Accelerating cavities with HOM damping for FCC-ee

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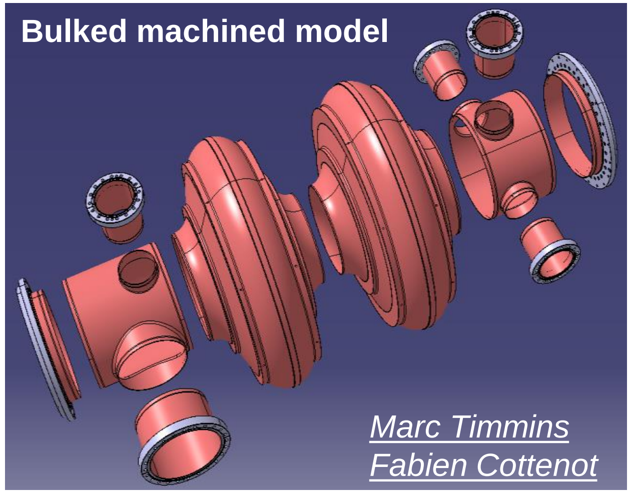
Overview

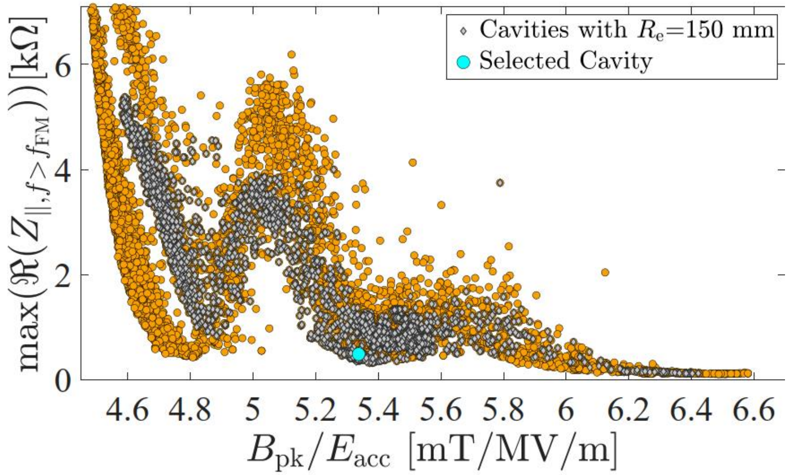
- 400 MHz RF system
  - Cavity design
  - HOM damping
  - Sensitivity analysis
- 800 MHz RF system
  - Cavity design
  - HOM damping
  - Sensitivity analysis

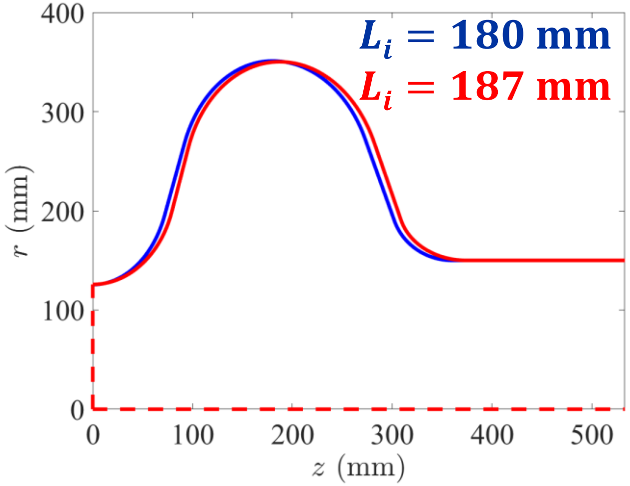
2-cell 400 MHz cavity shape

- **Initial Cavity Optimization**: $\text{minimize} \quad (B_{\text{pk}}/E_{\text{acc}}, \max(\Re(Z_{\parallel, f>f_{\text{FM}}}))$
- **Re-optimization for RPO Requirement:** also reduce the R/Q of the 0-mode in the FM passband → Resulting half-cell length of 180 mm
- **Material and target Q_0** → Nb/Cu at 4.5 K aiming for Q_0=2.7e9 at E_{acc}=10 MV/m
- **Ports**: 1 Port for FPC, two ports for HOM couplers, 1 port for pick up antenna and one port for possible use of FRT


Bulked machined model

Marc Timmins
Fabien Cottenot



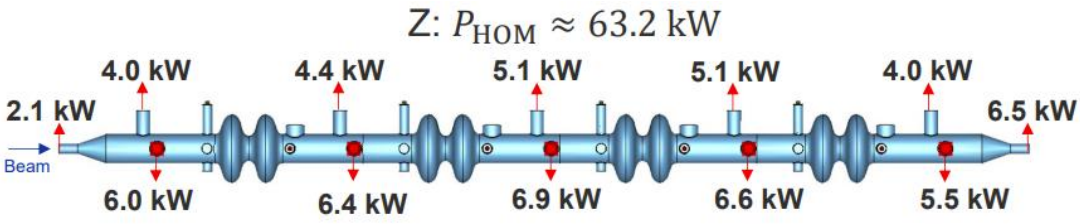


$L_i = L_e$ [mm]	R_{eq} [mm]	R/Q_π [Ω]	R/Q_0 [Ω]
187	350.190	181.1	0.63
180	351.041	182.7	0.004
$L_i = L_e$ [mm]	G [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]
187	234.7	2.0	5.33
180	232.7	2.0	5.33

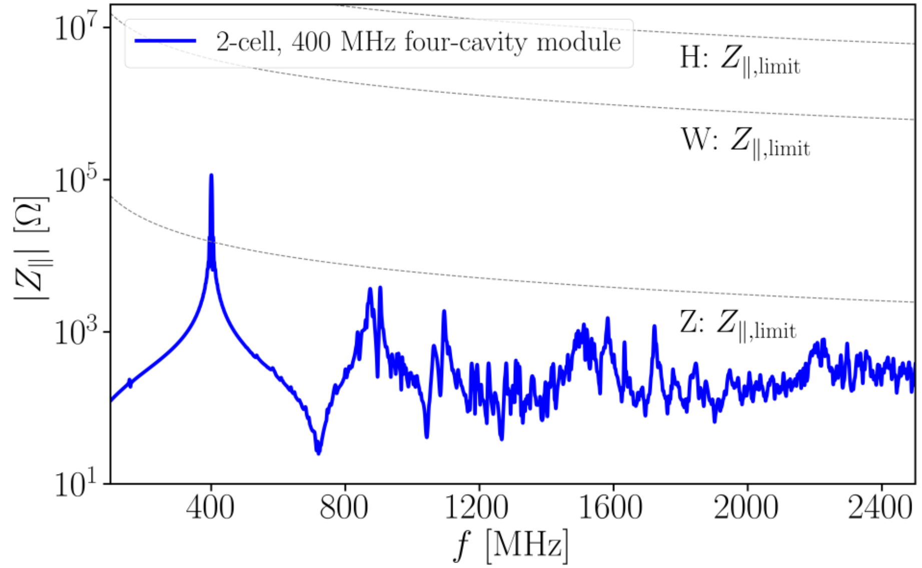
HOM study of 400 MHz cavities

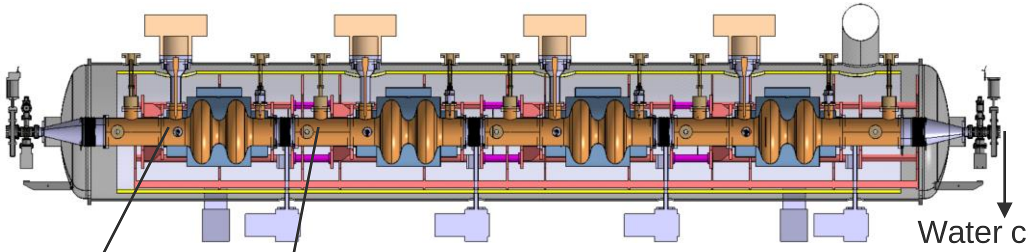
- Two hook-type coaxial couplers per cavity used for trapped dipole mode damping. **Total numbers: 8×66=528**
- Two coaxial lines between cavities for high-power HOM extraction. **Total numbers: 10×66=660**

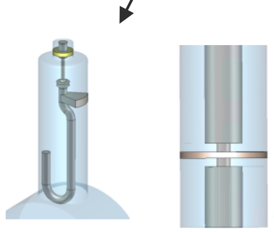
  (possibility of reducing this number should be checked)
- BLA between modules to absorb power propagating from modules out. **Total numbers=66+1=67**



HOM power of all 8 hook-type HOM couplers combined is around 0.7 kW (not shown in the figure above)

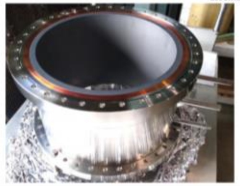






- Coaxial lines terminated by water-cooled absorbers
- Window to separate air and vacuum compromises broadband transmission (design study ongoing)

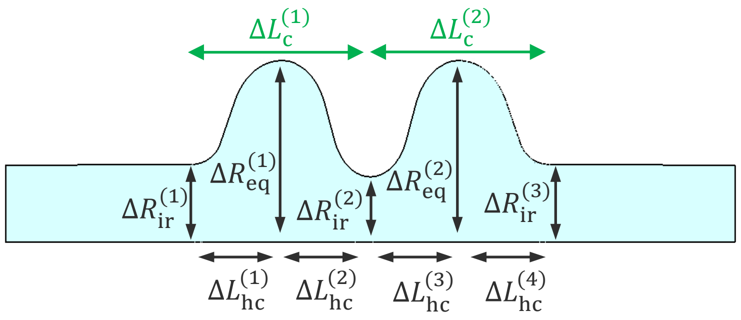
Water cooled BLA between modules

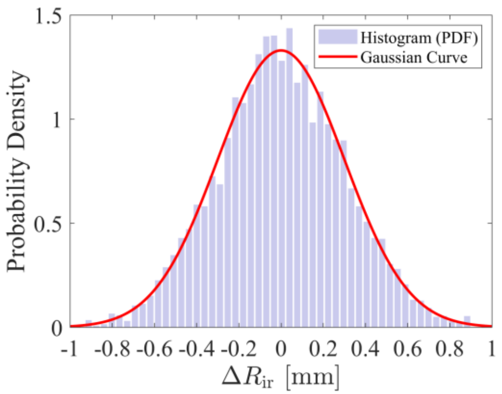


EIC BLA

Sensitivity analysis of the 2-cell 400 MHz cavity

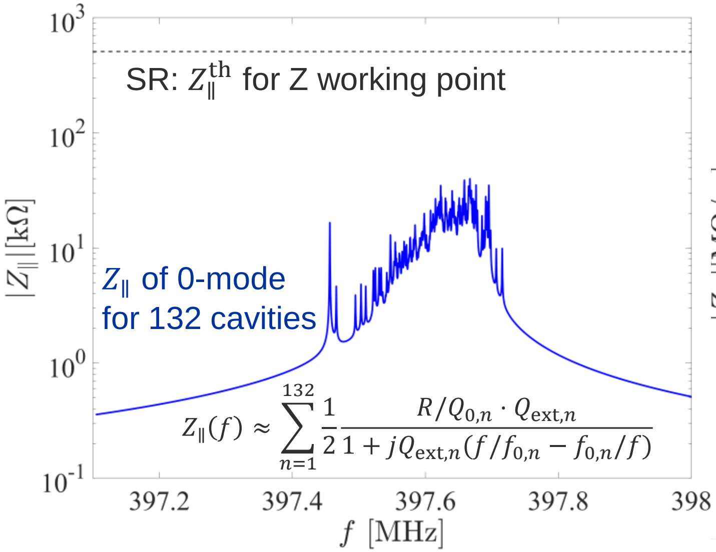
A perturbation with a standard deviation (std) of 0.3 mm, clamped at ±0.9 mm, was applied to $\Delta R_{\mathrm{ir}}^{(1,2,3)}$, $\Delta R_{\mathrm{eq}}^{(1,2)}$ and $\Delta L_{\mathrm{hc}}^{(1,2,3,4)}$. In each case, $\Delta L_{\mathrm{c}}^{(1)}$ and $\Delta L_{\mathrm{c}}^{(2)}$ were adjusted to tune the FM frequency to 400.79 MHz

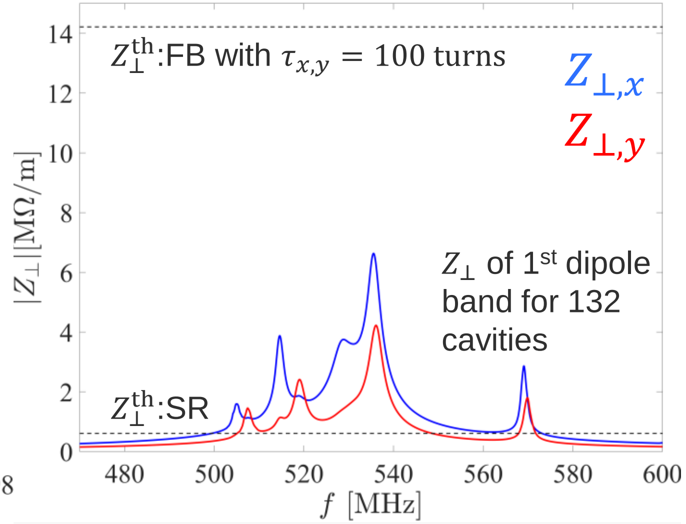




	f_0 [MHz]	R/Q$_0$ [Ω]	$E_{\mathrm{pk}}/E_{\mathrm{acc}}$ [-]	$B_{\mathrm{pk}}/E_{\mathrm{acc}}$ [mT/MV/m]	R/Q$_{\mathrm{FM}}$ [Ω]	G [Ω]
Mean	397.604	0.014	1.97	5.34	182.5	232.8
Std.	0.045	0.016	0.01	0.01	0.24	0.75
Worst case	-	0.10	2.02	5.38	-	230.2

Statistical data for 264 samples

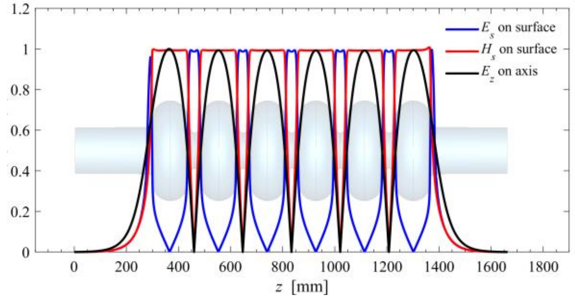




6-cell 800 MHz cavity

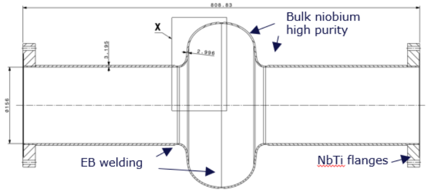
- **Cavity shape:**
  - 6-cell 800 MHz cavity → in total 856 cavities for booster and tt collider
  - 1.53 m long
  - Asymmetric end-cell shape for better HOM damping
  - 1 port for FPC, 4 ports for HOM couplers, 1 port for pick up antenna and 1 port for FRT
- **Material and target Q_0:**
  - $Q_0 = 3e10$ at $E_{\mathrm{acc}} = 20.3\ \mathrm{MV/m}$
  - Bulk Nb with electropolished and doped RF surface
  - Nb_3Sn coating as an option to operate at 4.5 K
- **Fabrication and R&D program**
  - Fabrication of 10 single-cell cavities at CERN (EN/MME) based on the RF design and mechanical design by CERN (SY-RF & EN-MME)
  - Collaboration with international partners to achieve required high Q0: FNAL, IJCLAB and Cornell

Courtesy Marco Chiodini

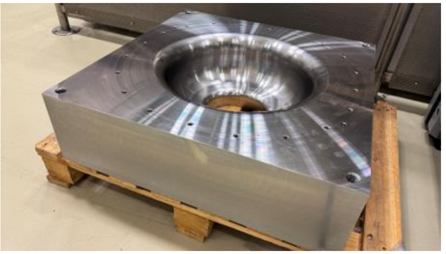


112 cavities for Z, W and H booster
408+336 additional cavities for ttbar operation

Courtesy Laurent Prever-Loiri



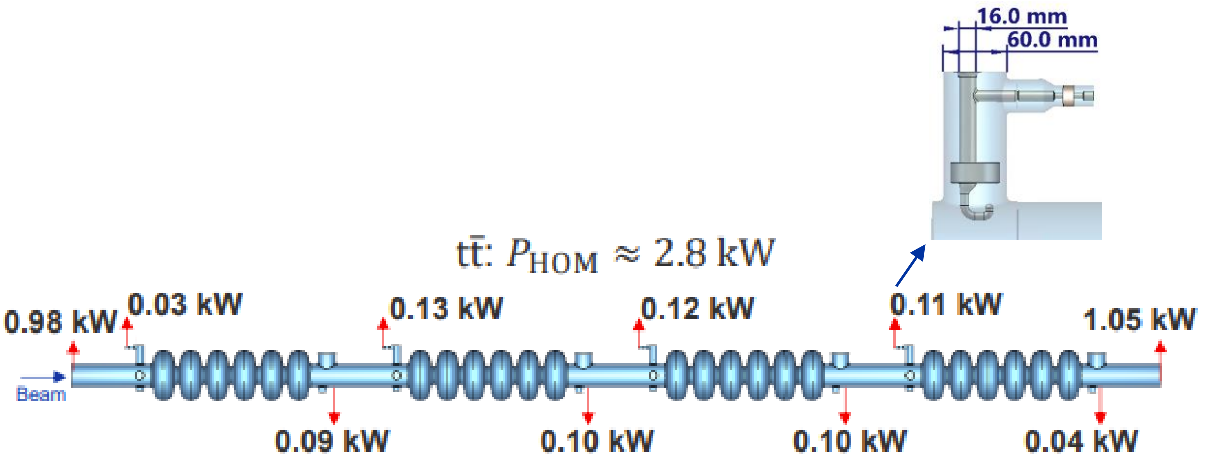
Courtesy F. Peauger

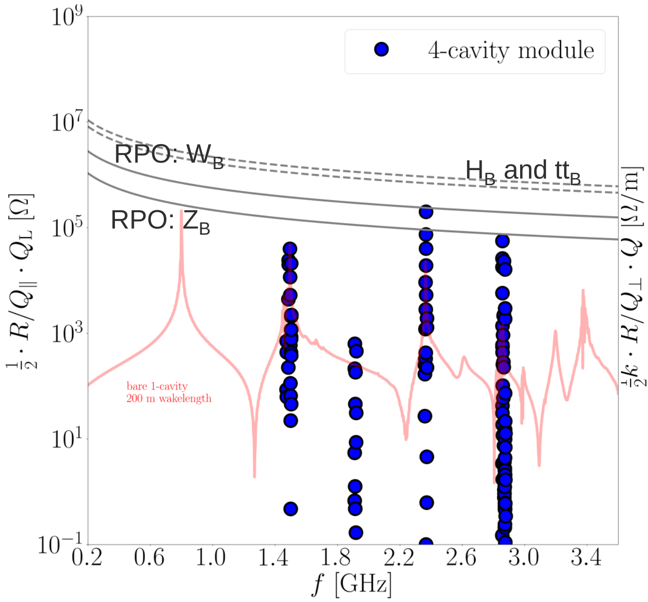


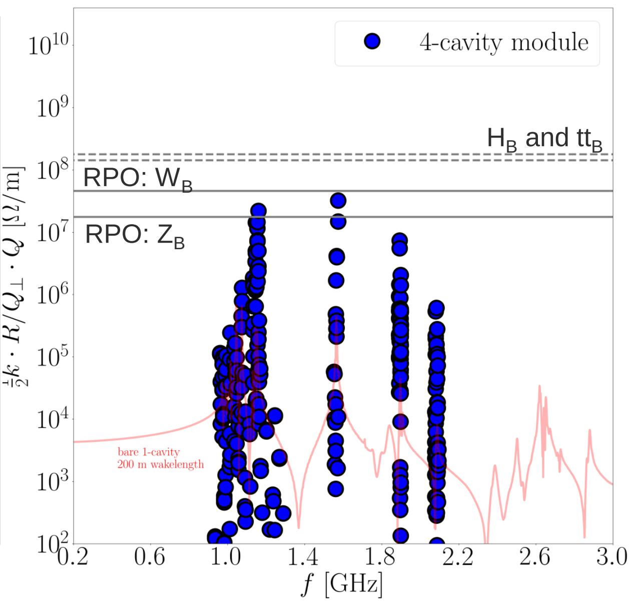
Deep drawing tests performed on copper sheets

HOM study of 6-cell 800 MHz cavity

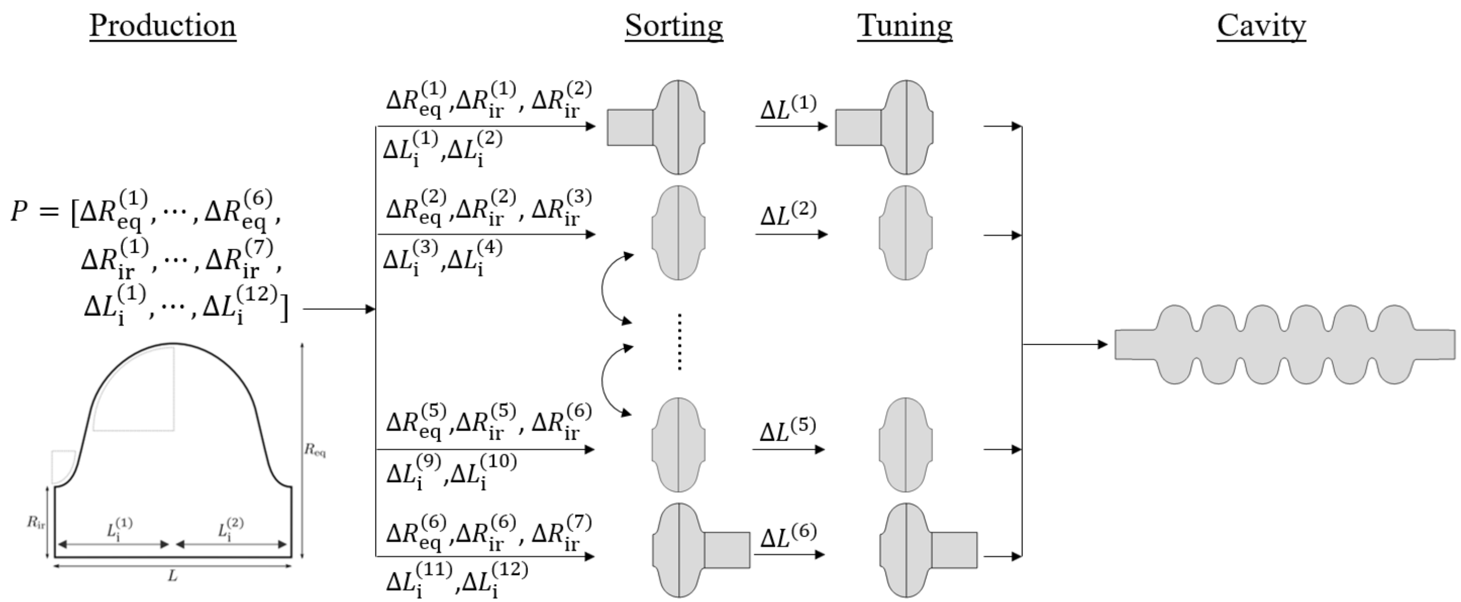
- **HOM power:**
  - tt collider highest HOM power. On average 0.7 kW per cavity
  - Up to 200 W per DQW HOM coupler
- **Total number of HOM couplers:**
  - **Z/W/H booster**: 4 DQW couplers per cavity → 4×112=448
  - **tt collider & booster**: 2 DQW per cavity → 2×(408+336)=1488
  - **BLA between cryomodules**: 113 for Z/W/H booster, 409 for tt collider; likely not needed for tt booster.
- **Impedance limit**:
  - Despite 100-turn transverse feedback and 3× energy loss/turn from wigglers in the longitudinal plane, the impedance limit remains very low for the Z booster in RPO
  - Frequency spread from cavity manufacturing tolerances can lower the total impedance of dangerous modes by a factor of 5–8





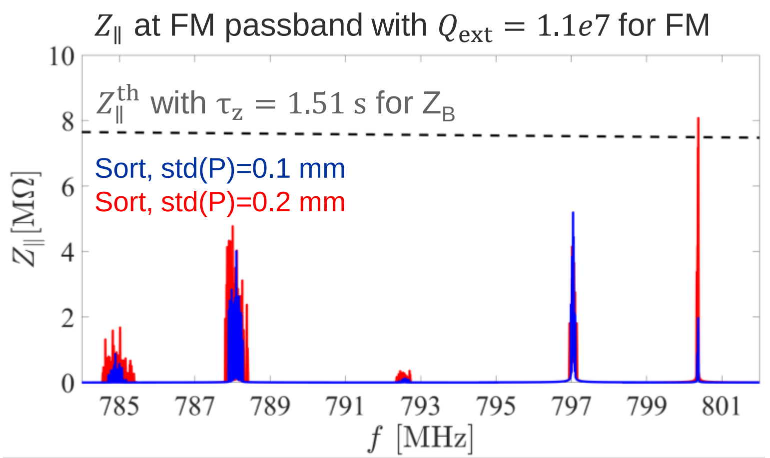


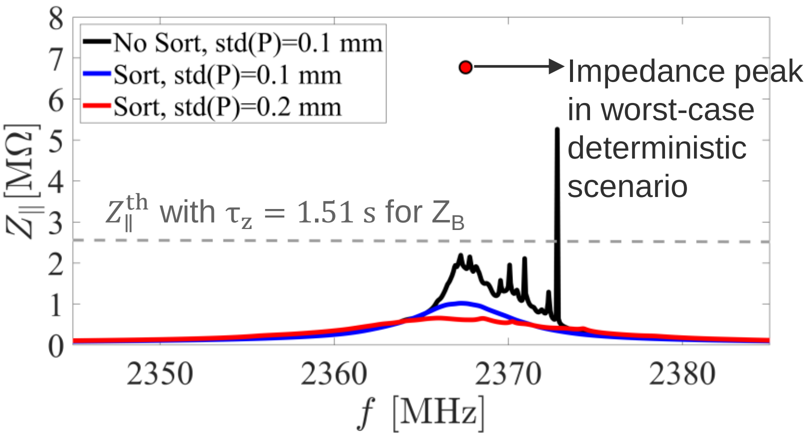
Perturbation analysis



- A **perturbation** applied to R_{ir}, R_{eq} and L_i with a standard deviation $\mathrm{std}(P)$ of 0.1 mm clamped at $3 \times \mathrm{std}(P)$. The length of each cell is then changed to tune the cells' frequency to 801.58 MHz.
- **Sorting before tuning**: the mid-cell with average frequency is installed at the last position (position 5), the remaining mid-cells are installed in order of decreasing frequency

A similar study on XFEL cavities: J. Corno, et al.Uncertainty modeling and analysis of the European X-ray free electron laser cavities manufacturing process, 2020





Impedance of TM012 passband of 112 bare cavities with open BC

Summary and outlook

Summary

- Updated 400 MHz and 800 MHz cavity designs to meet latest RPO RF requirements
- HOM damping via coaxial couplers inside cryomodule, and BLAs between cryomodules is considered
- Sensitivity studies confirm frequency spread reduces impedance peaks;
  – 400 MHz: robust performance
  – 800 MHz: perform cell sorting and monitor R/Q of 5π/6 mode during fabrication

Outlook

- Finalize mechanical study and design of HOM damping components
- Experimentally verify the reachability of Q_0 at the desired E_{acc} for the 400 MHz and 800 MHz cavities
- Refine high power coaxial line and BLA designs
- Address the challenge of low beam stability limits in the Z and W booster in RPO
- Plan experimental validation and prototype testing

Appendix

RF baseline updates

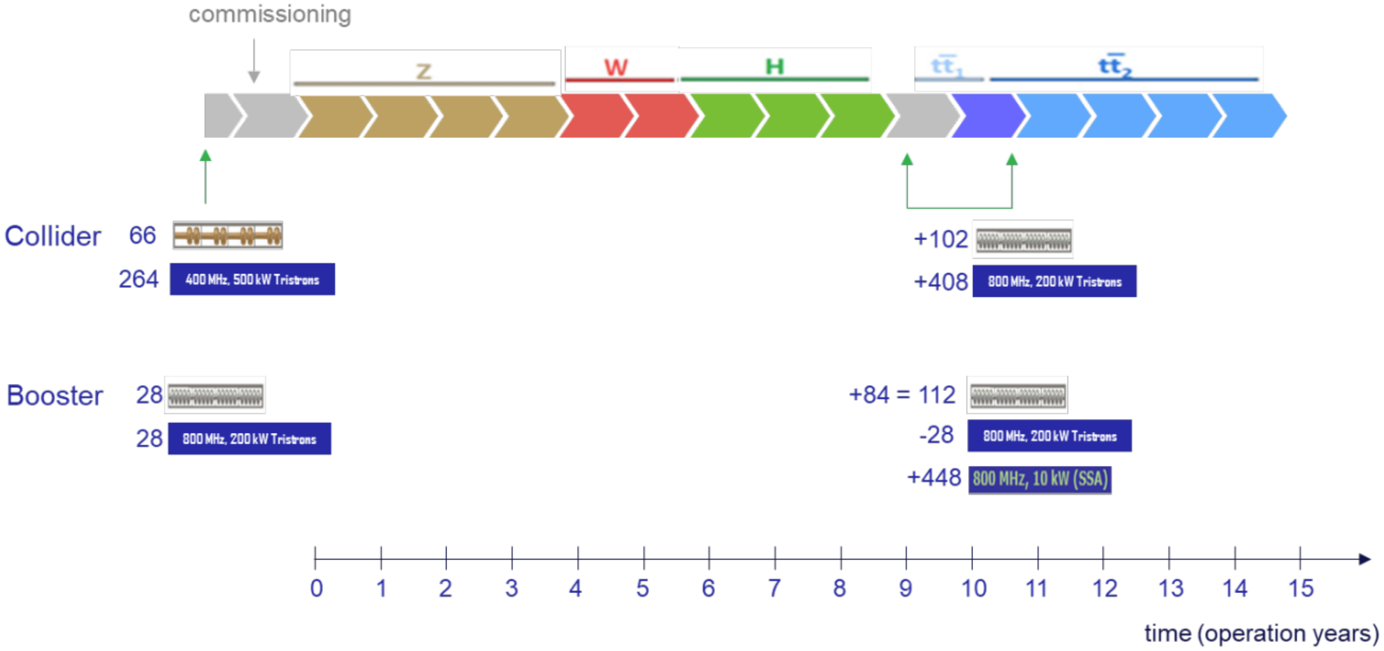
Collider cavities

	Z	W	H	tt
Beam energy [GeV]	45.6	80	120	182.5
Reverse phase operation	**Yes**	No	No	No
# cells/cavity	**2**	2	2	2/**6**
f [MHz]	400	400	400	400/800
# cavities	**264**	264	264	264/**408**
E_{acc} [MV/m]	**10.6**	10.6	10.6	10.6/20.1
$P_{\text{loss-dynamic}}$/cav [W]	130	128	128	128/27
Power per cav. [kW]	**380**	380	380	78/195

Booster cavities

	Z	W	H	tt
Injection energy [GeV]	20	20	20	20
Extraction energy [GeV]	45.6	80	120	182.5
Reverse phase operation	**Yes**	**Yes**	No	No
# cells/cavity	**6**	**6**	**6**	**6**
f [MHz]	800	800	800	800
# cavities	**112**	**112**	**112**	**448**
E_{acc} [MV/m]	2.5	12	15.6	20.25
Max Power per cav. [kW]	42	42	42	12.6

SRF layout



Q_0 target values

Cavity configuration		bare	dressed	cryomodule	operation
Orientation in test		vertical	vertical	horizontal	horizontal
Added elements			helium tank HOM couplers	FPC tuner shieldings	
400 MHz Cavity	E_{acc} [MV/m]	13	12.4	11.8	10.6
	Q_0	3.3×10^9	3.15×10^9	3×10^9	2.7×10^9
800 MHz Cavity	E_{acc} [MV/m]	24.8	23.6	22.5	20.25
	Q_0	3.8×10^{10}	3.65×10^{10}	3.5×10^{10}	3×10^{10}

FCC feasibility study report, March 2025

RF parameters of the collider cavities

Parameters	Z	W	ZH	$t\bar{t}$	
Common RF system for two beams	no	no	yes	yes	
RPO	yes	no	no	no	
Total RF voltage [MV]	89	1049	2098	2098	9202
Beam current [mA]	1283	135	53.6	10	
RF frequency [MHz]	400.79			400.79	801.58
Operating temperature [K]	4.5			4.5	2
Number of cells per cavity	2			2	6
Quality factor Q_0	2.7×10^9			2.7×10^9	3×10^{10}
Cavity voltage [MV]	7.95			7.95	22.5
Accelerating gradient E_{acc} [MV/m]	10.6			10.6	20.1
RF power per cavity [kW]	380			78	195
Coupling factor Q_L	9.2×10^5			4.5×10^6	4.1×10^6
Number of cryomodules	66			66	102
Number of cavities	264			264	408

RF parameters of the booster cavities

	Z	W	ZH	$t\bar{t}$
RPO at extraction	yes	yes	no	no
RF frequency [MHz]	801.58			
Operating temperature [K]	2			
Number of cells per cavity	6			
Quality factor Q_0	3×10^{10}			
Cavity voltage at extraction [MV]	5.6	13.5	17.5	22.8
E_{acc} [MV/m]	4.9	12.0	15.6	20.3
Max. RF power per cavity [kW]	42			8.9 / 12.7
Coupling factor Q_L	1×10^7			9.2×10^7 / 2.7×10^7
Number of cryomodules	28			112
Number of cavities	112			448

$t\bar{t}$ and booster stability parameters

- Low energy and long damping time at injection leads to a low beam instability impedance limit for the booster cavities
- A 100-turn feedback for the transverse plane, and a factor of three energy loss per turn from wigglers considered in the longitudinal plane impedance

Running mode	Z-booster	W-booster	Higgs-booster	ttbar-booster	ttbar-collider
Momentum compaction (α_c)	7.12e-6				7.52e-6
Current (I_0) [mA]	16.2	6.2	2.0	0.4	4.9×2
Injection					
Injection energy (E_0) [GeV]	20	20	20	20	
Long. Damping time (τ_z) [s]	4.52	4.52	4.52	4.52	
Sync. tune at injection	0.0262	0.0262	0.0262	0.0262	
$Z_{\parallel}^{\rm th}$ [MΩ] with SR	$2.0/f$ [GHz]	$5.3/f$ [GHz]	$16.3/f$ [GHz]	$81.4/f$ [GHz]	
$Z_{\perp}^{\rm th}$ [MΩ/m] with SR	1.7	4.3	13.4	66.9	
$Z_{\parallel}^{\rm th}$ [MΩ] with $\tau_z = 1.51\ s$	**$6.0/f$ [GHz]**	**$15.7/f$ [GHz]**	**$48.7/f$ [GHz]**	**$244/f$ [GHz]**	
$Z_{\perp}^{\rm th}$ [MΩ/m] with 100 turns FB	**494**	**1290**	**4000**	**20000**	
Extraction					
Extraction energy [GeV]	45.6	80	120	182.5	182.5
Long. Damping time at extraction [s]	0.382	0.0707	0.0209	0.00595	0.0059
Sync. tune at extraction	0.0163	0.0269	0.0458	0.0795	0.0881
$Z_{\parallel}^{\rm th}$ [MΩ] with SR	$33.7/f$ [GHz]	$1379/f$ [GHz]	$36933/f$ [GHz]	$1712e3/f$ [GHz]	$74372/f$ [GHz]
$Z_{\perp}^{\rm th}$ [MΩ/m] with SR	44.6	1.1e3	17.4e3	464e3	19e3

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

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

- Transversal damping time $(\tau_{xy}) = 2 \times$ longitudinal damping time (τ_z)
- $\beta_{xy} = 50$ m for all working points, $f_{\rm rev} = 3307$ Hz, $N_{\rm cav}$ is assumed 1 (a normalization to the number of cavities is needed)

Frequency spread coefficient

- If impedance for mode m modelled by $Z_{\parallel,m}(f) \approx \frac{1}{2}\frac{R/Q_{\parallel,m}\cdot Q_m}{1+jQ_m(f/f_m - f_m/f)} \rightarrow \boldsymbol{c} = \frac{\sum_{n=1}^{N_\mathrm{cav}} Z_{\parallel,n,m}}{N_\mathrm{cav} Z_{\parallel,1,m}}$: the ratio of the total impedance of N_cav cavities, each with a perturbed shape, to the impedance of N_cav cavities with identical shape

$f_n = 2\ \mathrm{GHz}$		$N_\mathrm{cav} = 1$	$N_\mathrm{cav} = 4$	$N_\mathrm{cav} = 10$	$N_\mathrm{cav} = 50$	$N_\mathrm{cav} = 100$	$N_\mathrm{cav} = 400$
$\sigma(f_n) = 10\ \mathrm{kHz}$	$Q_n = 1e3$	1	1	1	1	1	1
	$Q_n = 1e4$	1	1	1	1	1	0.99
	$Q_n = 1e5$	1	0.85	0.81	0.79	0.79	0.79
	$Q_n = 1e6$	1	0.51	0.35	0.29	0.26	0.25
$\sigma(f_n) = 100\ \mathrm{kHz}$	$Q_n = 1e3$	1	1	1	1	1	1
	$Q_n = 1e4$	1	0.85	0.82	0.80	0.79	0.78
	$Q_n = 1e5$	1	0.47	0.38	0.28	0.26	0.24
	$Q_n = 1e6$	1	0.31	0.18	0.087	0.065	0.05
$\sigma(f_n) = 1000\ \mathrm{kHz}$	$Q_n = 1e3$	1	0.86	0.82	0.79	0.80	0.79
	$Q_n = 1e4$	1	0.47	0.36	0.29	0.26	0.25
	$Q_n = 1e5$	1	0.29	0.16	0.08	0.065	0.05
	$Q_n = 1e6$	1	0.25	0.11	0.039	0.025	0.014

HOM power 800 MHz cavity

	Z booster	**W booster**	**H booster**	**tt booster**	**tt collider (SR)**	**tt collider (BS)**
No. bunches	1120	928	300	64	56	56
Particles/bunch (filling) [1e10]	2.725	1.268	1.268	1.268		
Particles/bunch (top-up) [1e10]	2.725	1.035	1.268	1.125	16.4	16.4
Beam current I_0 (filling) [mA]	16.17	6.23	2.02	0.43	-	-
Beam current I_0 (top-up) [mA]	16.17	5.09	2.02	0.38	4.9	4.9
Injection bunch length [mm]	4	4	4	4	-	-
Extraction bunch length [mm]	2.43	2.56	2.26	1.98	1.91	2.33
$k_\parallel$ at injection bunch length [V/pc]	2.67	2.67	2.67	2.67	-	-
$k_\parallel$ at extraction bunch length [V/pc]	3.49	3.39	3.64	3.94	4.02	3.57
P_{HOM} injection/filling [W]	**132.5**	**23.8**	**7.7**	**1.6**	**-**	**-**
P_{HOM} extraction/top up [W]	**190.3**	**21.9**	**11.6**	**2.2**	**825.0**	**710.8**

HOM power of 6-cell 800 MHz bare cavity using formula $P_{\mathrm{HOM}} = (k_\parallel - k_0) q I_0$

Perturbation analysis 6-cell 800 MHz (I)

		f_1 [MHz]	R/Q$_1$ [Ω]	f_2 [MHz]	R/Q$_2$ [Ω]	f_3 [MHz]	R/Q$_3$ [Ω]	f_4 [MHz]	R/Q$_4$ [Ω]	f_5 [MHz]	R/Q$_5$ [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	R/Q$_{FM}$ [Ω]	G [Ω]	Field Flatness [%]	Max $Z_\parallel$ TM012 [kΩ]
Perturbation (p) **Mean (p)=0 mm** **Std (p)=0.1 mm** **No cell sort**	Mean	784.911	0.005	788.121	0.126	792.555	0.015	797.039	0.401	800.358	0.061	2.052	4.364	630.162	272.209	98.896	106.4
	Std.	0.095	0.004	0.071	0.032	0.049	0.013	0.025	0.066	0.007	0.077	0.006	0.010	0.703	0.271	0.329	326.0
	Worst case	-	0.019	-	0.218	-	0.079	-	0.579	-	0.671	2.070	4.387	-	271.579	98.04	4781

		f_1 [MHz]	R/Q$_1$ [Ω]	f_2 [MHz]	R/Q$_2$ [Ω]	f_3 [MHz]	R/Q$_3$ [Ω]	f_4 [MHz]	R/Q$_4$ [Ω]	f_5 [MHz]	R/Q$_5$ [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	R/Q$_{FM}$ [Ω]	G [Ω]	Field Flatness [%]	Max $Z_\parallel$ TM012 [kΩ]
Perturbation (p) **Mean (p)=0 mm** **Std (p)=0.1 mm** **Cell sort**	Mean	784.928	0.005	788.097	0.152	792.551	0.006	797.045	0.393	800.356	0.064	2.053	4.365	630.205	272.185	98.903	13.6
	Std.	0.088	0.003	0.070	0.026	0.047	0.005	0.023	0.062	0.006	0.081	0.005	0.010	0.648	0.260	0.364	9.3
	Worst case	-	0.018	-	0.234	-	0.021	-	0.585	-	0.599	2.067	4.389	-	271.498	97.670	66.7

		f_1 [MHz]	R/Q$_1$ [Ω]	f_2 [MHz]	R/Q$_2$ [Ω]	f_3 [MHz]	R/Q$_3$ [Ω]	f_4 [MHz]	R/Q$_4$ [Ω]	f_5 [MHz]	R/Q$_5$ [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	R/Q$_{FM}$ [Ω]	G [Ω]	Field Flatness [%]	Max $Z_\parallel$ TM012 [kΩ]
Perturbation (p) **Mean (p)=0 mm** **Std (p)=0.2 mm** **Cell sort**	Mean	784.957	0.009	788.089	0.189	792.564	0.016	797.057	0.409	800.356	0.265	2.055	4.366	629.634	272.276	98.252	11.9
	Std.	0.175	0.007	0.132	0.059	0.087	0.015	0.044	0.127	0.011	0.345	0.010	0.017	1.512	0.530	0.591	8.9
	Worst case	-	0.042	-	0.439	-	0.068	-	0.795	-	1.999	2.089	4.422	-	270.728	96.637	65.1

Data from 250 samples

Perturbation analysis 6-cell 800 MHz (II)

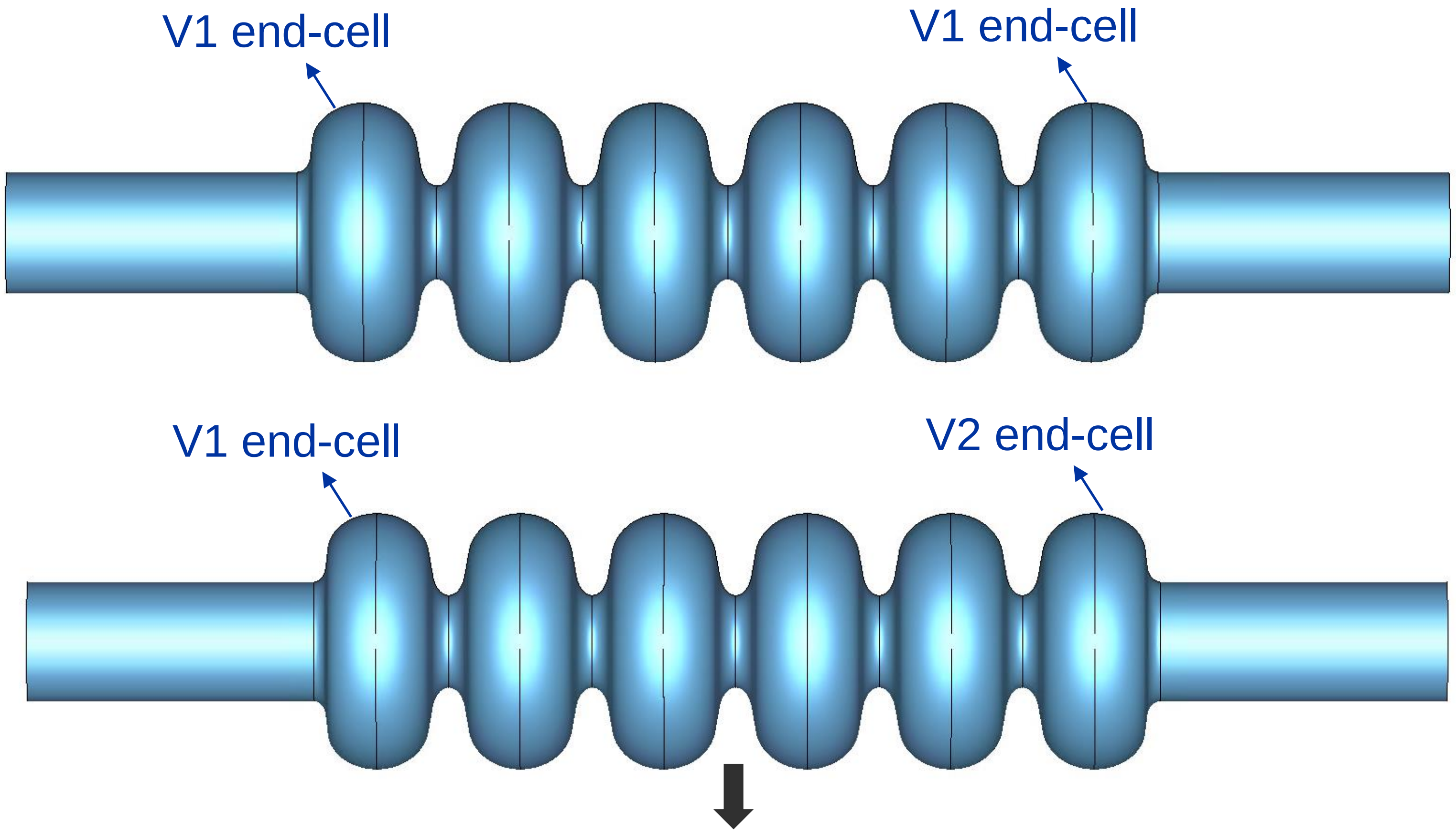
		f_1 [MHz]	R/Q$_1$ [Ω]	f_2 [MHz]	R/Q$_2$ [Ω]	f_3 [MHz]	R/Q$_3$ [Ω]	f_4 [MHz]	R/Q$_4$ [Ω]	f_5 [MHz]	R/Q$_5$ [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	R/Q$_{FM}$ [Ω]	G [Ω]	Field Flatness [%]	Max $Z_{\parallel}$ TM012 [kΩ]
Perturbation (p) **Mean (p)=0 mm** **Std (p)=0.3 mm** **Cell sort**	Mean	784.957	0.016	788.050	0.240	792.557	0.045	797.061	0.464	800.354	0.625	2.059	4.374	629.127	272.235	97.370	16.7
	Std.	0.279	0.016	0.212	0.105	0.139	0.048	0.069	0.213	0.018	0.819	0.012	0.026	2.426	0.837	0.965	31.8
	Worst case	-	0.084	-	0.662	-	0.309	-	1.370	-	5.274	2.101	4.470	-	269.834	94.643	421.6

		f_1 [MHz]	R/Q$_1$ [Ω]	f_2 [MHz]	R/Q$_2$ [Ω]	f_3 [MHz]	R/Q$_3$ [Ω]	f_4 [MHz]	R/Q$_4$ [Ω]	f_5 [MHz]	R/Q$_5$ [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	R/Q$_{FM}$ [Ω]	G [Ω]	Field Flatness [%]	Max $Z_{\parallel}$ TM012 [kΩ]
Perturbation (p) **Mean (p)=0.2 mm** **Std (p)=0.1 mm** **Cell sort**	Mean	784.884	0.006	788.064	0.154	792.531	0.014	797.035	0.405	800.354	0.642	2.044	4.366	625.227	273.258	98.812	14.0
	Std.	0.083	0.003	0.066	0.024	0.042	0.011	0.022	0.062	0.006	0.346	0.004	0.009	0.958	0.261	0.352	9.8
	Worst case	-	0.014	-	0.219	-	0.069	-	0.620	-	1.989	2.060	4.390	-	272.551	97.964	63.0

		f_1 [MHz]	R/Q$_1$ [Ω]	f_2 [MHz]	R/Q$_2$ [Ω]	f_3 [MHz]	R/Q$_3$ [Ω]	f_4 [MHz]	R/Q$_4$ [Ω]	f_5 [MHz]	R/Q$_5$ [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	R/Q$_{FM}$ [Ω]	G [Ω]	Field Flatness [%]	Max $Z_{\parallel}$ TM012 [kΩ]
Perturbation (p) **Mean (p)=-0.2 mm** **Std (p)=0.1 mm** **Cell sort**	Mean	784.989	0.004	788.149	0.155	792.586	0.004	797.063	0.401	800.361	0.327	2.062	4.366	634.024	271.226	98.971	13.8
	Std.	0.085	0.002	0.062	0.026	0.045	0.004	0.022	0.061	0.006	0.246	0.006	0.010	0.526	0.269	0.362	9.6
	Worst case	-	0.014	-	0.259	-	0.020	-	0.590	-	1.320	2.078	4.392	-	270.484	97.990	61.4

Data from 250 samples

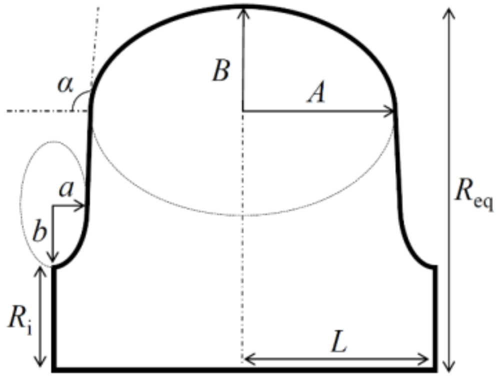
FM parameters of the 6-cell with asymmetric end-cells

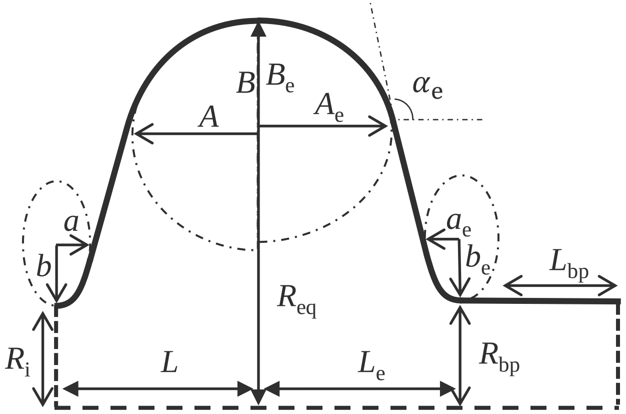


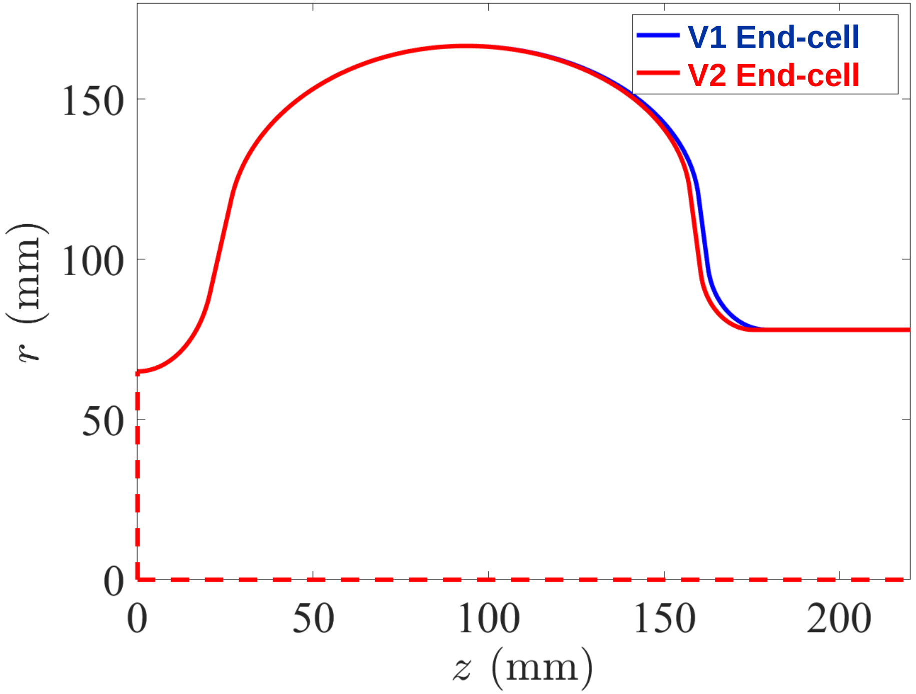
Selected design

Parameters	V1 end-cell	V1-V2 end-cell
FM		
Frequency [MHz]	801.584	801.584
R/Q [Ω]	630.4	630.2
Geometry Factor [Ω]	272.8	272.2
$G.R/Q$ [kΩ^2]	172.0	171.5
B_{pk}/E_{acc} [mT/(MV/m)]	4.31	**4.36**
E_{pk}/E_{acc} [-]	2.04	2.05
Cavity Active Length [mm]	1106.54	1102.497
Beam Pipe radius [mm]	78	78
Wall angle [degree]	100/96.9	100/96.9
Field Flatness [%]	99	99
HOM – Monopole modes		
Q_{ext} of mode f=1.494 GHz	5.0e3	**3.8e3**
Q_{ext} of mode f=2.368 GHz	9.0e3	**4.9e3**
Q_{ext} of mode f=3.38 GHz	1.0e4	**8.2e3**

800 MHz Cavity parameters





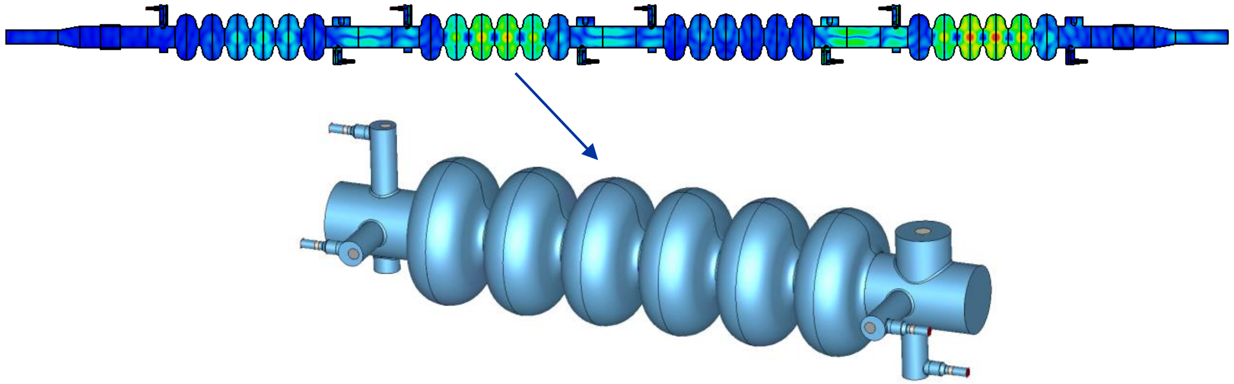


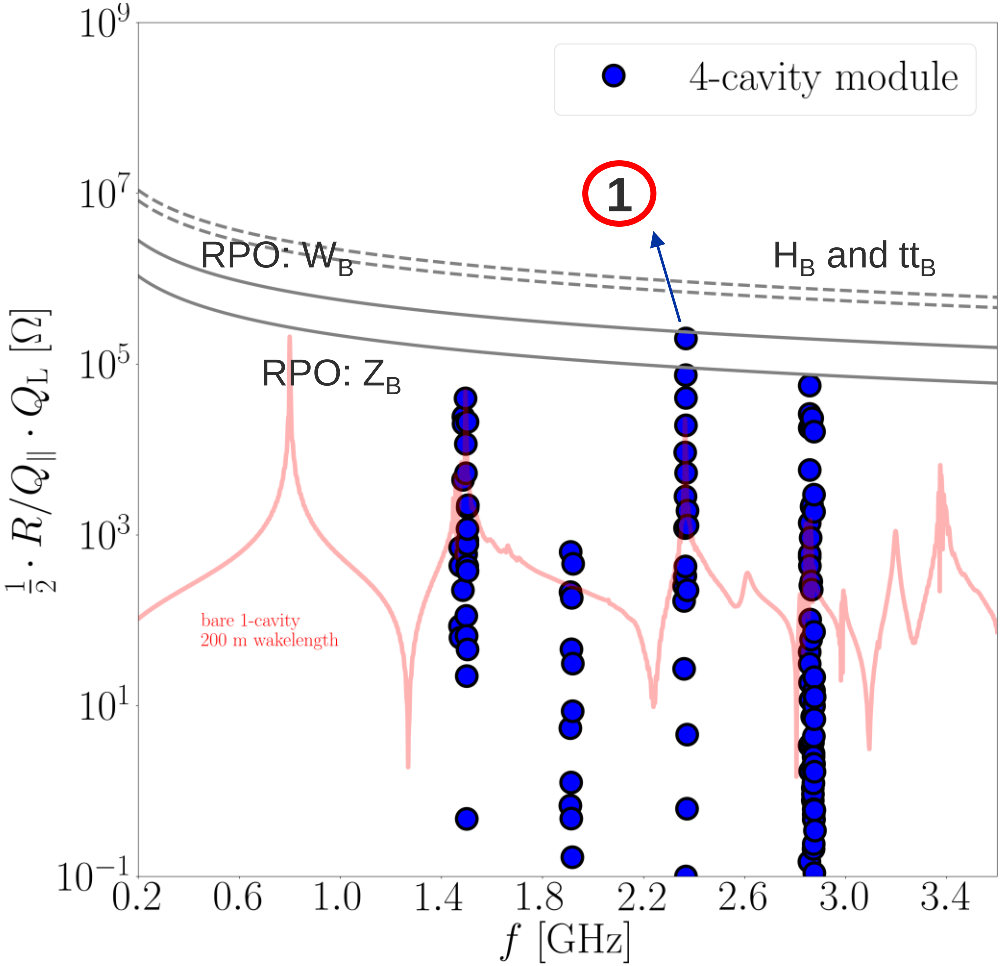
	A/A_{e} [mm]	B/B_{e} [mm]	a/a_{e} [mm]	b/b_{e} [mm]	$R_{\mathrm{i}}/R_{\mathrm{bp}}$ [mm]	L/L_{e} [mm]	R_{eq} [mm]	$\alpha/\alpha_{\mathrm{e}}$ [°]
V1 End-cell	67.72/66.5	57.45/51.0	21.75/17.0	35.6/23.0	60.0/78.0	93.5/85.77	166.591	100.0/96.9
V2 End-cell	67.72/64	57.45/49	21.75/15	35.6/21	60.0/78.0	93.5/81.727	166.591	100.0/96.9

$Z_{\parallel}$ of asymmetric end-cells with 4 DQW couplers

- Two additional DQW couplers, tuned for better damping of the 2.368 GHz mode, were added to the empty ports
- The impedance peak remains slightly above the limit; however, considering the frequency spread between cavities ($c = 0.12$ for this mode), stability is expected to be maintained in RPO

① $\boldsymbol{f = 2.3676\ \mathrm{GHz}, R/Q = 18.0\ \Omega, Q_{\mathrm{L}} = 22.4e3, c = 0.12}$

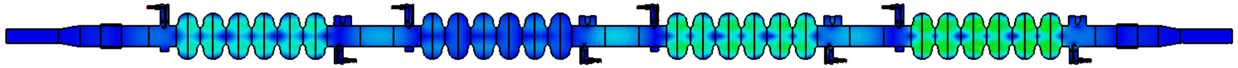




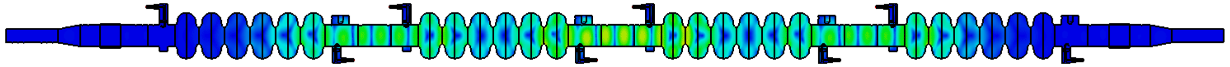
$Z_\perp$ of asymmetric end-cells with 4 DQW couplers

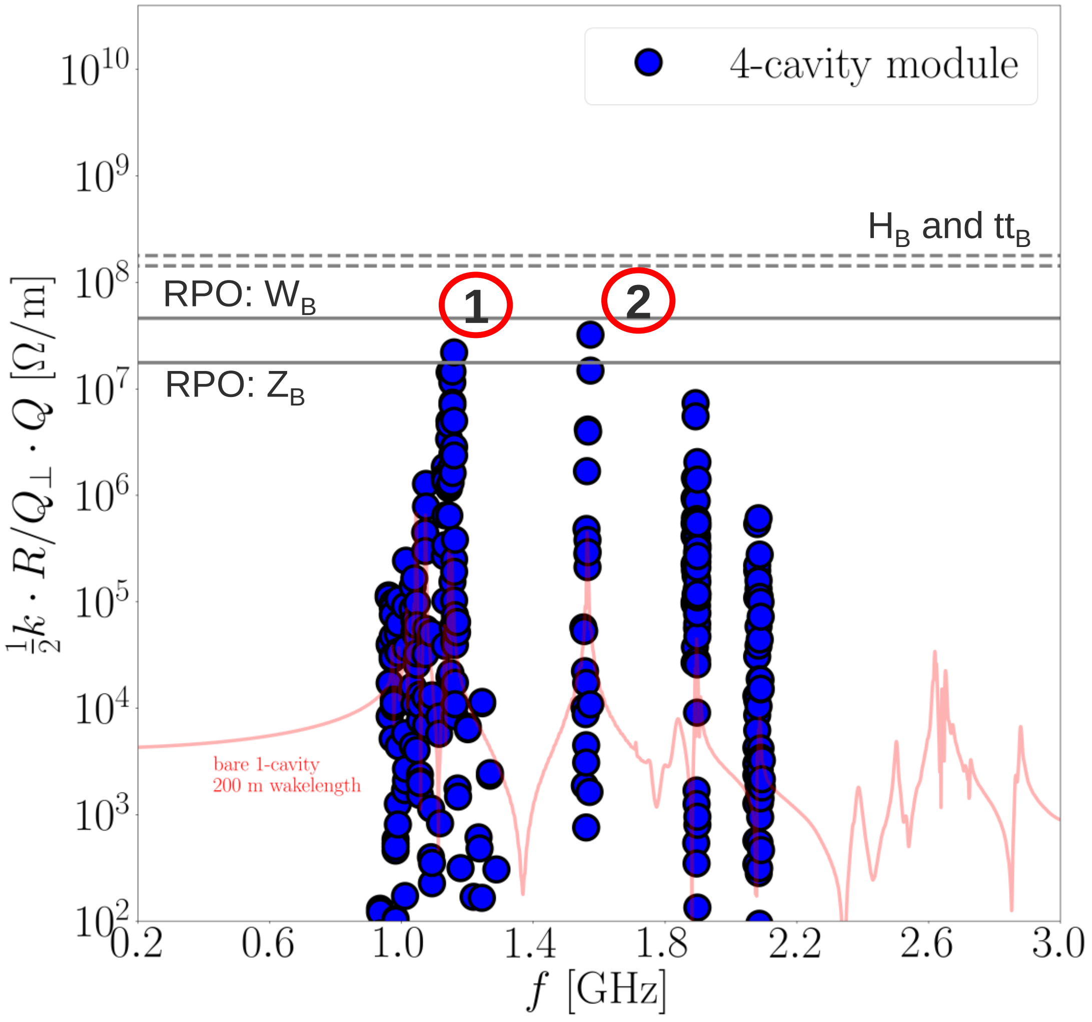
- For transverse impedance we are also close to the stability limit, but the frequency spread between cavities can improve the stability limit by at least a factor five

① $f = 1.154\ \mathrm{GHz}, R/Q_\perp = 54.0\ \Omega, Q_\mathrm{L} = 2.2e4 \longrightarrow c(\sigma = 0.5\ \mathrm{MHz}) = 0.18$, $c(\sigma = 1.0\ \mathrm{MHz}) = 0.12$

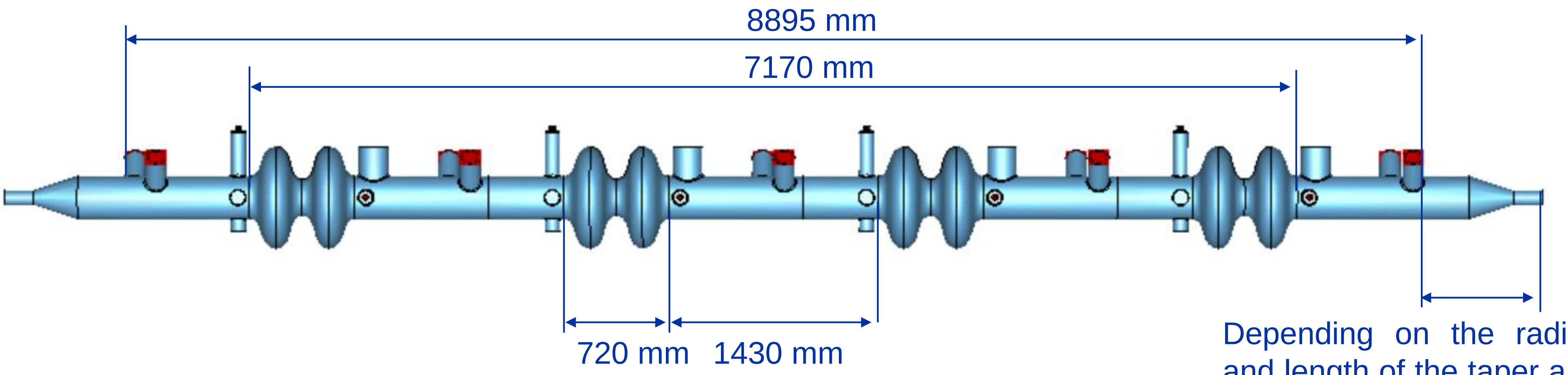


② $f = 1.574\ \mathrm{GHz}, R/Q_\perp = 53.5\ \Omega, Q_\mathrm{L} = 3.6e4 \longrightarrow c(\sigma = 0.5\ \mathrm{MHz}) = 0.17$, $c(\sigma = 1.0\ \mathrm{MHz}) = 0.11$





400 MHz Module length consideration



Depending on the radius and length of the taper and the length of bellows this length should be re-evaluated