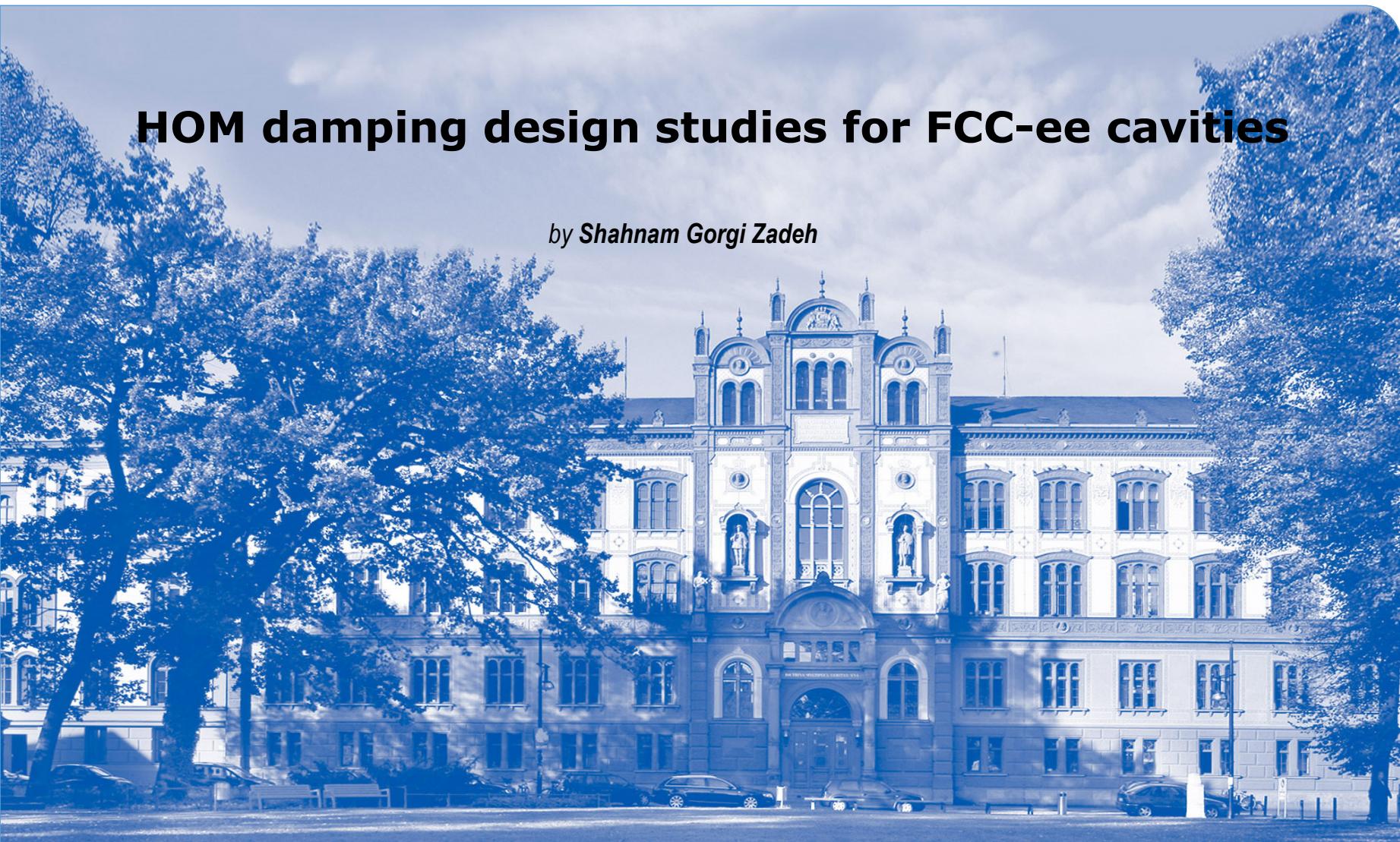




HOM damping design studies for FCC-ee cavities

by *Shahnam Gorgi Zadeh*



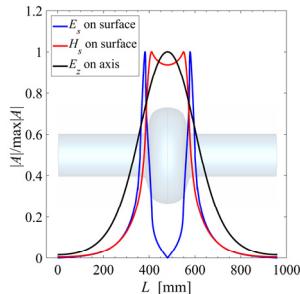
Outline

- Present RF baseline of FCC-ee
- HOM power and impedance calculation for the Z cavities
- HOM power and impedance calculation for the W and H cavities
- HOM power and impedance calculation for the $t\bar{t}$ cavities
- Conclusion

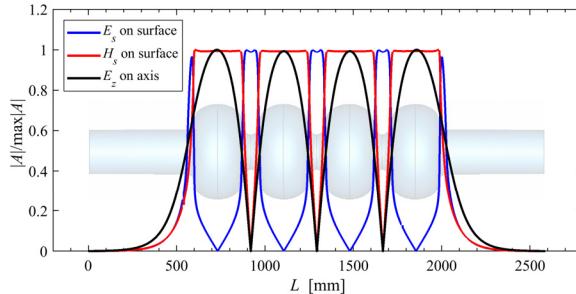
FCC-ee Present Baseline

- Due to high HOM power and tight beam stability requirements, single 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 the $t\bar{t}$

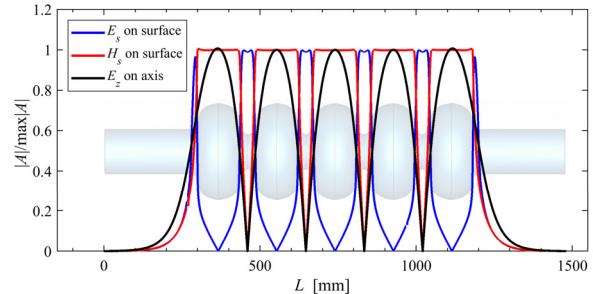
1-cell cavity at 400.79 MHz



4-cell cavity at 400.79 MHz



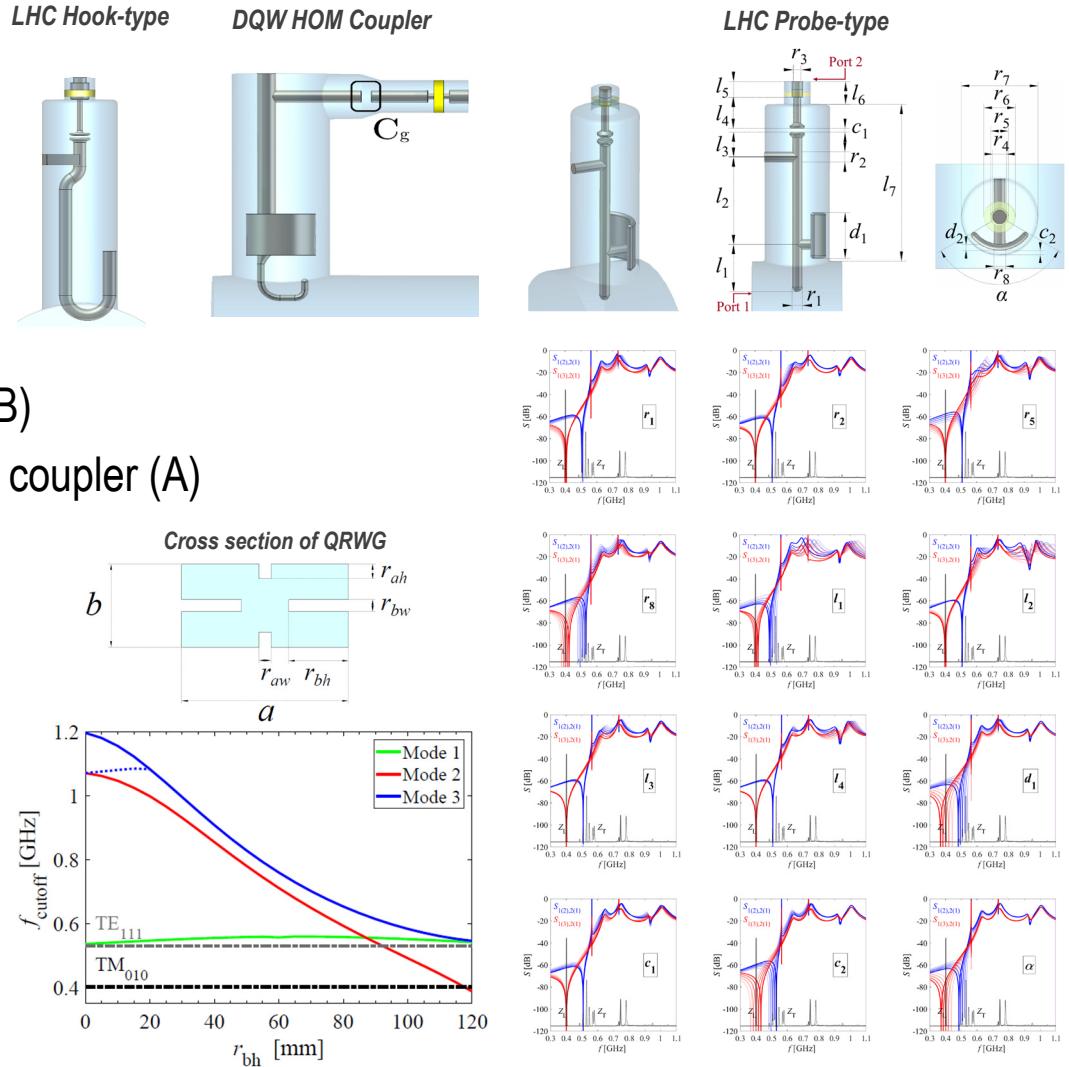
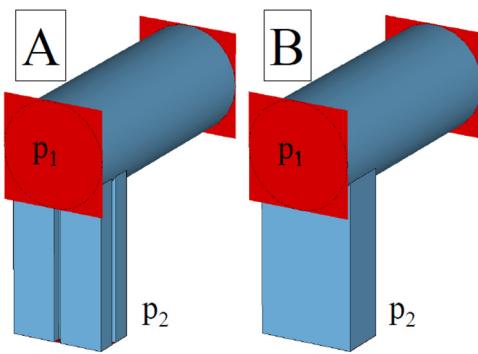
5-cell cavity at 801.58 MHz



For further details on the RF parameters of the cavities refer to the appendix, CDR and the FCC talks of previous years.

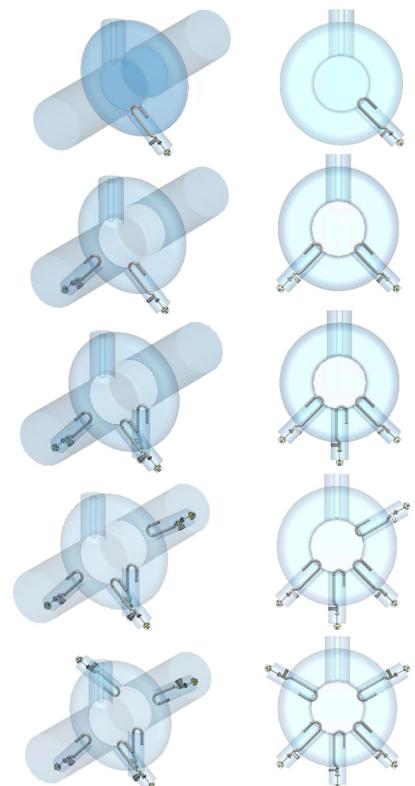
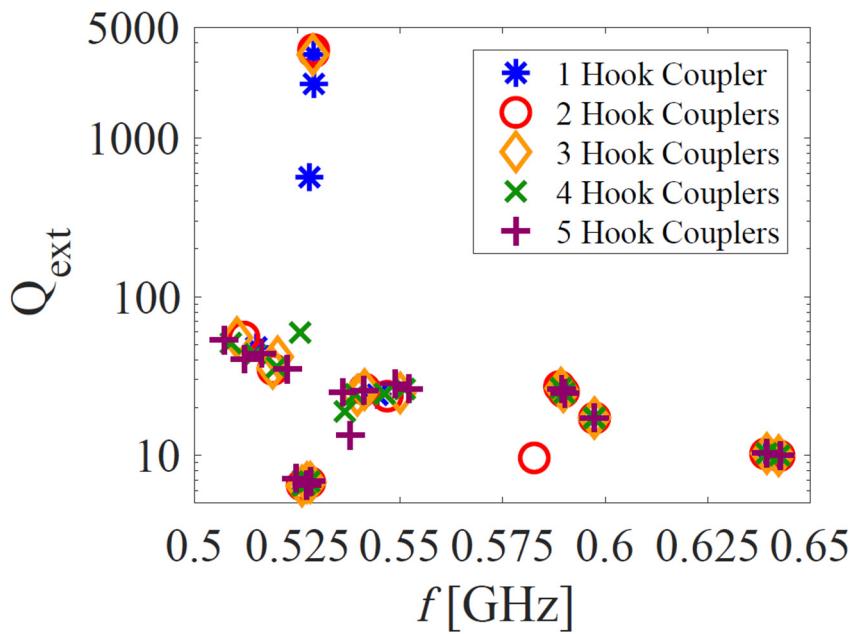
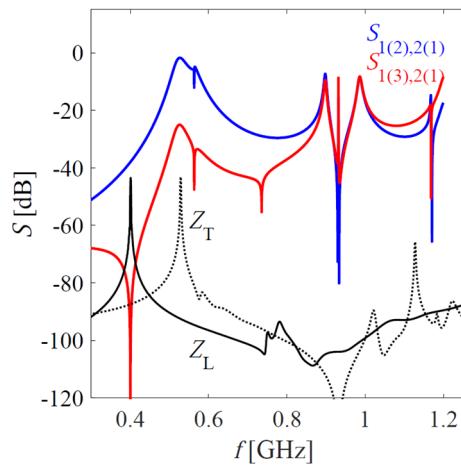
HOM couplers study

- Coaxial HOM couplers
 - LHC Hook-type coupler
 - LHC Probe-type coupler
 - DQW coupler
- Waveguide (WG) HOM couplers
 - Rectangular waveguide coupler (B)
 - Quad-ridged waveguide (QRWG) coupler (A)



HOM damping of the first dipole band of the Z option

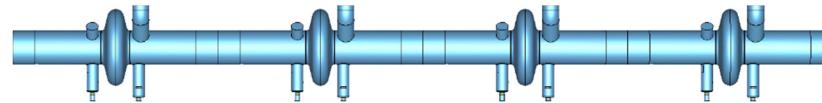
- HOM coupler is tuned with respect to the modes in the first dipole band
- By using four hook-type HOM couplers, the Q_{ext} of the modes in the first dipole band are reduced below 100



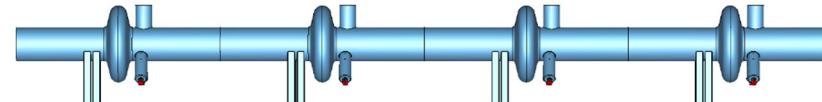
Various damping schemes for the Z Option

The damping schemes are compared with respect to the power propagating into the couplers and the longitudinal and transversal impedance of the cavities

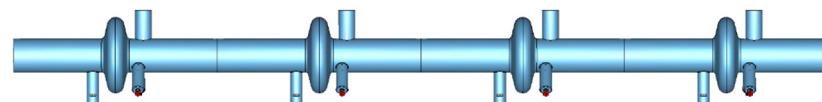
LHC (2H2P)



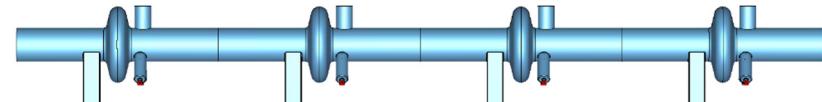
3H1QRWG



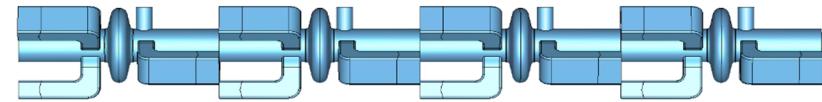
4H



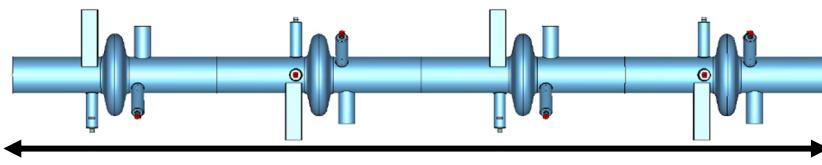
3H1RecWG



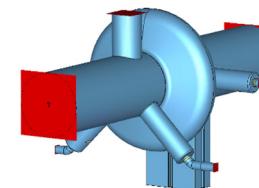
5RecWG



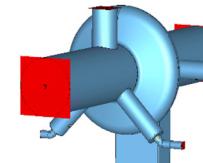
4H1RecWG



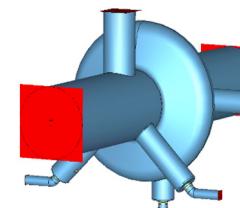
7.0 m



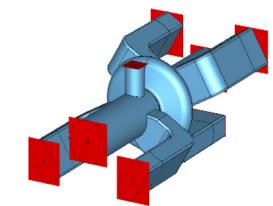
3 Hook-type couplers +
1 Quad ridged WG (3H1QRWG)



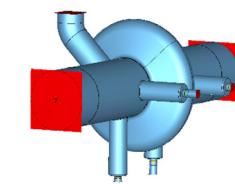
3 Hook-type couplers +
1 Rectangular WG (3H1RecWG)



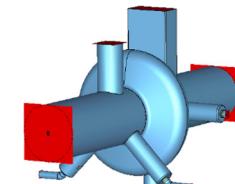
4 Hook-type couplers (4H)



5 Rectangular Waveguide
(5RecWG)



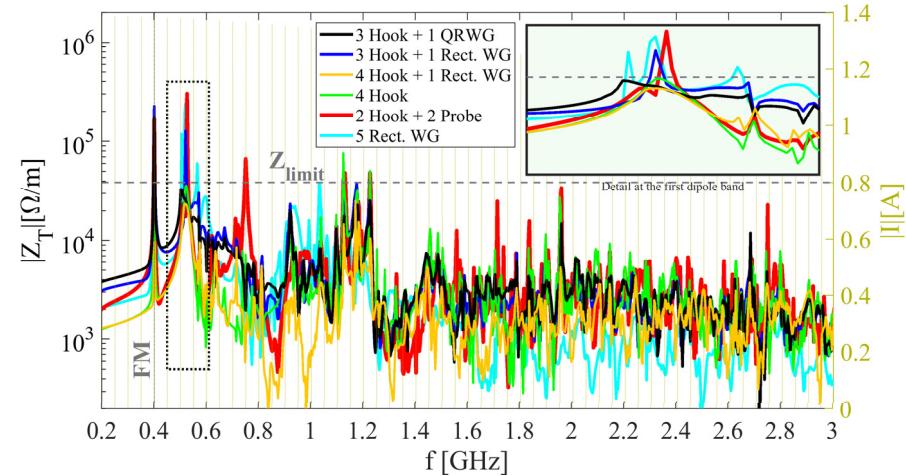
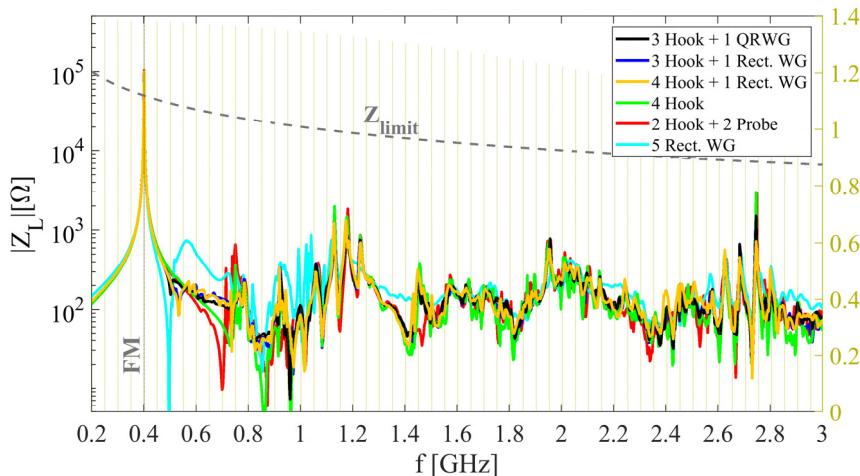
LHC-type couplers
2 Probe+2 Hook (2H2P)



4 Hook-type couplers +
1 Rectangular WG (4H1RecWG)

Impedance of the four-cavity module

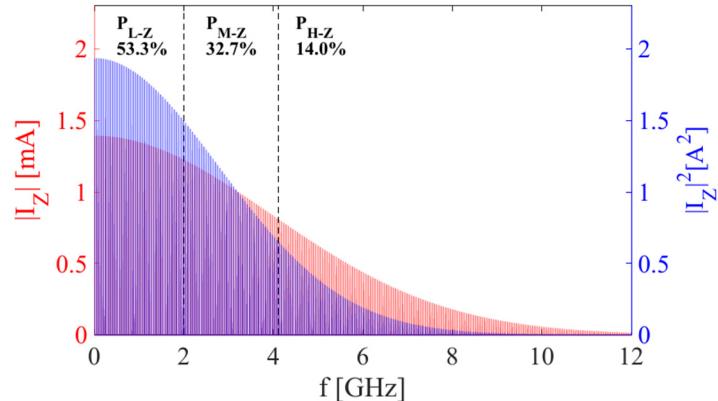
- No dangerous longitudinal mode is trapped in the module due to large beam-pipe radius
- There is a transverse kick at the FM created by the input coupler (the input coupler is inserted deep into the cavity to achieve low loaded quality factor). This kick could be mitigated by installing couplers in opposite direction in the module → see 4H1RecWG
- 3H1QRWG and 4H1RecWG damping schemes have a transverse impedance below the stability threshold set by synchrotron radiation



The wake impedance is calculated from a wakelength of 100 m excited by a beam with 5 mm offset from the center.

HOM power of the single-cell cavities

- The chosen damping scheme affects the total HOM power. The damping schemes with WGs in average produce stronger wakefield and subsequently more HOM power →
- A large portion of the HOM power propagates out of the beam-pipes (requires an absorber at the end of module)
- WGs absorb much more HOM power in comparison with coaxial couplers
- A combination of one WG (or QRWG) with hook-type couplers shows promising results in damping the impedances below threshold and absorbing the HOM power



The total power is approximated by

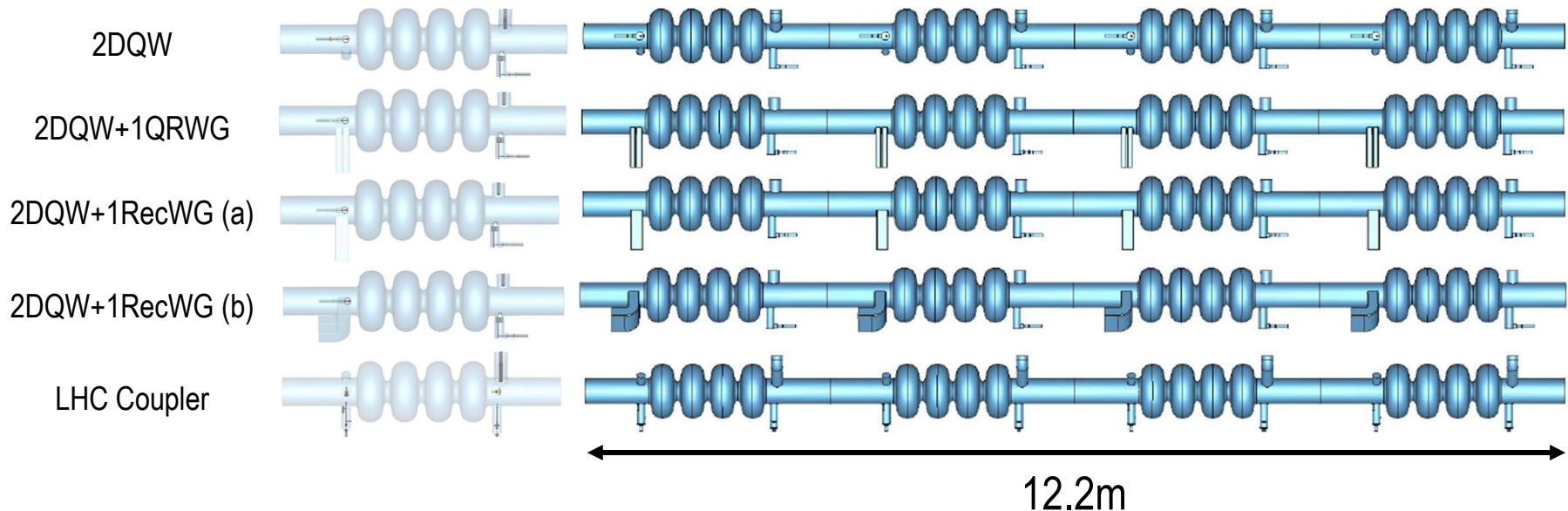
$$P_{tot-Z} = P_{L-Z} + P_{M-Z} + \frac{14.0}{32.7} P_{M-Z}$$

One Cavity	$k_{ }$ [V/pC]
4H	0.150
2H2P	0.161
5RecWG	0.227
3H1RecWG	0.165
3H1QRWG	0.169
4H1RecWG	0.178

	P_{L-Z}	P_{M-Z}	P_{t-Z}	BPs	FPC	Hooks	Probes	WGs
	[kW]						[%]	
One Cavity								
4H	2.08	1.59	4.35	86.83	8.74	4.43	-	-
2H2P	2.50	1.73	4.97	86.35	8.24	1.82	3.59	-
5RecWG	5.39	2.05	8.33	36.20	4.54	-	-	59.26
3H1RecWG	3.10	1.69	5.51	62.51	6.51	1.53	-	29.45
3H1QRWG	3.24	1.74	5.72	59.84	6.04	1.63	-	32.49
4H1RecWG	3.67	1.87	6.34	60.26	7.11	3.05	-	29.58
Four Cavity Module								
4H	5.93	7.93	17.25	61.78	29.65	8.57	-	-
2H2P	7.55	10.20	22.13	55.57	30.23	3.05	11.15	-
5RecWG	20.31	10.78	35.71	14.98	5.52	-	-	79.50
3H1RecWG	10.28	8.89	22.98	33.59	14.62	2.60	-	49.19
3H1QRWG	10.76	9.54	24.38	33.18	14.80	2.48	-	49.54
4H1RecWG	12.49	9.68	26.32	32.58	16.02	3.89	-	47.51

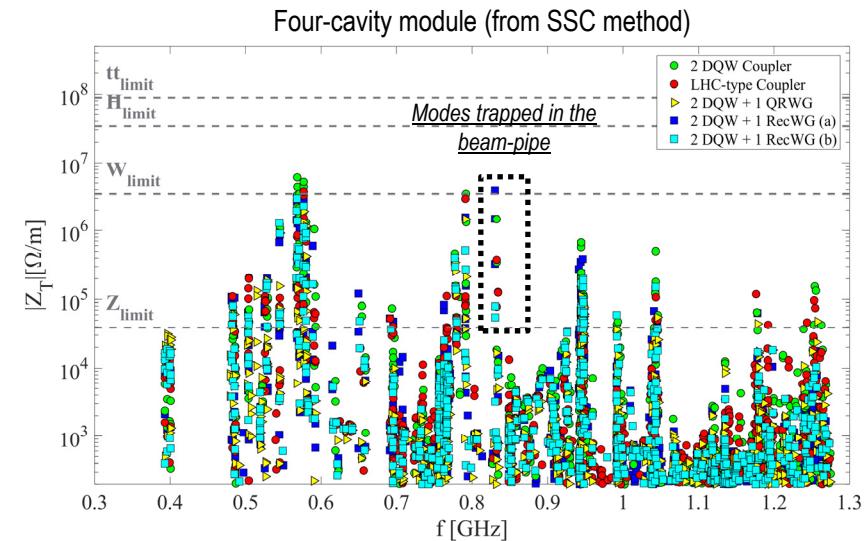
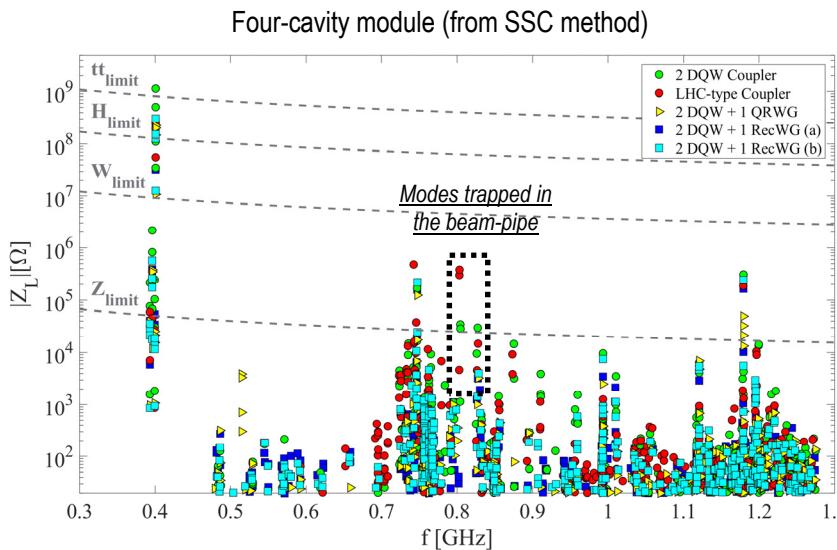
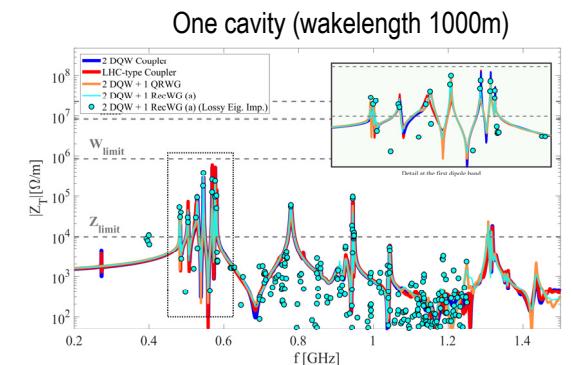
Various damping schemes for the W and H running

Five damping schemes are compared in the following slides



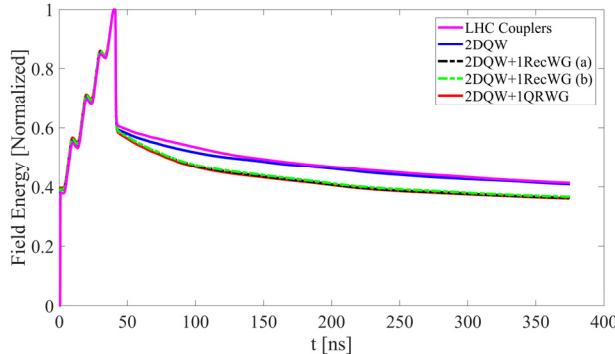
Impedance of the four-cell 400 MHz cavities

- The longitudinal and transverse impedance of all damping options stay below the impedance limit of H operating scenario
- The transverse impedance is marginally below the impedance limit of W
- Orientation of the WG couplers is crucial in the damping of modes trapped in the beam-pipes



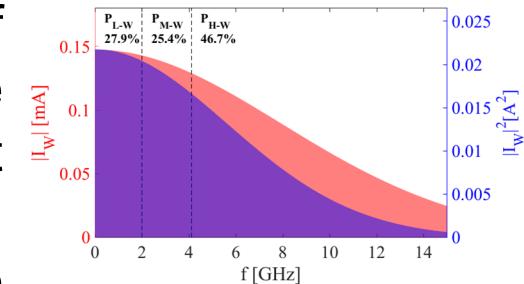
HOM power of the four-cell cavities for the W running

- The HOM power of the W option is in a critical range. If possible, the beam filling scheme of the W option should be designed such that there is no large beam spectral line at frequencies with large longitudinal impedance
- The HOM power of the H option is around 0.9 kW for the one cavity and below 4 kW for the four cavity module ($P_{resonance}$ is below 1 kW for all damping schemes)



The energy deposited into the module by the traversing beam is not fully decayed after 100 m.

So, in the calculation of P_t , the power corresponding to the interaction of beam current with highly resonating modes is underestimated.



The total power is approximated by

$$P_{t-W} = P_{L-W} + P_{M-W} + \frac{46.7}{25.4} P_{M-W}$$

	P_{L-W}	P_{M-W}	P_{t-W}^*	BPs	FPC	Hook	Probe	DQW	WG	$P_{resonance}^{**}$
	[kW]	[kW]	[kW]							[kW]
One Cavity										
2DQW	0.94	0.79	3.2	88.8	3.8	-	-	7.4	-	-
2DQW1QRWG	1.13	0.82	3.5	73.8	4.2	-	-	4.9	17.1	-
2DQW1RecWG (a)	1.14	0.82	3.5	74.0	4.2	-	-	4.8	17.0	-
2DQW1RecWG (b)	1.17	0.89	3.7	73.9	4.2	-	-	4.8	17.1	-
LHC	0.82	0.87	3.3	92.6	3.6	1.0	2.8	-	-	-
Four Cavity Module										
2DQW	3.25	2.78	11.1	54.4	30.8	-	-	14.8	-	13.4
2DQW1QRWG	5.39	3.30	14.7	29.9	13.6	-	-	8.9	47.6	5.3
2DQW1RecWG (a)	5.57	3.46	15.4	28.5	13.0	-	-	9.2	49.3	7.1
2DQW1RecWG (b)	6.27	3.69	16.7	27.2	12.0	-	-	8.6	52.2	10.5
LHC	3.08	3.05	11.7	51.8	34.1	4.7	9.4	-	-	20.8

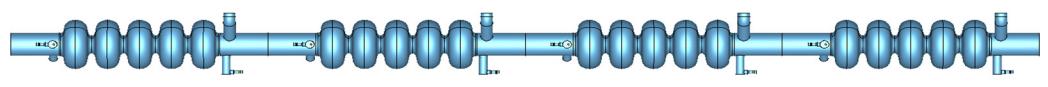
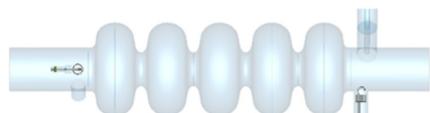
* This power is approximated from the wakefield calculation with a simulated wakelength of 100 m

** Resonance build-up power of the HOM with highest longitudinal impedance (using SSC method)

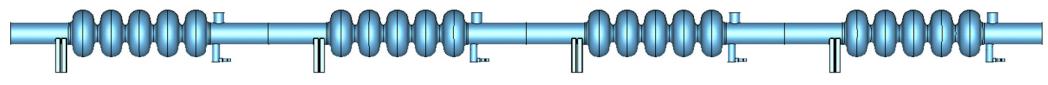
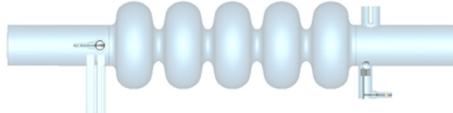
Various damping schemes for the $t\bar{t}$ running

Five damping schemes are compared in the following slides

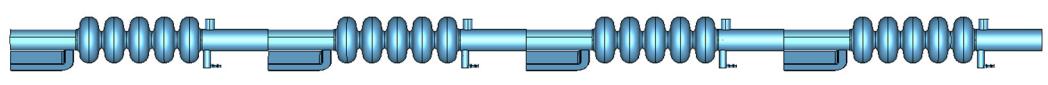
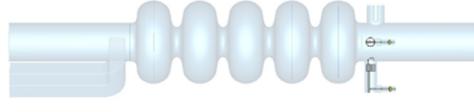
2DQW



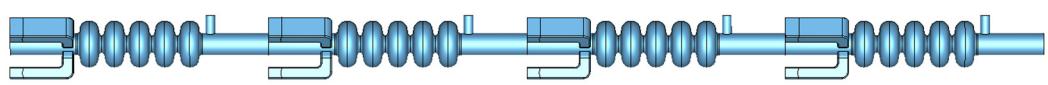
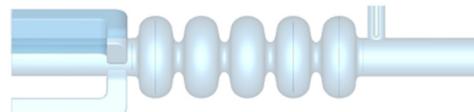
2DQW+1QRWG



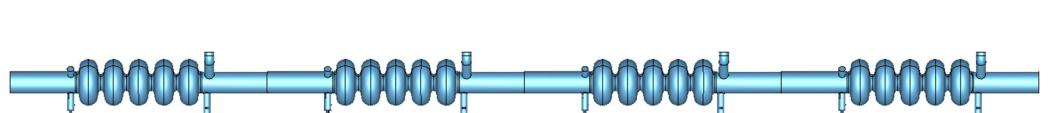
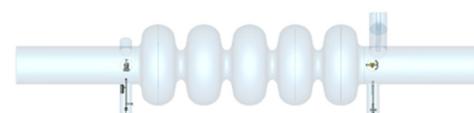
2DQW+1RecWG



3RecWG



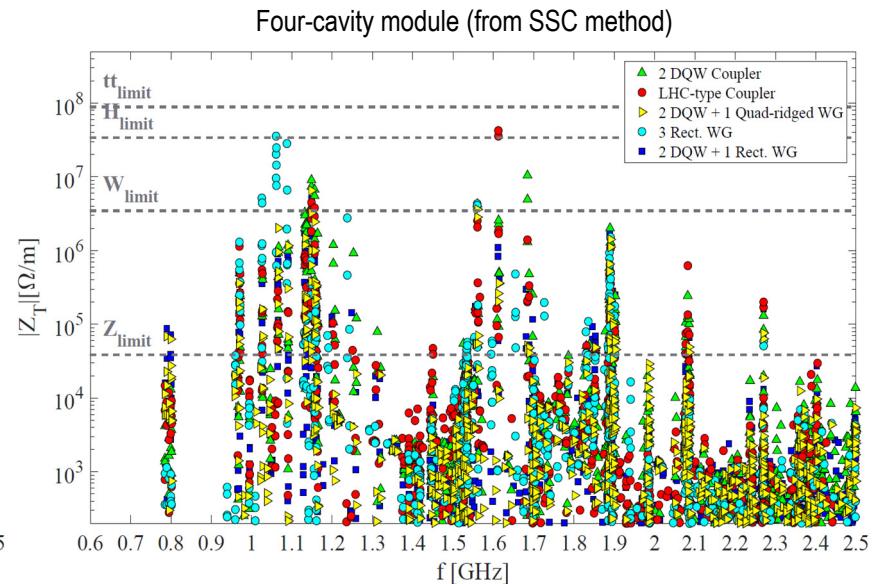
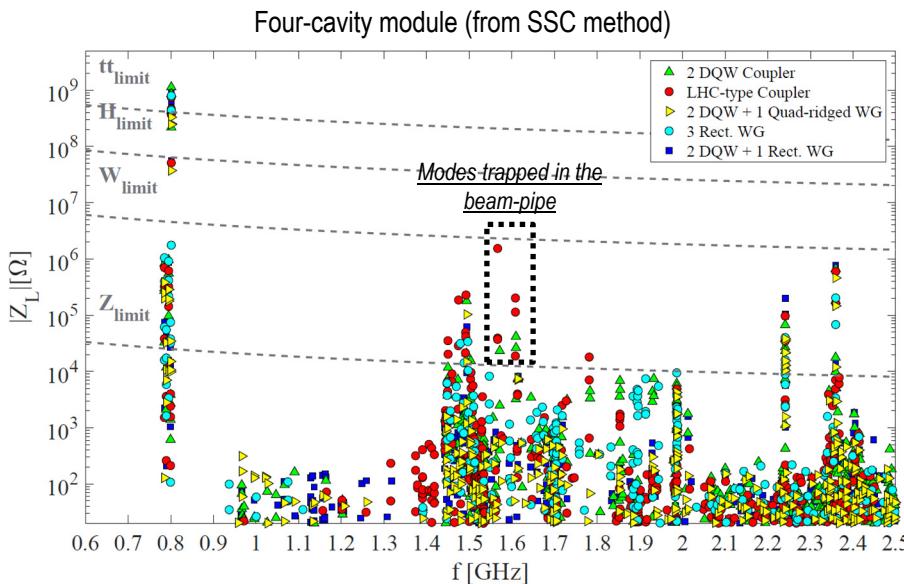
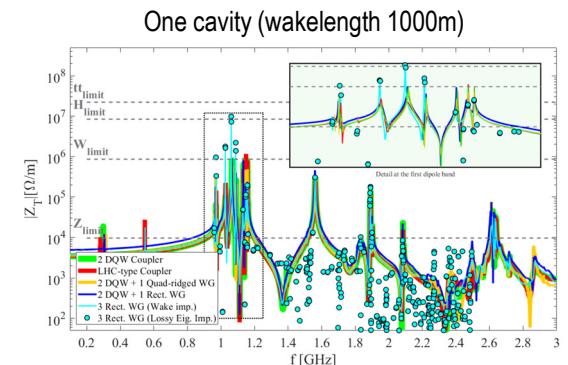
LHC Coupler



7.7 m

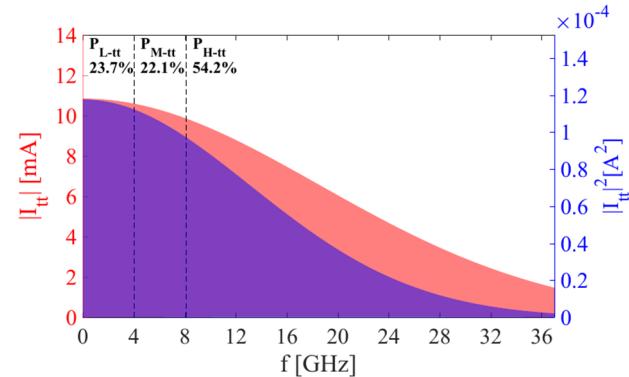
Impedance of the five-cell cavities

- The longitudinal and transverse impedance stays below the $t\bar{t}$ threshold for all studied damping schemes
- Coaxial couplers perform better than waveguide couplers in damping the first dipole band



HOM power of the five-cell cavities

- The HOM power of the cavities with different damping schemes is close to the result obtained from the formula $P = k_{||} q I$ for the bare cavities
- Most of the HOM power is generated at high frequencies and due to the low beam current the contribution of resonant build-ups in the total HOM power is negligible (the distance between spectral lines is 294 kHz)
- With one WG per cavity, around half of the HOM power is absorbed by the WG couplers



The total power is approximated by

$$P_{t-tt} = P_{L-tt} + P_{M-tt} + \frac{54.2}{22.1} P_{M-tt}$$

	P_{L-tt} [kW]	P_{M-tt} [kW]	P_{t-tt} [kW]	BPs	FPC	Hook	Probe	DQW	WG	$P_{resonance}$ [W]
				One Cavity						
2DQW	0.23	0.23	1.01	90.7	4.1	-	-	5.2	-	8
2DQW1QRWG	0.30	0.24	1.12	76.7	4.6	-	-	3.7	15.1	5
2DQW1RecWG	0.32	0.23	1.12	76.8	2.0	-	-	6.3	14.9	4
3RecWG	0.27	0.24	1.09	67.5	3.9	-	-	-	28.6	5.3
LHC	0.23	0.25	1.10	92.7	3.6	1.0	2.7	-	-	10.6

HOM power of the bare cavities approximated from loss factor

	1 cavity	2 cavities	3 cavities	4 cavities	5 cavities	6 cavities
$k_{ }$ [V/pC] ($\sigma_z = 2.5\text{mm}$)	2.93	5.86	8.83	11.8	14.77	17.74
HOM power for tt beam [kW]	1.10	2.20	3.33	4.45	5.57	6.69

Summary

- Z
- The chosen damping scheme affects the total HOM power. Around 20-30 kW of HOM power is expected in a four-cavity module (without tapering)
 - A combination of one WG (or QRWG) with hook-type couplers and absorbers at the end of the module is required to bring the impedances below the threshold and absorb the HOM power

- W
- Marginally below the transverse impedance threshold
 - The $P_{resonance}$ (hitting a beam spectral line) is critical and should be avoided e.g. by optimizing the beam filling scheme
 - A combination of WG (or QRWG) with DQW coupler is needed to damp the trapped modes and simultaneously absorb a significant amount of HOM power

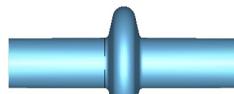
- H
- The impedances stay below the threshold for all studied damping schemes
 - The HOM power is below 4 kW with a $P_{resonance}$ below 1 kW for all damping schemes

- t̄t
- The impedances stay below the threshold for all studied damping schemes
 - The HOM power in module is below 5 kW with small contributions from $P_{resonance}$

Appendix

HOM Impedance of Cavities

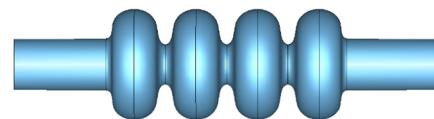
- The single-cell cavity for Z is designed with the main focus on HOM damping aspects
 - No dangerous trapped monopole mode
 - The first dipole band is trapped in the cavity and needs strong damping → both modes are at around 529 MHz
- The multi-cell cavities are optimized with the main focus on minimizing 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 the 400 MHz (or 800 MHz) cavity and rescaled to the other frequency (mechanical and thermal aspects are not studied here)



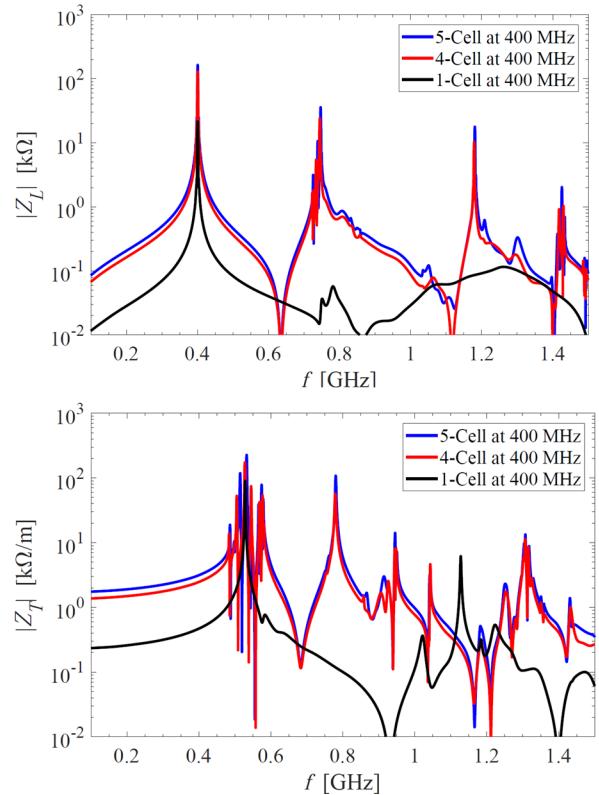
Single-cell at 400 MHz for Z



Five-cell at 800 MHz for tt̄



Four-cell at 400 MHz for W, H, tt̄



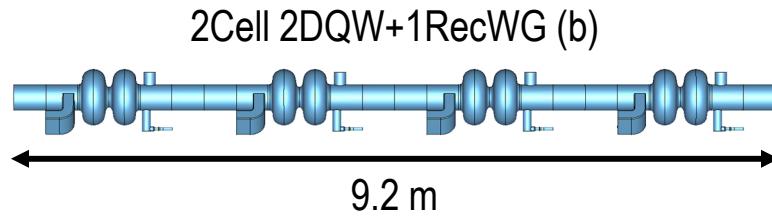
Impedance of the five-cell cavity is scaled to 400 MHz for comparison.
Impedances are for a bare cavity and the peaks are not fully resolved.

Main Parameters of the Cavities

Parameters	1-cell cavity	4-cell cavity	5-cell cavity
Frequency [MHz]	400.79	400.79	801.58
Number of Cells	1	4	5
Material	Nb/CU	Nb/CU	Bulk Nb.
Temperature [K]	4.5	4.5	2.0
R/Q [Ω]	79	411	521
Geometry Factor [Ω]	196.1	273.2	273.7
G.R/Q [Ω^2]	15452	112285	142597
B_{pk}/E_{acc} (mid-cell) [mT/(MV/m)]	4.1	4.2	4.2
E_{pk}/E_{acc} (mid-cell)	1.9	2.0	2.0
Cavity Active Length [mm]	240	1465.1	919.5
Iris radius [mm]	156	120	60
Beam Pipe radius [mm]	156	156	78
Wall angle (mid-cell) [degree]	102.8	100	100
Cell to cell coupling of mid cells [%]	-	2.25	2.25
Field Flatness [%]	-	99	99
$k_{ }$ [V/pC]	0.11 ($\sigma_z = 12.1$ mm)	2.27 ($\sigma_z = 2$ mm)	3.37 ($\sigma_z = 2$ mm)
Cutoff TE ₁₁ [GHz]	0.563	0.563	1.126
Cutoff TM ₀₁ [GHz]	0.736	0.736	1.471

2-cell cavity vs. 4-cell cavity

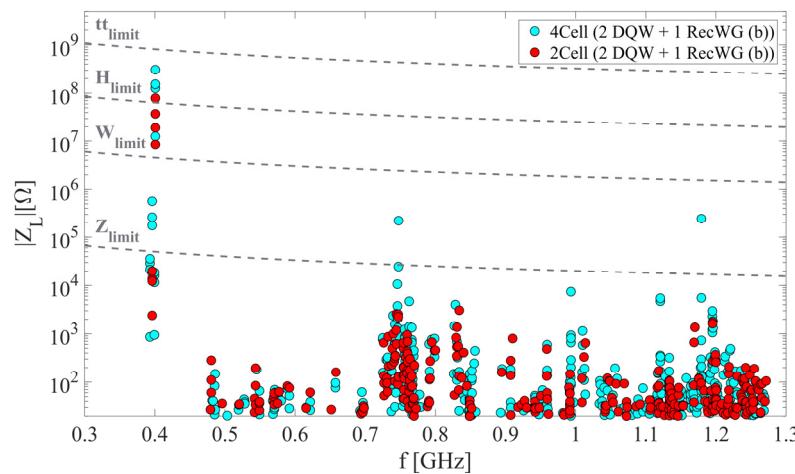
The HOM power corresponding to the interaction of the beam with highly resonating longitudinal modes, $P_{resonance}$, is significantly decreased by using 2-cell cavities for the W option



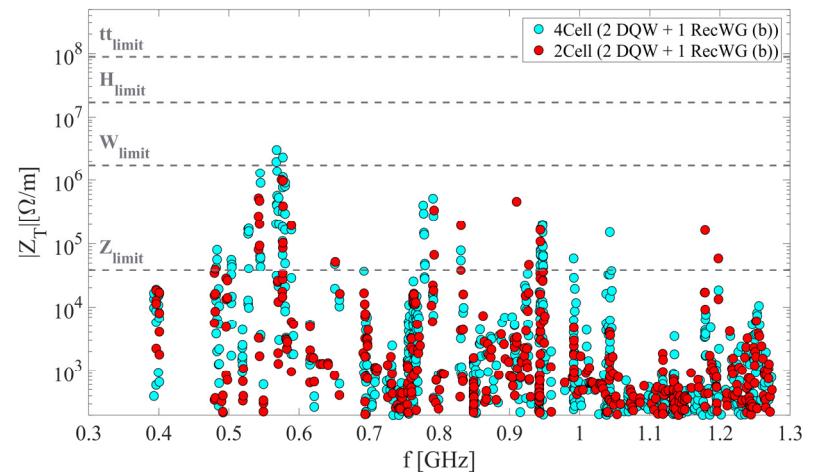
	P_{L-W}	P_{M-W}	P_{t-W}^*	BPs	FPC	DQW	RecWG	$P_{resonance}^{**}$
	[kW]					%		[kW]
Four Cavity Module								
2Cell 2DQW1RecWG (b)	3.14	2.82	11.1	33.8	11.5	4.9	49.9	0.1
4Cell 2DQW1RecWG (b)	6.27	3.69	16.7	27.2	12.0	8.6	52.2	10.5

* This power is approximated from the wakefield calculation with a simulated wakelength of 100 m

** Resonance build-up power of the HOM with highest longitudinal impedance (using SSC method)

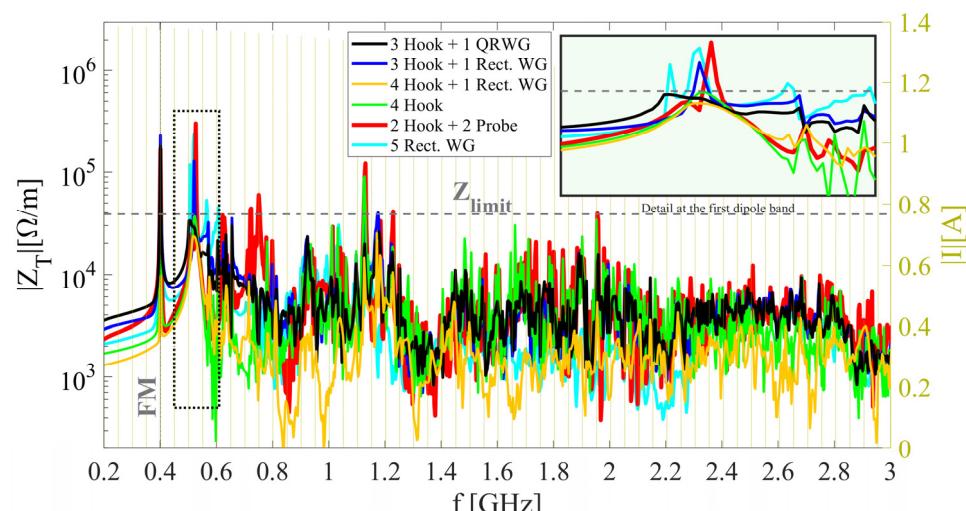
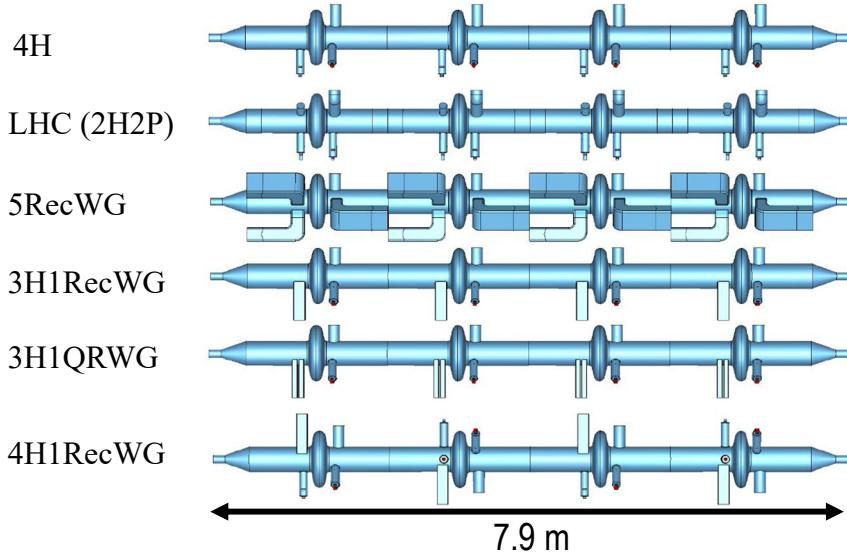


Impedance limit is normalized to the number of 2-cell cavities needed for operation at W and H energy.

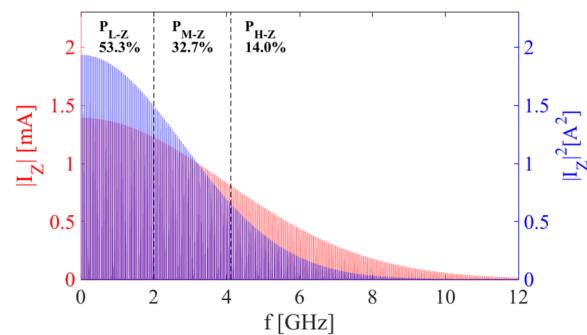


Four single-cell cavity module with tapering

Several damping schemes are compared with respect to the power propagated into the couplers and the impedance of the cavities



	P_{L-Z}	P_{M-Z}	P_{t-Z}	BPs	FPC	Hooks	Probes	RecWGs	QRWGs
	[kW]								
Four Cavity Module with Tapering									
4H	10.42	18.44	36.76	21.44	64.87	13.69	-	-	-
2H2P	10.39	18.28	36.49	19.46	64.57	6.22	9.75	-	-
5RecWG	21.50	18.22	47.52	8.95	7.35	-	-	83.70	-
3H1RecWG	13.80	18.65	40.43	13.55	27.64	3.11	-	55.70	-
3H1QRWG	15.22	20.37	44.31	12.80	27.88	2.85	-	-	56.47
4H1RecWG	16.41	20.68	45.94	15.40	26.78	4.05	-	53.77	-



The total power is approximated form

$$P_{tot-Z} = P_{L-Z} + P_{M-Z} + \frac{14.0}{32.7} P_{M-Z}$$

State Space Concatenation method (SSC)

