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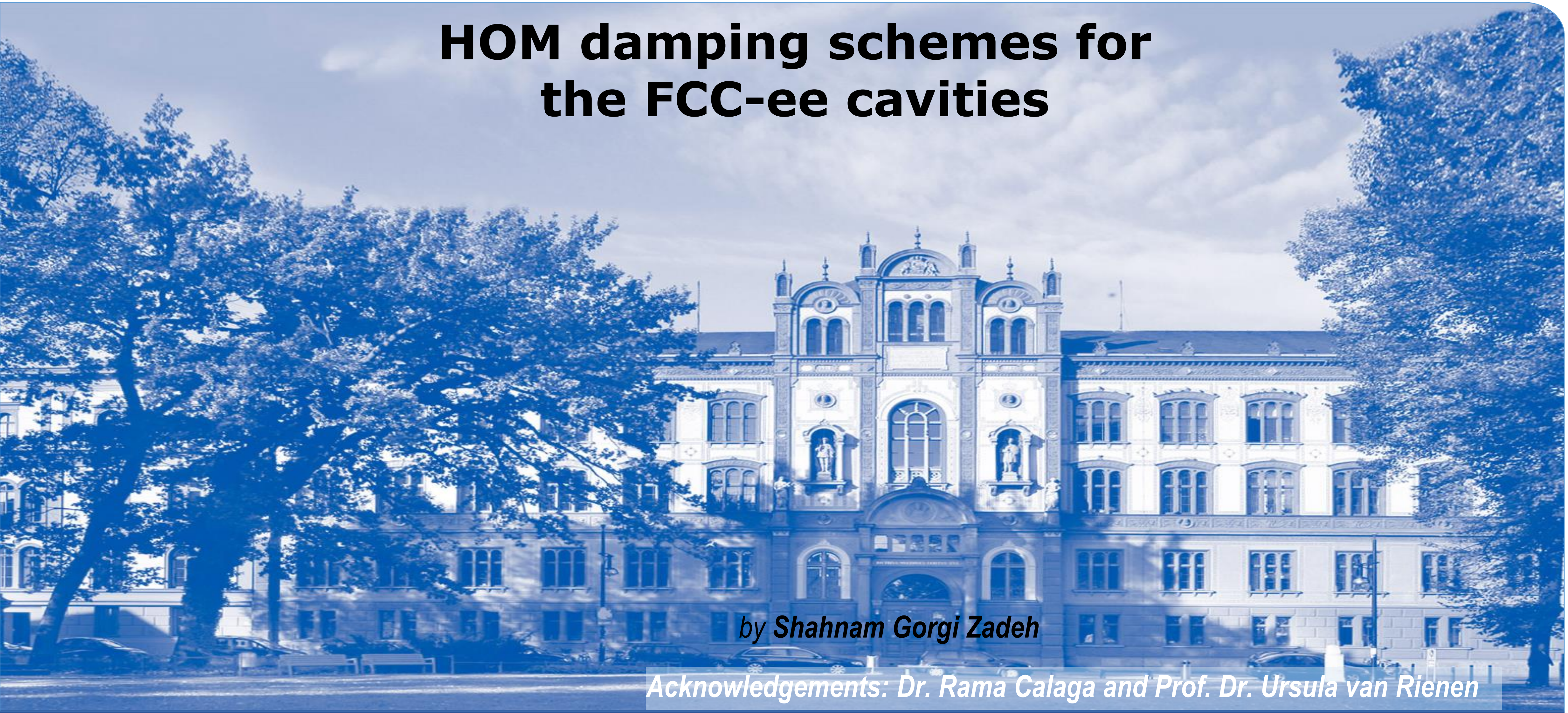
Traditio et Innovatio



HOM damping schemes for the FCC-ee cavities

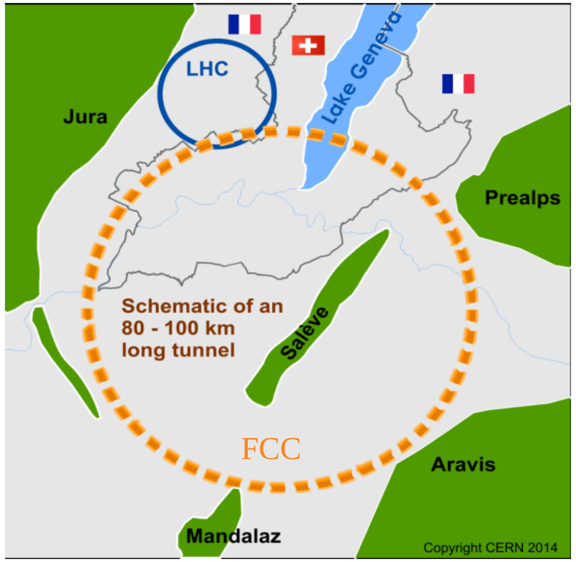
*by **Shahnam Gorgi Zadeh***

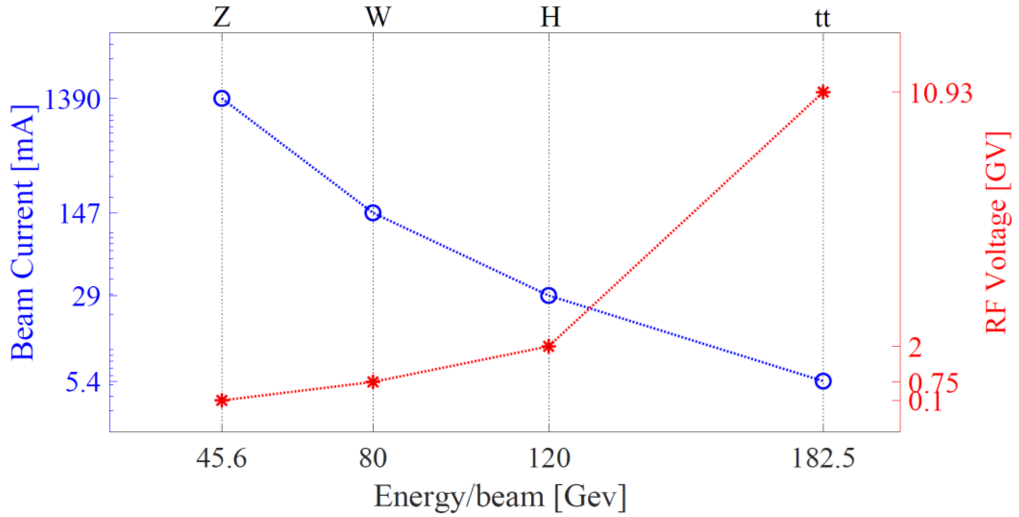
Acknowledgements: Dr. Rama Calaga and Prof. Dr. Ursula van Rienen

RF Parameters of FCC-ee

FCC-ee is a circular lepton collider designed to study four particles, i.e. Z, W, H and $t\bar{t}$

- Beam energies of FCC-ee range from 45.6 to 182.5 GeV
- The collider will be housed in a tunnel with around 100 km circumference
- The maximum synchrotron radiation loss is fixed to 50 MW/beam for each energy, thus the beam current is smaller at higher energy
- The FCC-ee machines could be divided into high current (Z, W) and high energy (H, $t\bar{t}$) setups, each case optimally demands a different cavity design approach





	FCC-Z	FCC-W	FCC-H	FCC-$t\bar{t}$	LEP2
Energy/beam [GeV]	45.6	80	120	182.5	105
Energy Loss/turn [GeV]	0.036	0.34	1.72	9.21	3.34
RF Voltage/beam [GV]	0.1	0.75	2.0	10.93	3.5
Beam Current [mA]	1390	147	29	5.4	3
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55	0.0012

FCC-ee Present Baseline

- Due to high HOM power and high input power per cavity, singe cell Nb/CU at 400 MHz is considered for the Z option
- Multi-cell cavity is considered for the W, H and $t\bar{t}$ options
  - ➢ 4-cell Nb/CU cavity at 400 MHz for the W and H
  - ➢ 4-cell Nb/CU cavity at 400 MHz + 5-cell Bulk Nb. cavity at 800 MHz for $t\bar{t}$ (present baseline)

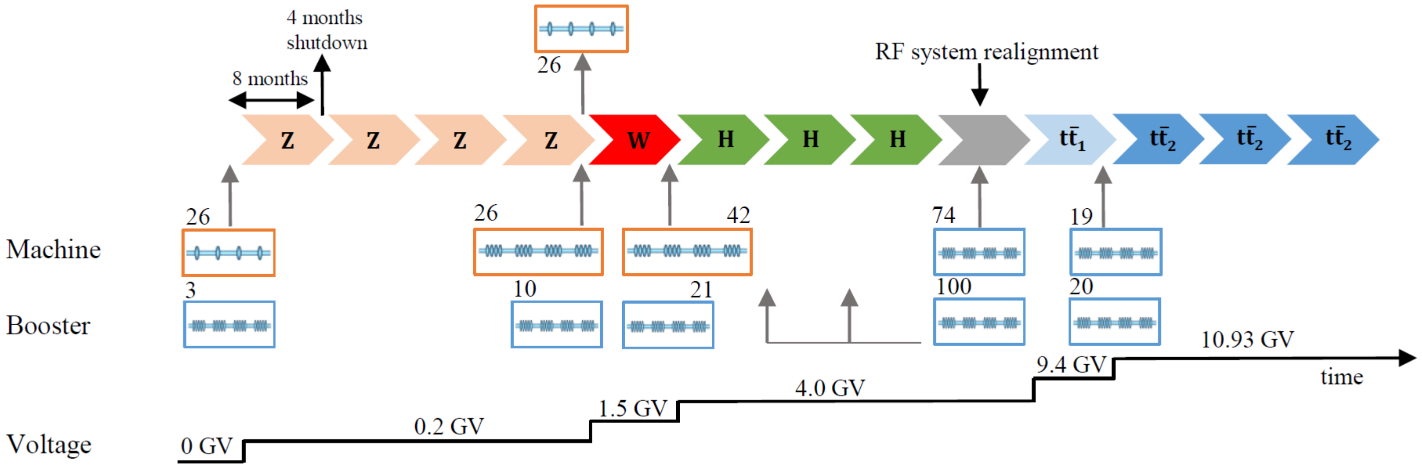


Figure adapted from: Andy Butterworth, "Options for the FCC Superconducting RF System", FCC week 2018, Amsterdam 2018

	Z	W	H	$t\bar{t}$	
Total beam voltage [GV]	0.1	0.75	2.0	10.93	
Beam Voltage [GV]	0.1	0.75	2.0	4.0	6.93
f [MHz]	400.79	400.79	400.79	400.79	801.58
No. cells / cavity	1	4	4	4	5
No. cavities[a]	52 × 2	52 × 2	136 × 2	272	372
No. cryomodules[a]	13 × 2	13 × 2	34 × 2	68	93
E_{acc} [MV/m]	5.1	9.6	9.8	9.8	19.9
P_{in} [kW]	962	962	367	150	158
Q_{L-opt} [10^6]	0.046	0.53	1.44	3.51	4.23
Δf_{opt} [kHz]	-11.2	-0.75	-0.08	-0.02	-0.075
P_{HOM} (SR/BS) [kW]	8.25/3.04	5.09/2.89	1.16/0.76	0.81/0.66	1.09/0.89
T Operation [K]	4.5	4.5	4.5	4.5	2.0
Material	Nb/Cu	Nb/Cu	Nb/Cu	Nb/Cu	Nb
P_{static} [kW]	0.87×2	1.39×2	3.64×2	7.28	3.96
$P_{dynamic}$ [kW]	0.74×2	9.31×2	25.51×2	51.03	28.29
P_{wp} [MW]	0.35×2	2.34×2	6.38×2	12.76	24.02

Mid-cell Optimization (I)

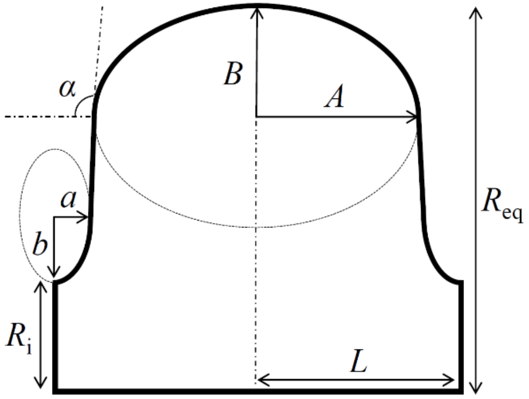
- In Multi-cell cavity optimization, the design of mid-cells and end-cells can be separated
- A Mid-cell is designed at 400.79 MHz and rescaled to 801.58 MHz for $t\bar{t}$ operation
- Minimizing the intrinsic cavity losses can save considerable energy on large scale for huge machines such as FCC_ee$t\bar{t}$
- Optimization problem of mid-cell can be formulated as:

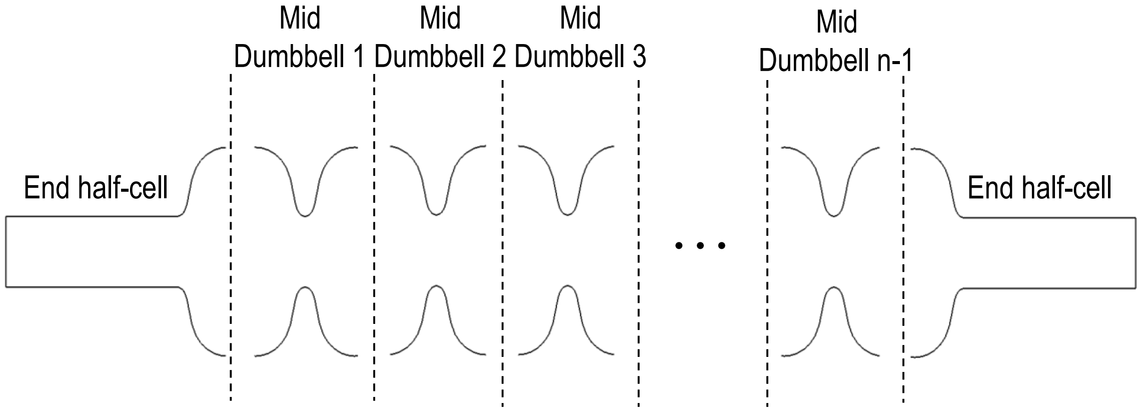
$$\max_{A,B,a,b} \; G \cdot R/Q$$

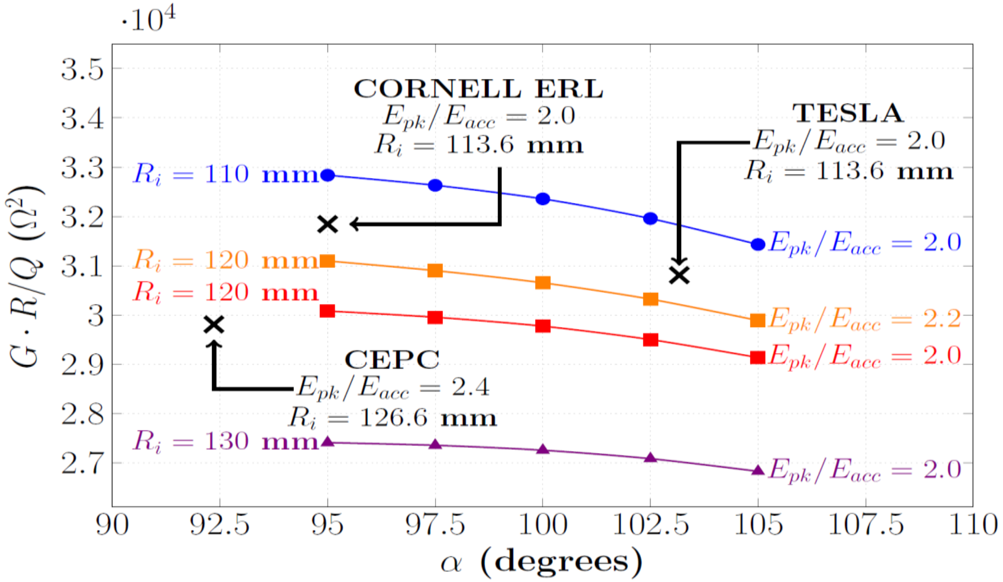
$$\text{s.t.} \;\; E_{pk}/E_{acc} \leq c_1$$

$$\alpha \geq c_2$$

$$R_i = c_3$$





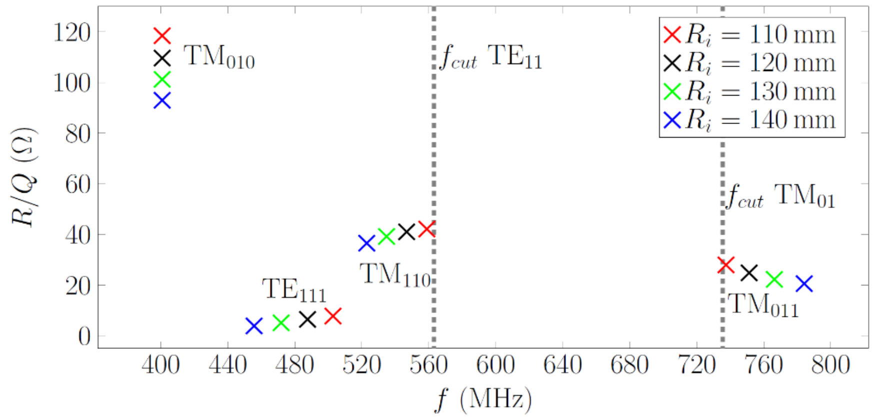


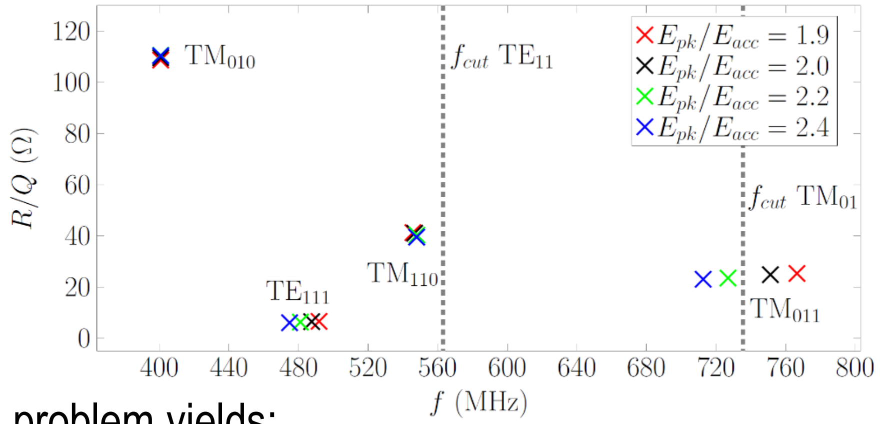
× *All radii are scaled to 400.79 MHZ.*

Mid-cell Optimization (II)

In selecting the constraints, the following points should be taken into account:

- High value of R/Q for the fundamental mode
- Sufficient distance between the frequency of the fundamental mode and the frequency of the first dipole mode
- The distance between the frequency of TE_{111} and TM_{110} should be minimal to have less constraints on the HOM coupler design
- A small value of E_{peak}/E_{acc} lowers the danger of field emission and helps to untrap the TM_{011} mode





× *Cut-off frequency is for a beam-pipe radius of 156 mm*

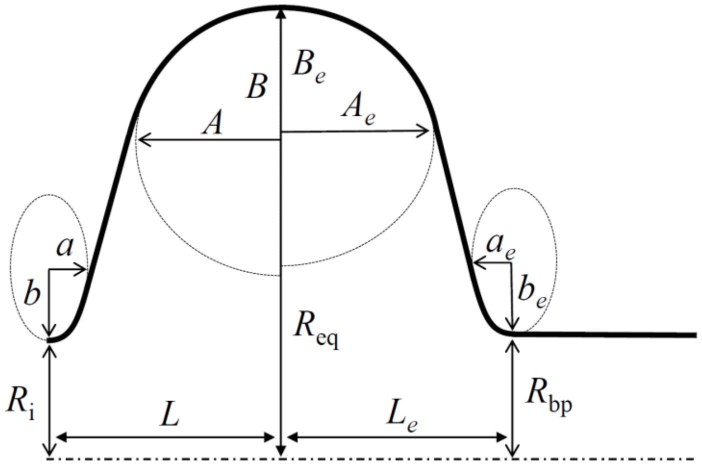
Selecting $R_i = 120\ mm$, $\alpha = 100$ and $E_{peak}/E_{acc} = 2.0$ in the optimization problem yields:

f [MHz]	A [mm]	B [mm]	a [mm]	b [mm]	R_i [mm]	R_{eq} [mm]	L [mm]	α [º]	E_{pk}/E_{acc} –	B_{pk}/E_{acc} $[\frac{mT}{MV/m}]$	R/Q [Ω]	G [Ω]	k [%]
400.79	135.44	114.90	43.50	71.19	120	333.182	187	100	2.0	4.2	109.5	272	2.25

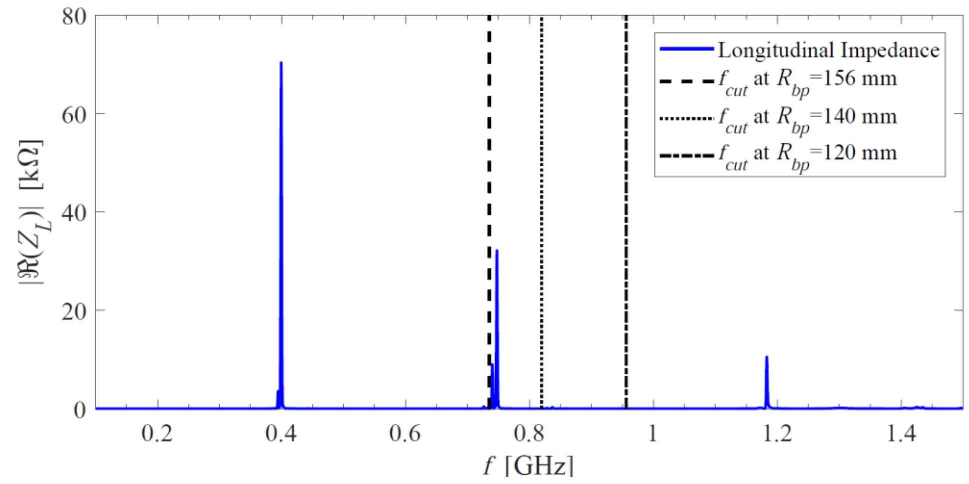
End-cell Optimization

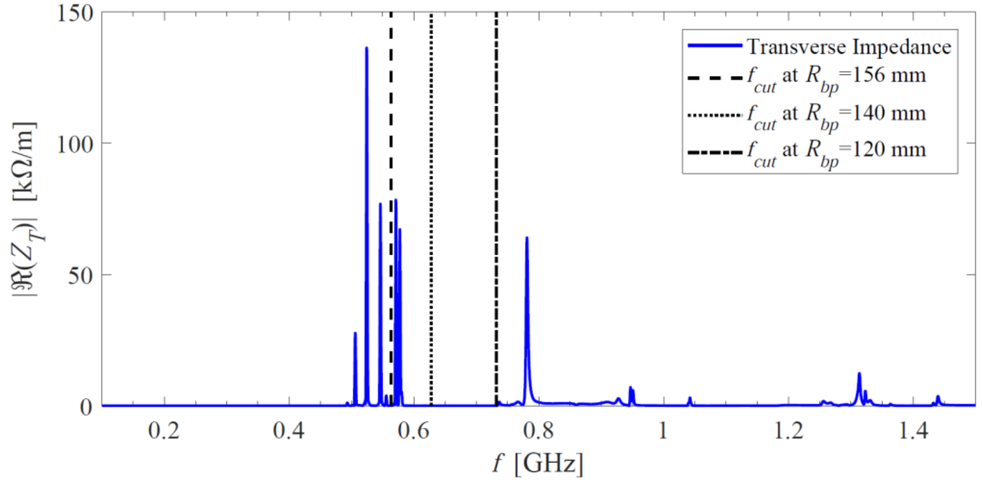
The end-cell is optimized under the following considerations:

- Inner half-cell is equal to the optimized mid-cells
- The value of E_{peak} and H_{peak} in the outer half-cell should be smaller than those values in the inner half-cell
- The end-cell aperture radius is varied to untrap the modes in the first HOM monopole band
- Obtain a flat field along the longitudinal axis
- Avoid having dangerous trapped modes in the cavity



Parameters	Value
A_e [mm]	133
B_e [mm]	102
a_e [mm]	34
b_e [mm]	46
R_{bp} [mm]	156
R_{eq} [mm]	333.182
L_e [mm]	171.532
α_e [°]	96.9



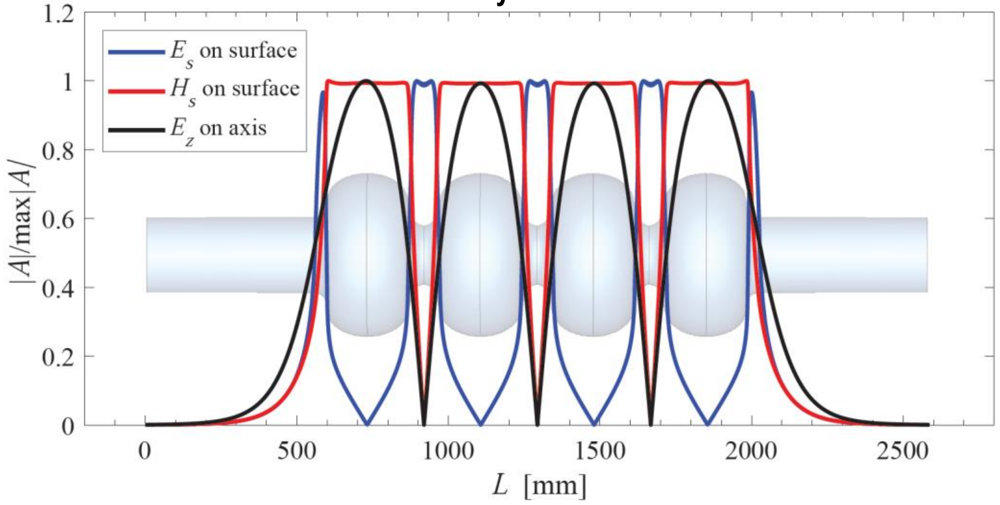


Impedances are for bare cavity and the peaks are not fully resolved.

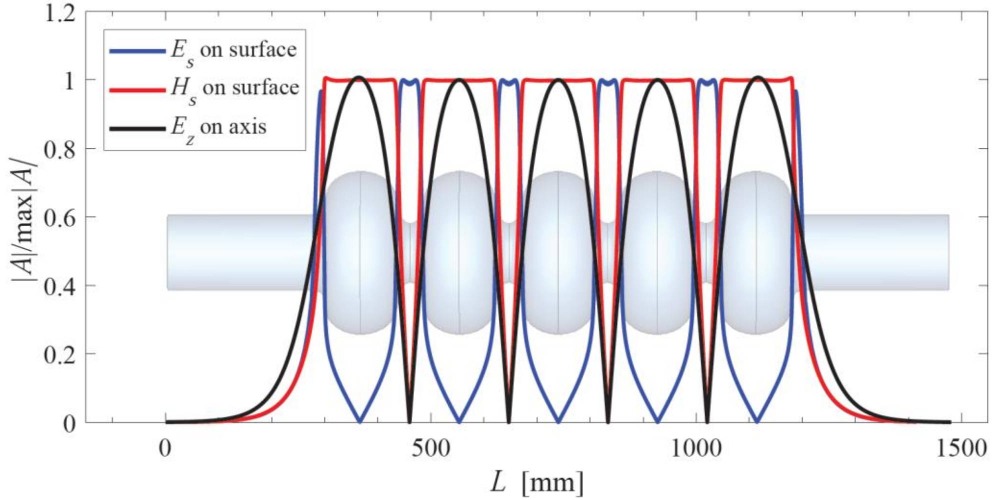
Main Parameters of the Multi-cell Cavities

Parameters	UROS. FCC-ee	UROS. FCC-ee	CERN LHeC Ver. 2	Jlab Ver. 2
Frequency [MHz]	400.79	801.58	801.58	801.58
Number of Cells	4	5	5	5
Material	Nb/CU	Bulk Nb.	Bulk Nb.	Bulk Nb.
Temperature [K]	4.5	2.0	2.0	2.0
R/Q [Ω]	411	521	393	523.9
Geometry Factor [Ω]	273.2	273.7	283	274.7
G.R/Q [Ω^2]	112285	142597	111219	143915
B_{pk}/E_{acc} (mid-cell) [$\mathrm{mT}/(\mathrm{MV}/\mathrm{m})$]	4.2	4.2	4.92	4.2
E_{pk}/E_{acc} (mid-cell)	2.0	2.0	2.4	2.26
Cavity Active Length [mm]	1465.1	919.5	935	917.9
Iris radius [mm]	120	60	80	65
Beam Pipe radius [mm]	156	78	80	65
Wall angle (mid-cell) [degree]	100	100	102.5	90
Cell to cell coupling of mid cells [%]	2.25	2.25	5.75	3.21
Field Flatness [%]	99	99	96	-
$k_{\|\|}(\sigma_z = 2\mathrm{mm})$ [V/pC]	2.27	3.37	2.63	2.74
Cutoff TE_{11} [GHz]	0.563	1.126	1.10	1.35
Cutoff TM_{01} [GHz]	0.736	1.471	1.43	1.77

4-cell cavity at 400.79 MHz



5-cell cavity at 801.58 MHz



Single Cell Cavity Design for the Z Option (I)

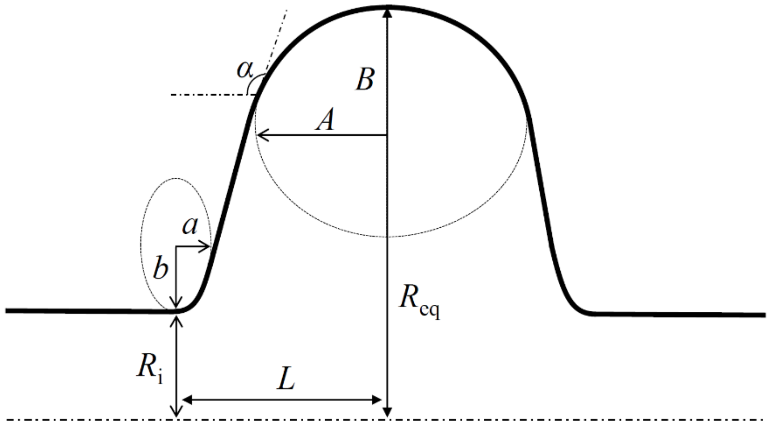
- The surface losses and peak surface fields are not so crucial for the Z option due to low E_{acc} (≈ 5 MV/m)
  - ➢ instead main focus is on the HOM aspects specially strong damping of the first dipole band
- In a single-cell part of the field leaks into the beam-pipe, thus the cell and beam-pipe are simulated together
- L is not fixed to $\lambda/4$ and is considered as a free variable in the optimization (in fact if highly influences the frequency of TE_{111} mode)
- Aperture radius is considered as a free variable (above 145 mm to untrap TM_{011} and have small loss factor)

- Ideally the following objectives have to be optimized at the same time:

$$\min_{A,B,a,b,L,Ri}\left(-|f_1 - f_0|, |f_1 - f_2|, \frac{R}{Q}_{\perp 1} + \frac{R}{Q}_{\perp 2}, -G_0 \cdot \frac{R}{Q}_0, \frac{E_{pk}}{E_{acc}}, \frac{B_{pk}}{E_{acc}}\right)$$

Subject to $\quad f_0 = 400.79\ \text{MHz},\ 90^o \le \alpha$

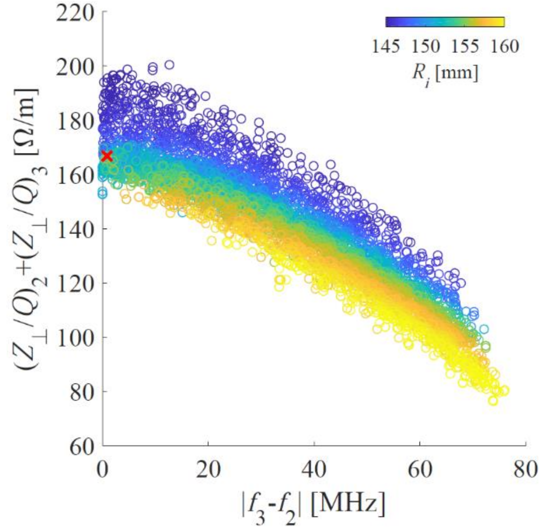
- ➢ ***Indices 0, 1 and 2 correspond to the first monopole mode, the first dipole mode and the second dipole mode respectively.***
- ➢ ***R_{eq} is used for tuning f_0 to the desired frequency.***

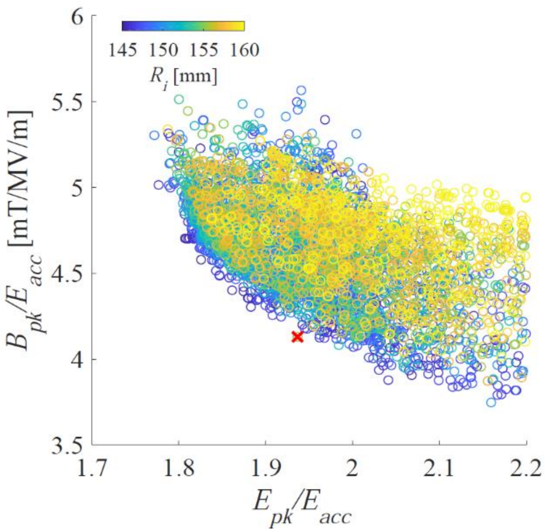


	G.R/Q	f of TE_{111}	f of TM_{110}	f of TM_{011}	$k_{\parallel}$
R_i ↑	↓	↓	↓	↑	↓

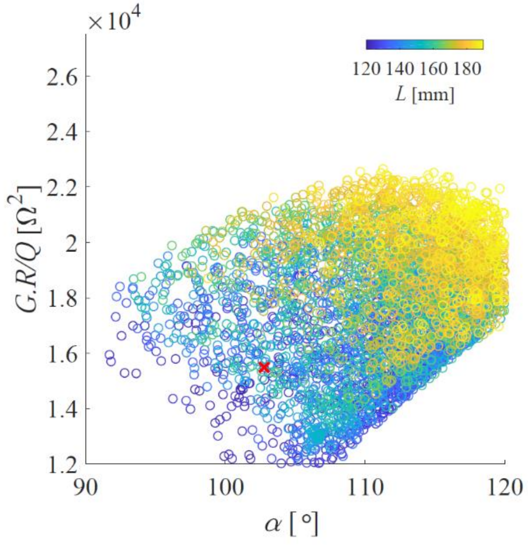
Single Cell Cavity Design for the Z Option (II)

- An evolutionary algorithm is used to sample the search space and find a compromise between objectives
- A geometry is selected for which the frequency of TE_{111} and TM_{110} are almost equal → simplifies the design of coaxial HOM couplers
- The frequency of the TE_{111} is well separated from the fundamental mode → good for both WG and coaxial coupler
- Surface loss is sacrificed but it is not an issue for the Z option
- The E_{peak}/E_{acc} and H_{peak}/E_{acc} are small for cavities with small L as E_{acc} is defined over shorter length

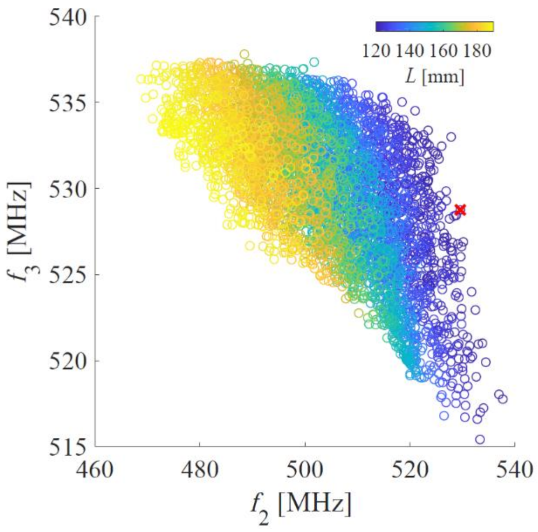




E_{acc} calculated with the actual length of the cell



R_i fixed to 156 mm

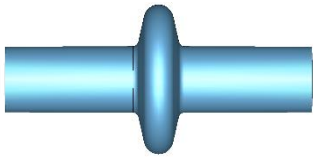


R_i fixed to 156 mm

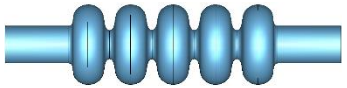
HOM Impedance of Cavities

- The single-cell cavity for Z is designed with the main focus on HOM damping aspects
  - ➢ No dangerous trapped monopole mode
  - ➢ The first dipole band is trapped in the cavity and needs strong damping → both modes are at around 529 MHz

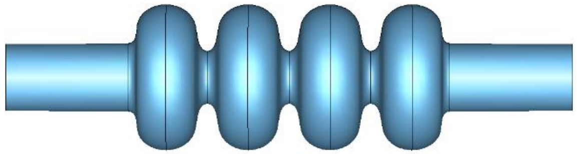
- The multi-cell cavities are optimized with the main focus on minimizing surface losses
  - ➢ The HOM spectrum of the four-cell and five-cell cavity is similar
  - ➢ A HOM coupler is designed with respect to the spectrum of 400 MHz (or 800 MHz) cavity and rescaled to the other frequency (mechanical and thermal aspects are not studied here)



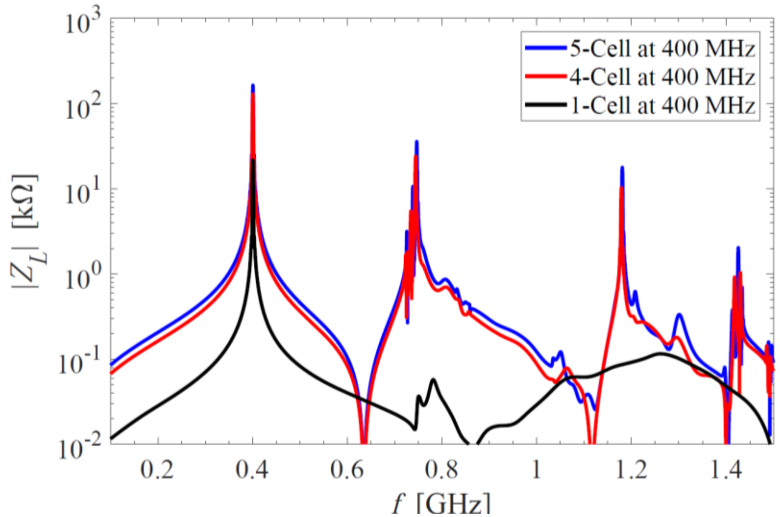
Single-cell at 400 MHz for Z

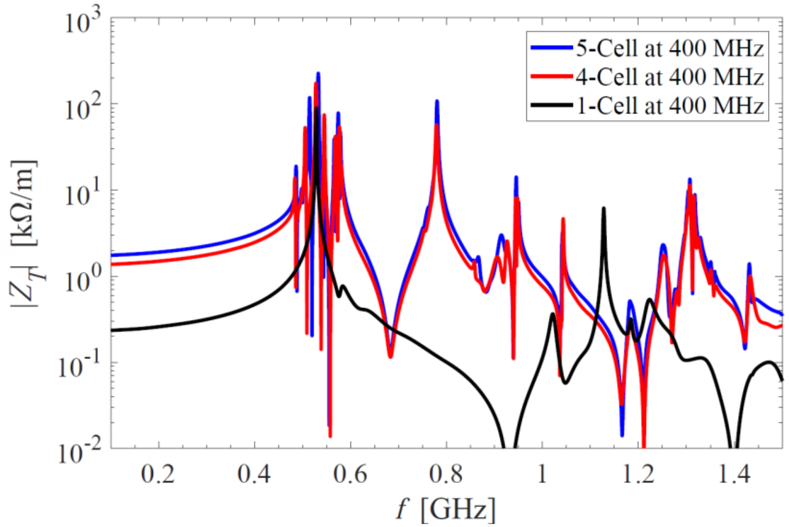


Five-cell at 800 MHz for $t\bar{t}$



Four-cell at 400 MHz for W, H, $t\bar{t}$

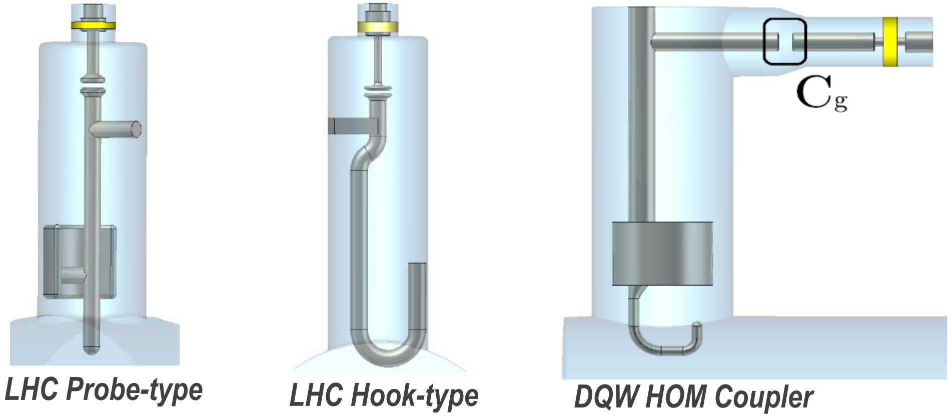


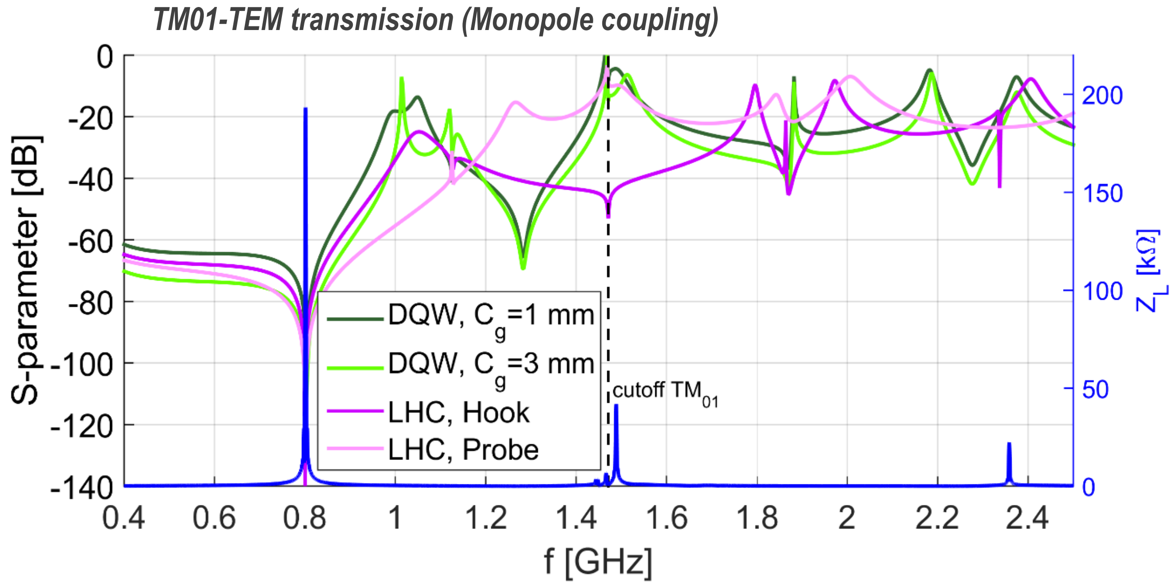


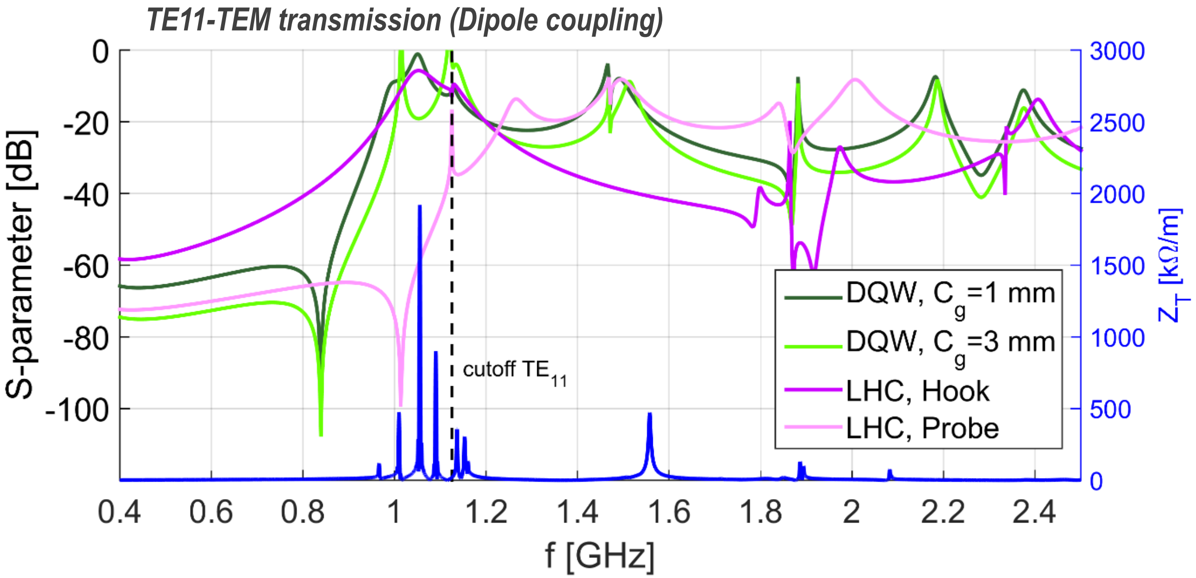
Impedance of the five-cell cavity is scaled to 400 MHz for comparison. Impedances are for bare cavity and the peaks are not fully resolved.

Coaxial HOM Coupler

- The notch effect of all couplers are tuned to 801.58 MHz for the monopole coupling.
- The DQW HOM coupler can deliver a high value of transmission at both first higher order dipole and monopole band.



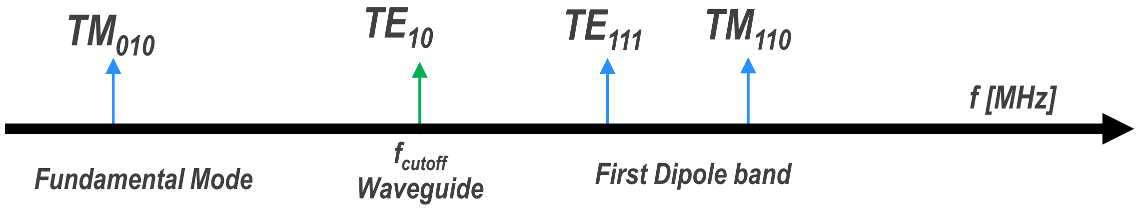


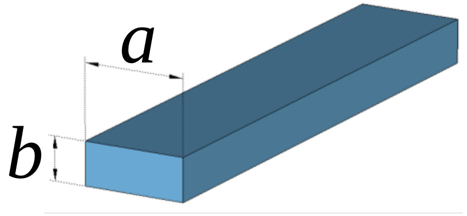


Impedances are for bare cavity and the peaks are not fully resolved.

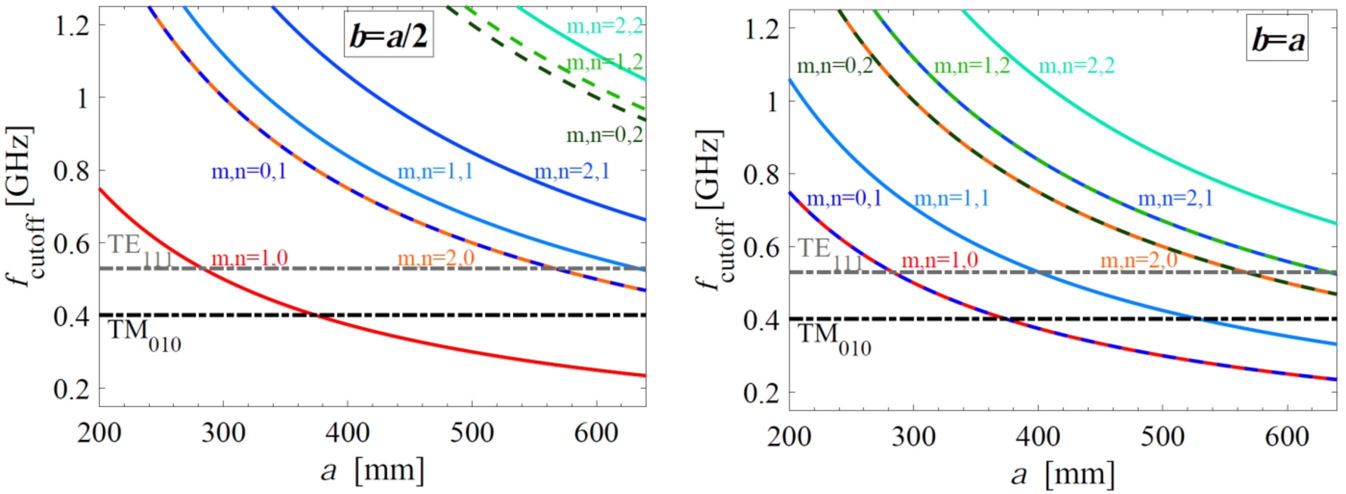
Rectangular Waveguide HOM Coupler

- The cutoff frequency of the first mode of the waveguide HOM coupler has to be between the fundamental mode of the cavity and the first dipole mode.
- Standard aspect ratio of 2:1 of the WG dimensions gives rise to maximum frequency band for one-mode operation
  - ➢ not efficient for damping the first dipole band with two polarizations
- Square-shaped WG has same cutoff frequency for the first two modes but
  - ➢ bulky specially at low frequencies
  - ➢ trapped modes could be created by the WG



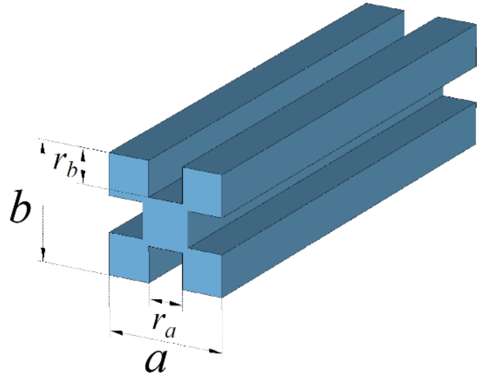


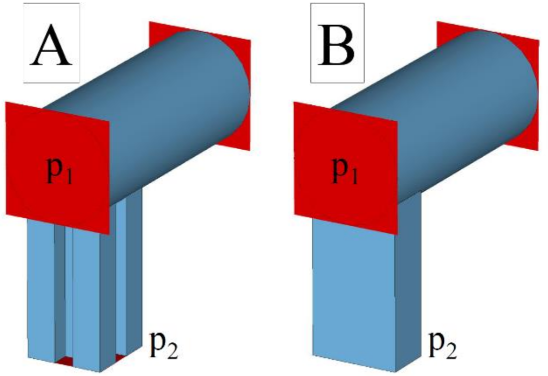
$$\left(f_{cutoff}\right)_{mn} = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$



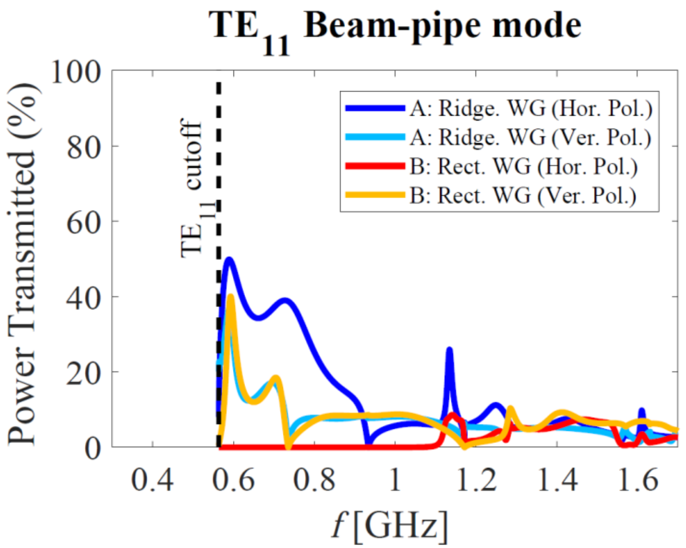
Quad-Ridged Waveguide

- The cutoff frequency could be lowered by adding ridges in the WG
- The damping of the two polarizations of the dipole modes is improved using quad-ridged WG

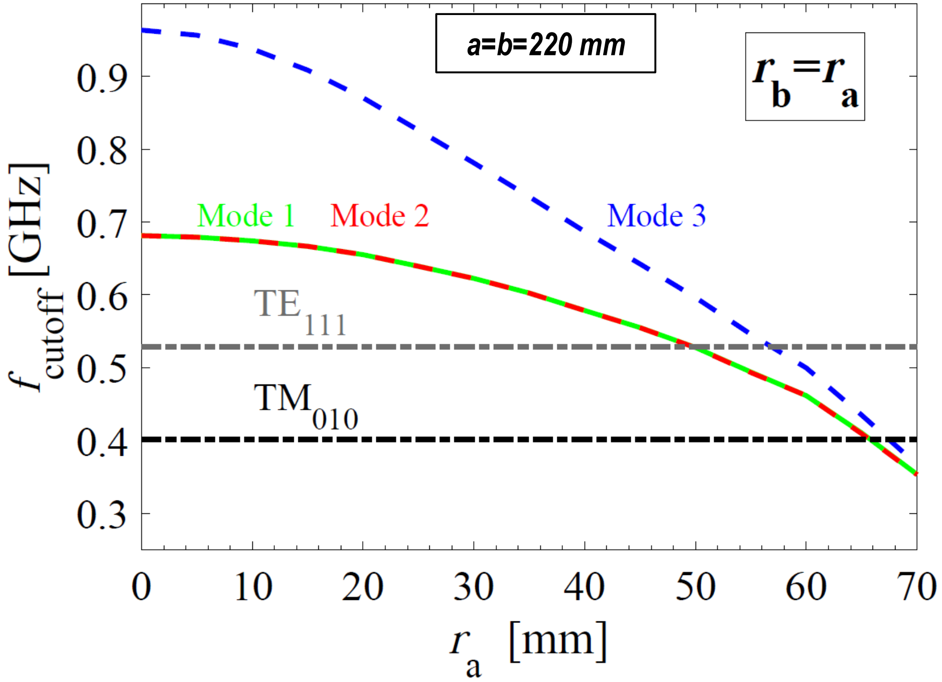




Quad-Ridged WG vs. Rect. WG with the same cross section area

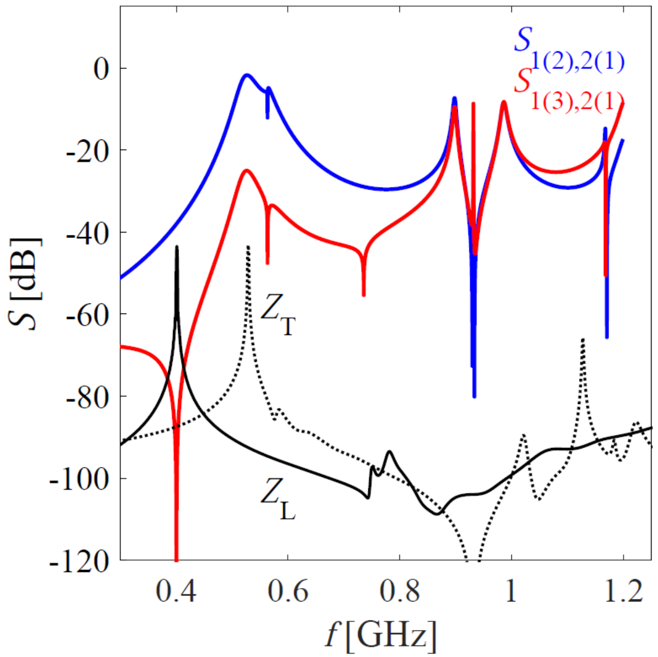


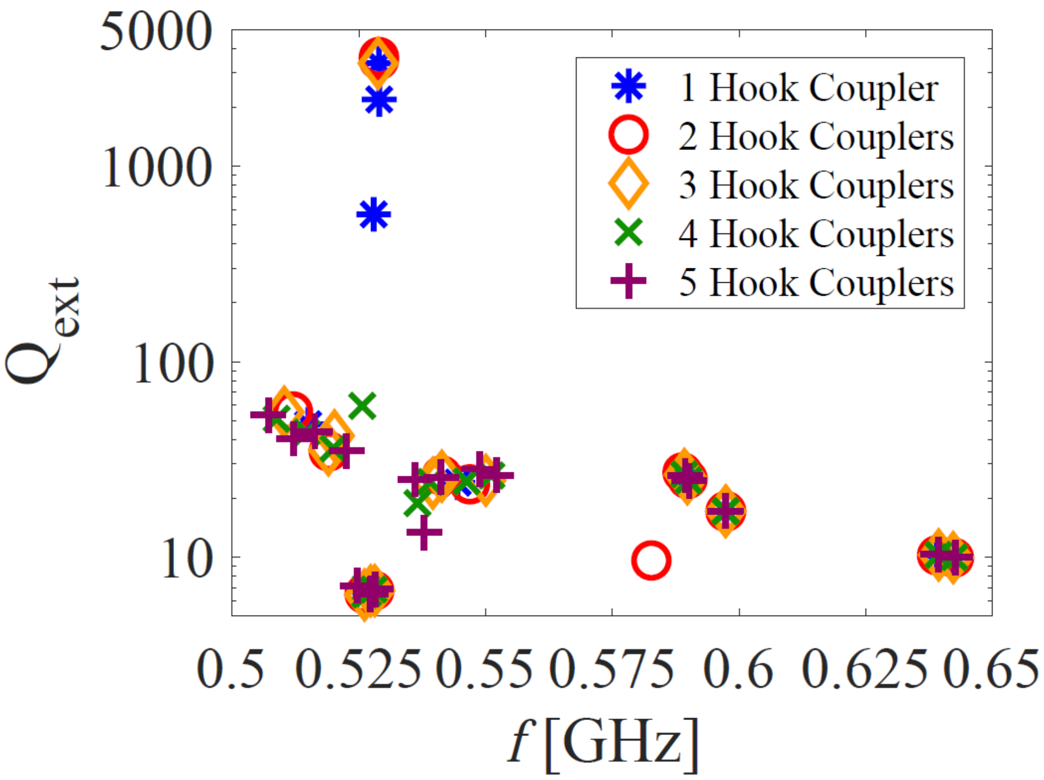
Power calculated from the S-parameters

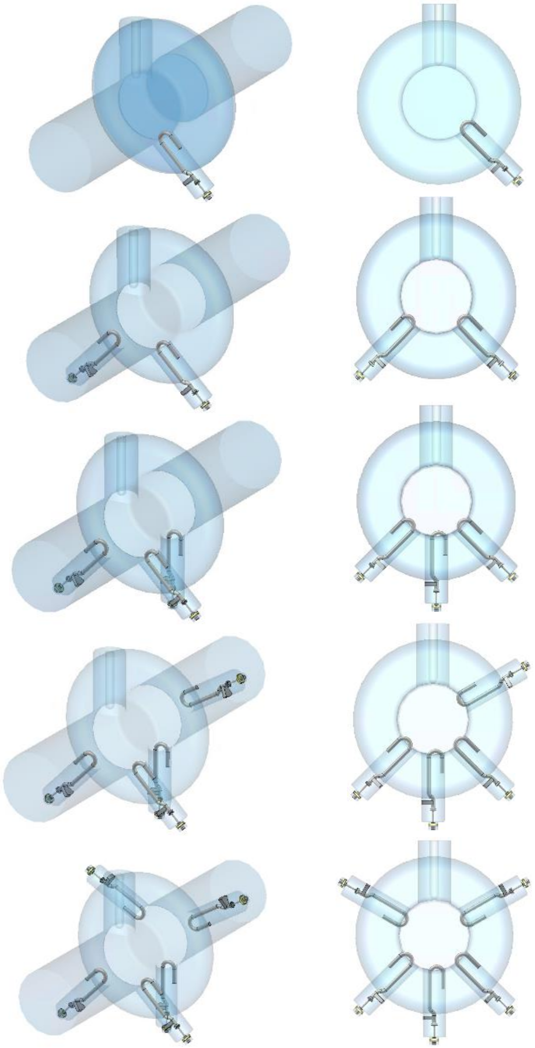


HOM Coupler Design for the Z Option

- HOM coupler is tuned with respect to the modes in the first dipole band
- By using four hook-type HOM couplers, the Q_{ext} of the modes in the first dipole band are reduced below 100

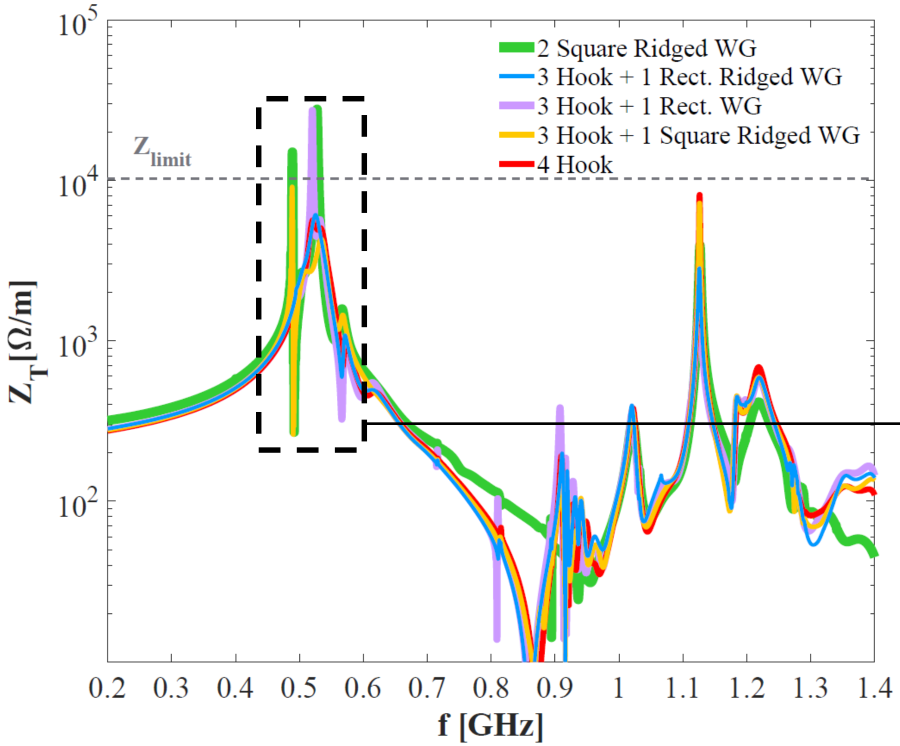


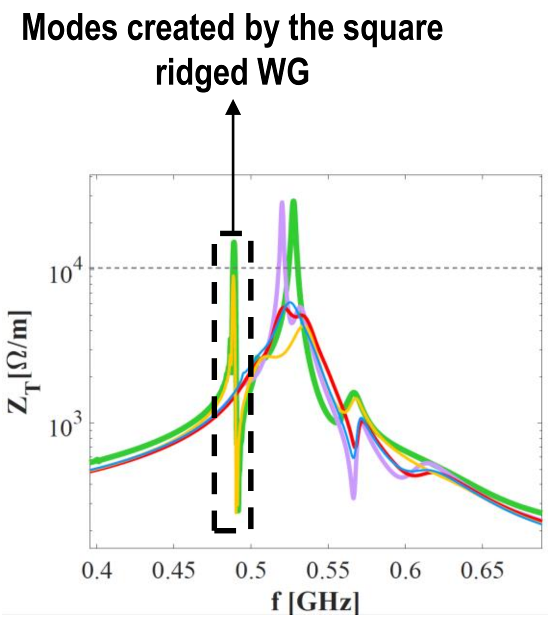


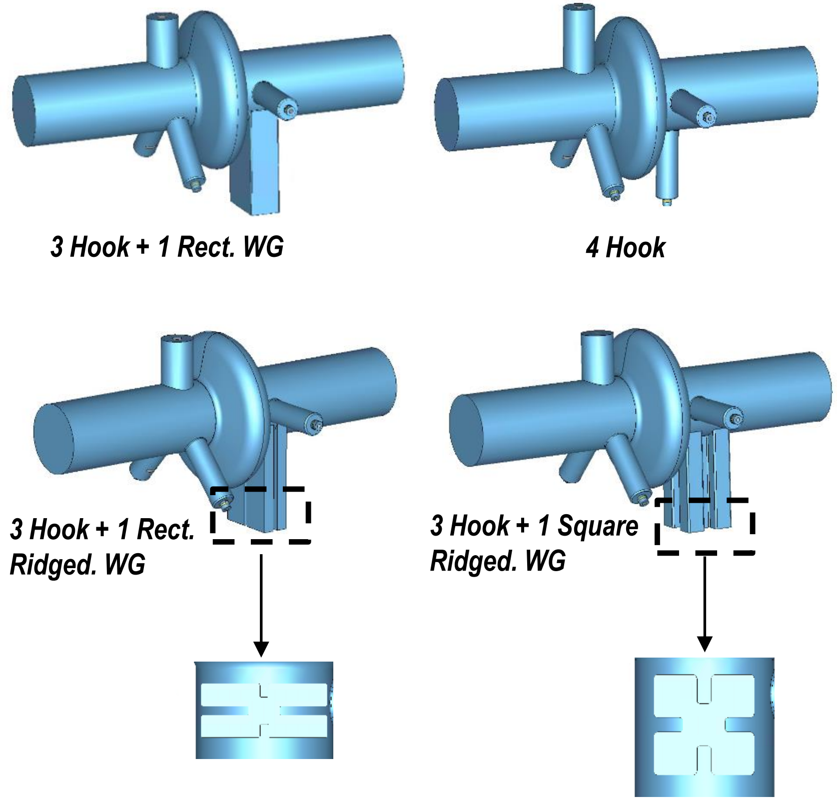


Wake Impedance of the Z Option

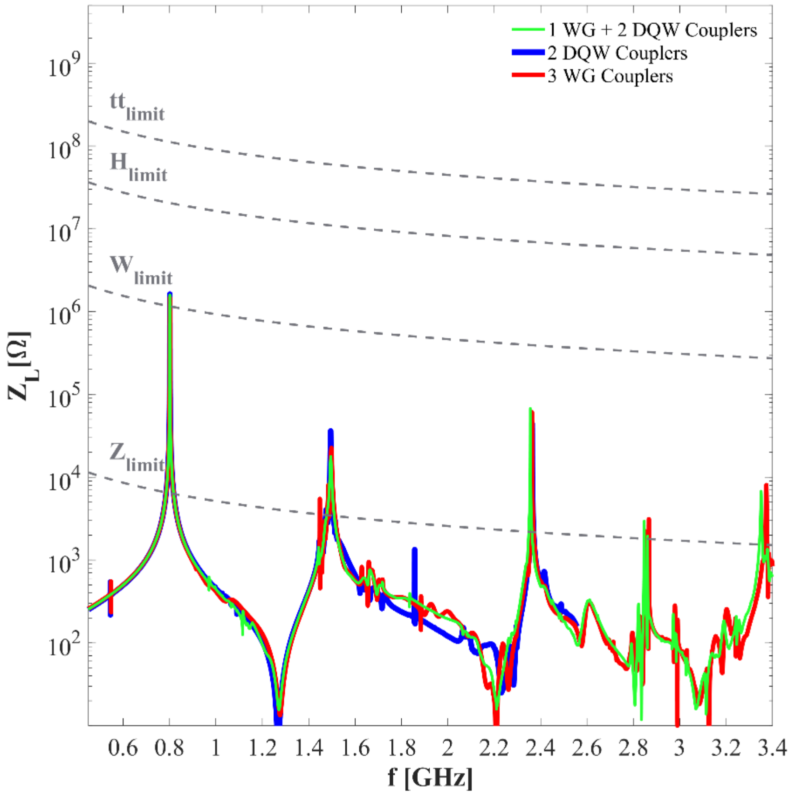
- A combination of hook-type coupler and quad-ridged WG can reduce the transverse impedance below the limit defined by synchrotron radiation
- Quad-ridged WG is optimized to have low cutoff frequency for the first two modes and avoid having modes trapped in the WG

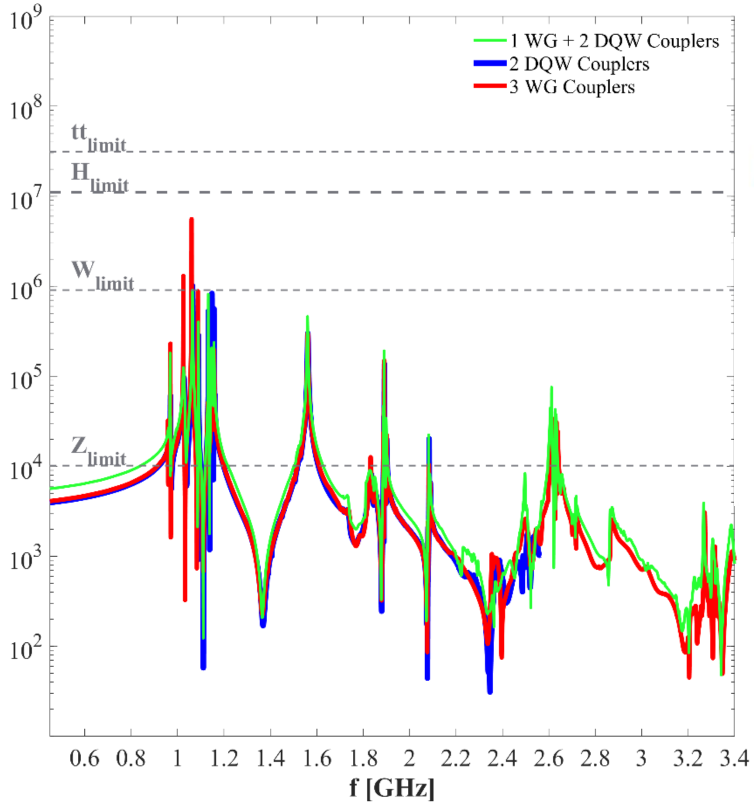


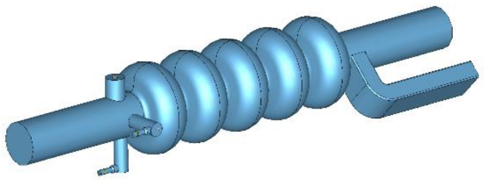




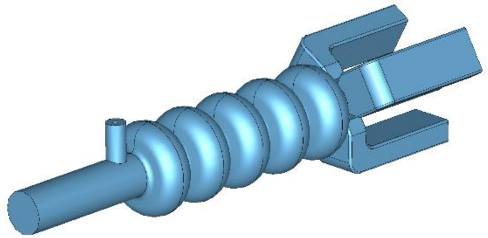
HOM Damping for the Multi-cell Cavities at 800 MHz



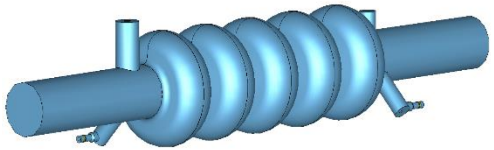




1 WG + 2 DQW Couplers
WG cutoff frequency is set at 1.11 GHz



3 WG Couplers
WG cutoff frequency is set at 0.91 GHz

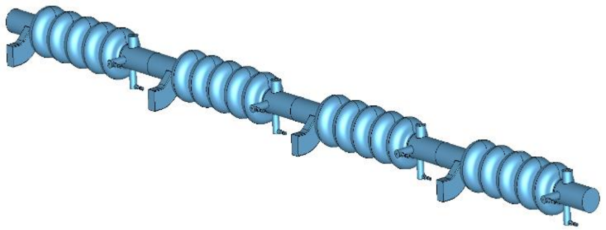


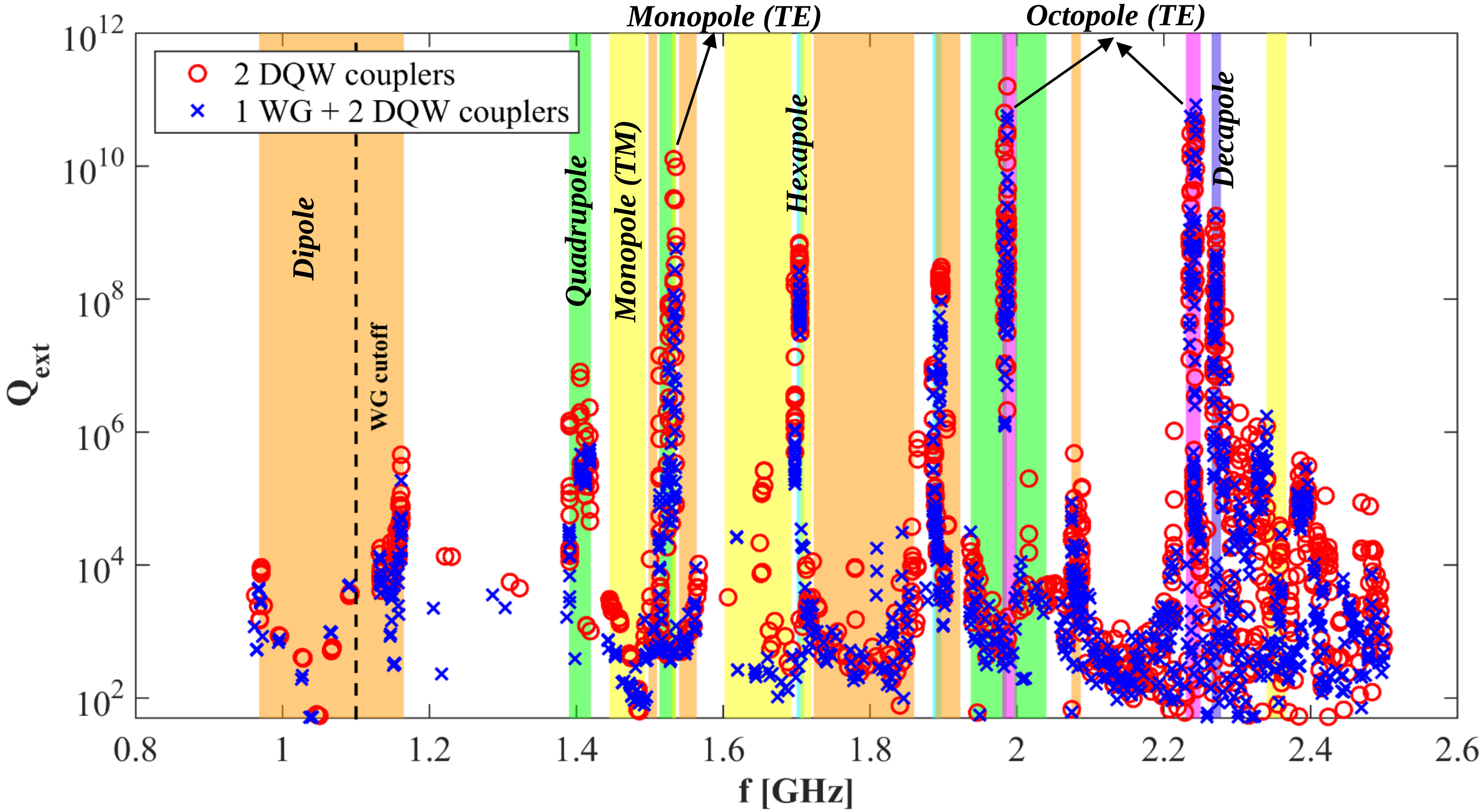
2 DQW Couplers

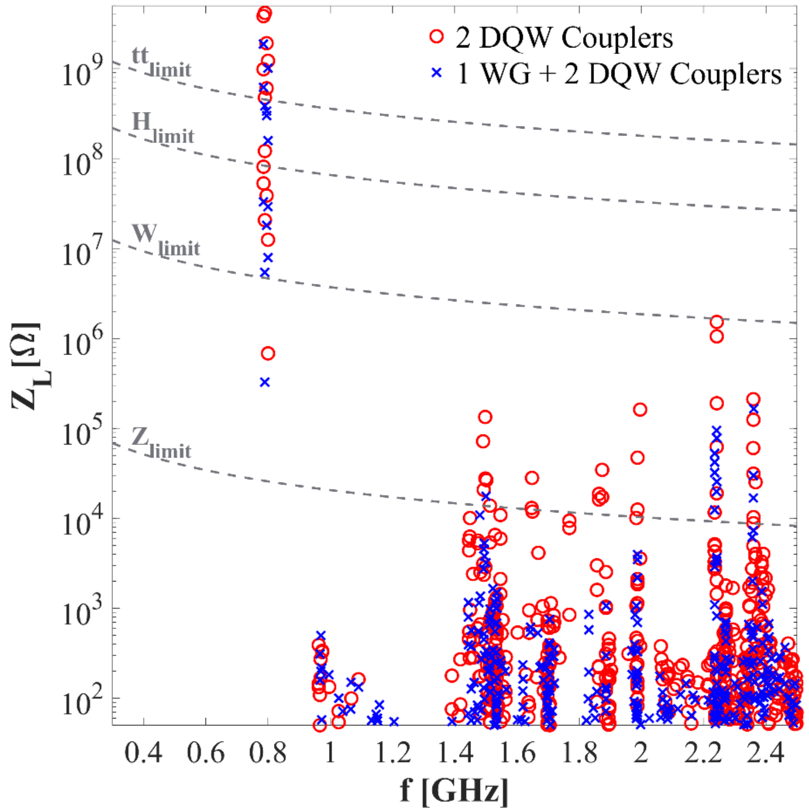
- Coaxial coupler performs better than waveguide couplers in damping the first dipole band
- No clear difference between 2 DQW and 2 DQW + 1 WG
  - ➢ Reason: beam pipes also act like WG and adding another WG does not make much difference
  - ➢ Yet, in a module composed of several cavities the effect of WG in damping HOMs is more visible

Quality Factor of Modes in a 4-Cavity Module

- The damping of monopole, dipole and quadrupole bands is improved by adding the WG
- Octopole and decapole modes are trapped, thus adding another coupler does not influence their damping - these modes however are not excited by on-axis beams

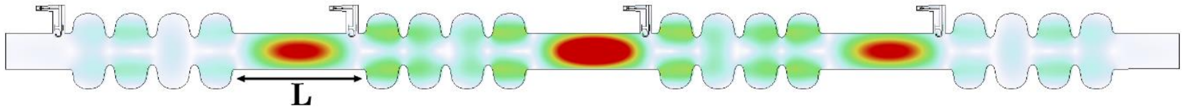




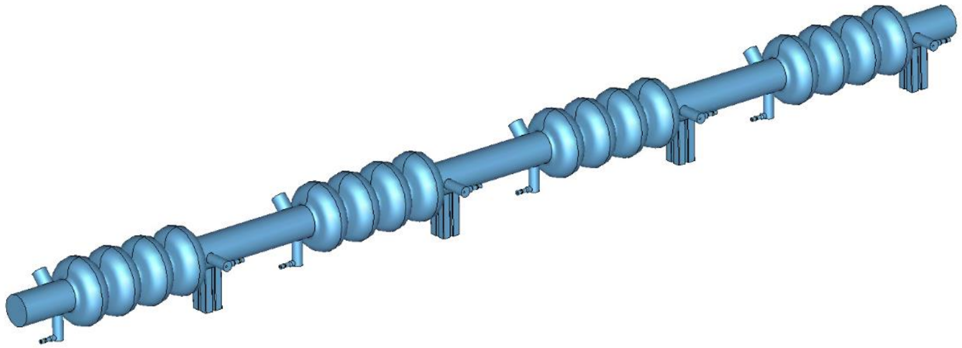


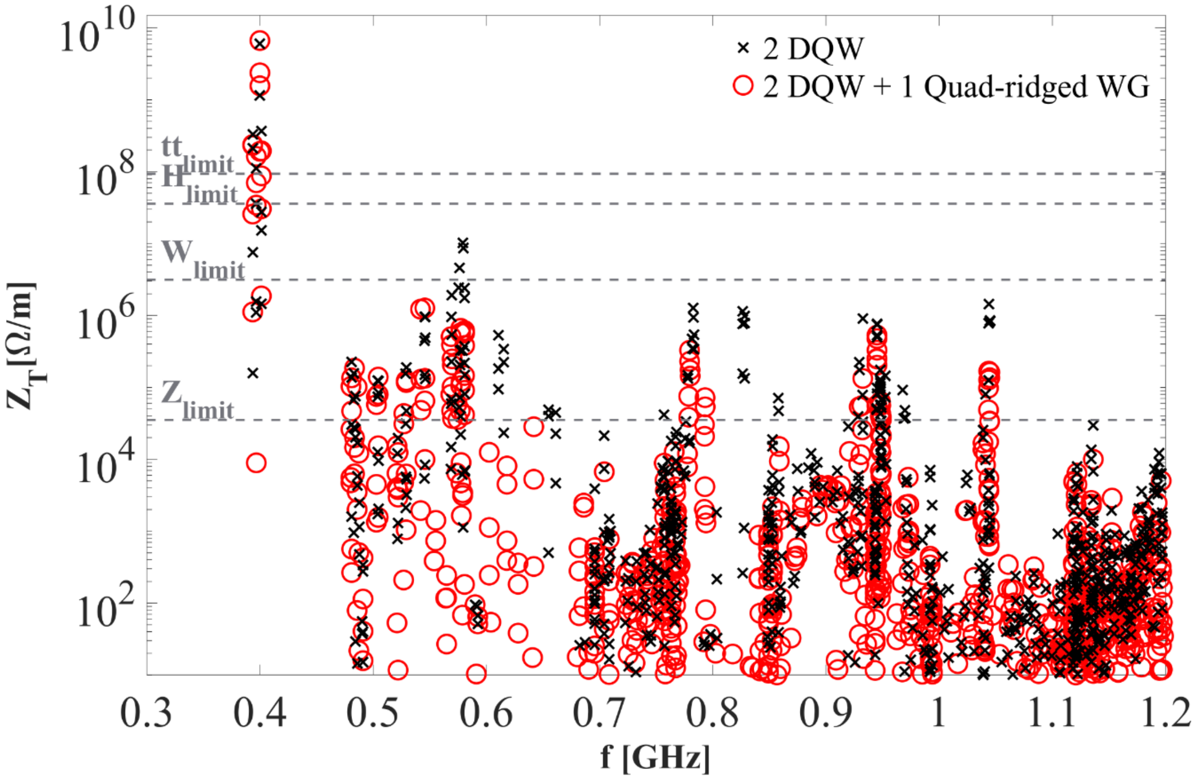
Modes Trapped in the Beam Pipes

- With 2 DQW HOM couplers, three dipole modes around 0.579 GHz have a transverse impedance above the W threshold. The energy of these modes is mainly located in the beam pipes.
- Adding a ridged WG coupler improves the damping of such modes.



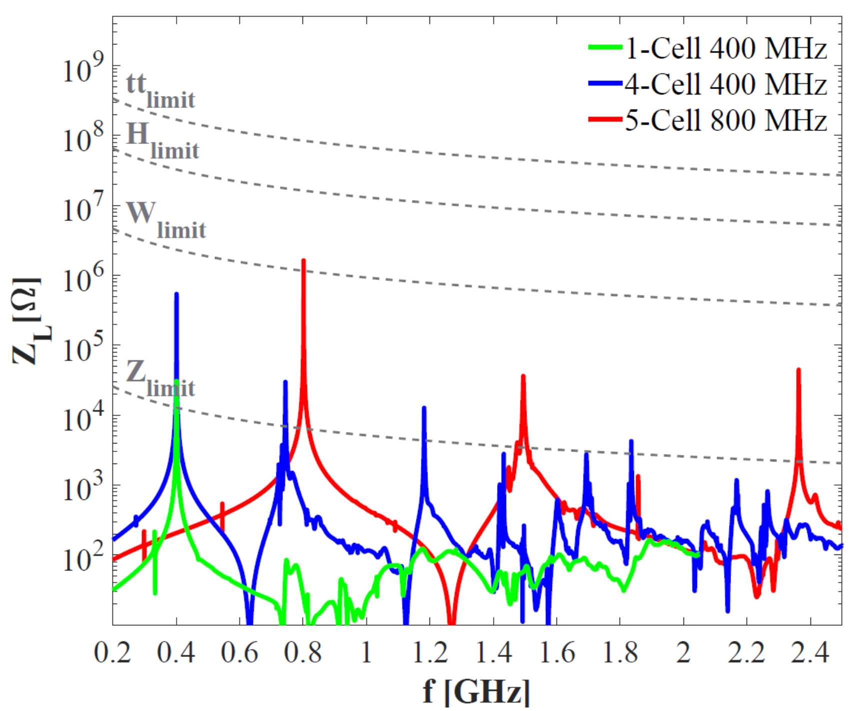
Electric field density of the dipole mode with highest transversal impedance at frequency 0.579 GHz

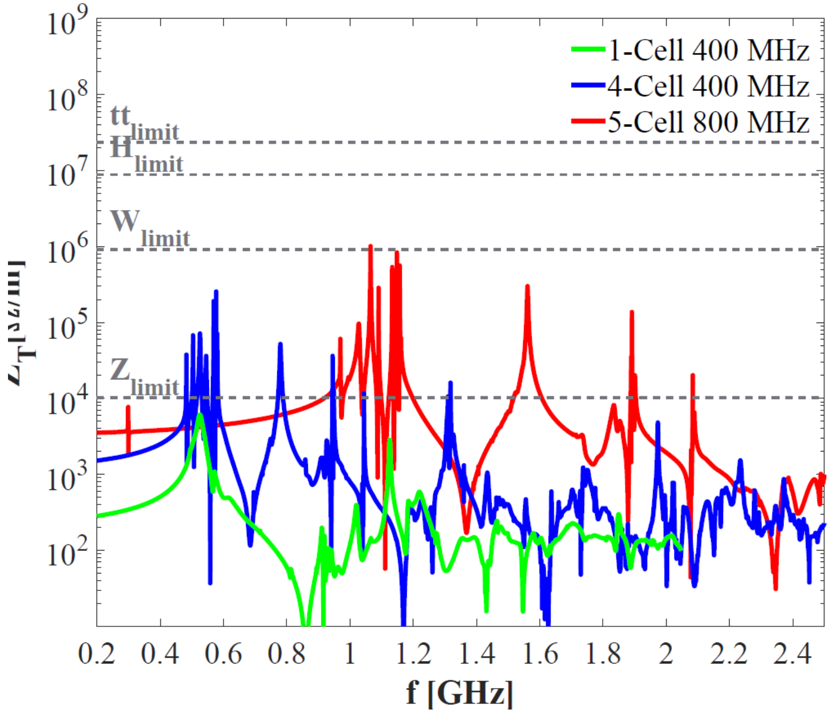


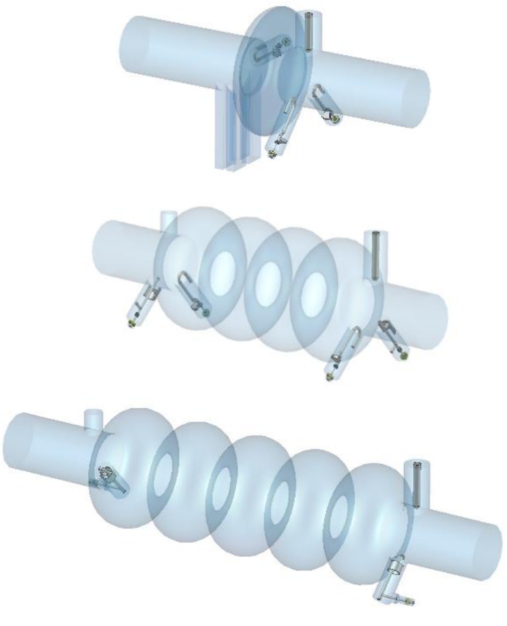


Impedance of Damped Cavities

- The stability threshold can increase by 1-2 orders of magnitude if the frequency spread between cavities is taken into account
- Using a feedback system can increase the stability threshold above the synchrotron radiation limit







1-cell cavity at 400 MHz (top)
4-cell cavity at 400 MHz (middle) and
5-cell cavity at 800 MHz (bottom)

Thresholds are normalized to the number of cavities needed at 400 MHz

Average HOM Power

- The high HOM power of Z machine reaffirms the choice of 1-cell cavity at 400 MHz
- Coaxial HOM coupler can handle the HOM power of H and $t\bar{t}$
- Bunch spectrum of the beam needed to make a more accurate estimation of HOM power

	Z	W	H	$t\bar{t}$
4-cell cavity at 400 MHz				
Bunch Length [mm]	P [kW]	P [kW]	P [kW]	P [kW]
SR (3.5, 3.0, 3.15, 1.97)	47.95	5.09	1.16	0.81
BS (12.1, 6.0, 5.3, 2.54)	17.34	2.89	0.76	0.66
5-cell cavity at 800 MHz				
Bunch Length [mm]	P [kW]	P [kW]	P [kW]	P [kW]
SR (3.5, 3.0, 3.15, 1.97)	66.11	6.94	1.59	1.09
BS (12.1, 6.0, 5.3, 2.54)	23.91	4.09	1.06	0.89
1-cell cavity at 400 MHz				
Bunch Length [mm]	P [kW]	P [kW]	P [kW]	P [kW]
SR (3.5, 3.0, 3.15, 1.97)	6.86	0.71	0.16	0.11
BS (12.1, 6.0, 5.3, 2.54)	2.53	0.43	0.11	0.09

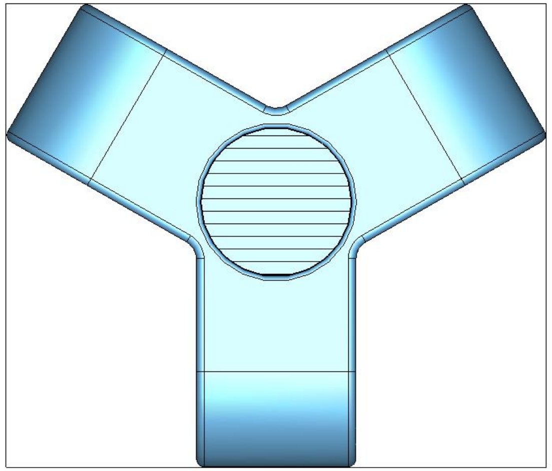
* Average HOM power for both BS and SR bunch lengths calculated from $P_{HOM} = k_{||} q_b I$

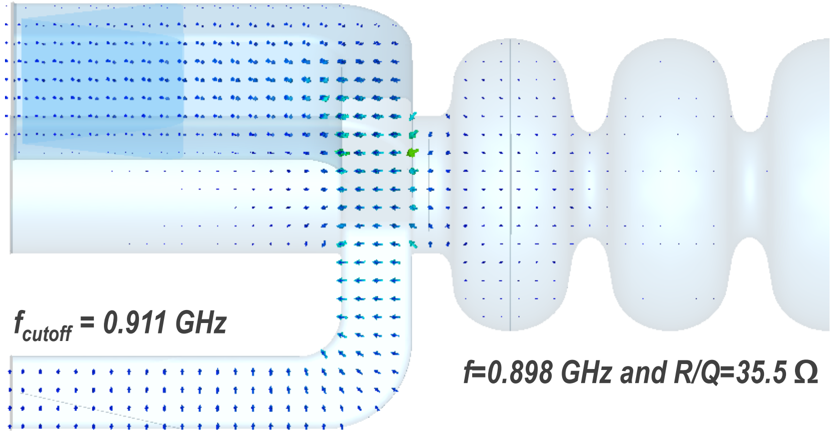
Summary

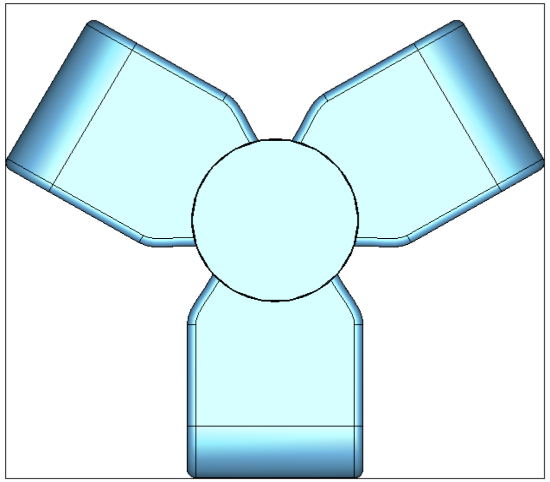
- A multi-cell cavity is designed for the W, H and $t\bar{t}$ options
  - Mid-cells optimized for minimal intrinsic losses with constraints on different figure of merits such as E_{pk}/E_{acc}
  - End-cells optimized to allow sufficient HOM damping without significantly changing E_{pk}/E_{acc} and B_{pk}/E_{acc} of the cavity
- A single-cell cavity is designed for the Z option with the main focus on HOM aspects of the cavity
- Waveguide couplers were compared with coaxial HOM couplers
- Quad-ridged WG introduced as an alternative to rectangular WG HOM couplers
- A single waveguide for high frequency modes with targeted coaxial dampers for low frequency HOMs looks very promising as we approach higher current with high HOM power

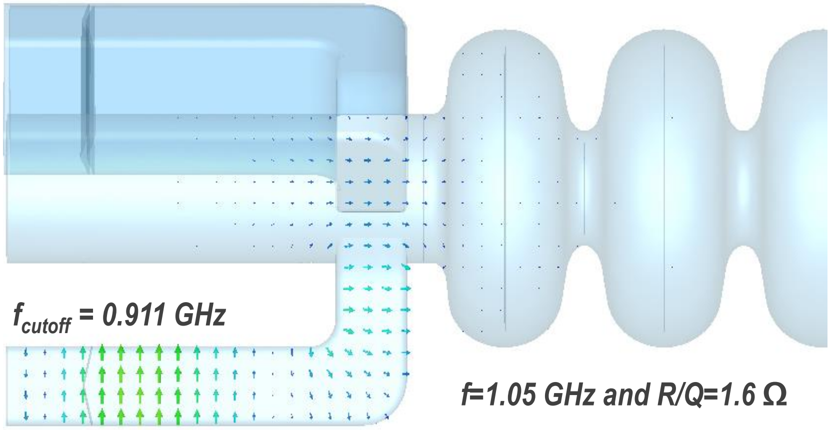
Appendix: Waveguide HOM coupler optimization

In designing the waveguide HOM coupler, special attention is given to the modes induced by the waveguide (boundaries of the waveguide can act like a small cavity)









Appendix: Eigenmode simulation of the module

A catalogue containing the information of all lossy HOMs with their frequency, quality factor, longitudinal and transversal *R/Q*, the percentage of coupling to each port, etc. for a 4-cell cavity at 400 MHz and a 5-cell cavity at 800 MHz is generated using the State Space Concatenation (SSC) method to simulate the whole module.