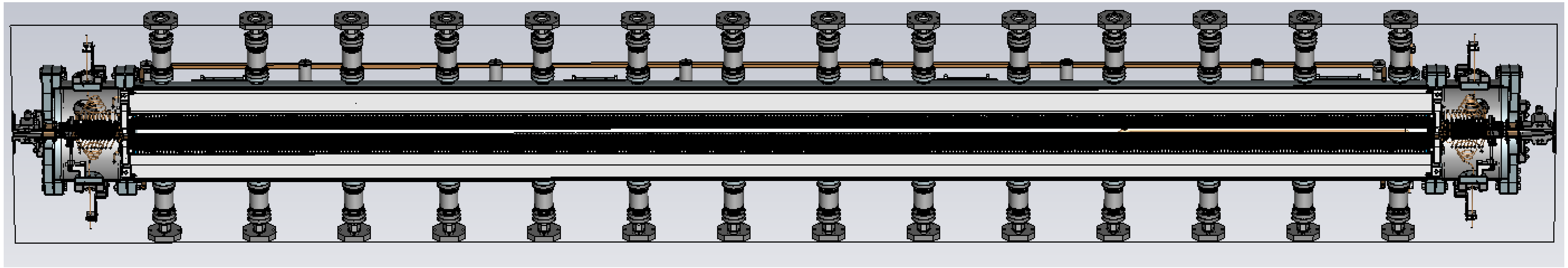
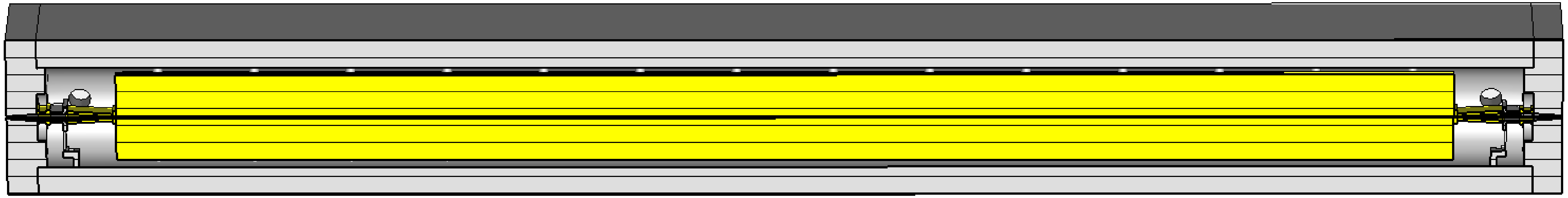
UPDATES ON METHODS AND MODEL IN IMPEDANCE SIMULATIONS FOR AN IVU AT PETRA

CONTENT

- Undulator Geometry
- Simulation Procedure
  - Solvers
    - New Domain Decomposition Solver
  - Shunt Impedance Calculation
- Results
  - Broadband
  - Modelling Impact
  - Domain Decomposition Solver
- Conclusion

GEOMETRY





Entry Body Exit

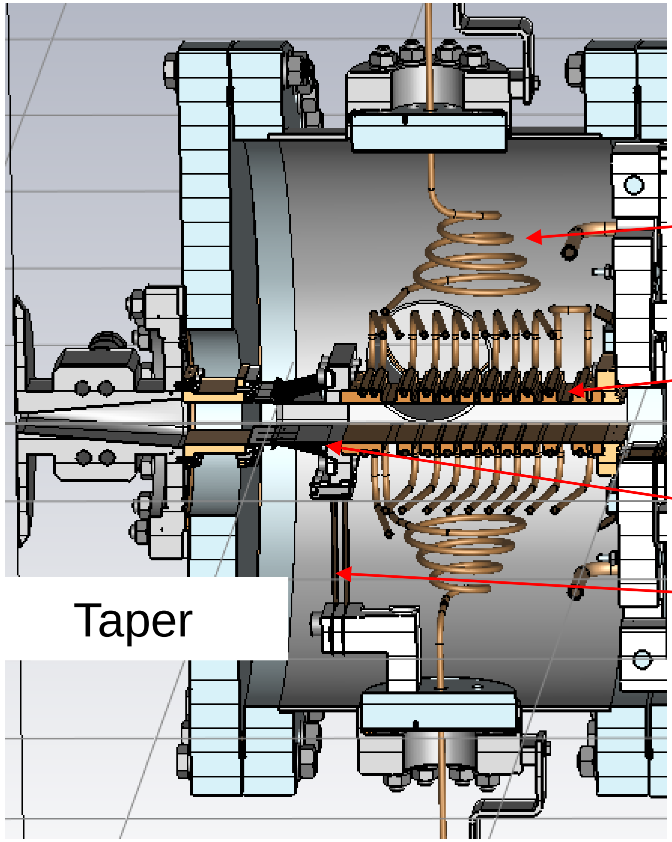
Grey: stainless steel: 1.4e6 S/m

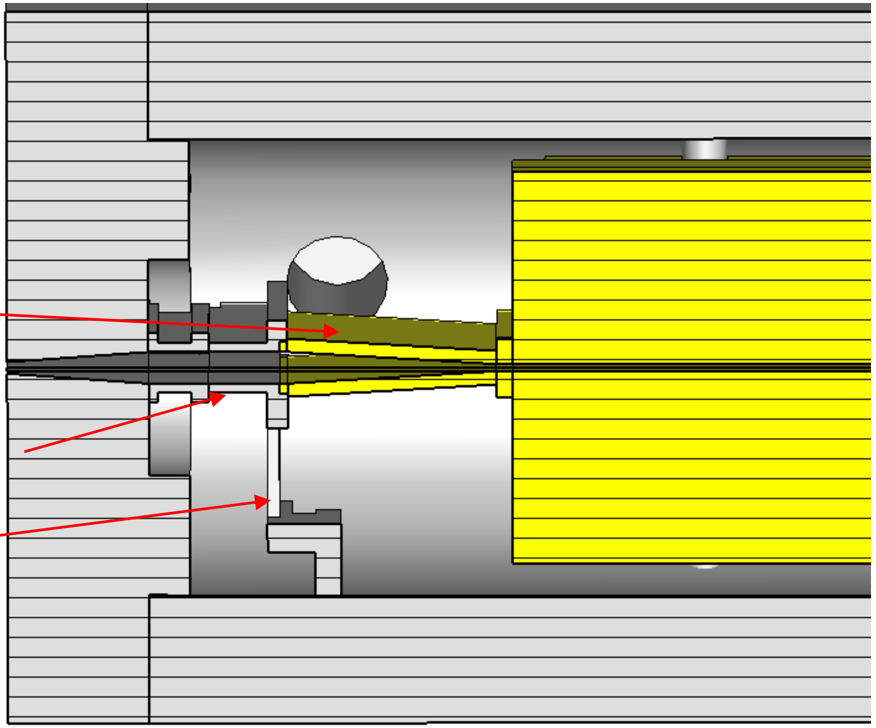
Yellow: aluminium: 3.56e7 S/m

GEOMETRY

Grey: stainless steel: 1.4e6 S/m

Yellow: aluminium: 3.56e7 S/m

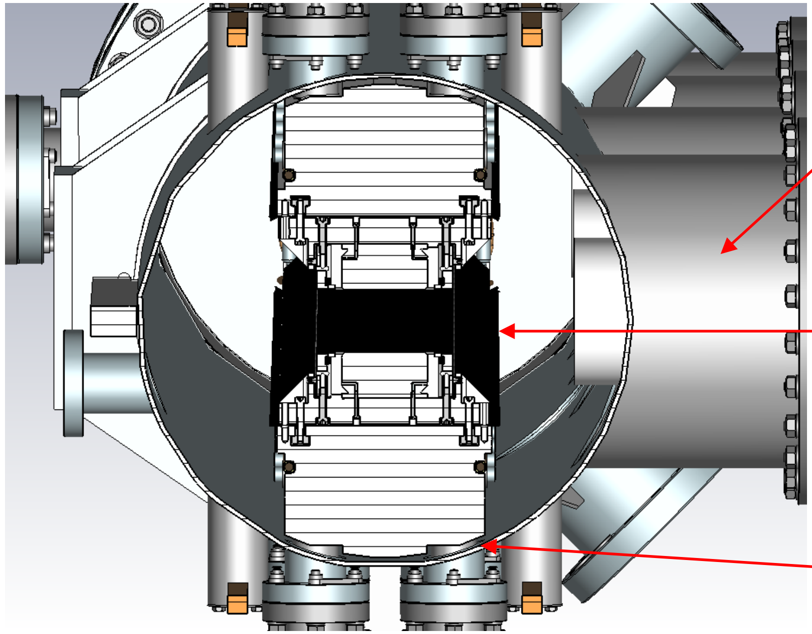




GEOMETRY

Grey: stainless steel: 1.4e6 S/m

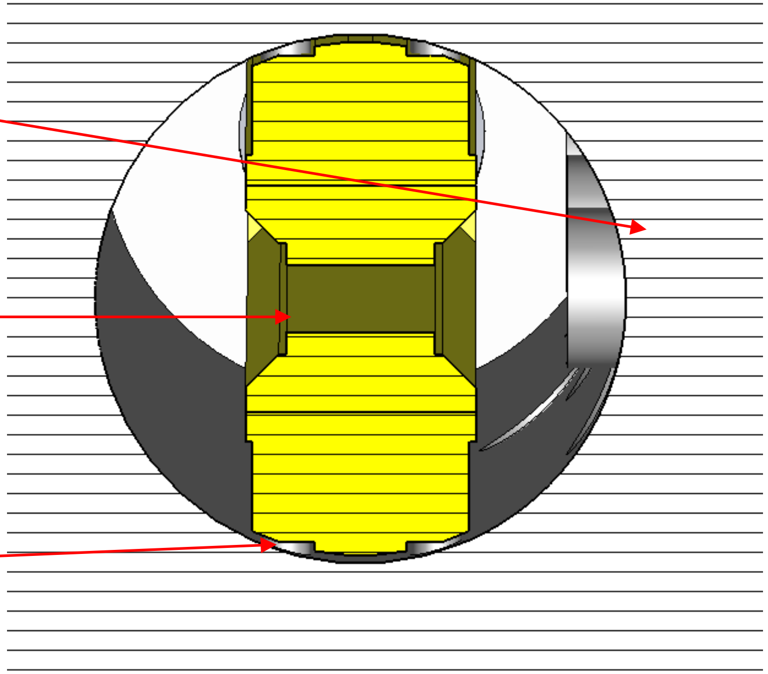
Yellow: aluminium: 3.56e7 S/m



Vacuum ports

Magnet structure

Pillars



SIMULATION PROCEDURE
CHALLENGES

- Large model at high frequency
  - 1 GHz
  - 4.6 m length
  - 32 cm diameter
- Unknown material parameters
  - Multiple simulations required
- Large number of resonances (155)
- High quality factors (up to 10000)
  - Strong dependence on material parameters

- Challenging for all available solvers
  - CST wakefield solver
    - High quality factors
  - CST eigenmode solver
    - Large number of resonances
  - FELIS (in-house impedance solver in FD)
    - Large number of resonances

SIMULATION PROCEDURE
APPLIED SOLVERS

- FELIS (in-house impedance solver in FD)
  - Longitudinal coupling impedances by integration
  - Transverse impedances by Panofsky-Wenzel theorem
  - Shunt impedances by rational decomposition
- CST wakefield solver
  - Established method
  - Inefficient for this problem
  - Reference for the coupling impedances
- CST eigenmode solver
  - Longitudinal shunt impedances by integration
  - Transverse shunt impedances by Panofsky-Wenzel theorem
  - Comparison of shunt impedances

SIMULATION PROCEDURE
FELIS – PROBLEM FORMULATION

- Weak formulation per subdomain: find $E \in H(\mathrm{curl})$ such that $\forall v \in H(\mathrm{curl})$:

$$\int_\Omega \mu^{-1}\, \nabla \times E \cdot \nabla \times v \,\mathrm{d}V - \omega^2 \int_\Omega \varepsilon\, E \cdot v \,\mathrm{d}V =$$

$$\underbrace{-j\omega \int_\Omega J_\mathrm{s} \cdot v \mathrm{d}V}_{\text{Excitation current}} - \underbrace{\int_{\Sigma_\mathrm{SI}} n \cdot [v \times \mu^{-1}\, \nabla \times E]\,\mathrm{d}S}_{\text{Resistive wall}} - \underbrace{\int_{\Sigma_\mathrm{WG}} n \cdot [v \times \mu^{-1}\, \nabla \times E]\,\mathrm{d}S}_{\text{Waveguides}}$$

- Waveguide BC: $\mu^{-1} n \times \nabla \times E = \mu^{-1} n \times \nabla \times E^{\mathrm{Inc}} - j\omega \sum_{m=1}^{\infty} Y_m^{\mathrm{TX}}(\omega) a_m (E - E^{\mathrm{Inc}})\, e_m^{\mathrm{TX}})$
  - $a_m(E) = \int_{\Sigma_\mathrm{WG}} e_m^{\mathrm{TM}} \cdot E \,\mathrm{d}S$
- Resistive wall BC: $\mu^{-1} n \times \nabla \times E = \mathrm{j}\omega Y_\mathrm{SI}(\omega) n \times n \times E$

SIMULATION PROCEDURE
FELIS – PROBLEM FORMULATION

- Weak formulation per subdomain: find $E \in H(\mathrm{curl})$ such that $\forall v \in H(\mathrm{curl})$:

$$\int_\Omega \mu^{-1}\, \nabla \times E \cdot \nabla \times v \,\mathrm{d}V - \omega^2 \int_\Omega \varepsilon\, E \cdot v \,\mathrm{d}V =$$

$$\underbrace{-j\omega \int_\Omega J_s \cdot v \mathrm{d}V}_{\text{Excitation current}} - \underbrace{\int_{\Sigma_{\mathrm{SI}}} n \cdot [v \times \mu^{-1}\, \nabla \times E]\,\mathrm{d}S}_{\text{Resistive wall}} - \underbrace{\int_{\Sigma_{\mathrm{WG}}} n \cdot [v \times \mu^{-1}\, \nabla \times E]\,\mathrm{d}S}_{\text{Waveguides}} - \underbrace{\int_{\Sigma_{\mathrm{DDM}}} n \cdot [v \times \mu^{-1}\, \nabla \times E]\,\mathrm{d}S}_{\text{DDM interface}}$$

- Waveguide BC: $\mu^{-1} n \times \nabla \times E = \mu^{-1} n \times \nabla \times E^{\mathrm{Inc}} - j\omega \sum_{m=1}^{\infty} Y_m^{\mathrm{TX}}(\omega) a_m (E - E^{\mathrm{Inc}})\, e_m^{\mathrm{TX}})$
  - $a_m(E) = \int_{\Sigma_{\mathrm{WG}}} e_m^{\mathrm{TM}} \cdot E \,\mathrm{d}S$
- Resistive wall BC: $\mu^{-1} n \times \nabla \times E = \mathrm{j}\omega Y_{\mathrm{SI}}(\omega) n \times n \times E$

SIMULATION PROCEDURE
FELIS – DOMAIN DECOMPOSITION

- Classical zeroth order OTC
  - $n \times H = -Y(\omega) n \times (n \times E))$
- MTC
  - $n \times H = -\sum_{m=1}^{\infty} Y_m^{\mathrm{TX}}(\omega) n \times (n \times E_m^{\mathrm{TX}}))$
  - $\mu^{-1}[n \times \nabla \times E] = \sum_{m=1}^{\infty} Y_m^{\mathrm{TX}}(\omega) \alpha_m^{\mathrm{TX}}(E)\, e_m^{\mathrm{TX}})$
- MTC with beam
  - $\mu^{-1}[n \times \nabla \times (E - E^{\mathrm{Inc}})] = \sum_{m=1}^{\infty} Y_m^{\mathrm{TX}}(\omega) \alpha_m^{\mathrm{TX}}(E - E^{\mathrm{Inc}})\, e_m^{\mathrm{TX}})$
- Added GMRES iteration procedure
  - Required for resonant structures

SIMULATION PROCEDURE
FELIS – IMPEDANCE CALCULATION

- Available data
  - Field solution E
  - Current of driving beam I_s on path L_s
  - Current of test beam I_t on path L_t
- Longitudinal impedance
  - $Z_\parallel = -\frac{1}{I_0^2}\int_L I(z) E_z(\mathbf{r}_\perp, z)\,\mathrm{d}z$
- Vertical impedance by Panofsky-Wenzel theorem
  - $Z_y = \frac{c}{\omega}\frac{\partial}{\partial y} Z_\parallel(\mathbf{r}_\perp)$
  - $Z_y \approx \frac{c}{\omega}\frac{(Z_{\parallel,\mathrm{t}} - Z_{\parallel,\mathrm{s}})}{\Delta y}$

SIMULATION PROCEDURE
FELIS – SHUNT IMPEDANCE CALCULATION

Impedance

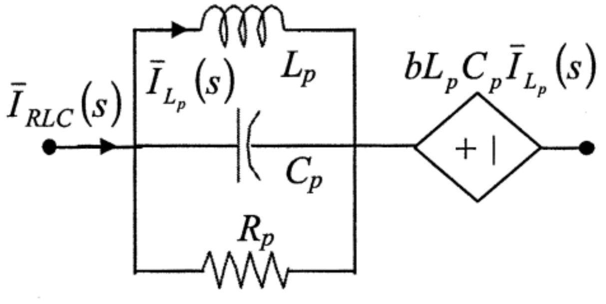
↓ Vector fitting

Pole residual decomposition

$$Z(\sigma) = d + \sigma e + \sum_{k=1}^{K} \frac{c_k}{\sigma - p_k}$$

↓ Equivalent circuit

Shunt impedance



Per mode

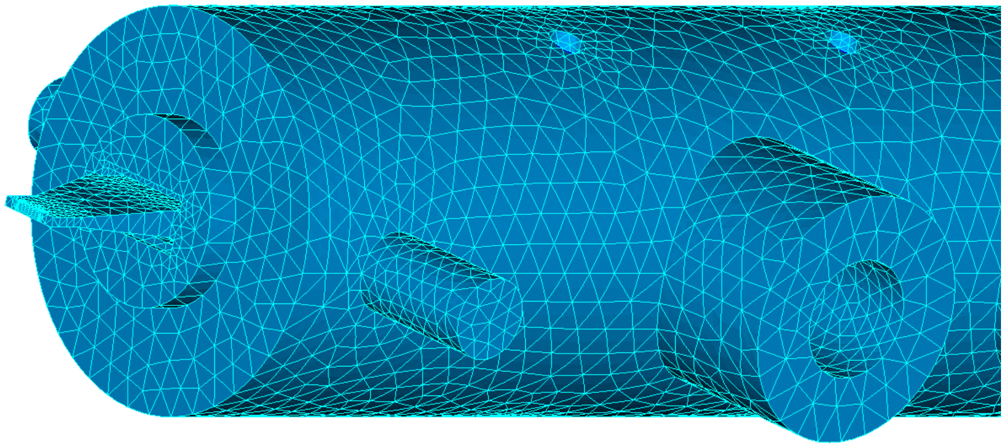
Giulio Antonini, *SPICE Equivalent Circuits of Frequency-Domain Responses*

SIMULATION PROCEDURE
EIGENMODE SOLVER – SHUNT IMPEDANCES

- No modes propagating in the beam pipes
  - Direct integration
  - $V_i = \int_{z_0}^{z_1} E_{z,i} e^{jk_i z} \mathrm{d}z$
- Longitudinal shunt impedances
  - $R_{\mathrm{s},i} = \frac{|V_i|^2 Q_i}{2 W_i \omega_i}$
- Vertical shunt impedances by Panovsky-Wenzel theorem
  - $R_{\mathrm{sy},i} = \frac{c}{\omega} \frac{\partial}{\partial y} R_{\mathrm{s},i}(\mathbf{r}_\perp)$
  - $R_{\mathrm{sy},i} \approx \frac{c}{\omega} \frac{(R_{\mathrm{s},i}(\mathbf{r}_\perp + \Delta y e_y) \ - R_{\mathrm{s},i}(\mathbf{r}_\perp))}{\Delta y}$

SIMULATION PROCEDURE
CONFIGURATION

- Geometry
  - 5 mm gap
  - 1.25 mm vertical beam displacement
- Felis
  - 12 cells per wavelength
    - 240 000 hex and tet mesh cells
    - 4th order basis function

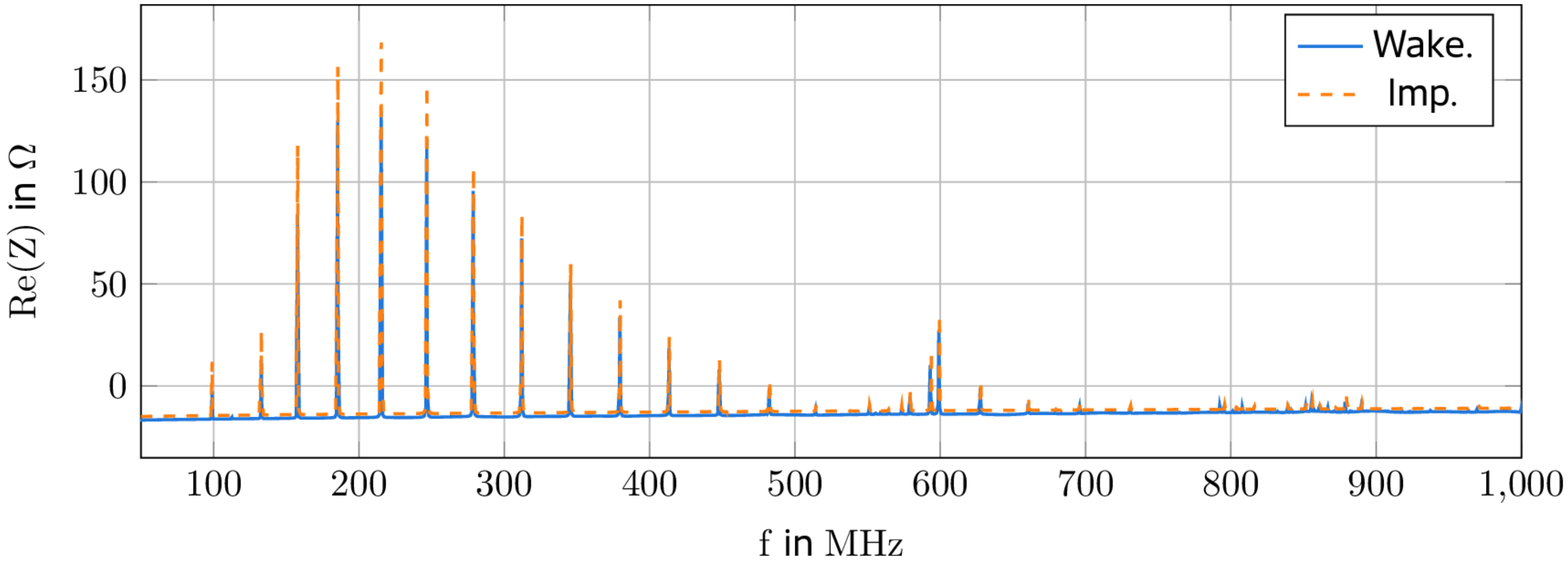


- CST Wakefield solver
  - 25 cells per wavelength
    - 14.5 million hex cells
  - 2 km of integrated wake length
    - 30 dB decay in field energy
- CST Eigenmode Solver
  - 30 cells per wavelength
    - 1.6 million tet cells
    - 2nd order basis functions

RESULTS
LONGITUDINAL COUPLING IMPEDANCE

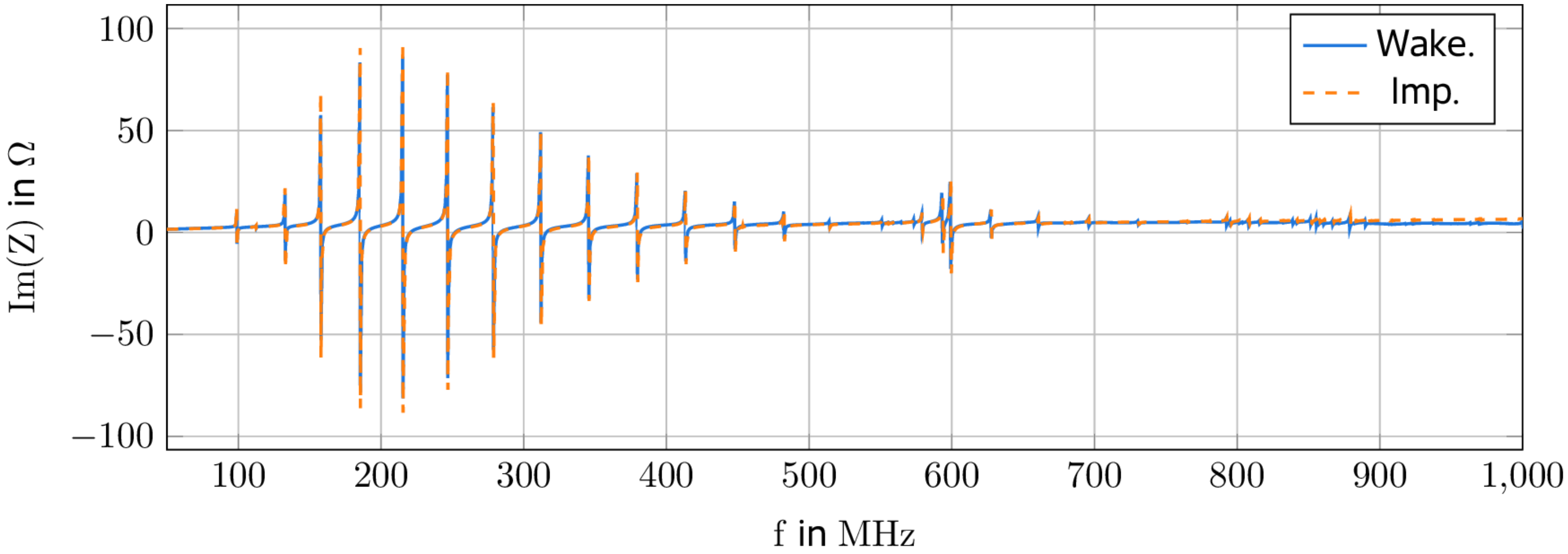
- Perfect match in the overall trend
- Perfect agreement in resonance frequencies

- Impedance peaks of wakefield solver are lower due to cos² window
- Small offset of 1.7 Ω



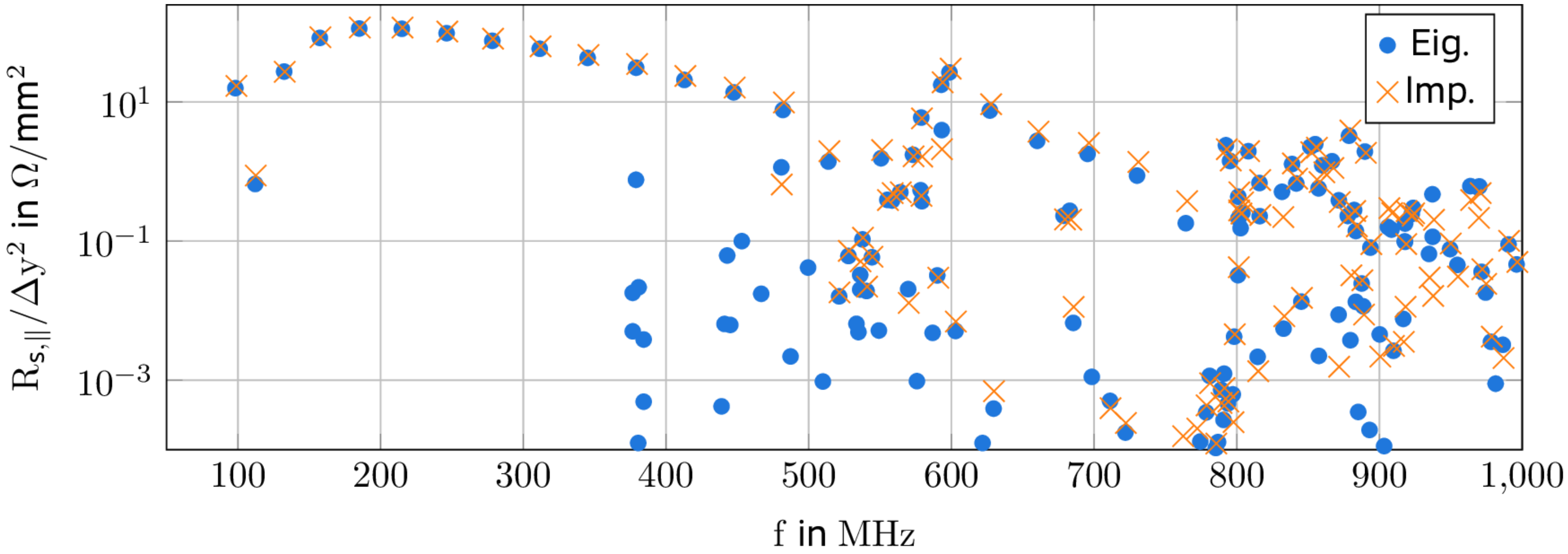
RESULTS
LONGITUDINAL COUPLING IMPEDANCE

- Perfect agreement
- Impedance peaks of wakefield solver are lower due to cos² window



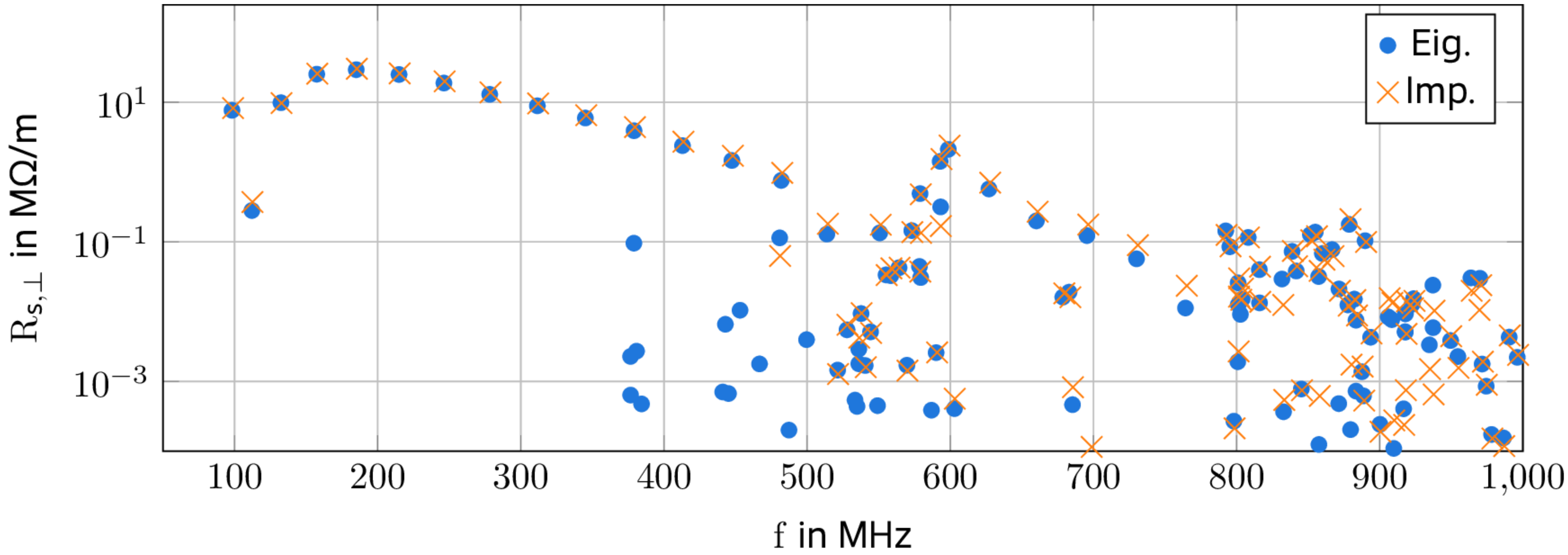
RESULTS
LONGITUDINAL SHUNT IMPEDANCES

- Normalized by beam displacement
- Some shunt impedances missing for the impedance solver due to vector fitting
- Perfect agreement at lower frequencies
- Increasing deviation due to mesh
- Highest shunt impedances around 200 MHz



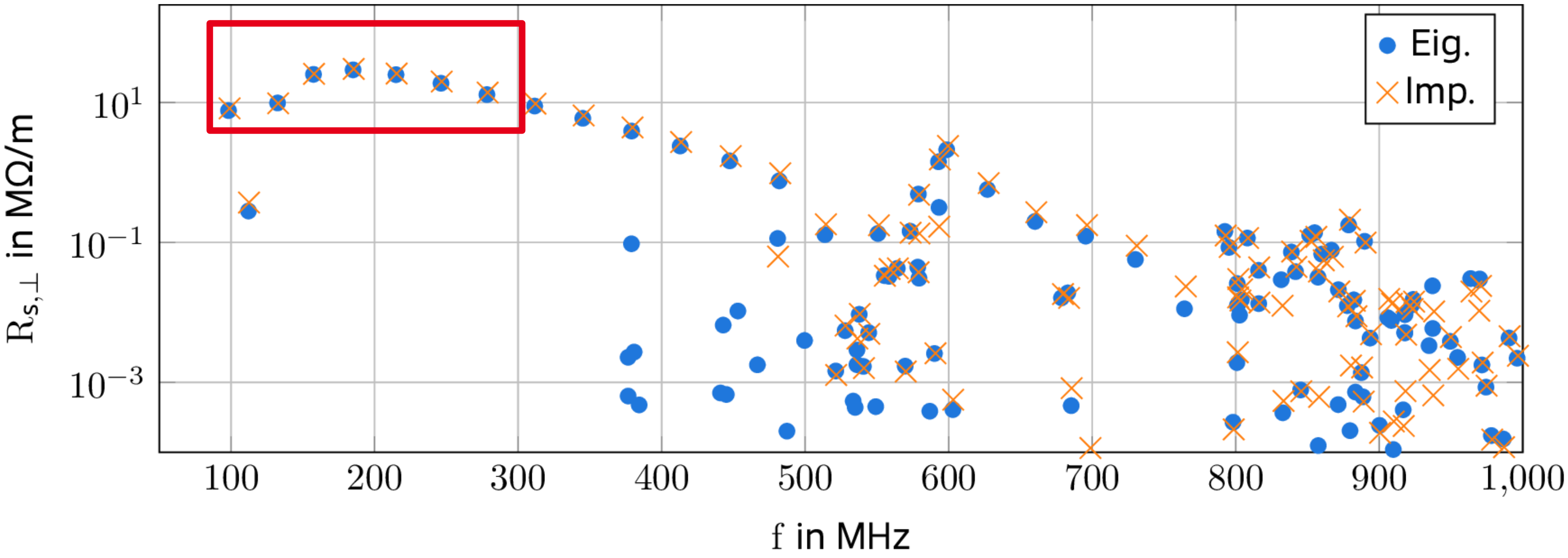
RESULTS
TRANSVERSE SHUNT IMPEDANCES

- Threshold for instability: 16.4 MΩ/m
- Highest shunt impedances around 200 MHz
- No critical shunt impedances above 300 MHz



RESULTS
TRANSVERSE SHUNT IMPEDANCES

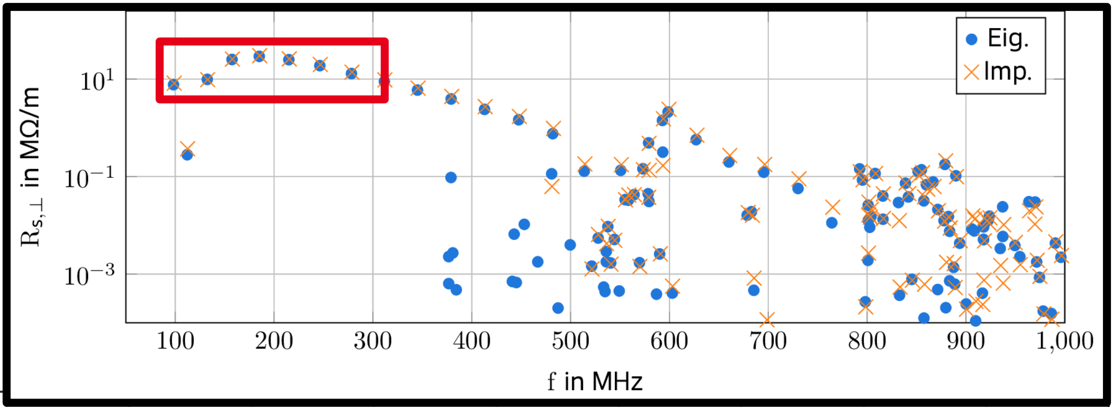
- Threshold for instability: 16.4 MΩ/m
- Highest shunt impedances around 200 MHz
- No critical shunt impedances above 300 MHz

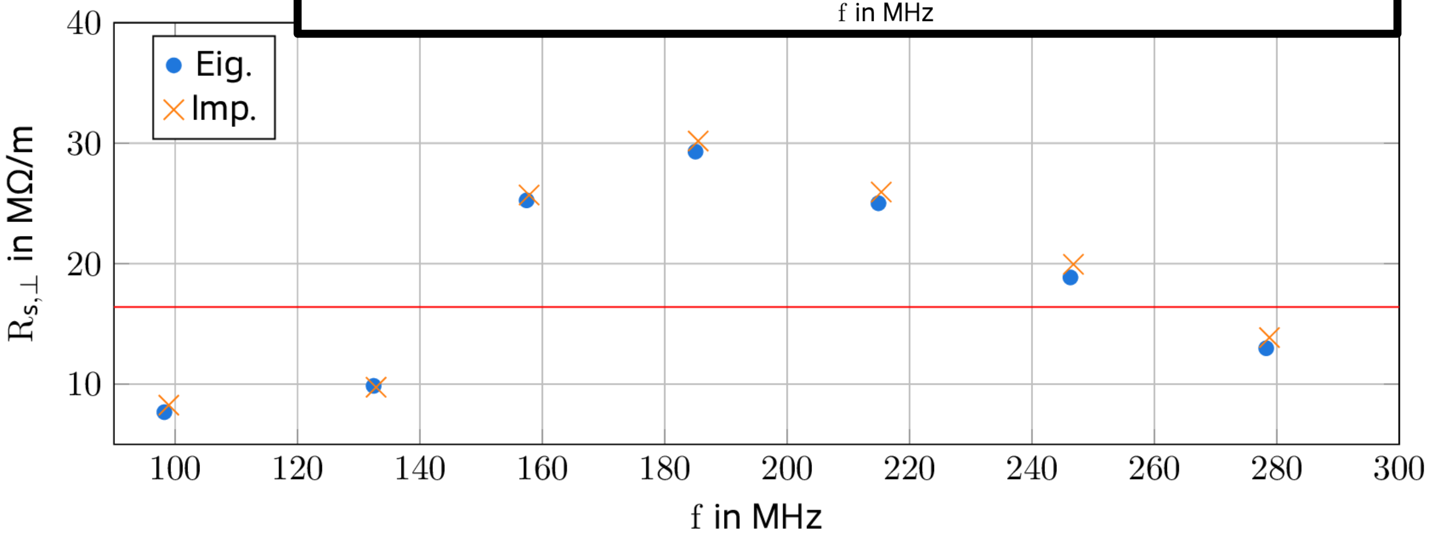


RESULTS
TRANSVERSE SHUNT IMPEDANCES

- Threshold for instability: 16.4 MΩ/m
- Four shunt impedances above threshold

Index	F in Mhz	Q	$Z_{s,\perp}$ in MΩ/m
1	99.0	1265	8.25
2	133	1089	9.74
3	158	1069	25.7
4	185	1072	30.2
5	215	1095	26.0
6	247	1129	19.9
7	279	1168	13.9



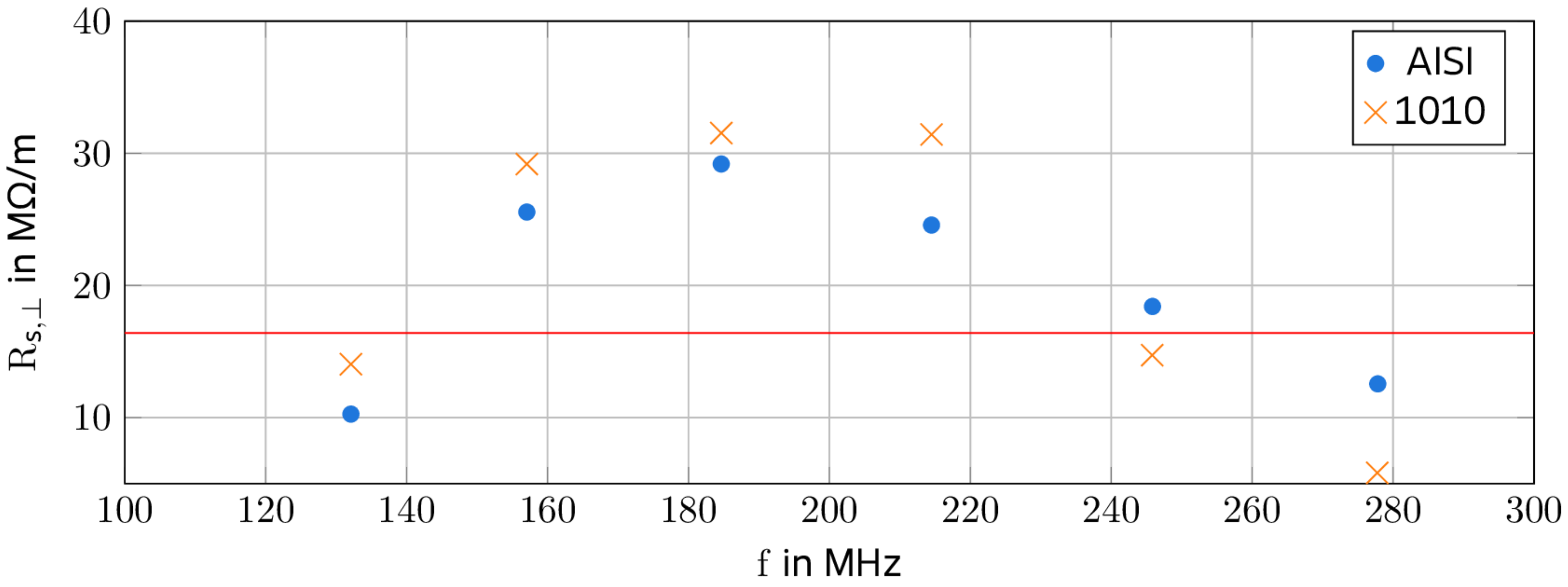


TECHNISCHE UNIVERSITÄT DARMSTADT

RESULTS
UNCERTAIN MATERIAL PROPERTIES

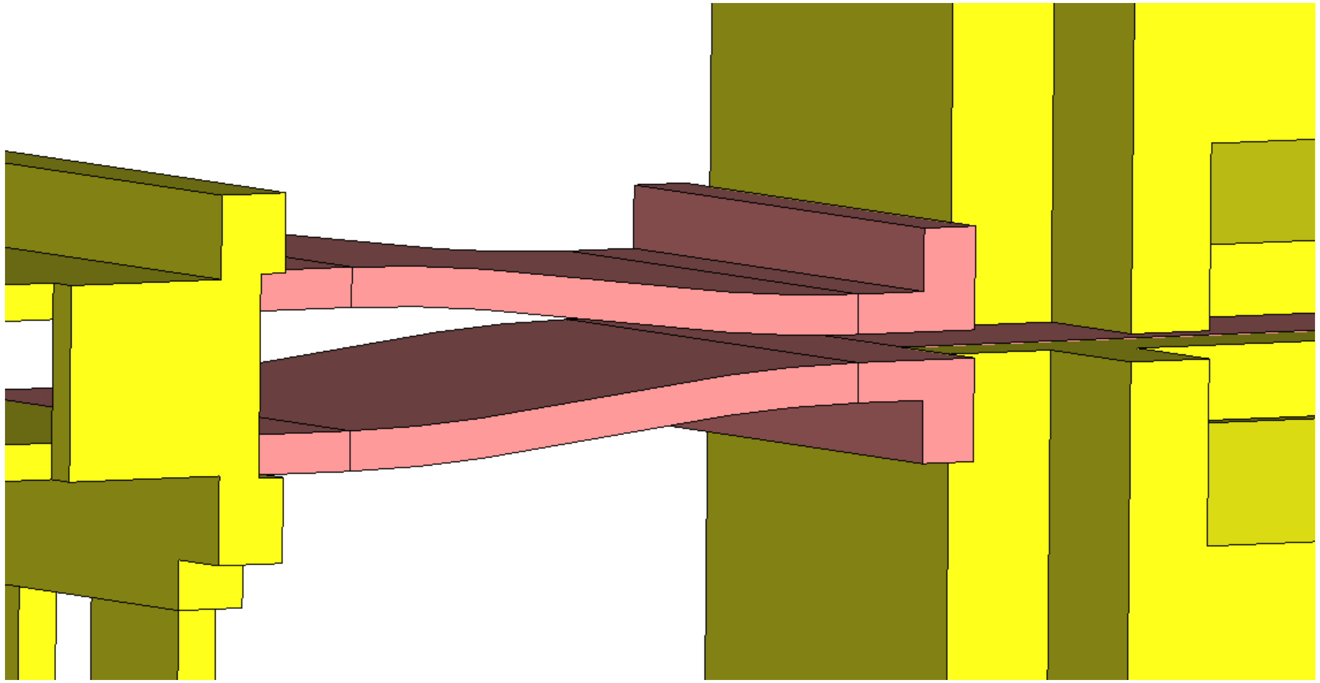
- AISI 317: $\sigma = 1.4\text{e}6\ \text{S/m}$
- Steel 1010: $\sigma = 7\text{e}6\ \text{S/m}$

- Steel conductivity causes some uncertainty in transverse shunt impedances



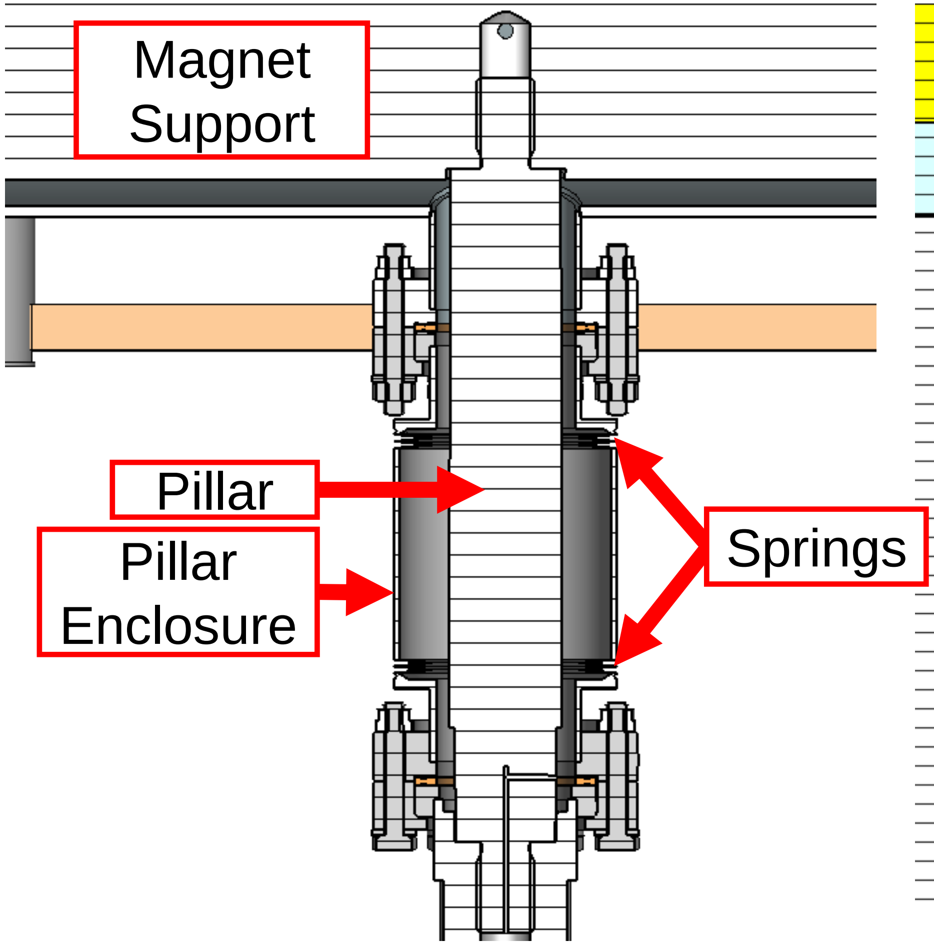
RESULTS
IMPROVED MODEL

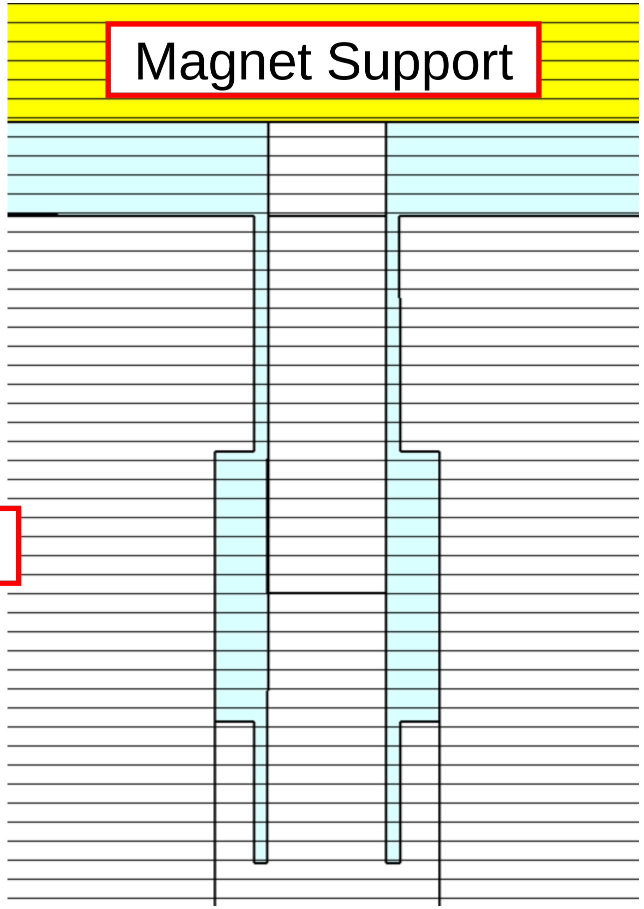
- Accurate modelling of copper parts
- Curved flexible taper



RESULTS
IMPROVED MODEL

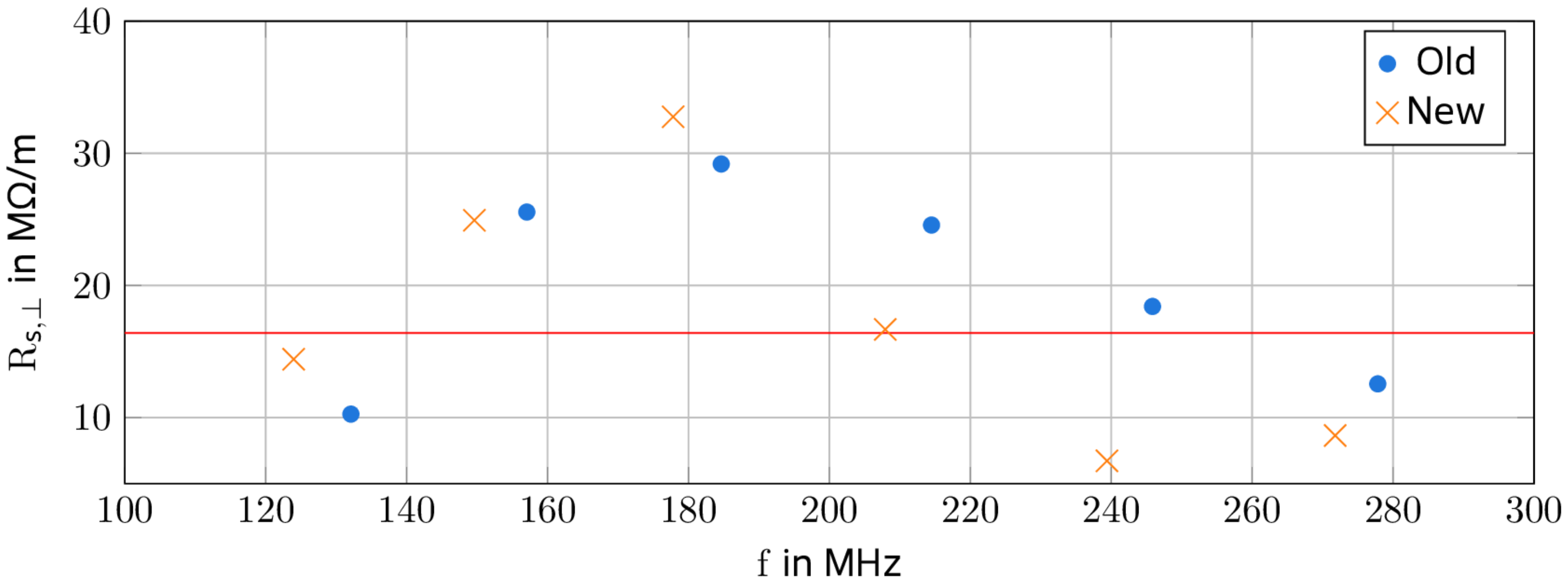
- Accurate modelling of copper parts
- Curved flexible taper
- Accurate pillar geometry
- Still unknown steel material properties
  - $\sigma = 1.4\mathrm{e}6\ \mathrm{S/m}$



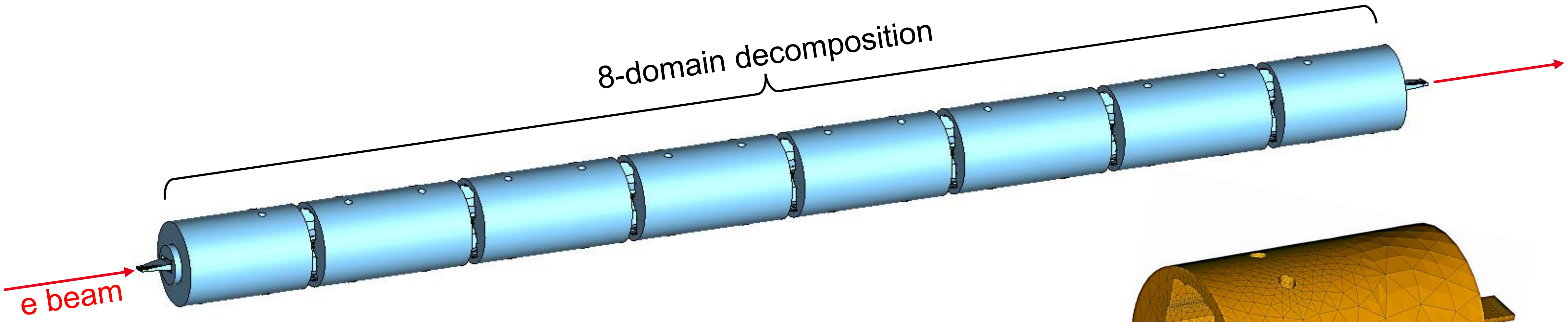


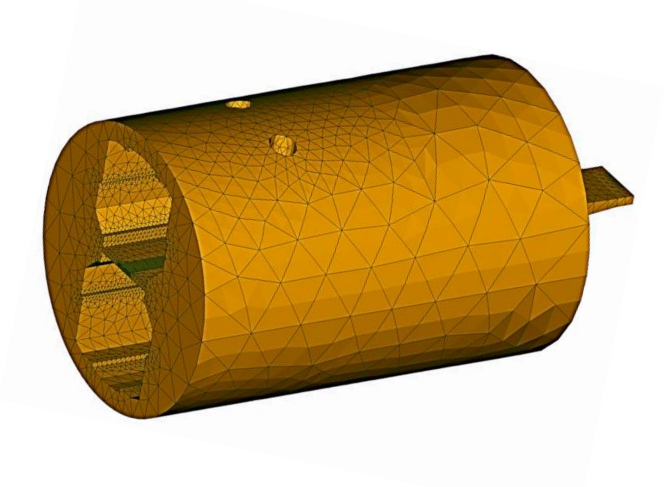
RESULTS
IMPROVED MODEL

- Moderate change of shunt impedances
- Strong change of resonance frequencies
  - Mainly due to new pillar model



RESULTS
DOMAIN DECOMPOSITION SOLVER

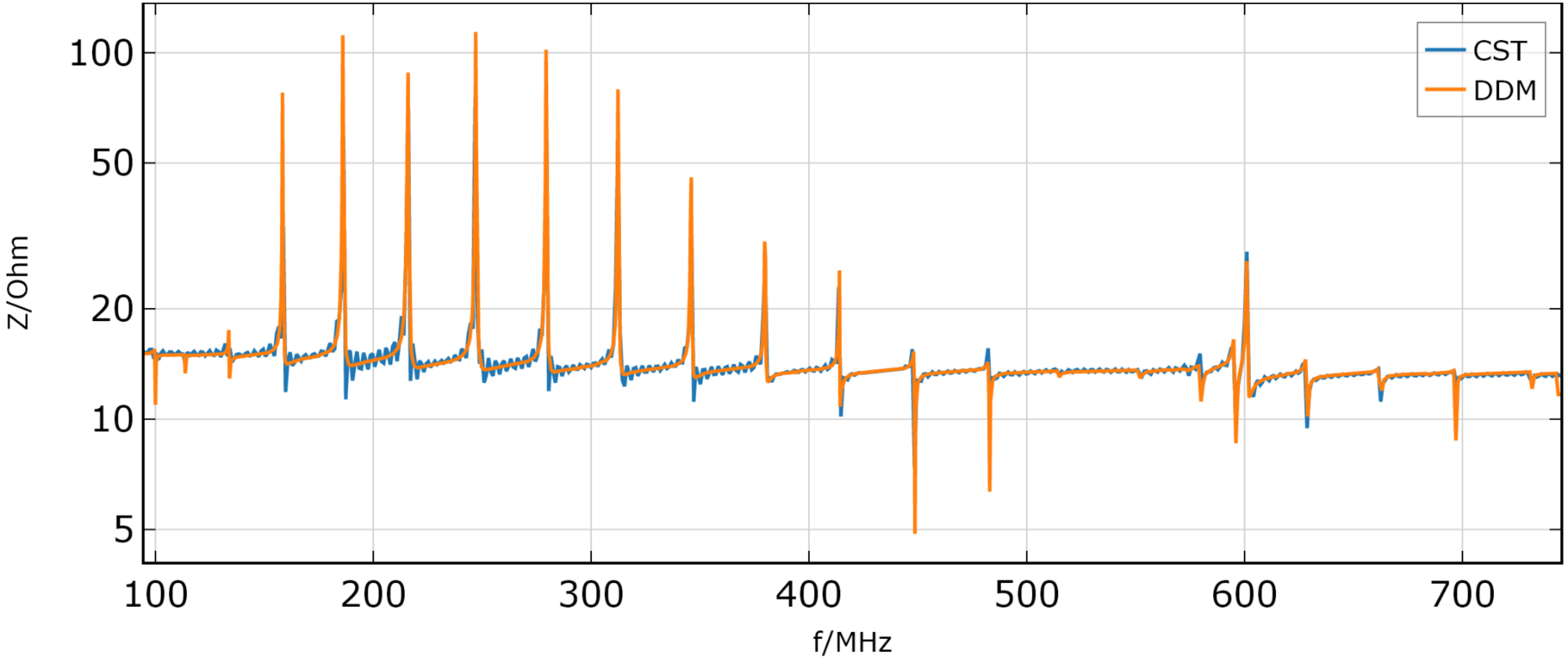




- Old Geometry
- ~700.000 vol. elements (4th order)
  - 38e6 DOFs, 1.5 TB Ram
- 8 MPI nodes at Lichtenberg II
  - 96 cores and 384 GB / node
- MTC with 22 modes
- ~30 DMM iterations / frequency point

RESULTS
DOMAIN DECOMPOSITION SOLVER

- Reference: CST Wakefield solver
- Perfect agreement
- Rudimentary fast frequency sweep
- Less than 5h of computations



CONCLUSION

- Shunt impedances up to 1 Ghz with high solver accuracy
- Transverse shunt impedances around 200 MHz are critical
- Unknown steel conductivity creates small uncertainty
- Improved model
  - Moderate change of shunt impedances
  - Strong change of resonance frequencies
- Domain decomposition solver
  - Enables application of HPC ressources
  - Fast results at high accuracy