1.5 GHz Single-Mode-Cavity

Für PETRA IV

- Hochfrequenz-Technik

M. Bousonville, S. Karau, P. Hülsmann (MHF)
H. Bienert, M. Pröll, M. Lemke (ZM1)
S. Vilcins (MDI)

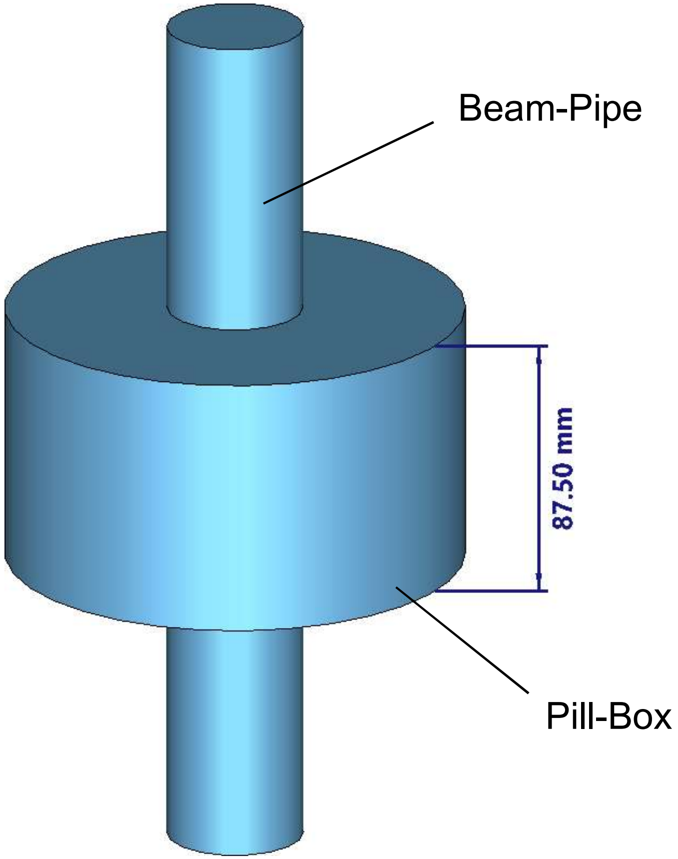
Engineering Day, Hamburg, 20. Juni 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Simple Example of an Acceleration Cavity

Mode Overview of a Pill-Box Cavity for 1.5 GHz up to 3.0 GHz

Mode	f_{res} [GHz]	Q_0 [1]
TM_{010}	1.500	24150
TE_{111}	2.004	25642
	2.004	25642
TM_{011}	2.289	20144
TM_{110}	2.315	26413
	2.315	26413
TE_{211}	2.540	28050
	2.540	28050
TM_{111}	2.801	19238
	2.801	19238
TE_{011}	2.910	49620
...	...	...

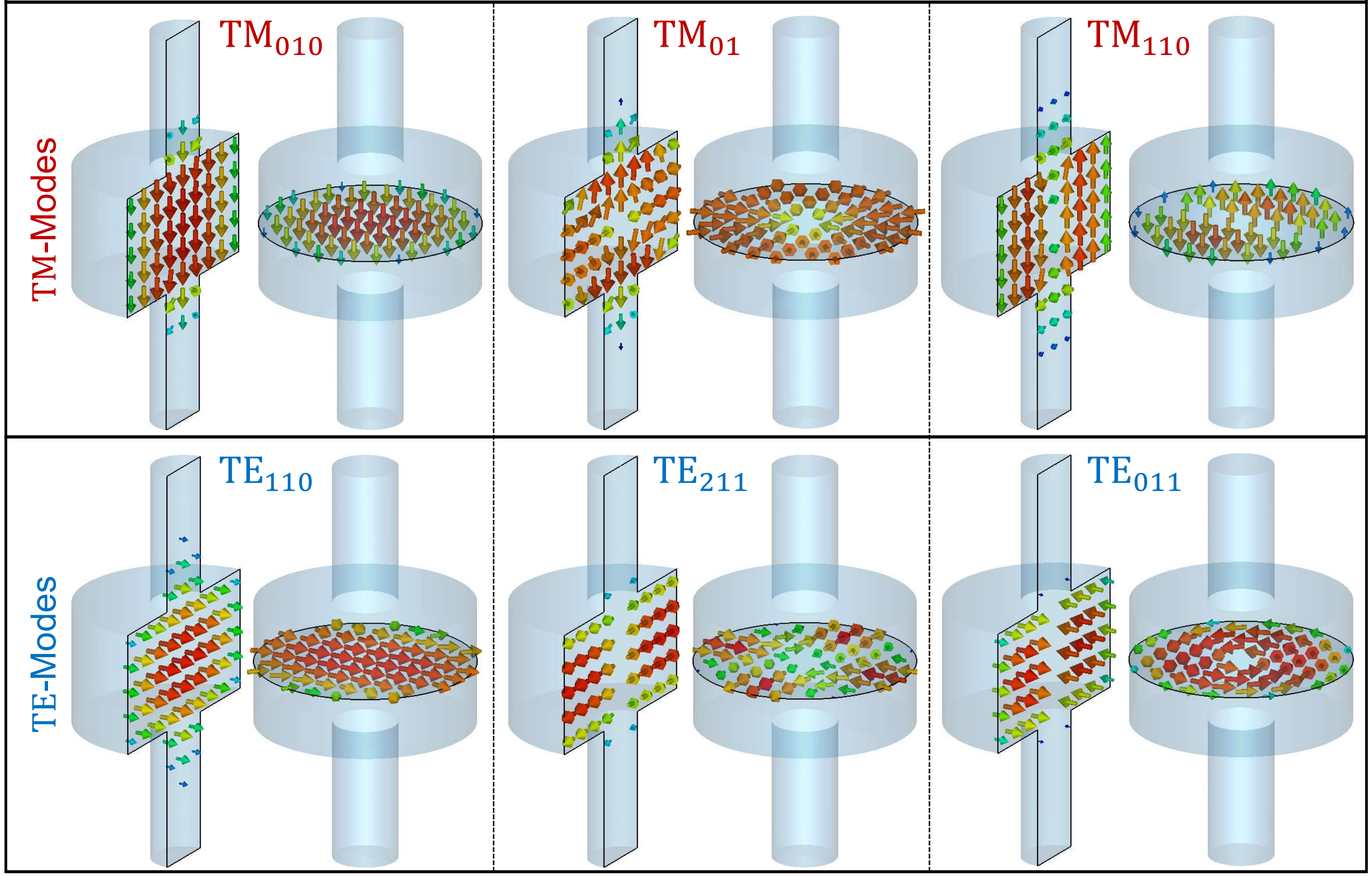


Simple Example of an Acceleration Cavity

Mode Overview of a Pill-Box Cavity for 1.5 GHz up to 3.0 GHz

Mode	f_{res} [GHz]	Q_0 [1]
TM_{010}	1.500	24150
TE_{111}	2.004	25642
	2.004	25642
TM_{011}	2.289	20144
TM_{110}	2.315	26413
	2.315	26413
TE_{211}	2.540	28050
	2.540	28050
TM_{111}	2.801	19238
	2.801	19238
TE_{011}	2.910	49620
...	...	...

E-Field Patterns of different Modes

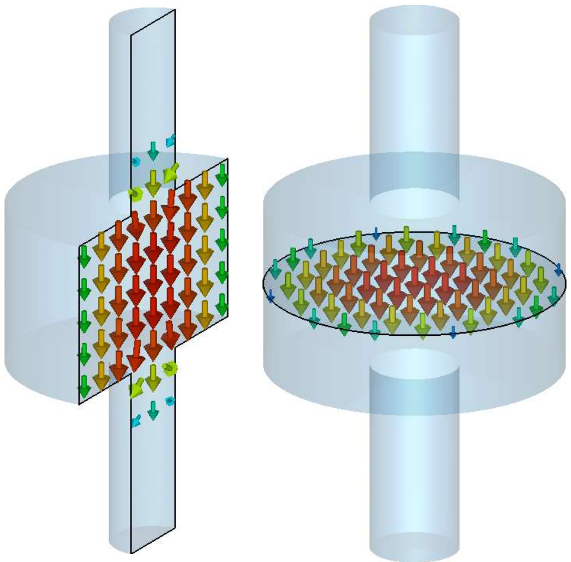


Simple Example of an Acceleration Cavity

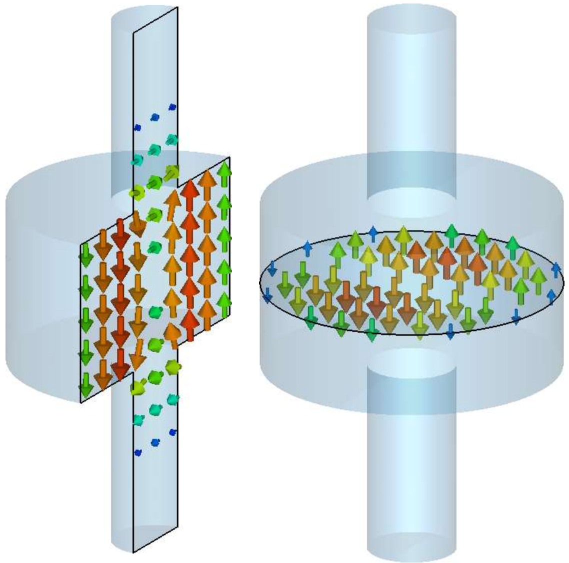
Mode Overview of a Pill-Box Cavity for 1.5 GHz up to 3.0 GHz: 2 Modes which are presented as examples

Mode	f_{res} [GHz]	Q_0 [1]
TM_{010}	**1.500**	**24150**
TE_{111}	2.004	25642
	2.004	25642
TM_{011}	2.289	20144
TM_{110}	2.315	26413
	2.315	**26413**
TE_{211}	2.540	28050
	2.540	28050
TM_{111}	2.801	19238
	2.801	19238
TE_{011}	2.910	49620
…	…	…

E-Field Pattern of TM_{010}



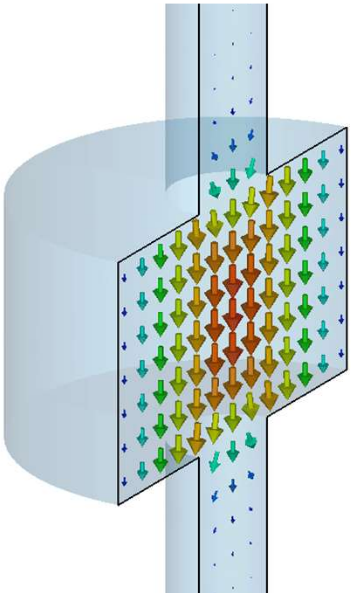
E-Field Pattern of TM_{110}



Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

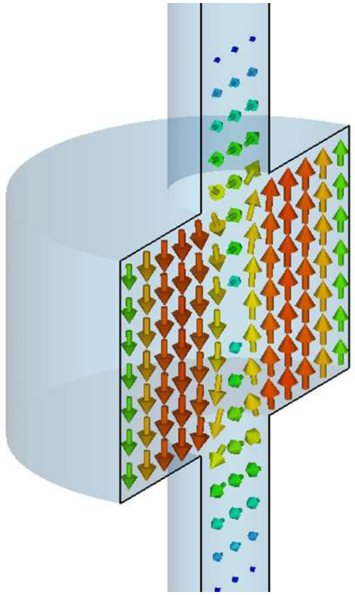
E-Field Pattern of exemplary Modes TM_{010} & TM_{110} of a Pill-Box Cavity for 1.5 GHz

E-Field of TM_{010}



f_{res}	1.500 GHz
Q_0	24150

E-Field of TM_{110}

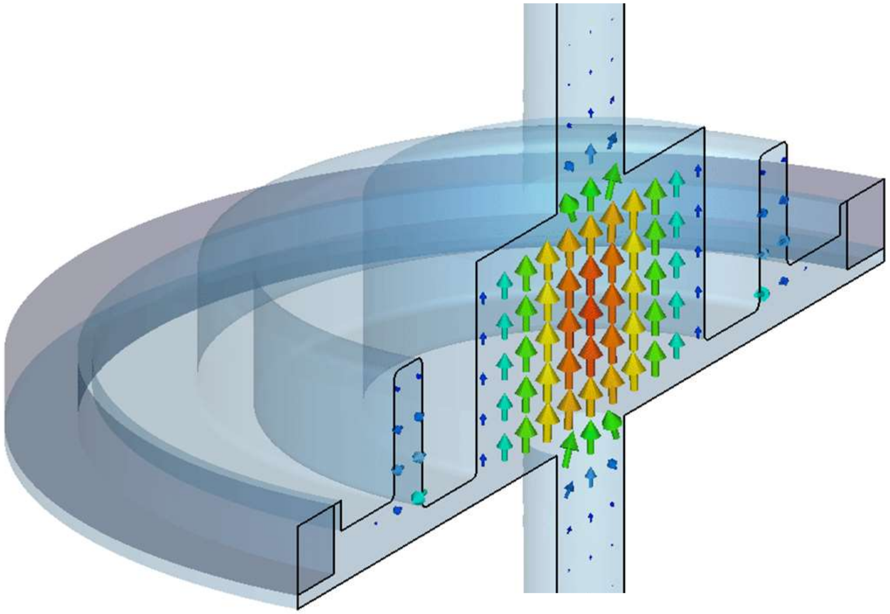


f_{res}	2.315 GHz
Q_0	26413

Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

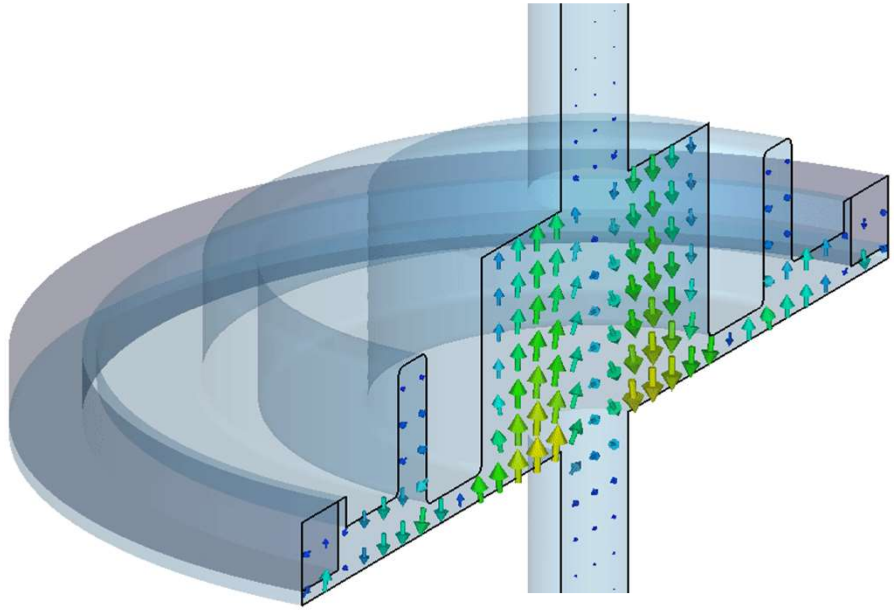
E-Field Pattern of exemplary Modes TM_{010} & TM_{110} of a Choke Mode Cavity for 1.5 GHz

E-Field of TM_{010}



f_{res}	1.500 GHz	
Q_0	20456	85% of 24150

E-Field of TM_{110}



f_{res}	2.229 GHz
Q_0	14

Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

Structure and Principle of Operation

Cylindrically <u>Radial-Line</u> ending with a Damper on a Cavity

- All TM-Modes (and most TE-Modes) will excite the Radial-Line
- Only not critical TE_{0nq} can not excite the Radial-Line

All critical Modes are damped, but also acceleration Mode TM_{010}.

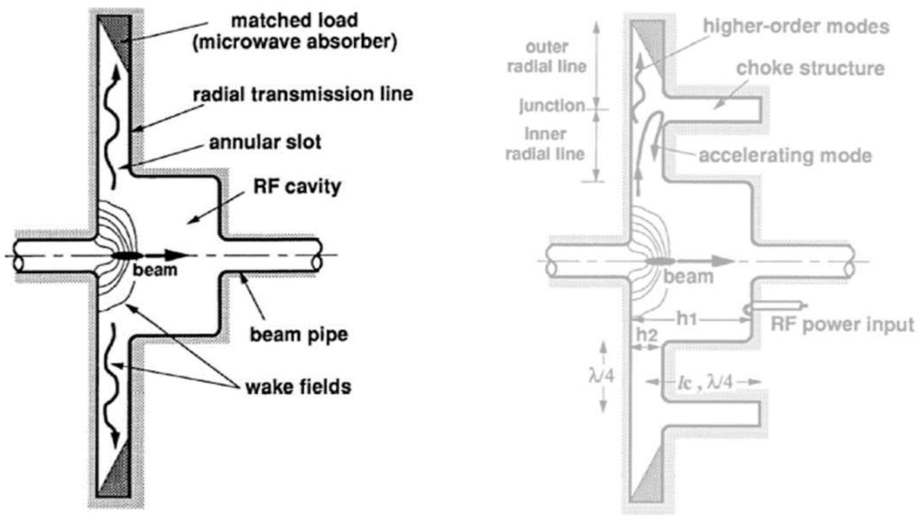
Adding a <u>Choke</u> in the Radial-Line to protect TM_{010} Mode

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

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

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

Acceleration Mode is only slightly reduced by additional metal loss.



(a) Radial Line Damper (b) Choke Mode Cavity

Sketch from T. Shintake, “The Choke Mode Cavity”, 1992.

Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

Structure and Principle of Operation

Cylindrically <u>Radial-Line</u> ending with a Damper on a Cavity

- All TM-Modes (and most TE-Modes) will excite the Radial-Line
- Only not critical TE_{0nq} can not excite the Radial-Line

All critical Modes are damped, but also acceleration Mode TM_{010}.

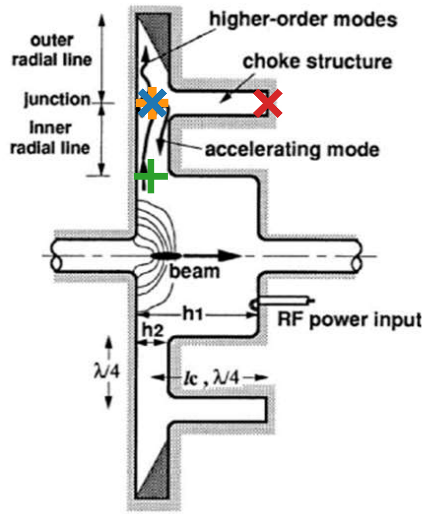
Adding a <u>Choke</u> in the Radial-Line to protect $\mathbf{TM_{010}}$ Mode

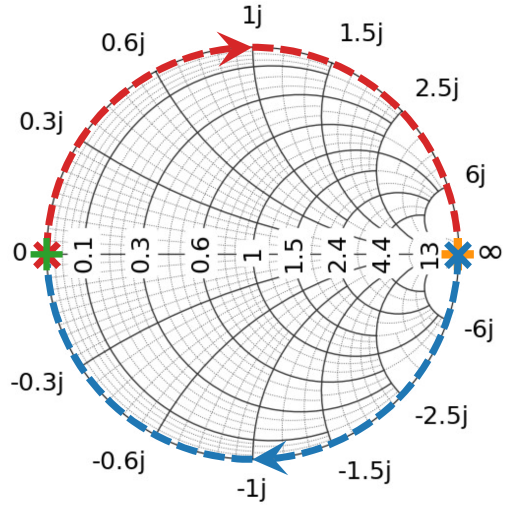
- The **Short** will be transformed by $\lambda/4$ into an **Open.**
- Serial junction added impedance $\boldsymbol{Z}_{\mathbf{choke}} = \infty$ and $\boldsymbol{Z}_{\mathbf{damper}}$

$$\boldsymbol{Z}_{\mathbf{junction}} = \boldsymbol{Z}_{\mathbf{choke}} + \boldsymbol{Z}_{\mathbf{damper}} = \infty \text{ (Open)}$$

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

Acceleration Mode is only slightly reduced by additional metal loss.





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

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Design of the Cavity-Body

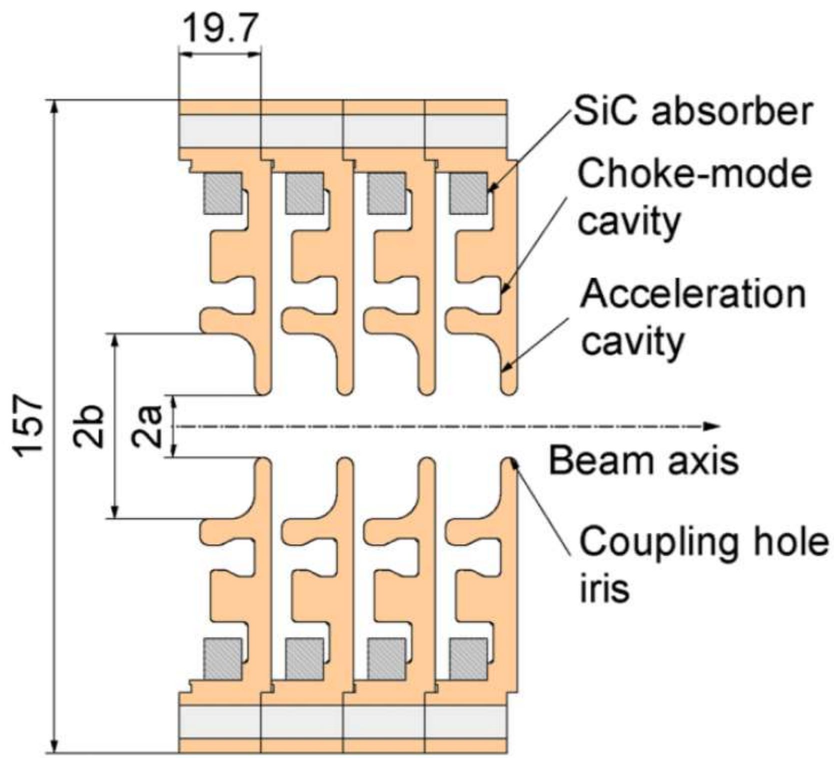
Selection of the Damping Material

- Adapted idea of single Ring of Siliziumcarbid (SiC) from *T. Inagaki et al., "High-gradient C-Band Linac for a Compact X-Ray Free-Electron Laser Facility", 2014.*
- Material parameters for RF-Simulations:
  - $\varepsilon_r = 20$
  - $\tan\delta_E = 0.25$

Real paras. vary along Fabrication, Frequency & Temperature.

Optimization of the TM_{010} Mode of the Cavity

- Rounding of the outer Cavity Edges:
  - Included on Top-Side: Reduces the Losses of the Cavity
  - Missing on Back-Side: Excitation of Radial-Line by all TM-Modes
- Noses are included:
  - At the Transitions of Cavity and Beam-Pipe
  - to increase the effective Shuntimpedance.
- Cavity Parameters:
  - $Q_0 = 19784$
  - $R_{\mathrm{sh,eff}} = 1.704\ \mathrm{M\Omega}$



Sketch from *T. Inagaki et al., "High-gradient C-Band Linac for a Compact X-Ray Free-Electron Laser Facility", 2014.*

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Design of the Cavity-Body

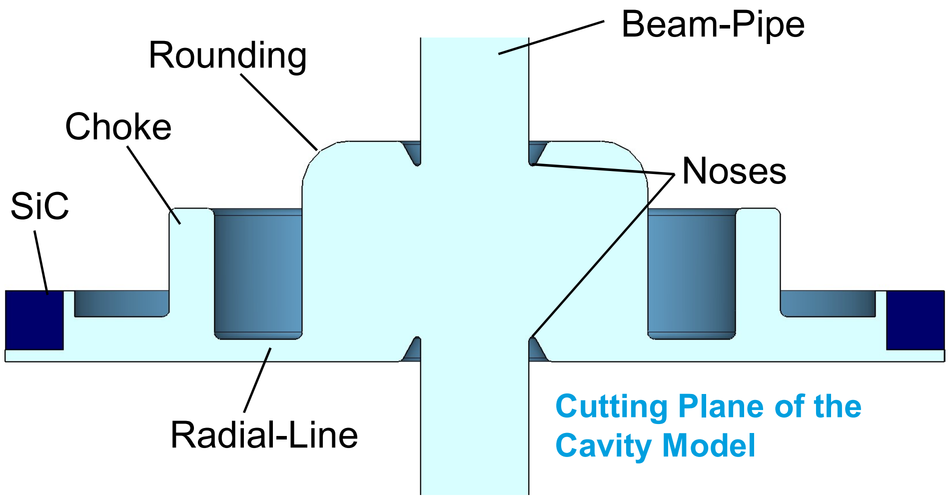
Selection of the Damping Material

- Adapted idea of single Ring of Siliziumcarbid (SiC) from
  T. Inagaki et al., "High-gradient C-Band Linac for a Compact X-Ray Free-Electron Laser Facility", 2014.
- Material parameters for RF-Simulations:
  - $\varepsilon_r = 20$
  - $\tan\delta_E = 0.25$

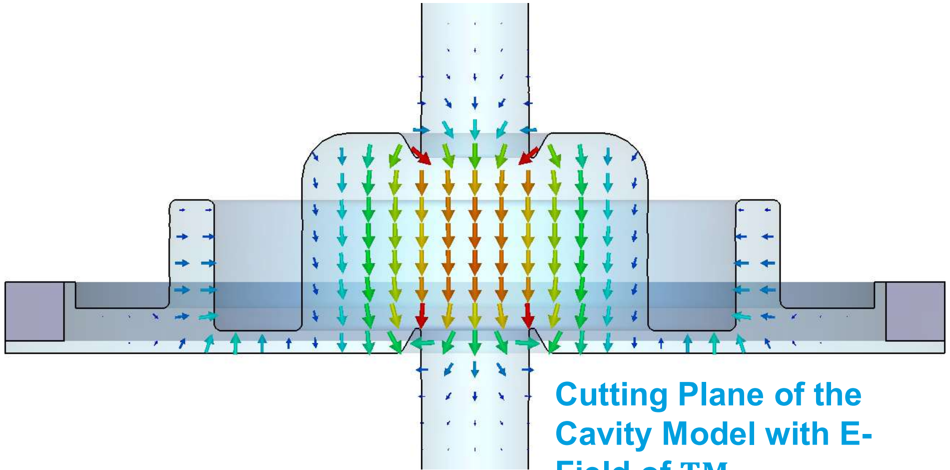
Real paras. vary along Fabrication, Frequency & Temperature.

Optimization of the TM_{010} Mode of the Cavity

- Rounding of the outer Cavity Edges:
  - Included on Top-Side: Reduces the Losses of the Cavity
  - Missing on Back-Side: Excitation of Radial-Line by all TM-Modes
- Noses are included:
  - At the Transitions of Cavity and Beam-Pipe
  - to increase the effective Shuntimpedance.
- Cavity Parameters:
  - $Q_0 = 19784$
  - $R_{\mathrm{sh,eff}} = 1.704\ \mathrm{M\Omega}$

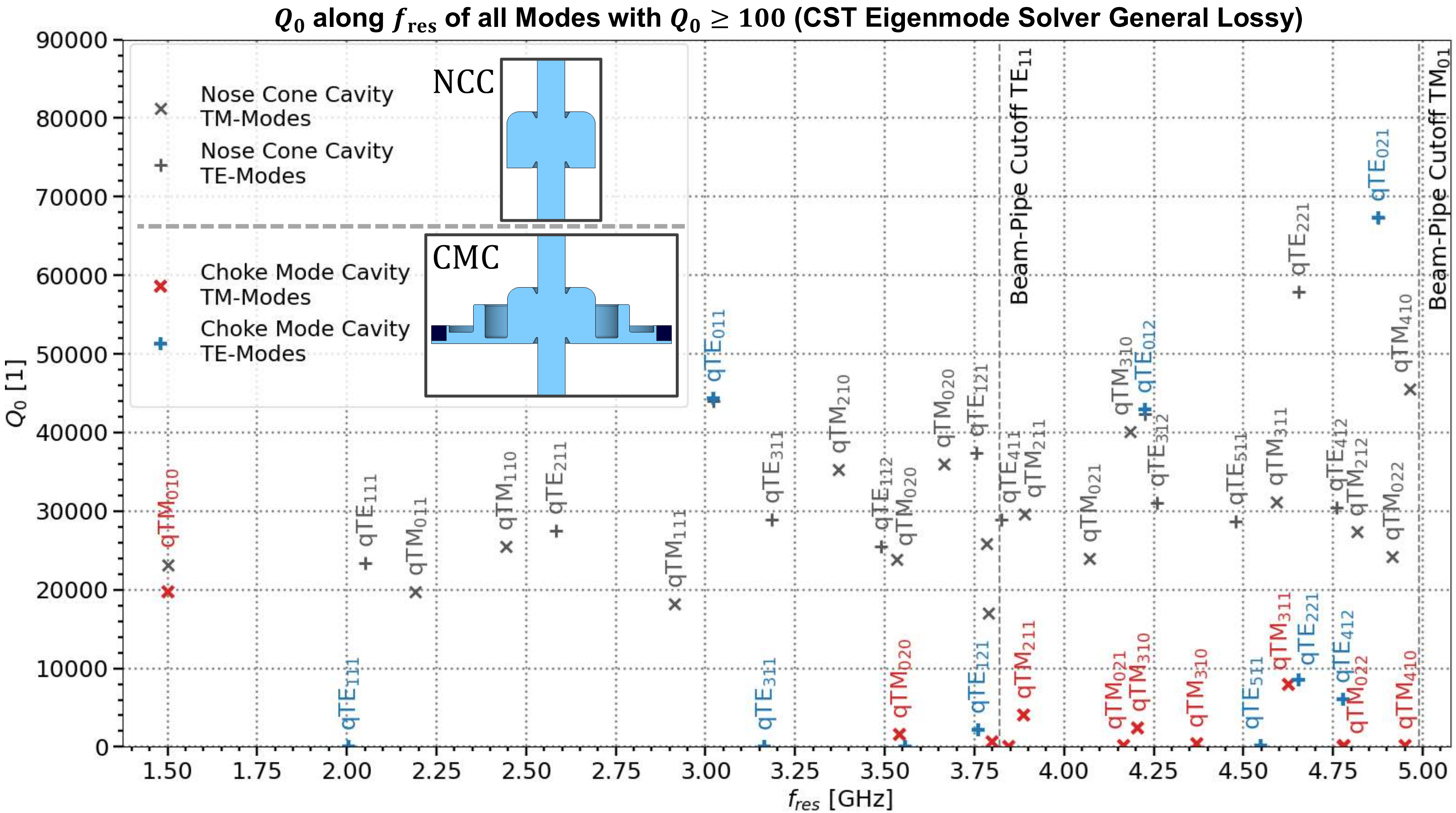


Cutting Plane of the Cavity Model


Cutting Plane of the Cavity Model with E-Field of TM_{010}

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Mode Overview of Nose-Coned Choke-Mode-Cavity by CST Eigenmode-Solver



Results

Protection of qTM_{010}

- $Q_0(\mathrm{NCC}) = 23157$
- $Q_0(\mathrm{CMC}) = \underline{19784}$
  85%

Damping of other qTM

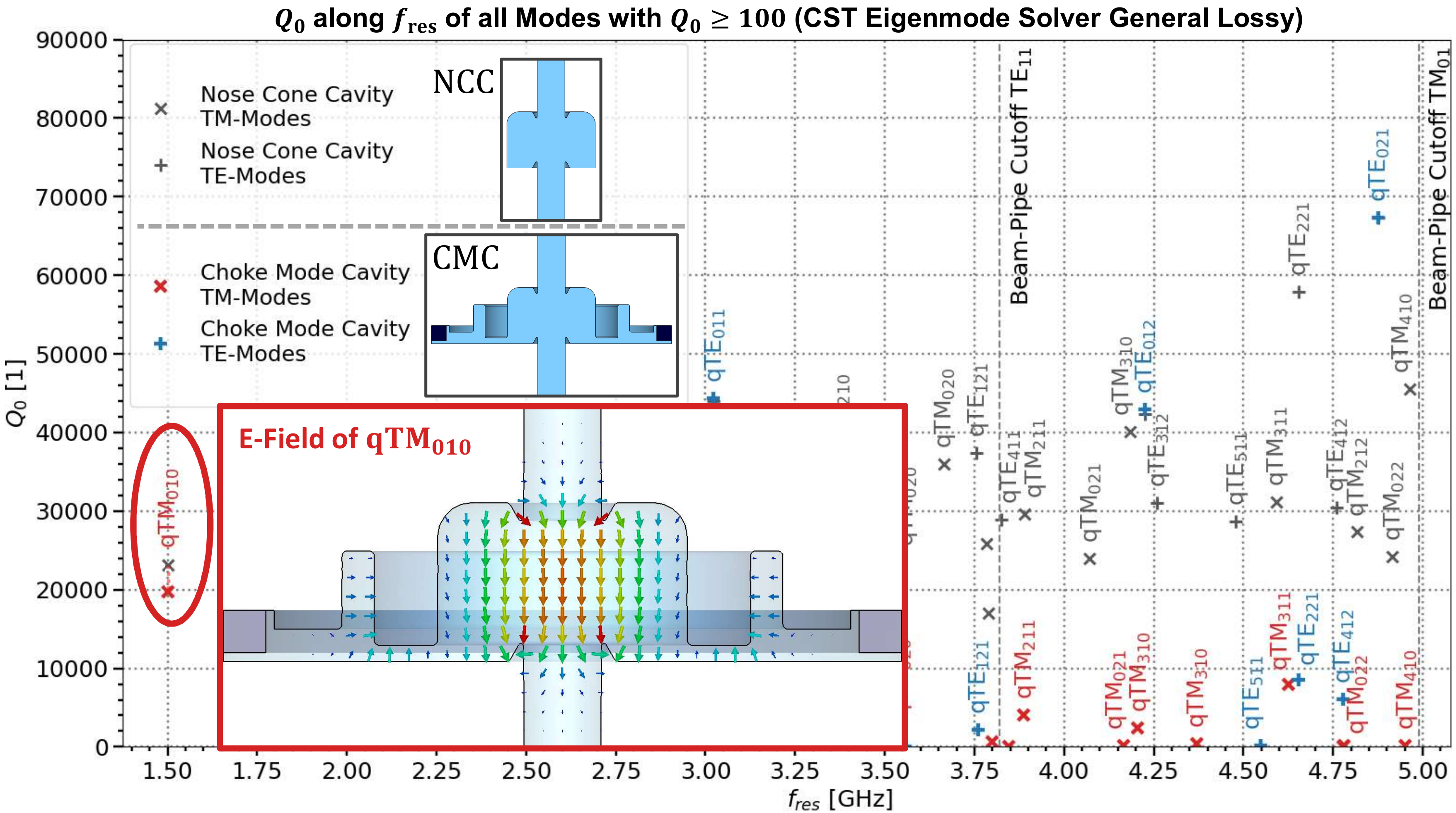
- Strongly reduced Q_0:
  $Q_0(\mathrm{qTM}_{011}) \approx 8$
  $Q_0(\mathrm{qTM}_{110}) \approx 17$
- Highest HOM-TM:
  $Q_0(\mathrm{qTM}_{311}) \approx 8000$
  with f_{res} next to Choke 3rd resonance
  $4.5\mathrm{GHz} = 3 \cdot 1.5\mathrm{GHz}$

Damping of qTE

- Only qTE_{0nq} are undamped, because can not excite Radial-Line
- But can never interact with the Bunch

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Mode Overview of Nose-Coned Choke-Mode-Cavity by CST Eigenmode-Solver



Results

Protection of qTM_{010}

- $Q_0(\text{NCC}) = 23157$
- $Q_0(\text{CMC}) = \underline{19784}$

  85%

Damping of other qTM

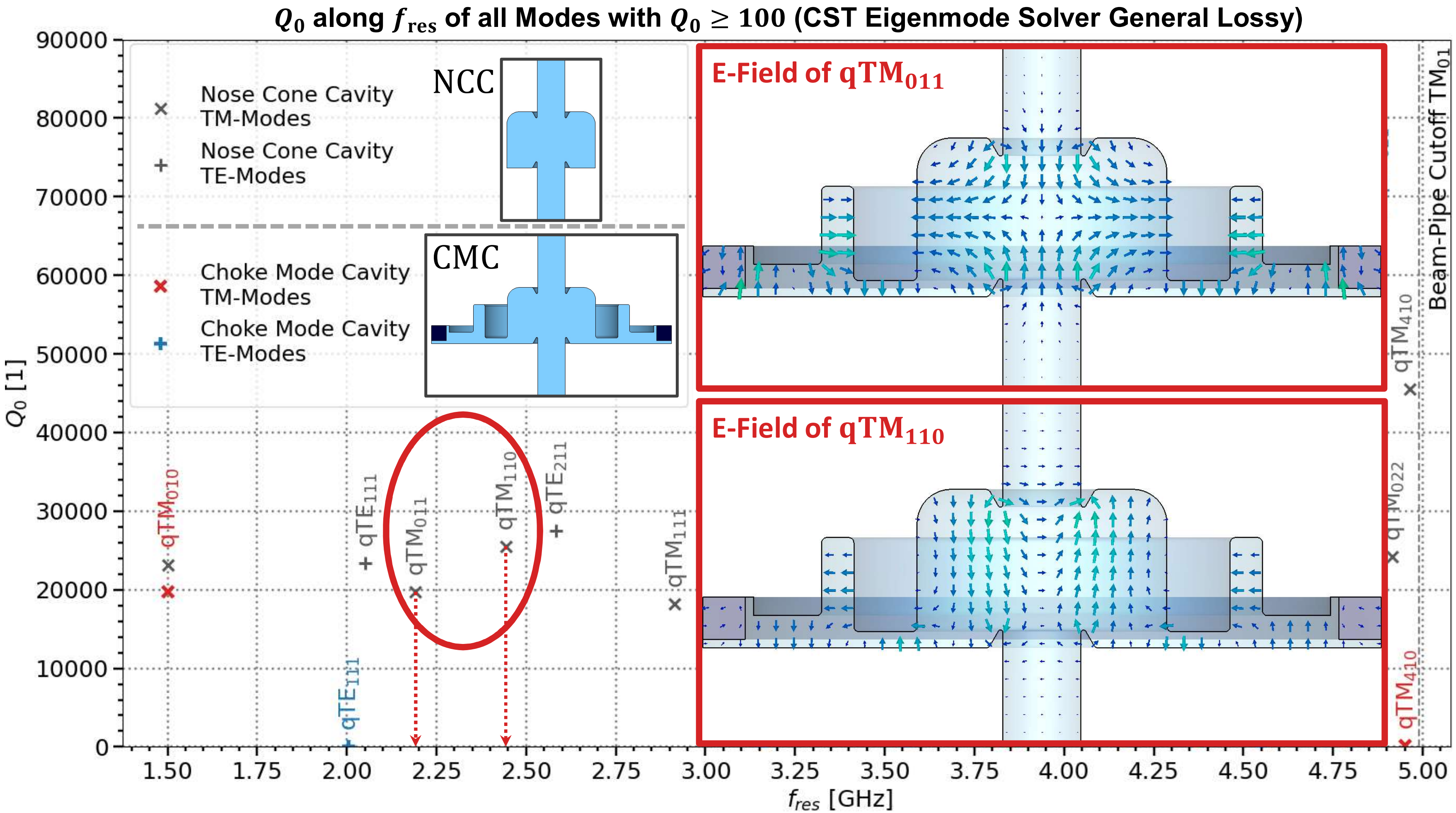
- Strongly reduced Q_0:
  $Q_0(qTM_{011}) \approx 8$
  $Q_0(qTM_{110}) \approx 17$
- Highest HOM-TM:
  $Q_0(qTM_{311}) \approx 8000$
  with f_{res} next to Choke 3rd resonance
  $4.5\text{GHz} = 3 \cdot 1.5\text{GHz}$

Damping of qTE

- Only qTE_{0nq} are undamped, because can not excite Radial-Line
- But can never interact with the Bunch

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Mode Overview of Nose-Coned Choke-Mode-Cavity by CST Eigenmode-Solver



Results

Protection of qTM_{010}

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

Damping of other qTM

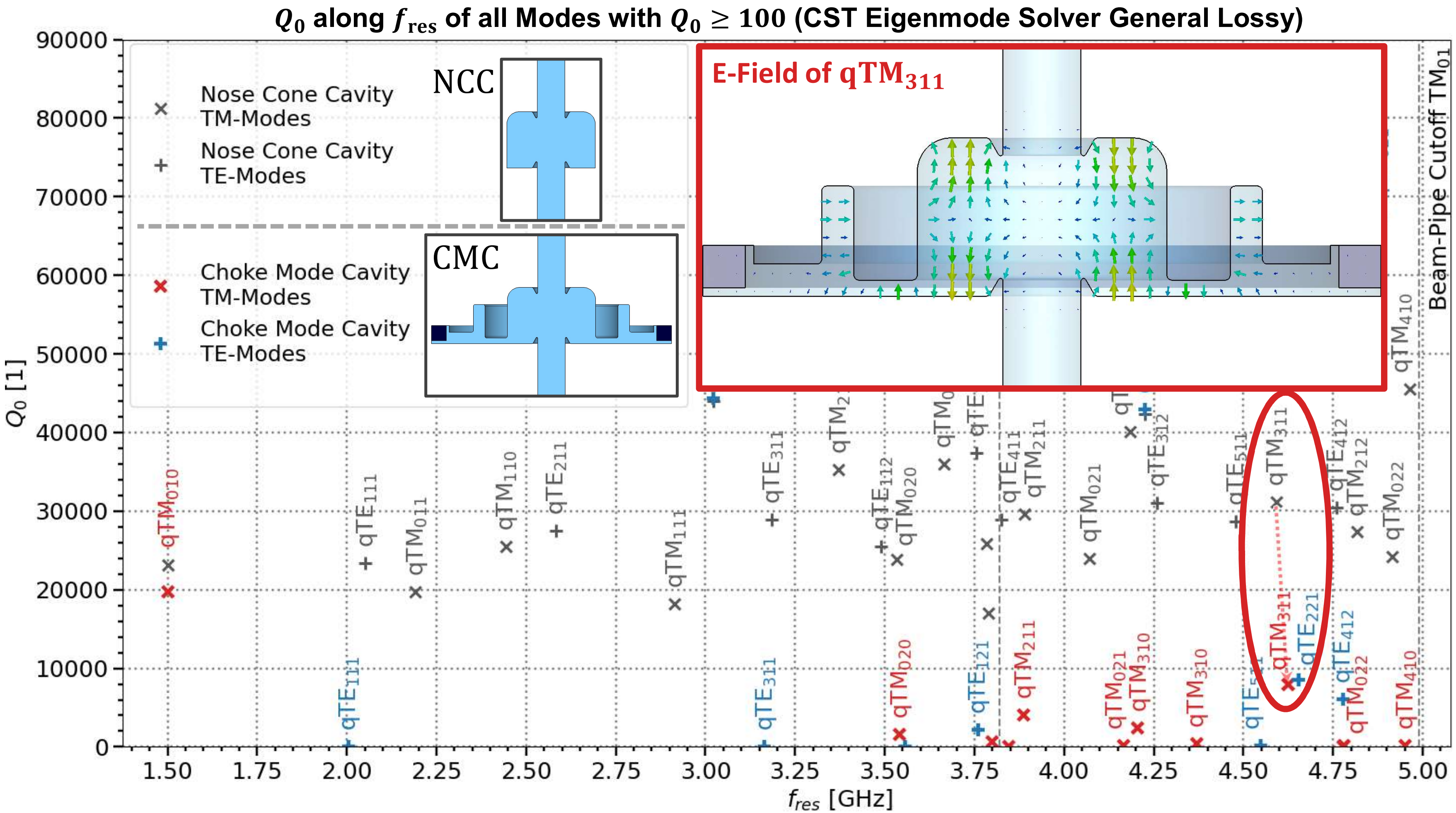
- Strongly reduced Q_0: $Q_0(qTM_{011}) \approx 8$ $Q_0(qTM_{110}) \approx 17$
- Highest HOM-TM: $Q_0(qTM_{311}) \approx 8000$ with f_{res} next to Choke 3rd resonance $4.5\mathrm{GHz} = 3 \cdot 1.5\mathrm{GHz}$

Damping of qTE

- Only qTE_{0nq} are undamped, because can not excite Radial-Line
- But can never interact with the Bunch

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Mode Overview of Nose-Coned Choke-Mode-Cavity by CST Eigenmode-Solver



Results

Protection of qTM_{010}

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

Damping of other qTM

- Strongly reduced Q_0:
  $Q_0(qTM_{01}) \approx 8$
  $Q_0(qTM_{110}) \approx 17$
- Highest HOM-TM:
  $Q_0(qTM_{311}) \approx 8000$
  with f_{res} next to
  Choke 3rd resonance
  $3 \cdot 1.5\ \text{GHz} = 4.5\ \text{GHz}$

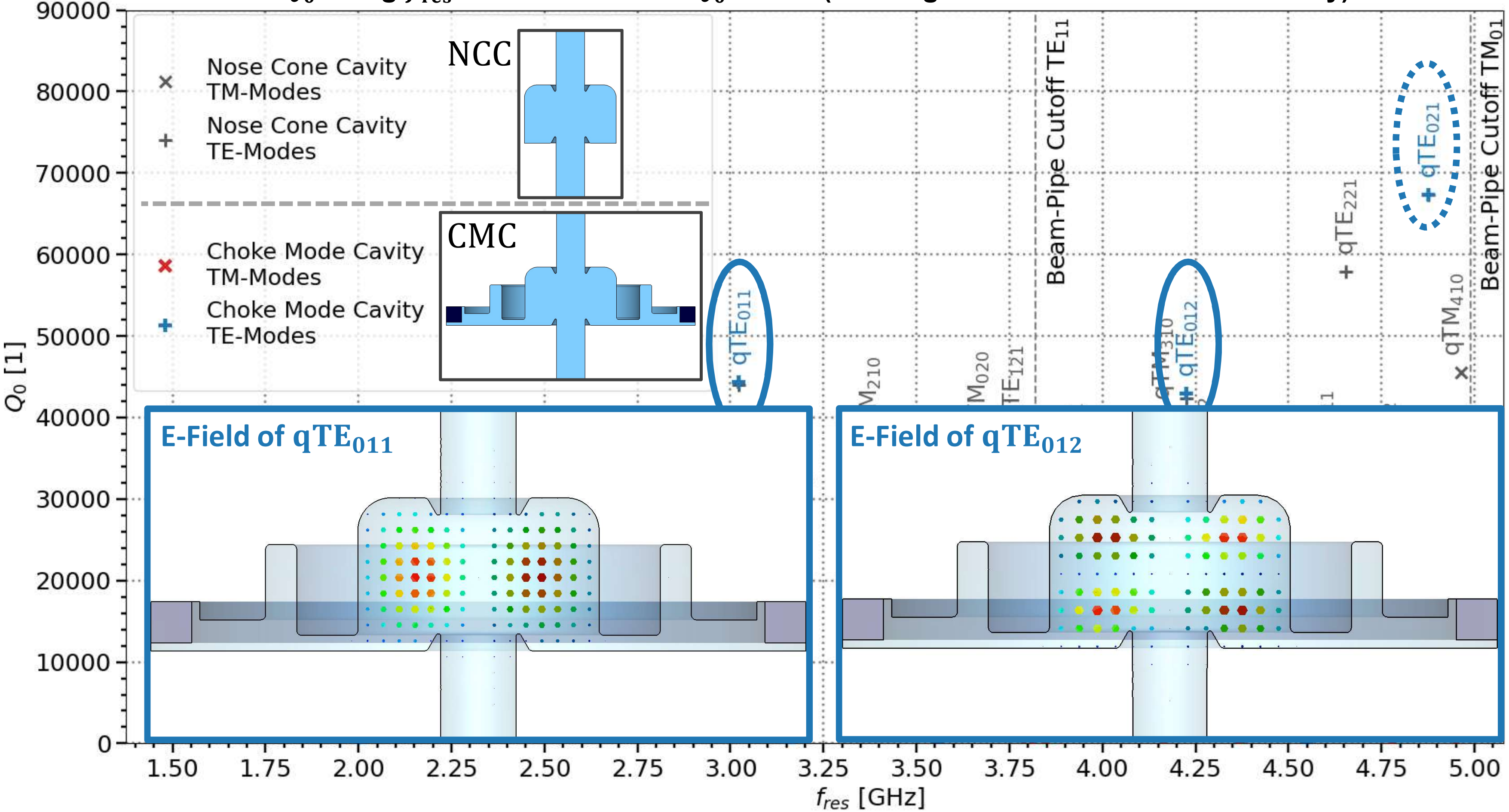
Damping of qTE

- Only qTE_{0nq} are undamped, because can not excite Radial-Line
- But can never interact with the Bunch

RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Mode Overview of Nose-Coned Choke-Mode-Cavity by CST Eigenmode-Solver

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



Results

Protection of qTM_{010}

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

Damping of other qTM

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

Damping of qTE

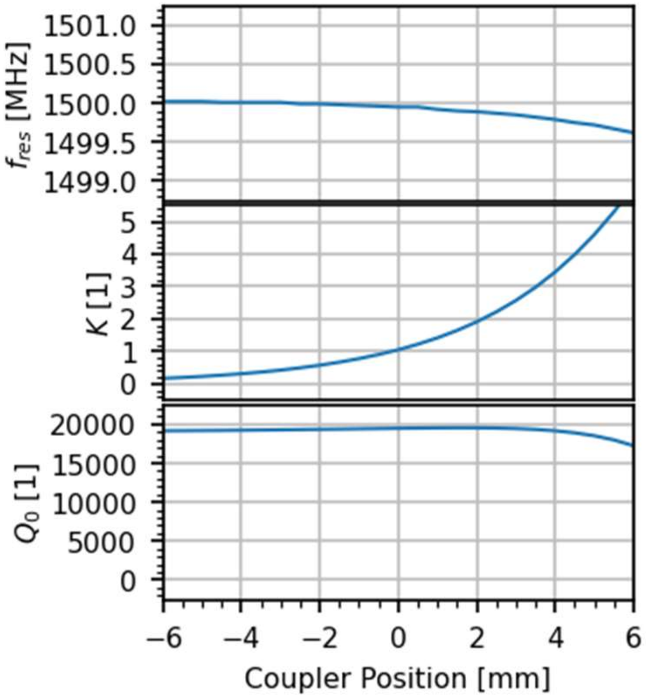
- Only qTE_{0nq} are undamped, because can not excite Radial-Line
- But can never interact with the Bunch

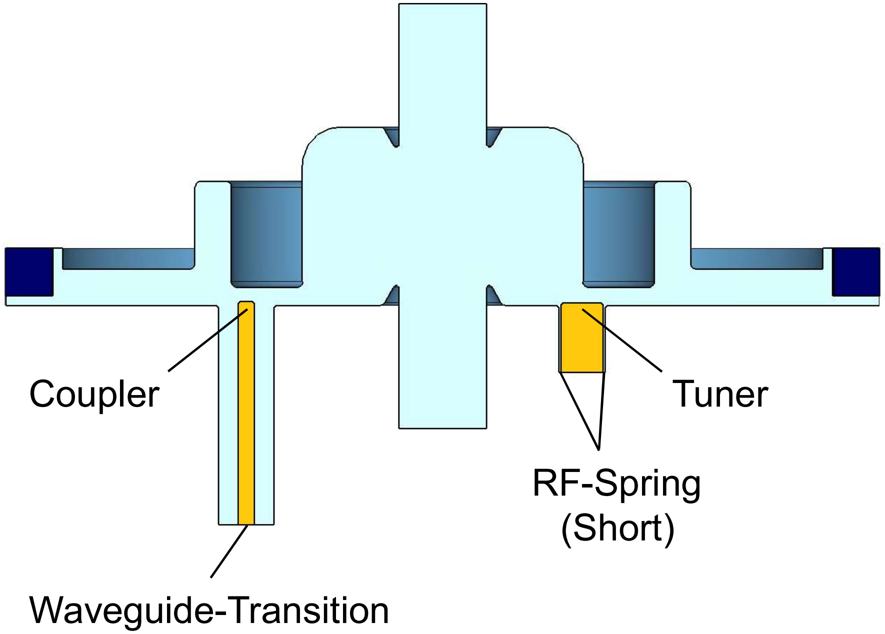
RF-Design of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

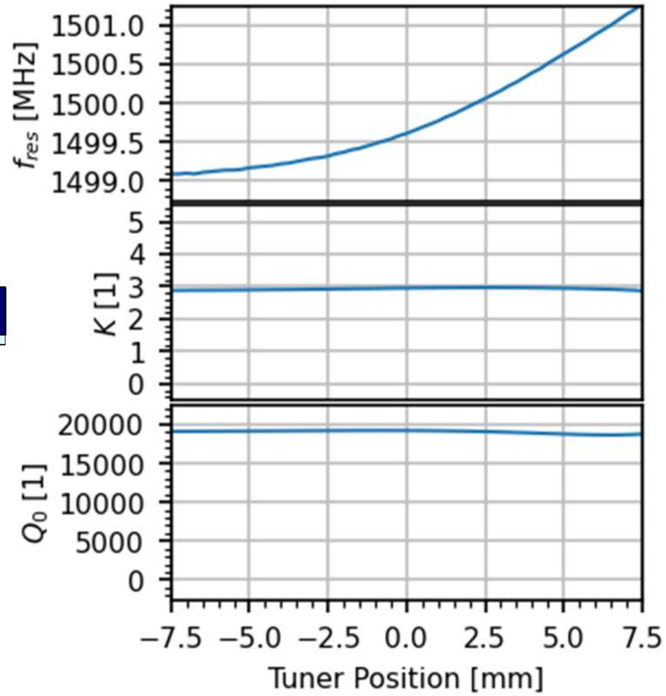
Coupler- and Tuner-System of the Nose-Coned Choke-Mode-Cavity

Coupler
- Capacitive Coupler in the Radial-Line
- Coaxial-Line 75Ω (Copper)
- Actively adjustable $K \approx 0.2 \text{ to } 5.0$

Tuner
- Capacitive Tuner in the Radial-Line (180° to Coupler)
- Coaxial-Line 10Ω (Copper)
- Tunable Resonant-Frequency $\Delta f_{\text{res}} \approx \pm 1.0 \text{ MHz}$







RF-Properties of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

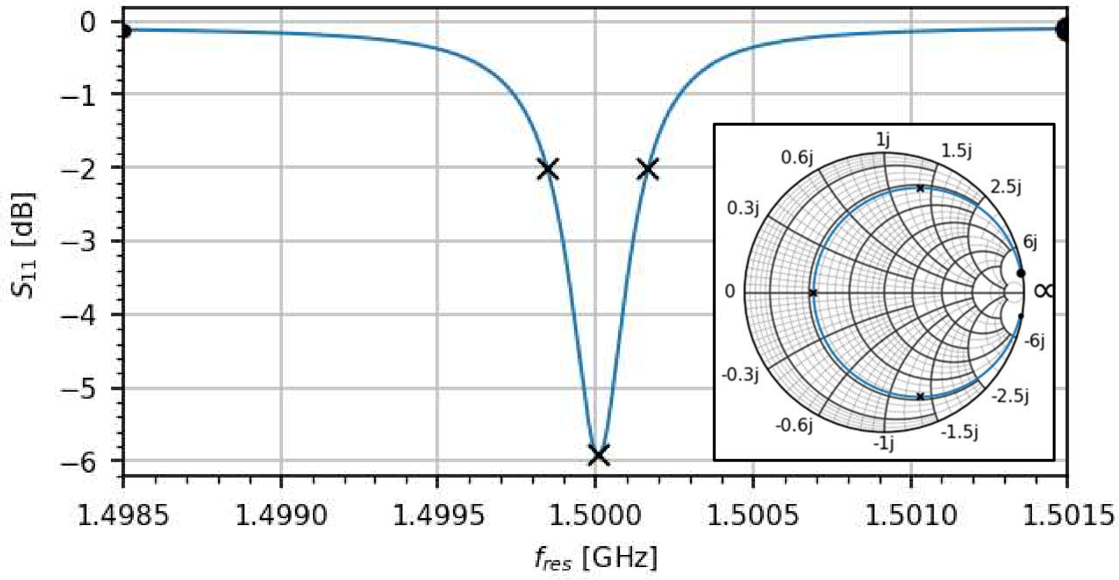
RF-Power for normal and doubled Gradient with $K = 3$ at $1.5\ \mathrm{GHz}$

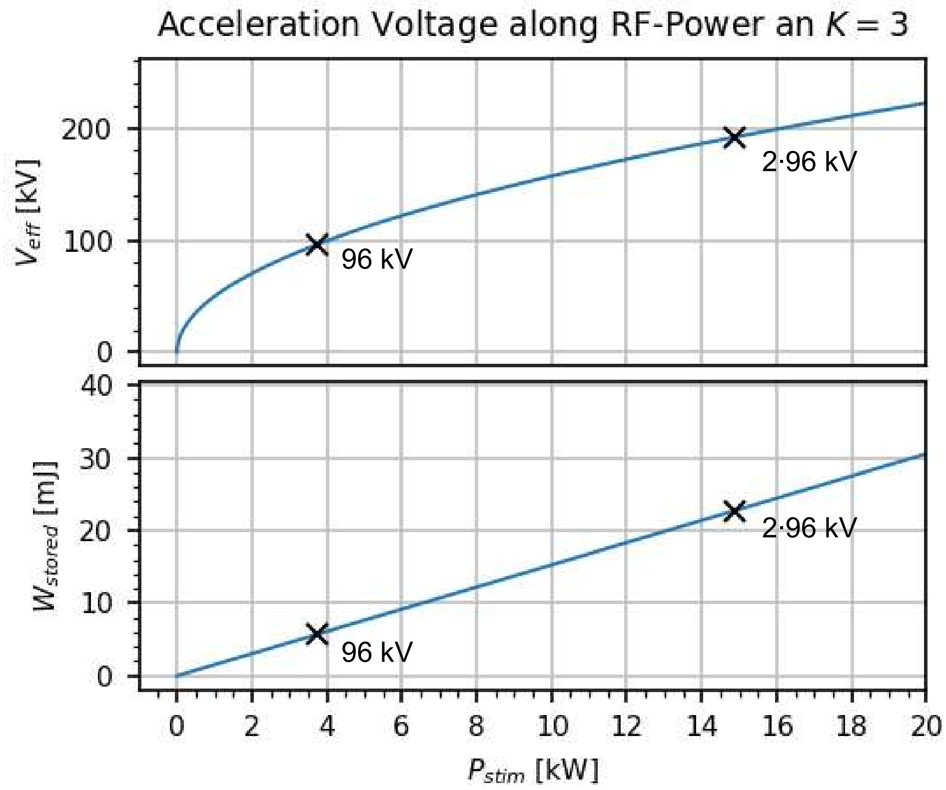
RF-Power for two Examples

- $V_{\mathrm{eff}} = 96\ \mathrm{kV}$ (norm Gradient)
- $V_{\mathrm{eff}} = 2 \cdot 96\ \mathrm{kV} = 192\ \mathrm{kV}$ (doubled Gradient)

Coupler & Tuner positioned for

- $f_{\mathrm{res}} = 1.5\ \mathrm{GHz}$
- $K = 3$



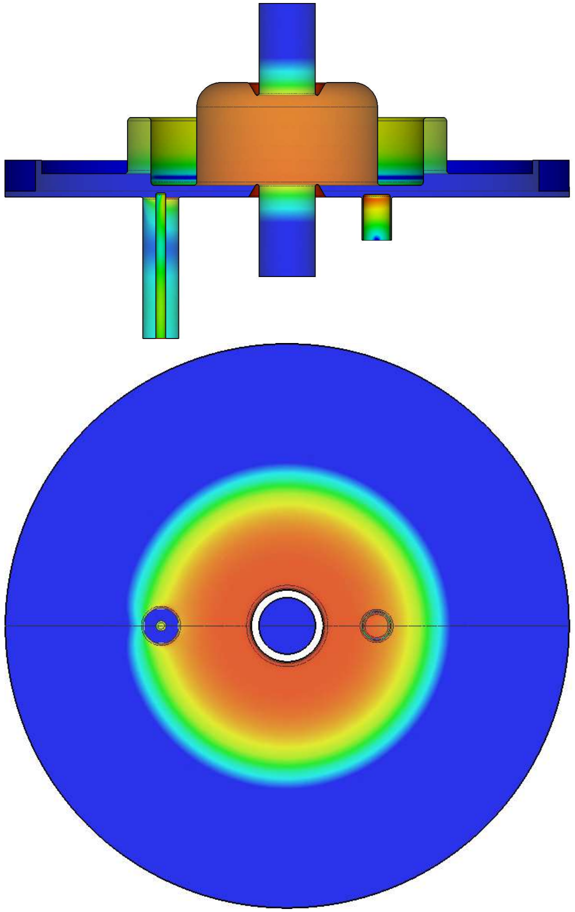


V_{eff}	P_{stim}	W_{stored}
96 kV	3722 W	5.688 mJ
2·96 kV = 192 kV	14.89 kW	22.75 mJ

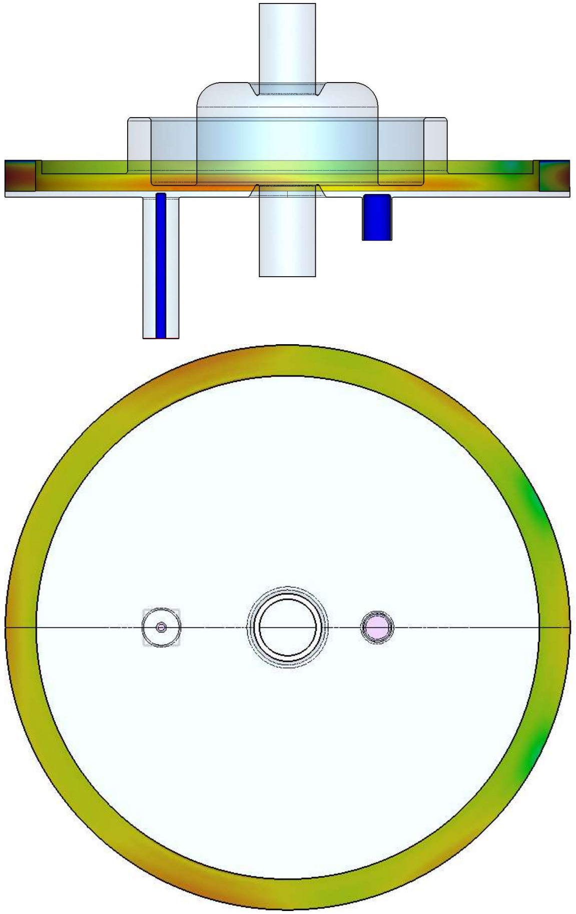
RF-Properties of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Power-Loss Distribution with $K = 3$ at $1.5\ \mathrm{GHz}$

Surface Power Loss Dens (Metal Loss) logarithm

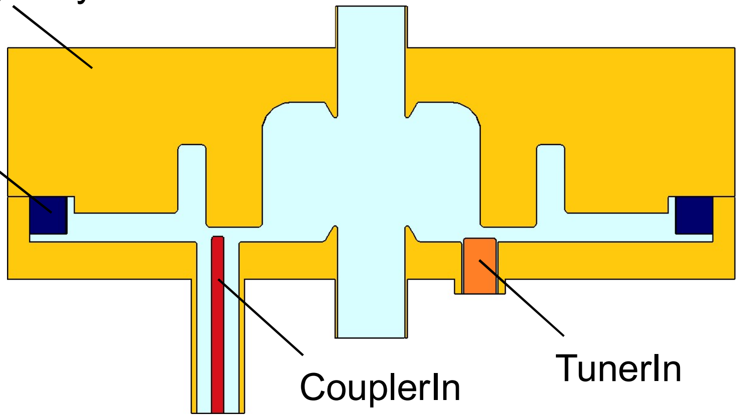


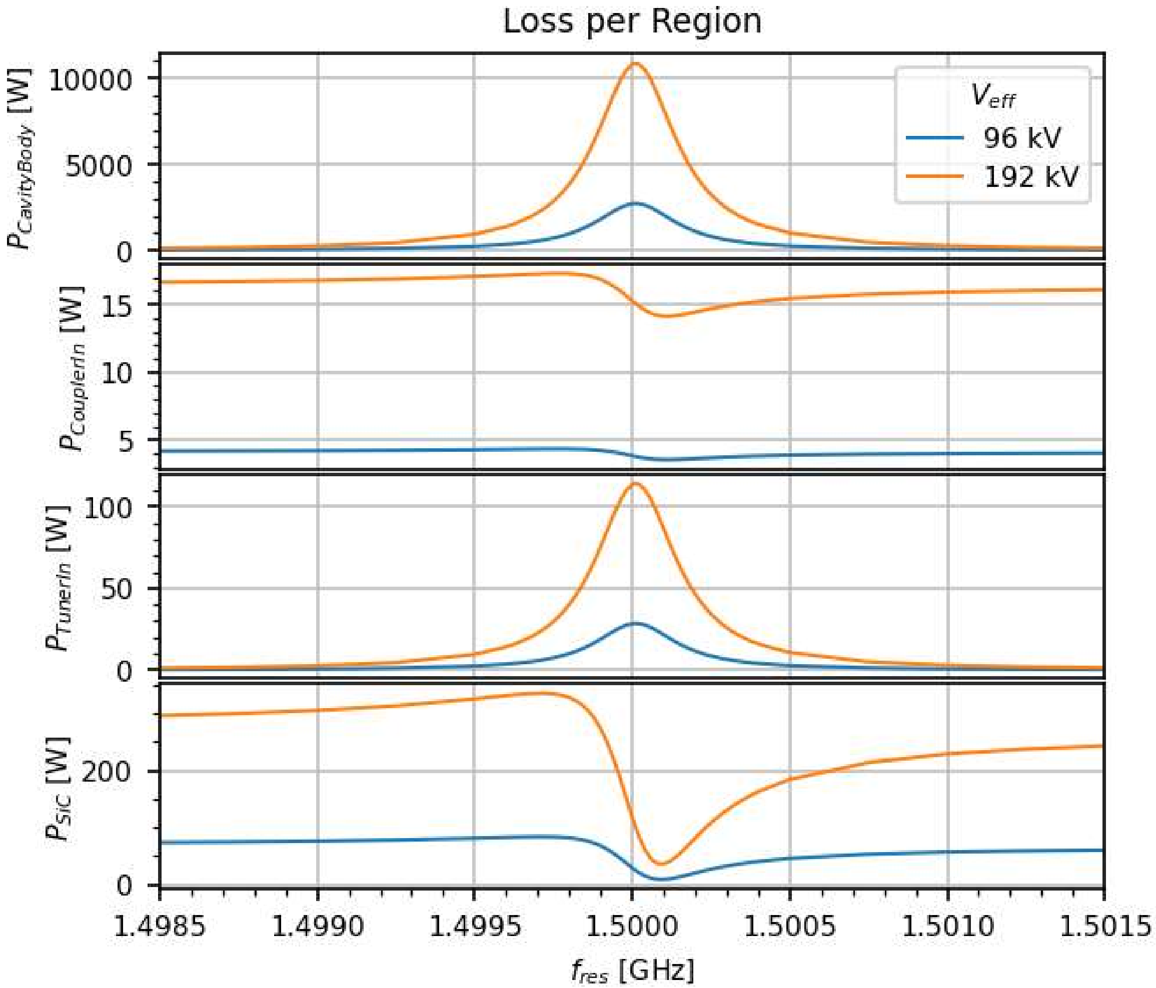
Power Loss Dens (Dielectric Loss.) logarithm



RF-Properties of an One Cell 'Choke-Mode-Cavity' for 1.5 GHz

Power-Loss in Copper-Regions and Siliziumcarbid (SiC) with $K = 3$ at $1.5\ \mathrm{GHz}$





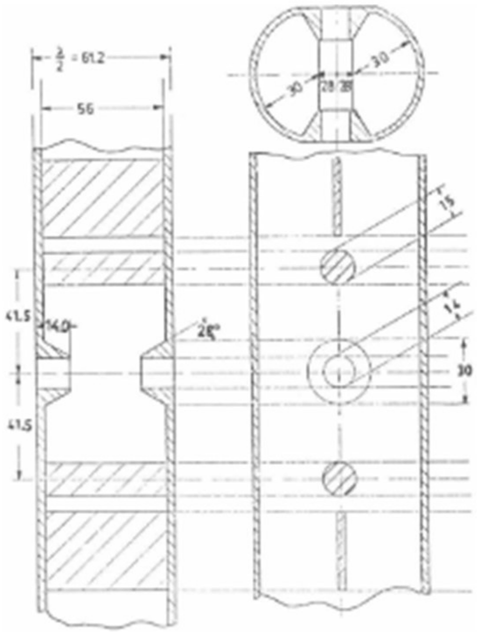
Values at f_{res}	$V_{eff} = 96\ \mathrm{kV}$	$V_{eff} = 192\ \mathrm{kV}$
P_{stim}	3722 W	14.89 kW
W_{stored}	5.388 mJ	22.75 mJ
$P_{CavityBody}$	2.71 kW	10.9 kW
$P_{CouplerIn}$	3.77 W	15.1 W
$P_{TunerIn}$	28.6 W	114 W
P_{SiC}	25.6 W	103 W

Appendix

Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

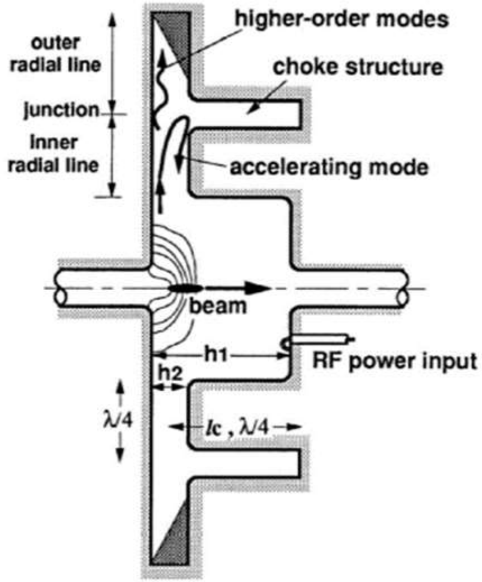
Examples of HOM-Damping Cavities Concepts

Not Pill-Box like Cavity an Resonance-Point (accel. by TE_{111}) in a single Waveguide



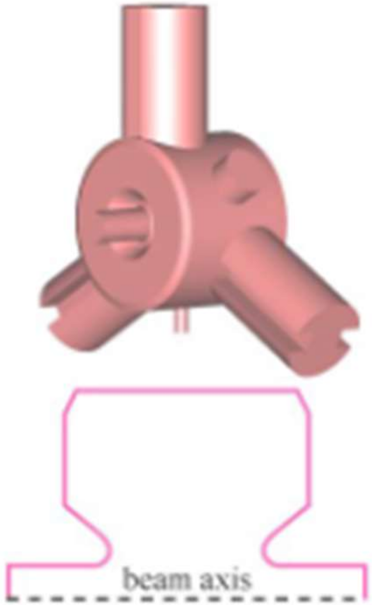
H. Herminghaus, H. Euteneuer “Beam Blowup in Race Track Microtrons”, 1979

Pill-Box like Cavity (accel. by TM_{010}) with Radial-Line-Damper for HOM-Damping



T. Shintake, “The Choke Mode Cavity”, 1992.

Pill-Box like Cavity (accel. by TM_{010}) with three Waveguides for HOM-Damping

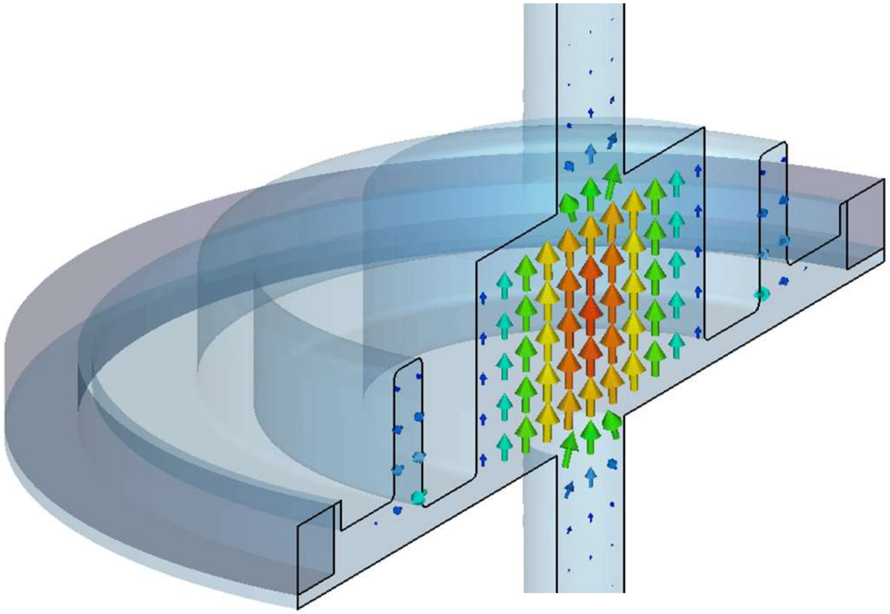


F. Marhauser, E. Weihreter “HOM Damped 500 MHz Cavity Design for 3rd Generation SR Sources”, 2001

Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

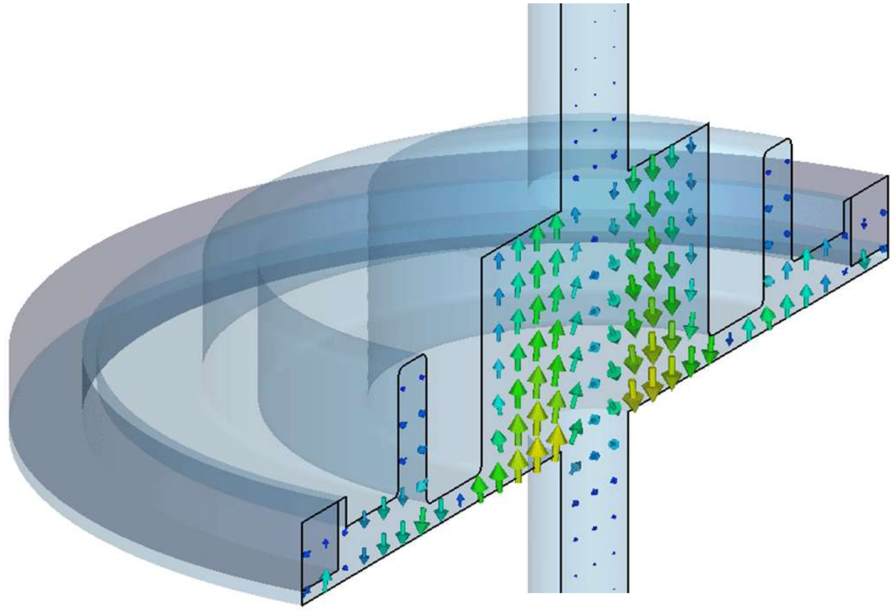
E-Field Pattern of exemplary Modes TM_{010} & TM_{110} of a Choke Mode Cavity for 1.5 GHz

E-Field of TM_{010}



f_{res}	1.500 GHz	
Q_0	20456	85% of 24150

E-Field of TM_{110}

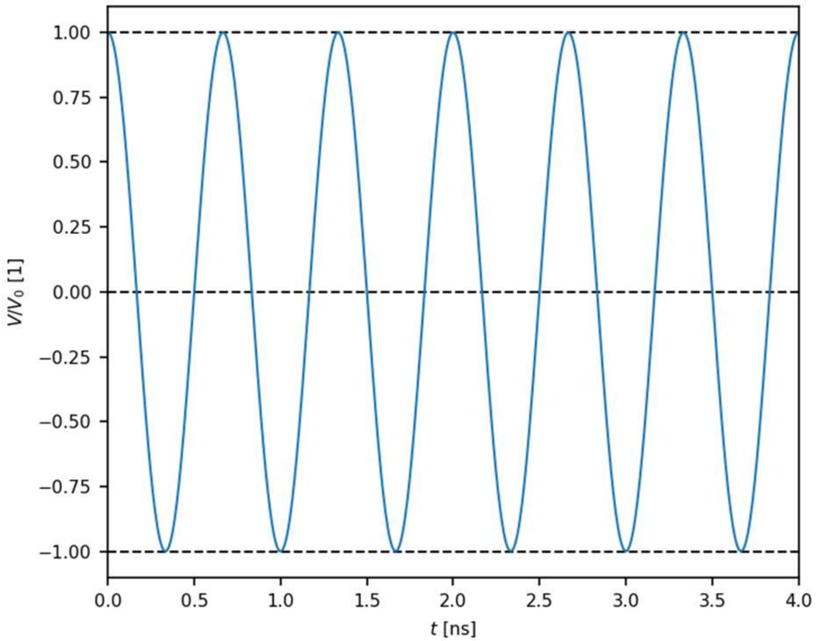


f_{res}	2.229 GHz
Q_0	14

Principle of the 'Choke-Mode-Cavity' of T. Shintake in 1992

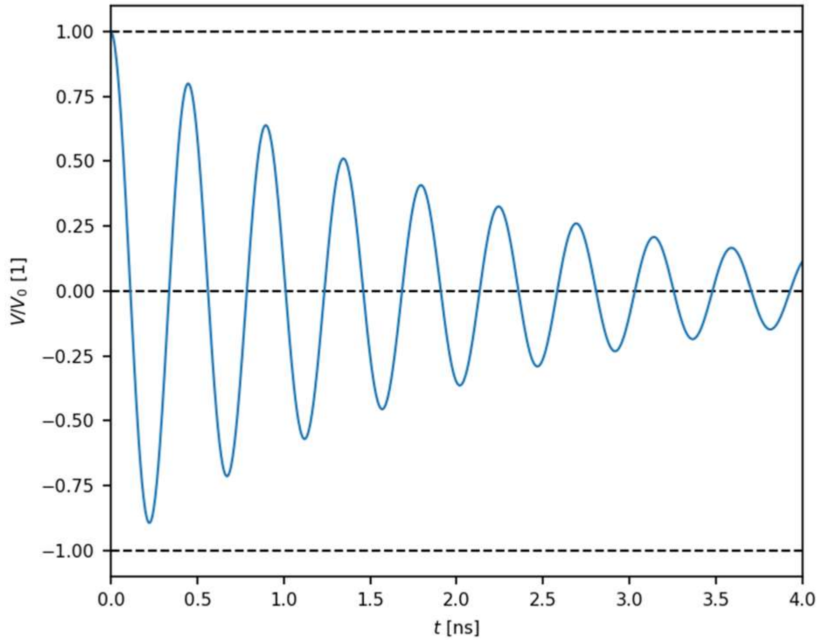
E-Field Pattern of exemplary Modes TM_{010} & TM_{110} of a Choke Mode Cavity for 1.5 GHz

E-Field of TM_{010}



f_{res}	1.500 GHz	
Q_0	20456	85% of 24150

E-Field of TM_{110}



f_{res}	2.228 GHz
Q_0	14