Calculation of Complex Eigenmodes for TESLA 1.3 GHz and BC0 structures

TECHNISCHE UNIVERSITÄT DARMSTADT

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Status Meeting
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Outline

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- Eigenvalue calculation for the 1.3 GHz TESLA 9-cell structure
  - Acceleration mode below cut-off frequency of the beam tubes, calculation of field maps for various main coupler penetration depths
  - Higher order modes above the cut-off frequency of the beam tubes, influence of different boundary conditions to terminate the beam tubes

- Postprocessing of the field data calculated for BC0
  - Longitudinal loss parameter
  - Kick parameter

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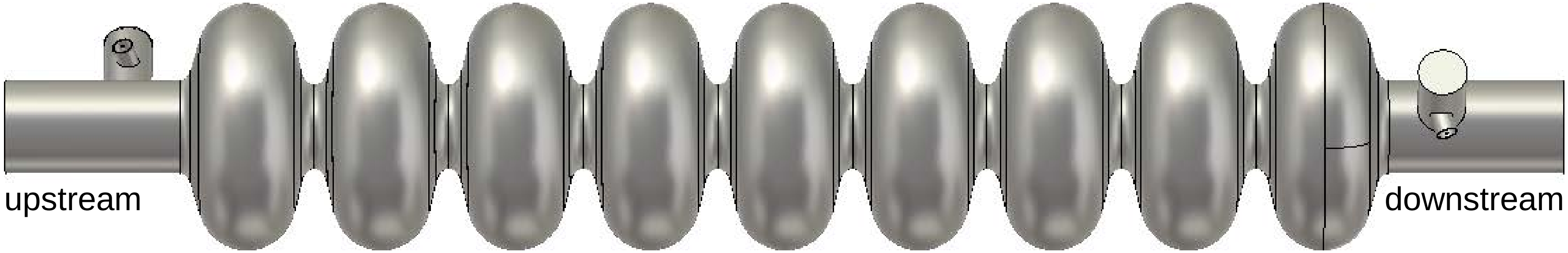
  - Kick parameter

Motivation

- Linac: Cavities
  - Photograph

http://newsline.linearcollider.org

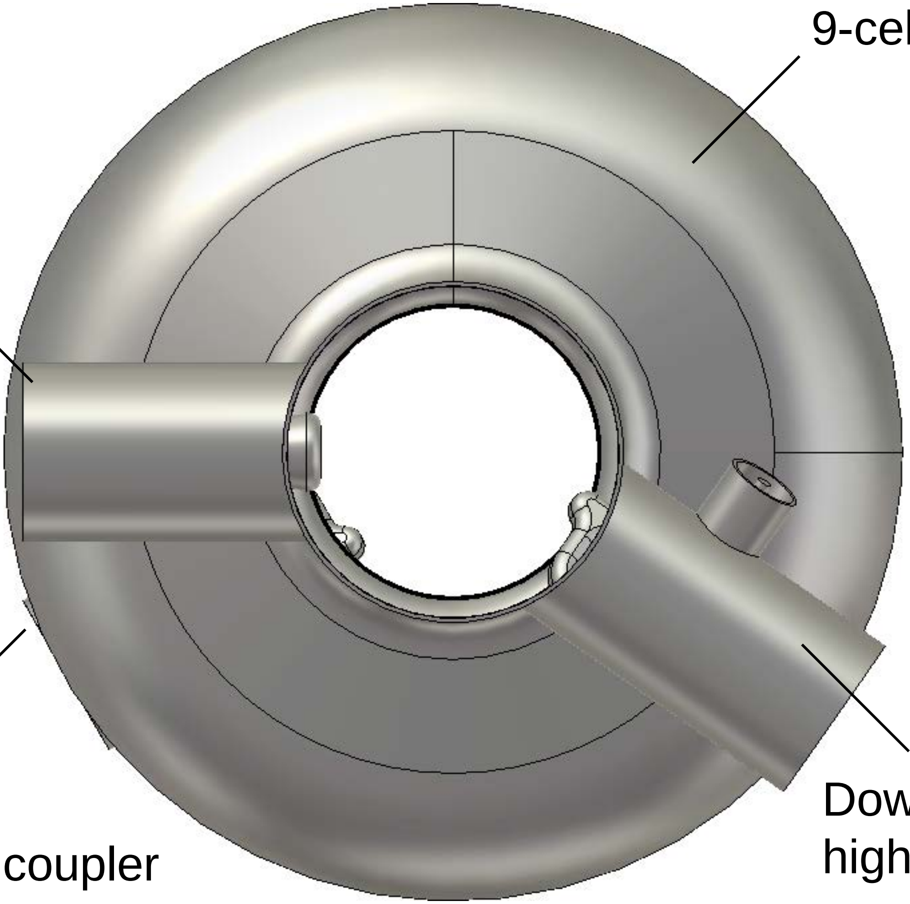
  - Numerical model



CST Studio Suite 2014

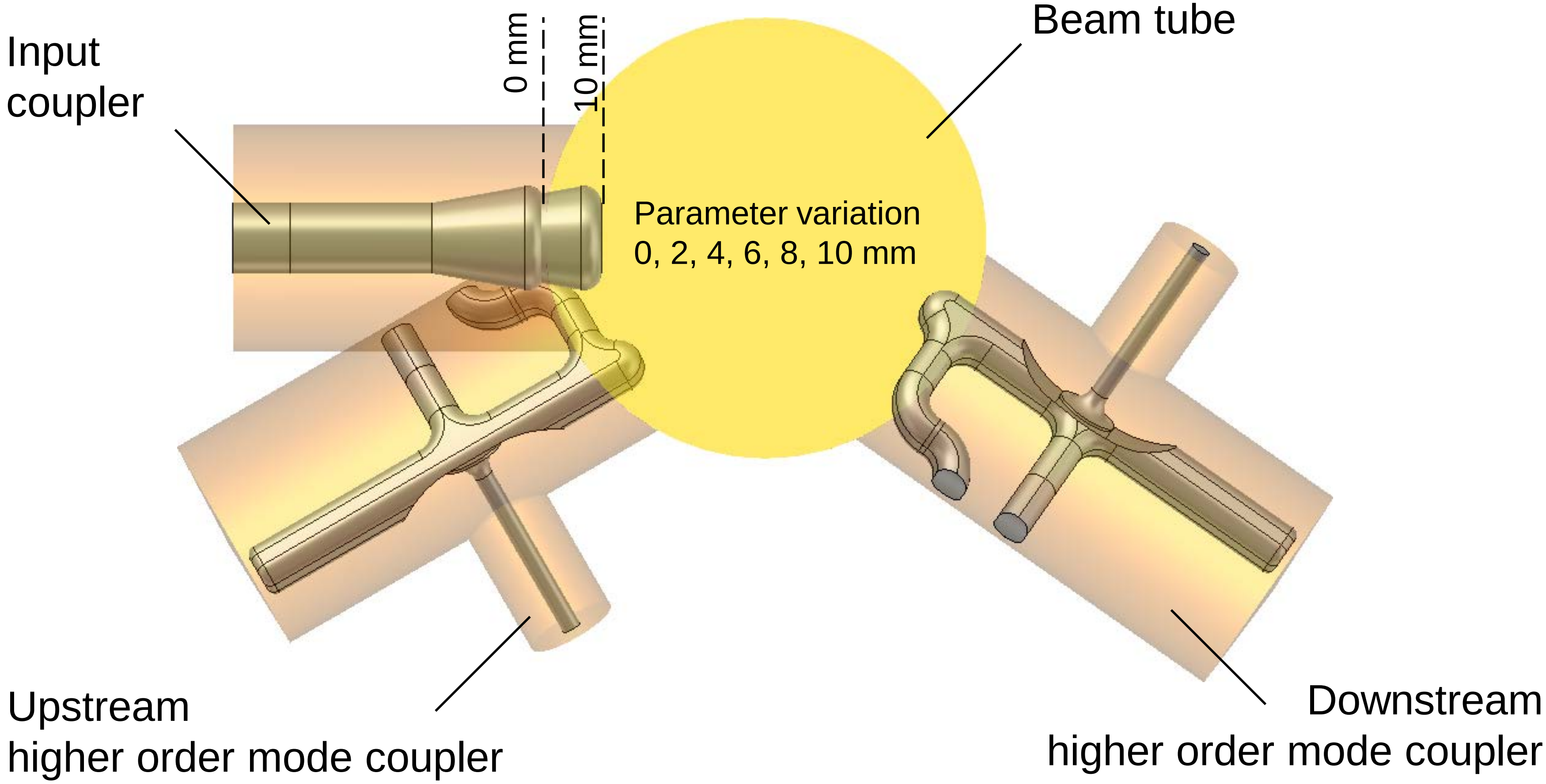
Motivation

- Superconducting resonator



Motivation

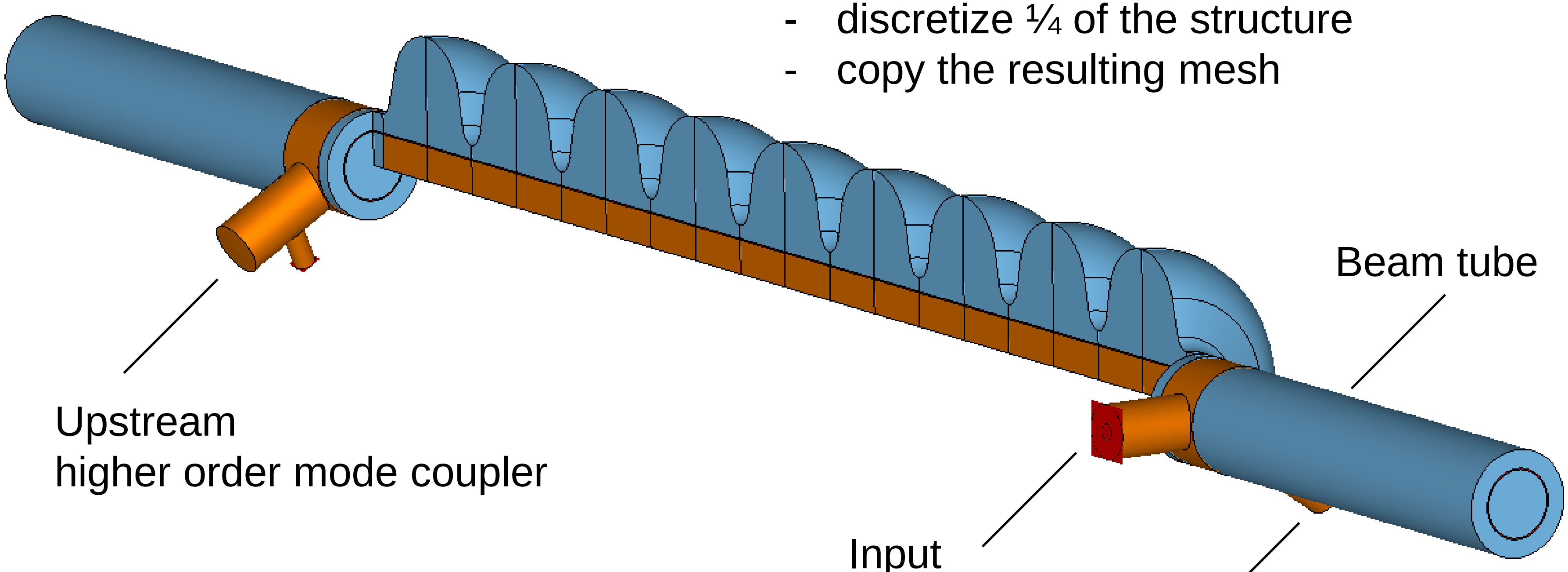
- Superconducting resonator modeling



Numerical Modeling

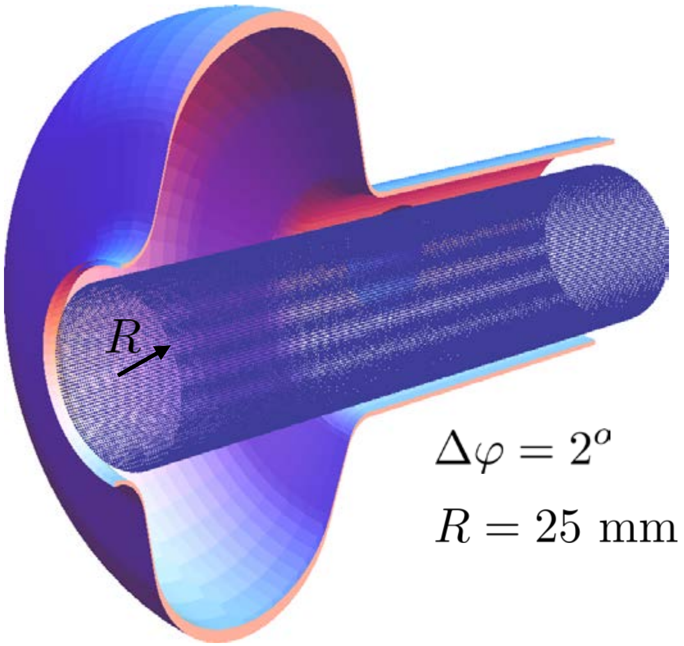
- Superconducting resonator modeling

Procedure
- discretize ¼ of the structure
- copy the resulting mesh



Numerical Modeling

- Field reconstruction using the Kirchhoff integral
  - Field values inside a closed surface can be determined once the surface field components are available
  - Kirchhoff integral



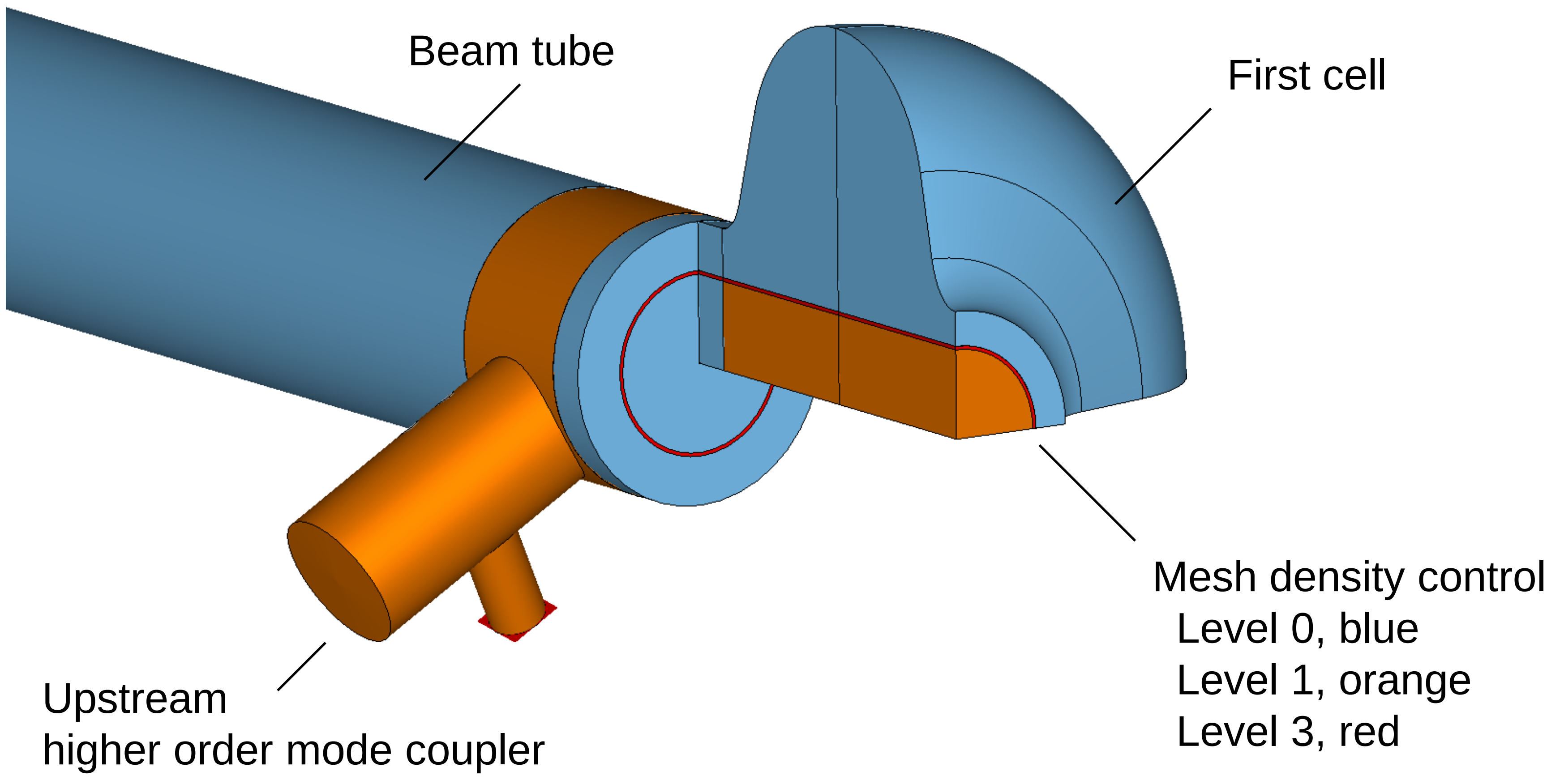
$$G = \frac{e^{-ik|\vec{r}-\vec{r}\,'|}}{4\pi|\vec{r}-\vec{r}\,'|} \qquad k = \frac{2\pi f}{c_0}$$

$$\vec{E}(\vec{r}) = \int \Big(k(\vec{n}' \times ic_0\vec{B}')\,G - (\vec{n}' \times \vec{E}') \times \nabla G - (\vec{n}' \cdot \vec{E}')\,\nabla G\Big)\,\mathrm{d}A'$$

$$ic_0\vec{B}(\vec{r}) = \int \Big(k(\vec{n}' \times \vec{E}')\,G - (\vec{n}' \times ic_0\vec{B}') \times \nabla G - (\vec{n}' \cdot ic_0\vec{B}')\,\nabla G\Big)\,\mathrm{d}A'$$

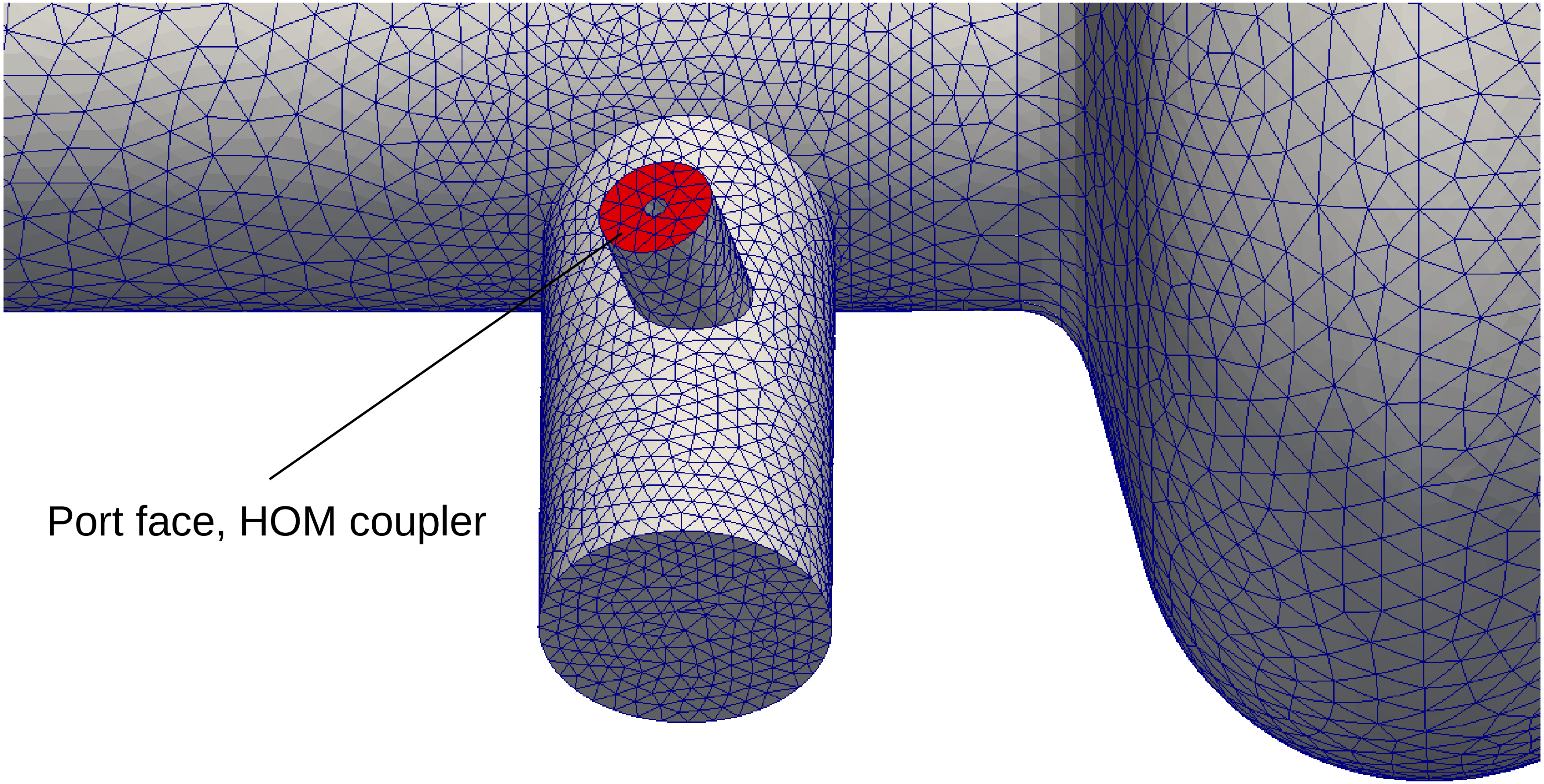
Numerical Modeling

- Superconducting resonator modeling



Computational Model

- Port boundary condition



Computational Model

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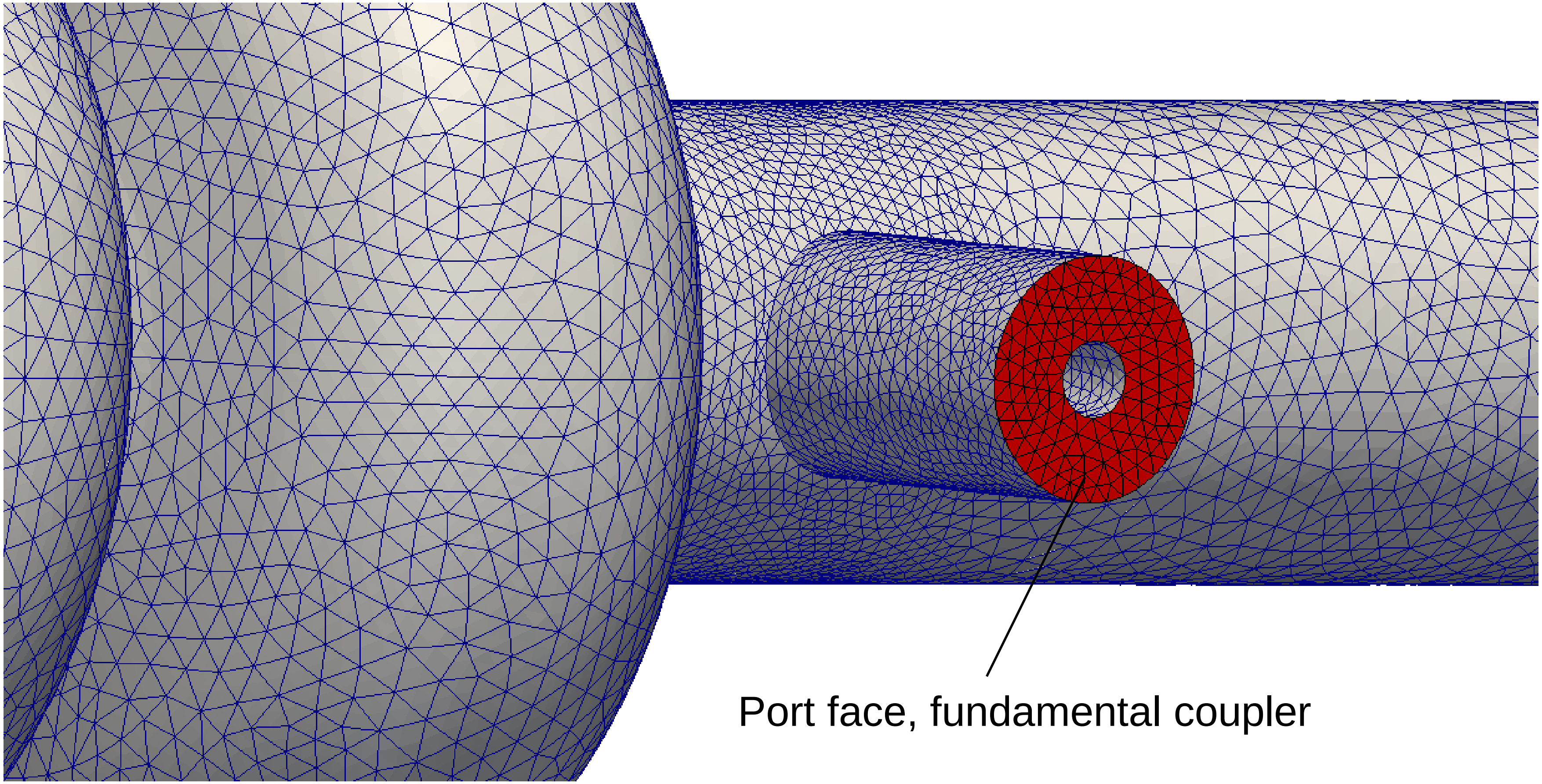
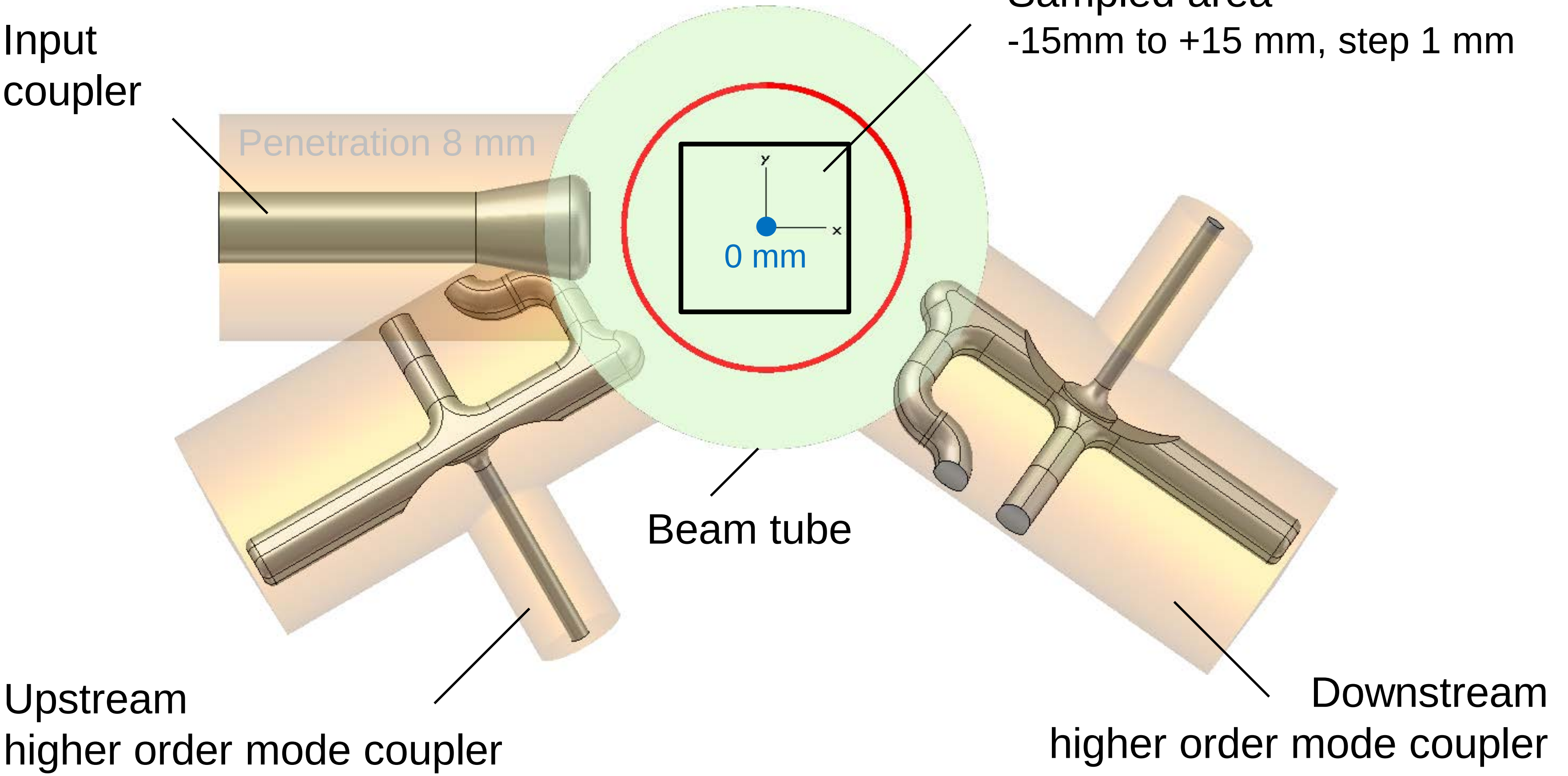


Numerical Modeling

- Superconducting resonator



Numerical Results

- Superconducting resonator
  - Convergence study

Main coupler depth	Number of tets	Resonance freqency	Quality factor
8 mm	366 955	1.300055 GHz	$2.832\ 10^6$
8 mm	720 324	1.300032 GHz	$2.753\ 10^6$
8 mm	1 320 954	1.300012 GHz	$2.735\ 10^6$
8 mm	2 131 752	1.300005 GHz	$2.670\ 10^6$
8 mm	3 284 180	1.300002 GHz	$2.667\ 10^6$

Estimated accuracy

$$\Delta f \approx 10^{-5}$$

$$\Delta Q \approx 10^{-3}$$

Numerical Results

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- Superconducting resonator
  - Eigenvalue calculation

Main coupler depth	Number of tets	Resonance freqency	Quality factor
0 mm	3 290 937	1.300003 GHz	$12.605\ 10^6$
2 mm	3 288 250	1.300002 GHz	$8.304\ 10^6$
4 mm	3 286 608	1.300002 GHz	$5.571\ 10^6$
6 mm	3 285 819	1.300002 GHz	$3.812\ 10^6$
8 mm	3 284 180	1.300002 GHz	$2.667\ 10^6$
10 mm	3 282 786	1.300002 GHz	$1.909\ 10^6$

➡ Complex-valued field components are available within the FEM or the Kirch-hoff‘s integral formulation for any specified main coupler penetration depth. File format for ASTRA input has been provided by DESY (thanks to Martin).

Outline

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  - Longitudinal loss parameter
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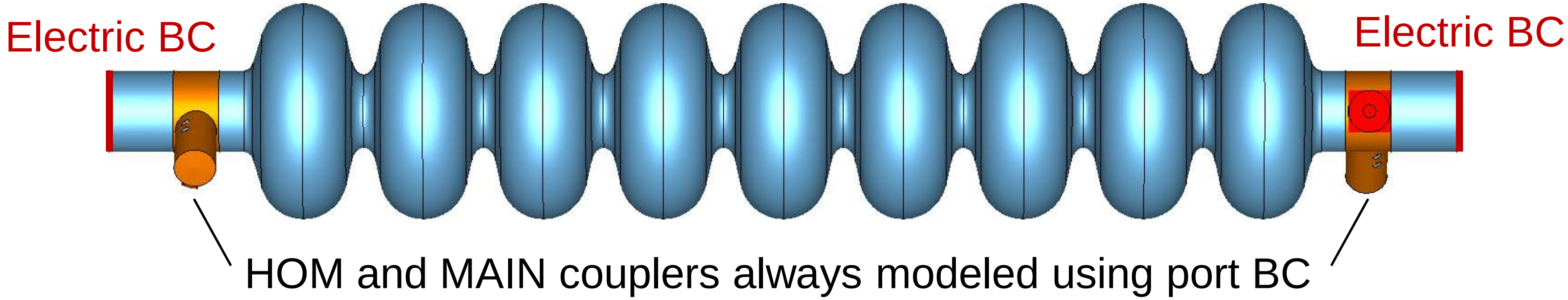
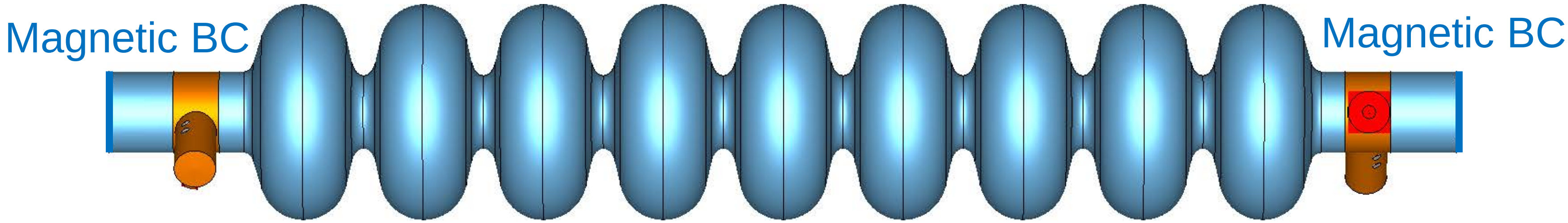
Numerical Examples

- Influence of boundary conditions at the beam tube
  - Close tube using PEC material

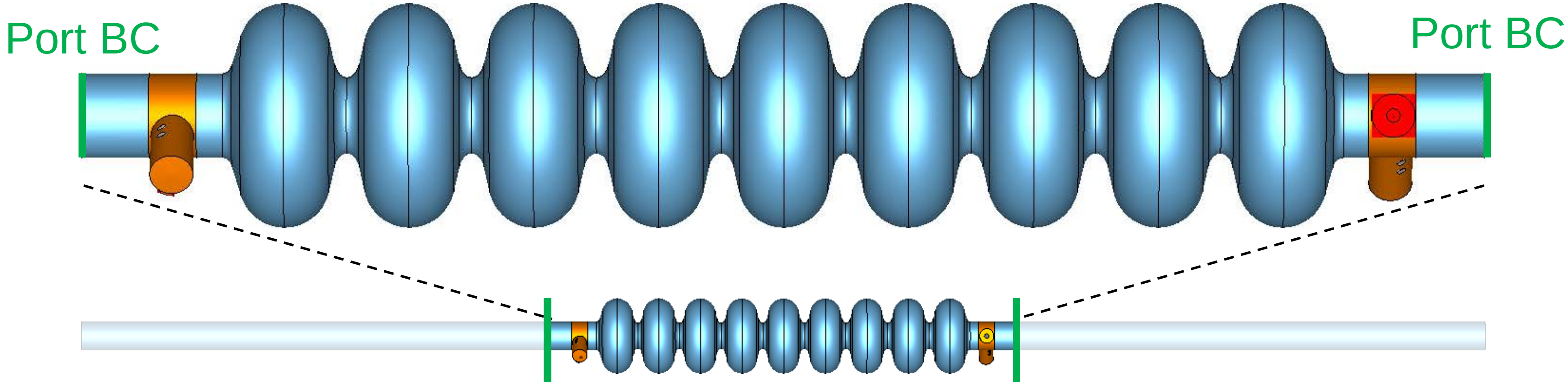


  - Close tube using PMC material

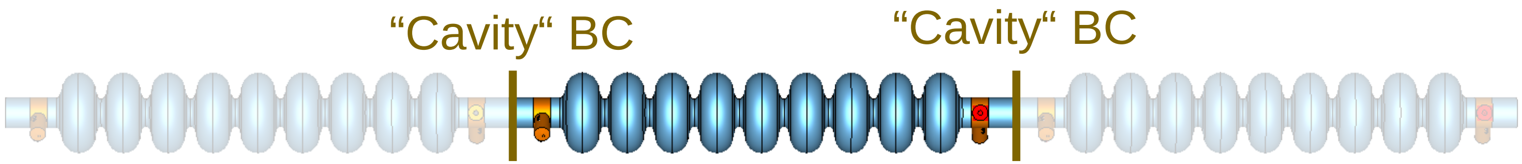


Numerical Examples

- Influence of boundary conditions at the beam tube
  - Infinite tube using port boundary conditions



  - "Cavity" boundary condition



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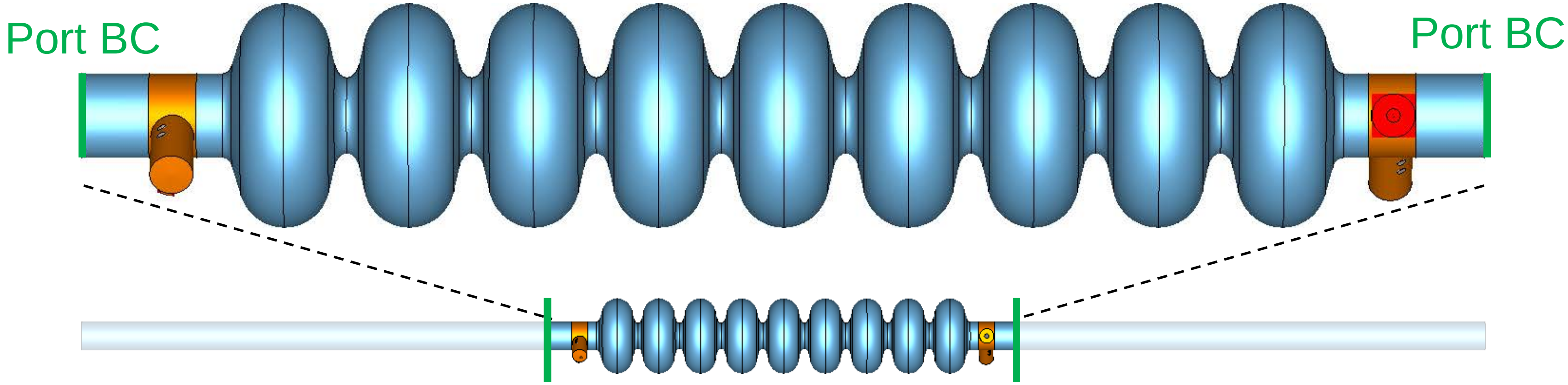

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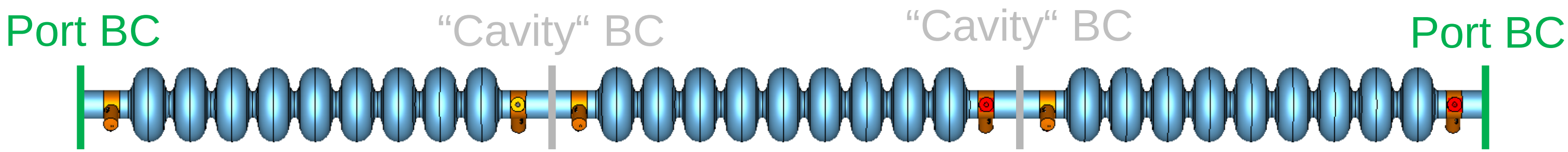
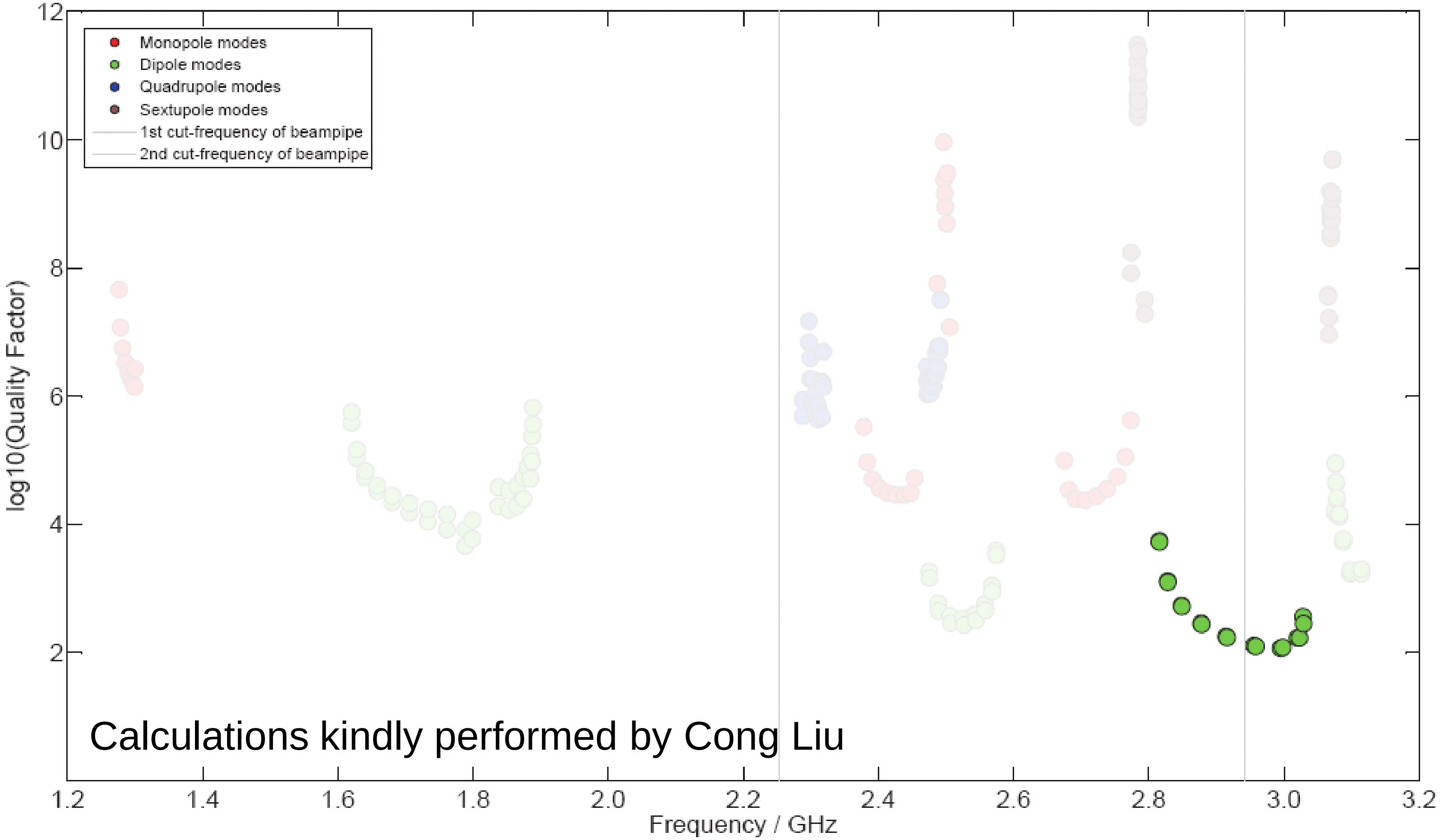


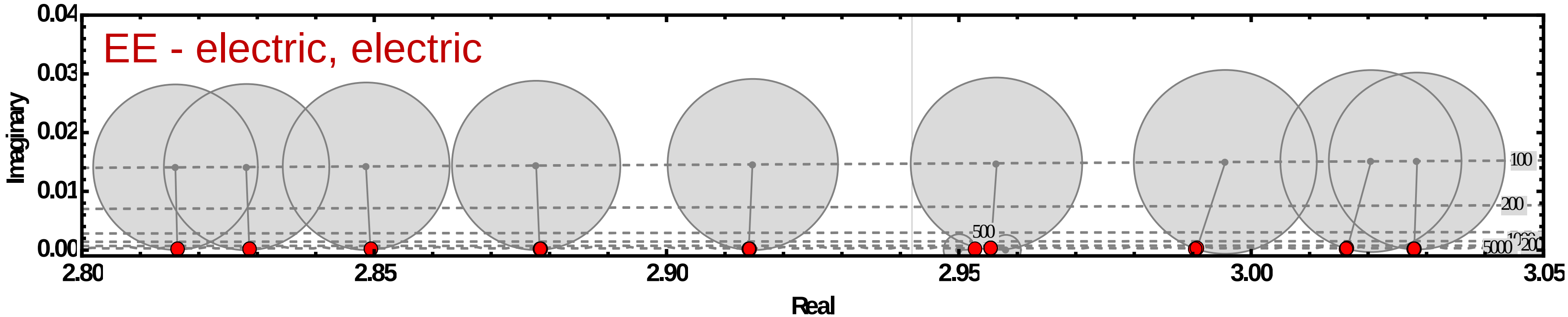
Numerical Examples

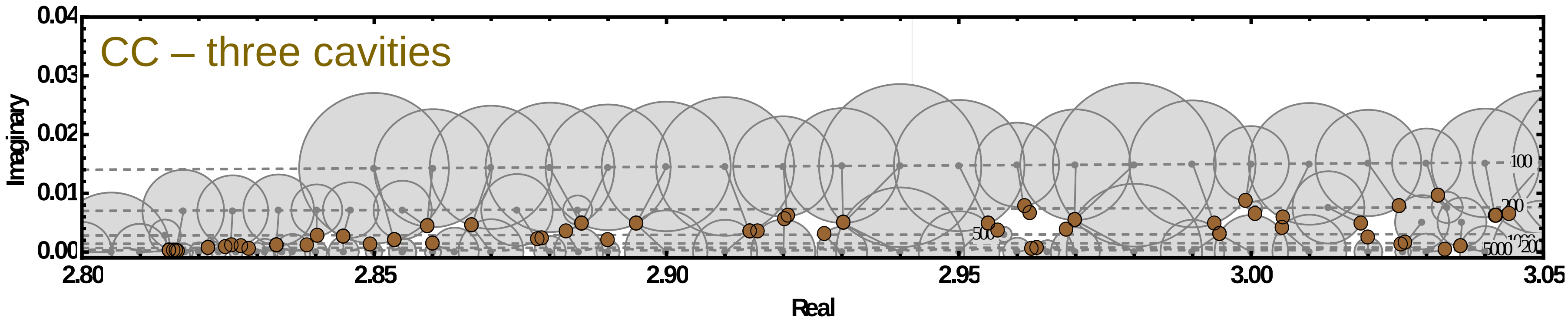
- Quality factor versus frequency (1.3 GHz structure)



Numerical Examples

- Quality factor versus frequency
  - Comparison using different beam-tube boundary conditions





Numerical Examples

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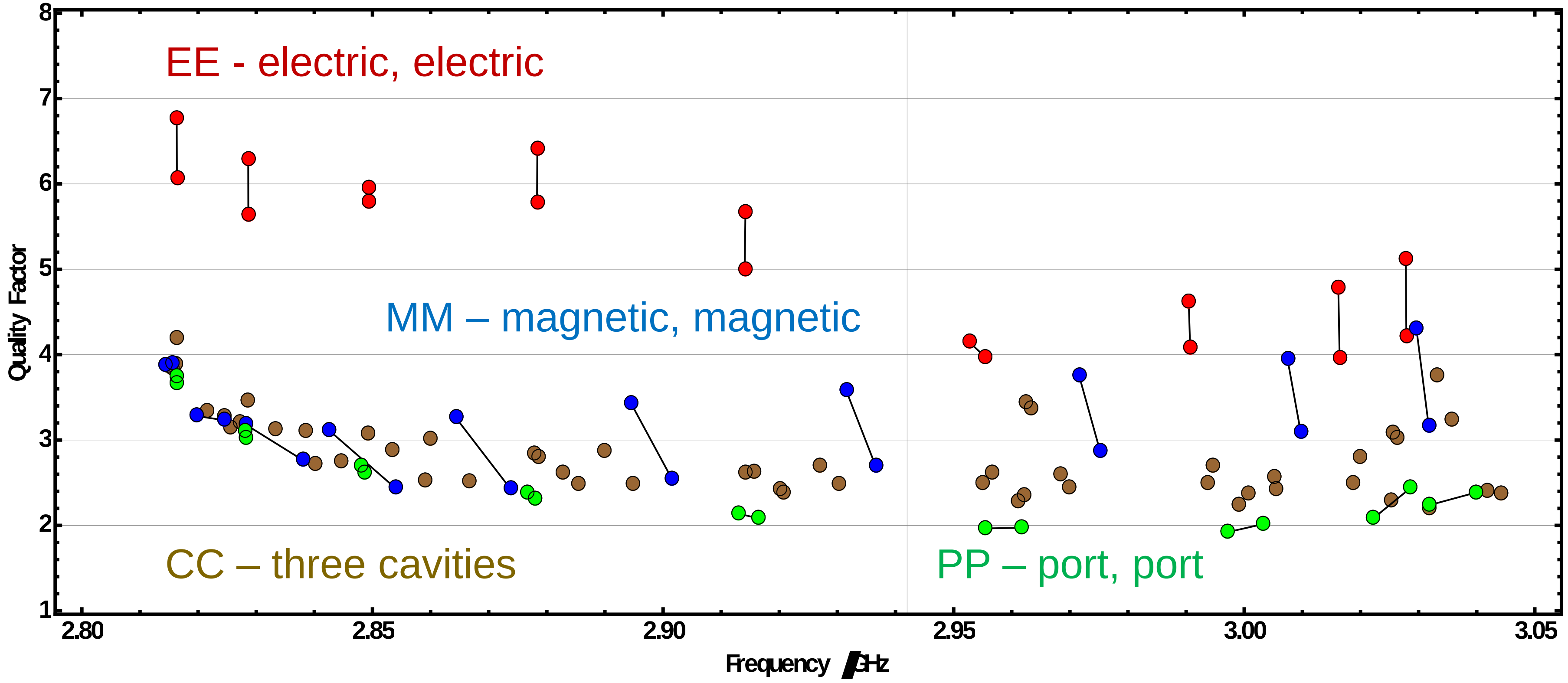

Numerical Examples

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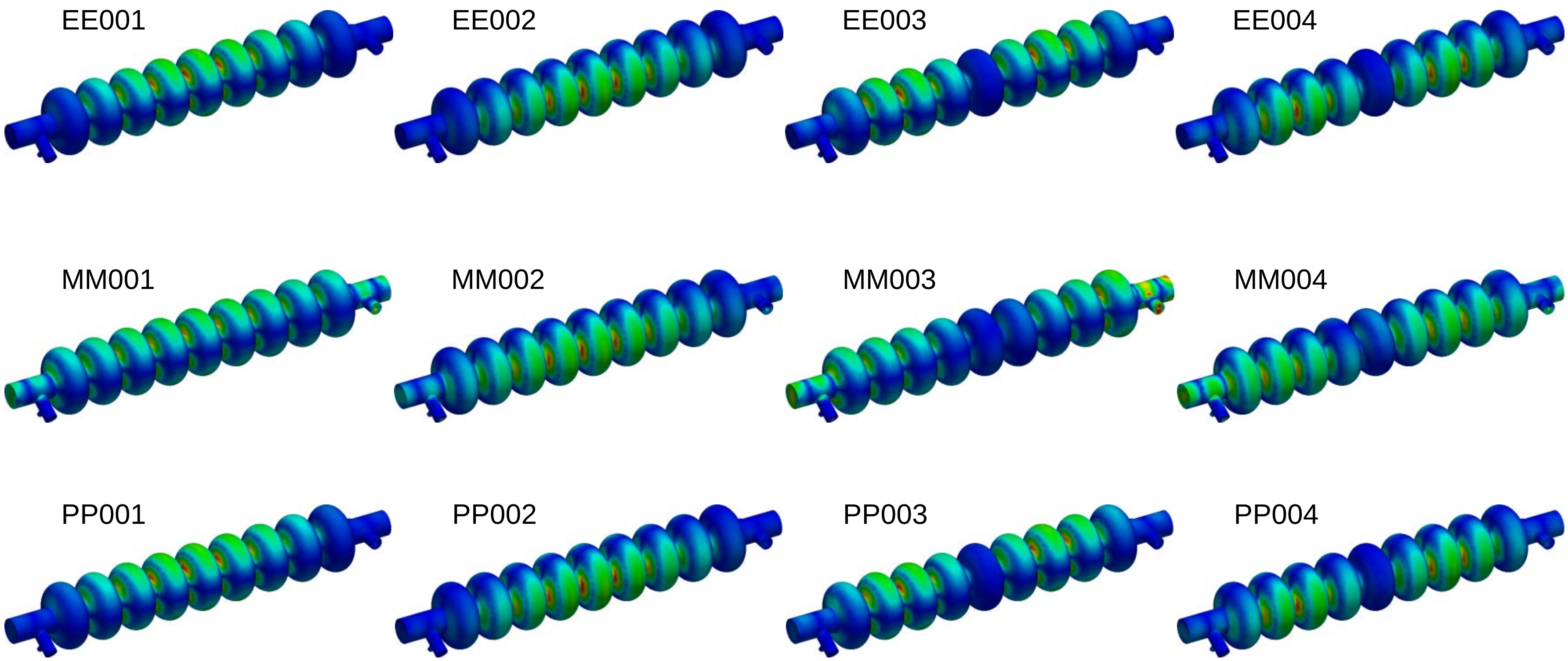
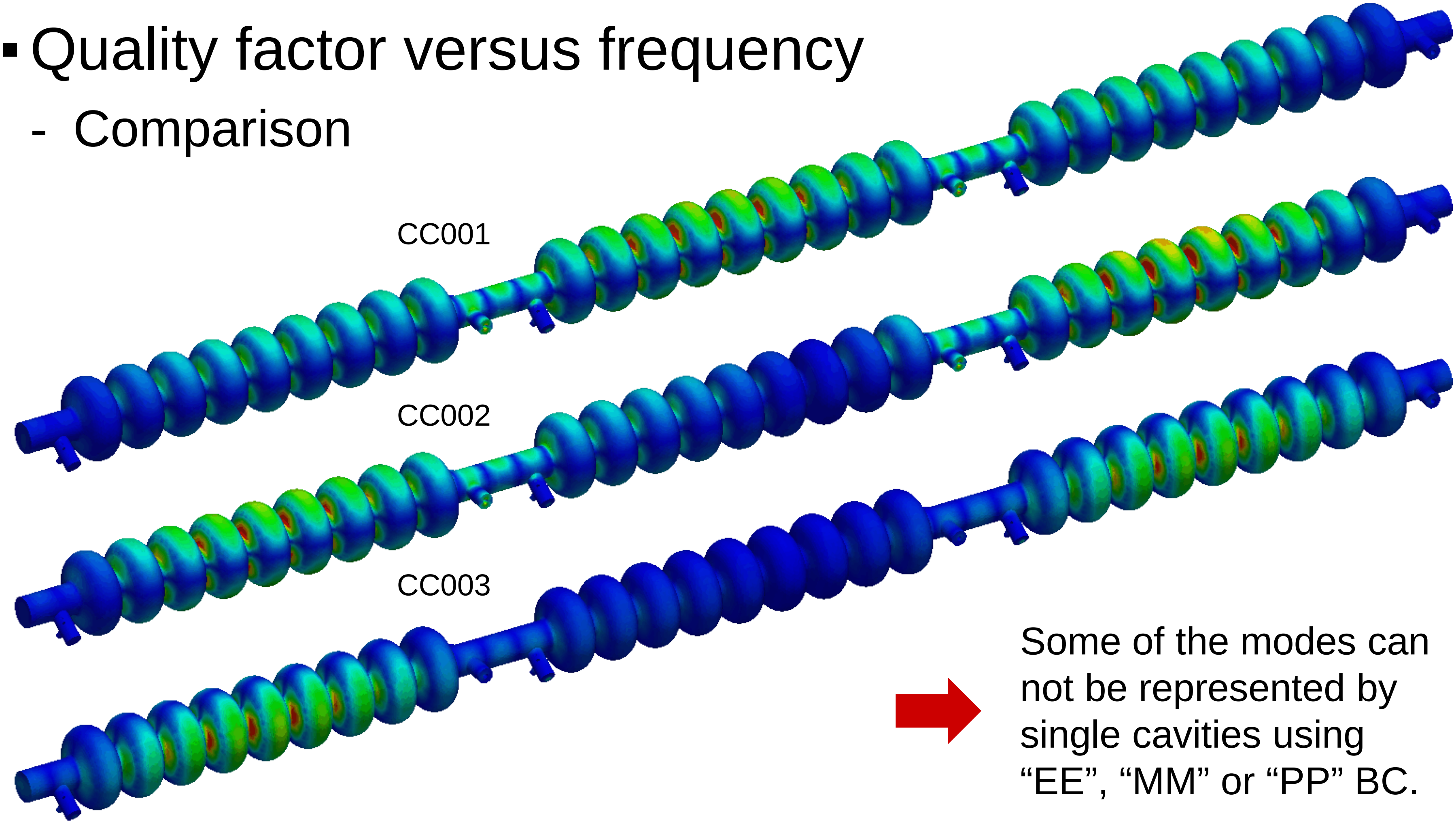


Numerical Examples

- Quality factor versus frequency
  - Comparison



Some of the modes can not be represented by single cavities using "EE", "MM" or "PP" BC.

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  - Kick parameter

Computational Model

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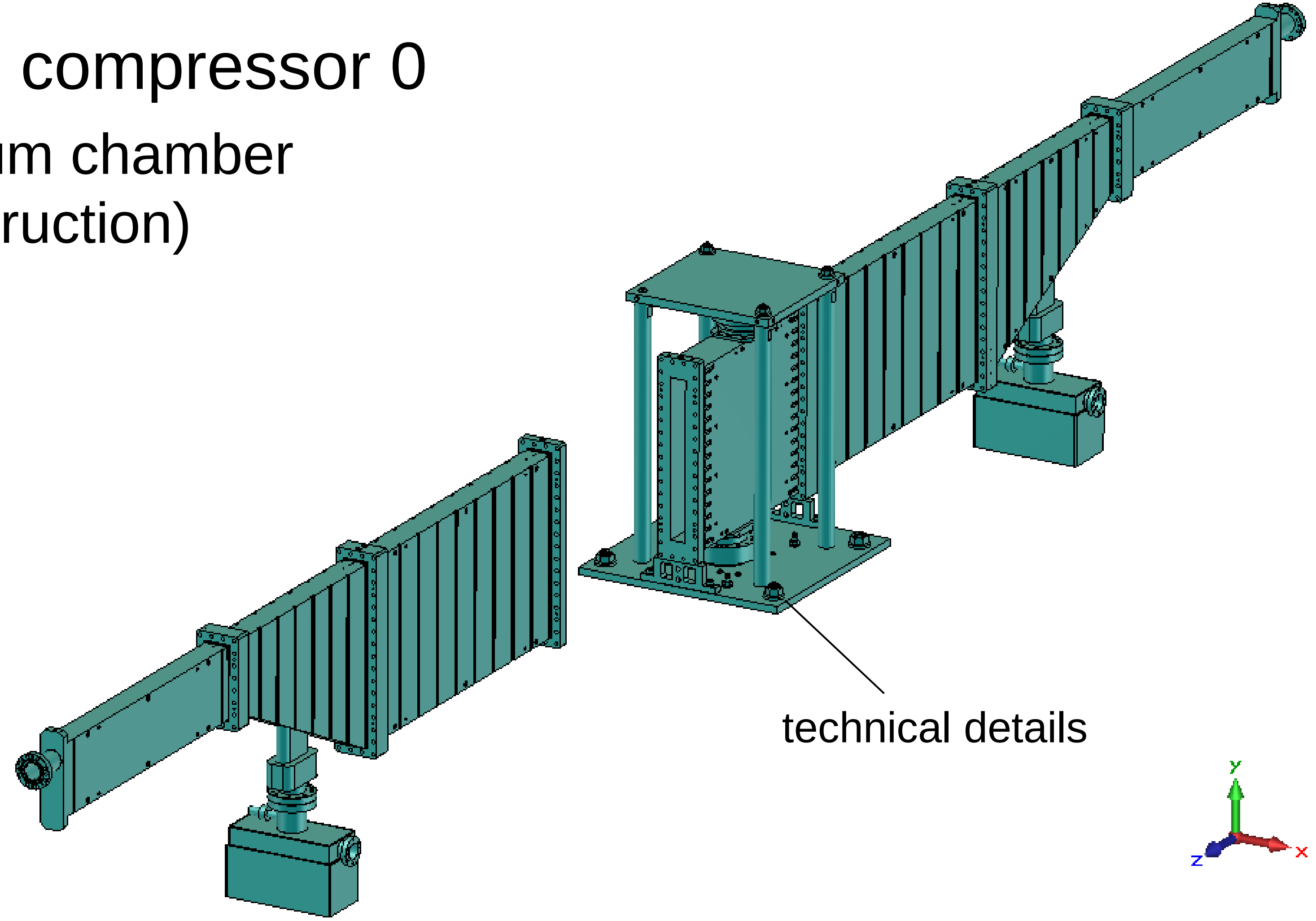
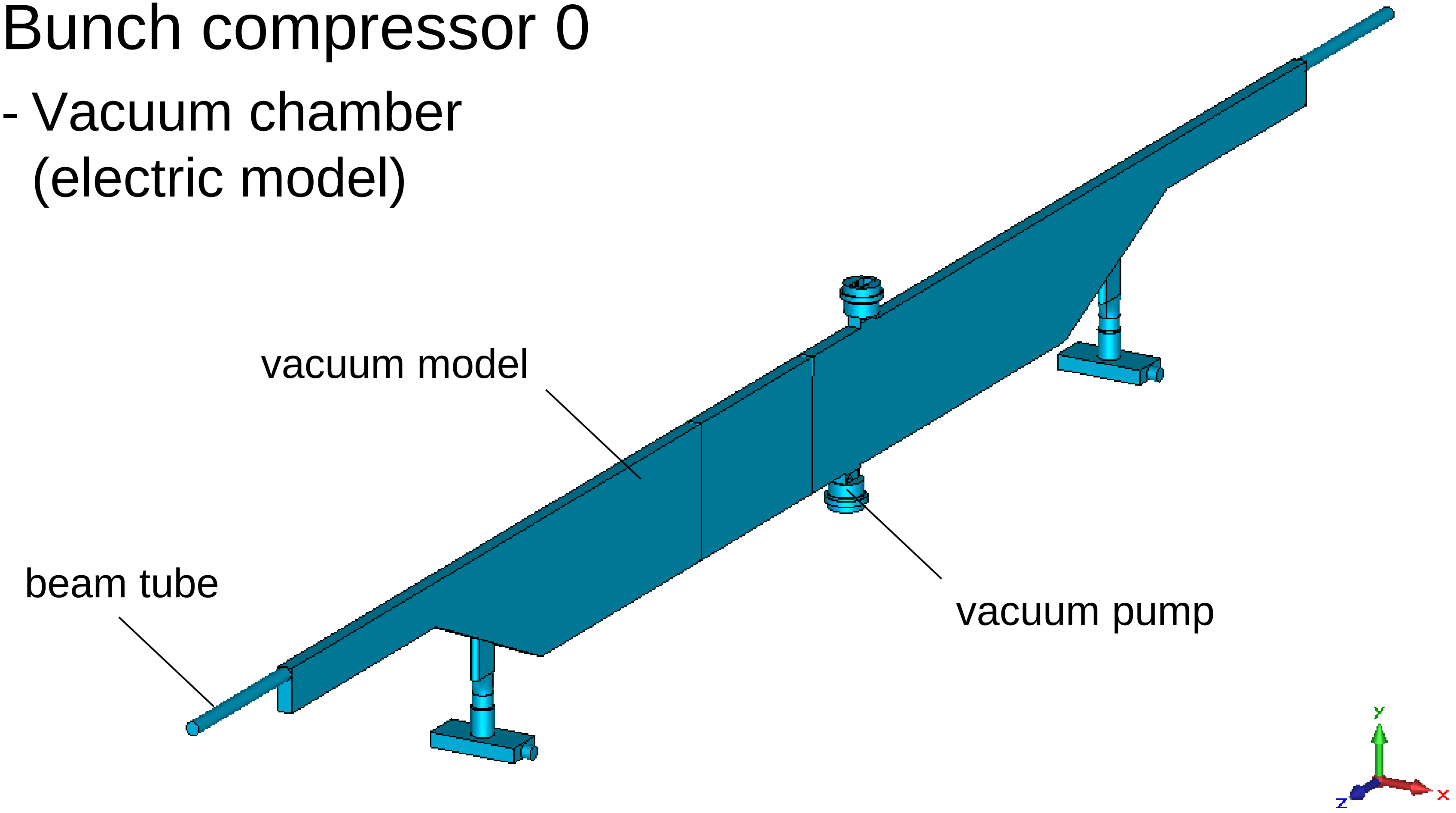
- Bunch compressor 0
  - Vacuum chamber (construction)



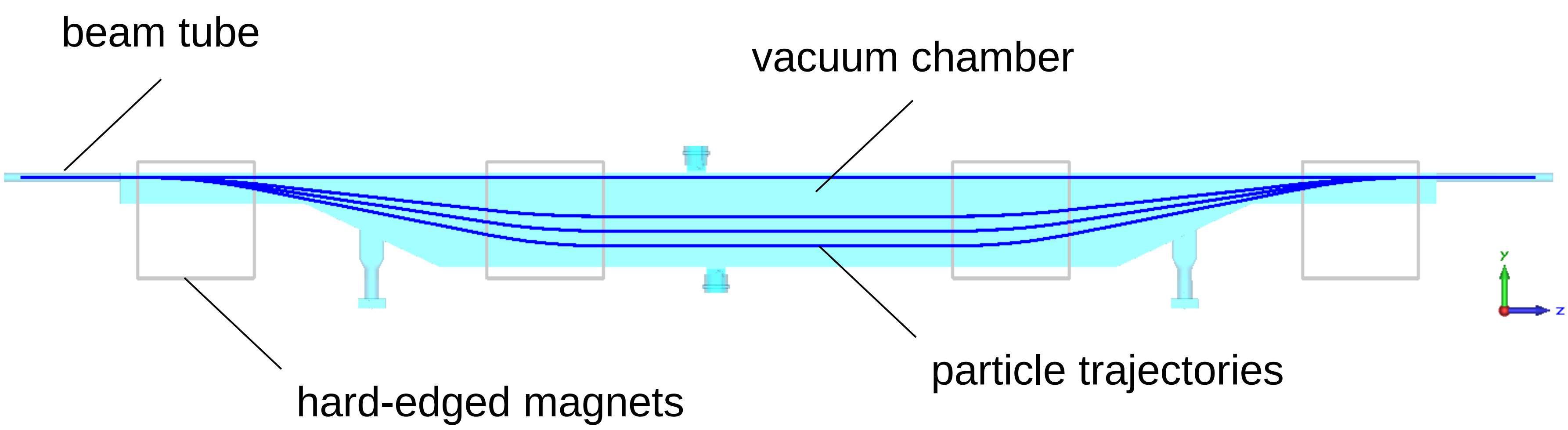
Computational Model

- Bunch compressor 0
  - Vacuum chamber (electric model)



Computational Model

- Bunch compressor 0
  - Particle trajectories
    - Hard-edged magnets: analytical calculation of particle trajectories
    - Determination of local coordinates aligned to tangential direction
    - Specification of sample points to evaluate eigenmode fields



Implementation

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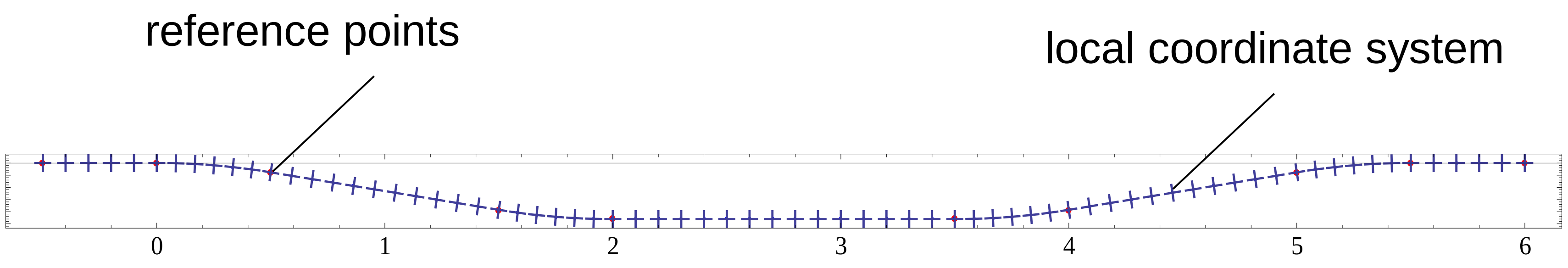
- Eigenvalue solver and auxiliary programs
  - Postprocessing
    - Change point evaluation from existing ‘line’ to new ‘arbitrary list’
    - Specify list of points along selected trajectory
    - Evaluate field components for all determined modes and all points
    - Transform field components to the particles coordinate system
    - Perform path integration to determine loss and kick parameter



Implementation

- Eigenvalue solver and auxiliary programs
  - Definition of the longitudinal loss and kick parameter
    - Resulting energy

$$W_{\mathrm{res},\nu} = q^2 \underbrace{\frac{1}{2} \left| \int_{t_0}^{t_1} e^{i\omega_\nu t'} \, \dot{\vec{r}}_{(\vec{r}_{(t')})} \cdot \vec{e}_{\nu(\vec{r}_{(t')})} \, \mathrm{d}t' \right|^2}_{k_{\nu,||}}$$

$k_{\nu,||}$ — Longitudinal loss parameter

    - Kick parameter

$$\vec{k}_\nu = \frac{1}{q^2} \int_{t_0}^{t_1} \frac{\mathrm{d}\vec{p}}{\mathrm{d}t'} \, \mathrm{d}t' = \int_{t_0}^{t_1} \left(\frac{a_{\nu(t')}}{q} \, \vec{e}_{\nu(t')} - \vec{v} \times \vec{h}_{\nu(t')} \, \mu \, \omega_\nu \, \frac{A_{\nu(t')}}{q} \right) \, \mathrm{d}t'$$

$$c_{\nu(t)} = q \, \dot{\vec{r}}_{(\vec{r}_{(t)})} \cdot \vec{e}_{\nu(\vec{r}_{(t)})}$$

Excitation

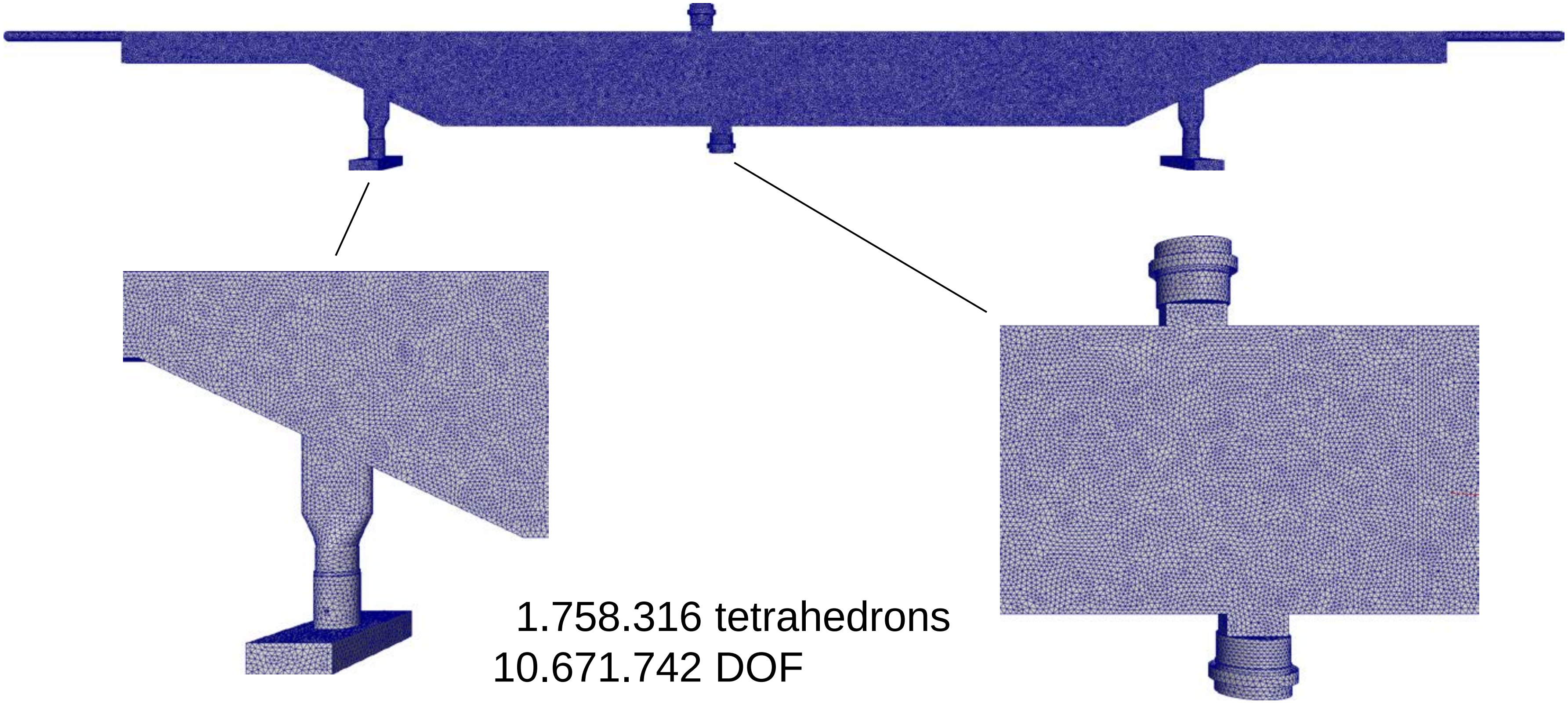
$$a_{\nu(t)} = -\mathrm{Re} \left(e^{i\omega_\nu t} \int_{-\infty}^{t} e^{i\omega_\nu \tau} c_{\nu(\tau)} \, \mathrm{d}\tau \right)$$

$$A_{\nu(t)} = c_0 \int_{-\infty}^{t} a_{\nu(t)} \, \mathrm{d}\tau$$

Amplitude

Simulation Results

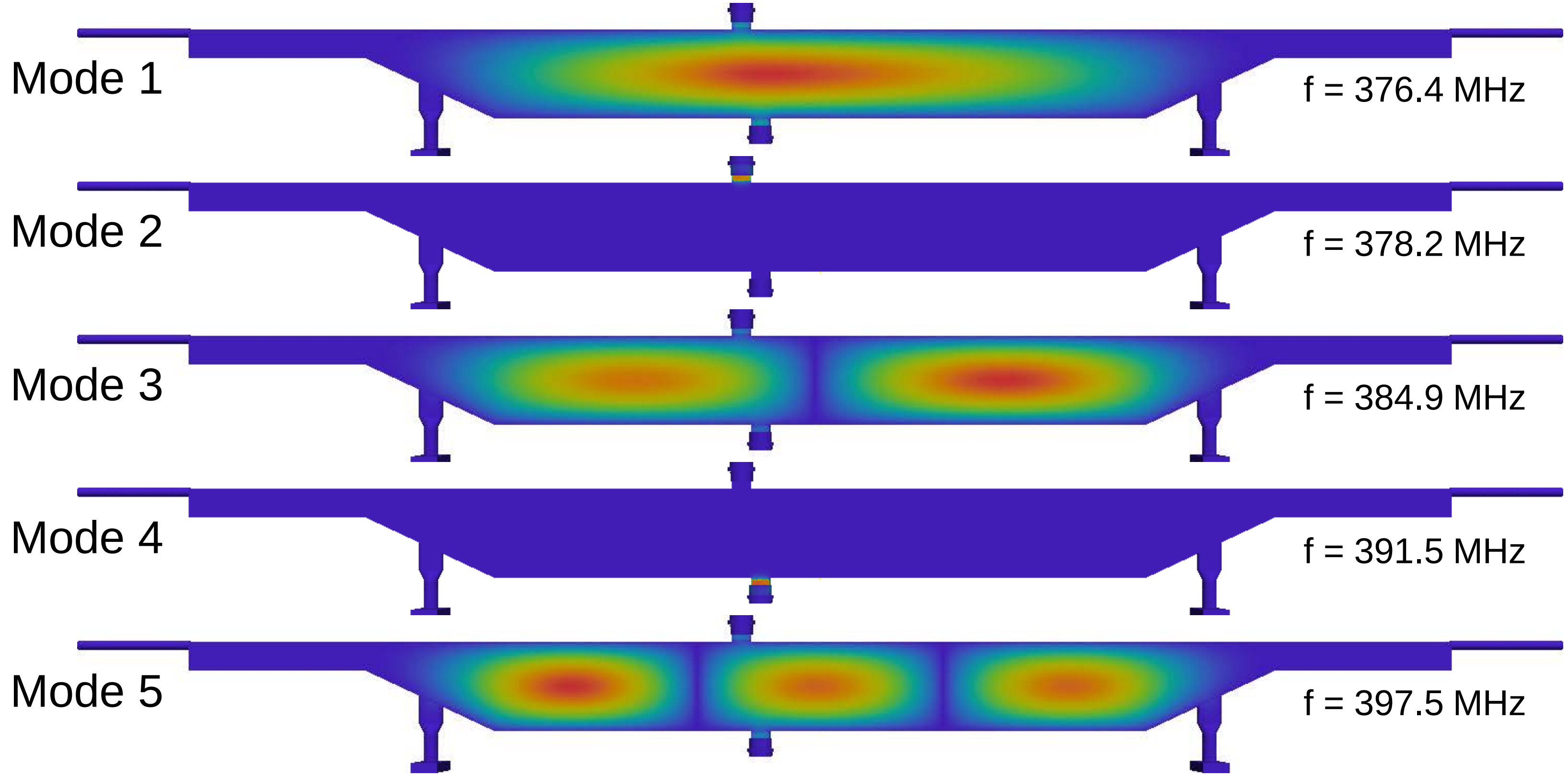
- Eigenvalue solver using real-value arithmetic
  - Computational mesh



1.758.316 tetrahedrons
10.671.742 DOF

Simulation Results

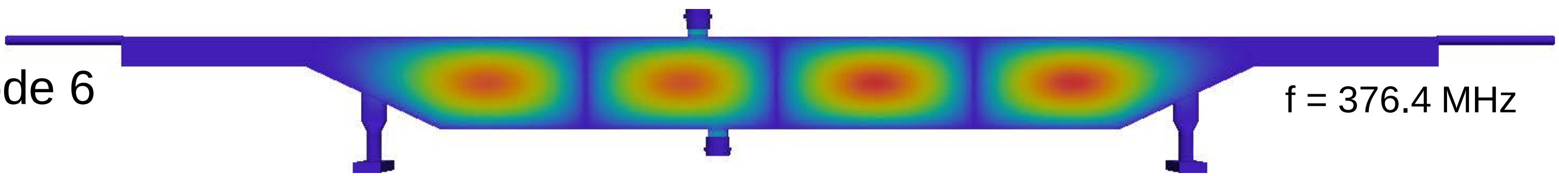
- Eigenvalue solver
  - Field pattern of the electric field strength



Simulation Results

- Eigenvalue solver
  - Field pattern of the electric field strength

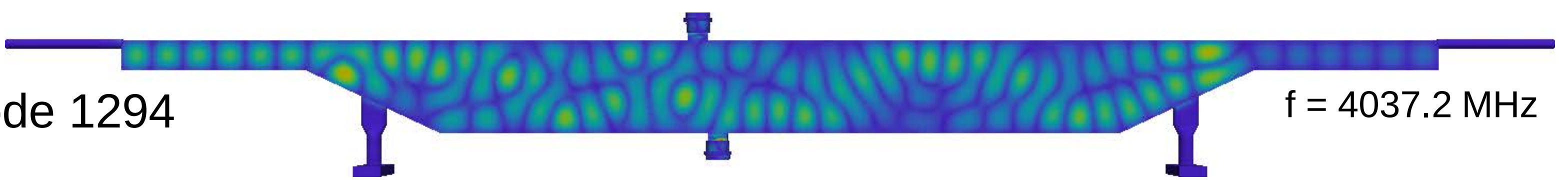
Mode 6



f = 376.4 MHz

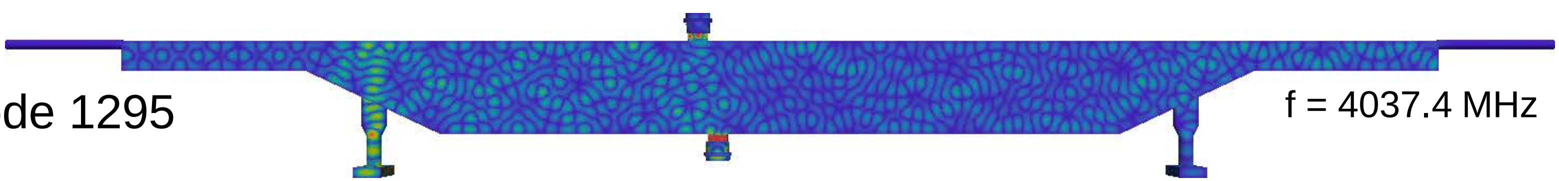
… more than 1000 modes have been examined (all modes up to 4 GHz).

Mode 1294



f = 4037.2 MHz

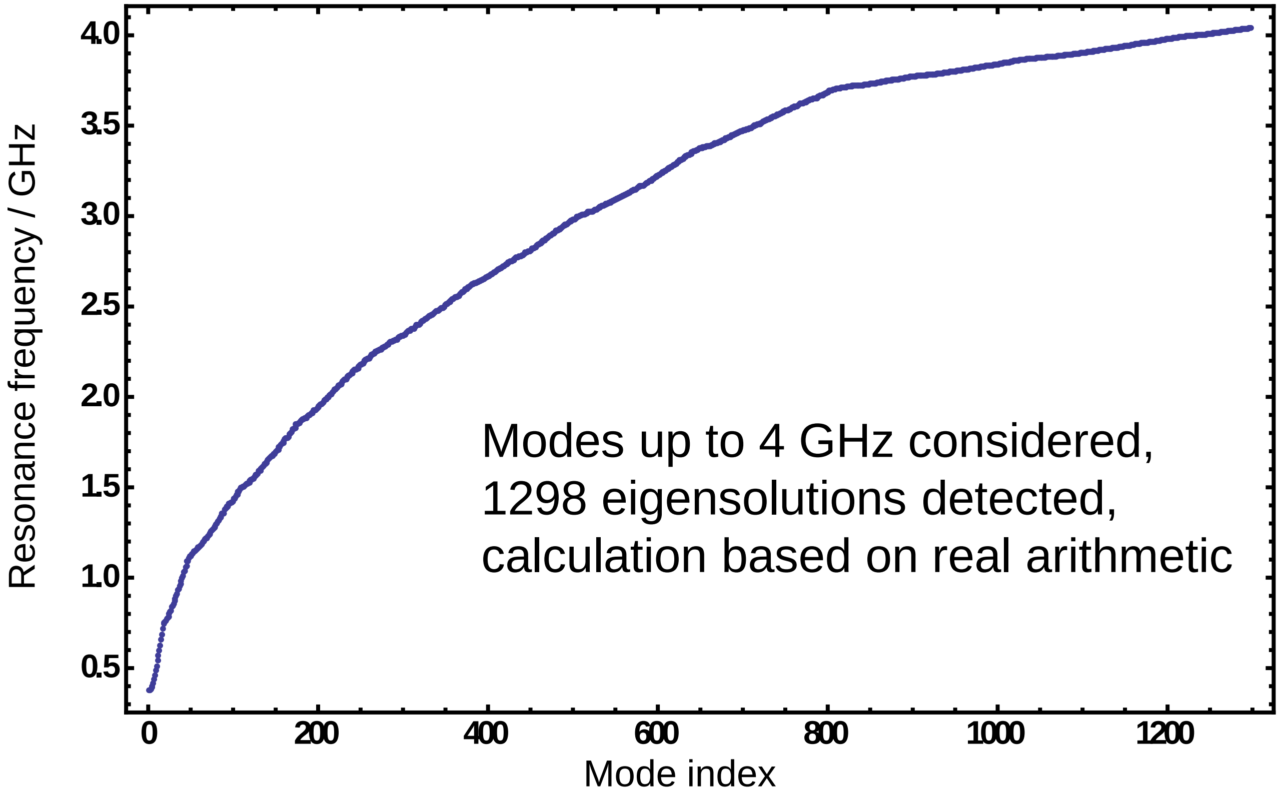
Mode 1295



f = 4037.4 MHz

Simulation Results

- Eigenvalue solver
  - Frequency distribution



Simulation Results

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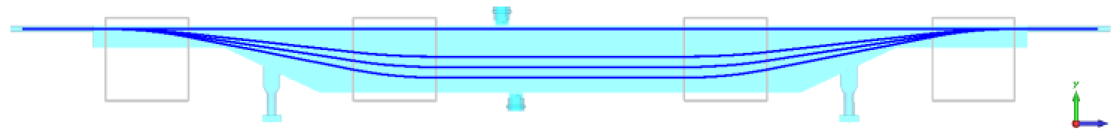
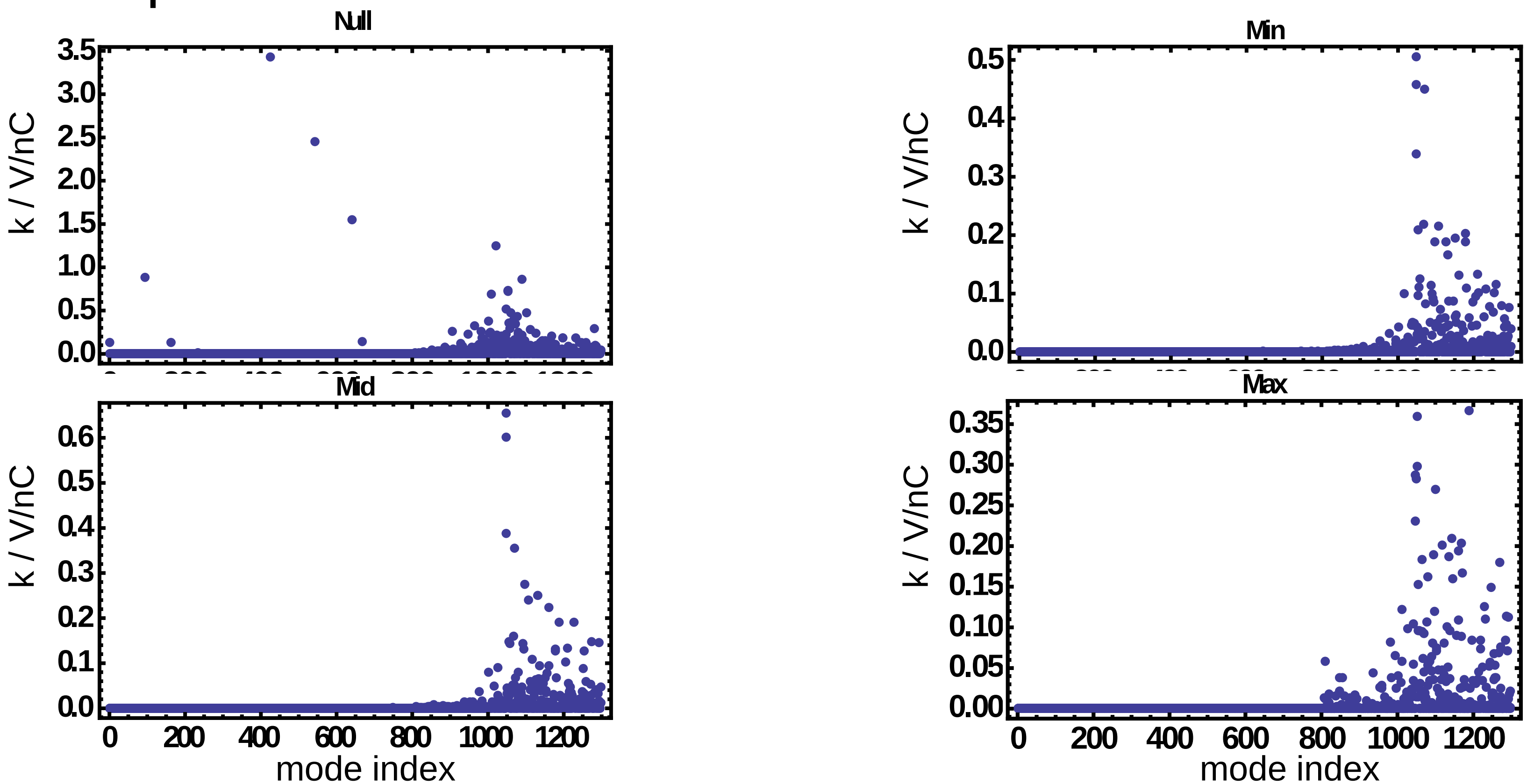
- Eigenvalue solver
  - Loss parameter





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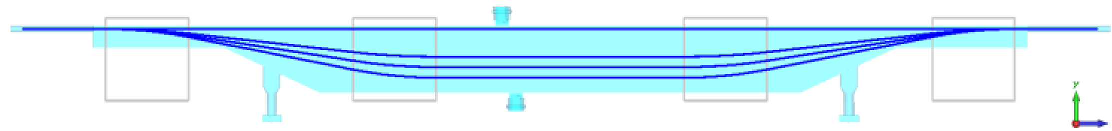

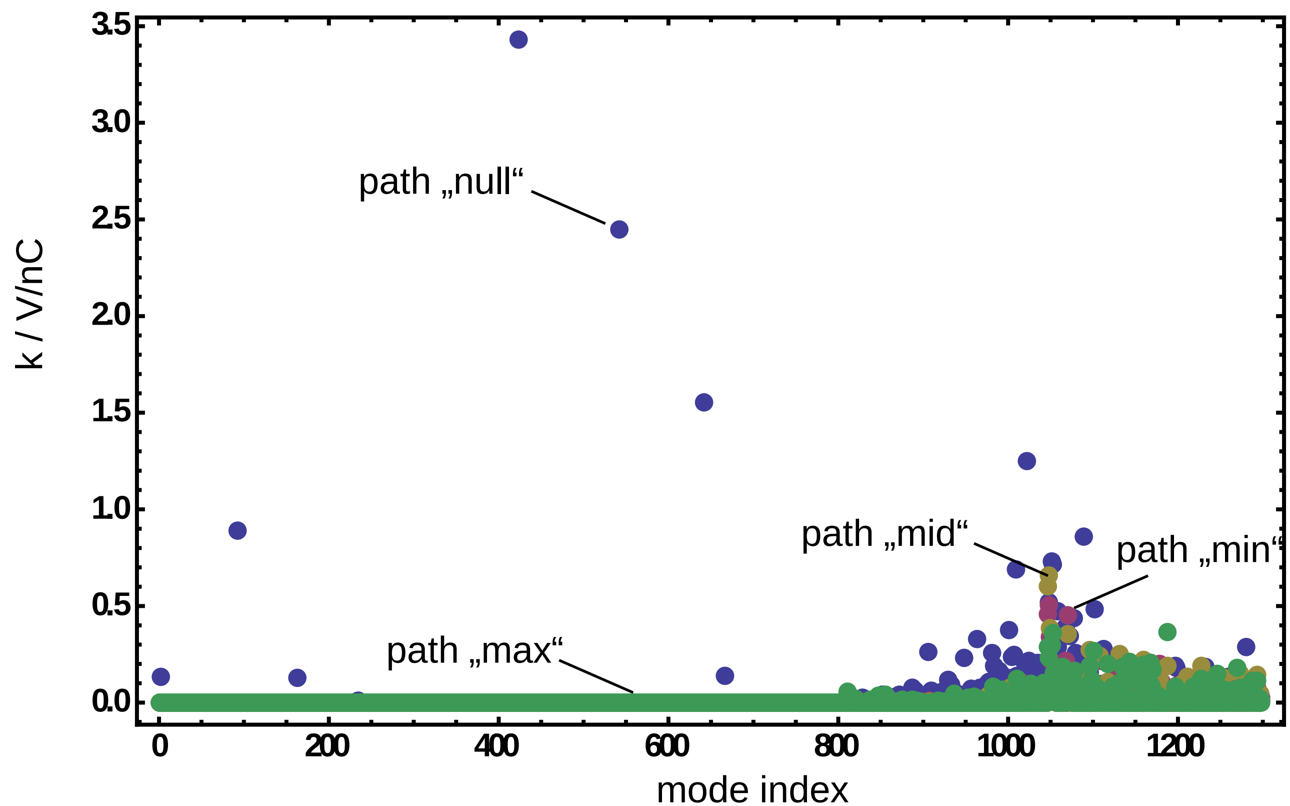

Comparison to the TESLA 1.3 GHz structure

mode	f /GHz	$k^{(0)}$/ V/(pC)
MM-28	3.0971	0.02
MM-29	3.0971	$0.377\ 10^{-04}$
Band 4		
MM-30	3.3898	$0.981\ 10^{-02}$
MM-31	3.3921	$0.388\ 10^{-02}$
MM-32	3.4055	$0.592\ 10^{-02}$
MM-33	3.4261	$0.977\ 10^{-02}$
MM-34	3.4541	$0.144\ 10^{-02}$
MM-35	3.4885	$0.689\ 10^{-02}$
MM-36	3.5283	$0.538\ 10^{-02}$
MM-37	3.5719	$0.163\ 10^{-05}$
MM-38	3.6174	$0.954\ 10^{-02}$
MM-39	3.6650	0.03

TESLA 2001-33
R. Wanzenberg

Simulation Results

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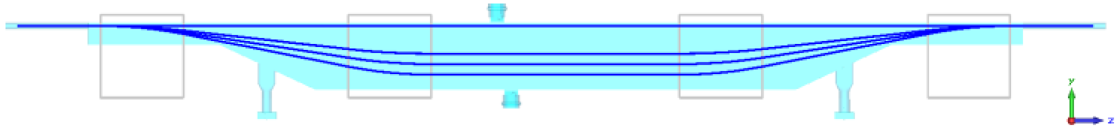
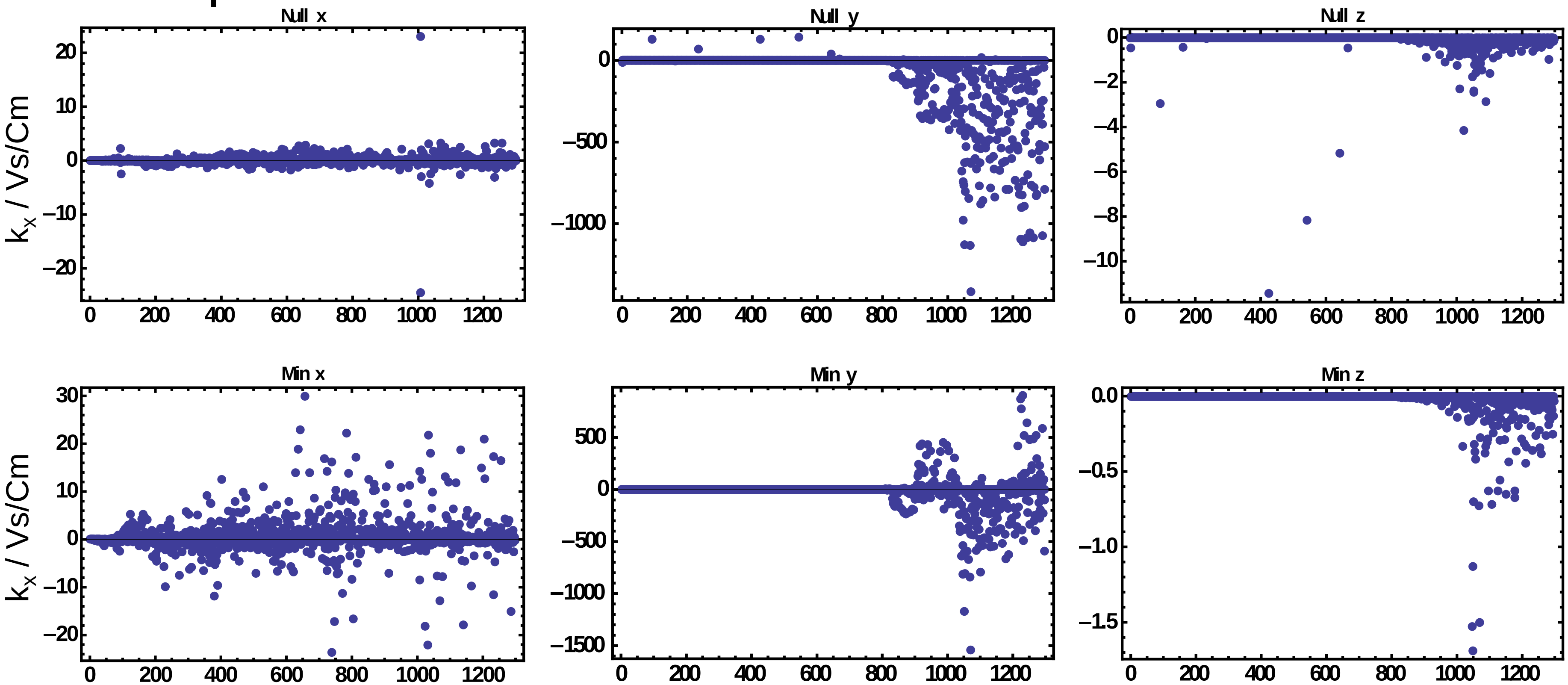
- Eigenvalue solver
  - Kick parameter

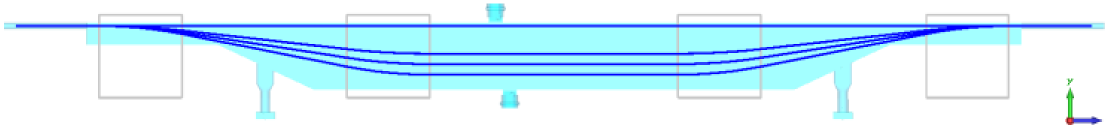


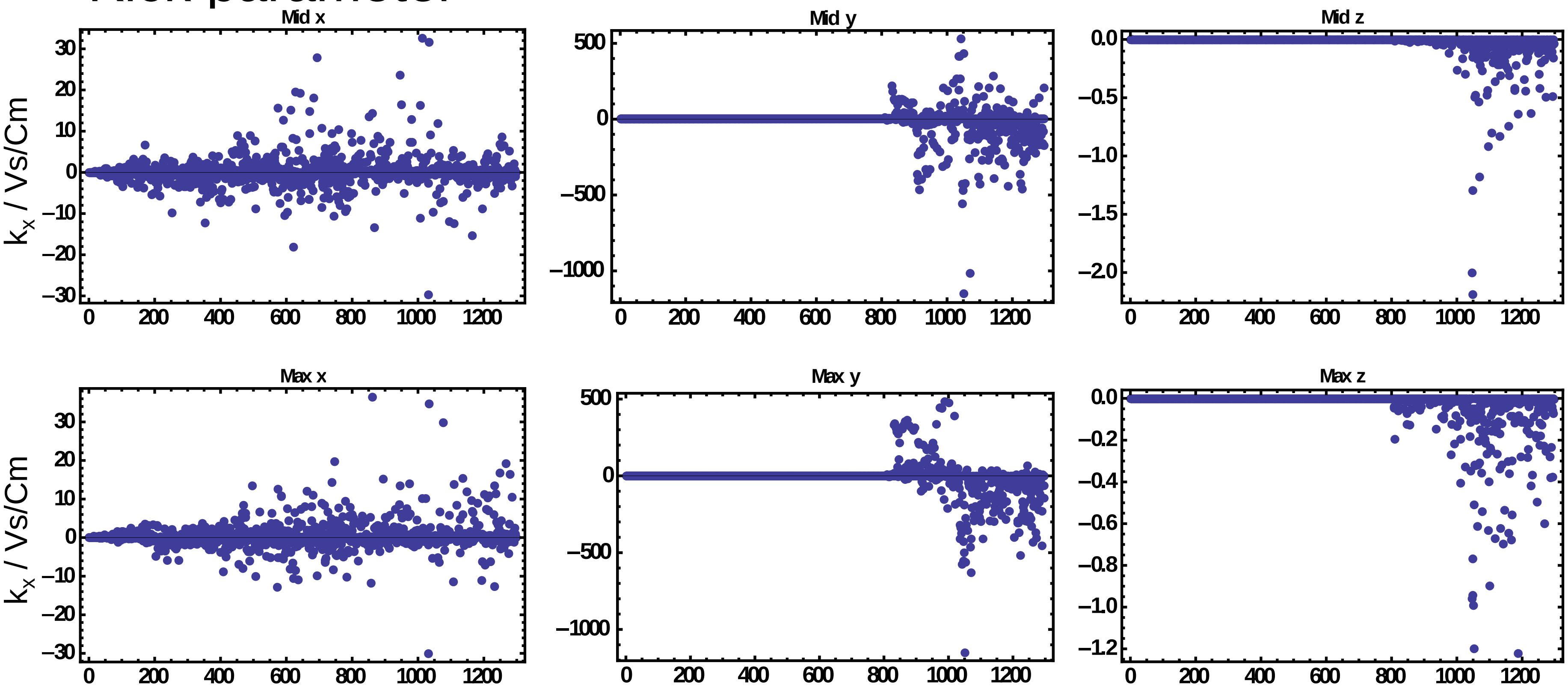


Simulation Results

TECHNISCHE UNIVERSITÄT DARMSTADT

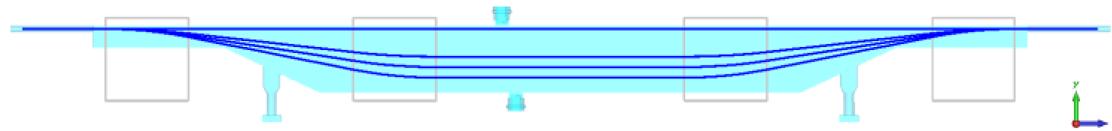
- Eigenvalue solver
  - Kick parameter





Simulation Results

- Eigenvalue solver
  - Accuracy estimation



Loss parameter

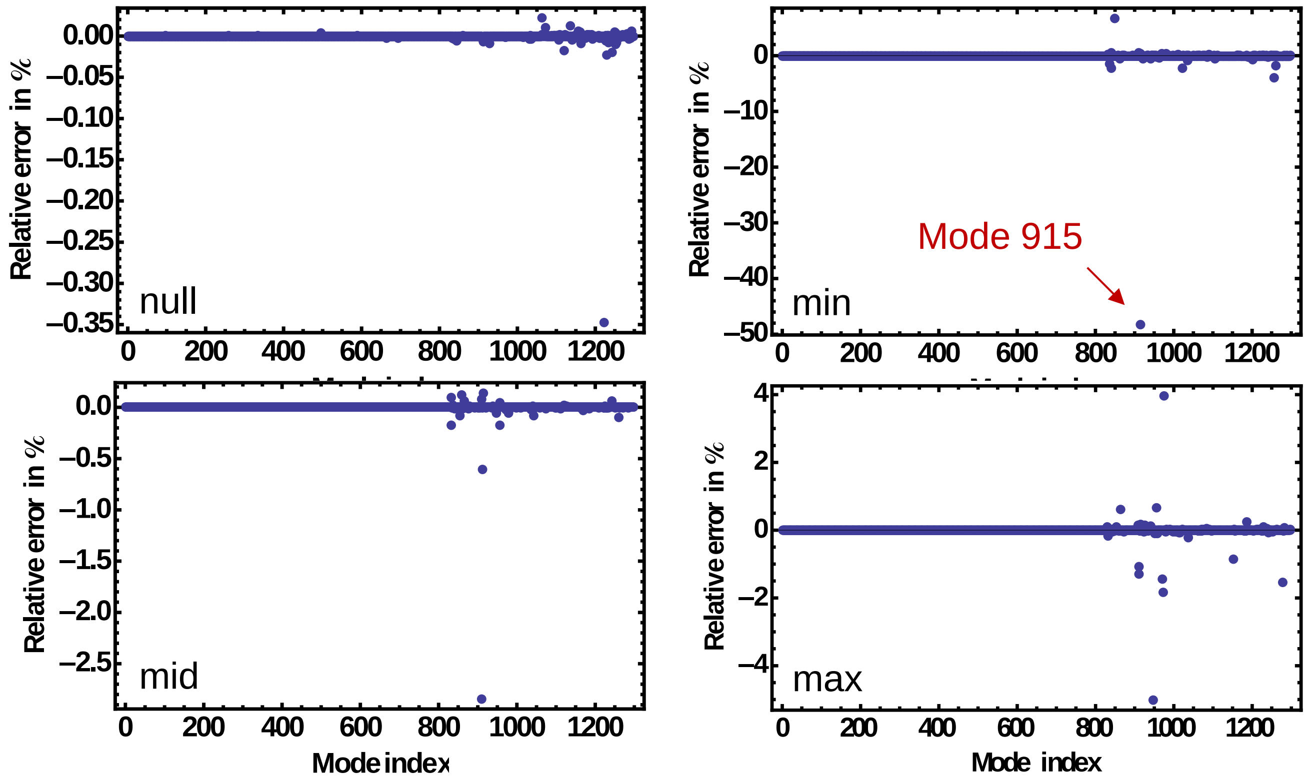
$$k_{||} = \frac{V_\mathrm{L}^2}{4W_\mathrm{tot}}$$

Kick parameter

$$\vec{k} = \frac{1}{q^2}\int_{t_0}^{t_1} \frac{\mathrm{d}\vec{p}}{\mathrm{d}t'}\,\mathrm{d}t'$$

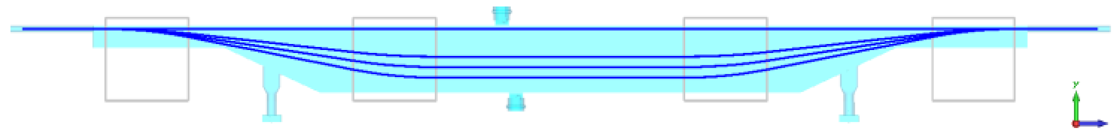
Error definition

$$\mathrm{err} = \frac{k_{||} - \vec{k}|_z \cdot \beta c_0}{\vec{k}|_z \cdot \beta c_0}$$



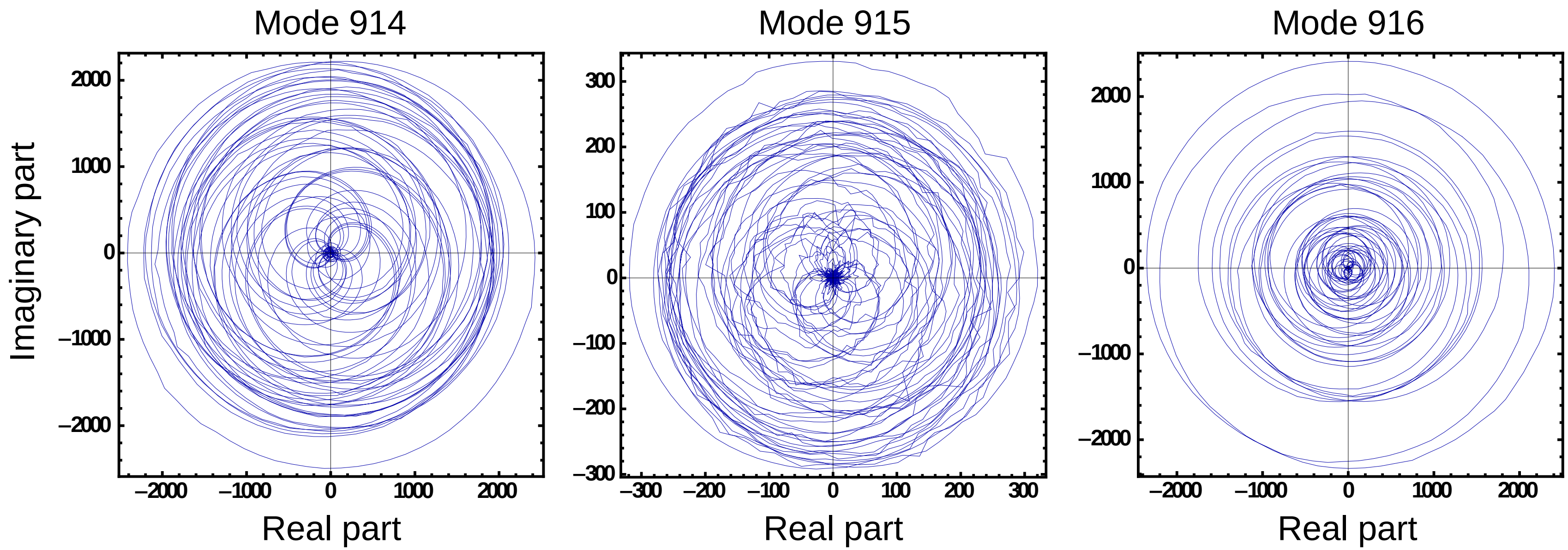
Simulation Results

- Eigenvalue solver
  - Accuracy estimation path “min”



$$k_{||} = \frac{1}{4W} \left| \int_{\vec{r}(t_0)}^{\vec{r}(t_1)} e^{i\omega t'} \left(\vec{t}_{\text{path}} \cdot \vec{E} \right) \mathrm{d}s' \right|^2$$

Integrand



Summary / Outlook

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- Summary:
  - Eigenvalue calculations concentrating on the accelerating mode for the TESLA 1.3 GHz structure performed based on various main coupler penetration depth
  - Field maps for the various setups provided
  - Comparison of the eigenvalue distribution (fourth dipole passband) using different beam-tube boundary conditions
  - Postprocessing of the BC0 vacuum chamber modes, determination of longitudinal loss and kick parameter

Motivation

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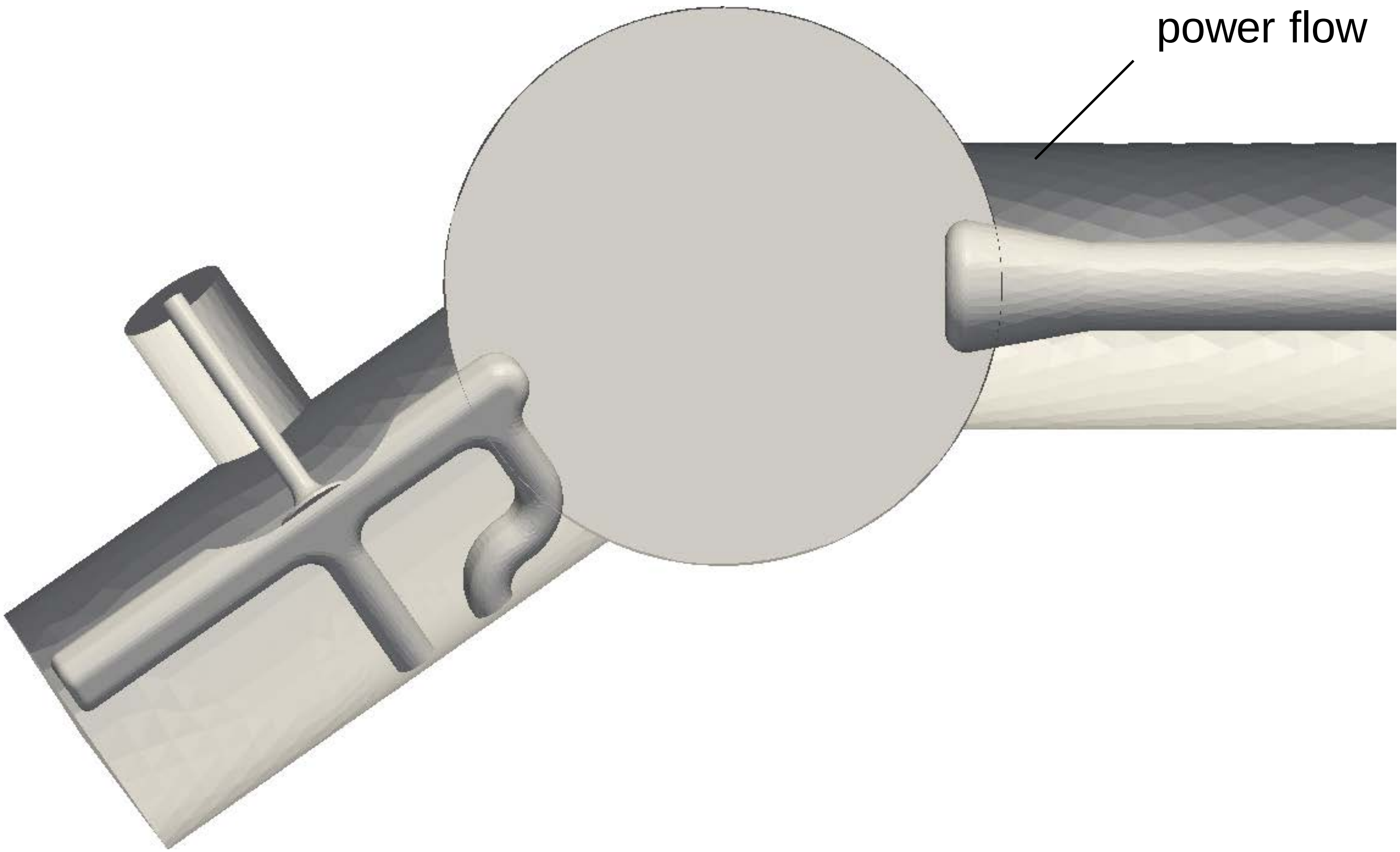
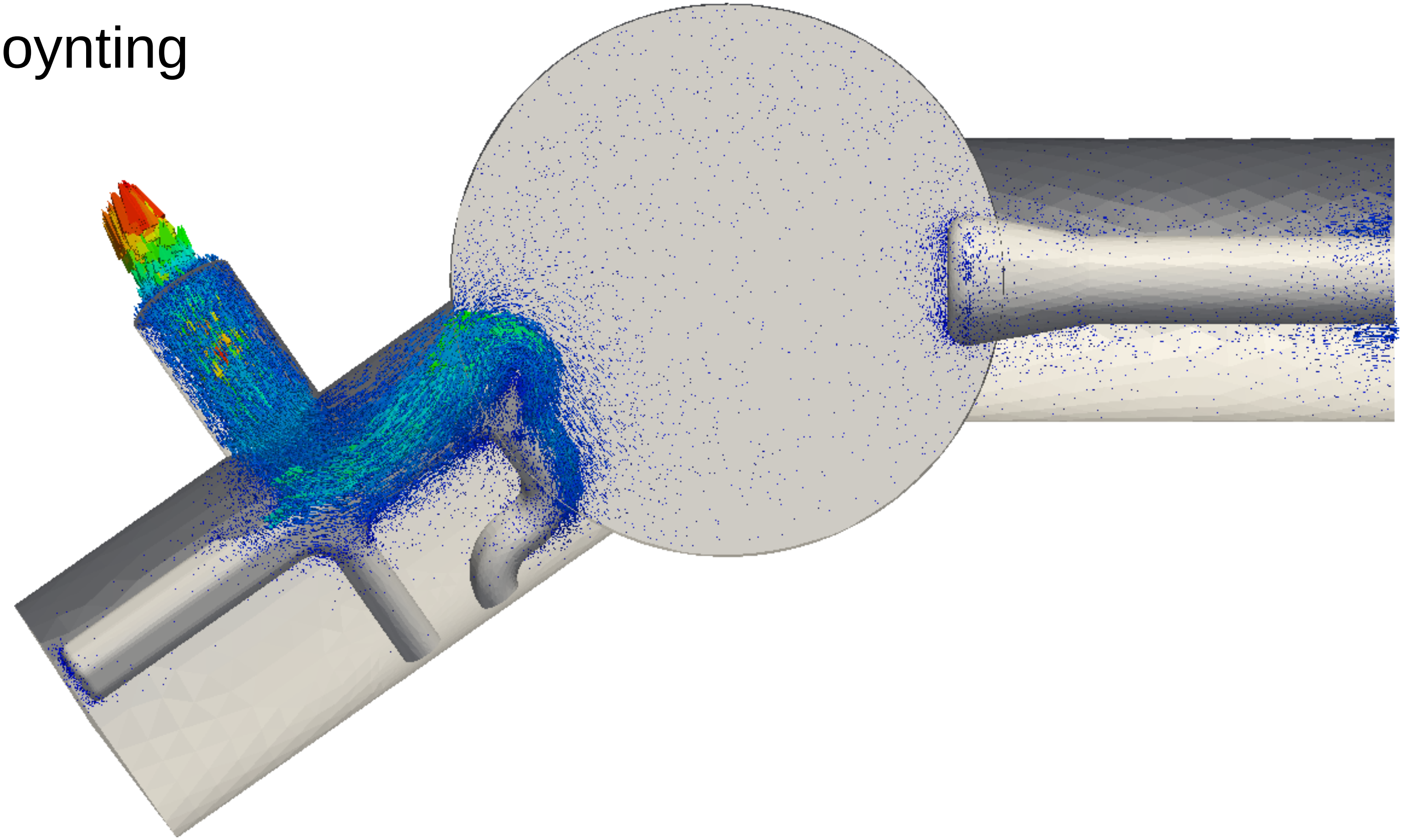
- HOM Coupler



Motivation

- HOM Coupler
  - Poynting



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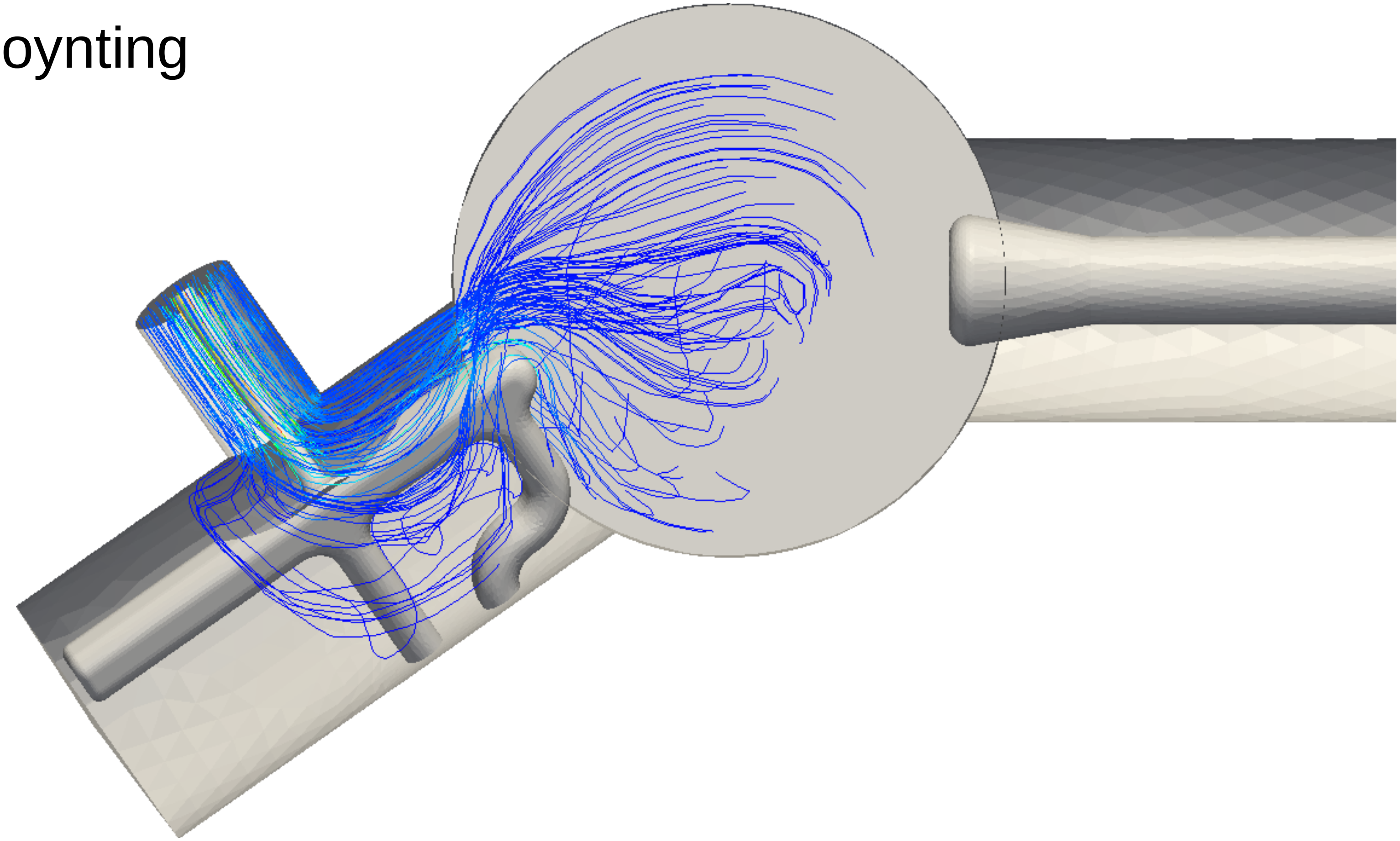

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