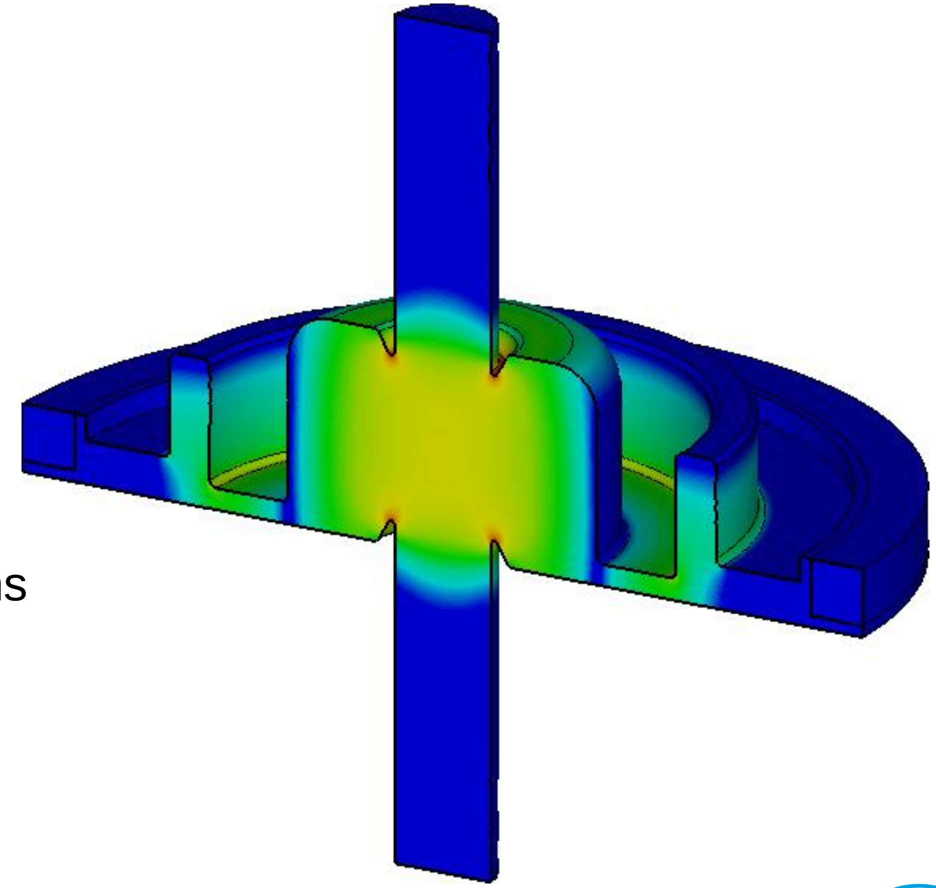
Numerical Optimization of the Shintake Cavity



Simon Karau, Peter Hülsmann, Michael Bousonville, Silke Vilcins
Hamburg, MHF, 2023-12-04

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Overview

Table of Contents

1. Principle of the Choke-Mode-Cavity

Concept of the Choke-Mode-Cavity by T. Shintake 1992

Cylindrically Radial-Line ending with a Damper on a Cavity

- All TM-Modes (and most TE-Modes) will excite the Radial-Line
- and will be attenuated by the Damper.

Adding a Choke in the Radial-Line to protect TM_{010} Mode

- The **Short** will be transformed by $\lambda/4$ into an **Open.**
- Serial junction added impedance $Z_{\mathrm{choke}} = \infty$ and Z_{damper}

  $$Z_{\mathrm{junction}} = Z_{\mathrm{choke}} + Z_{\mathrm{damper}} = \infty \text{ (Open)}$$

  and has a infinitely impedance independent of the damper.
- Distance of $\lambda/4$ transforms the **Open** into a **Short** with $Z_{\mathrm{wall}} = 0$.

Damping of Higher Order Modes (HOMs):

- Almost all HOMs are strongly attenuated
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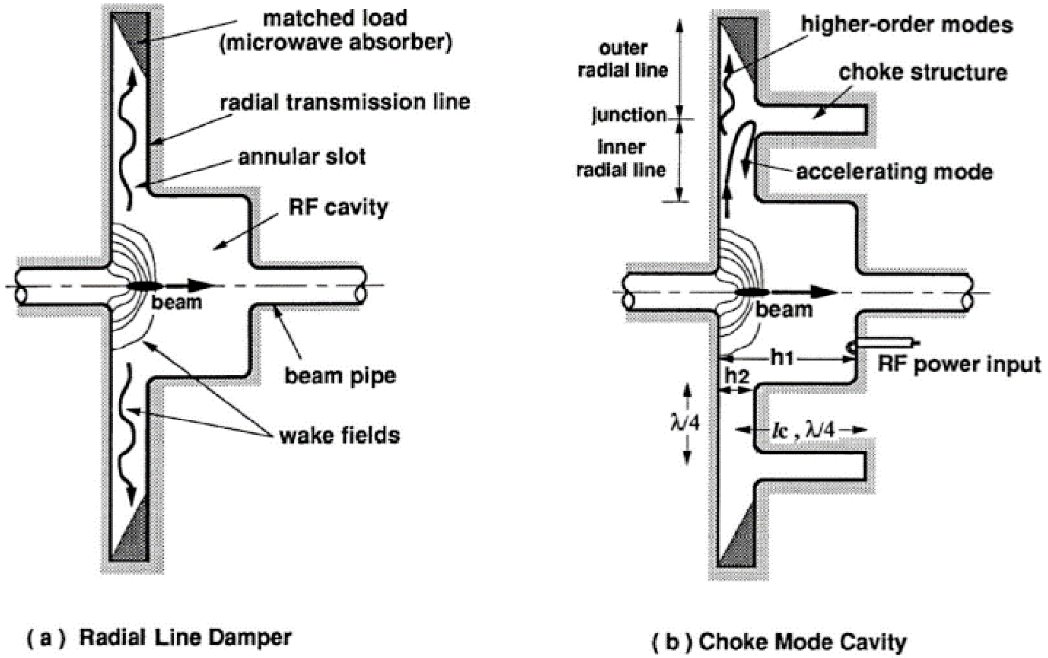

Sketch from T. Shintake, "The Choke Mode Cavity", 1992.

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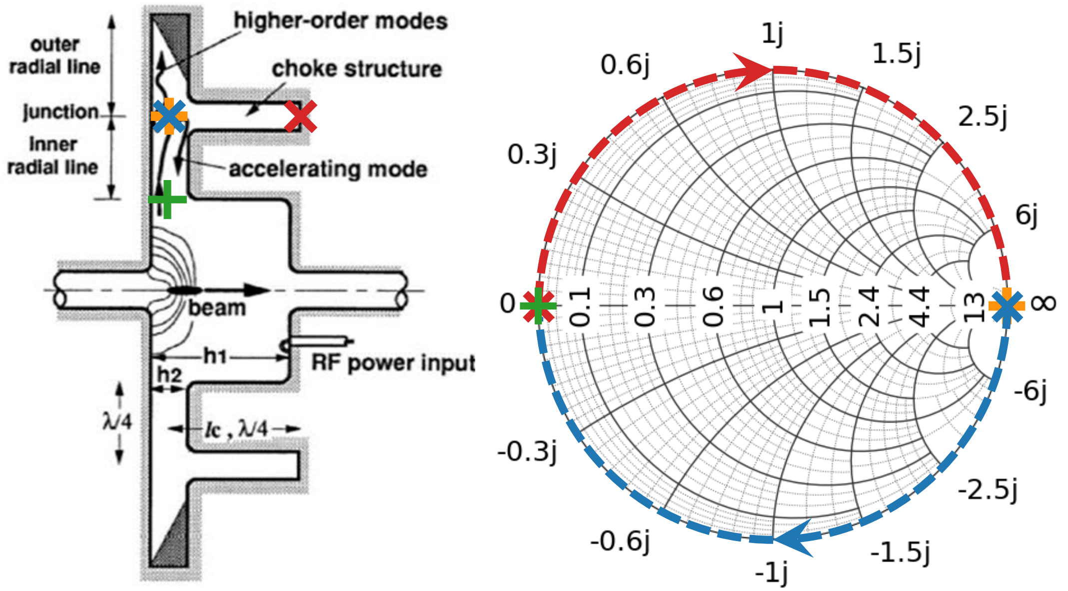

Sketch from *T. Shintake, "The Choke Mode Cavity", 1992* and an added Smith Chart visualization of the Choke

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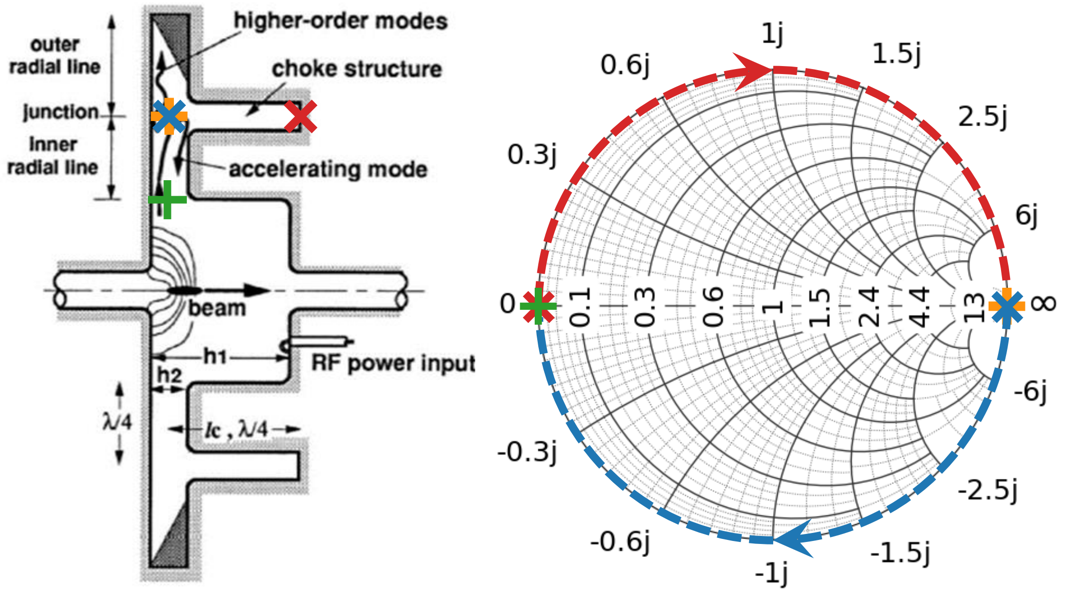

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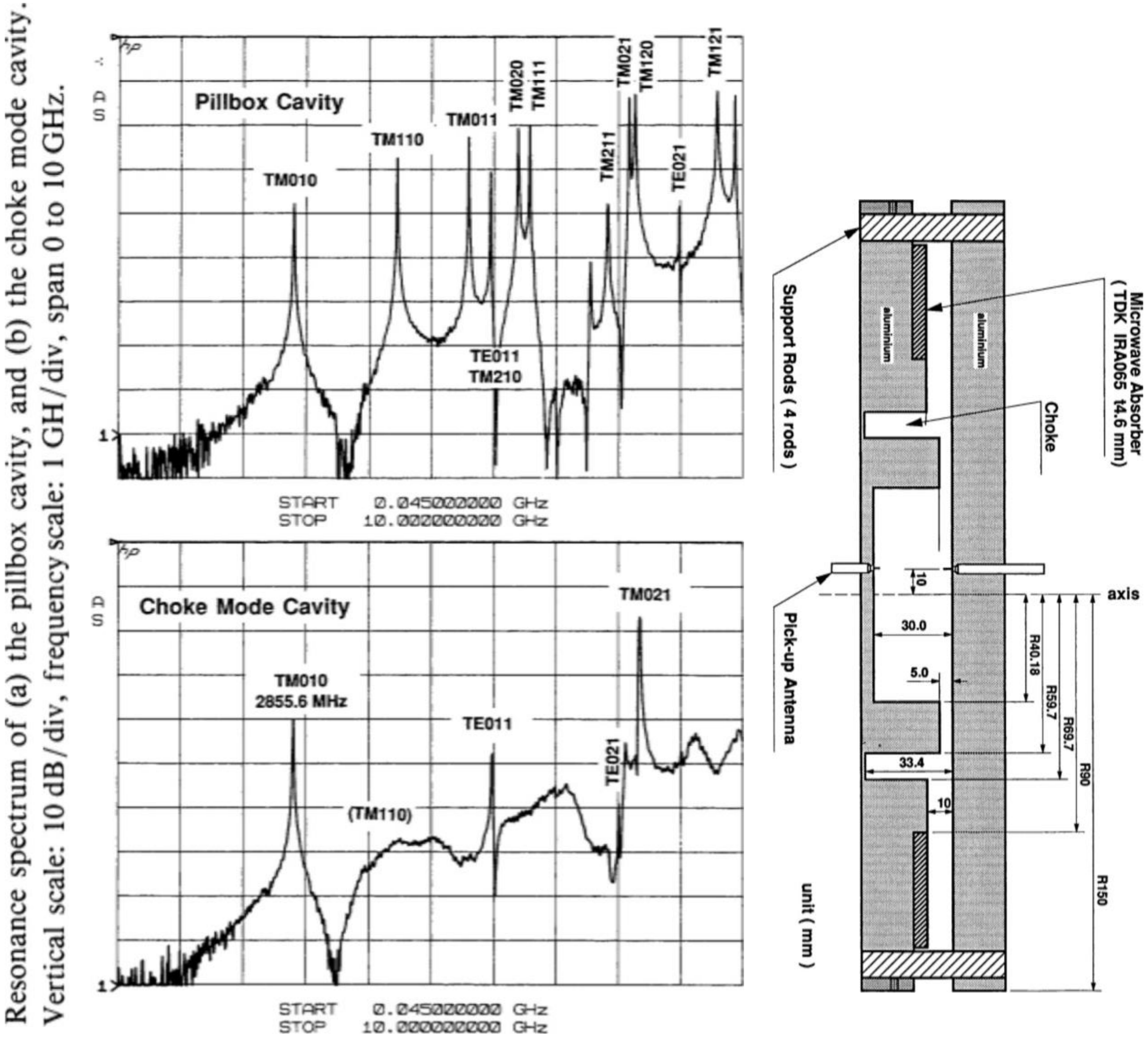
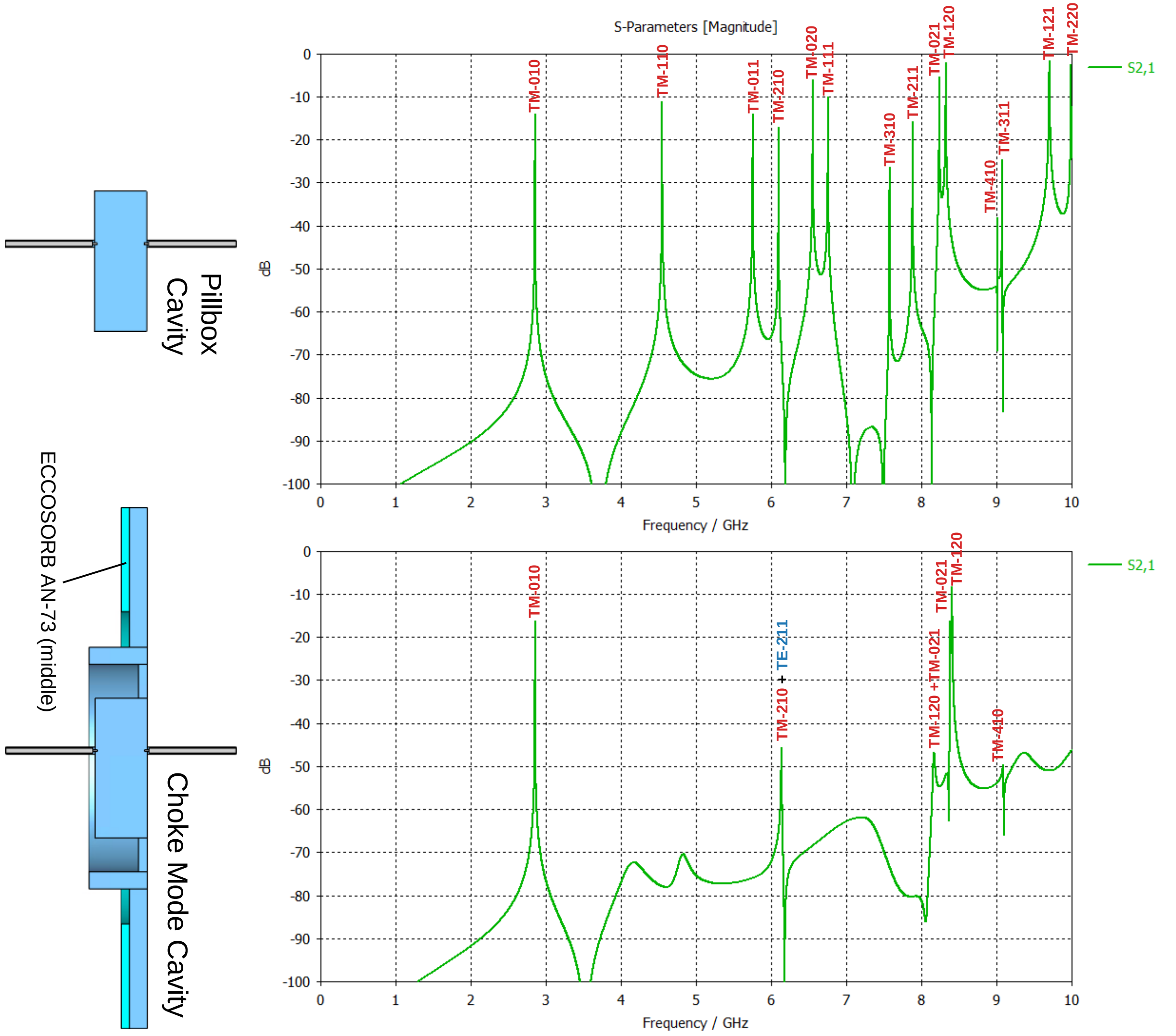
Rough Verification of Measured Cavity Spectrum of the Original Paper by CST Frequency-Domain-Solver

Cavity S-Paras. from *T. Shintake, "The Choke Mode Cavity", 1992*



CST Frequency-Domain-Solver S-Params.



2. One-Cell 1.5 GHz Choke-Mode-Cavity

General Cavity Structure and Optimization of TM_{010} Mode by CST Eigenmodesolver

1.5 GHz Pill-Box Choke-Mode-Cavity (CMC)

I. Starting Point

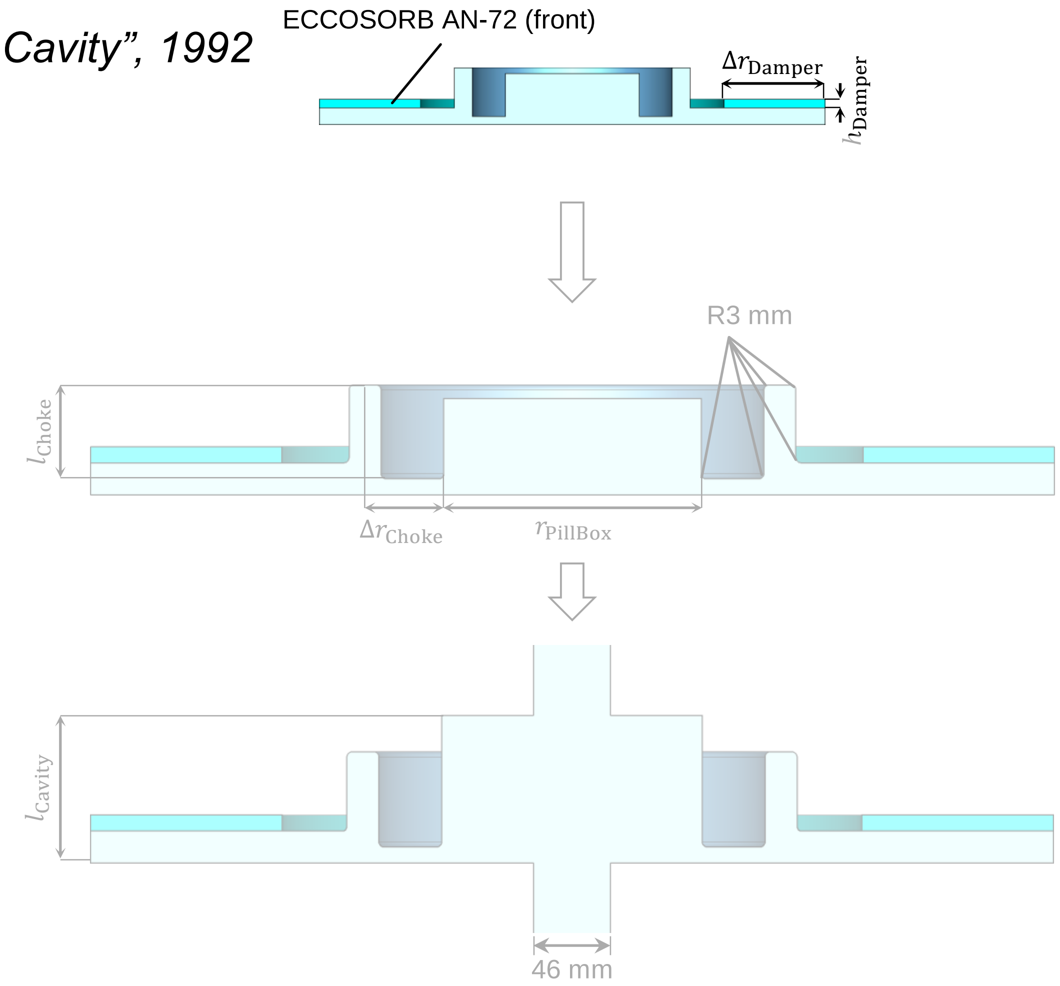
- Exemplary $2.867\ \mathrm{GHz}$ Cavity from *T. Shintake, “The Choke Mode Cavity”, 1992*
- Damper:
  - CST Material Library: ECCOSORB AN-72 (front)
  - $\Delta r_{\mathrm{Damper}} = 60\ \mathrm{mm}$ & $h_{\mathrm{Damper}} = 5\ \mathrm{mm}$

II. Scaling of the Model to $1.5\ \mathrm{GHz}$

- Scaling by Factor 1.9 & Rounding Edges with $R = 3\ \mathrm{mm}$
- Reoptimization of the Structure by CST Eigenmodesolver
  - Get r_{PillBox} to get $f_{\mathrm{res}} = 1.500\ \mathrm{GHz}$
  - Find l_{Choke} & $\Delta r_{\mathrm{Choke}}$ by Iterations for:
    - $f_{\mathrm{res}} = 1.500\ \mathrm{GHz}$
    - $\max\{Q_0\}$

III. Pill-Box Choke-Mode-Cavity with Beam-Pipe

- Adding the $\emptyset = 46\ \mathrm{mm}$ Petra IV Beam-Pipe
- Optimization of Pill-Box Length l_{Cavity} for max. $R_{\mathrm{sh,eff}}$
- Reoptimization of the Structure by CST Eigenmodesolver
  - ...



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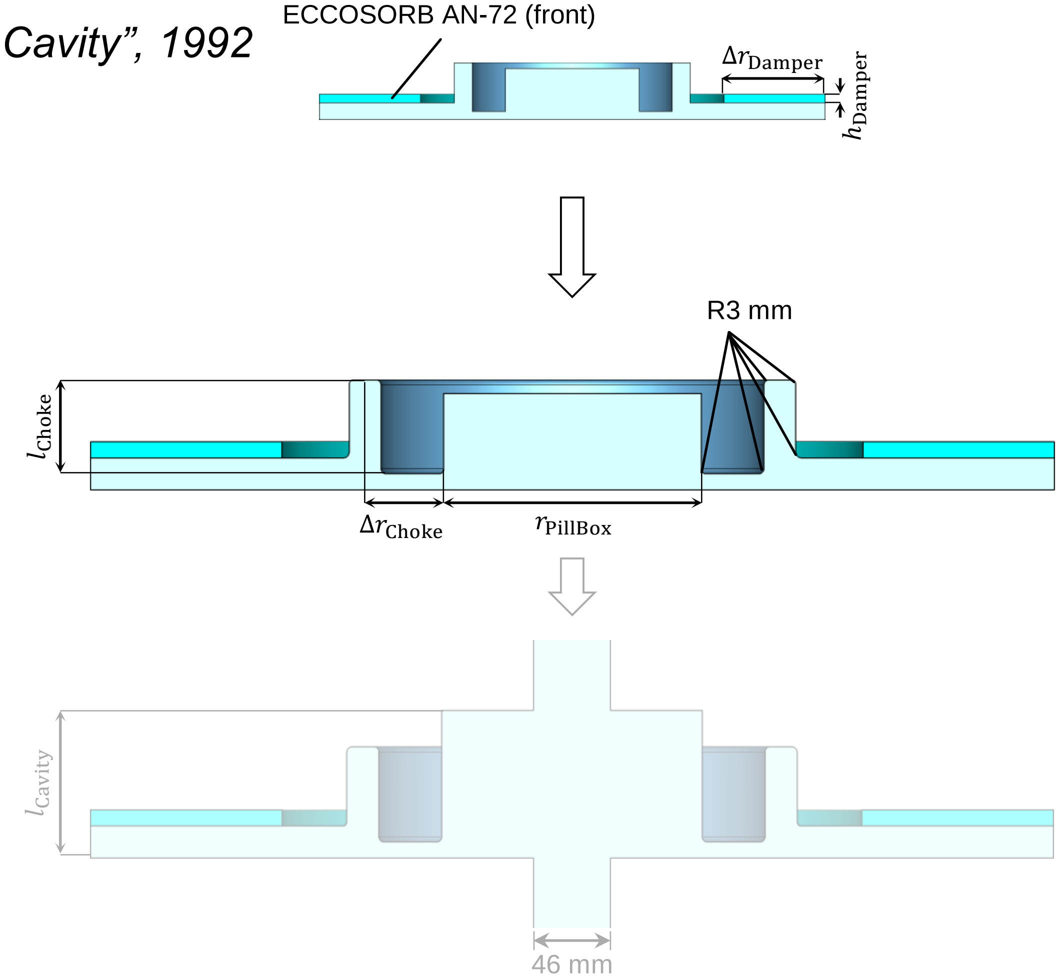

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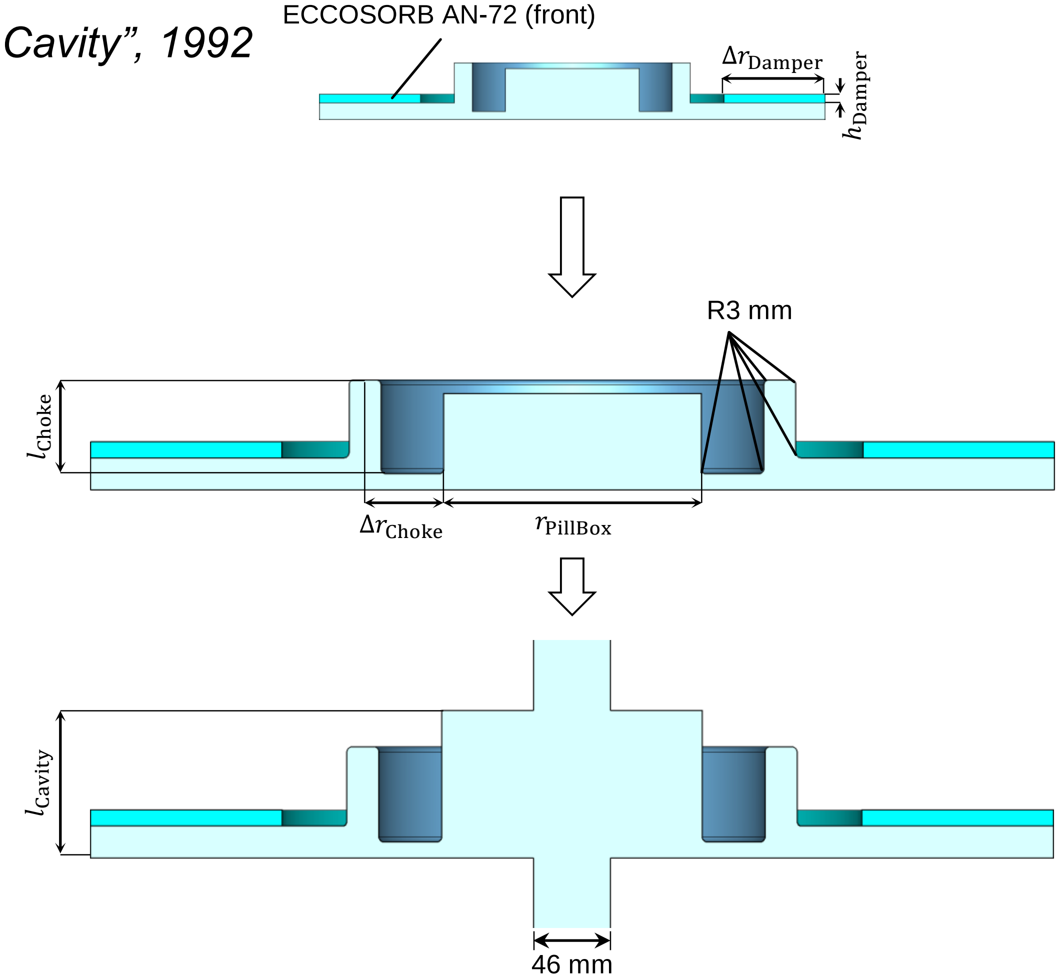


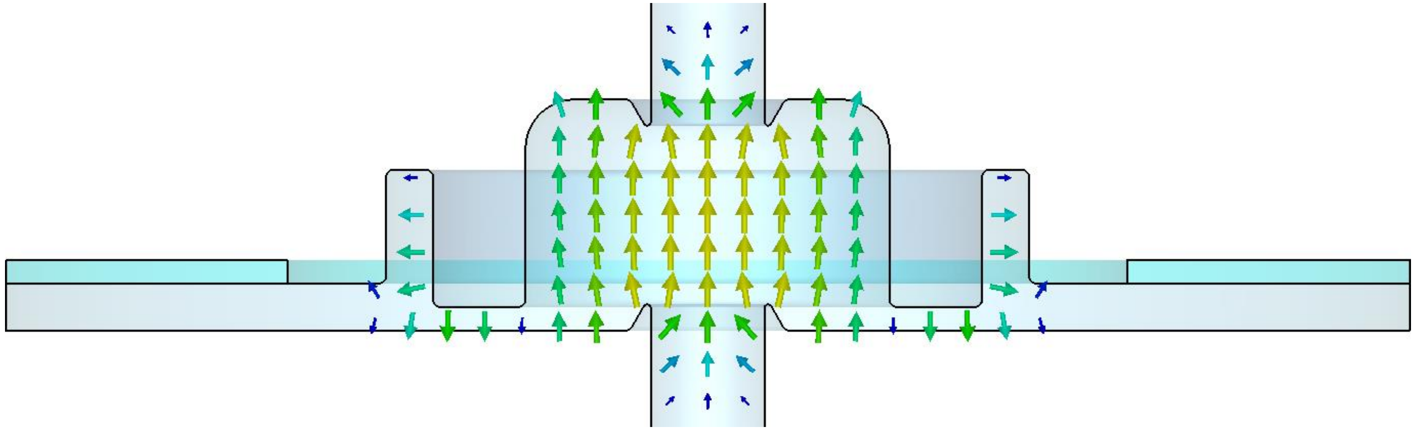
2. One-Cell 1.5 GHz Choke-Mode-Cavity

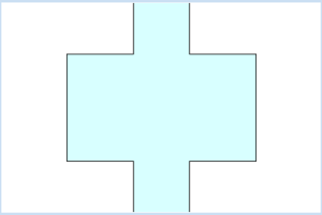
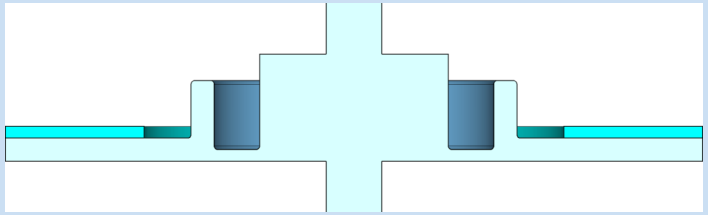
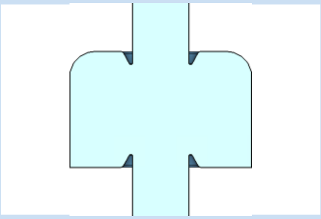
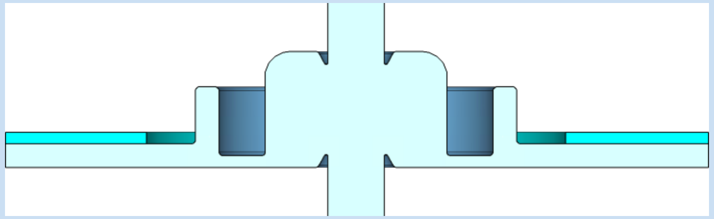
General Cavity Structure and Optimization of TM_{010} Mode by CST Eigenmodesolver

Nose-Cone Optimization

For further Optimization of the Cavity

- Noses are included:
  - At the Transitions of Cavity and Beam-Pipe
  - to increase the Volume of Stored Energy.
- Rounding of the outer Cavity Edges:
  - Reduces the Losses of the Cavity,
  - but are not used at the Back-Side, to ensure
  - the excitation of the Radial-Line by all TM-Modes.



	Pill-Box with Beam-Pipe		Nose-Cone with Beam-Pipe	
qTM_{010}	Pill-Box	Pill-Box with Choke-Mode-Damper	Nose-Cone	Nose-Cone with Choke-Mode-Damper
				
f_{res} [GHz]	1.500	1.500	1.500	1.500
Q_0 [1]	24153	20492 (85%)	23216	19782 (85%)
$R_{\mathrm{sh,eff}}$ [MΩ]	1.899	1.468 (77%)	2.202	1.706 (77%)
$R_{\mathrm{sh,eff}}/Q_0$ [Ω]	78.6	71.6 (91%)	94.8	86.2 (91%)
Λ_c [1]	61%	61%	66%	66%

2. One-Cell 1.5 GHz Choke-Mode-Cavity

Selection of a Damping Material

General selection of an Damping Material

- First Simulations used non-practical Damping Materials
- As a real usable Damping Material
  - the Idea of single Ring of Siliziumcarbid (SiC) was adapted from
  - *T. Inagaki et al., "High-gradient C-Band Linac for a Compact X-Ray Free-Electron Laser Facility", 2014.*

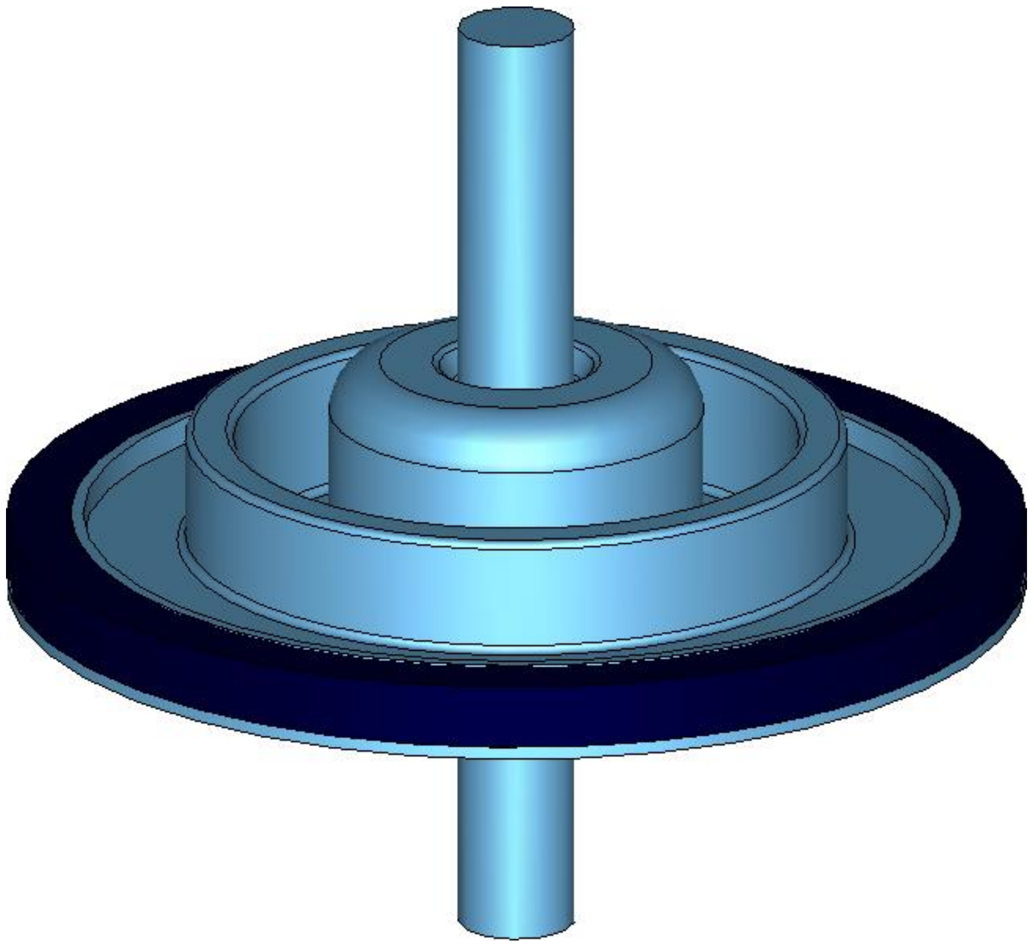
  because of the simplicity and suitable Material Properties

Simulation Parameters

- RF Material Parameters ($\underline{\varepsilon}_r$) of SiC vary widely between
  - Manufacturing Technique,
  - Frequency and
  - Temperature

  and must be measured to get precise Values.
- For Simulation before a Material Measurement
  - $\varepsilon_r = 20$
  - $\tan\delta_E = 0.25$

  are used.



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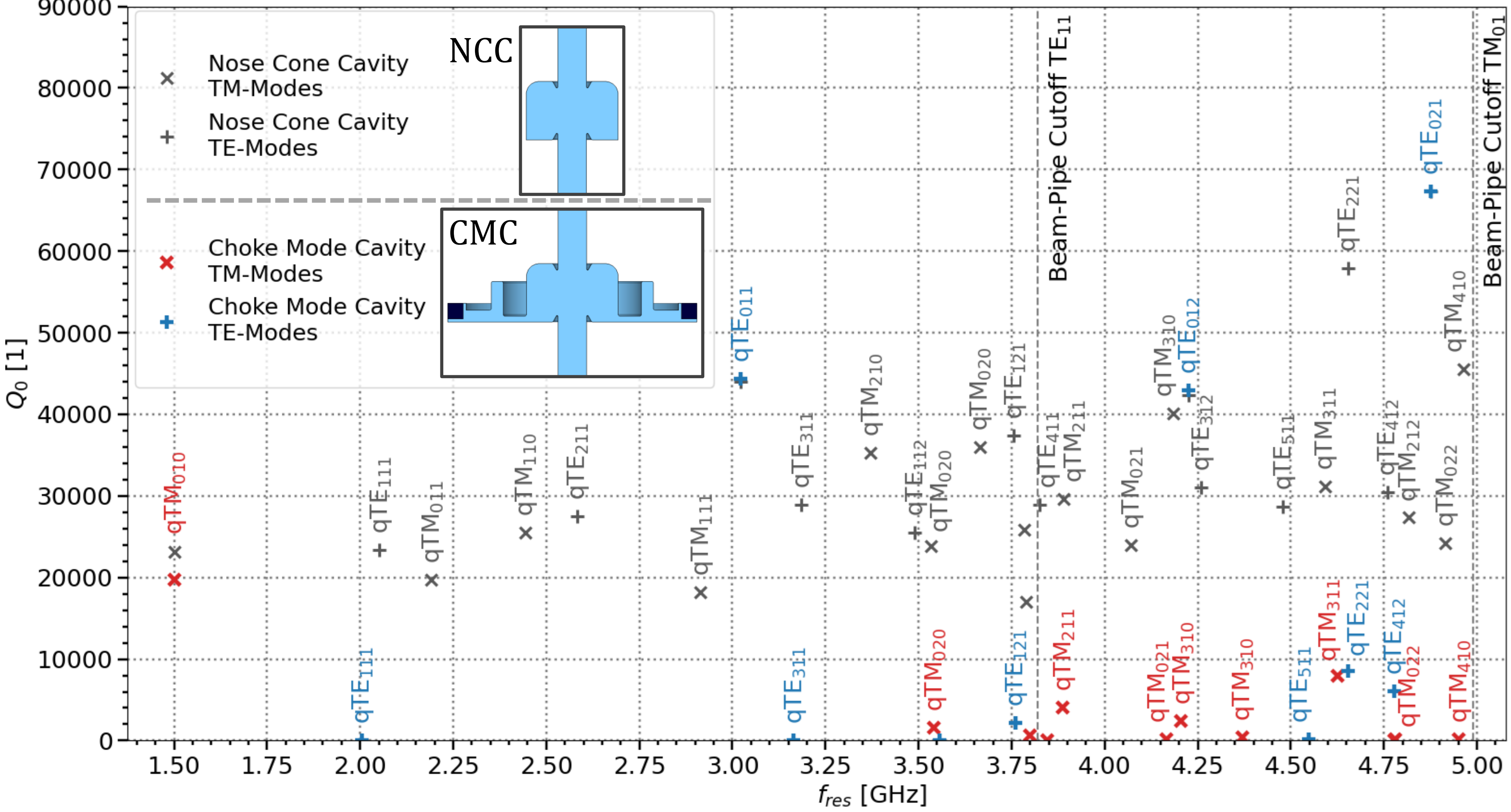
Mode Overview of Nose-Coned Choke-Mode-Cavity by CST Eigenmodesolver

Q_0 along f_{res} of all Modes with $Q_0 \geq 100$ (CST Eigenmode Solver General Lossy)



Results

qTM_{010} Mode

- $Q_0(\text{NCC}) = 23157$
- $Q_0(\text{CMC}) = \frac{19784}{85\%}$

Decreasing of other qTM

- Strongly reduced Q_0: $Q_0(qTM_{011}) \approx 8$ $Q_0(qTM_{110}) \approx 17$
- Highest HOM-TM: $Q_0(qTM_{311}) \approx 8000$ with f_{res} next to Choke 3[rd] resonance $4.5\text{GHz} = 3 \cdot 1.5\text{GHz}$

Decreasing of qTE

- Most qTE are also strongly reduced
- Only qTE_{0nq} are undamped, because can not excite Radial-Line

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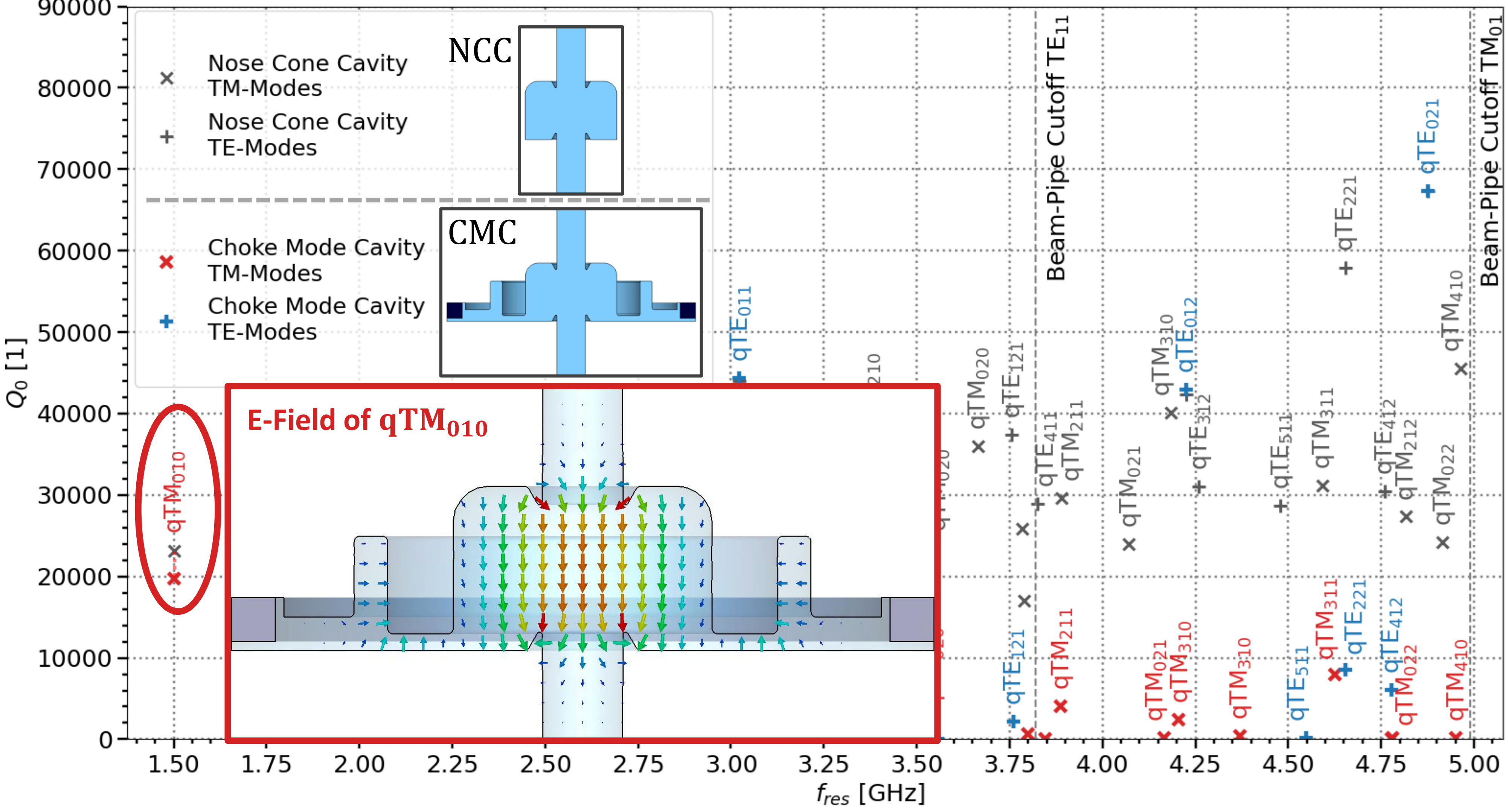

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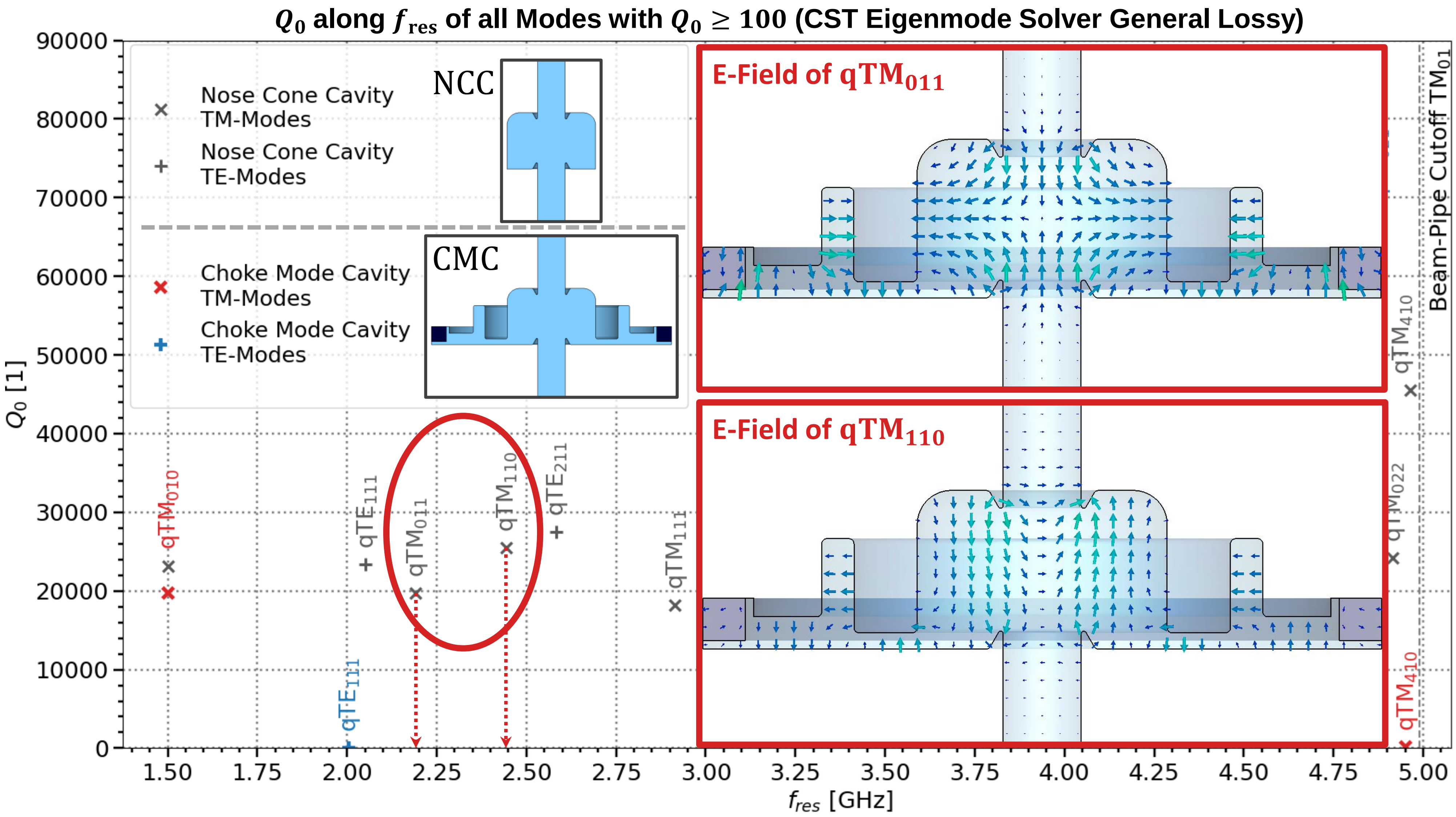

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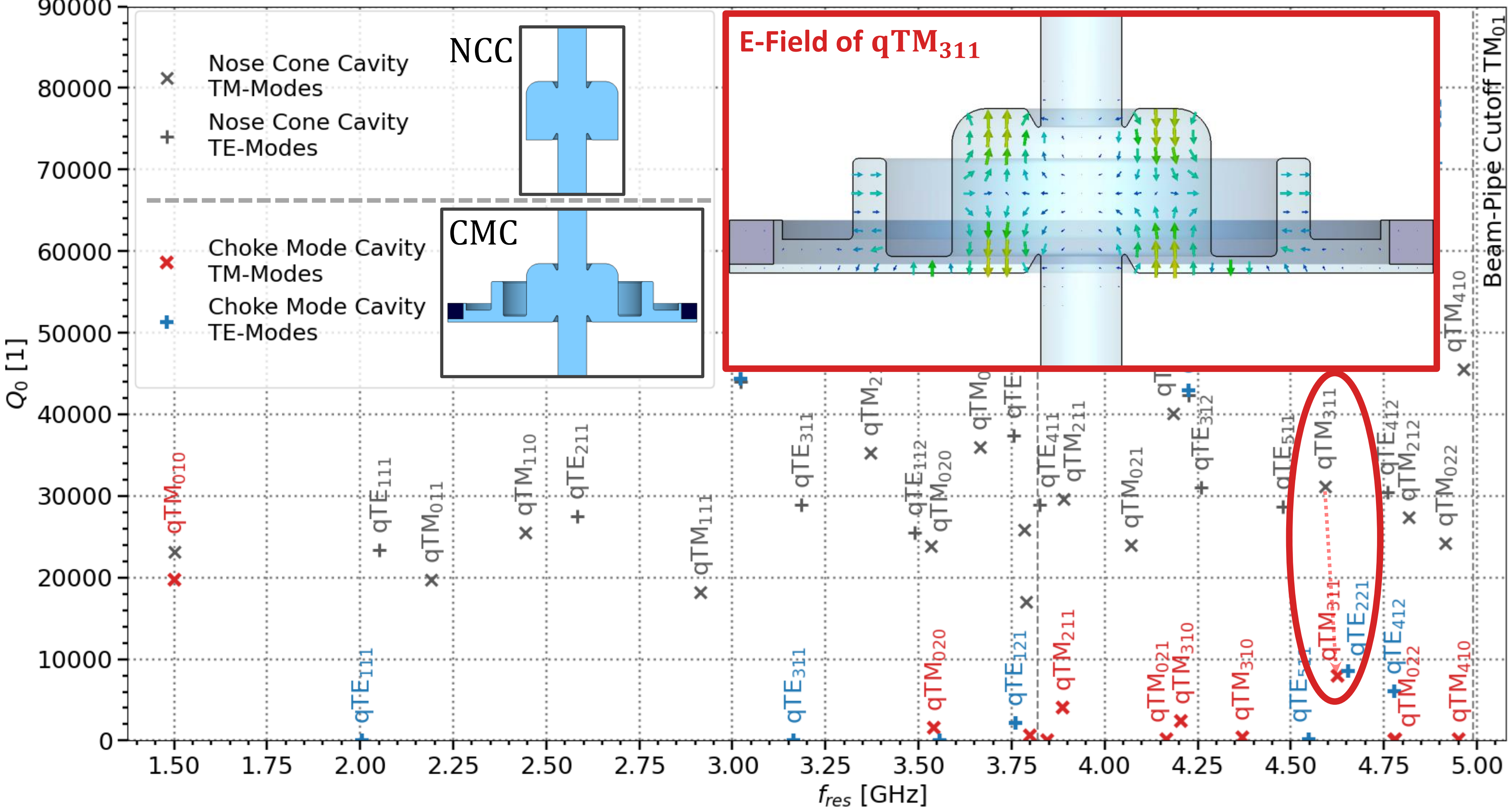

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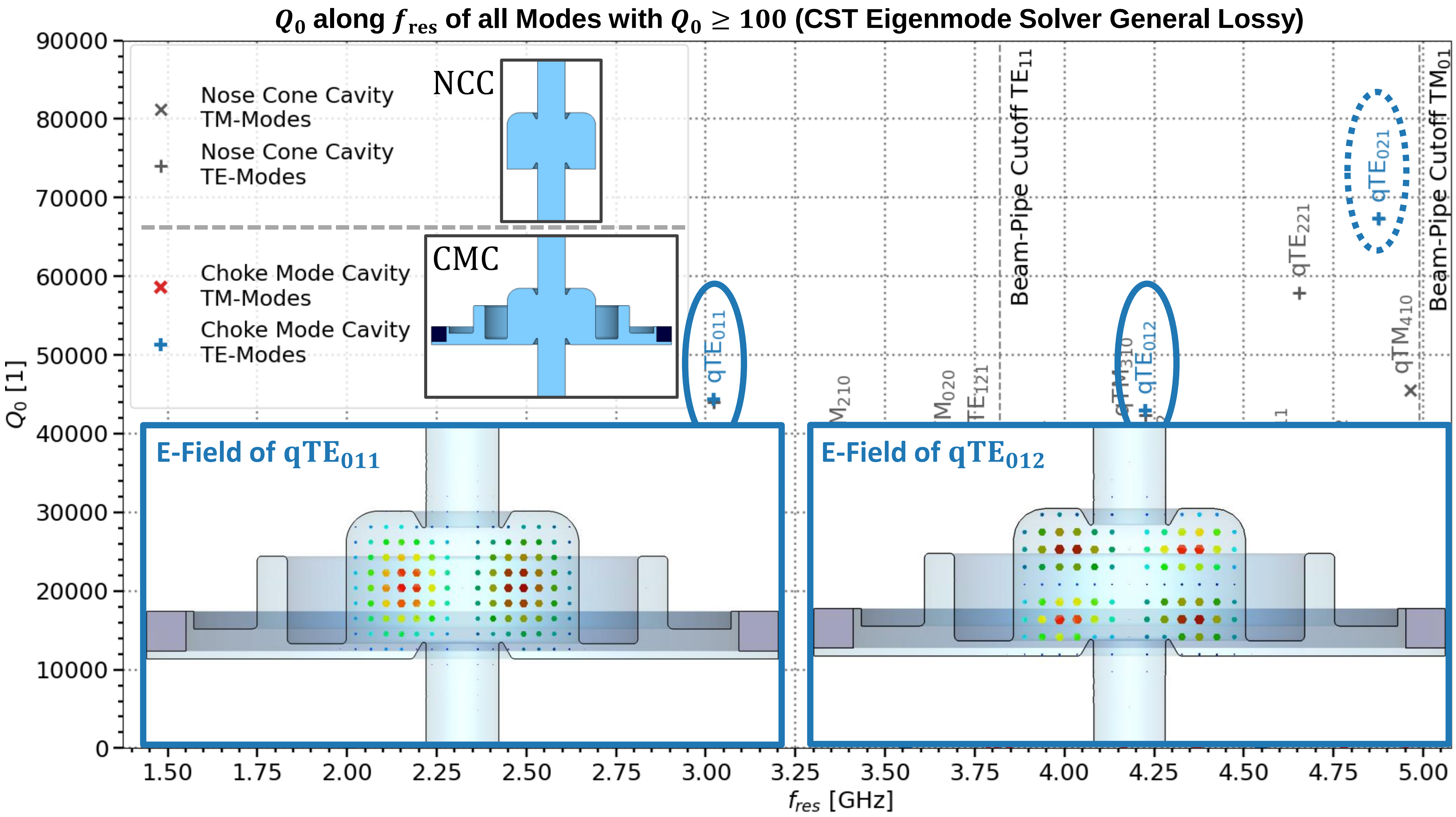

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3. Coupler and Tuner System

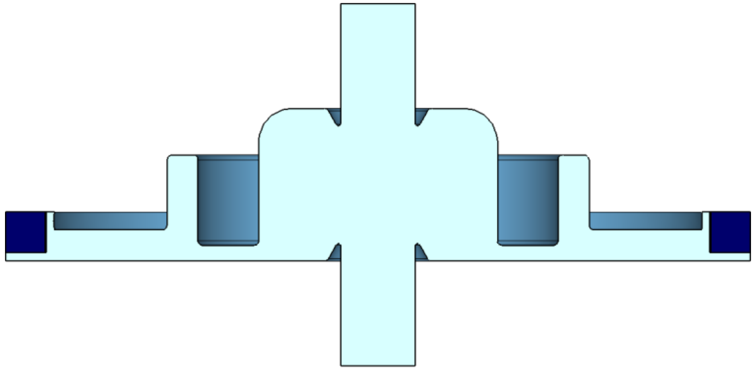
Specification of the Coupler & Tuner System

Specification

- Keep manufacturing as simple as possible
  - Two Half Shells (Back & Top) without $45°$ Drilling
  - The Choke should not be turn around
- Actively adjustable Coupling Factor

  Range: $K \approx 0.2 \text{ to } 5$
- Broadband Tunable Resonant-Frequency

  Range: $\Delta f_{\text{res}} \approx \pm 1.5\ \text{MHz}$ (or more)
  to allow complete Detuning of the Cavity



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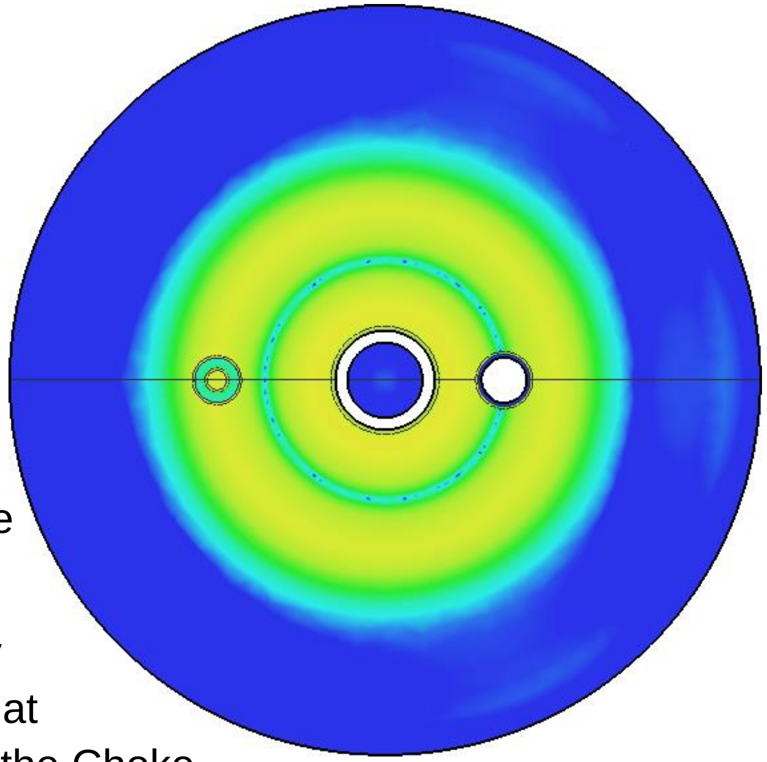

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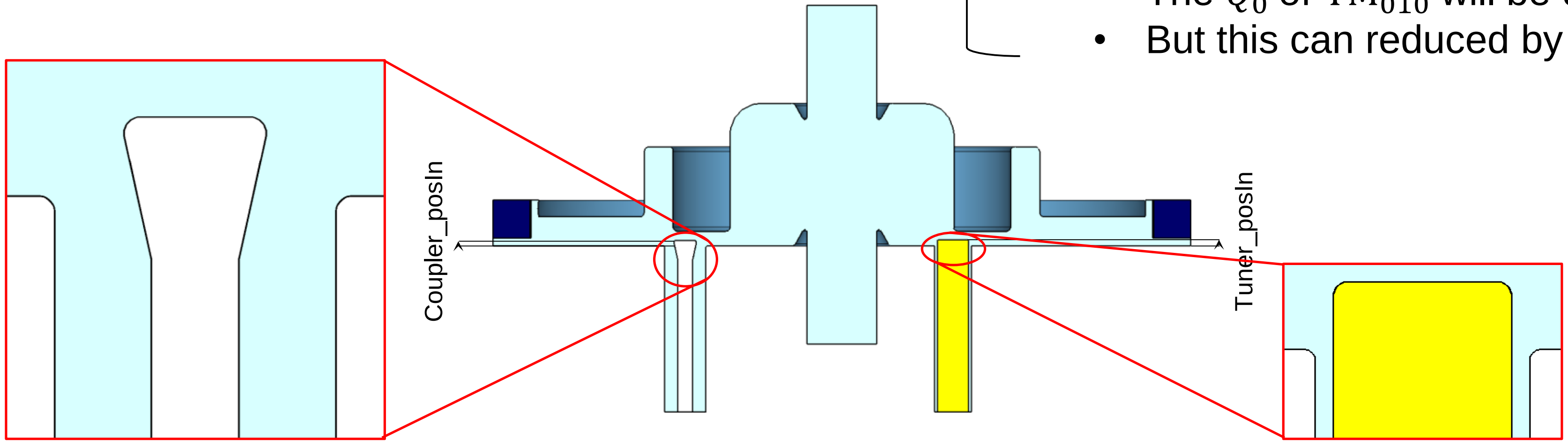
  to allow complete Detuning of the Cavity

This is necessary:

- A capacitive Coupling and Tuning,
- Positioned in the Radial-Line

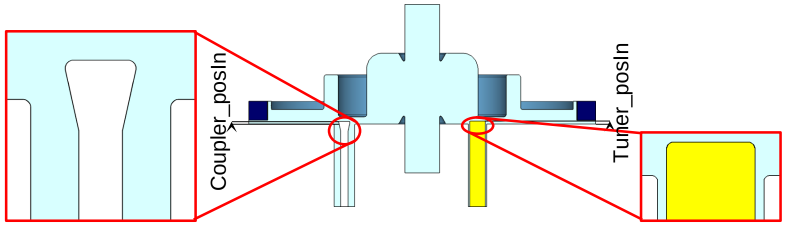
Some Disadvantage:

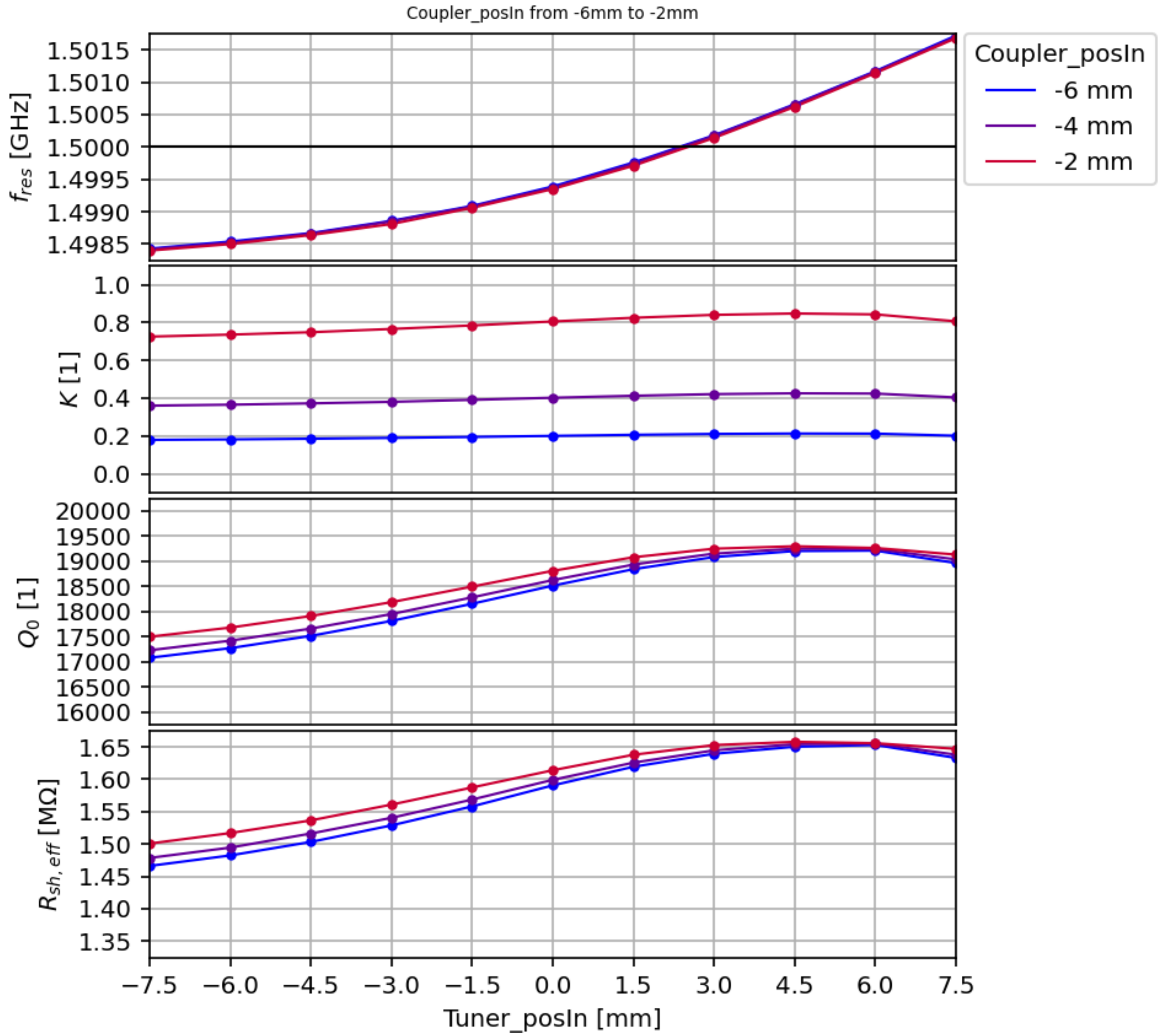
- No longer perfect Symmetry
- Some part of the RF-Power at $1.5\ \mathrm{GHz}$ can tunneling throw the Choke
  - The Q_0 of TM_{010} will be decreased in some way
  - But this can reduced by optimization

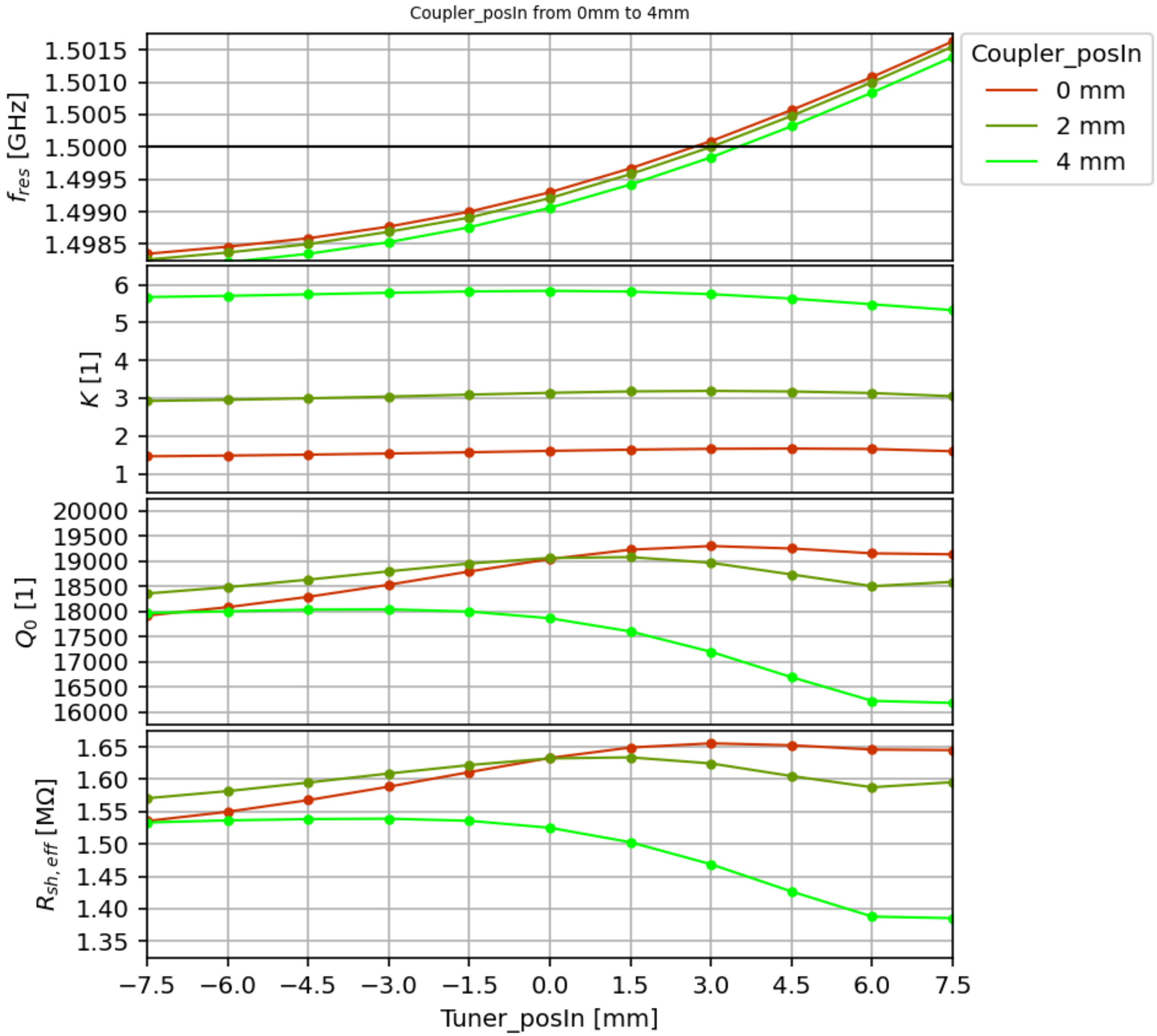


3. Coupler and Tuner System

Coupler & Tuner in the Radial-Line







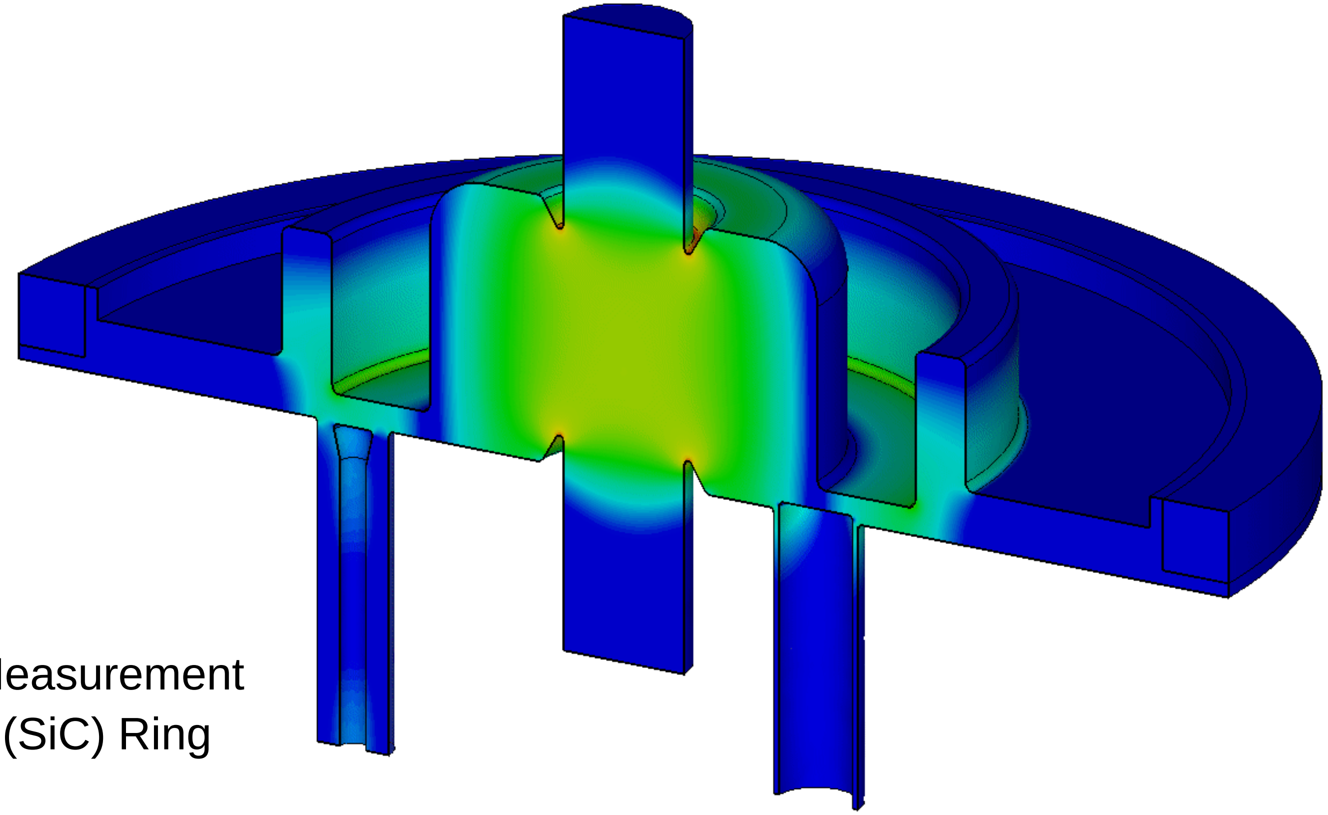
Summary and Outlook

Results & Next Steps

Curent Design

Simulated One-Cell 1.5 GHz Cavity Design

- Damping of all HOMs (Except TE_{0nq})
- Coupling and Tuning in the Radial-Line
  - Adjustable Coupling-Factor
  - Broadband Tunable Resonant-Frequency
- With a very simple structure



Next Steps

- Adding of Coaxial-Lines Sensors for Mode Measurement
- Selection and Purchase of an Siliciumcarbid (SiC) Ring
- Creation of a Prototype

Thank you

References

1. T. Shintake, “The Choke Mode Cavity”, *Jpn. J. Appl. Phys.*, pp. pp. L 1567-L1570, 1992.
2. T. Inagaki et al., “High-gradient C-Band Linac for a Compact X-Ray Free-Electron Laser Facility”, Phys. Rev. ST Accel. Beams, vol. 17, p. 080702, 2014.

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