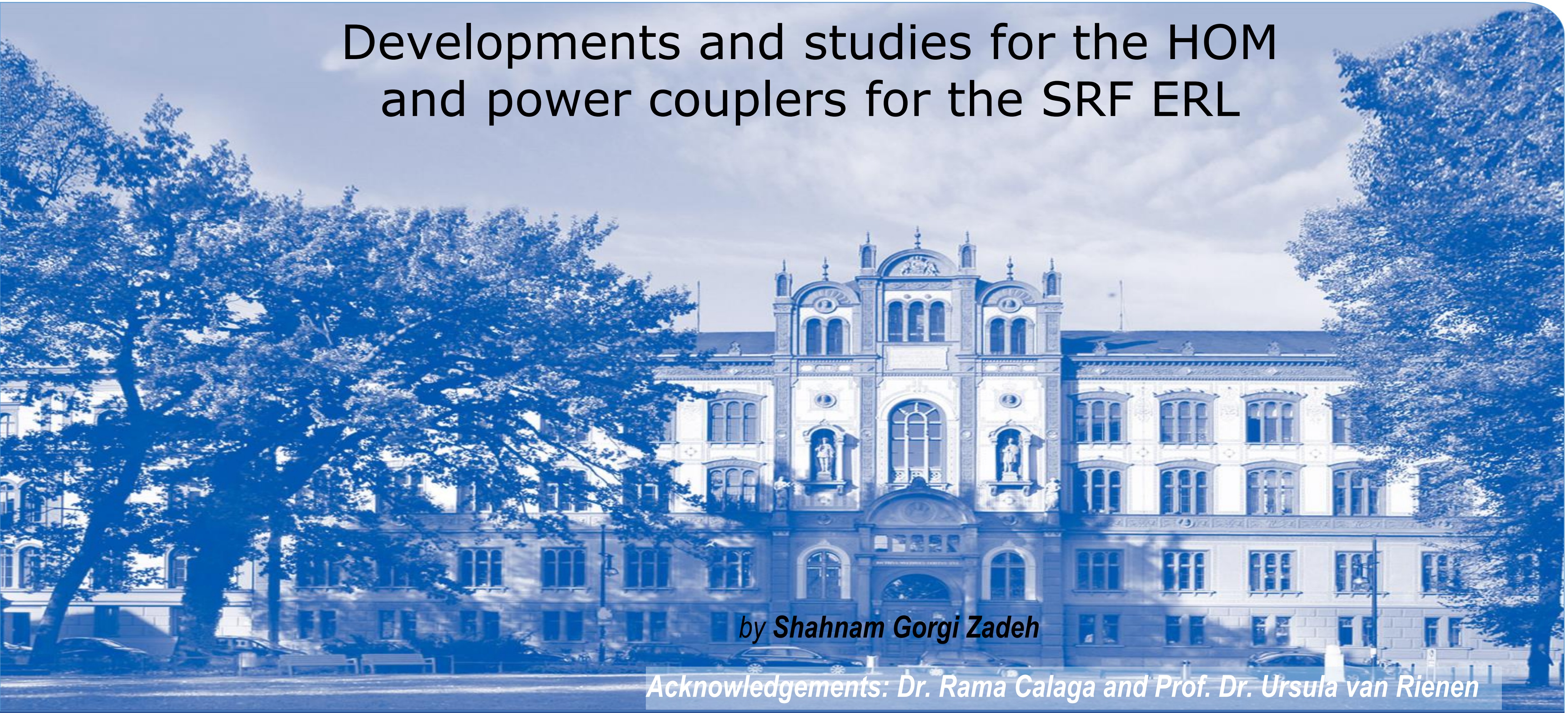


Developments and studies for the HOM and power couplers for the SRF ERL

by ***Shahnam Gorgi Zadeh***

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

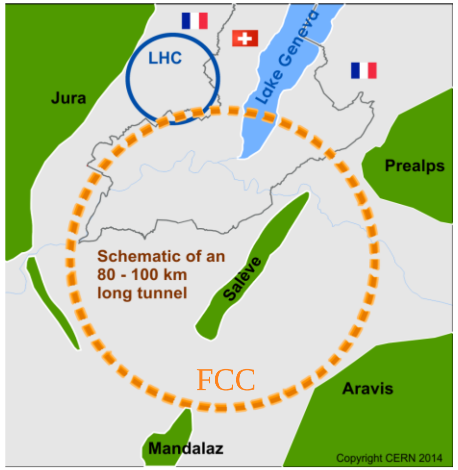
RF parameters of PERLE and $t\bar{t}$ operation of FCC-ee

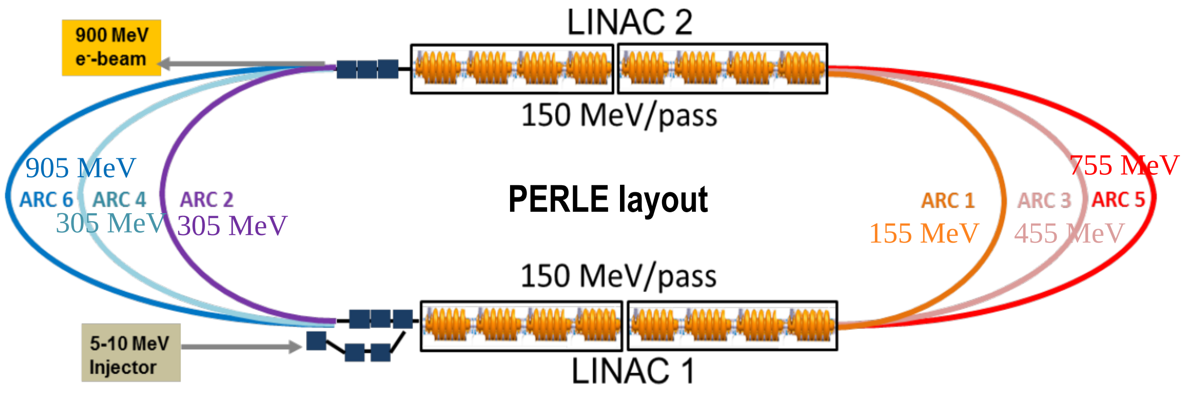
FCC-ee is a circular lepton collider designed to study four particles, i.e. Z, W, H and $t\bar{t}$

- Beam energies of FCC-ee range from 45.6 to 182.5 GeV
- The collider will be housed in a 100 km tunnel
- A multi-harmonic RF system including 5-cell 801.58 MHz cavities is foreseen for $t\bar{t}$

The PERLE facility aims at a maximum energy of 1 GeV

- Five-cell cavities operating at 801.58 MHz are chosen as the baseline for PERLE
- PERLE can serve as a starting point to FCC-eh





Ref: PERLE, Powerful Energy Recovery Linac for Experiments, conceptual design report, May 2017

	PERLE	FCC-$t\bar{t}$
Injection energy [MeV]	5	-
Maximum beam energy [GeV]	1	182.5
Bunch charge [pC]	320	36850
RMS Bunch Length (SR/BS) [mm]	3	1.97/2.54
Beam Current [mA]	15	5.4
Bunch spacing [ns]	25	3396
RF frequency [MHz]	801.58	400.79 / 801.58
RF Voltage	300 MV/pass	10.93 GV
Duty factor	CW	CW

ERL option for FCC-he

Energy of protons: 50 TeV

Energy of electrons: 60 GeV

Number of Passes: 6

Beam current: 6.6-25.6 mA

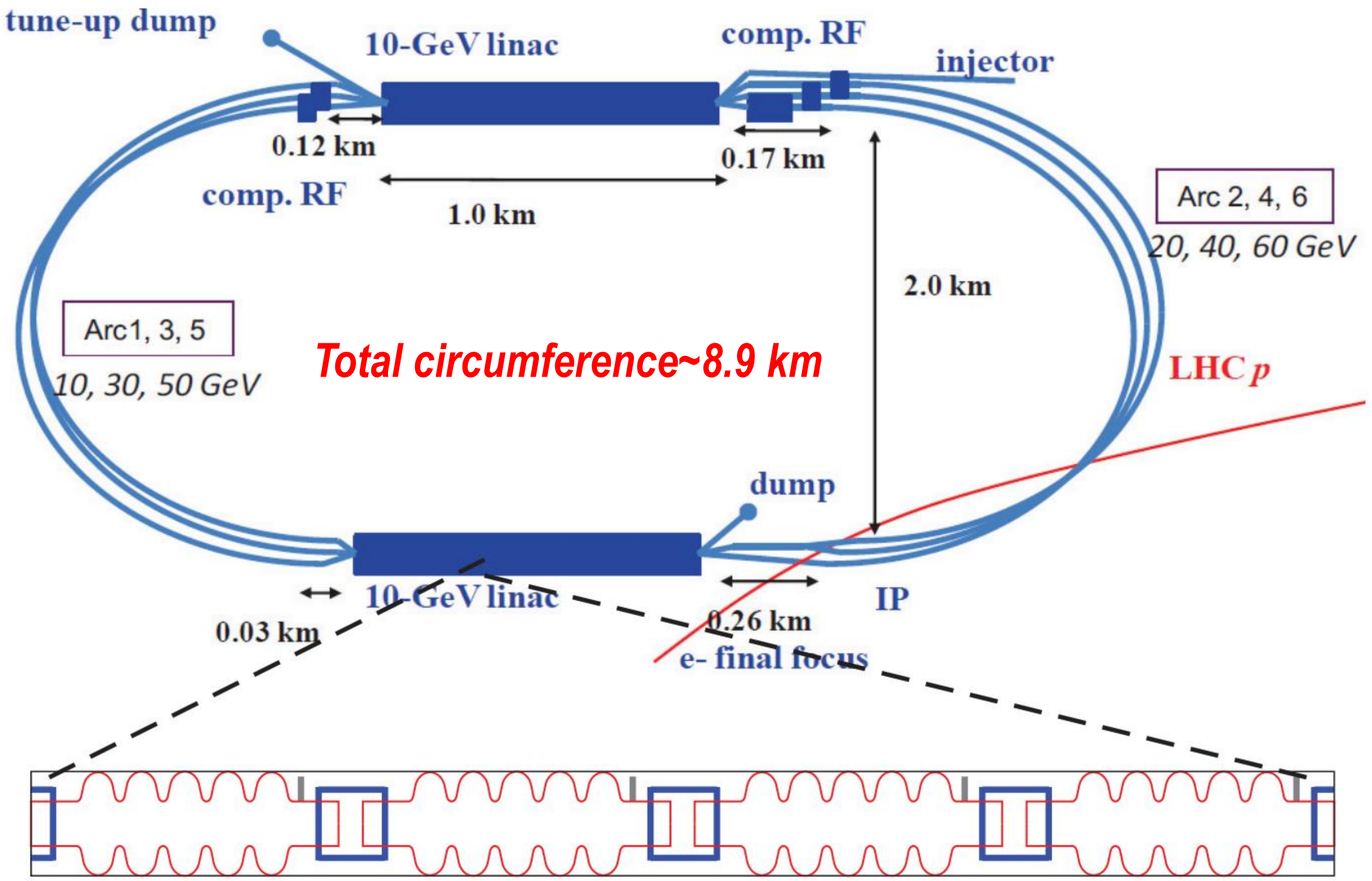
Two 10 GeV linacs

Frequency: 801.58 MHz (h=20)

Voltage: 18.7 MV/cavity

Total 1068 5-cell cavities

Cryo losses: (~ 25 MW at $Q_0=3\times10^{10}$)



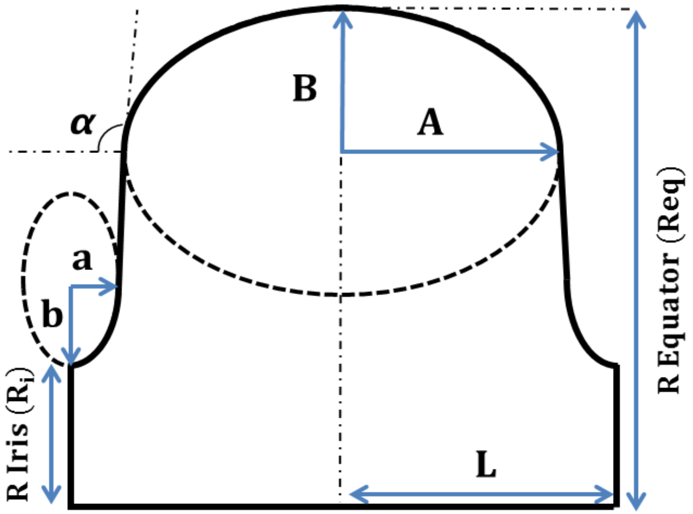
Basic unit: 5-cell cavity into 4-cavity module

Ref: R.Calaga, et al. SRF FOR FUTURE CIRCULAR COLLIDERS. SRF2015, Canada,

Mid-cell optimization (I)

An elliptic cavity cell is characterized by different geometrical parameters. By proper selection of these parameters we try to optimize several figures of merit of the cavity such as:

- **Normalized electric field** (E_{peak}/E_{acc}): avoid field emission
- **Normalized magnetic field** (B_{peak}/E_{acc}): avoid magnetic break down limit
- **Geometric Shunt Impedance** ($R/Q = \frac{V^2}{\omega_0 U}$): minimize surface losses by maximizing $G \cdot R/Q$
- **Geometry Factor:** $G = \frac{\mu_0 \omega_0 \int_V H^2 dv}{\int_S H^2 ds} = R_s Q_0$
- **Cell-to-cell coupling**: $k_{cc} = 2\frac{f_\pi - f_0}{f_\pi + f_0}$
- **Wall slope angle** α: mechanical stability, cleaning, etc.



The total power dissipated in the cavity wall due to intrinsic losses is calculated by:

$$P_{loss} = \frac{1}{2} R_s \int_S |H|^2 \, ds = \frac{V^2}{G \cdot R/Q} R_s$$

Mid-cell optimization (II)

Minimizing the intrinsic cavity losses can save considerable energy on large scale for huge machines such as FCC_eett̄.

Optimization problem of mid-cell can be formulated as:

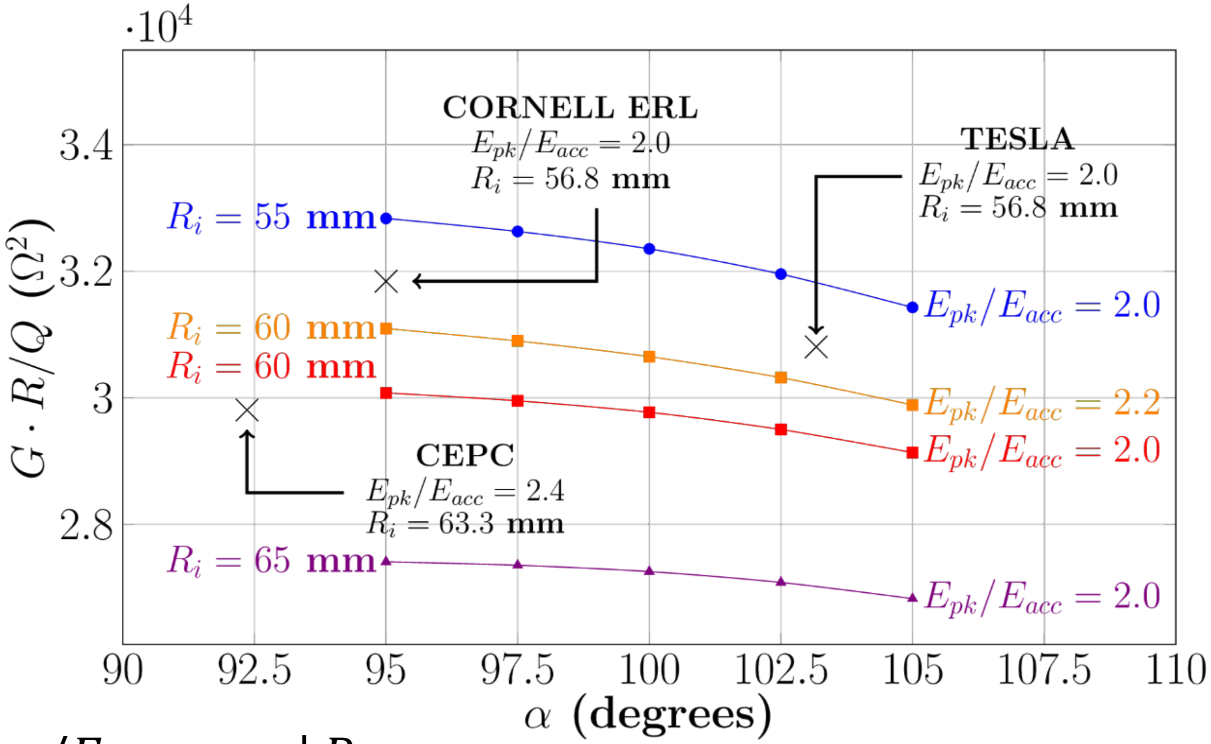
$$\max_{A,B,a,b} G \cdot R/Q$$

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

$$\alpha \geq c_2$$

$$R_i = c_3$$

- $G \cdot R/Q$ depends only on the shape of cavity
- L is taken as the quarter of the wavelength
- R_{eq} is used for tuning the frequency to 801.58 MHz
- Different cavity shapes can be compared by the constraints of this optimization, i.e. by the values of E_{pk}/E_{acc}, α and R_i

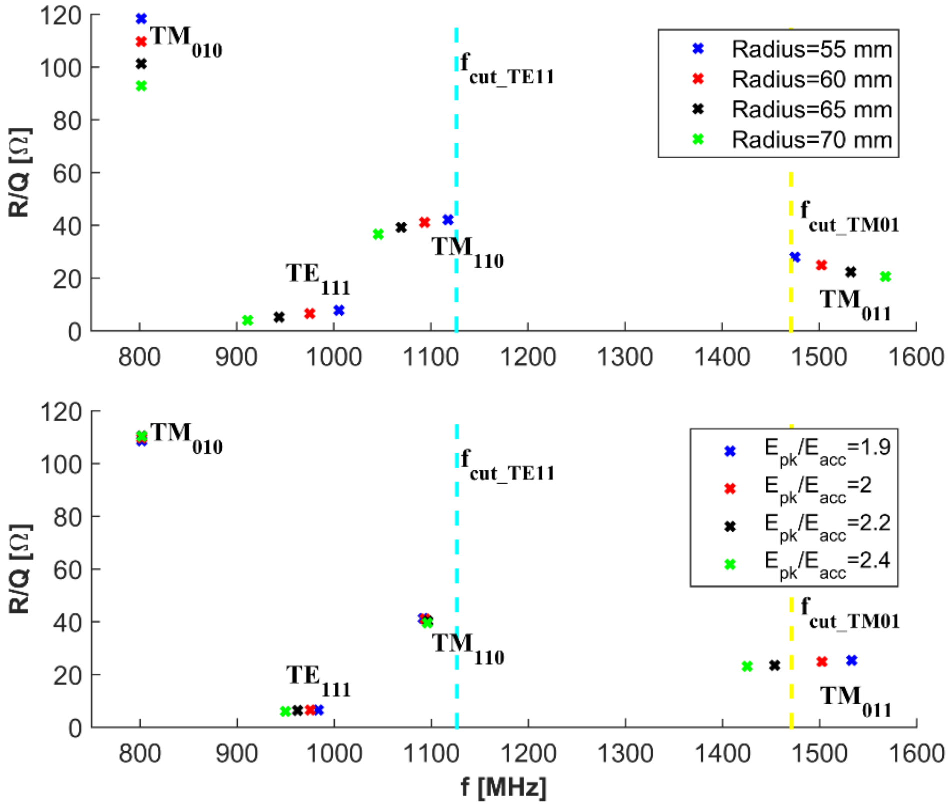


× *All radii are scaled to 801.58 MHZ.*

Mid-cell optimization (III)

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

- High value of R/Q for 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 HOM coupler design
- A small value of E_{peak}/E_{acc} helps to lower the danger of field emission



× *Cut-off frequency is for beam-pipe radius of 78 mm*

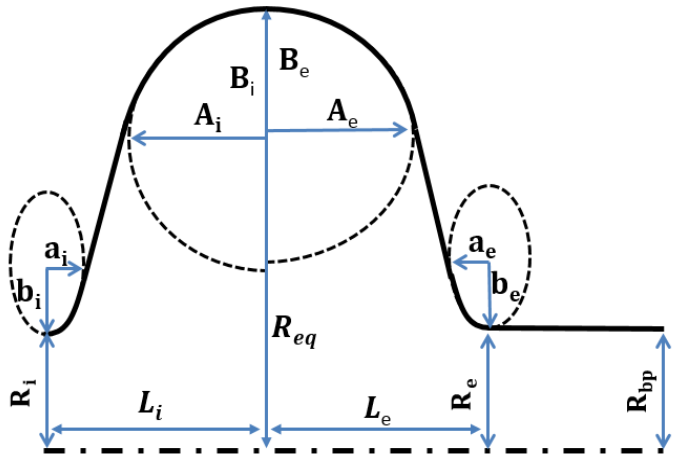
Selecting $ri = 60\ mm$, $\alpha = 100$ and $E_{peak}/E_{acc} = 2.0$ in the optimization problem yields:

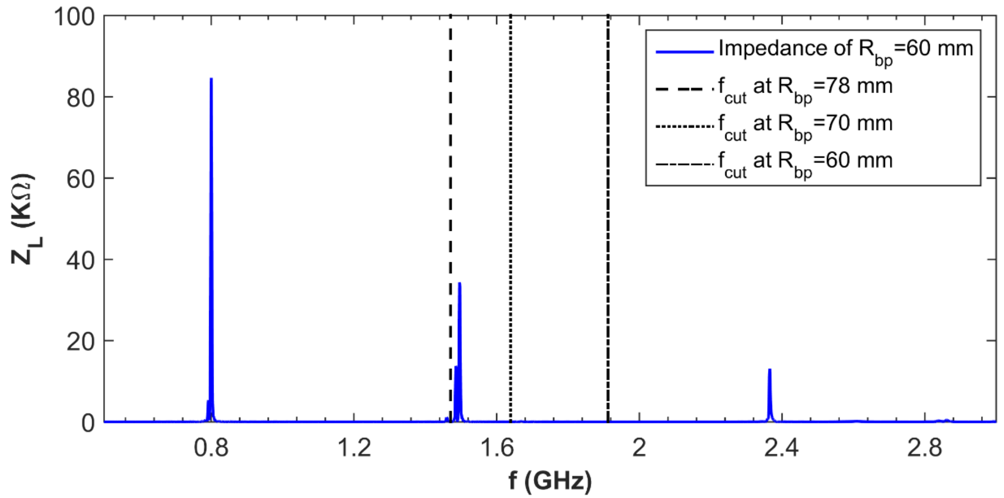
f [MHz]	A [mm]	B [mm]	a [mm]	b [mm]	Ri [mm]	R_{eq} [mm]	L [mm]	α [º]	E_{pk}/E_{acc} _	B_{pk}/E_{acc} $[\frac{mT}{MV/m}]$	R/Q [Ω]	G [Ω]	k [%]
801.58	67.72	57.45	21.75	35.6	60	166.59	93.5	100	2.0	4.2	109.4	272	2.25

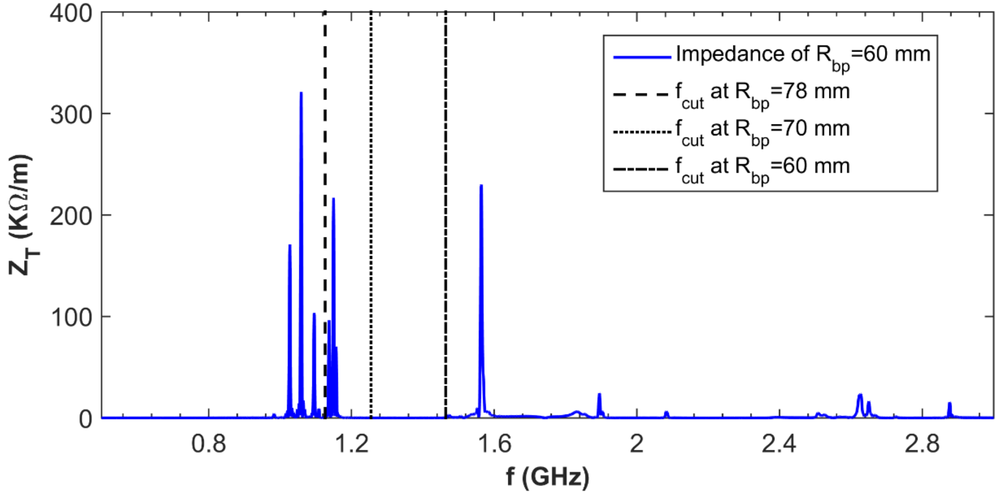
End-cell optimization (I)

The end-cell is optimized under the following considerations:

- Inner half-cell is equal to the optimized mid-cells
- Keep location of E_{peak} and H_{peak} in the inner half-cell
- Vary the end-cell aperture radius to get sufficiently small Q_{ext} in particular in the first monopole and dipole band
- Obtain a flat field along the longitudinal axis
- Avoid having dangerous trapped modes in the cavity





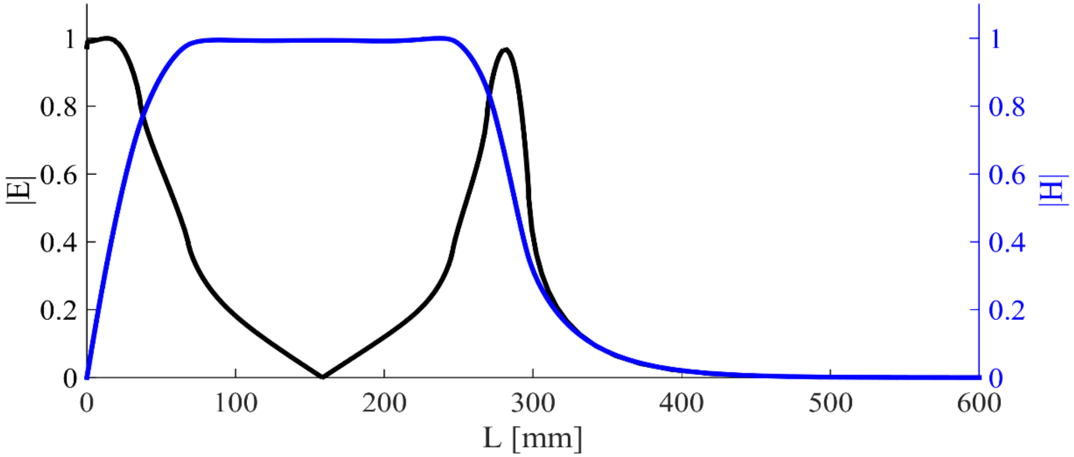


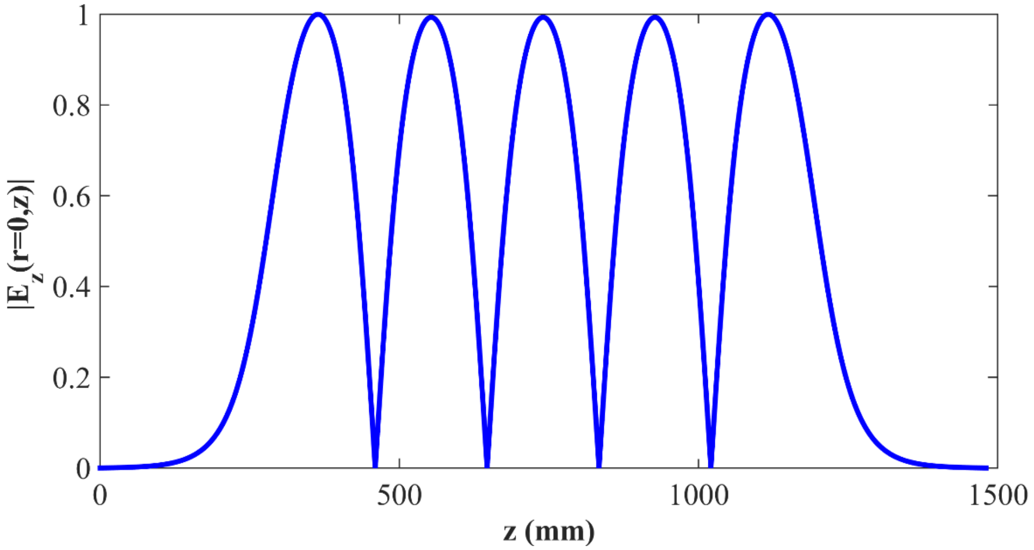
Impedances are for bare cavity and the peaks are not fully resolved.

End-cell optimization (II)

- Parameter sweep in four-dimensional space over the four parameters A_e, B_e, a_e and b_e of the end-cell
- SLANS to simulate the geometry
- The maximum magnetic field in the outer half-cell is 0.5% higher than that in the inner half-cell
- The E_{pk} location is in the inner side of the end-cell
- This automatically yields a high value of field flatness (99%)

Parameters	Value
A_e [mm]	66.5
B_e [mm]	51
a_e [mm]	17
b_e [mm]	23
R_{bp} [mm]	78
R_{eq} [mm]	166.59
L_e [mm]	85.77
α_e [°]	96.9



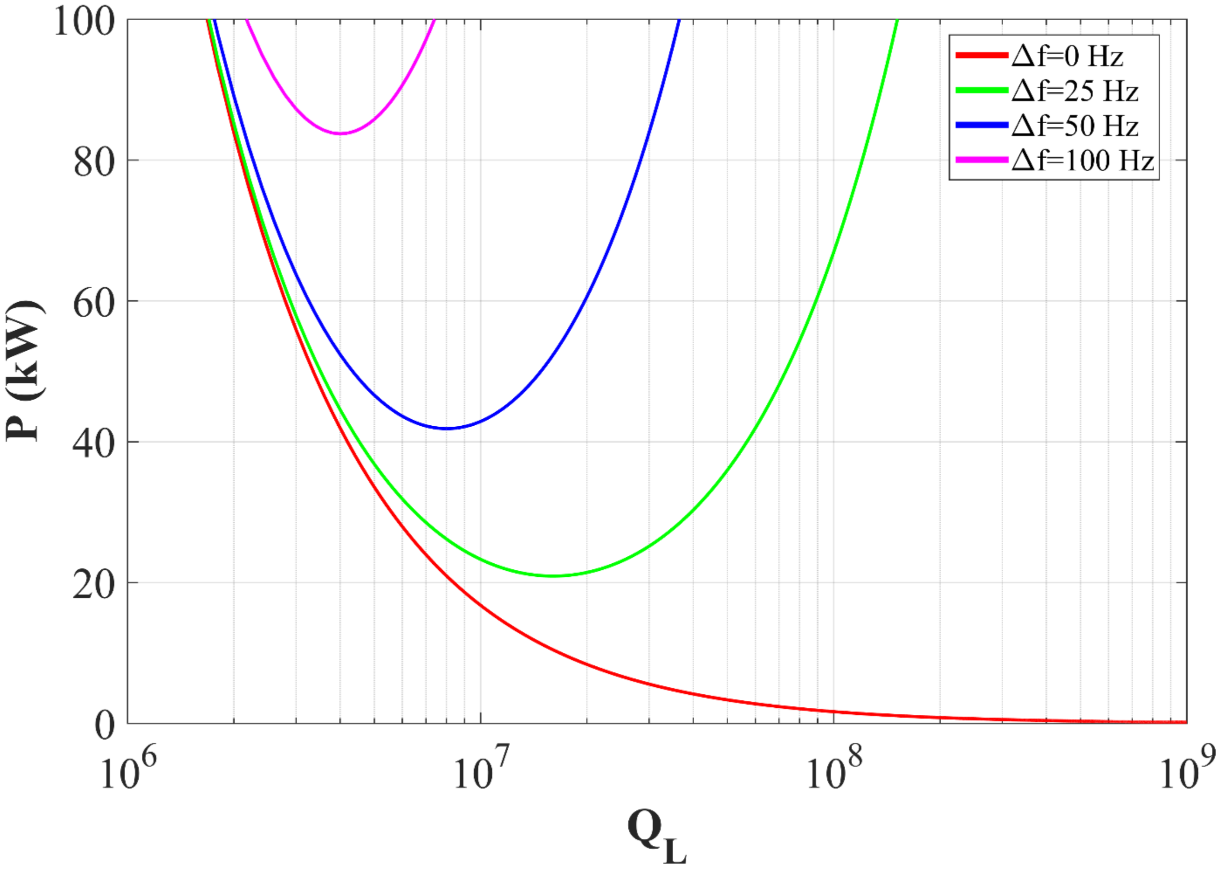


Main Parameters

Parameters	UROS. FCC-ee	CERN LHeC Ver. 2	Jlab Ver. 2
Frequency [MHz]	801.58	801.58	801.58
Number of Cells	5	5	5
Material	Bulk Nb.	Bulk Nb.	Bulk Nb.
Temperature [K]	2.0	2.0	2.0
R/Q [Ω]	521	393	523.9
Geometry Factor [Ω]	273.7	283	274.7
G.R/Q [Ω]	142597	111219	143915
B_{pk}/E_{acc} (mid-cell) $[\mathrm{mT}/(\mathrm{MV}/\mathrm{m})]$	4.2	4.92	4.2
E_{pk}/E_{acc} (mid-cell)	2.0	2.4	2.26
Cavity Active Length [mm]	919.5	935	917.9
Iris radius [mm]	60	80	65
Beam Pipe radius [mm]	78	80	65
Wall angle (mid-cell) [degree]	100	102.5	90
Cell to cell coupling of mid cells [%]	2.25	5.75	3.21
Field Flatness [%]	99	96	-
$k_{\|\|}(\sigma_z = 2\mathrm{mm})$ [V/pC]	3.37	2.63	2.74
Cutoff TE_{11} [GHz]	1.126	1.10	1.35
Cutoff TM_{01} [GHz]	1.471	1.43	1.77
Cryo dynamic losses / cavity (E_{acc}=18.7 MV & Q_0=10^{10}) [W]	67.1	89	66.7
Wall plug power / cavity (COP=800 W/W) [kW]	53.7	71.2	53.4

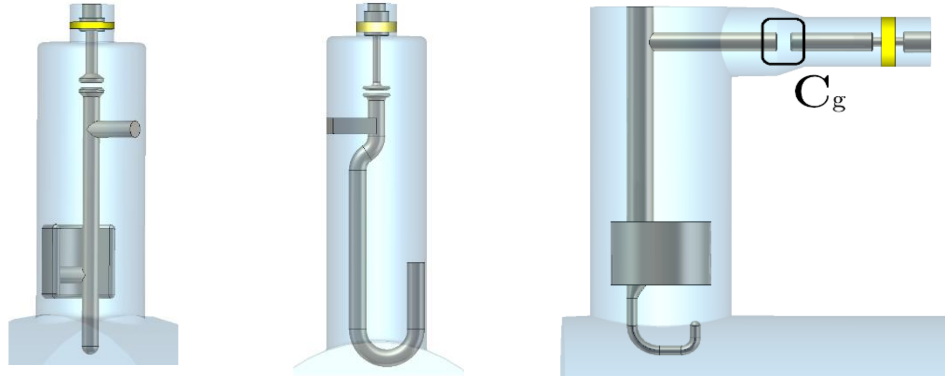
Input Power

Assuming zero beam loading for PERLE operation, with a Q_L of 10^7 and a cavity voltage of 18.7 MV, the required RF power is less than 43 kW. However, this requires that the cavity detuning is less than 50 Hz for stable operation.



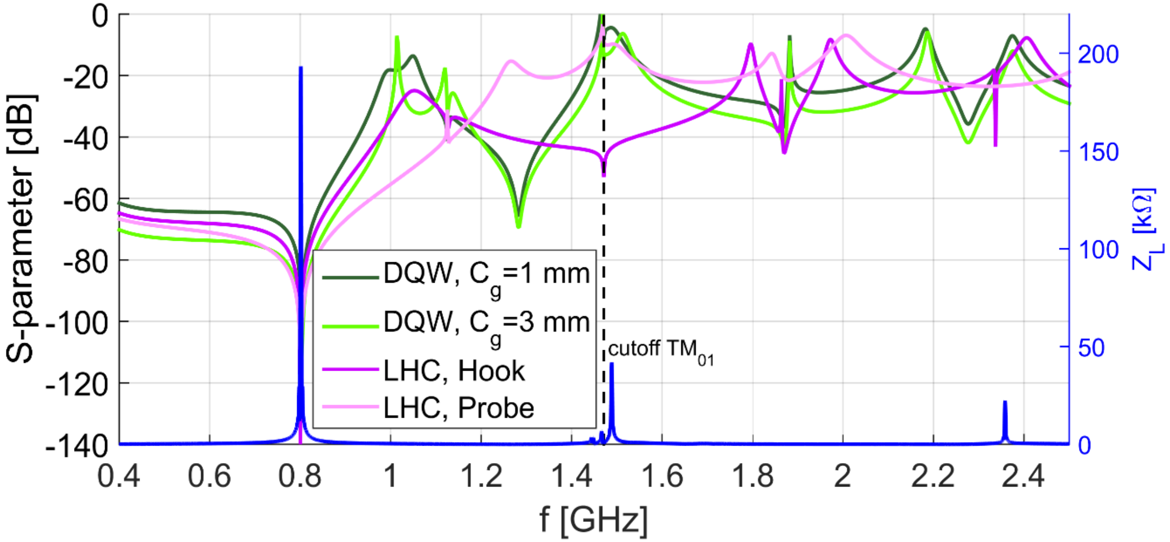
HOM Coupler

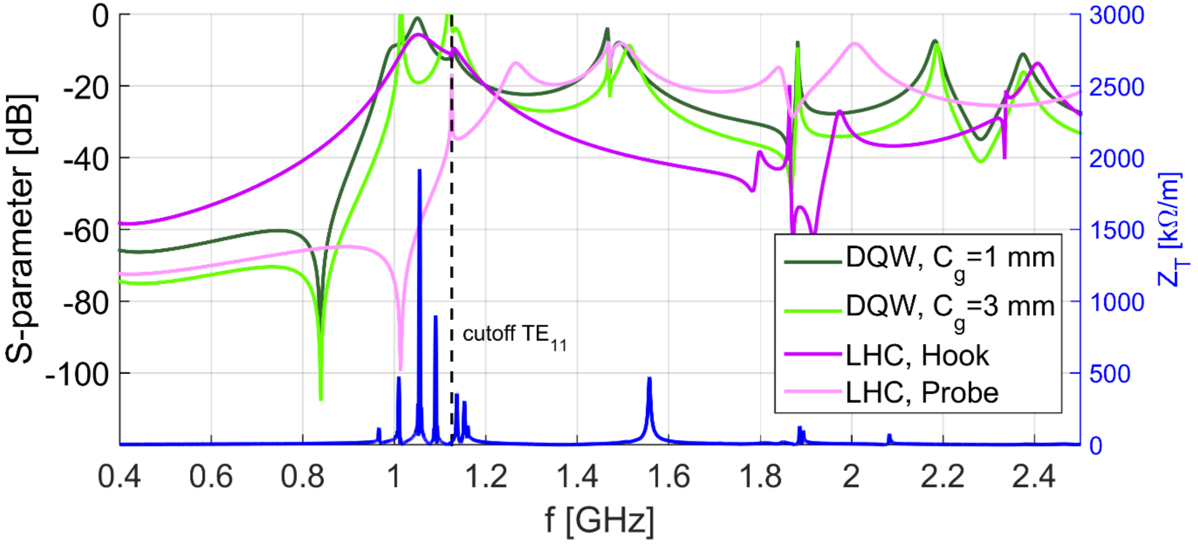
- The notch effect of all couplers is tuned to 801.58 MHz for the monopole coupling.
- The DQW HOM coupler can deliver a high value of transmission at both first higher order dipole and monopole band.



LHC Probe-type *LHC Hook-type* *DQW HOM Coupler*

TM01-TEM transmission (Monopole coupling)



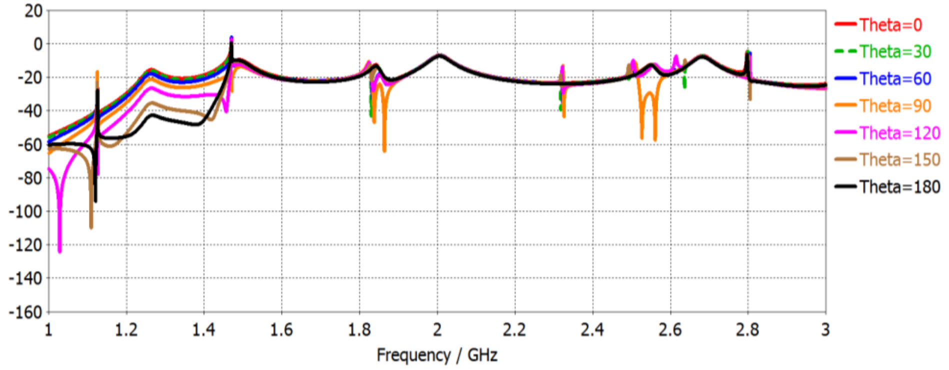


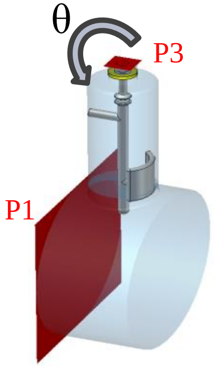
Impedances are for bare cavity and the peaks are not fully resolved.

HOM coupler’s angle

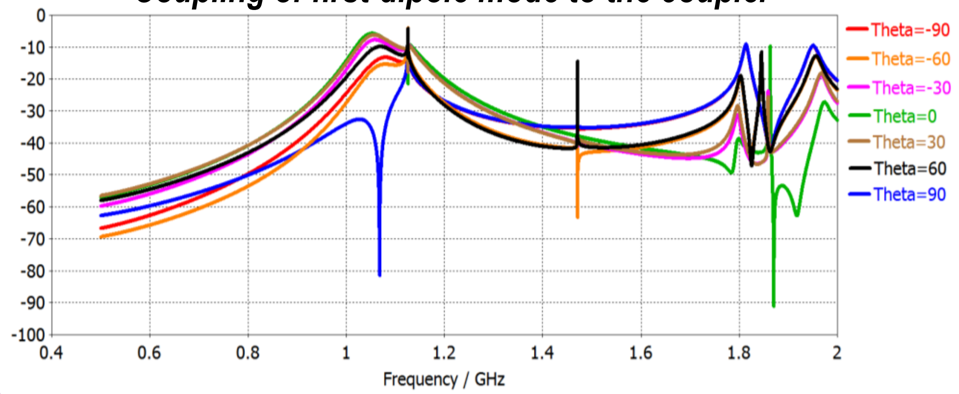
- The angle $\theta = 0$ is selected to have high transmission at first monopole band (1.44 to 1.49 GHz) and first dipole band (0.97 to 1.16 GHz) for monopole and dipole coupling, respectively
- An angle of 90° between the couplers is chosen as an optimal condition in which the sum of shunt impedances of the first dipole band has the lowest value

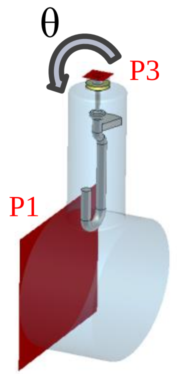
Coupling of first monopole mode to the coupler

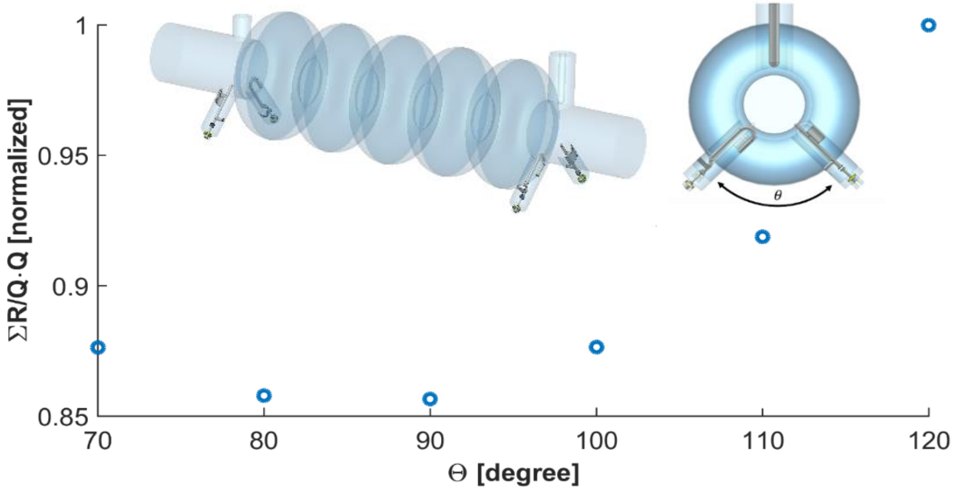




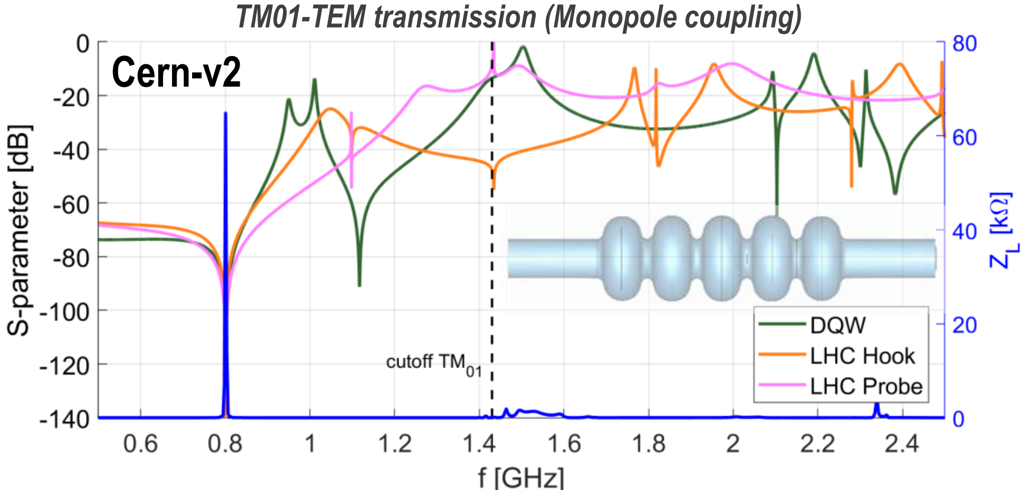
Coupling of first dipole mode to the coupler

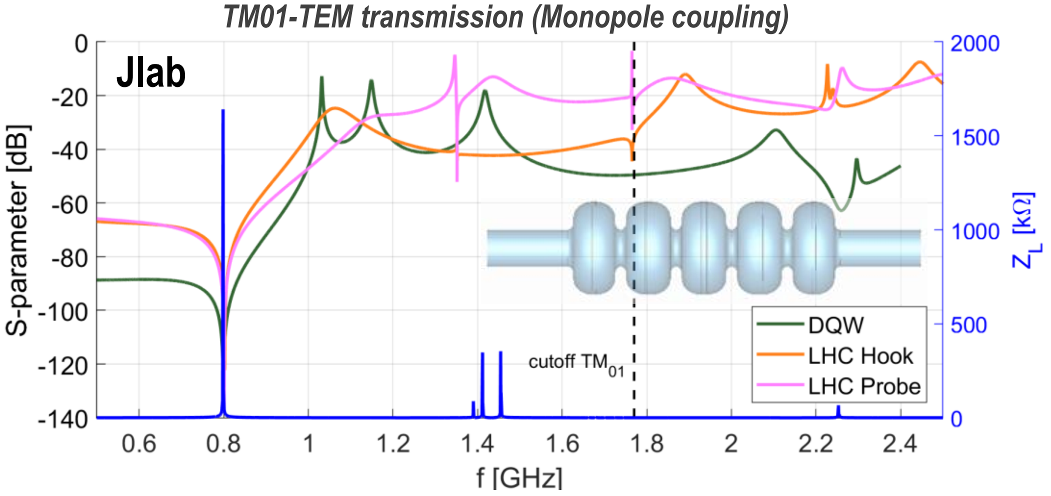


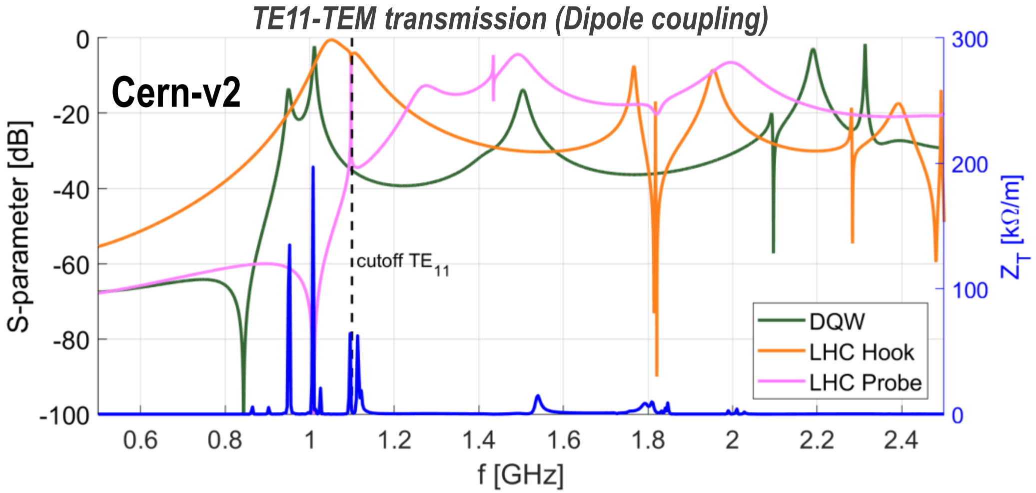


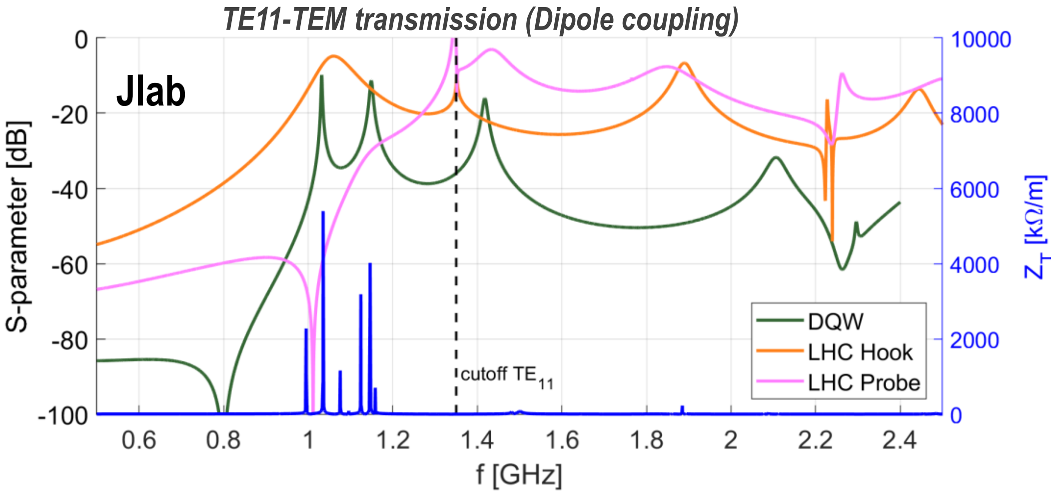


Cernv2 and Jlab 5-cell HOM coupler optimization


TM01-TEM transmission (Monopole coupling)

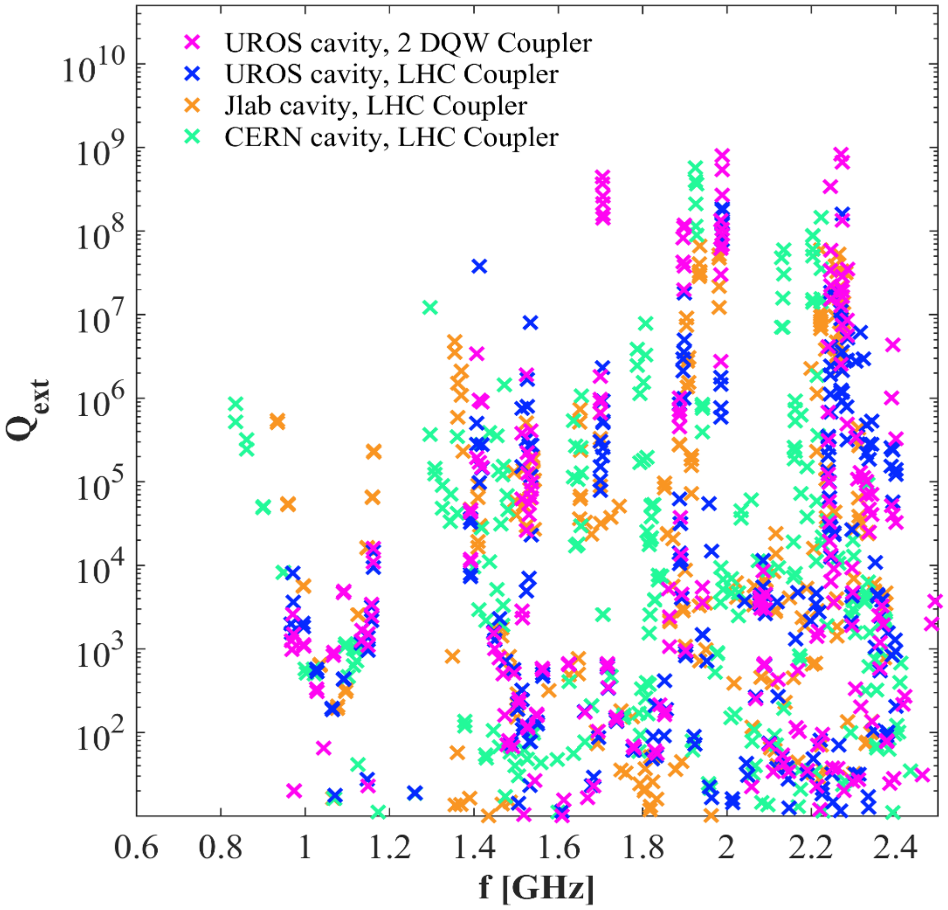

TM01-TEM transmission (Monopole coupling)


TE11-TEM transmission (Dipole coupling)

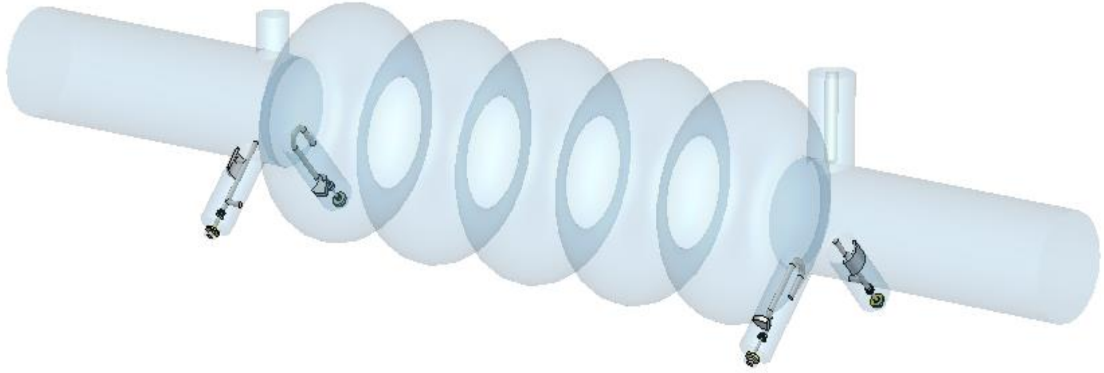

TE11-TEM transmission (Dipole coupling)

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

Q_{ext} of Cernv2, Jlab and UROS cavity



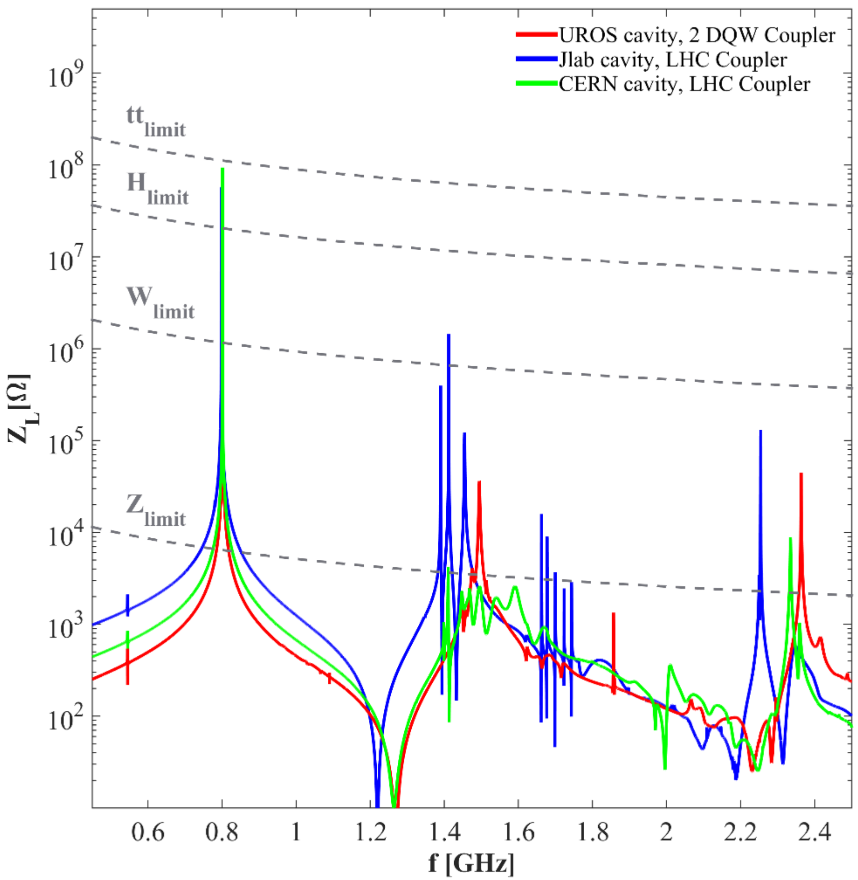
Nonlinear eigenmode solver of CST STUDIO 2018 is used for the calculation of Q_{ext}

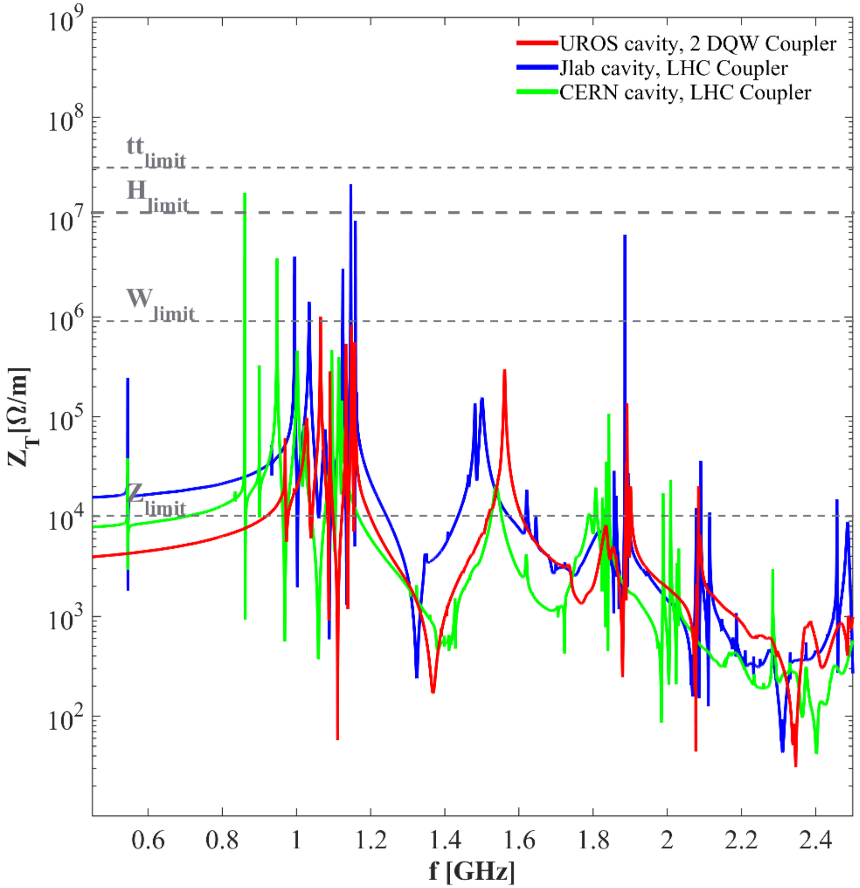


- Q_{ext} of first dipole band of UROS cavity is smaller because the frequencies of the first dipole band modes are more concentrated and could be damped easier by the HOM coupler.
- Few dipole modes of the first dipole band of the UROS cavity are above cutoff frequency and their damping is eased by the help of the beam pipes.
- Using different type of couplers (LHC type couplers) lowers the risk of having high Q_{ext} in frequencies for which the coupler is not tuned (that helps to avoid having a trapped mode with Q_{ext} close to Q_0 of the cavity)

Cernv2, Jlab and UROS cavity impedance with coaxial couplers

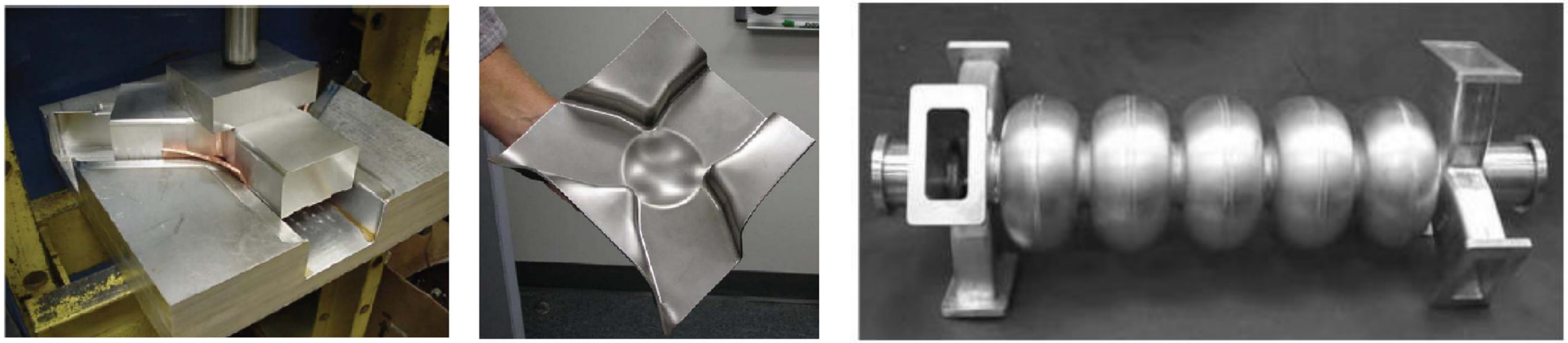
The impedance threshold is given by that impedance for which the growth rate of the instability equals the damping rate of the instability, which typically is defined by synchrotron radiation.





Waveguide HOM coupler

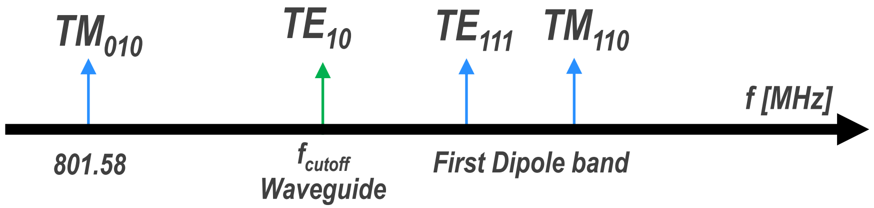
- Waveguide HOM couplers have simpler design and are less sensitive to geometrical perturbations
- A fundamental mode rejection filter is not required
- Above the cutoff frequency rectangular waveguide couplers offer very broadband damping
- HOM power is dissipated at room temperature
- Capable of damping kilowatts
- The bulky shape of couplers complicate the cryomodule design



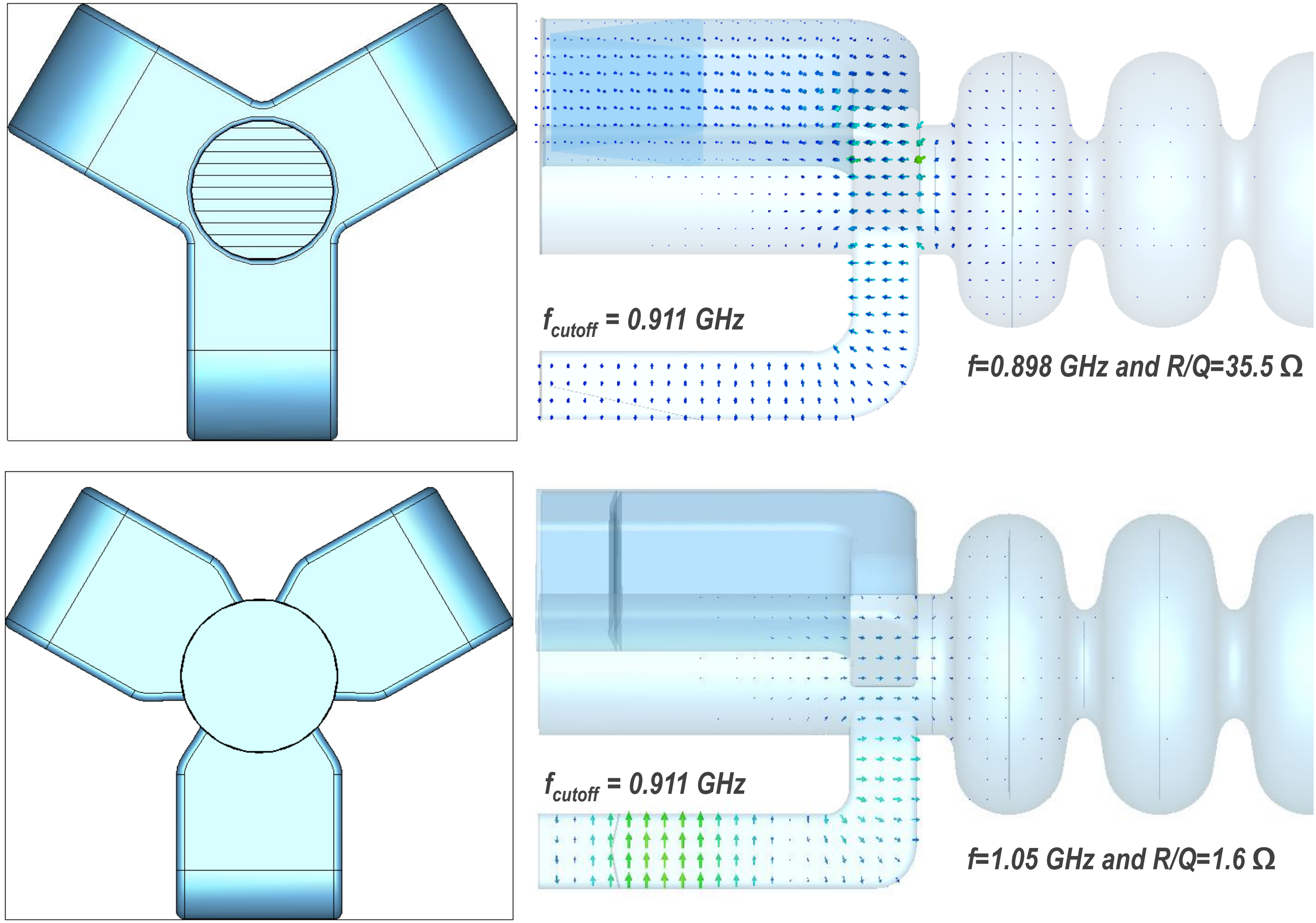
Ref: R. Rimmer et. al. HOM10, Cornell, Waveguide HOM damping studies at JLab Workshop on Higher-Order-Mode Damping in Superconducting RF Cavities (Ithaca, USA)

Waveguide HOM coupler optimization

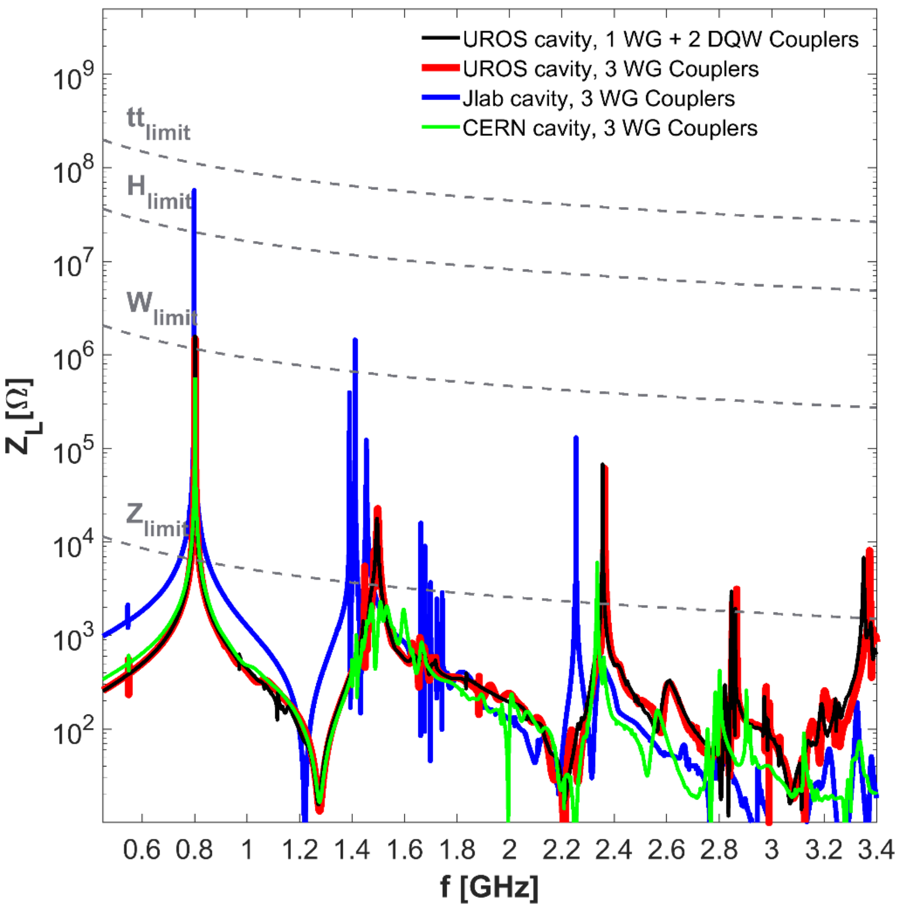
- The cutoff frequency of the first mode of a waveguide HOM coupler has to be between the fundamental mode of the cavity and the first dipole mode.

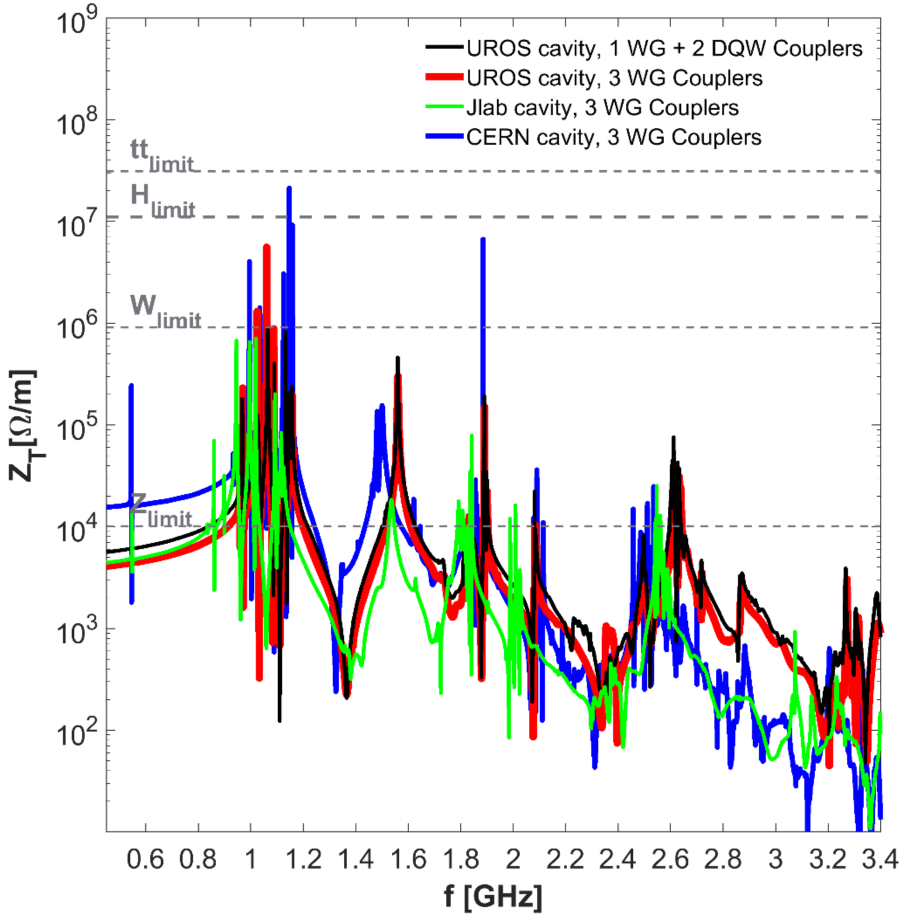


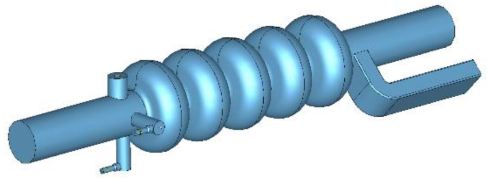
- In designing the waveguide HOM coupler, special attention is given to the modes induced by the waveguide (boundaries of the waveguide can act like a small cavity)



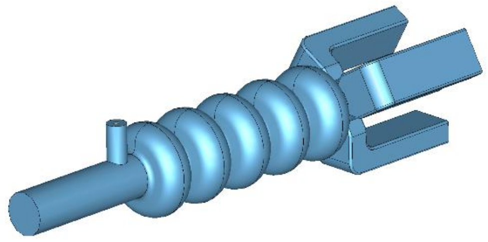
Cernv2, Jlab and UROS cavity impedance with Waveguide damping







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

Coaxial coupler performs better than waveguide couplers in damping the first dipole band

There are different versions of Jlab cavity. For further information see “Next Generation HOM damping” by F. Marhauser

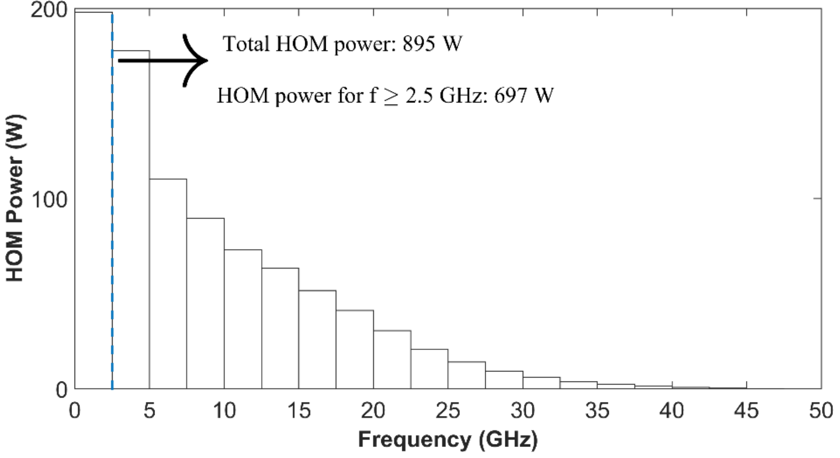
HOM power of 5-cell at 800 MHz

- The average HOM power deposited by the beam in the cavity structure is approximated by $P_{HOM} = k_{||} q_b I$
- If the main spectral line of the beam falls on the HOM resonance of the cavity then the voltage builds up in the cavity and the HOM power can rise significantly. In such a case, the HOM power can be estimated from

$$P_{HOM} = \frac{R}{Q} Q_L \, {I_0}^2$$

- Bunch spectrum of the beam needed to make a more accurate estimation of HOM power

HOM power distribution of $\mathbf{t\bar{t}}$



Average HOM power

	PERLE	tt
5-cell cavity at 800 MHz		
Bunch Length [mm]	3	1.97/2.54
P [kW]	0.01	1.09/0.89

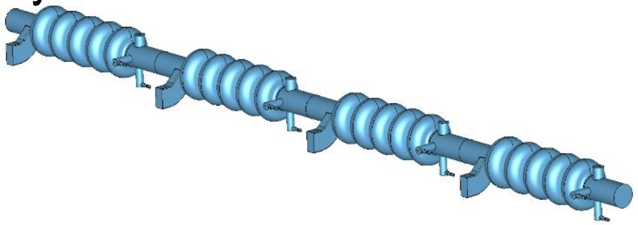
* Average HOM power calculated from $P_{HOM} = k_{||} q_b I$

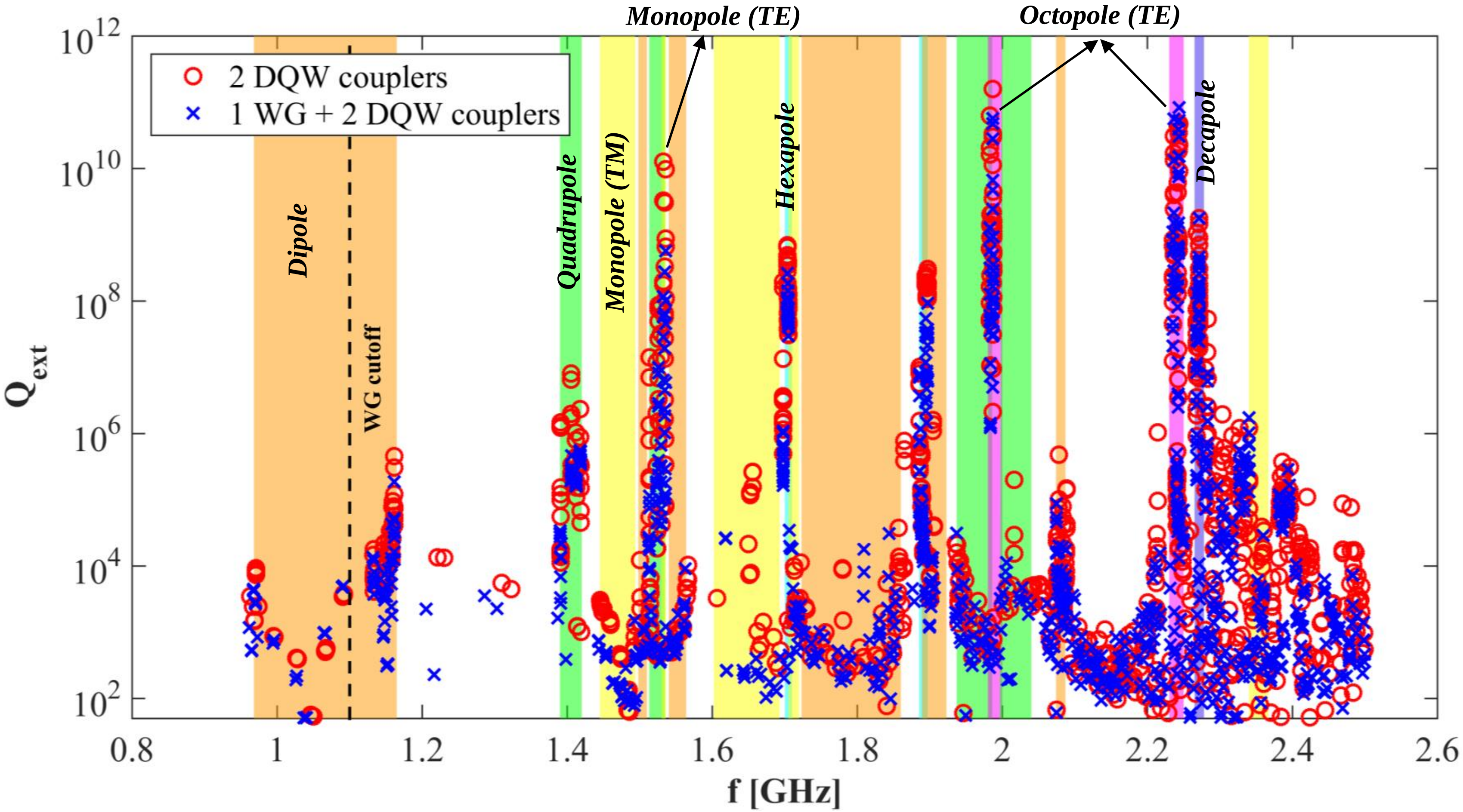
	PERLE	tt
5-cell cavity at 800 MHz		
f^* [GHz]	P_{res} [W]	
1.49	16	8
2.36	20	10

* Resonance excitation power of two monopole modes with the highest longitudinal impedance

Quality factor of modes in a 4-cavity module

- Above the waveguide's cutoff frequency 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.





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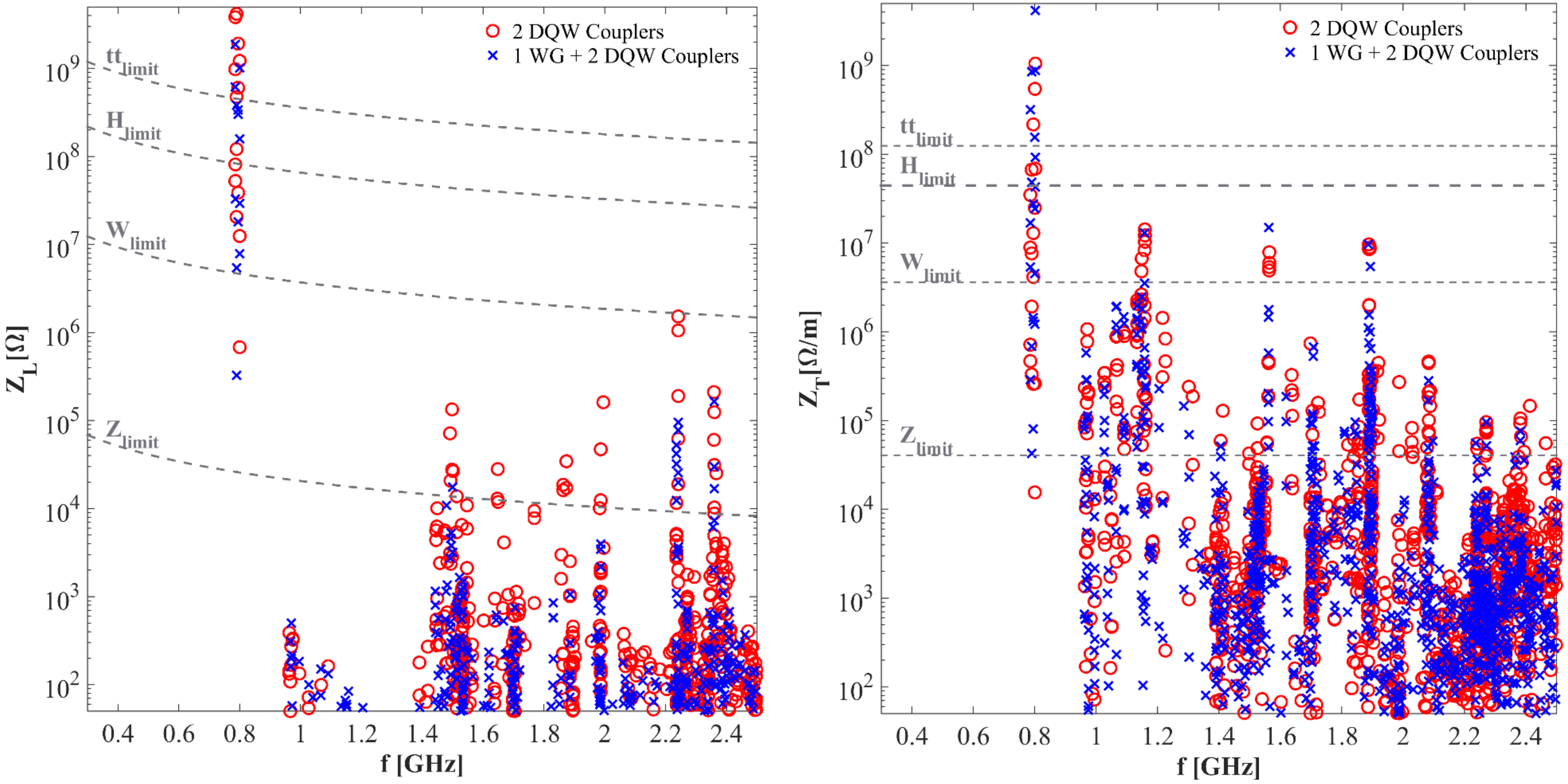
Traditio et Innovatio

Impedance of a 4-cavity module

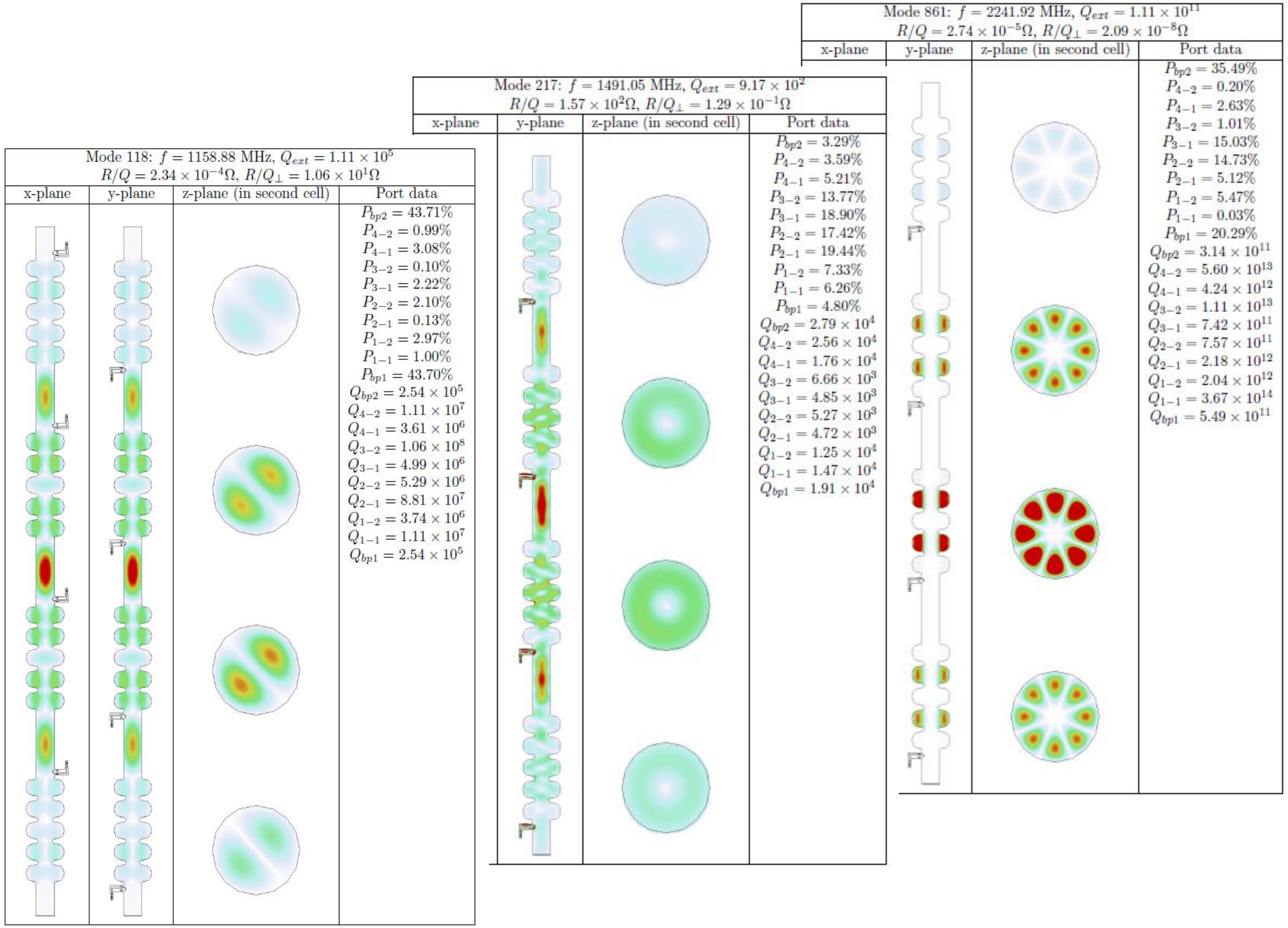
- The stability threshold can increase by 1-2 orders of magnitude if the frequency spread between modules is taken into account.
- Using a feedback system can increase the stability threshold above the synchrotron radiation limit.



Impedance thresholds are normalized to the number of modules

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.



Mode 118: $f = 1158.88$ MHz, $Q_{ext} = 1.11 \times 10^5$
$R/Q = 2.34 \times 10^{-4}\Omega$, $R/Q_\perp = 1.06 \times 10^1\Omega$

x-plane	y-plane	z-plane (in second cell)	Port data
			$P_{bp2} = 43.71\%$ $P_{4-2} = 0.99\%$ $P_{4-1} = 3.08\%$ $P_{3-2} = 0.10\%$ $P_{3-1} = 2.22\%$ $P_{2-2} = 2.10\%$ $P_{2-1} = 0.13\%$ $P_{1-2} = 2.97\%$ $P_{1-1} = 1.00\%$ $P_{bp1} = 43.70\%$ $Q_{bp2} = 2.54 \times 10^5$ $Q_{4-2} = 1.11 \times 10^7$ $Q_{4-1} = 3.61 \times 10^6$ $Q_{3-2} = 1.06 \times 10^8$ $Q_{3-1} = 4.99 \times 10^6$ $Q_{2-2} = 5.29 \times 10^6$ $Q_{2-1} = 8.81 \times 10^7$ $Q_{1-2} = 3.74 \times 10^6$ $Q_{1-1} = 1.11 \times 10^7$ $Q_{bp1} = 2.54 \times 10^5$

Mode 217: $f = 1491.05$ MHz, $Q_{ext} = 9.17 \times 10^2$
$R/Q = 1.57 \times 10^2\Omega$, $R/Q_\perp = 1.29 \times 10^{-1}\Omega$

x-plane	y-plane	z-plane (in second cell)	Port data
			$P_{bp2} = 3.29\%$ $P_{4-2} = 3.59\%$ $P_{4-1} = 5.21\%$ $P_{3-2} = 13.77\%$ $P_{3-1} = 18.90\%$ $P_{2-2} = 17.42\%$ $P_{2-1} = 19.44\%$ $P_{1-2} = 7.33\%$ $P_{1-1} = 6.26\%$ $P_{bp1} = 4.80\%$ $Q_{bp2} = 2.79 \times 10^4$ $Q_{4-2} = 2.56 \times 10^4$ $Q_{4-1} = 1.76 \times 10^4$ $Q_{3-2} = 6.66 \times 10^3$ $Q_{3-1} = 4.85 \times 10^3$ $Q_{2-2} = 5.27 \times 10^3$ $Q_{2-1} = 4.72 \times 10^3$ $Q_{1-2} = 1.25 \times 10^4$ $Q_{1-1} = 1.47 \times 10^4$ $Q_{bp1} = 1.91 \times 10^4$

Mode 861: $f = 2241.92$ MHz, $Q_{ext} = 1.11 \times 10^{11}$
$R/Q = 2.74 \times 10^{-5}\Omega$, $R/Q_\perp = 2.09 \times 10^{-8}\Omega$

x-plane	y-plane	z-plane (in second cell)	Port data
			$P_{bp2} = 35.49\%$ $P_{4-2} = 0.20\%$ $P_{4-1} = 2.63\%$ $P_{3-2} = 1.01\%$ $P_{3-1} = 15.03\%$ $P_{2-2} = 14.73\%$ $P_{2-1} = 5.12\%$ $P_{1-2} = 5.47\%$ $P_{1-1} = 0.03\%$ $P_{bp1} = 20.29\%$ $Q_{bp2} = 3.14 \times 10^{11}$ $Q_{4-2} = 5.60 \times 10^{13}$ $Q_{4-1} = 4.24 \times 10^{12}$ $Q_{3-2} = 1.11 \times 10^{13}$ $Q_{3-1} = 7.42 \times 10^{11}$ $Q_{2-2} = 7.57 \times 10^{11}$ $Q_{2-1} = 2.18 \times 10^{12}$ $Q_{1-2} = 2.04 \times 10^{12}$ $Q_{1-1} = 3.67 \times 10^{14}$ $Q_{bp1} = 5.49 \times 10^{11}$

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Summary

- An optimization method was used to optimize the mid-cells for minimal losses with constraints on the different figures of merit of an elliptical cavity.
- The end-cell was designed to maintain field-flatness in the cavity and also to allow sufficient HOM damping without significantly changing E_{pk}/E_{acc} and B_{pk}/E_{acc} of the cavity.
- A DQW HOM coupler can yield similar performance as a combination of both LHC-type couplers in damping of dangerous monopole and dipole modes of the designed cavity.
- The HOM power of PERLE operation is in the order of ten Watt.
- Waveguide couplers were compared with coaxial HOM couplers. Multiple waveguides is an overkill and not practical. However, 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 .
- A catalogue containing the mode spectrum of the module is created that can serve as reference for beam dynamic analysis.