1-cell and 2-cell 400 MHz cavity RF designs for FCC-ee

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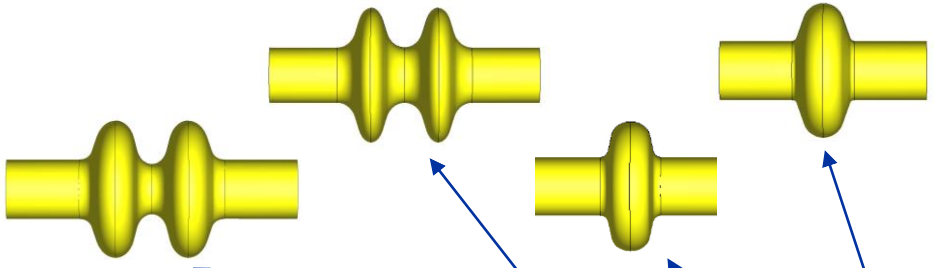
Overview

- Recent updates on cavity shapes
- Single-cell 400 MHz cavity
  - HOM coupler optimization
  - Beam impedance and HOM power calculation
- Two-cell 400 MHz cavity
  - HOM coupler optimization
  - Beam impedance and HOM power calculation
- Increasing cells per cavity for $t\bar{t}$ and booster

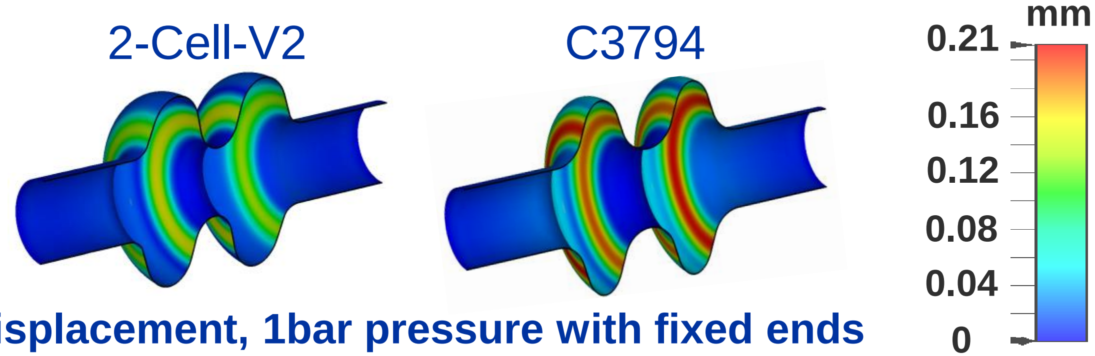
Recent updates on the 1-cell & 2-cell cavity shapes

- **Single-cell 400 MHz cavity**: quasi-LHC cavity was developed with an aperture radius and length similar to that of the LHC cavity, but with improved Higher-Order Mode (HOM) properties

- **Two-cell 400 MHz cavity**: the 2-Cell-V2 cavity design provides improved mechanical properties and $B_{\mathrm{pk}}/E_{\mathrm{acc}}$ compared to the previous design, albeit with a trade-off in HOM properties



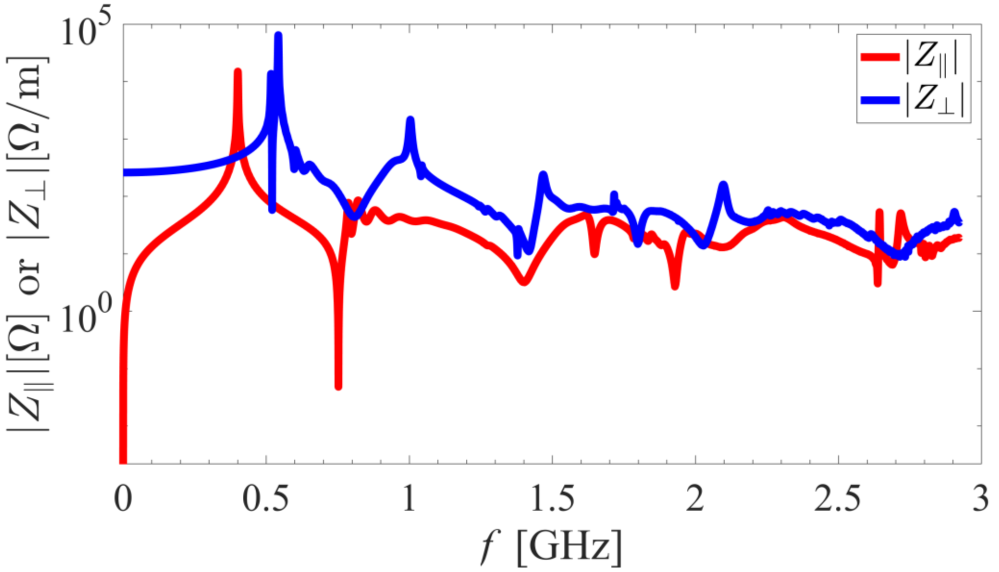
Parameters	2-Cell-V2	C3794	QLHC	LHC
Number of cells	2	2	1	1
Thickness (mm)	2.75	2.75	2.75	2.75
Tuning Sensitivity Δf/Δz [kHz/mm]	-139.6	-109	-269.5	-242.8
Cavity Stiffness k_{cav} [kN/mm]	8.0	9.1	9.1	20.4
Pressure Sensitivity fixed ends k_{p} [Hz/mbar]	23.1	119.9	24.4	9.3
Max VM stress fixed ends [MPa] (1 bar applied)	31.6	34	36.8	26.9
$G.R/Q$ [kΩ²]	42.5	30.3	20.9	22.2
R/Q [Ω]	181.1	152.5	87.6	88.1
$E_{\mathrm{pk}}/E_{\mathrm{acc}}$ [-]	2.0	2.05	2.21	2.3
$B_{\mathrm{pk}}/E_{\mathrm{acc}}$ [mT/MV/m]	5.33	6.40	5.36	5.1
$k_{\parallel}$ ($\sigma_z = 8.01\ mm$) [V/pC]	0.380	0.295		
$k_{\parallel}$ ($\sigma_z = 12.1\ mm$) [V/pC]			0.132	0.146

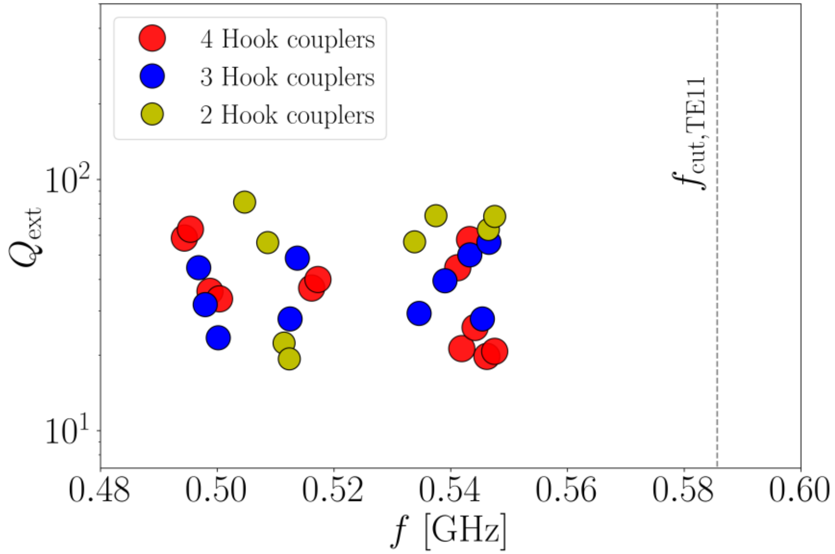


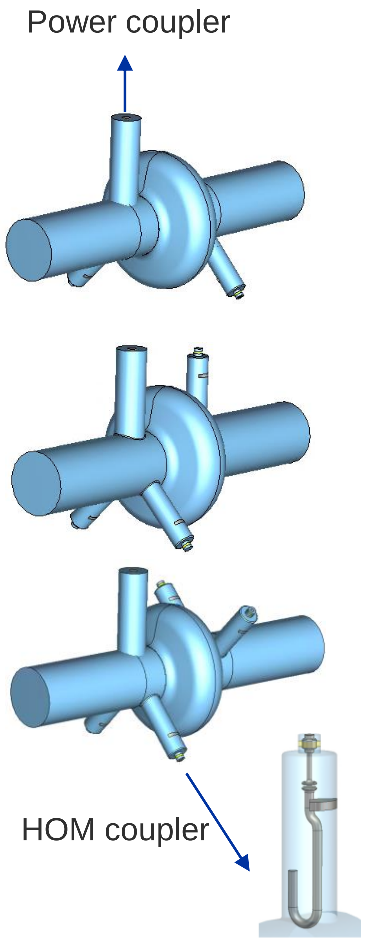
Displacement, 1bar pressure with fixed ends

HOM coupler optimization for the single-cell cavity

- No longitudinal mode is trapped in the single-cell. The first dipole passband must be strongly damped
- The LHC-type hook coupler is connected to the cavity and optimized to push the Q_{ext} of modes in the first dipole passband below 100

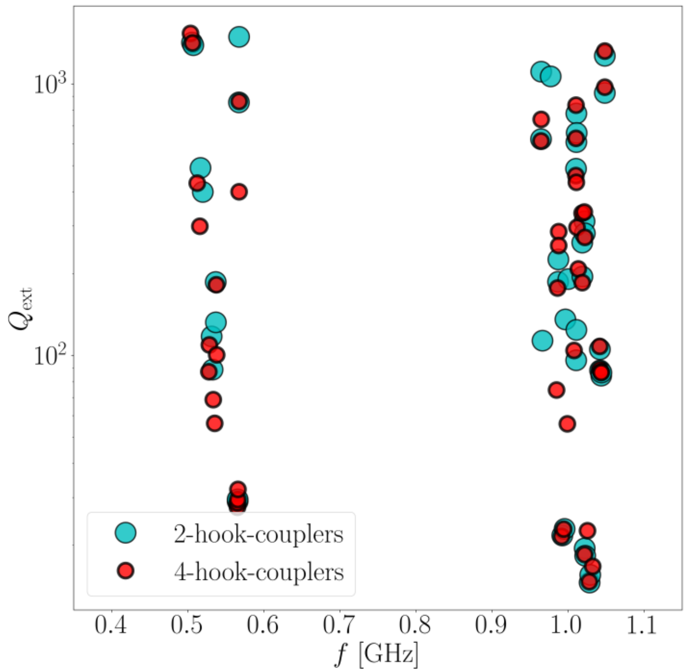


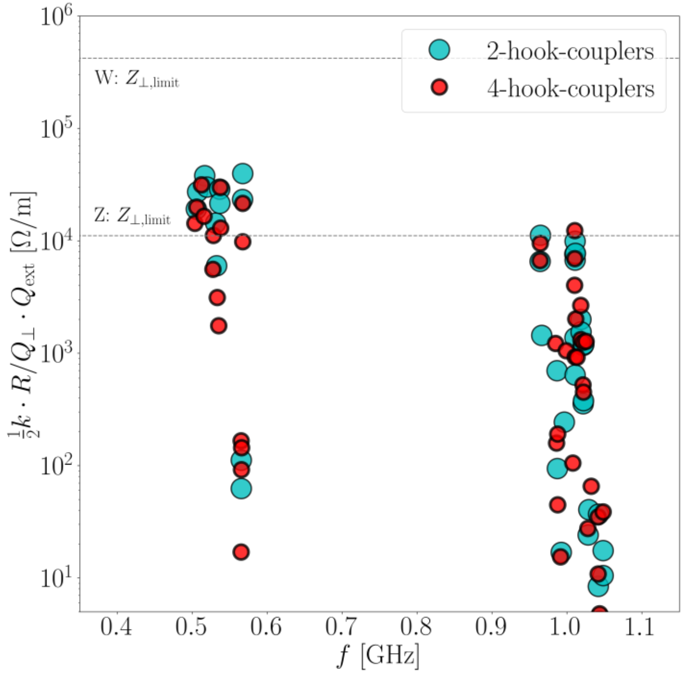


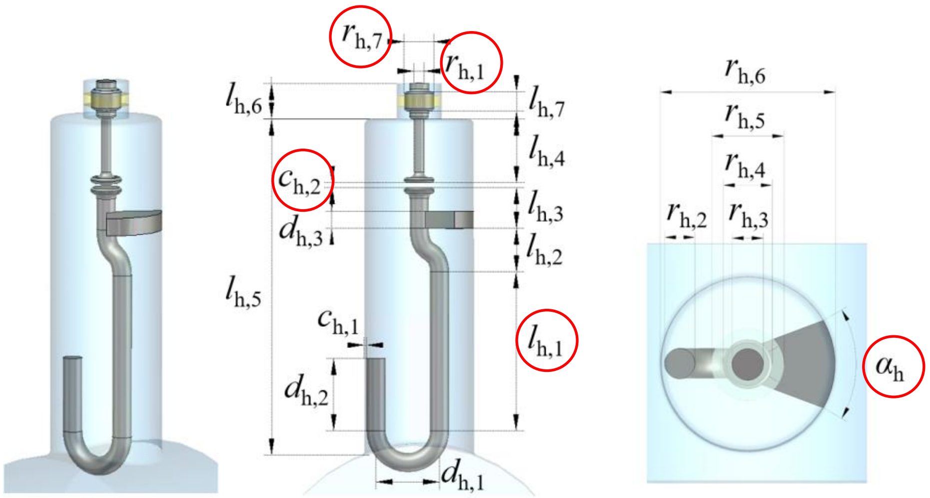


HOM coupler optimization for the two-cell cavity

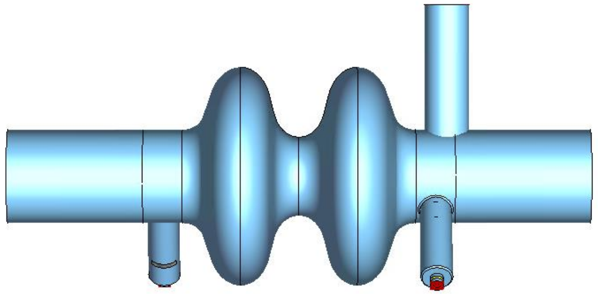
- The damping scheme employed in the two-cell cavities is similar to the one suggested for the single-cell cavity, utilizing two hook-type couplers to effectively damp the dipole modes





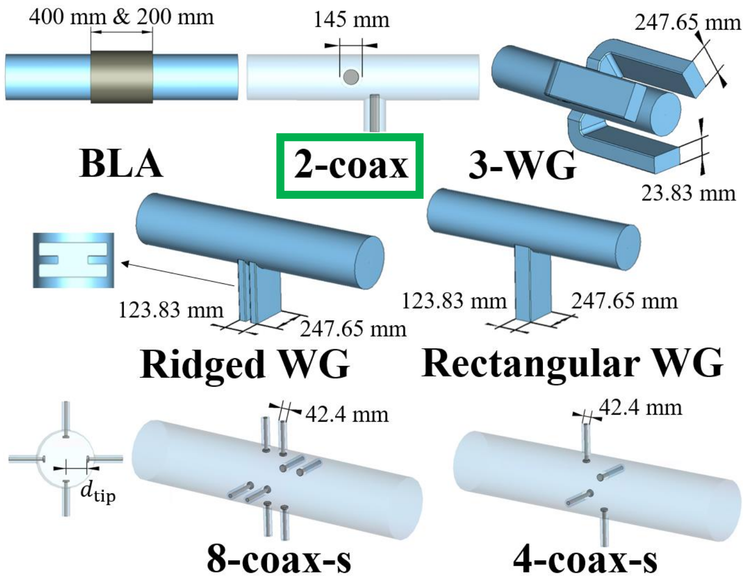


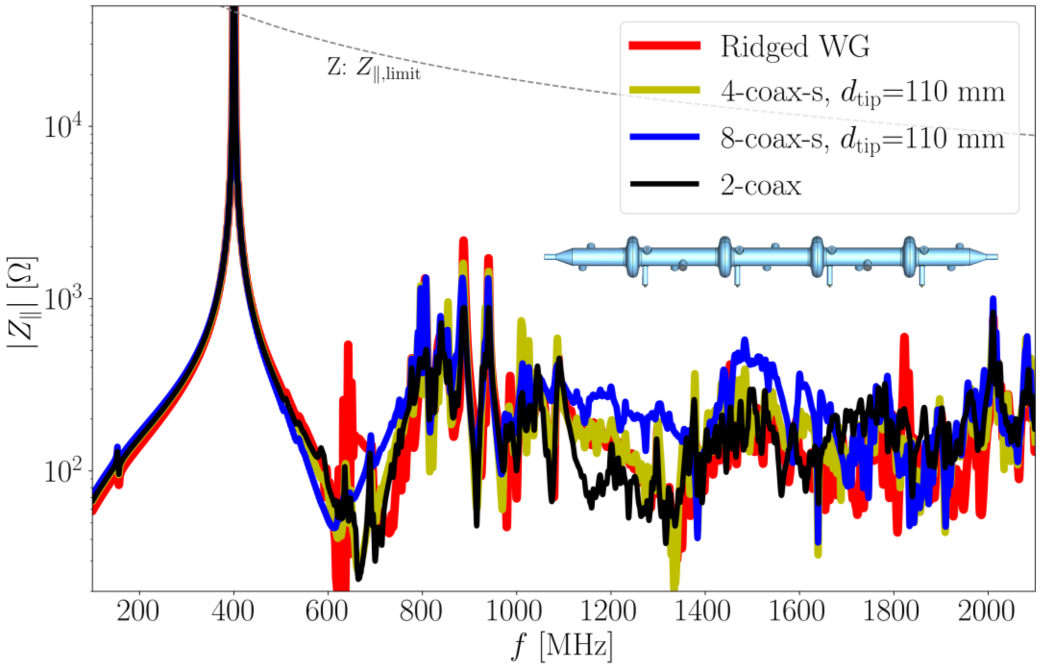
The encircled parameters are varied by trust region optimization method and Genetic algorithm to minimize transversal impedance



Couplers for HOM power extraction

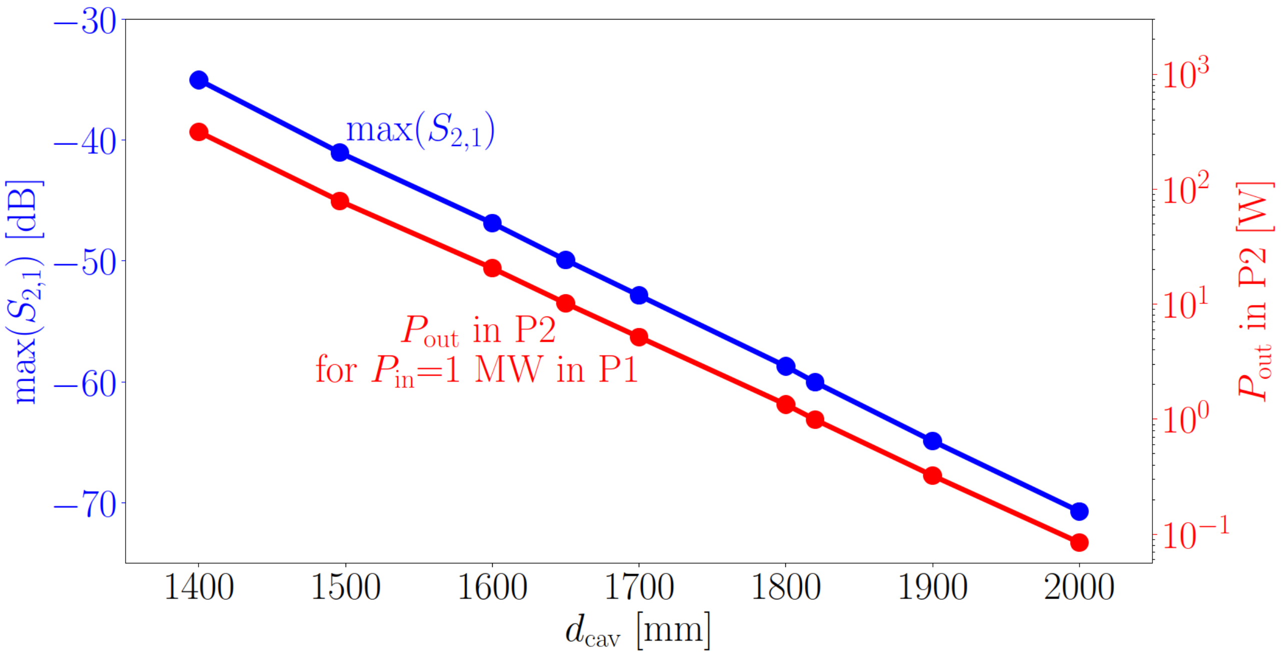
- A coupler required between cavities to
  - Take the HOM energy arising from the broadband part of the impedance out of the module
  - Damp modes created in the beam pipe (BP)

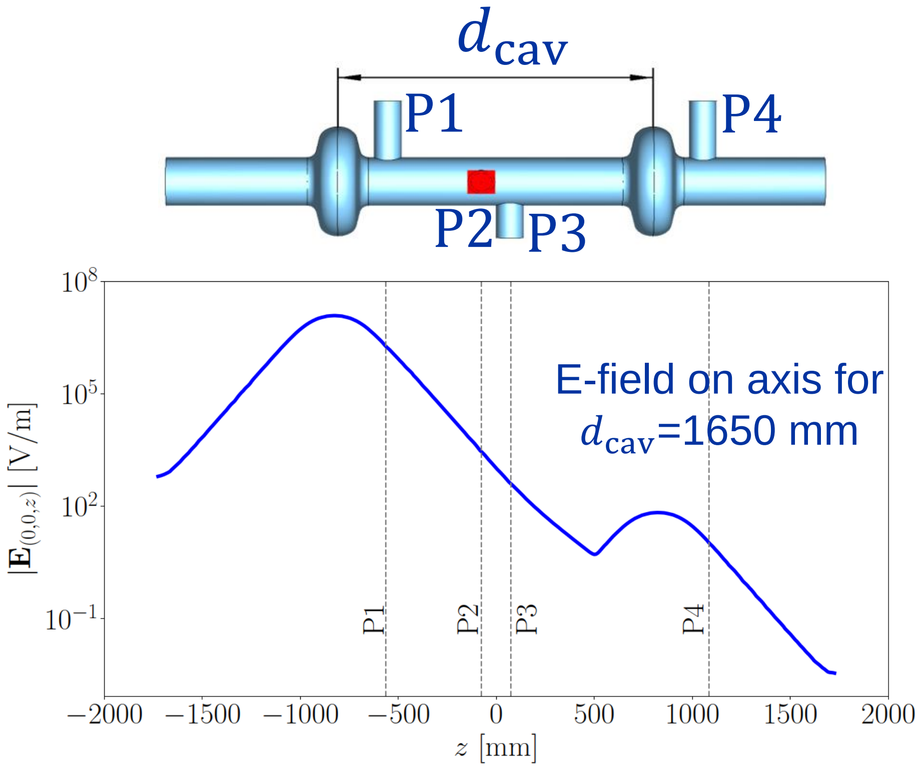




Cavity distance in a module

- To achieve a maximum $S_{2,1}$ transmission of ~ -50 dB between FPC and the coaxial HOM coupler on the BP, a minimum distance of 1650 mm between cavities is required

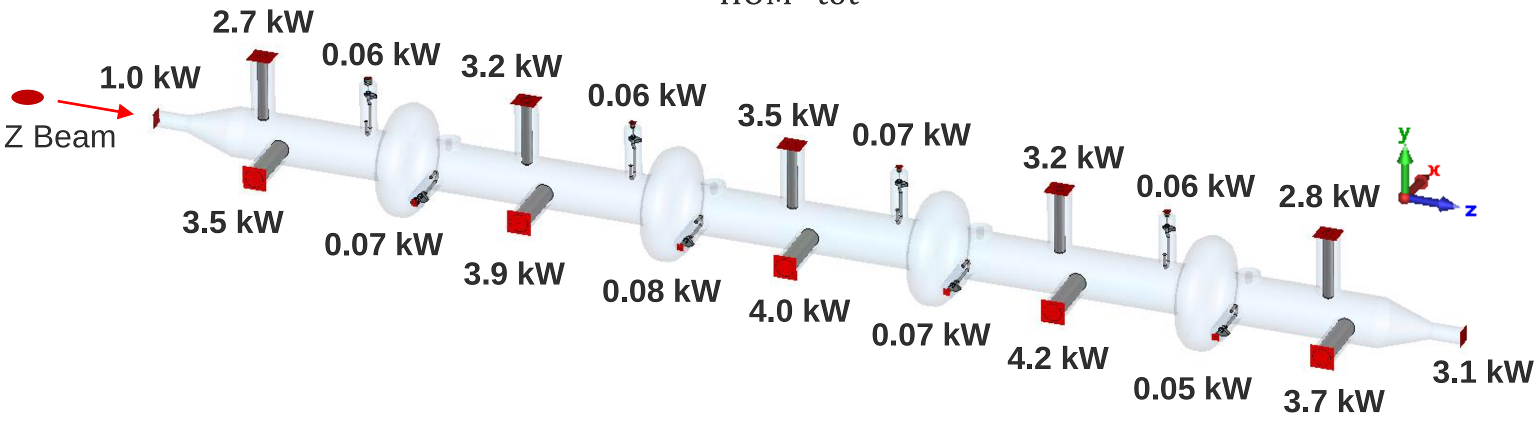




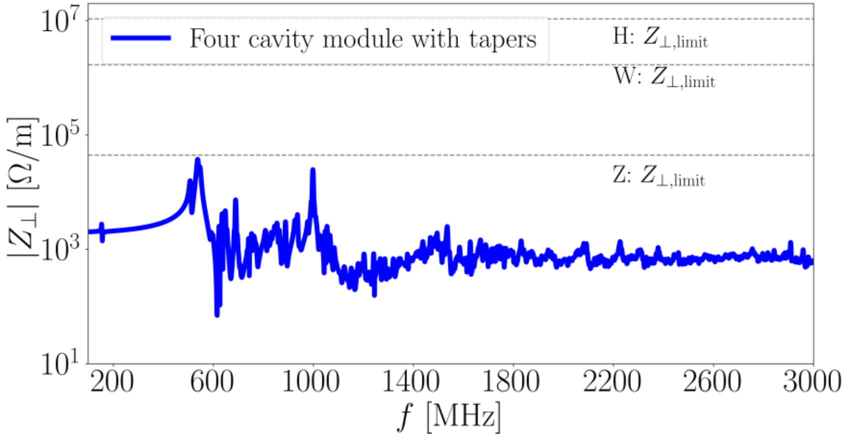
HOM power and Impedance in the Z working point

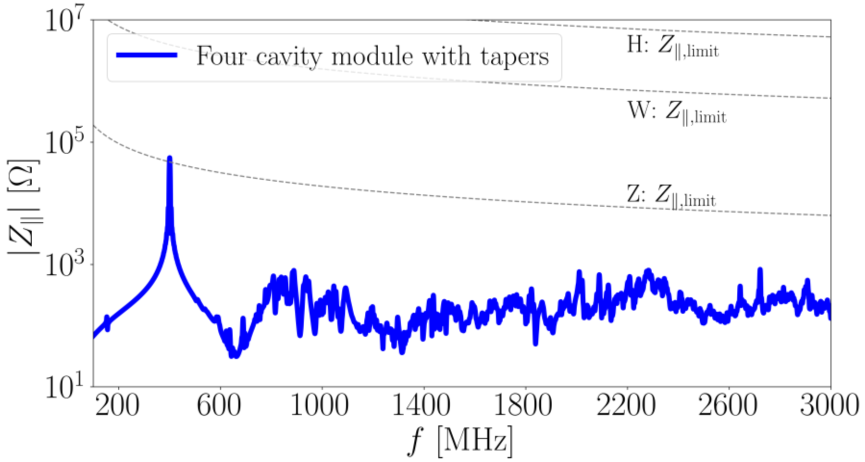
- **Single-cell 400 MHz damping scheme**: 2 hook-type couplers + 2 FPC-like coaxial couplers between cavities

Z: $P_{\mathrm{HOM-tot}} \approx 39.3\ \mathrm{kW}$



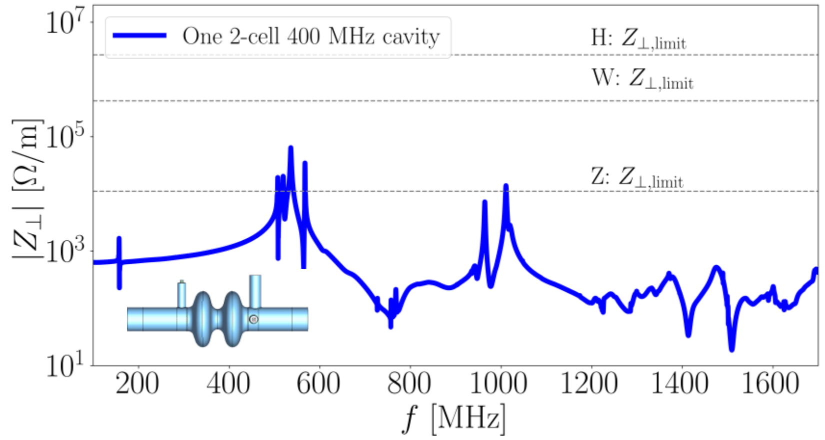
HOM power distribution in the module



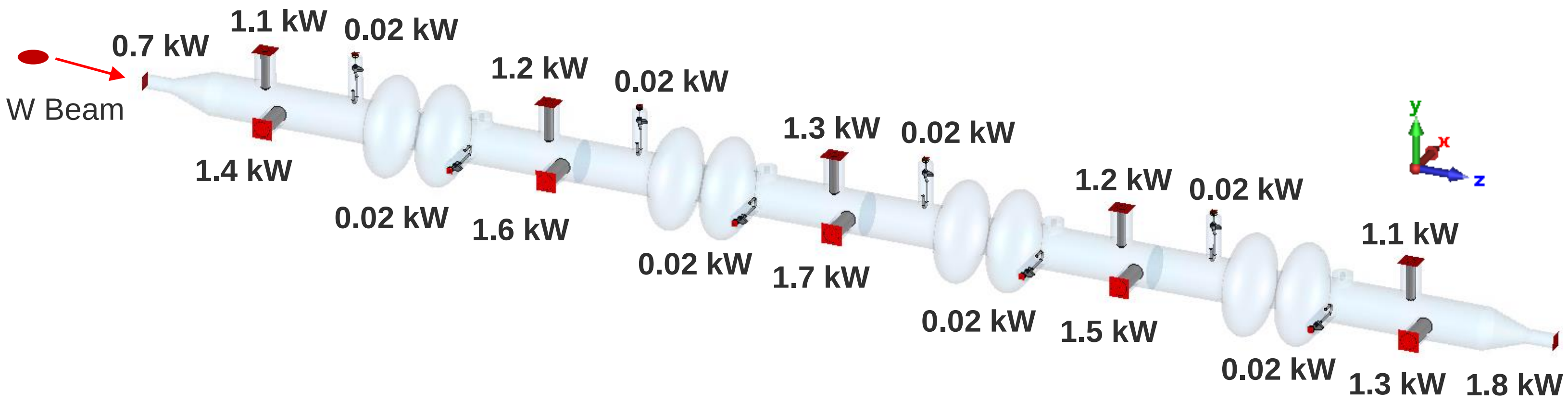


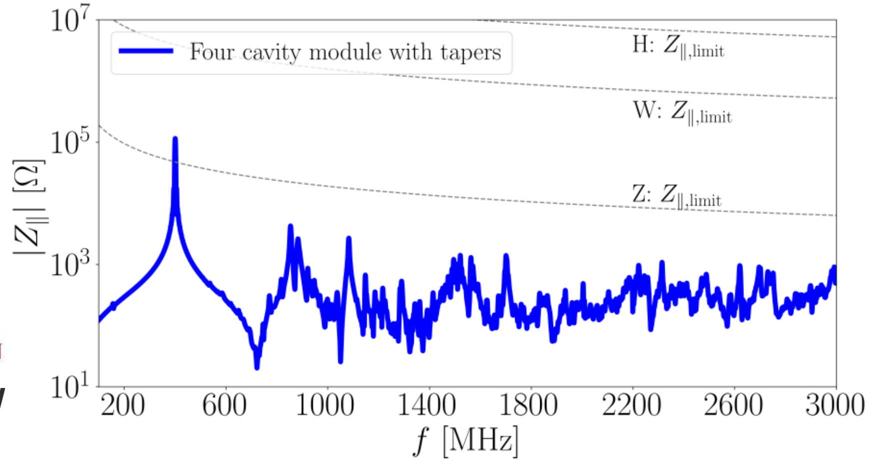
HOM power and Impedance in the W working point

- **Two-cell 400 MHz damping scheme:** 2 hook-type couplers + 2 FPC-like coaxial couplers between cavities



W: $P_{\mathrm{HOM-tot}} \approx 16.2$ kW



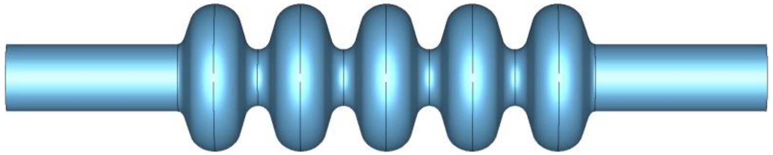


HOM power distribution in the module

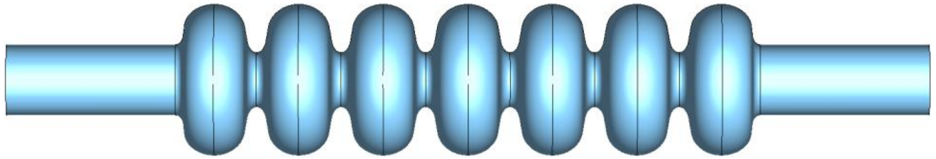
Higher number of cells per cavity for $t\bar{t}$ and booster

- The $t\bar{t}$ collider and booster in FCC-ee require the highest number of cavities. Investigating an increase in the number of cells per cavity from five to higher values is worthwhile. This modification can have a significant impact on the total cost, as it would require fewer cavities and result in a shorter RF structure.

UROS 5



UROS 7

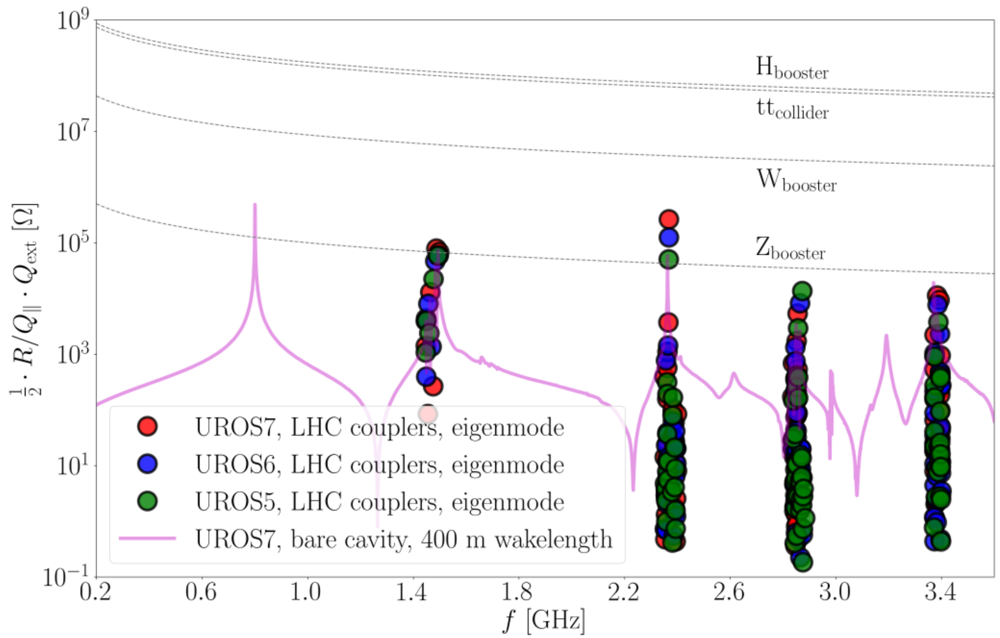


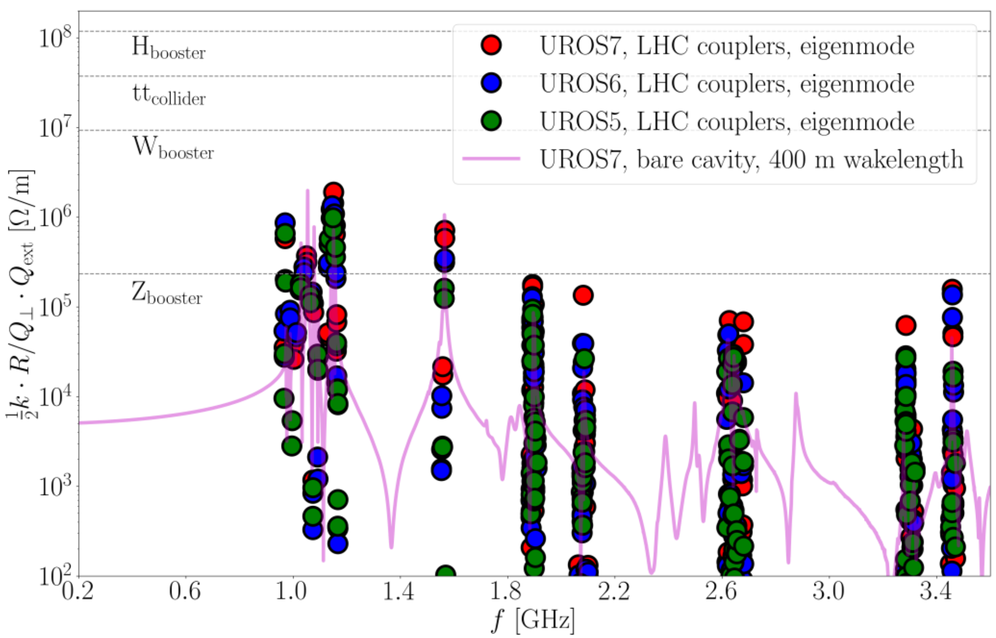
	ttbar2			ttbar2		
	Collider (2 beams)			booster		
# cell / cav	5	6	7	5	6	7
E_{acc} [MV/m]	22.33	22.17	22.33	22.52	22.59	22.55
# cavities (N_{cav})	**448**	376	**320**	544	452	388
Total length [m] ($\approx N_{cav}(L_{acc} + 2\lambda)$)	754	703	658	916	845	798
FM Pcav [kW]	**178**	212	**249**	9	11	13
N_{cells}^2/k_{cc}	**1111**	1600	**2178**	1111	1600	2178
P_{HOM} [kW] ($t\bar{t}_2$) ($\sigma_z = 2.66$ mm)	**0.81**	0.95	**1.08**	-	-	-
Cavity design	UROS5	UROS6	UROS7	UROS5	UROS6	UROS7

* N_{cells}^2/k_{cc} for Tesla 9-cell 1.3 GHz cavity is 4091

Impedance comparison between 5- to 7-cell cavity

- In all cases the transversal impedances are below the beam stability threshold of $t\bar{t}_{collider}$





Assumption: The impedance stability limits are calculated from the parameters of the collider ring → only the beam current is divided by 10 for the booster

"Tentative values, to be updated later"

Conclusion

- Recent updates on the adopted cavity shapes was presented
- HOM damping method for single-cell and two-cell 400 MHz cavities include
  - Two hook-type couplers to damp trapped dipole modes
  - Two large coaxial HOM couplers between the cavities for HOM power extraction
- Longitudinal and transversal impedances are below the stability limit → only for the Z-working point a bunch-by-bunch feedback system might be needed to maintain transversal stability
- Increasing the number of cells per cavity beyond five for the 800 MHz cavity can lead to a reduced number of required cavities, albeit with higher input power, increased HOM power, and a greater field flatness coefficient. While the current indications suggest that these trade-offs may not pose significant issues, it is still worth considering thorough investigations in light of their potential advantages.

appendix

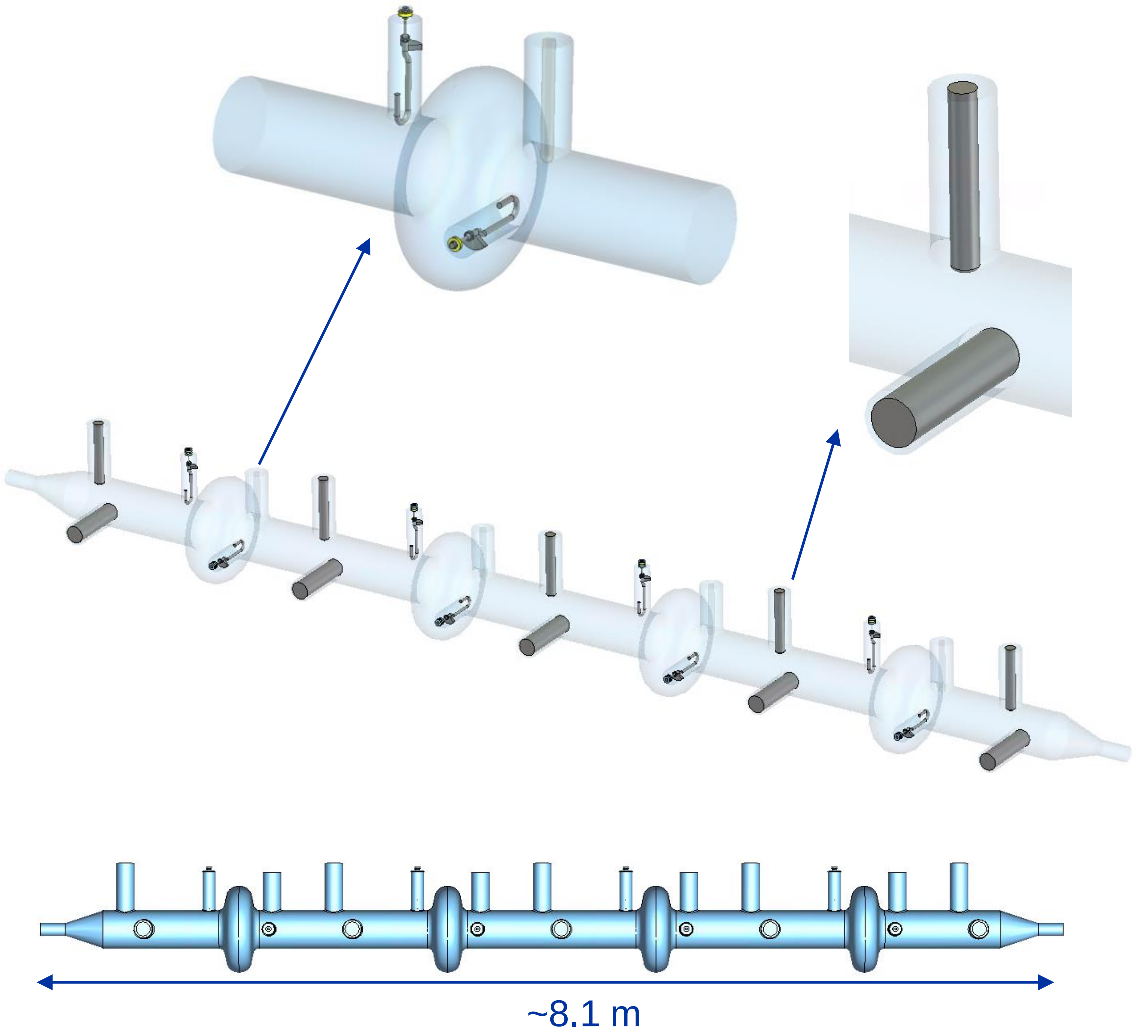
Beam parameter assumptions

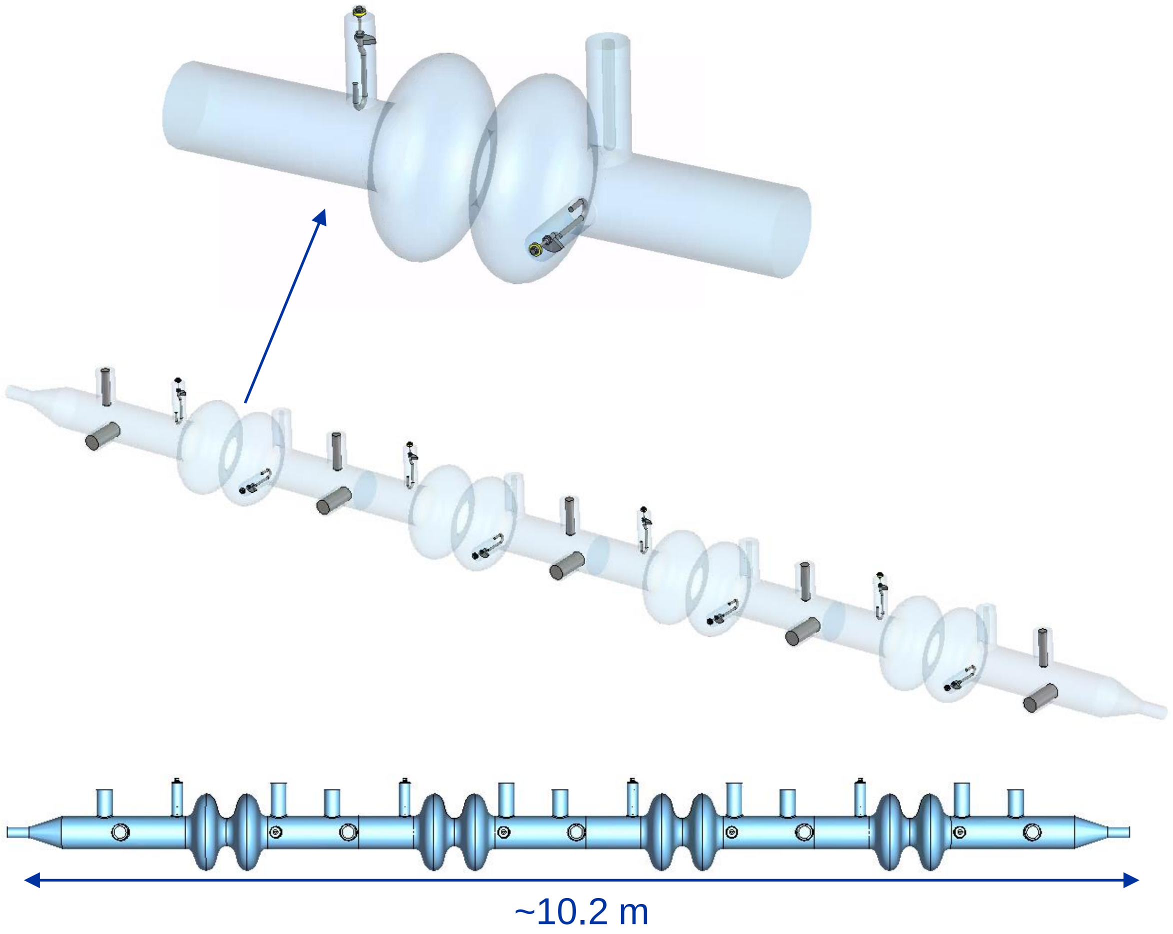
Table 1: FCC-ee collider parameters as of Jan. 19, 2023

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bending radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.370	1.89	10.1
SR power / beam	[MW]	50			
Beam current	[mA]	1270	134	26.7	4.94
Bunches / beam		9200	688	260	40
Bunch population	[10^{11}]	2.60	3.68	2.04	2.33
Horizontal emittance ε_x	[nm]	0.71	2.16	0.67	1.55
Vertical emittance ε_y	[pm]	1.42	4.32	1.34	3.10
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.34	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.565 / 53.595		100.556 / 98.590	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.143	0.069 / 0.176	0.103 / 0.179	0.157 / 0.220
Bunch length (SR/BS) σ_z	[mm]	4.37 / 15.9	3.55 / 9.09	3.34 / 5.78	1.89 / 2.66
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.1 / 0	2.1 / 9.4
Harmonic number for 400 MHz		121200			
RF freuqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0370	0.0800	0.0327	0.0881
Long. damping time	[turns]	1158	215	63.8	18.3
RF acceptance	[%]	1.6	3.3	1.9	3.1
Energy acceptance (DA)	[%]	±0.8	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.139	0.011 / 0.139	0.014 / 0.126	0.093 / 0.136
Luminosity / IP	[10^{34}/cm^{2}s]	186	21.4	6.94	1.20
Lifetime (q + BS + lattice)	[sec]	1120	–	< 1660	< 4170
Lifetime (lum)[b]	[sec]	980	960	620	750

K. Oide, Status of collider optics, Jan. 2023

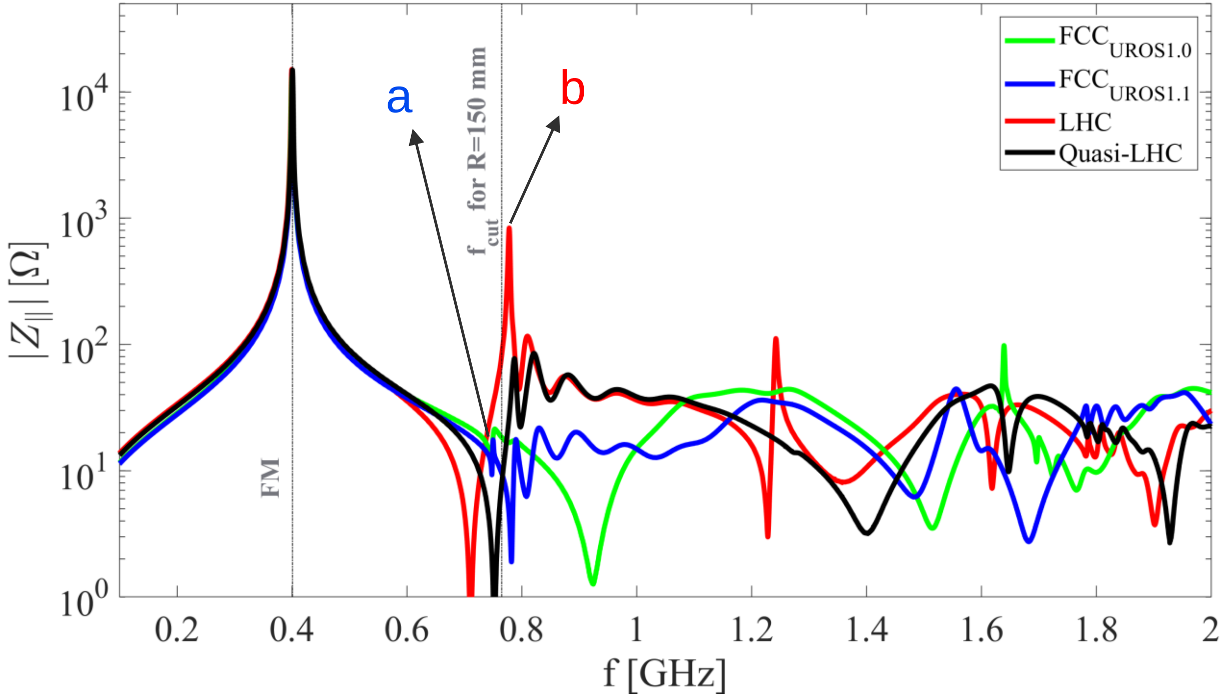
HOM damping scheme





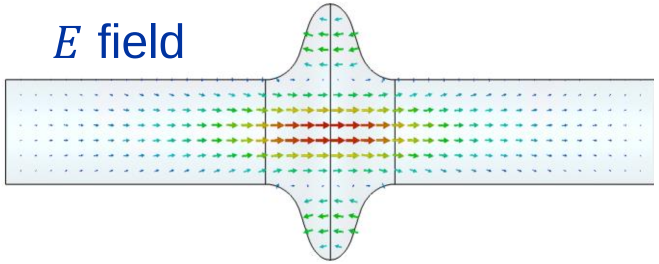
Longitudinal Impedance of single-cell

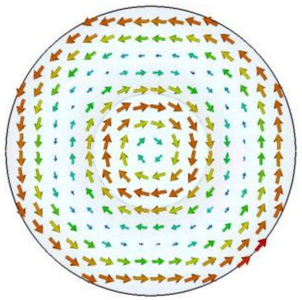
- QLHC has a smaller longitudinal impedance peak compared to LHC
- There is a trapped mode below BP cutoff frequency for UROS1.1 cavity with small R/Q



H field

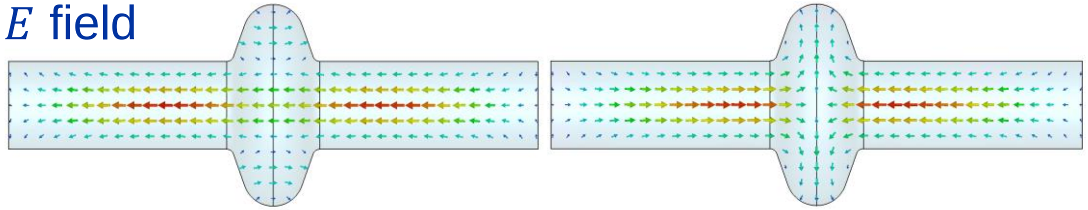
E field





a: f=749.28 MHz, R/Q=0.006 Ω (PMC BC)
a: f=749.06 MHz, R/Q=0.37 Ω (PEC BC)
Mode with small R/Q below cutoff frequency

E field

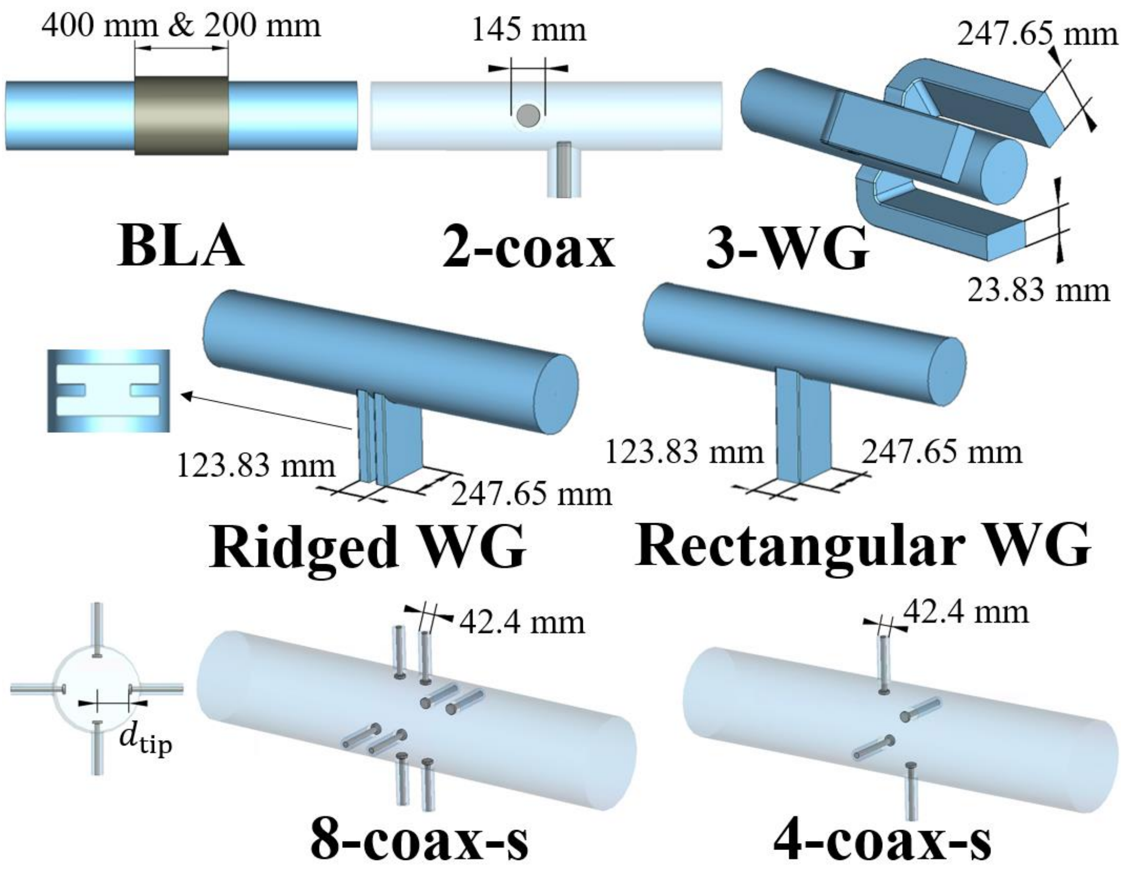


H field

b: f=777.5 MHz, R/Q=0.7 Ω, $Q_{\mathrm{ext}} = 314$ (Open BC)

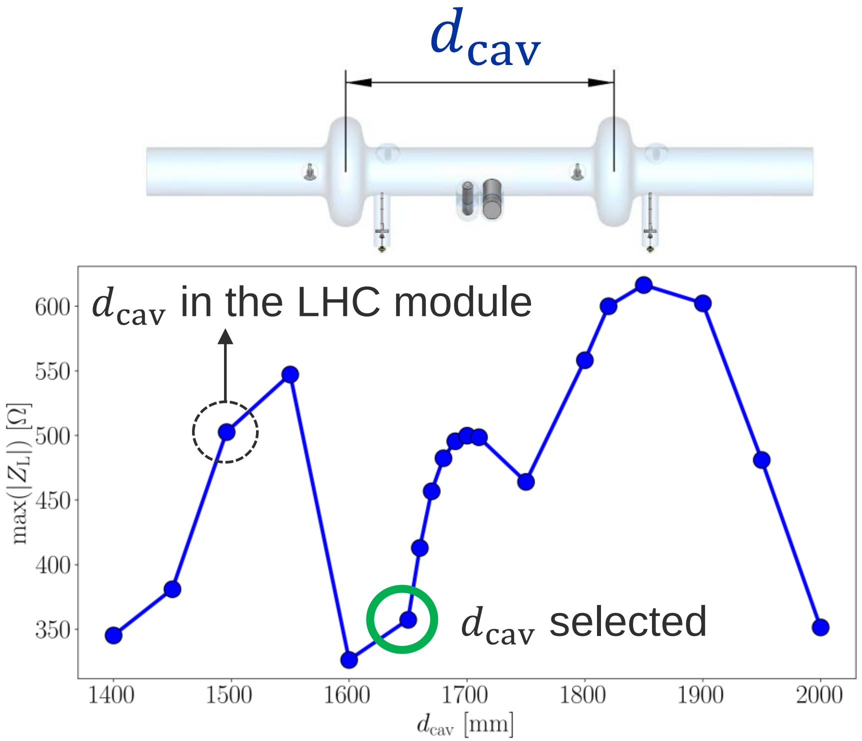
b: f=773.4 MHz, R/Q=1.1 Ω, $Q_{\mathrm{ext}} = 475$ (Open BC)

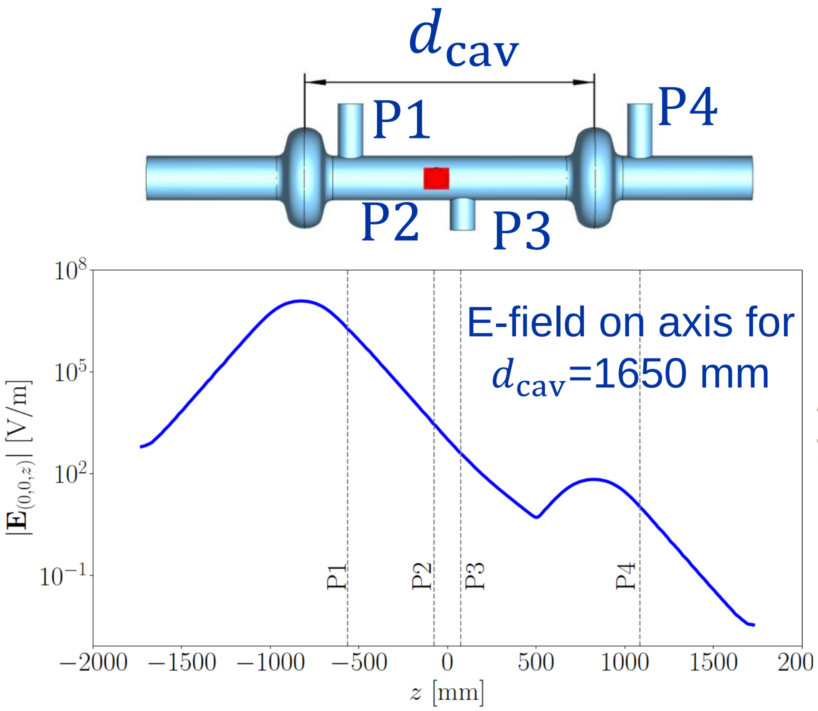
Loss factor of HOM couplers

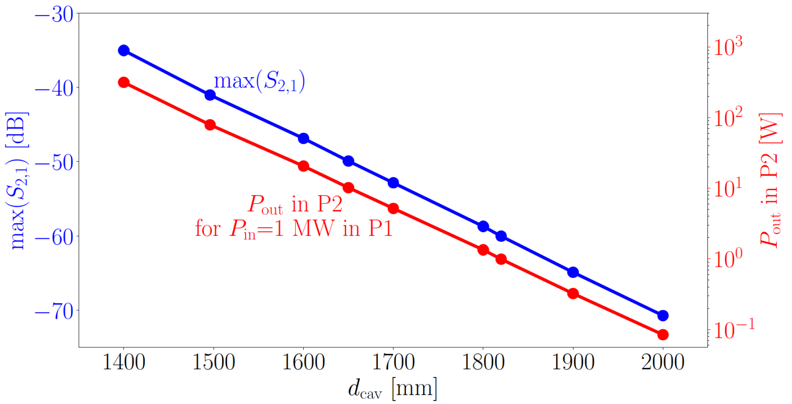


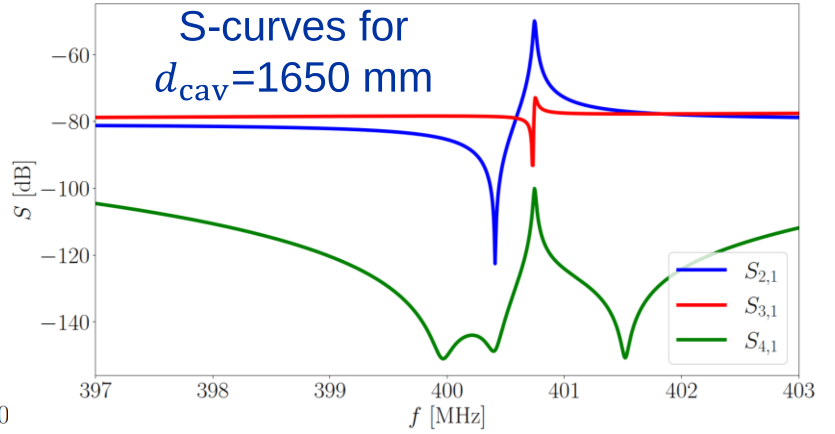
	$k_{\parallel}$ (σ_z=14.5 mm) [V/pC]	P_{HOM} [kW]
Quasi-LHC cavity	$k_{\parallel}$=0.119	
	$k_{\parallel,0}$=0.054	
	$k_{\parallel,\mathrm{HOM}}$=0.065	3.22
cavity+2-hook+FPC	$k_{\parallel,\mathrm{HOM}}$=0.090	4.47
BLA	0.137 (400 mm BLA)	6.83
	0.0703 (200 mm BLA)	3.50
3-WG	0.0271	1.35
Ridged WG	0.0233	1.16
Rectangular WG	0.0211	1.05
2-coax	0.0375 (d_{tip}=110 mm)	1.87
4-coax-s	0.0379 (d_{tip}=110 mm)	1.89
8-coax-s	0.108 (d_{tip}=100 mm)	5.38
	0.0723 (d_{tip}=110 mm)	3.60
	0.0425 (d_{tip}=120 mm)	2.12
	0.0206 (d_{tip}=130 mm)	1.03

Cavity distance in a module









RF parameters for $t\bar{t}$ and its booster

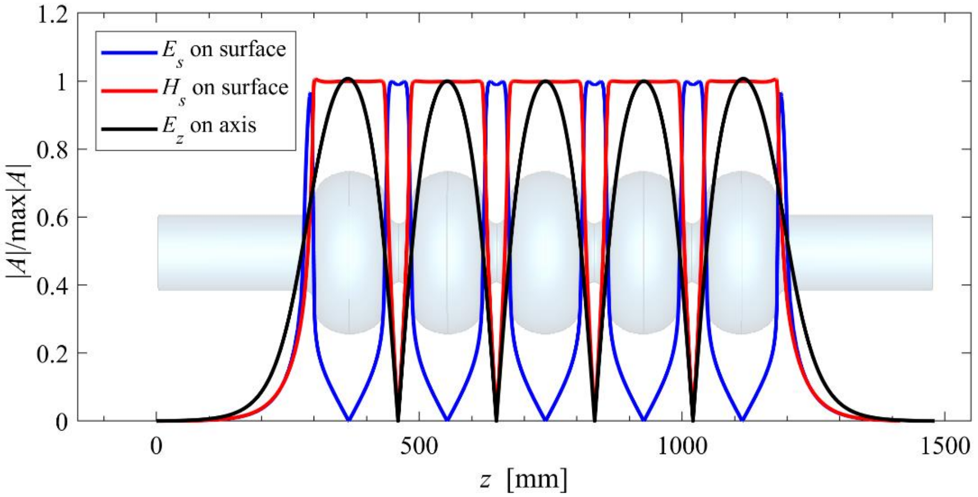
	ttbar2			ttbar2		
	Collider (2 beams)			booster		
# cell / cav	5	6	7	5	6	7
RF Frequency [MHz]	801.58	801.58	801.58	801.58	801.58	801.58
RF voltage [MV]	9355	9355	9355	11455	11455	11455
E_{acc} [MV/m]	22.33	22.17	22.33	22.52	22.59	22.55
Vcavity [MV]	20.88	24.88	29.23	21.06	25.34	29.52
#cells	2240	2256	2240	2720	2712	2716
# cavities (N_{cav})	448	376	320	544	452	388
# CM	112	94	80	136	113	97
Total length [m]	754	703	658	916	845	798
T operation [K]	2	2	2	2	2	2
dyn losses/cav [W]	31.0	36.6	42.8	4.7	5.7	6.5
stat losses/cav [W]	8	8	8	8	8	8
FM Q_{ext}	4.7E+06	4.7E+06	4.6E+06	9.5E+07	9.5E+07	9.4E+07
Detuning [kHz]	-0.05	-0.05	-0.05	-0.002	-0.002	-0.003
FM Pcav [kW]	178	212	249	9	11	13
rhob [m]	9936	9936	9936	9936	9936	9936
Energy [GeV]	182.5	182.5	182.5	182.5	182.5	182.5
energy loss [MV]	10100	10100	10100	10100	10100	10100
$\mathrm{Cos}(\emptyset_s)$	0.86	0.86	0.86	0.86	0.86	0.86
Beam current [A]	0.010	0.010	0.010	0.0005	0.0005	0.0005
L_{acc} [m]	0.935	1.122	1.309	0.935	1.122	1.309
#cav/CM	4	4	4	4	4	4
R/Q [ohm]	521	627	739.3	521	627	739.3
G [ohm]	272.9	272.8	272.7	272.9	272.8	272.7
Q_0	2.70E+10	2.70E+10	2.70E+10	2.70E+10	2.70E+10	2.70E+10
$E_{\mathrm{p}}/E_{\mathrm{acc}}$	2.05	2.04	2.04	2.05	2.04	2.04
$B_{\mathrm{p}}/E_{\mathrm{acc}}$	4.33	4.31	4.3	4.33	4.31	4.3
E_{p} [MV/m]	46	45	46	46	46	46
B_{p} [mT]	97	96	96	98	97	97
Cavity design	UROS5	UROS6	UROS7	UROS5	UROS6	UROS7

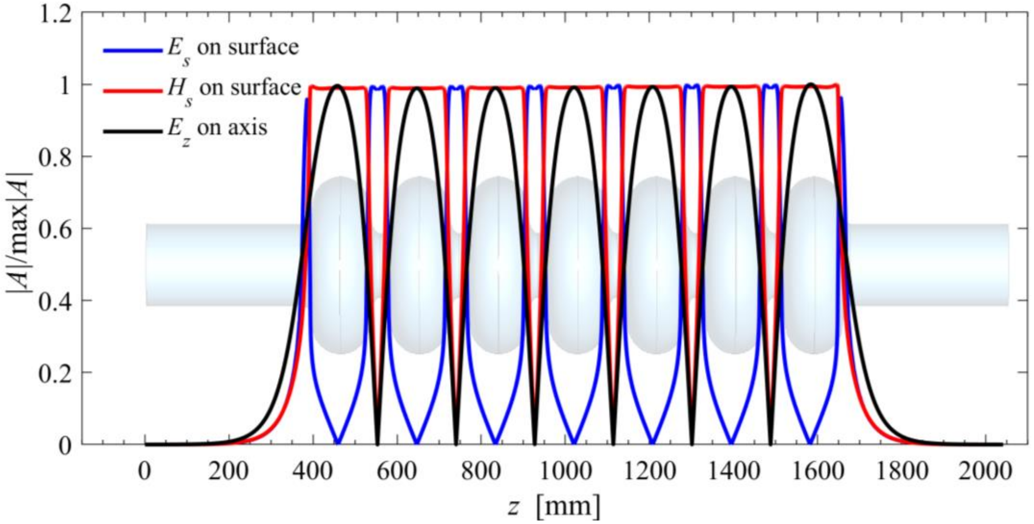
- Total length $\approx N_{\mathrm{cav}}(L_{\mathrm{acc}} + 2\lambda)$
- A duty cycle of 15% is considered in the dynamic loss calculation for the booster cavities
- RF voltage and $\mathrm{Cos}(\emptyset_S)$ of ttbar2 is taken from

Optimising the offset phase for the double RF system, Oct. 2022, A. Vanel

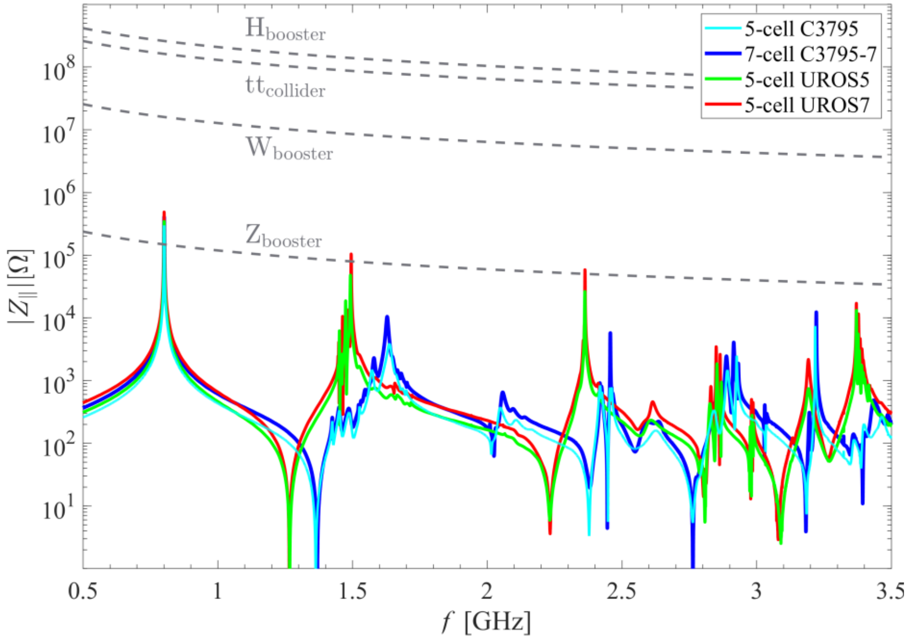
Main parameters of the cavities

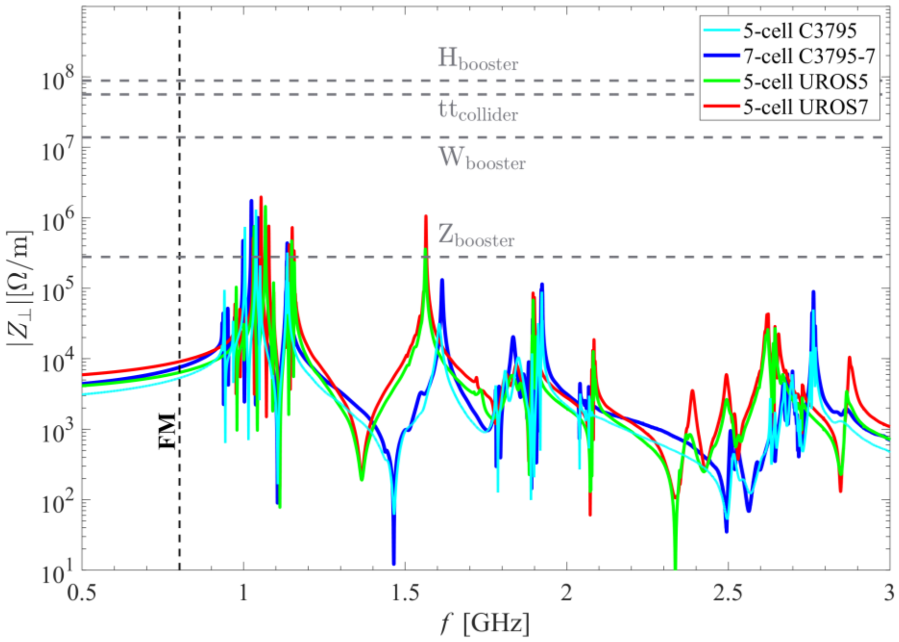
Parameters	UROS5	UROS6	UROS7
Frequency [MHz]	801.58	801.58	801.58
Number of cells	5	6	7
R/Q [Ω]	521	627.0	739.3
Geometry factor [Ω]	272.9	272.8	272.7
$G.R/Q$ [kΩ^2]	142.2	171.0	201.6
B_{pk}/E_{acc} $[mT/(MV/m)]$	4.33	4.31	4.30
E_{pk}/E_{acc} [-]	2.05	2.04	2.04
Cavity active length [mm]	919.5	1106.5	1293.5
Iris radius [mm]	60	60	60
Beam pipe radius [mm]	78	78	78
Wall angle [degree]	100/96.9	100.969	100/96.9
Cell to cell coupling of mid-cells (k_{cc}) [%]	2.25	2.25	2.25
Field flatness [%]	99	99	98.9
N_{cells}^2/k_{cc}	1111	1600	2178
$k_{\|\|}(\sigma_z = 2.66\ mm)$ [V/pC]	2.82	3.32	3.81
P_{HOM} [kW] ($t\bar{t}_2$)	0.81	0.95	1.08
Cutoff TE_{11} [GHz]	1.126	1.126	1.126
Cutoff TM_{01} [GHz]	1.471	1.471	1.471





Impedance comparison between 5-cell and 7-cell cavity





$$Z_{\parallel}^{\mathrm{th}} = \frac{2(E_0/q_e)\nu_s}{N_{\mathrm{cav}} f I_0 \alpha_c \tau_z}$$

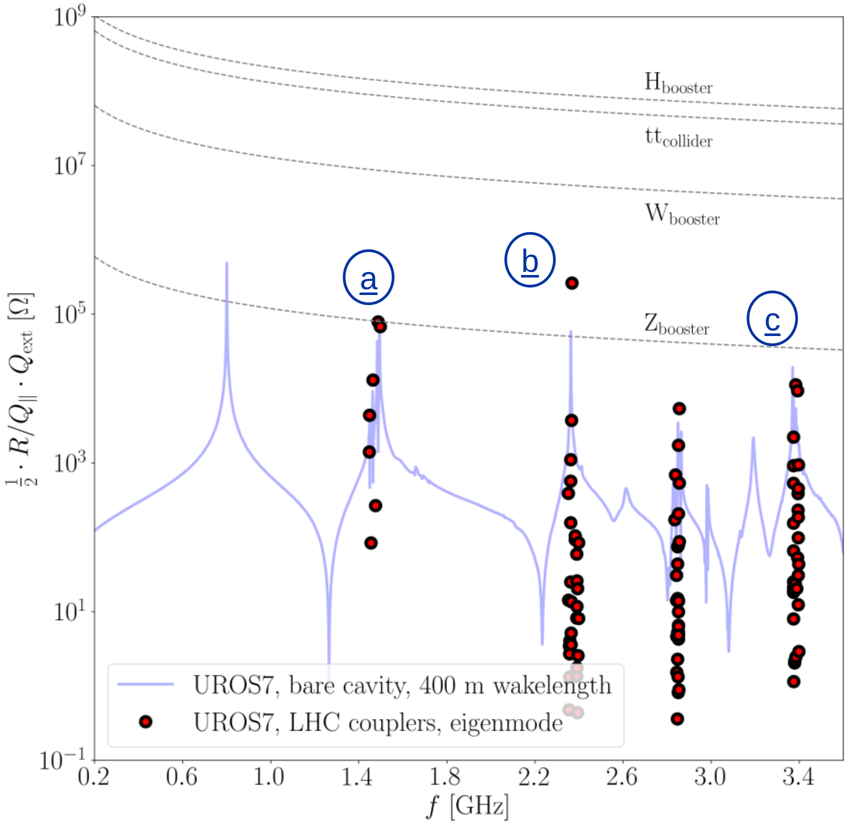
$$Z_{\perp}^{\mathrm{th}} = \frac{2(E_0/q_e)}{N_{\mathrm{cav}} f_{\mathrm{rev}} I_0 \beta_{\mathrm{xy}} \tau_{\mathrm{xy}}}$$

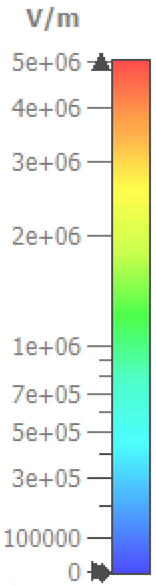
Assumption: The impedance stability limits are calculated from the parameters of the collider ring → only the beam current is divided by 10 for the booster

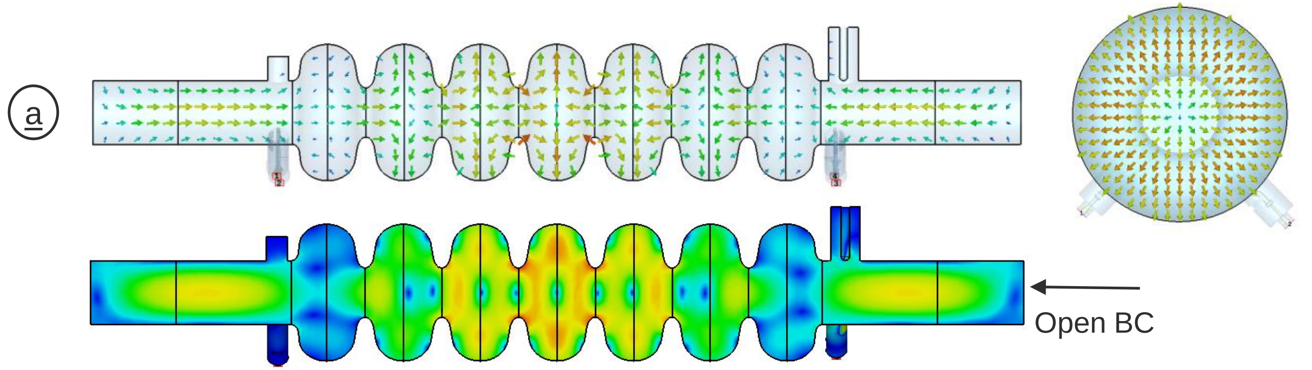
"Tentative values, to be updated later"

Impedances are for bare cavity derived from a wakelength of 400 m

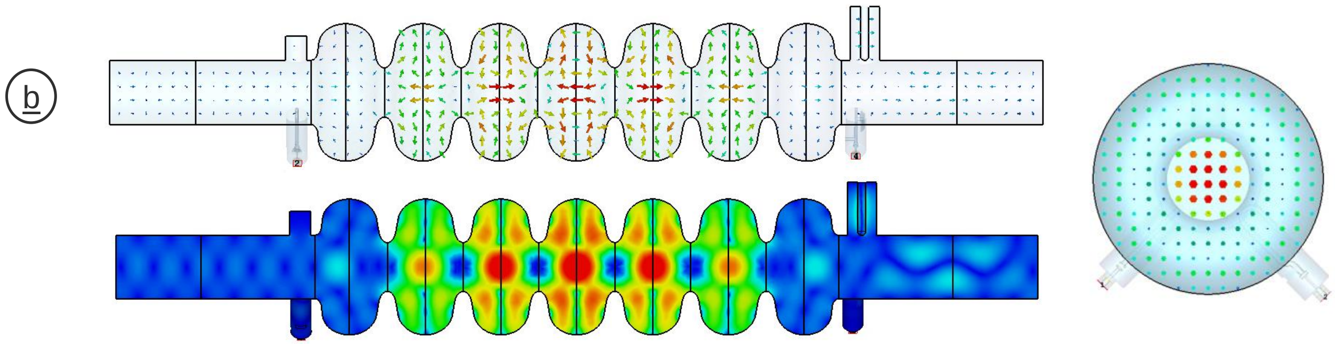
$Z_{\parallel}$ of UROS7 cavity



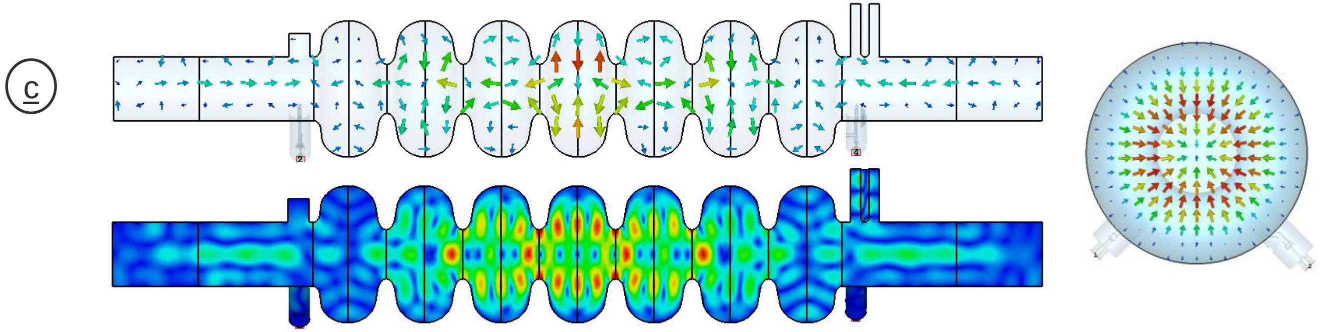




$f = 1.498$ GHz, $R/Q = 100.8$ Ω, $Q_{\text{ext}} = 1.35e3$

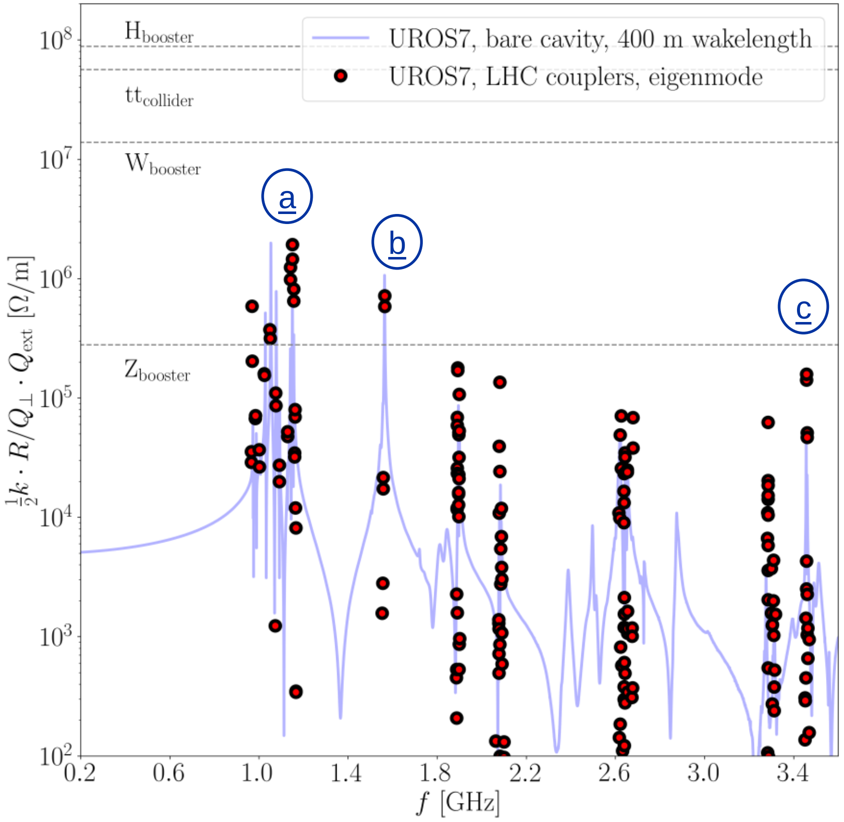


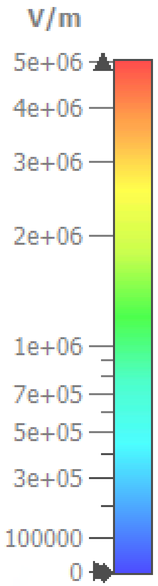
$f = 2.368$ GHz, $R/Q = 34.1$ Ω, $Q_{\text{ext}} = 1.5e4$

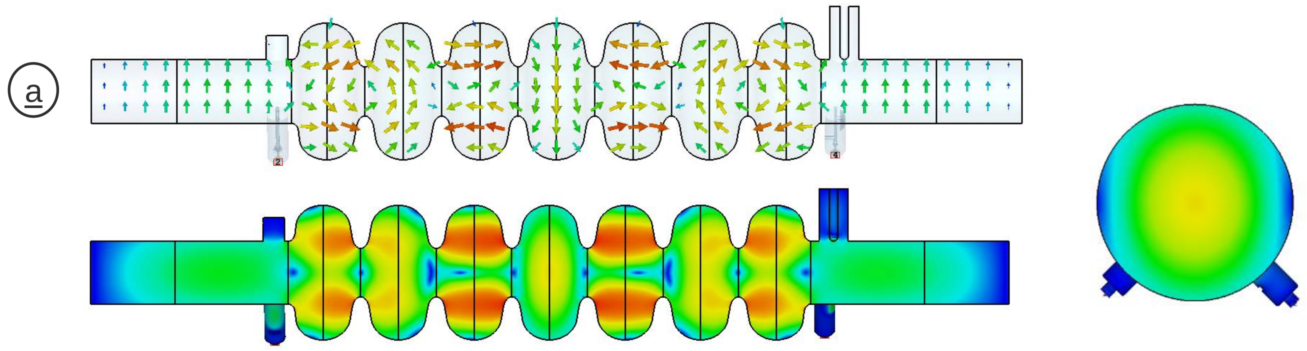


$f = 3.384$ GHz, $R/Q = 9.0$ Ω, $Q_{\text{ext}} = 2.5e3$

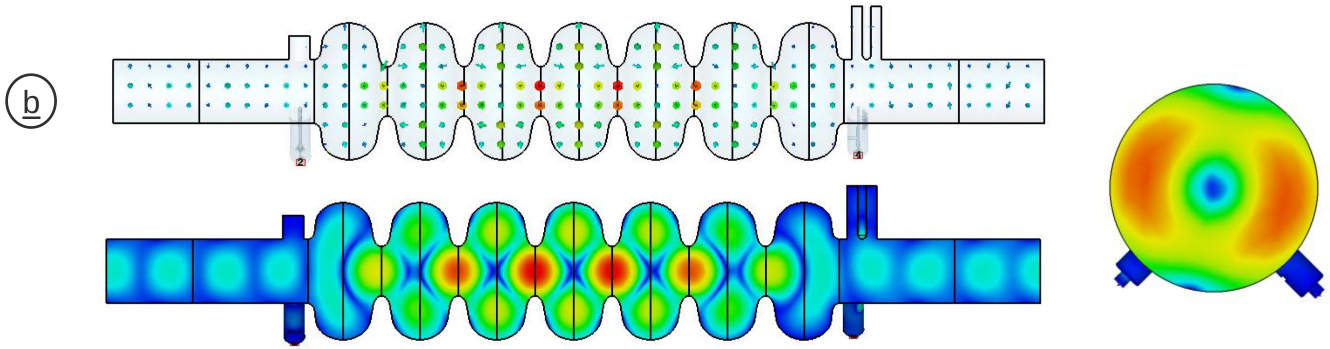
$Z_\perp$ of UROS7 cavity



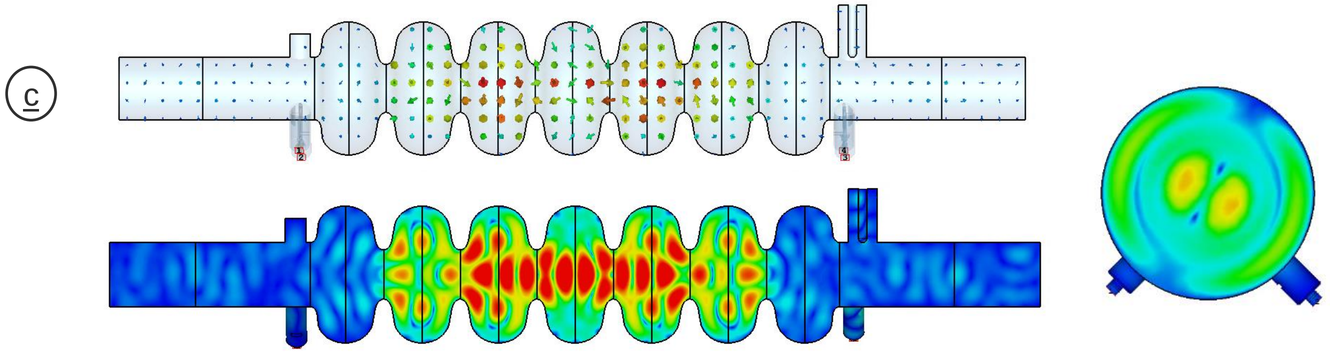




$f = 1.151$ GHz, $R/Q_\perp = 38.9$ Ω, $Q_{\text{ext}} = 4.1e3$

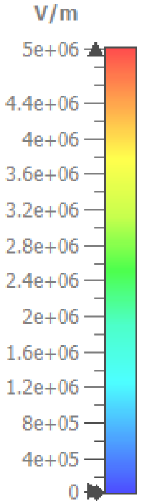


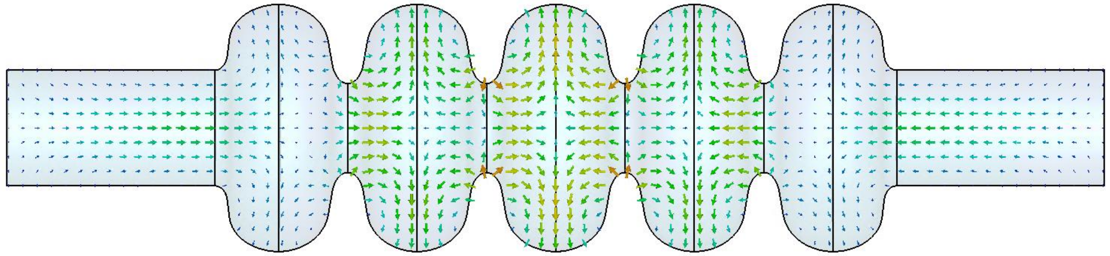
$f = 1.565$ GHz, $R/Q_\perp = 42.4$ Ω, $Q_{\text{ext}} = 1.0e3$



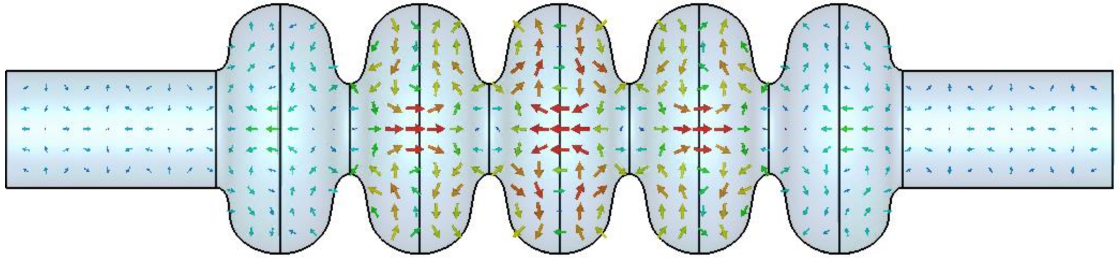
$f = 3.458$ GHz, $R/Q_\perp = 0.28$ Ω, $Q_{\text{ext}} = 1.5e4$

UROS5 HOMs

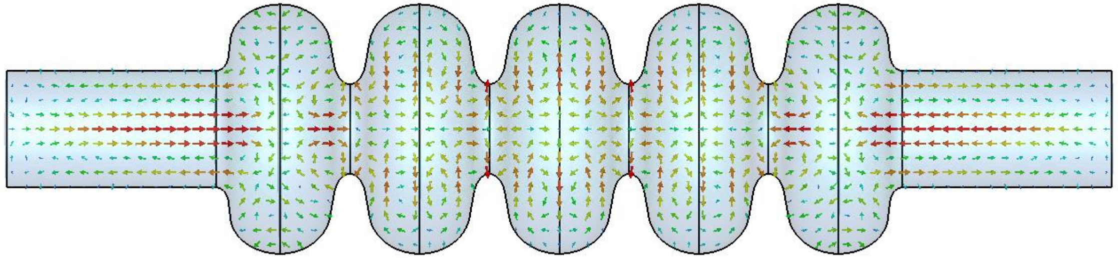




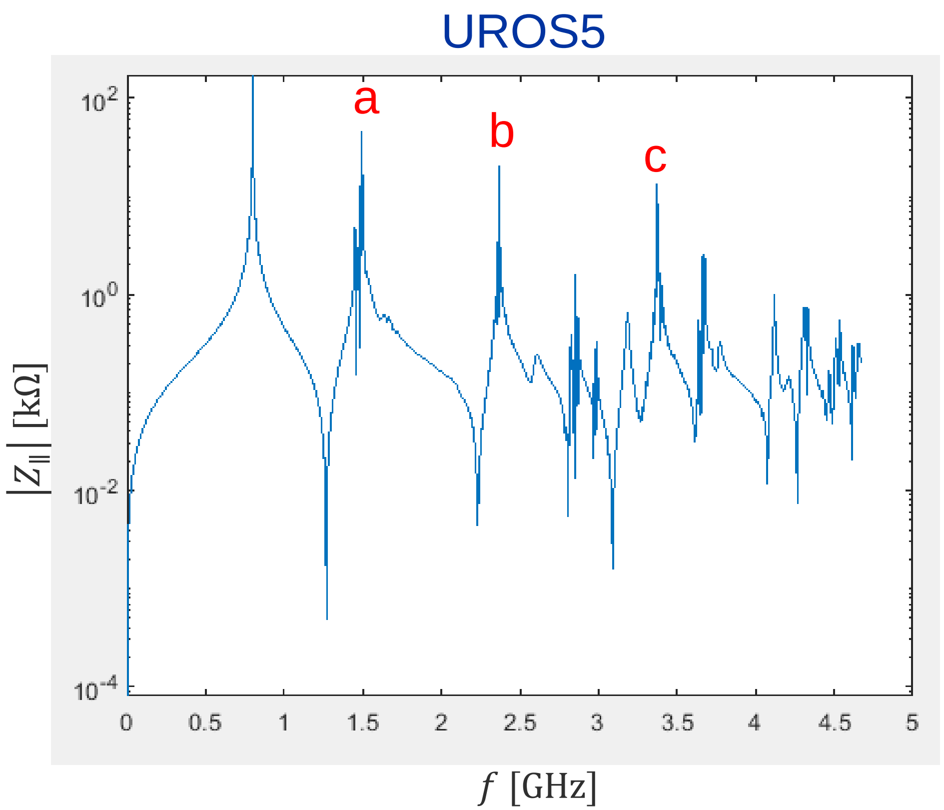
a: $f = 1.495\ \text{GHz}, R/Q = 99\ \Omega, Q_{\text{ext}} = 3.9e3$



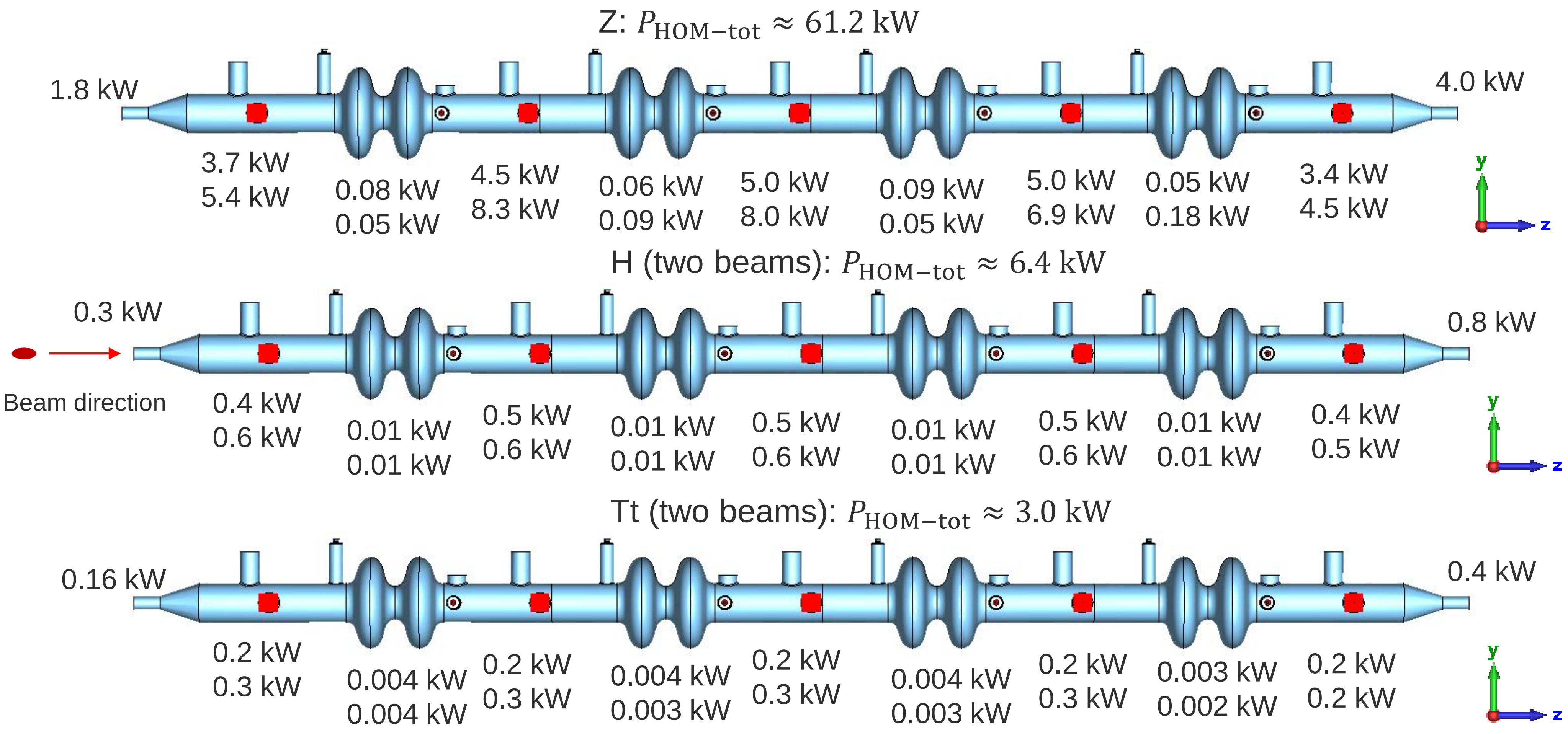
b: $f = 2.37\ \text{GHz}, R/Q = 19\ \Omega, Q_{\text{ext}} = 3.8e3$



c: $f = 3.38\ \text{GHz}, R/Q = 7.2\ \Omega, Q_{\text{ext}} = 8.2e3$

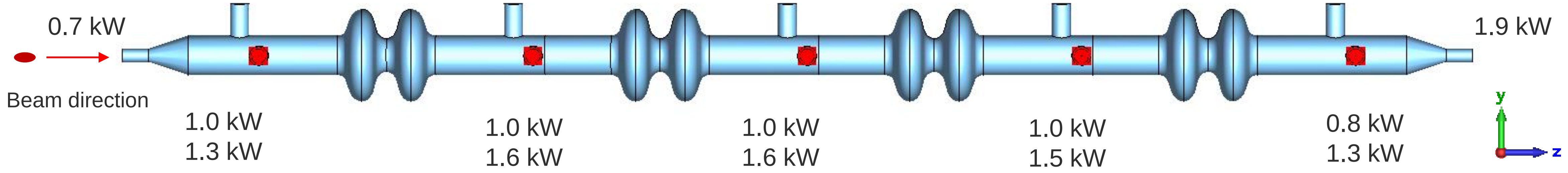


HOM power for Z, H and $t\bar{t}$ beam in two-cell cavity module

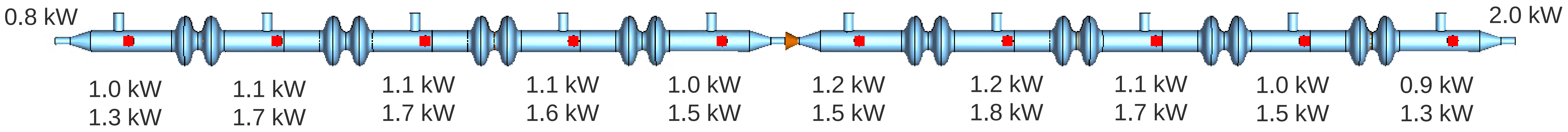


HOM power for W beam in two modules

W: $P_{\mathrm{HOM-tot}} \approx 14.7\ \mathrm{kW}$



W: $P_{\mathrm{HOM-tot}} \approx 28.2\ \mathrm{kW}$



Hook-type coupler and FPC is eliminated to simplify the simulation setup → results into smaller total HOM power