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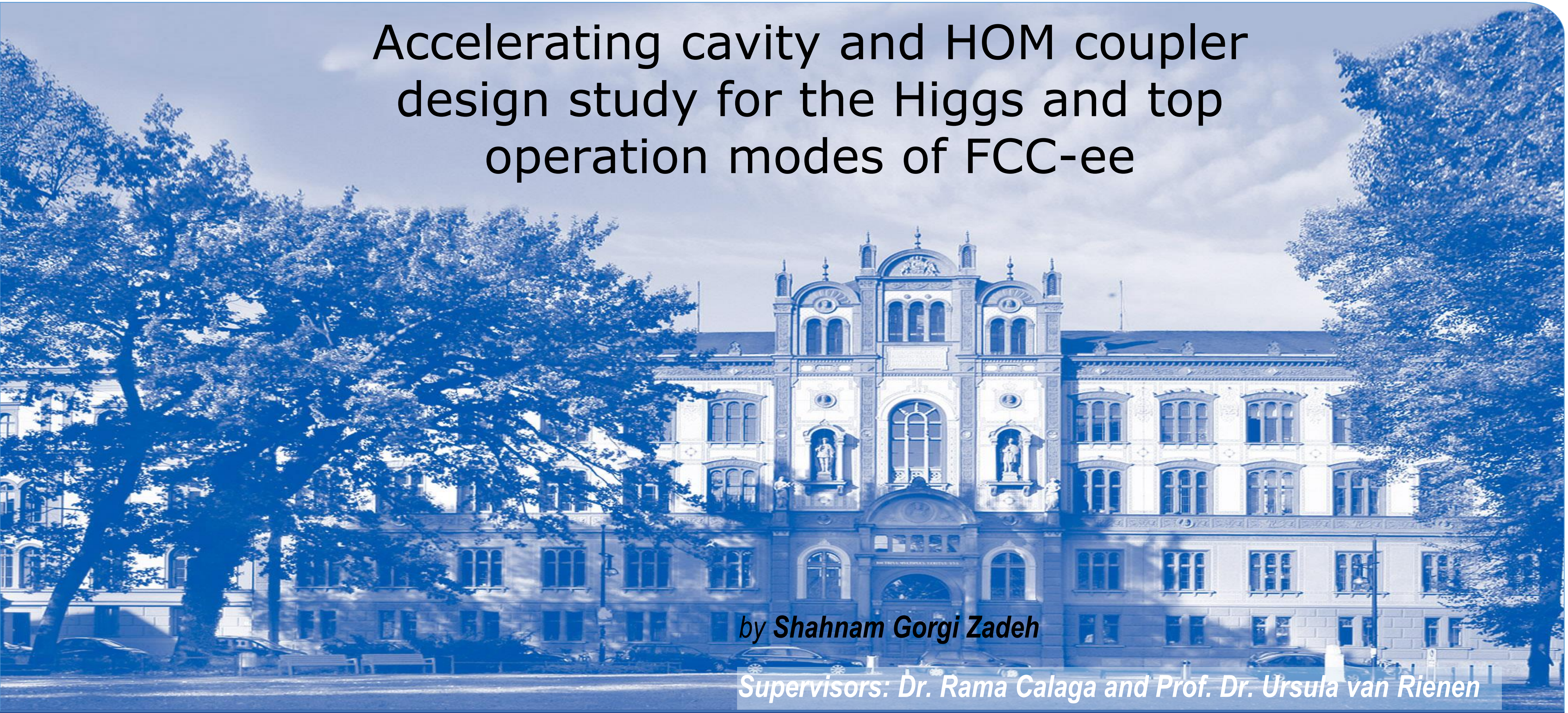

Accelerating cavity and HOM coupler design study for the Higgs and top operation modes of FCC-ee

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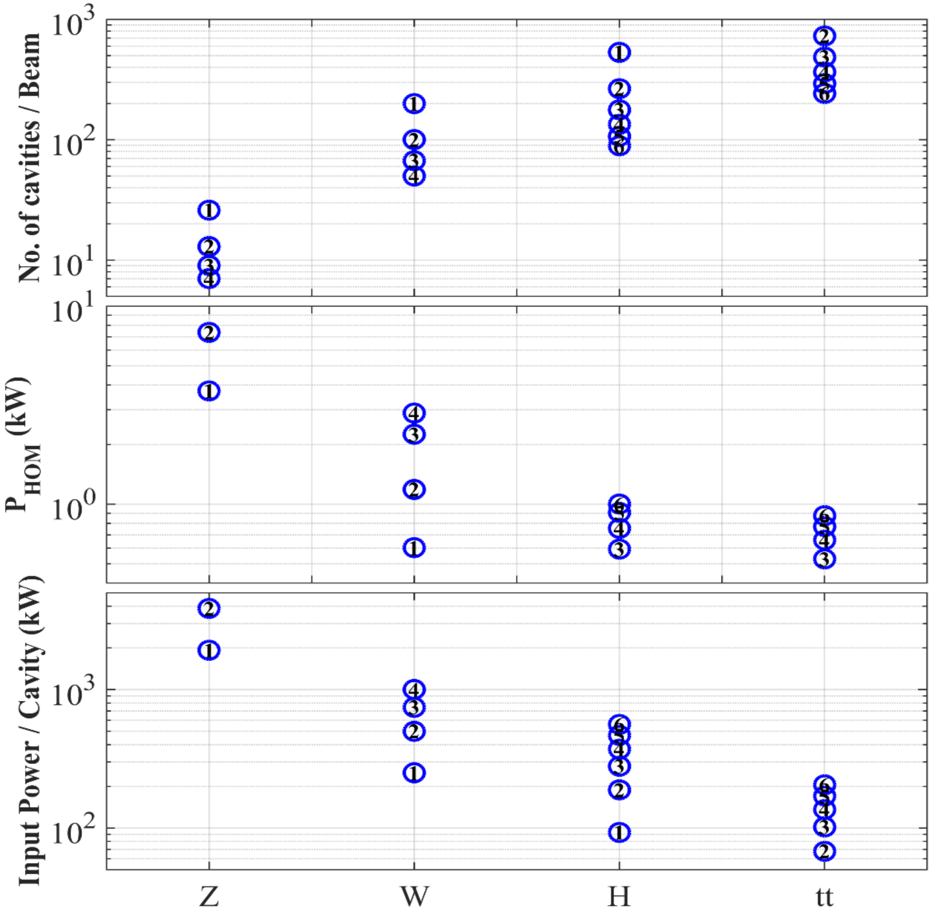
RF parameters

	FCC-Z	FCC-W	FCC-H	FCC-$t\bar{t}$	LEP2
Energy/beam [GeV]	45.6	80	120	182.5	105
Bunches/beam	16640	2000	328	48	4
Bunch Population [10^{11}]	1.7	1.5	1.8	2.3	4.2
RMS Bunch Length (SR/BS) [mm]	3.5/12.1	3.0/6.0	2.75/3.82	1.97/2.54	11.5
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
Energy Loss/turn [GeV]	0.036	0.34	1.72	9.21	3.34
RF Voltage [GV]	0.1	0.75	2.0	10.93	3.5

- For the Z-pole a single-cell Nb/Cu cavity at 400 MHz is chosen as a baseline.
- Multi-cell cavity is considered for W, H and $t\bar{t}$ (4-cell cavity at 400 MHz and 5-cell cavity at 800 MHz are studied).



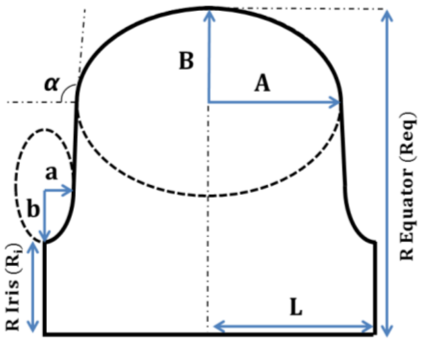
- The numbers inscribed in the circle markers indicate the number of cells per cavity
- The number of cavities is determined by the upper limit of E_{acc}=10 MV/m
- The plots are for 400 MHz cavities
- HOM power is calculated for BS bunch length

Mid-cell optimization (I)

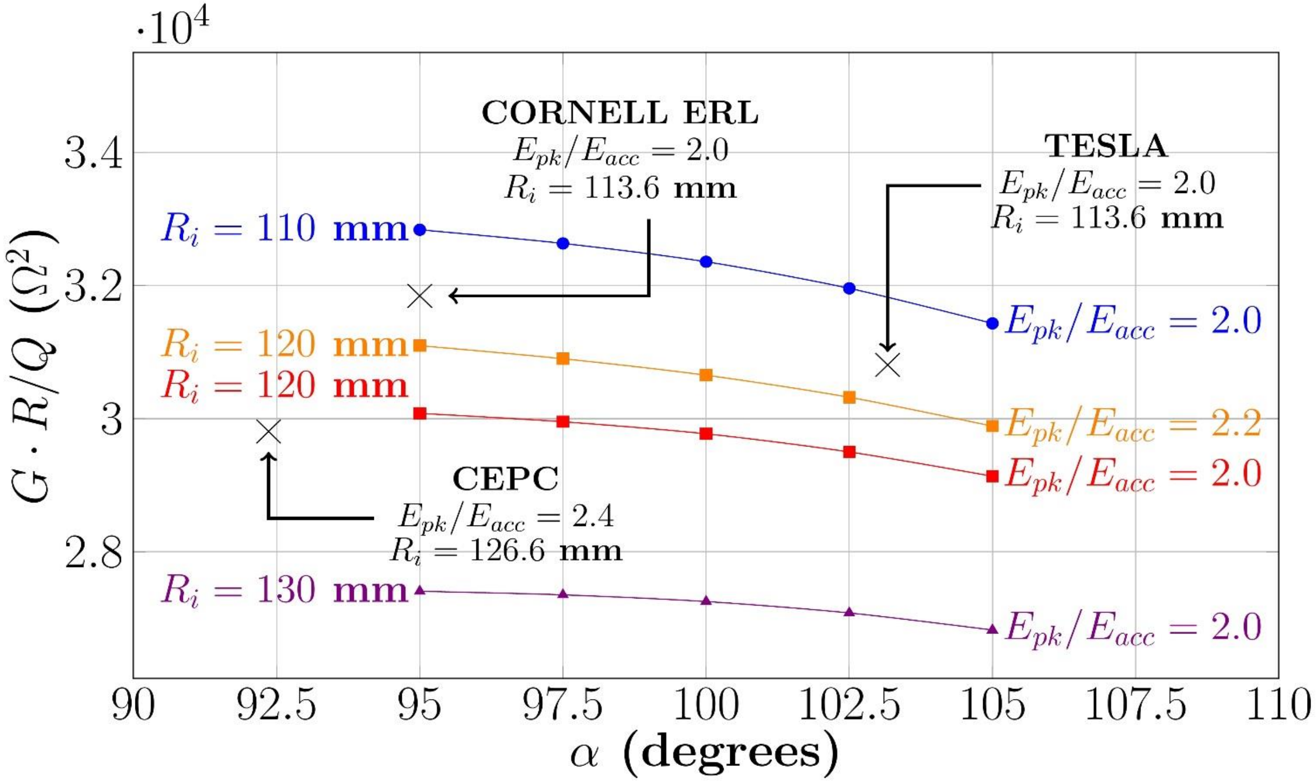
Minimizing the intrinsic cavity losses can save considerable energy on large scale for huge machines such as FCC_eeH and FCC_eett̄ .

Optimization problem of mid-cell can be formulated as:

$$\max_{A,B,a,b} G.R/Q$$
$$\text{s.t. } E_{pk}/E_{acc} \leq c_1$$
$$\alpha \geq c_2$$
$$R_i = c_3$$



Cavity Parametrization

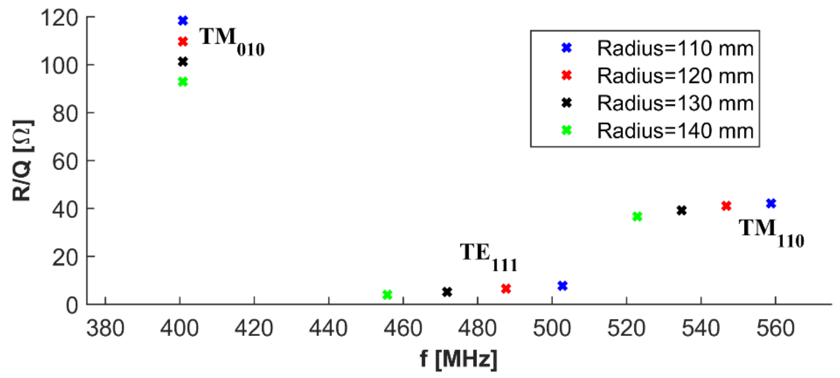


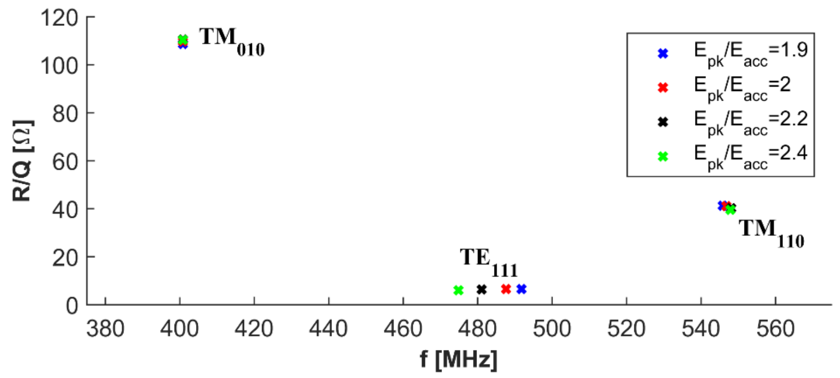
- All radii are for cavities scaled to 400.79 MHz

Mid-cell optimization (II)

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

- High value of R/Q for 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





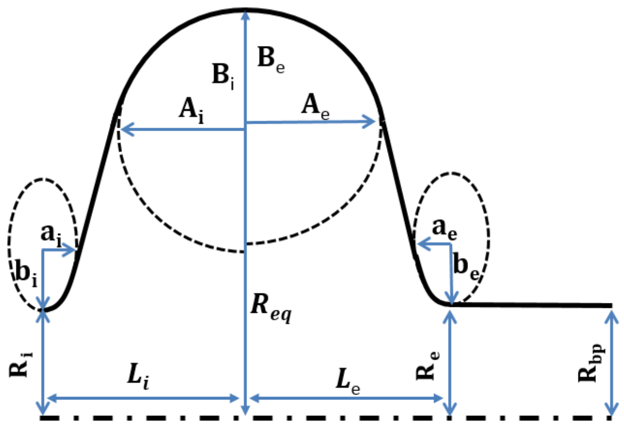
Selecting $Ri = 120\ mm$, $\alpha = 100$ and $E_{peak}/E_{acc} = 2.0$ in the optimization problem yields:

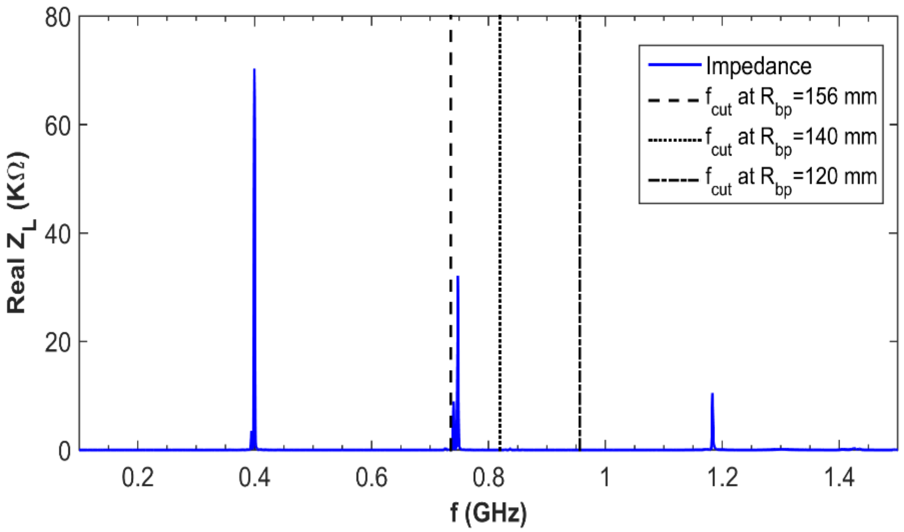
f [MHz]	A [mm]	B [mm]	a [mm]	b [mm]	Ri [mm]	R_{eq} [mm]	L [mm]	α [º]	E_{pk}/E_{acc} –	B_{pk}/E_{acc} $[\frac{mT}{MV/m}]$	R/Q [Ω]	G [Ω]	k [%]
400.79	135.44	114.90	43.50	71.19	120	333.182	187	100	2.0	4.2	109.5	272.3	2.25

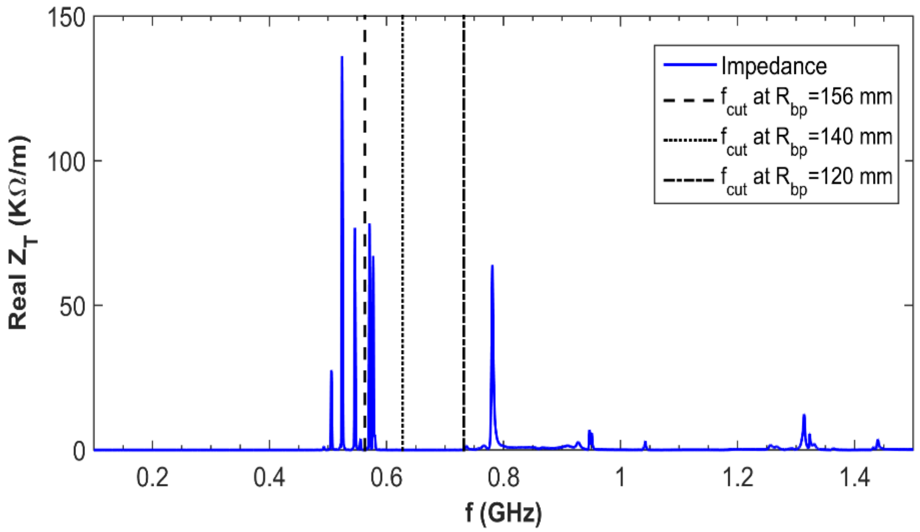
End-cell optimization (I)

End-cell is optimized with the following considerations:

- Inner half-cell is equal with 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



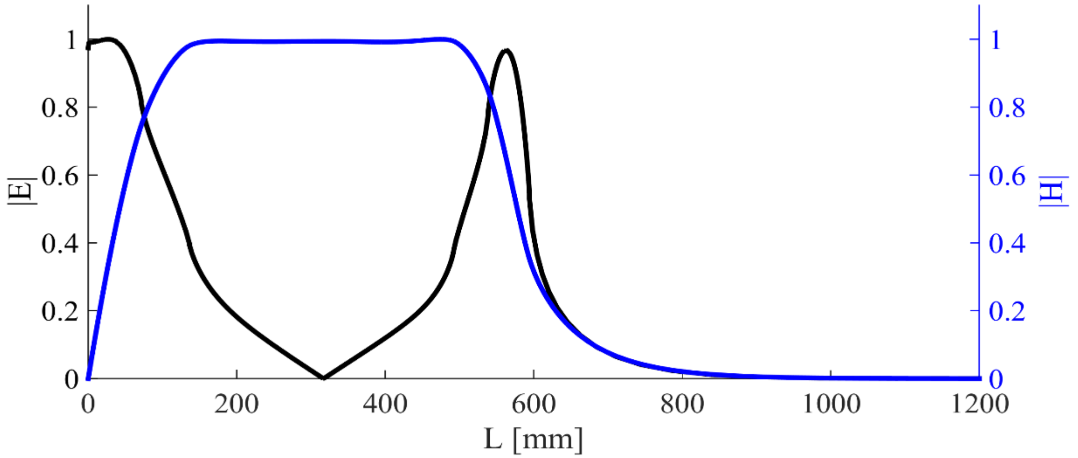




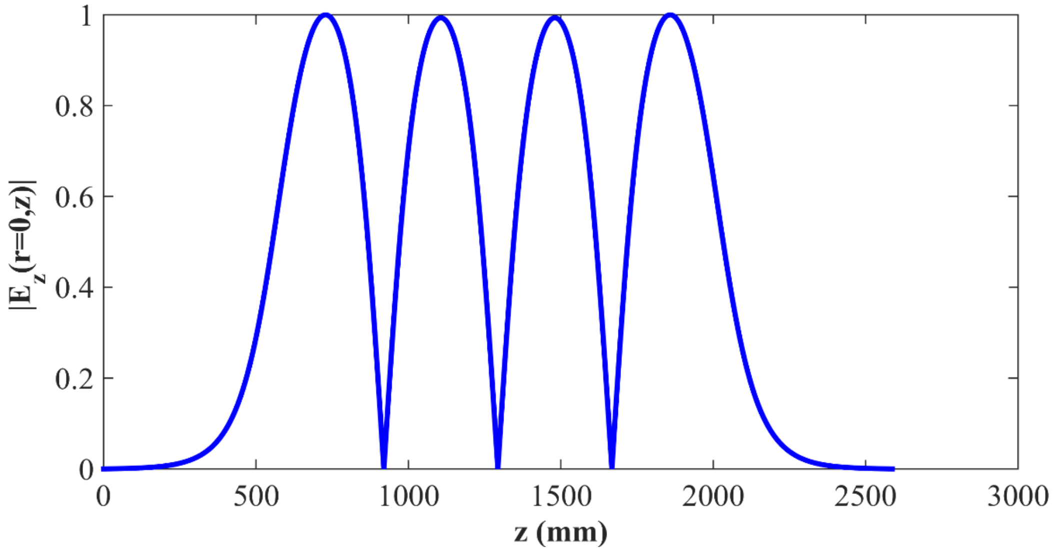
Impedances are for bare cavity and the peaks are not fully resolved.

End-cell optimization (II)

- A parameter sweep in four-dimensional space over four parameters A_e, B_e, a_e and b_e of the end-cell is carried out
- SLANS is used 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
- A high value of field flatness (99%) is obtained automatically



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



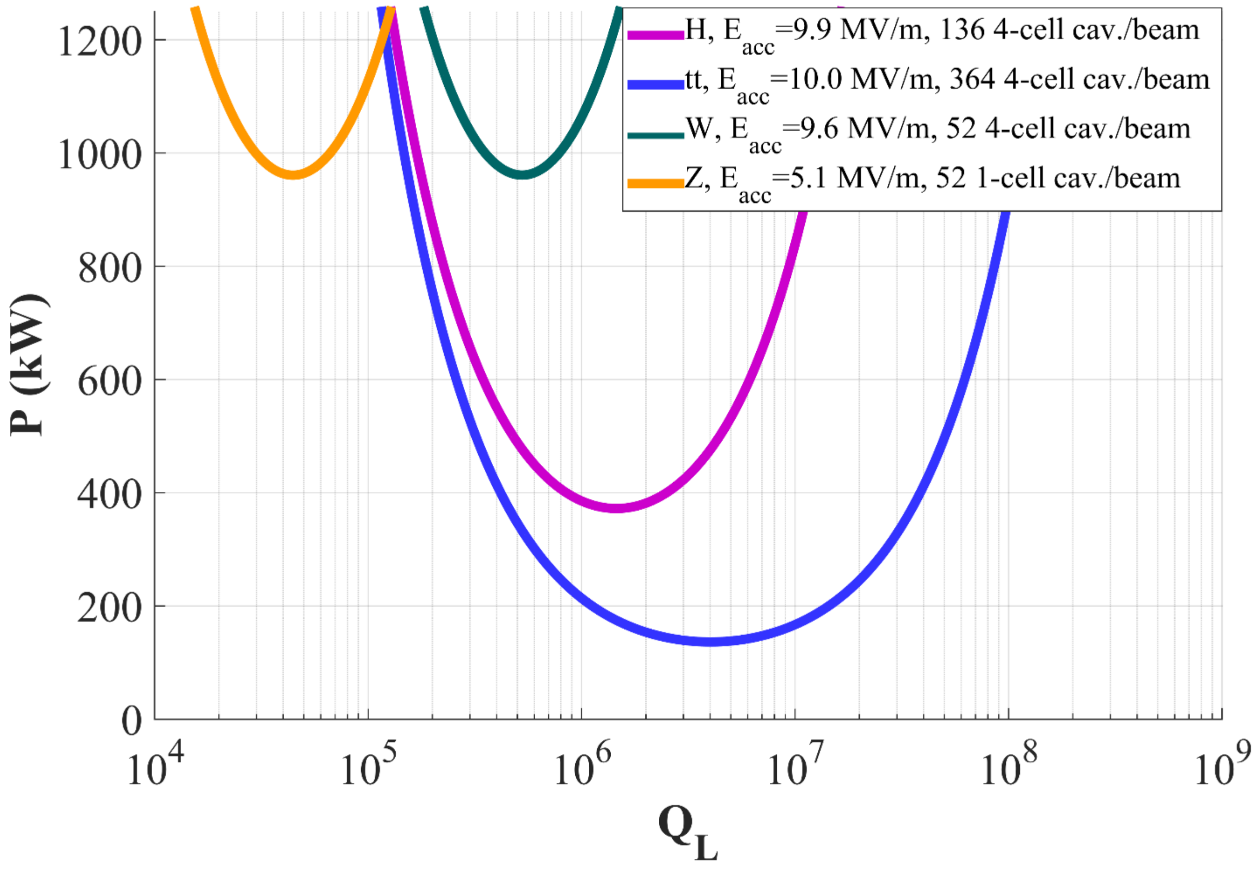
Main Parameters

Parameters	Ros. FCC-ee	Ros. 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
R/Q [Ω]	411	521	393	523.9
Geometry Factor [Ω]	273.2	273.7	283	274.7
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
E_{acc} [MV/m]	10	20	20	20
No. of cavities needed for H machine	134×2	108×2	108×2	108×2
Cutoff TE_{11} [GHz]	0.563	1.126	1.10	1.35
Cutoff TM_{01} [GHz]	0.7355	1.471	1.43	1.77

Input Coupler

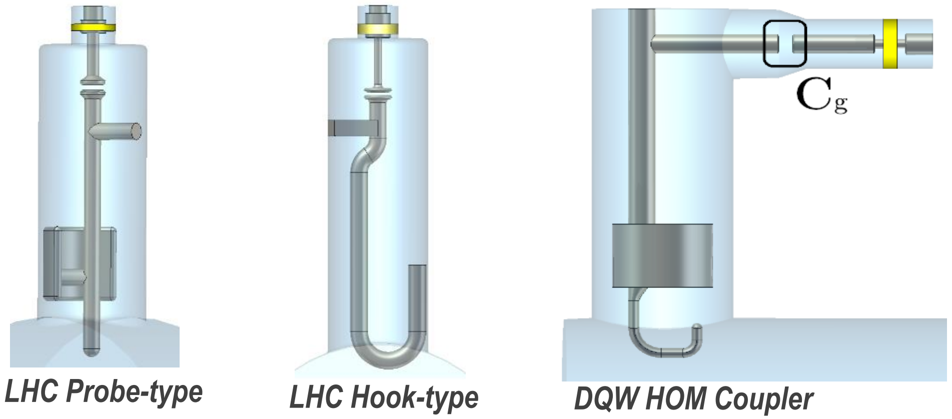
The impedance between generator and combined beam-cavity system should be matched in order to minimize reflected power, consequently allowing to transfer maximum power to the cavity and thus to the beam.

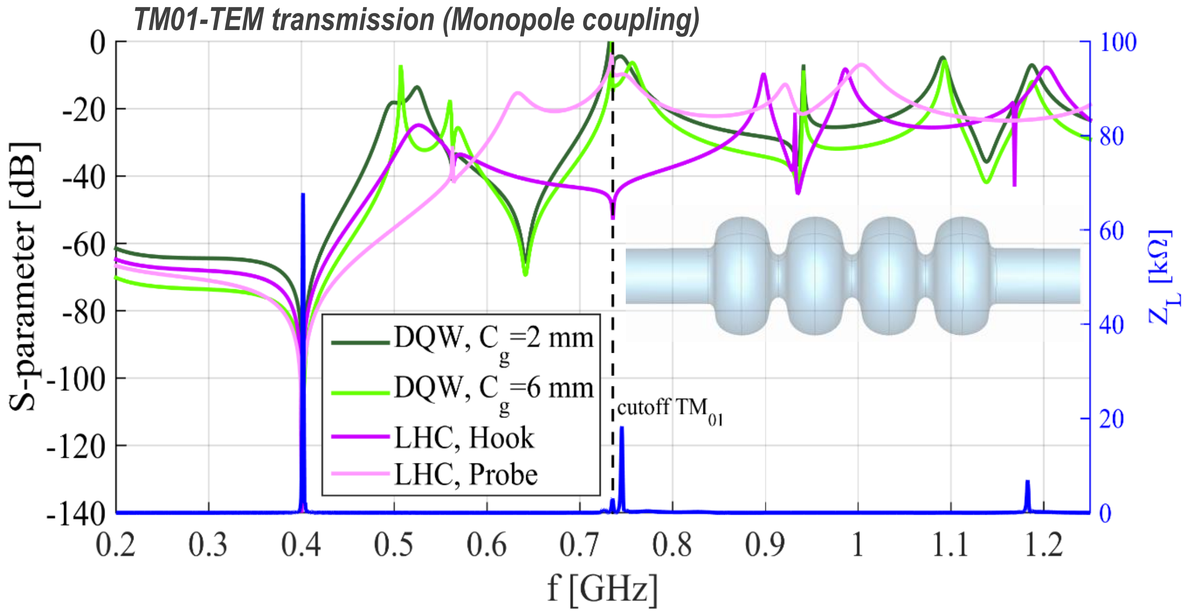
- Operating 52 cavities at optimum Q_L of W results into around 11% and 21% increase in the total power for H and $t\bar{t}$ operations, respectively.
- Operating 272 cavities at $Q_L = 2 \times 10^6$ for H and $t\bar{t}$ results into around 4% increase in total power in comparison with operating all cavities at their optimal point.
- With a fixed E_{acc}, changing the number of cells has insignificant influence on optimum Q_L because $Q_{L-opt} \propto V_{cav}/(R/Q)$

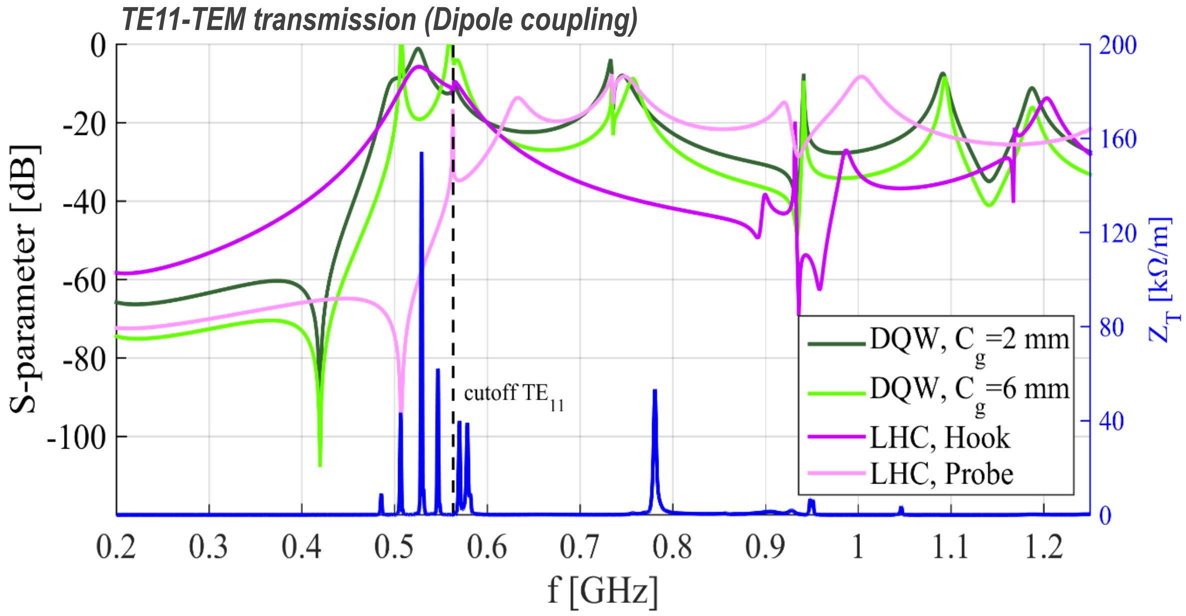


HOM Coupler

- The notch effect of all couplers is tuned to 400.79 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.





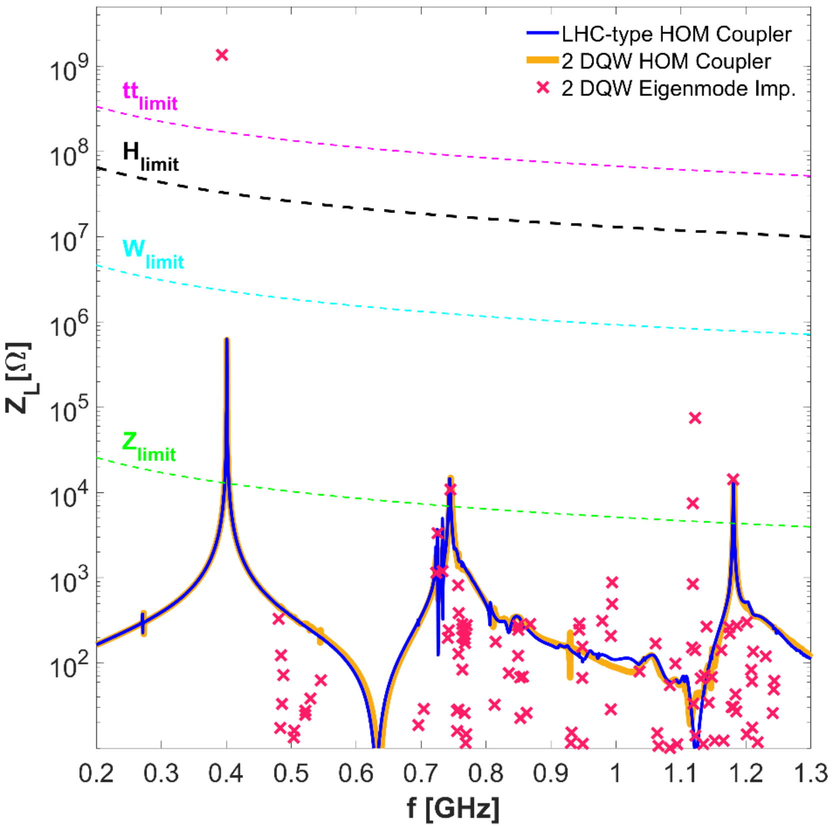


Impedances are for bare cavity and the peaks are not fully resolved.

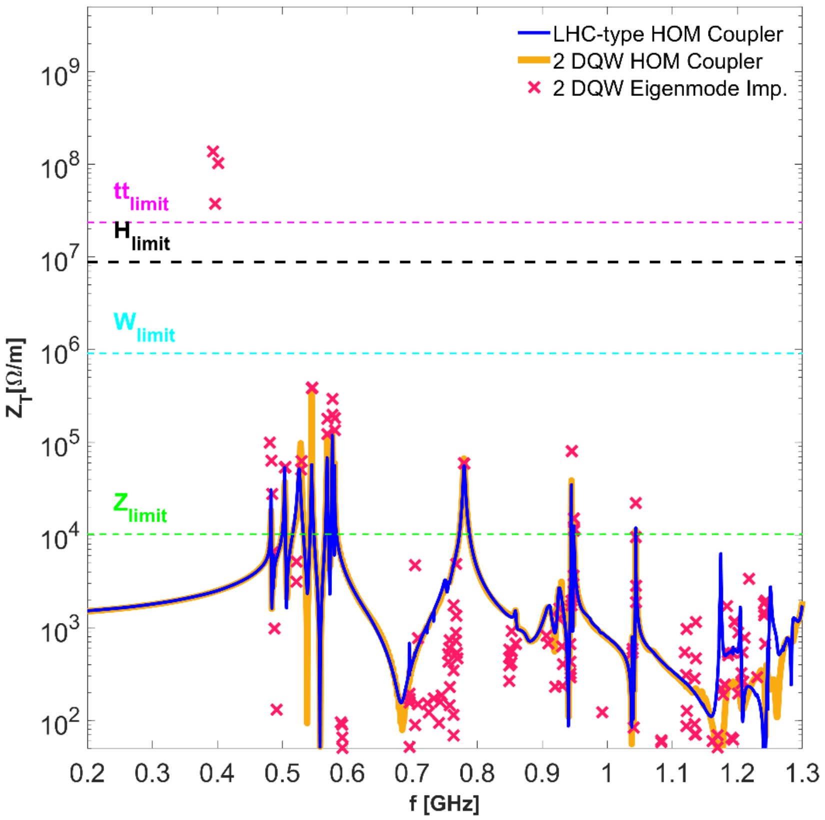
Beam stability threshold

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

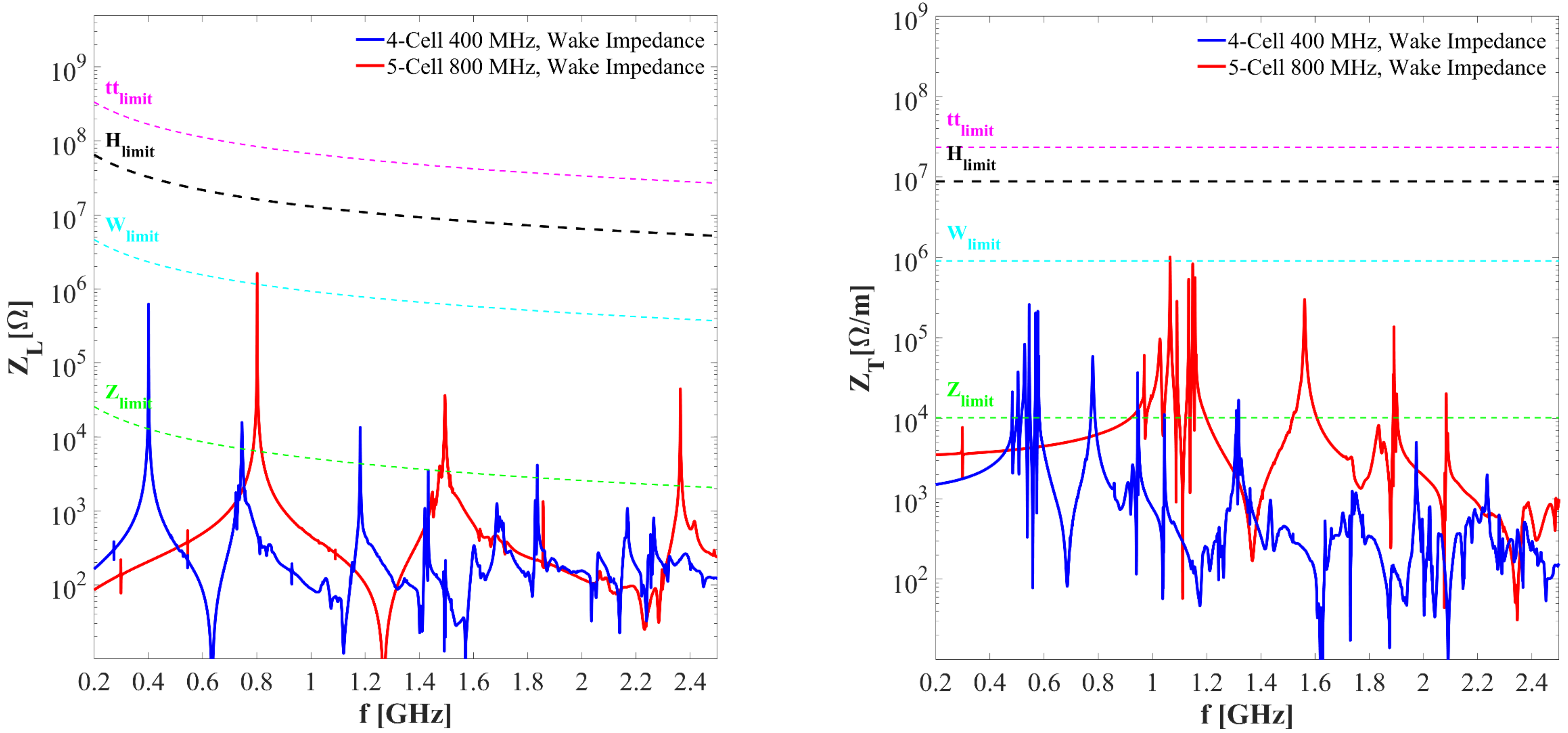
Longitudinal Impedance



Transversal Impedance



Impedance comparison



- Impedance are calculated from a wake length of 1000 m.
- Thresholds are normalized to the number of cavities needed at 400 MHz.

HOM power

Resonant excitation of dangerous monople modes

	Z	W	H	tt
4-cell cavity at 400 MHz				
f* [GHz]	P_{res} [W]	P_{res} [W]	P_{res} [W]	P_{res} [W]
0.75	42081	471	24	3
1.18	55142	617	18	3
5-cell cavity at 800 MHz				
f* [GHz]	P_{res} [W]	P_{res} [W]	P_{res} [W]	P_{res} [W]
1.49	124118	1388	54	7
2.36	200861	2246	87	12

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

Average HOM power

	Z	W	H	tt
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

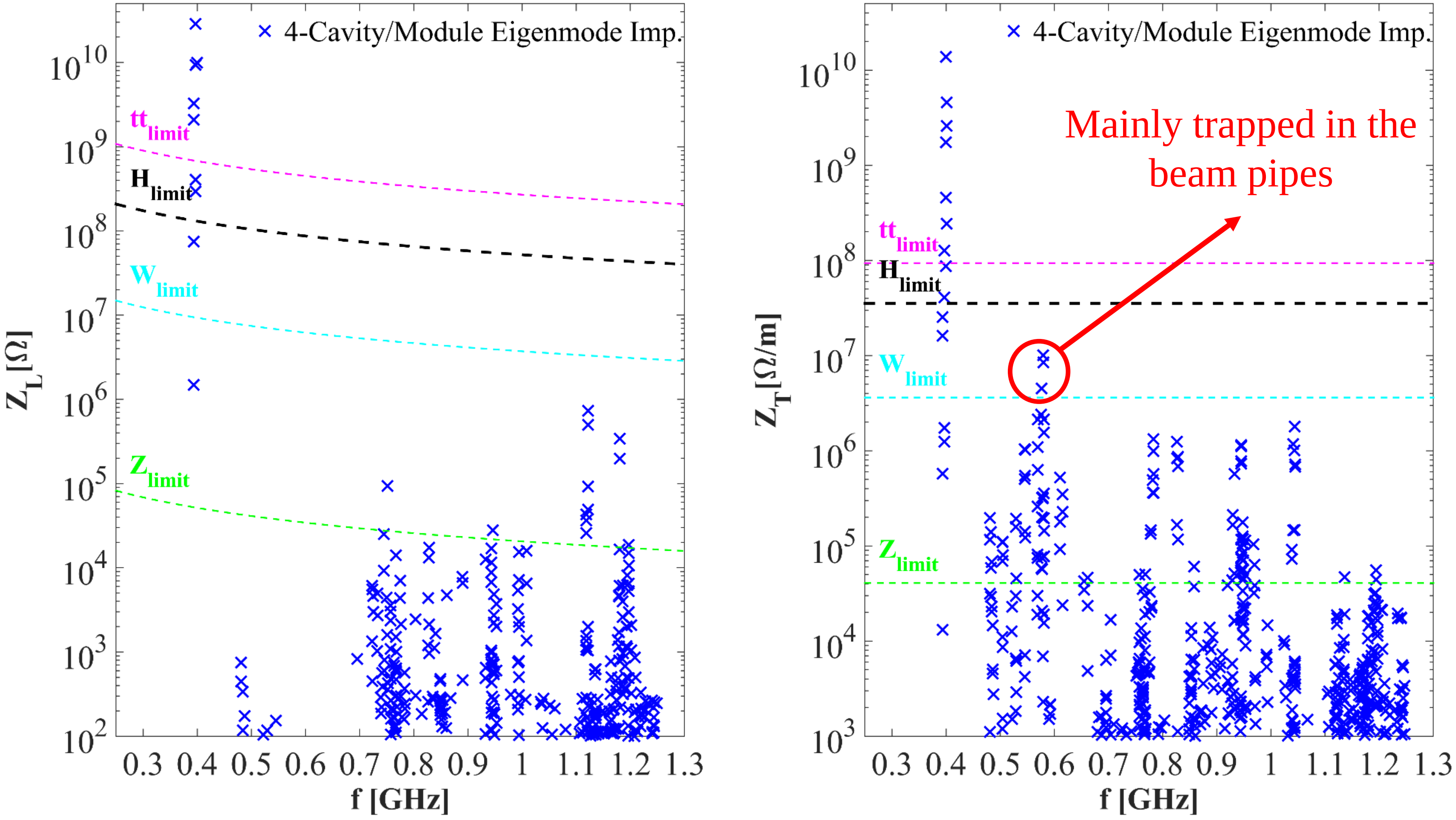
* Average HOM power for both BS and SR bunch lengths calculated from $P_{HOM} = k_{||} q_b I$

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 of a module composed of 4-cell 400 MHz cavities



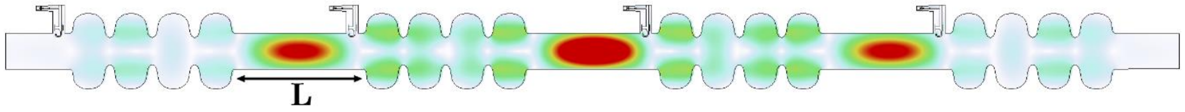
Impedance thresholds are normalized to the number of modules

Modes trapped in the beam pipes

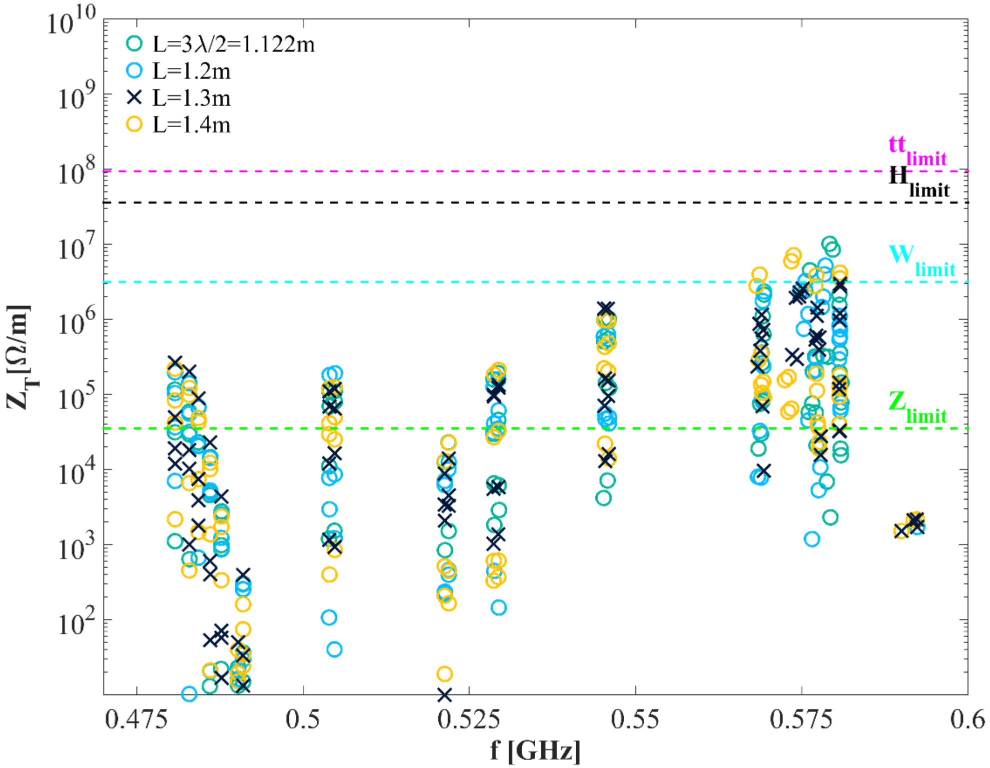
- For a beam pipe of radius 156 mm, the distance $3\lambda/2$ between cavities ensures that the field of the fundamental mode at 400.79 MHz attenuates below -120 dB along the beam pipe.

- 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.

- Varying the length between the cavities can lower the transverse impedance of these modes.

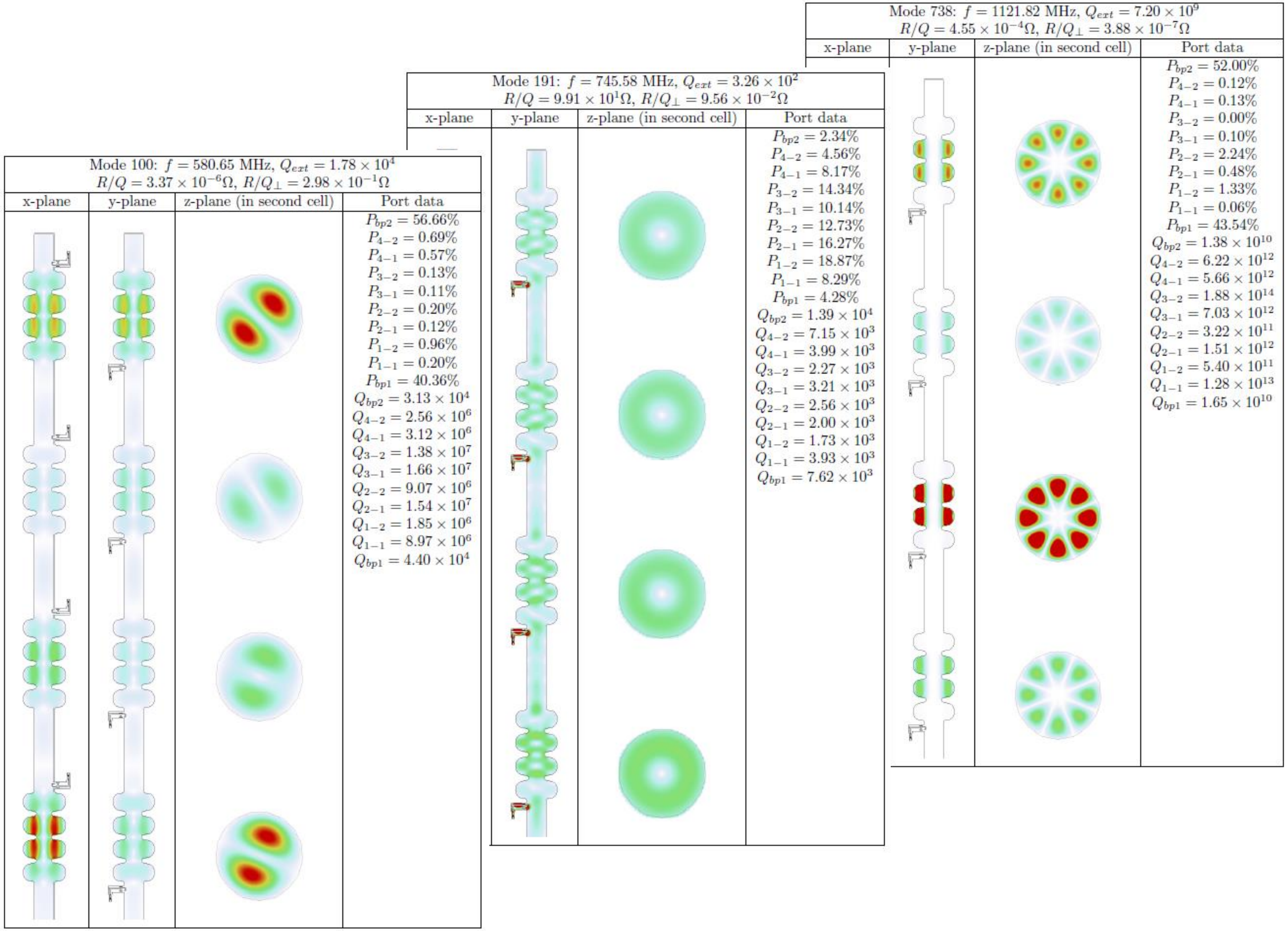


Electric field density of the dipole mode with highest transversal impedance at frequency 0.579 GHz



Module simulation

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. State Space Concatenation (SSC) method is used to simulate the whole module.



The current hybrid scheme for FCC-ee at 400 and 800 MHz

1-Cell cavity at 400 MHz	4-Cell cavity at 400 MHz	5-Cell cavity at 800 MHz	
Z 0.1	W 0.75	H 2.0	5.465 … $t\bar{t}$ 10.93 (GV)

		400 MHz	800 MHz
Z	No. Cav	52×2	
	E_{acc} [MV/m]	2.8	
	P_{cav} [kW]	962	
	Q_{ext} [10^6]	0.045	
	P_{HOM} [kW] (SR / BS)	9.5 / 3.7	
W	No. Cav	52×2	
	E_{acc} [MV/m]	9.6	
	P_{cav} [kW]	962	
	Q_{ext} [10^6]	0.53	
	P_{HOM} [kW] (SR / BS)	5.09 / 2.89	
H	No. Cav	136×2	
	E_{acc} [MV/m]	9.8	
	P_{cav} [kW]	367	
	Q_{ext} [10^6]	1.44	
	P_{HOM} [kW] (SR / BS)	1.16 / 0.76	
$t\bar{t}$	No. Cav	136×2	186×2
	E_{acc} [MV/m]	9.8	19.9
	P_{cav} [kW]	150	158
	Q_{ext} [10^6]	3.51	4.22
	P_{HOM} [kW] (SR / BS)	0.81 / 0.66	1.09 / 0.89

The total cavities needed for both beams are :

- 104 1-cell cavities at 400 MHz (26 4-Cavity module)
- 272 4-cell cavities at 400 MHz (68 4-cavity module)
- 372 5-cell cavities at 800 MHz (93 4-cavity module)

Advantage:

- More economical to combine W with H (less cavities)
- Less impedance and HOM power for H

Challenges:

- High HOM power of 5.1 kW (2.9 kW) for W
- Impedance of W close to threshold
- Large difference in Q_{ext} between W and others
- High input power of around 1 MW is required

Reorder and align both rings for the rest

Three possible staging scenarios

		Z	W	H		tt		
	Total beam voltage [GV]	0.1	0.75	2.0		5.465		10.93
Scenario 1	Voltage [GV]	0.1	0.75	2.0		2.0 (5.465)	3.465	Reorder and align both rings for the rest
	f [MHz]	400	400	400		400	800	
	No. cell per cavity	1	4	4		4	5	
	No. Cavities per beam	52	52	136		136 (364)	186	
	E_{acc} [MV/m]	5.1	9.6	9.8		9.8 (10.0)	19.9	
	P_{cav} [kW]	962	962	367		150 (137)	158	
	Q_{ext} [10^6]	0.045	0.53	1.44		3.51 (4.01)	4.22	
	P_{HOM} (SR / BS) [kW]	9.5 / 3.7	5.09 / 2.89	1.16 / 0.76		0.81 / 0.66	1.09 / 0.89	
Scenario 2	Voltage [GV]	0.1	0.75	2.0		2.0 (5.465)	3.465	Reorder and align both rings for the rest
	f [MHz]	400	400	400		400	800	
	No. cell per cavity	1	2	2		2	5	
	No. Cavities per beam	52	100	268		268 (732)	186	
	E_{acc} [MV/m]	5.1	10.0	10.0		10.0 (10.0)	19.9	
	P_{cav} [kW]	962	500	186		76 (68)	158	
	Q_{ext} [10^6]	0.045	0.59	1.58		3.86 (4.33)	4.22	
	P_{HOM} (SR / BS) [kW]	9.5 / 3.7	1.91 / 1.19	0.44 / 0.31		0.28 / 0.24	1.09 / 0.89	
Scenario 3	Voltage [GV]	0.1	0.75	0.75	1.25	0.75	4.715	Reorder and align both rings for the rest
	f [MHz]	400	400	400	800	400	800	
	No. cell per cavity	1	2	2	5	2	5	
	No. Cavities per beam	52	100	100	68	100	252	
	E_{acc} [MV/m]	5.1	10.0	10.0	19.7	10.0	20.0	
	P_{cav} [kW]	962	500	207	430	77	167	
	Q_{ext} [10^6]	0.045	0.59	1.44	1.51	3.84	4.03	
	P_{HOM} (SR / BS) [kW]	9.5 / 3.7	1.91 / 1.19	0.44 / 0.31	1.59 / 1.06	0.28 / 0.24	1.09 / 0.89	

Summary

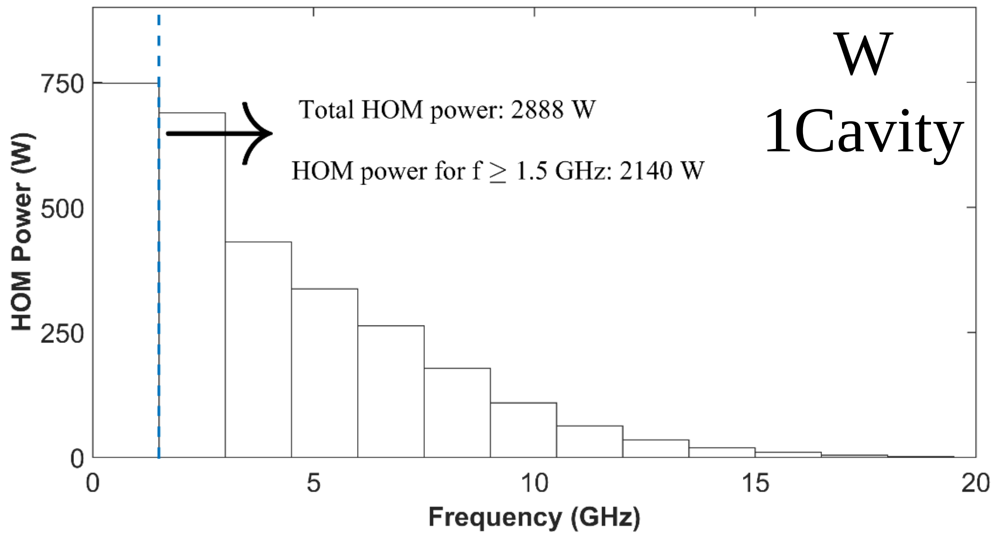
- Single cell Nb/Cu cavity at 400 MHz is considered for Z machine
- A 4-cell cavity at 400 MHz and a 5-cell cavity at 800 MHz was designed
- An optimization method was used to optimize the mid-cells for minimal losses with constraints on the different figures of merit of an elliptical cavity
- A fixed input coupler could be used for both H and $t\bar{t}$ options at the cost of 4% increase in the total input power
- Obstacles of using 4-cell cavity at 400 MHz for W are
  - High input power and different Q_{ext} compared with that for H and $t\bar{t}$
  - High HOM power of around 5.1 kW (for SR bunch length) and 2.9 kW (for BS bunch length)
  - Transverse impedance is close to the limit set by synchrotron radiation

APPENDIX

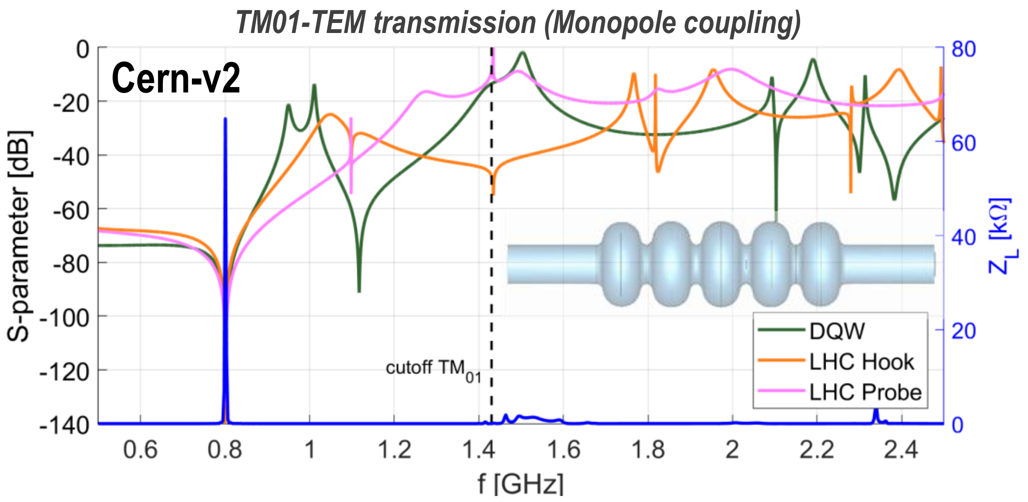
HOM Power of a Module Composed of 4-cell Cavities at 400 MHz

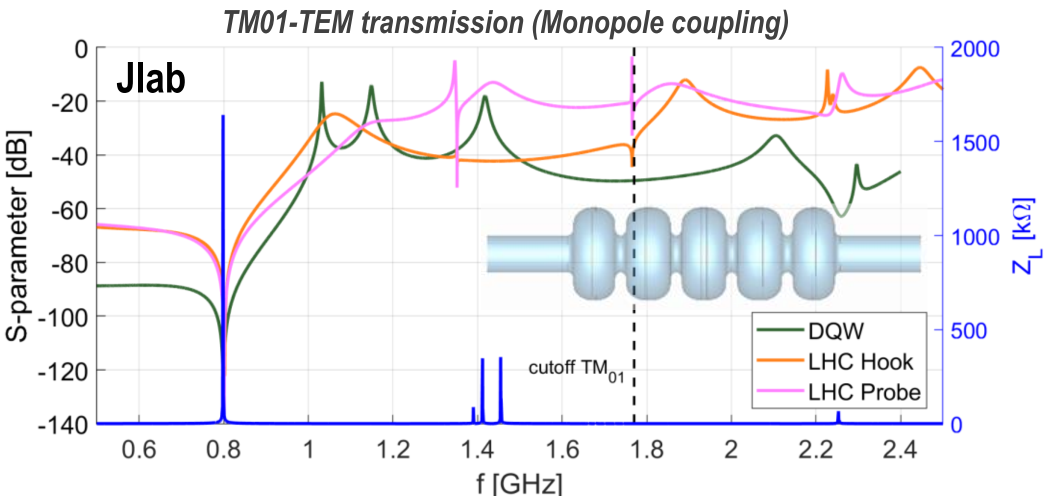
- The HOM power for the H and $t\bar{t}$ options are around 1 kW for one cavity/module
- The HOM power for the W option, on the other hand, for one cavity/module is 5.1 kW and 2.9 kW for SR and BS bunch length respectively
- Most of the HOM power is generated in the high frequency range where typically it is described by a broadband impedance model. Most of the resonances in this frequency range are above the beam pipe cutoff frequency and propagate out of the cavity via the beam pipes.

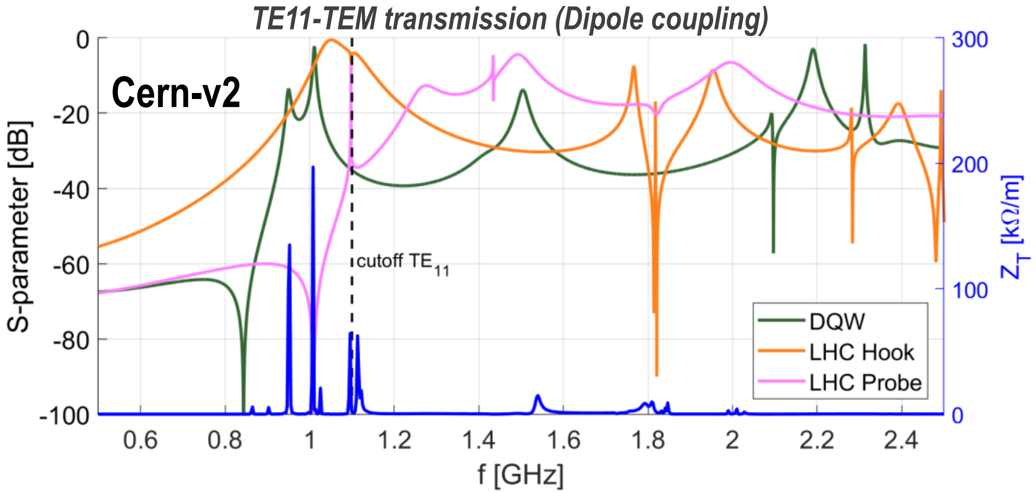
	1 cavity	2 cavities	3 cavities	4 cavities	5 cavities	6 cavities
$k_{\|\|}(\sigma_z = 6.0\ mm)$ [V/pC]	1.06	2.18	3.29	4.41	5.521	6.64
$k_{\|\|}(\sigma_z = 5.3\ mm)$ [V/pC]	1.16	2.33	3.51	4.69	5.88	7.06
$k_{\|\|}(\sigma_z = 2.54\ mm)$ [V/pC]	1.91	3.51	5.13	6.75	8.38	10.01
HOM power for W beam [kW]	2.89	5.86	8.90	11.92	14.95	17.97
HOM power for H beam [kW]	0.76	1.51	2.29	3.06	3.84	4.61
HOM power for $t\bar{t}$ beam [kW]	0.66	1.19	1.73	2.28	2.82	3.37

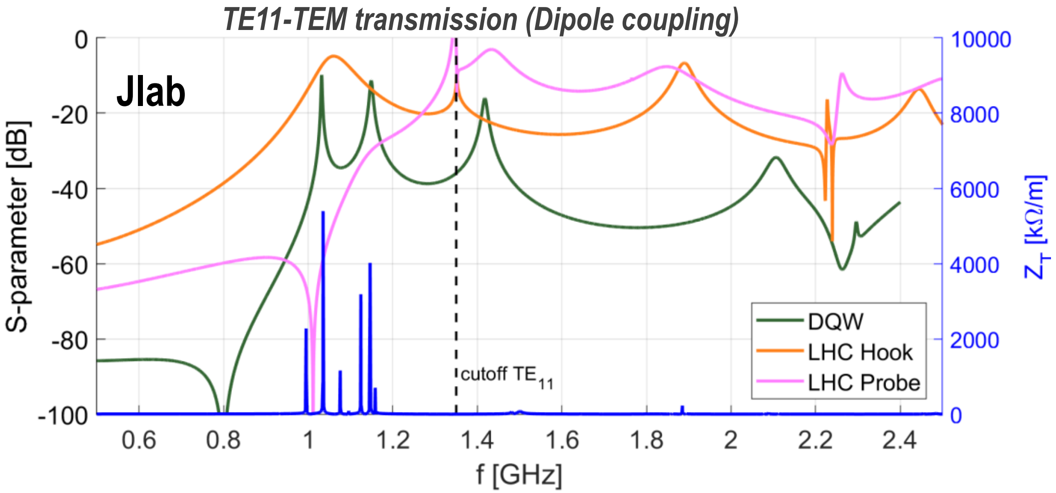


Cernv2 and Jlab 5-cell HOM coupler optimization



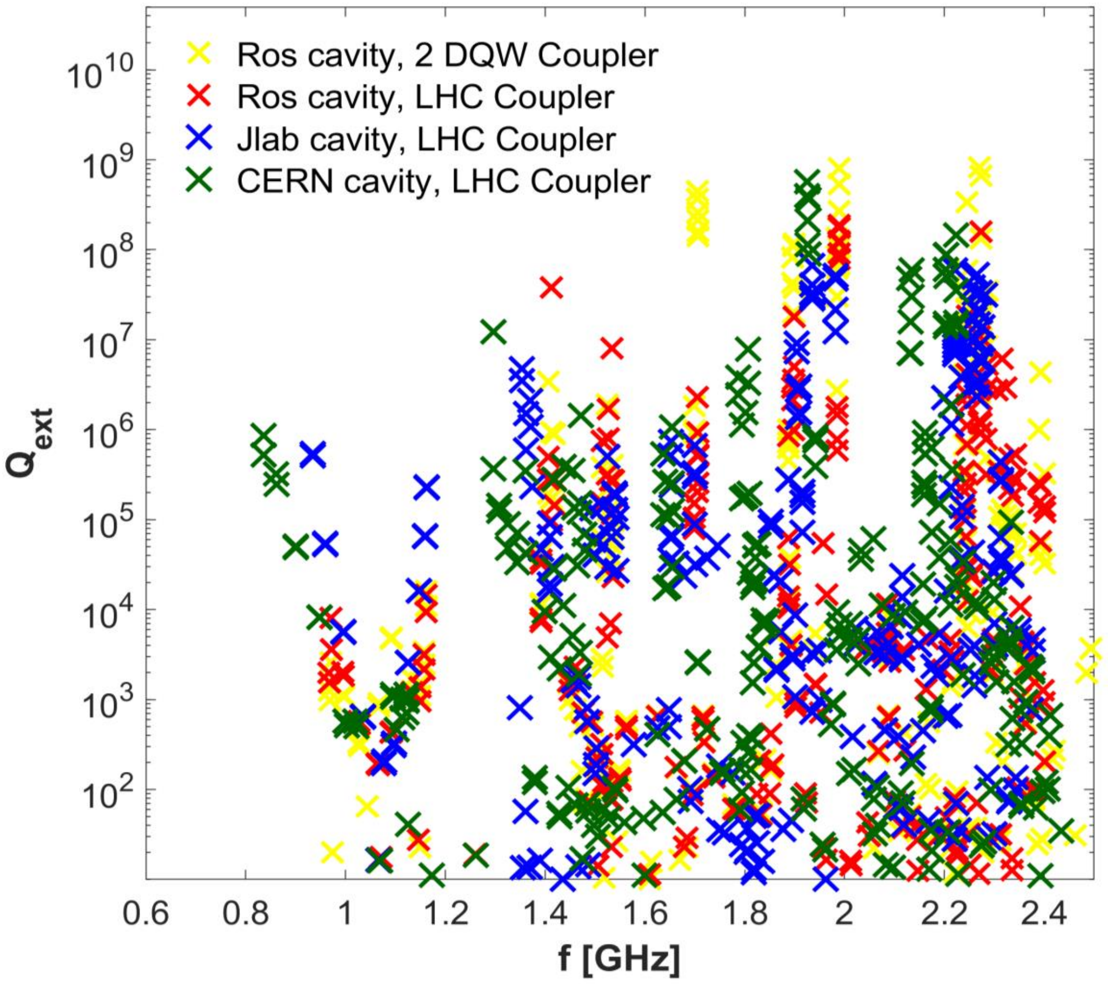




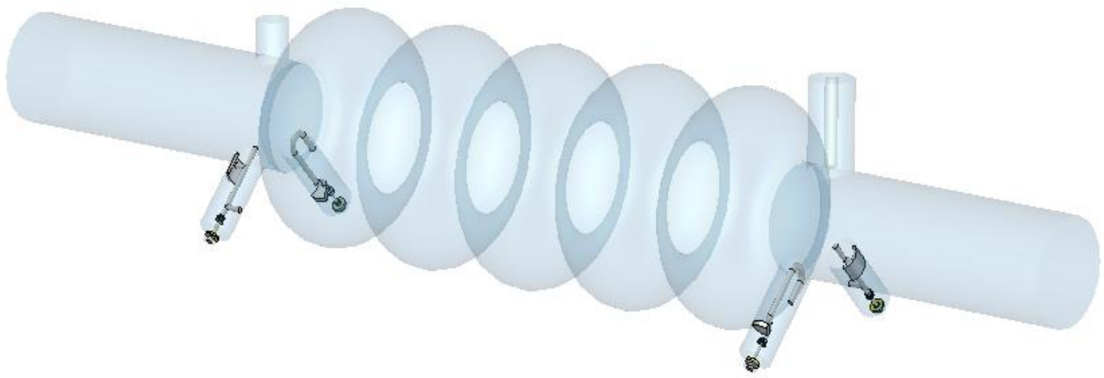


Impedances are for bare cavity and the peaks are not fully resolved.

Q_{ext} of Cernv2, Jlab and Ros cavity

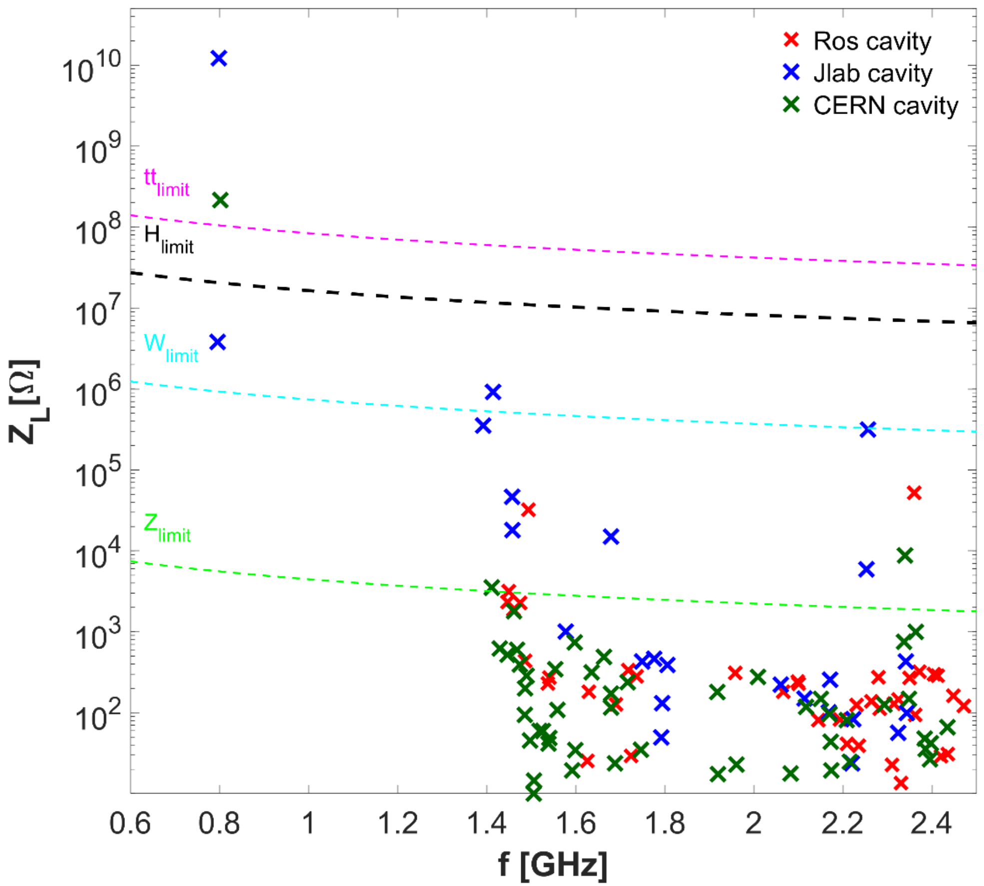


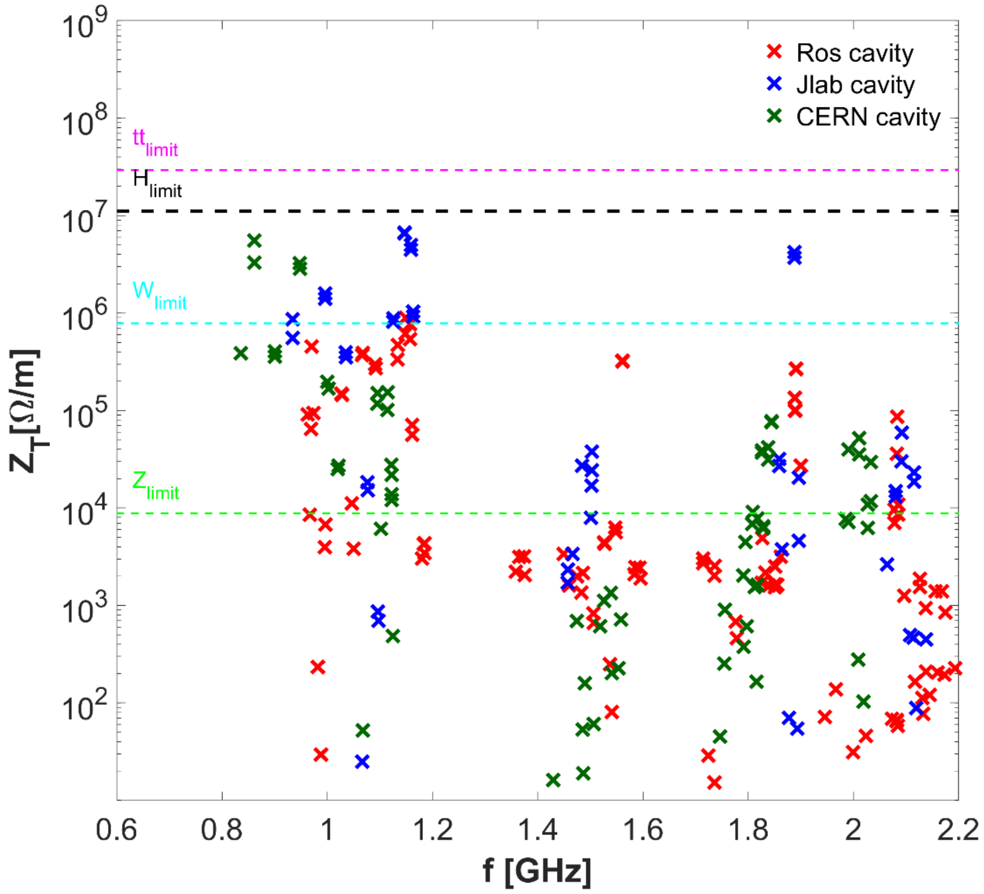
Nonlinear eigenmode solver of CST studio 2018 is used for the calculation of Q_{ext}



- Q_{ext} of first dipole band of Ros 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 Ros cavity are above cutoff frequency and their damping is eased by help of beam pipes.
- Using different type of couplers (LHC type couplers) lowers the chance 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 Ros cavity impedance





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Impedance of 2-cell cavity at 400 MHz