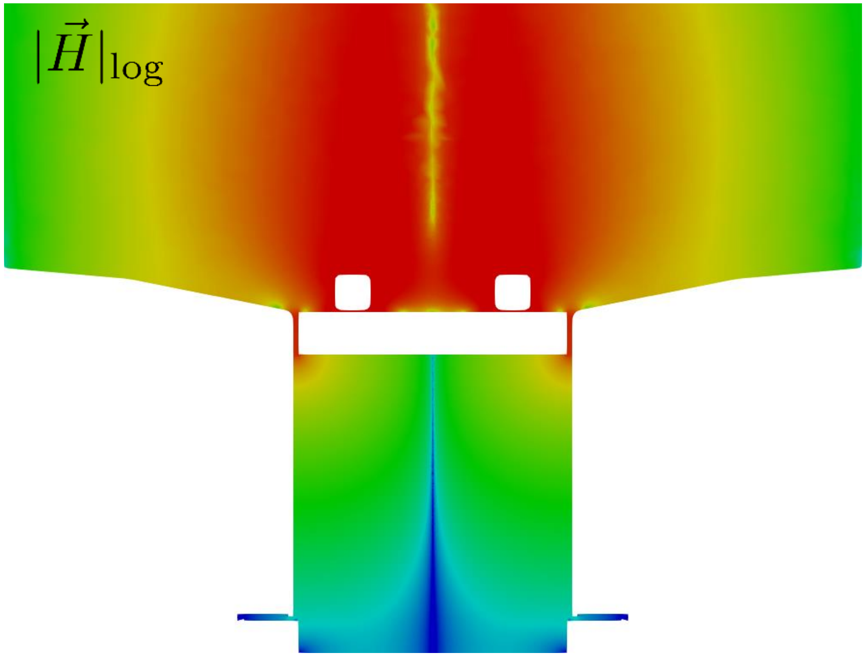


Simulation Model B



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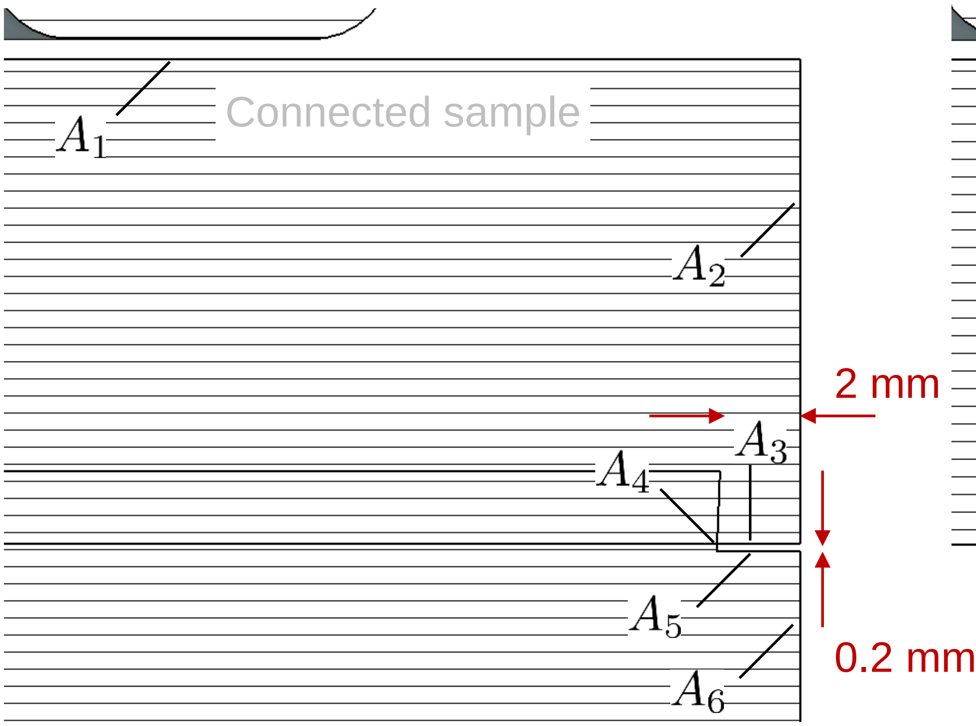
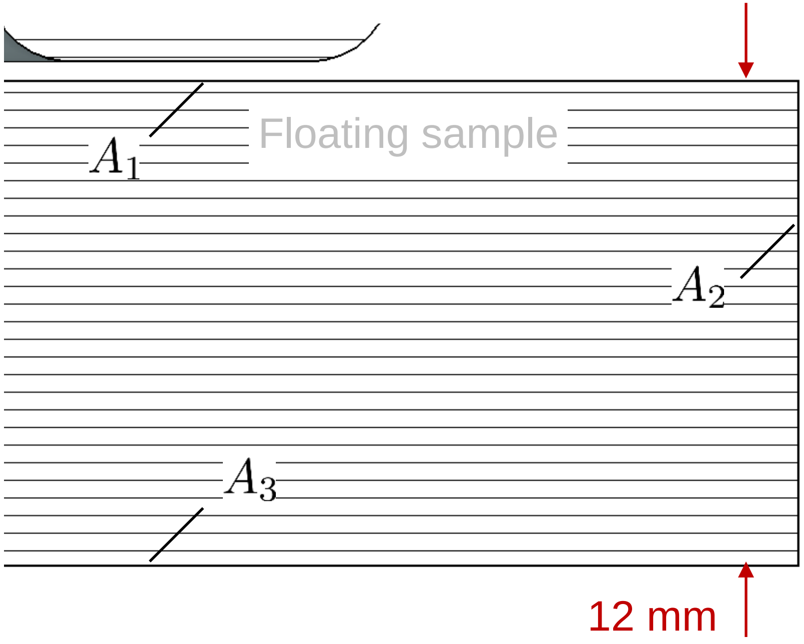


Simulation Model B



Quadrupole Resonator

- Postprocessing
  - Simulation results

$$P_\nu = \frac{1}{4}\,\mu\,\omega\,\delta\,I_\nu \qquad I_\nu = \iint_{A_\nu} \vec{H}\cdot\vec{H}\,\mathrm{d}A$$

N_{DOF}=63.101.356 N_{DOF}=72.847.286

Mode	Parameter	Model A	10.327.702 tets	Model B	11.635.139 tets
Quadrupole 1	f_{res} / MHz	431.741		431.588	
	I_1 / kA²	102.243	99.39 %	102.154	99.29 %
	I_2 / kA²	0.436	0.42 %	0.692	0.67 %
	I_3 / kA²	0.017	0.02 %	0.035	0.03 %
	I_4 / kA²	0.002	0.00 %		
	I_5 / kA²	0.017	0.02 %		
	I_6 / kA²	0.153	0.15 %		

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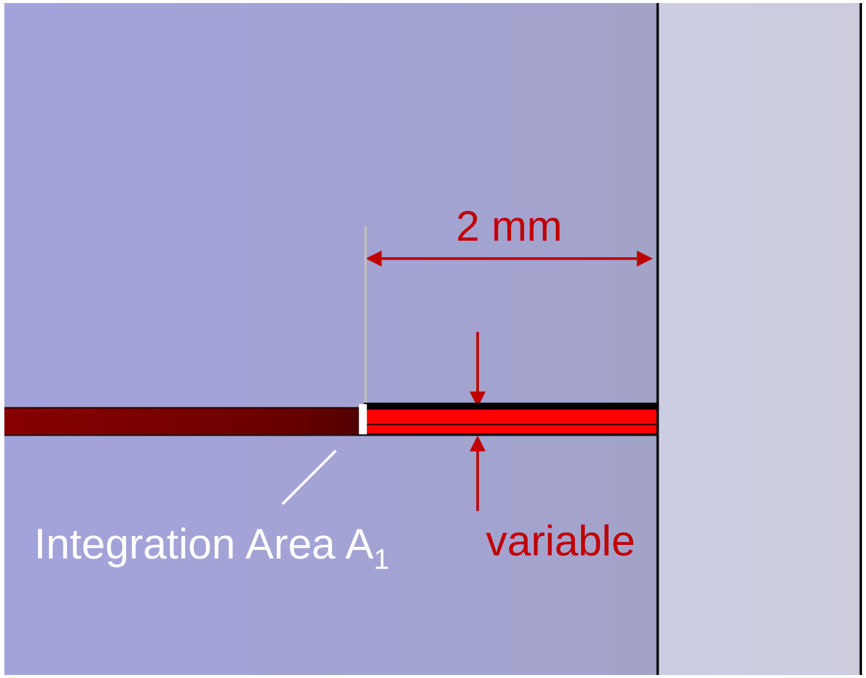
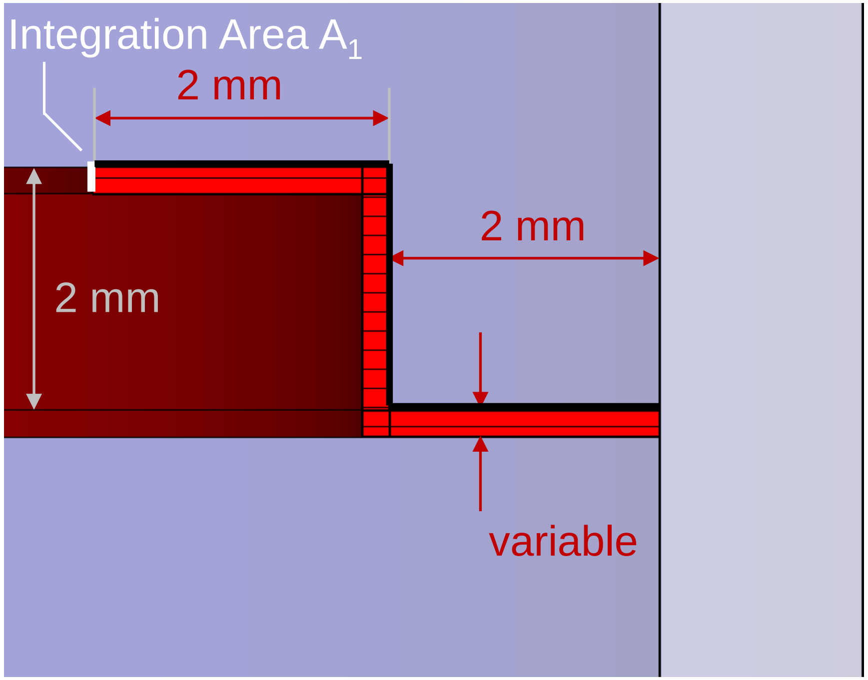
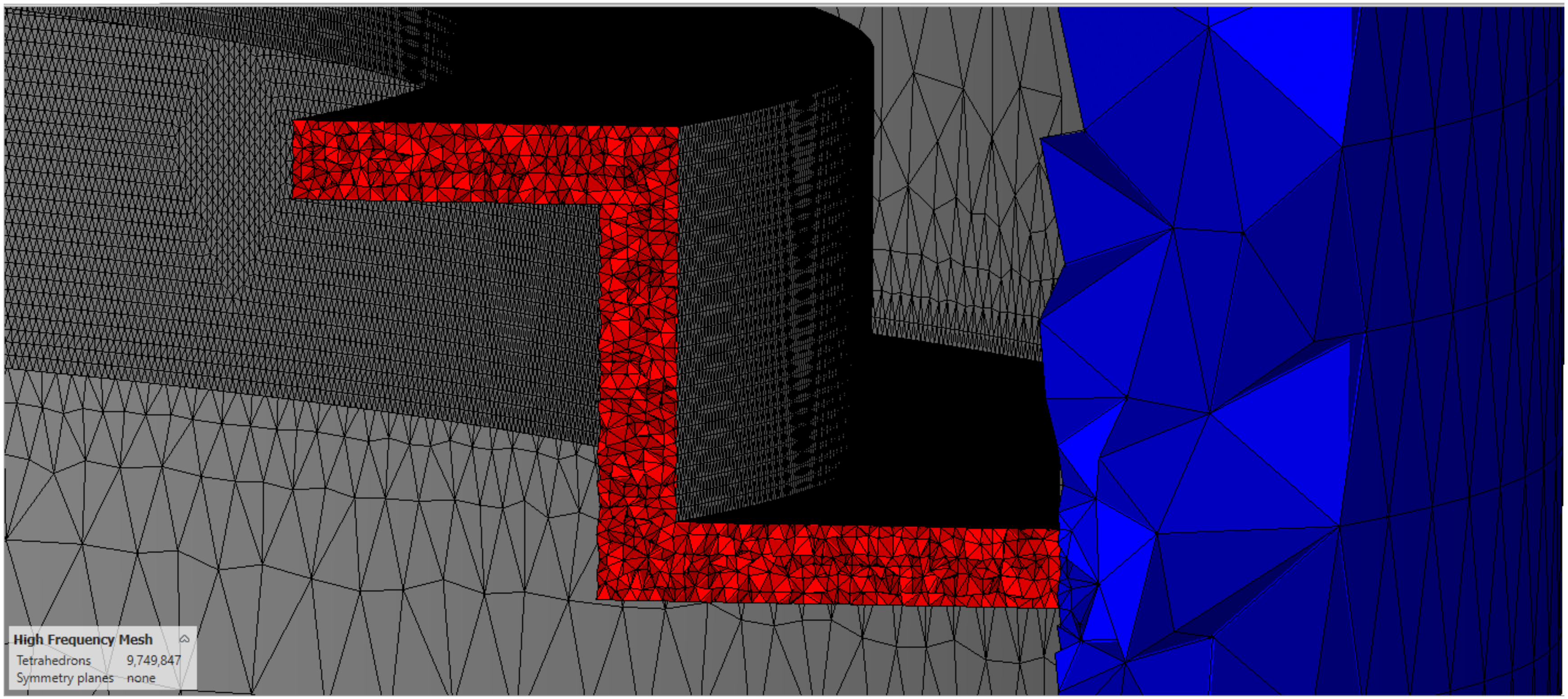


Simulation Model B



Quadrupole Resonator

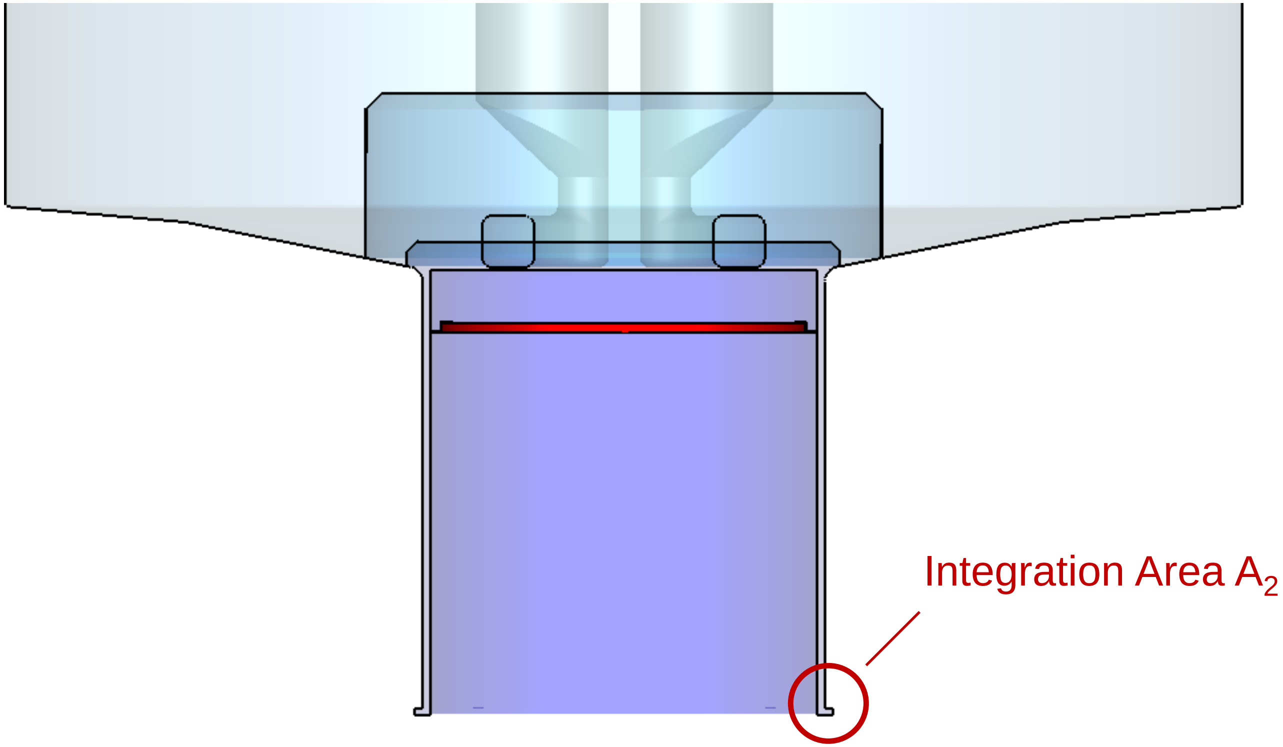
- Geometry Information
  - Simulation Model B



Quadrupole Resonator

- Geometry Information
  - Model simplifications

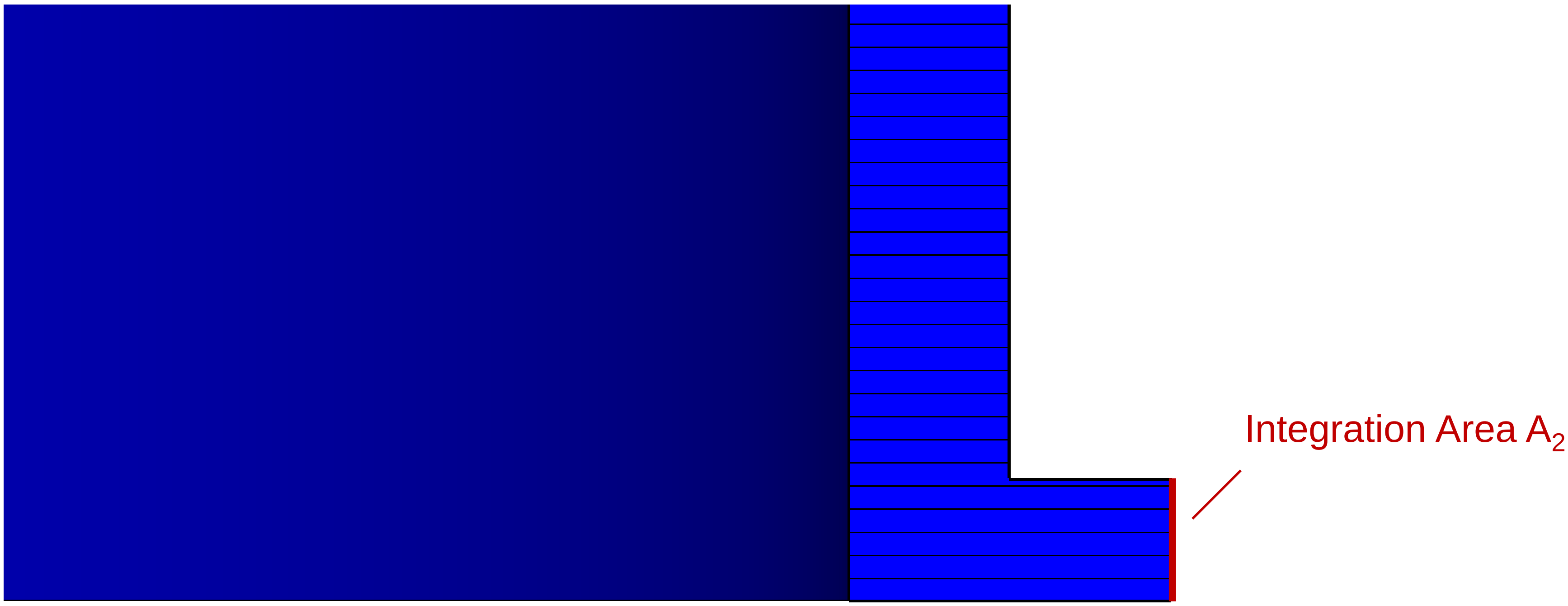
Simulation Models A and B



Quadrupole Resonator

- Geometry Information
  - Model simplifications

Simulation Models A and B

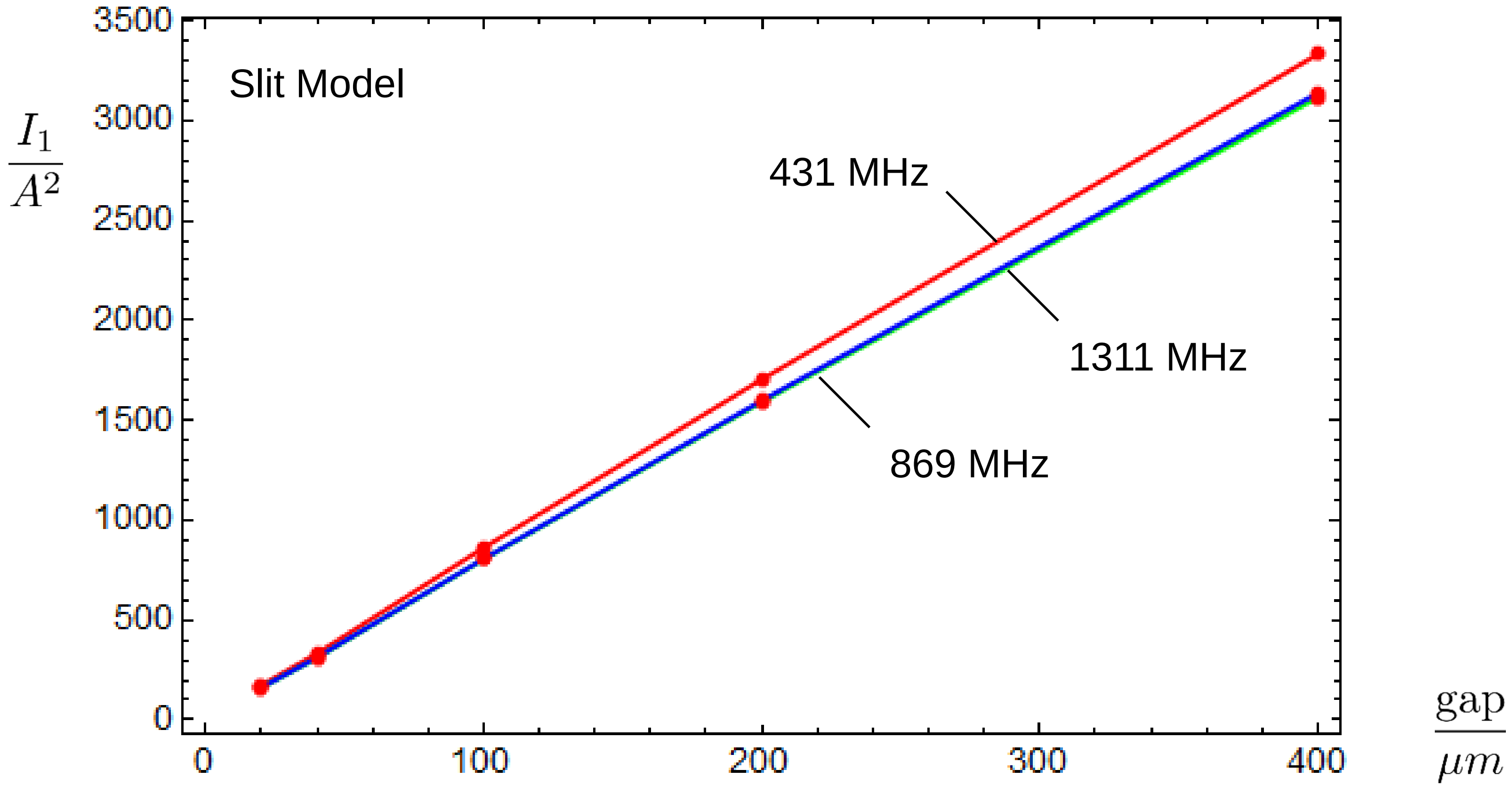


Quadrupole Resonator

- Postprocessing

$$P_\nu = \frac{1}{4}\,\mu\,\omega\,\delta\,I_\nu \qquad I_\nu = \iint_{A_\nu} \vec{H}\cdot\vec{H}\,\mathrm{d}A$$

  - Simulation results



Quadrupole Resonator

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  - Simulation results

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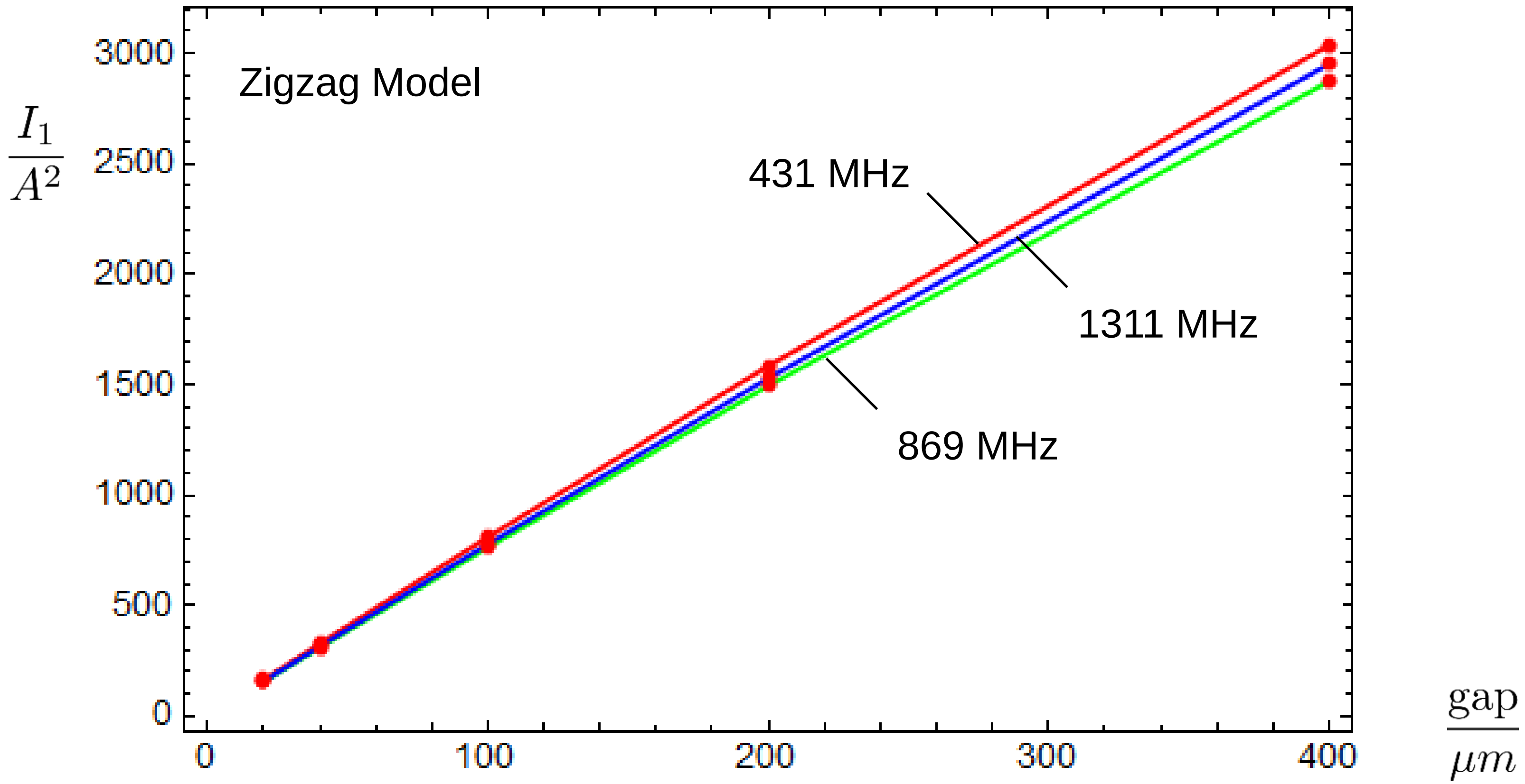

Quadrupole Resonator

- Postprocessing
  - Simulation results

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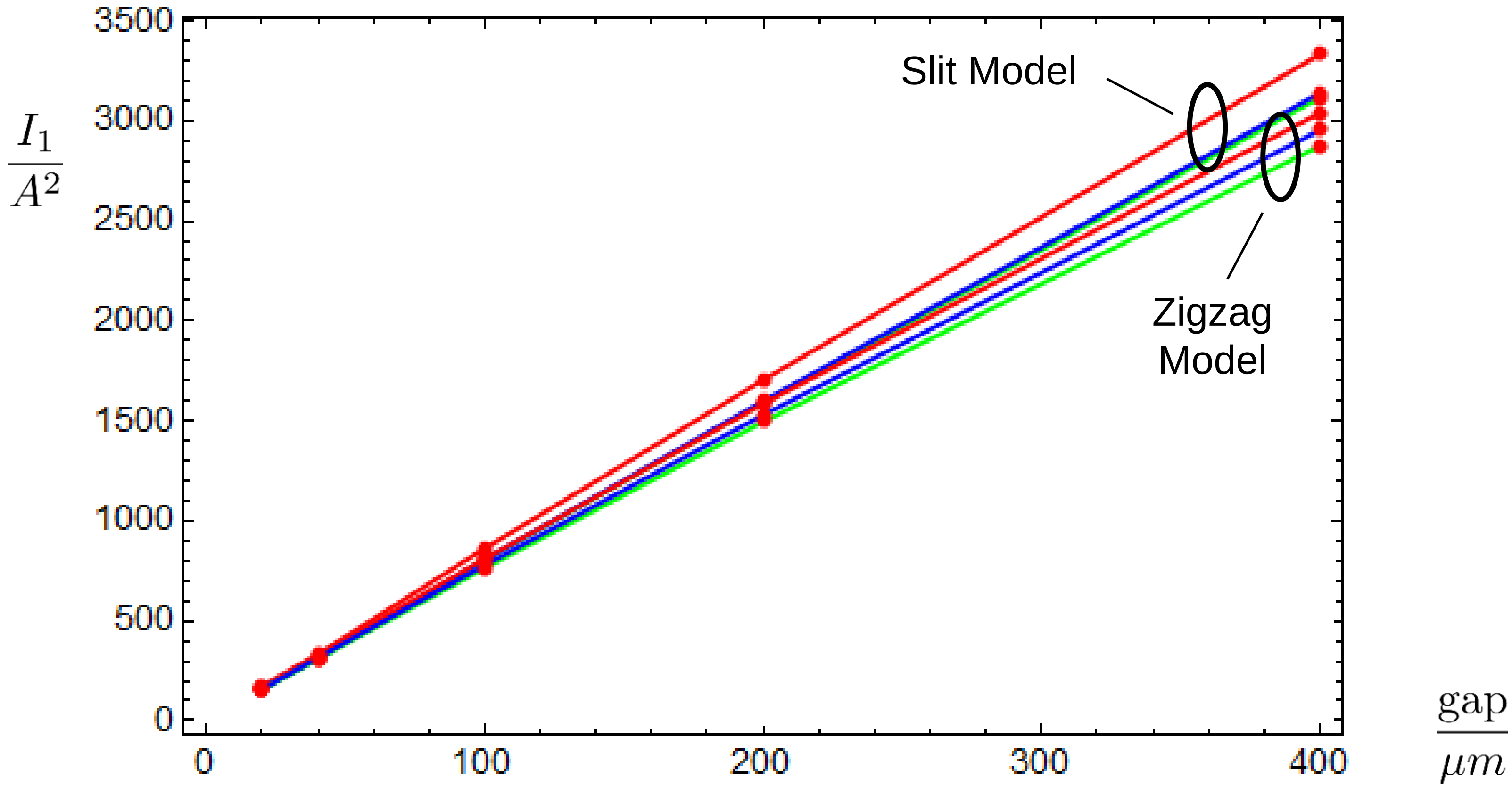

Quadrupole Resonator

- Postprocessing

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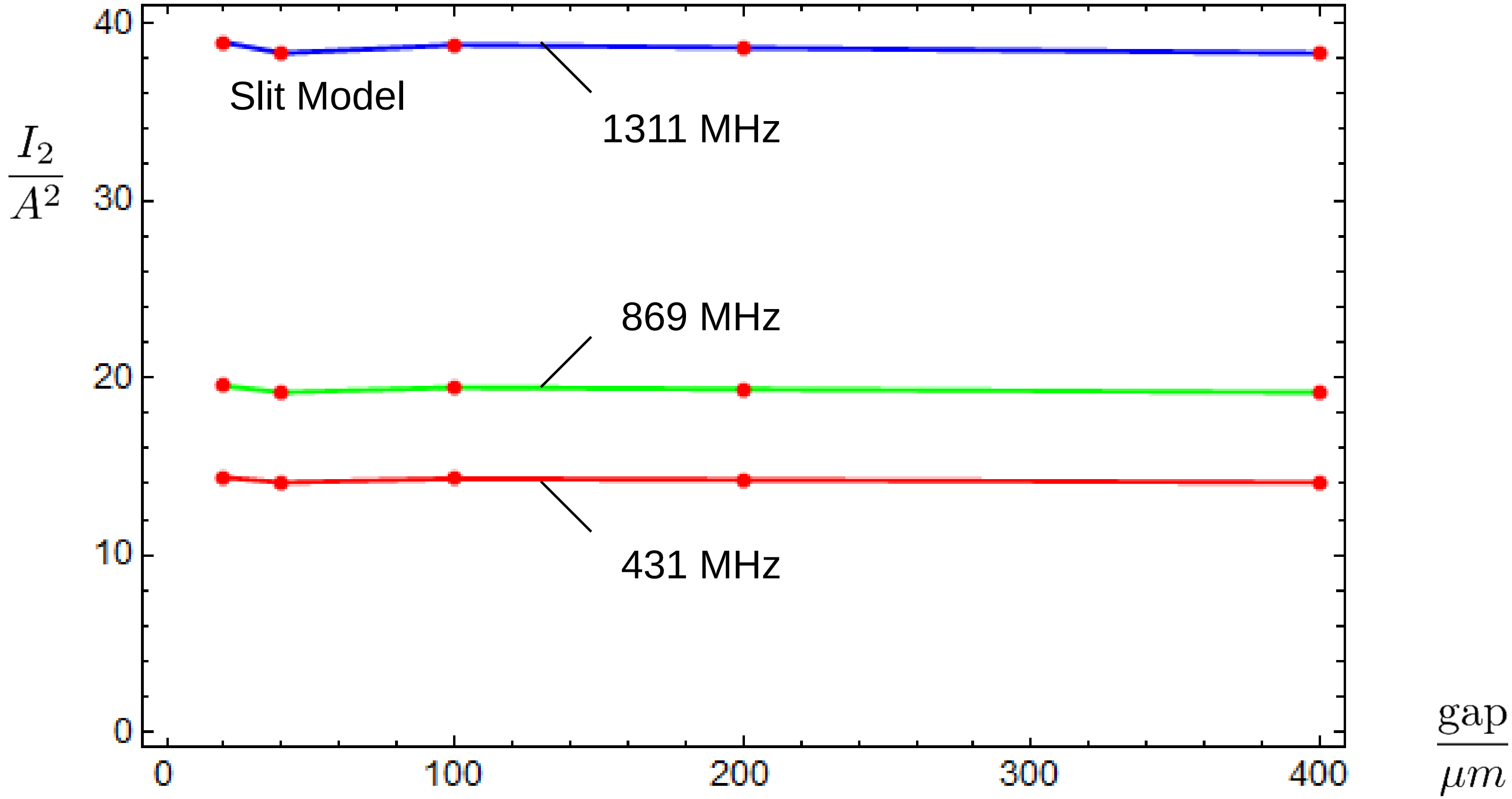
  - Simulation results



Quadrupole Resonator

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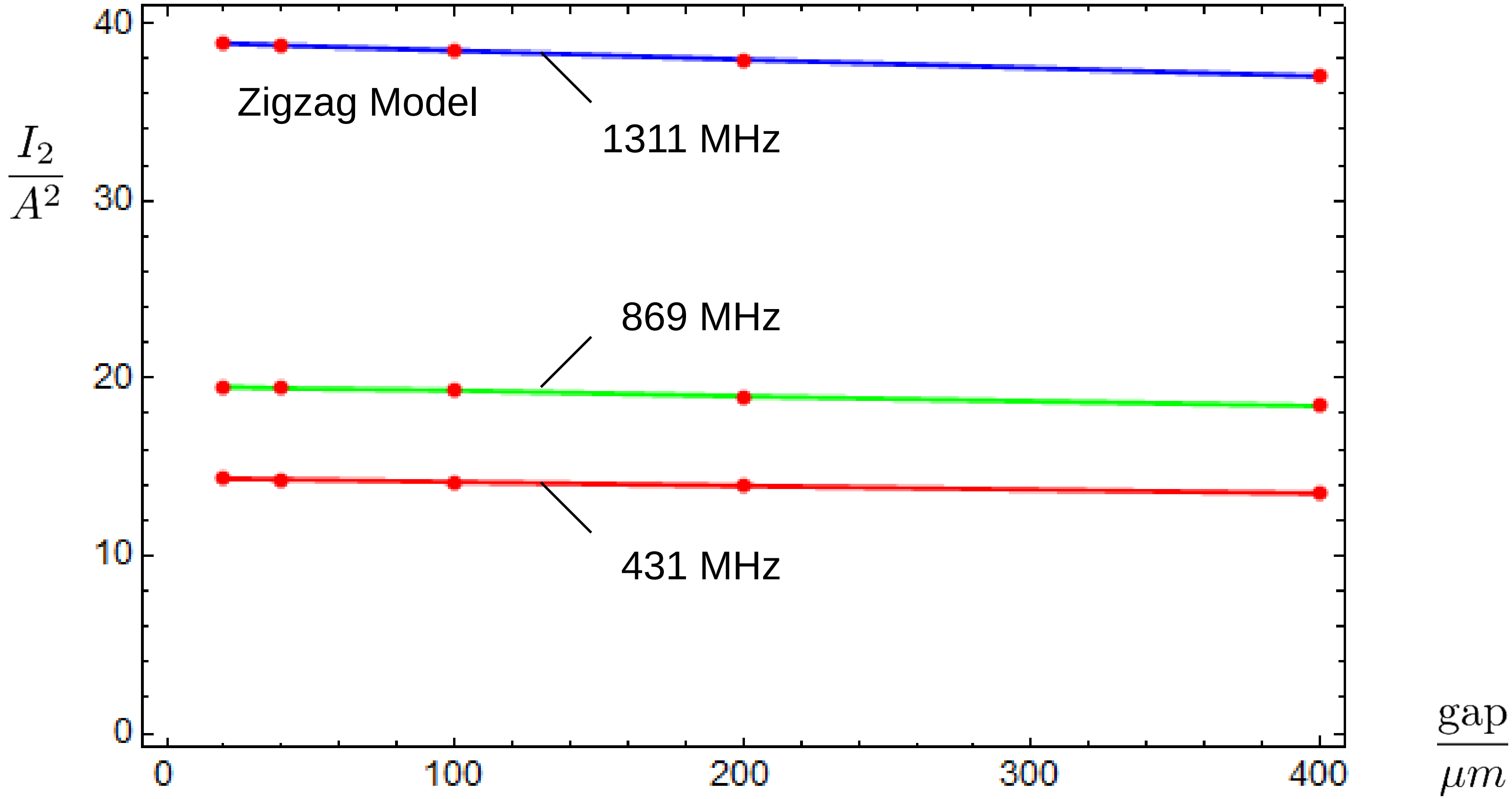
  - Simulation results



Quadrupole Resonator

- Postprocessing

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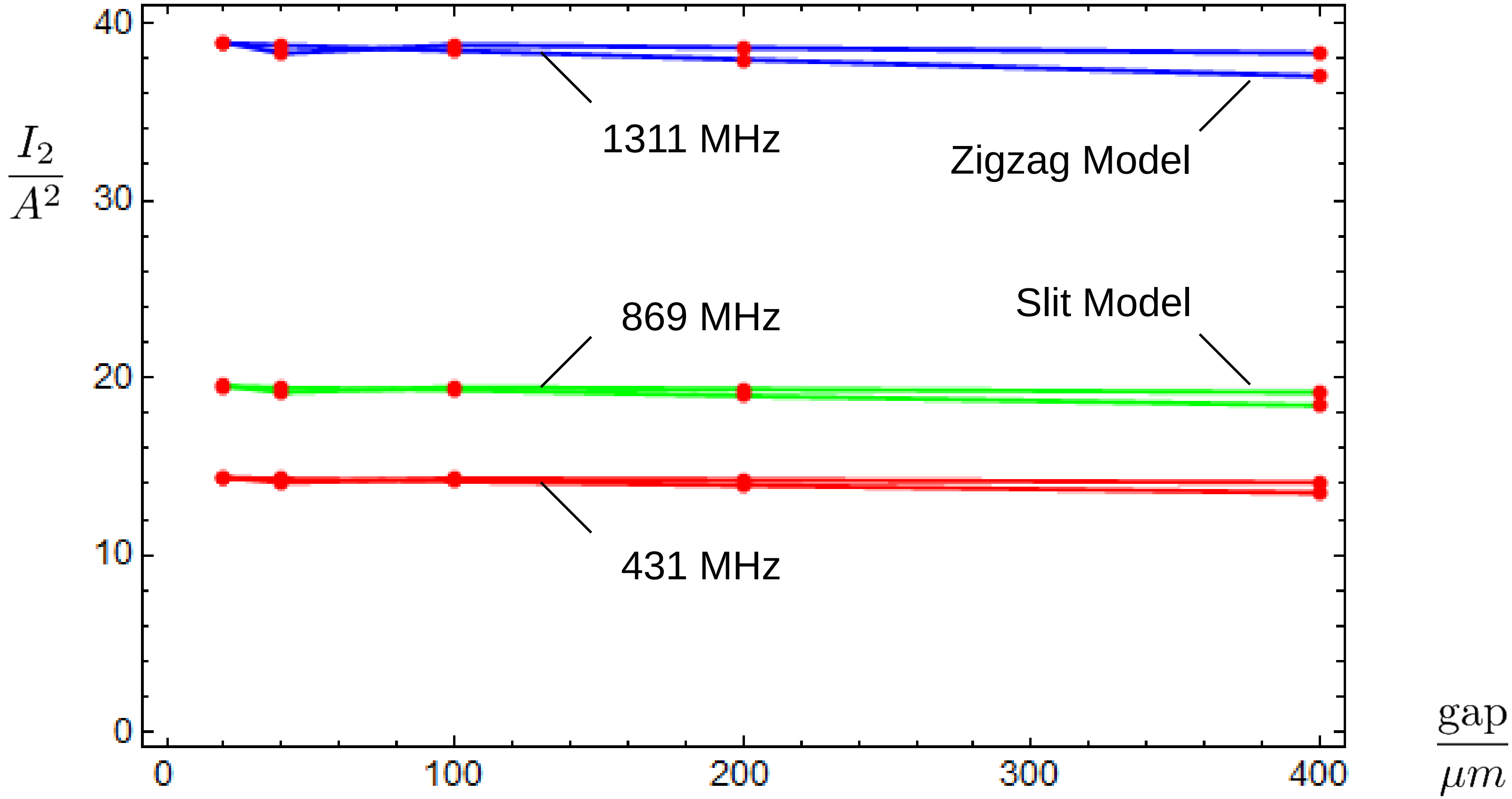
  - Simulation results



Outline

- Motivation
- Numerical Solver Development
  - Superconducting Billards (lossless)
  - TESLA Resonators (lossy)
- Quadrupole Resonator
  - Mounting Cylinder (short/long slit)
  - Mounting Cylinder (connected/isolated sample)
  - Mounting Cylinder (straight/zigzag slit)
- Summary

Summary

- Numerical eigenmode calculations based on second order FEM and curved tetrahedral elements
  - Precise geometric modeling of the QPR
  - Accurate field calculation due to fine mesh resolution and parallel high performance computing

- Postprocessing of the calculated electromagnetic fields
  - Normal conductive Indium seal can dramatically reduce the quality factor of the entire QPR setup
  - Indium seal losses are proportional to the thickness of the resulting slit