HOM loss study for the FCC-ee 400 MHz cavities

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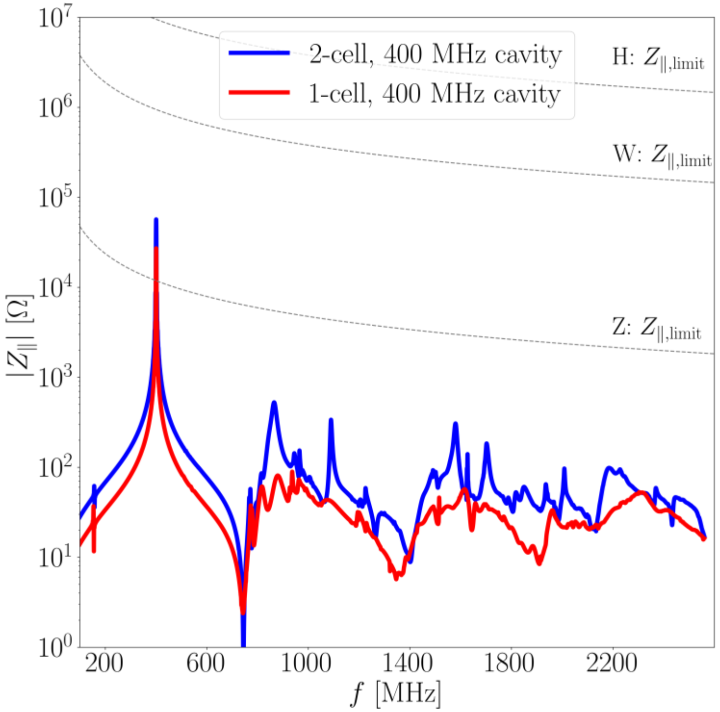
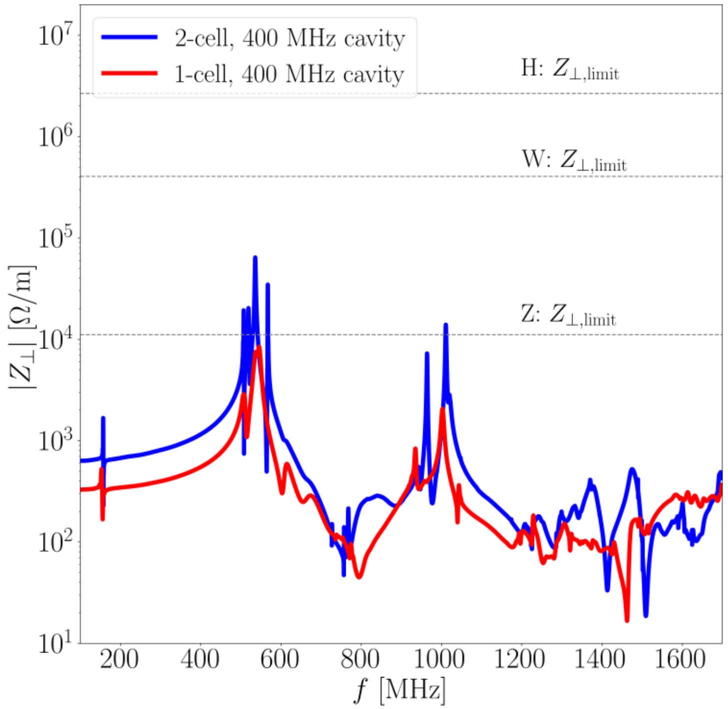
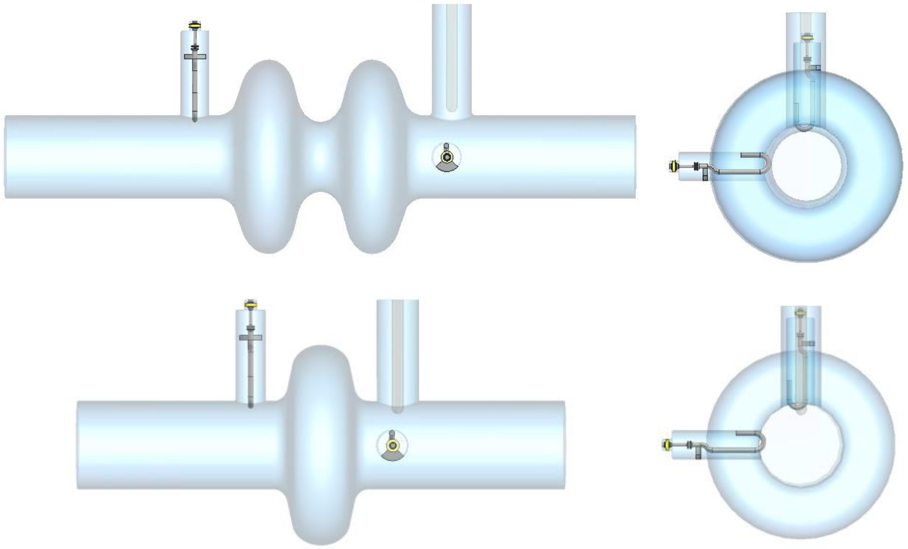
Beam coupling impedance of the 400 MHz cavities







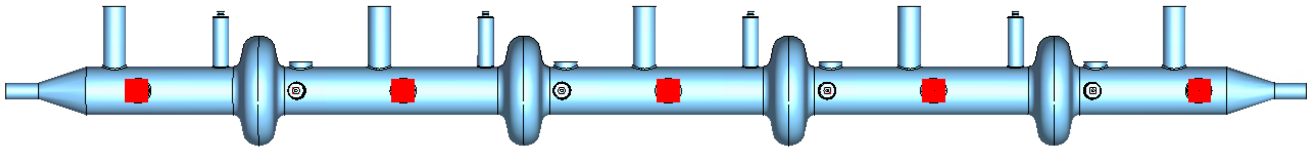
- The 1-cell and 2-cell 400 MHz cavities are designed to have no modes with high $Z_{\parallel}$ trapped in them
- For the damping of the trapped dipole modes with high $Z_{\perp}$, two hook-type coaxial couplers are used, similar to the ones used in the LHC cavities
- Two simple FPC-size coaxial couplers are placed on beam pipe (BP) between cavities for higher order mode (HOM) power extraction (see slide 4)

HOM power in the Z working point from loss factor

- HOM power could be approximated from loss factor as following:

$\boldsymbol{P_{HOM}} = (\boldsymbol{k_{\parallel}} - \boldsymbol{k_0})\boldsymbol{q^2}/\boldsymbol{t_b} = (\boldsymbol{k_{\parallel}} - \boldsymbol{k_0})\boldsymbol{q I_0}$ → single bunch excitation assuming HOMs field decay before next bunch arrives

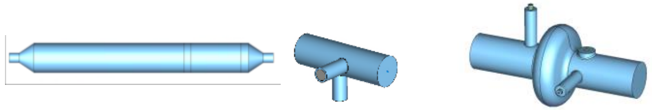
$\boldsymbol{k_{\parallel}}$: total longitudinal loss factor
$\boldsymbol{k_0}$: FM loss factor
$\boldsymbol{q}$: bunch charge
(34.3e3 pC for Z and 23.2e3 pC for W)
$\boldsymbol{I_0}$: average beam current
(1.27 A for Z and 0.137 A for W)
$\boldsymbol{t_b}$: average bunch spacing
(27 ns for Z and 170 ns for W)



HOM power for 1-cell 400 MHz
BS bunch length:
$P_{\mathrm{HOM}}\ [\mathrm{kW}] \approx 8.9 + (N_{\mathrm{cav}} + 1) \times 1.5 + N_{\mathrm{cav}} \times 3.7$

SR bunch length:
$P_{\mathrm{HOM}}\ [\mathrm{kW}] \approx 73.5 + (N_{\mathrm{cav}} + 1) \times 4.6 + N_{\mathrm{cav}} \times 9.1$

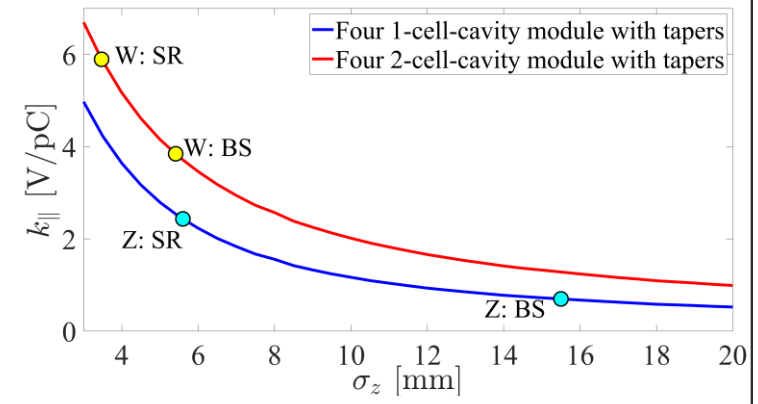
↓ Tapers ↓ 2-coax couplers ↓ Cavities

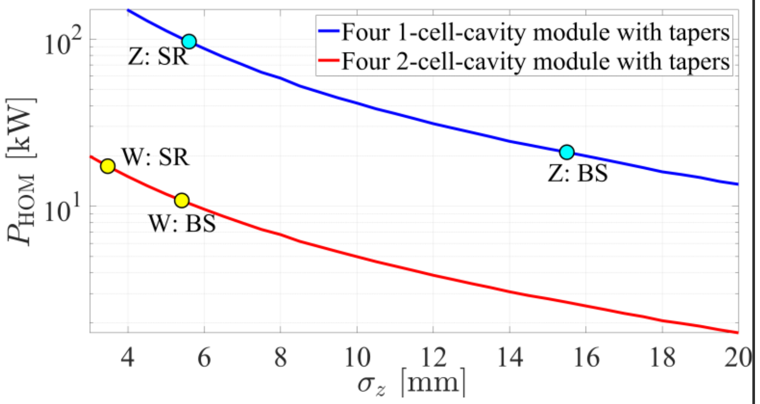


400 MHz system	Tapers (100 mm to 300 mm)	2-coax	Cavity + FPC + 2 Hook couplers
$k_{\parallel}$ [V/pC] ($\boldsymbol{\sigma_z}$= **15.5 mm**)	0.205	0.035	0.139 ($k_0 = 0.054$ V/pC)
P_{HOM} [kW]	8.9	1.5	3.7
$k_{\parallel}$ [V/pC] ($\boldsymbol{\sigma_z}$= **5.6 mm**)	1.687	0.105	0.264 ($k_0 = 0.055$ V/pC)
P_{HOM} [kW]	73.5	4.6	9.1

HOM power distribution in the Z and W working points

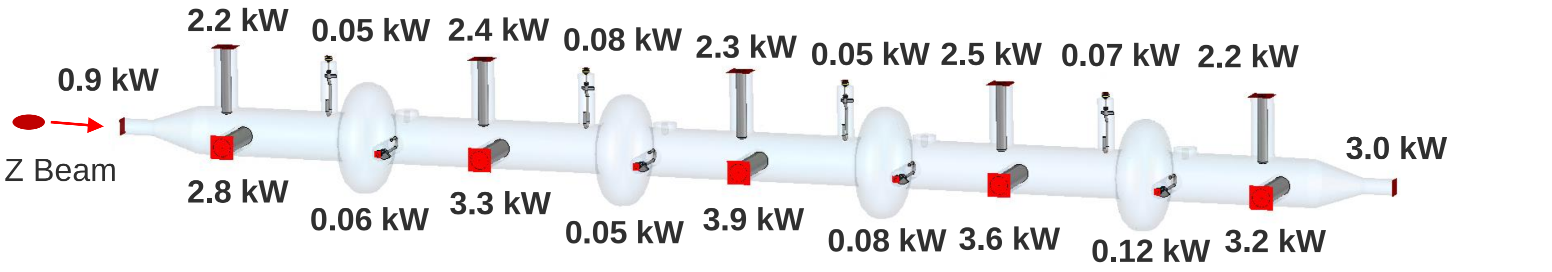
2D axisymmetric and no couplers:
$$P_{\text{HOM}} = (k_{\parallel} - k_0) q I_0$$



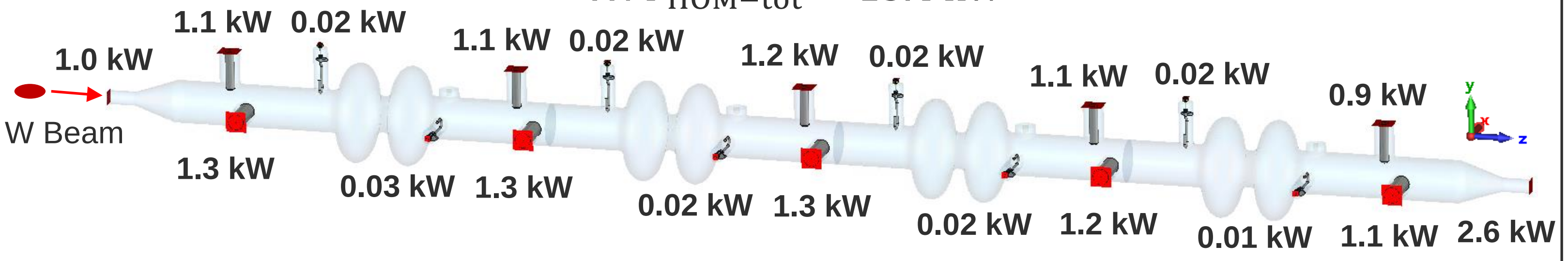


Power in 3D axisymmetric structure from: $P_{\text{HOM}} = I_0^2 \sum_{n=-\infty}^{n=\infty} \left|\hat{I}_n\right|^2 \Re[Z_{\parallel}(n\omega_{\text{rev}})]$

Z: $P_{\text{HOM-tot}} \approx 32.9$ kW

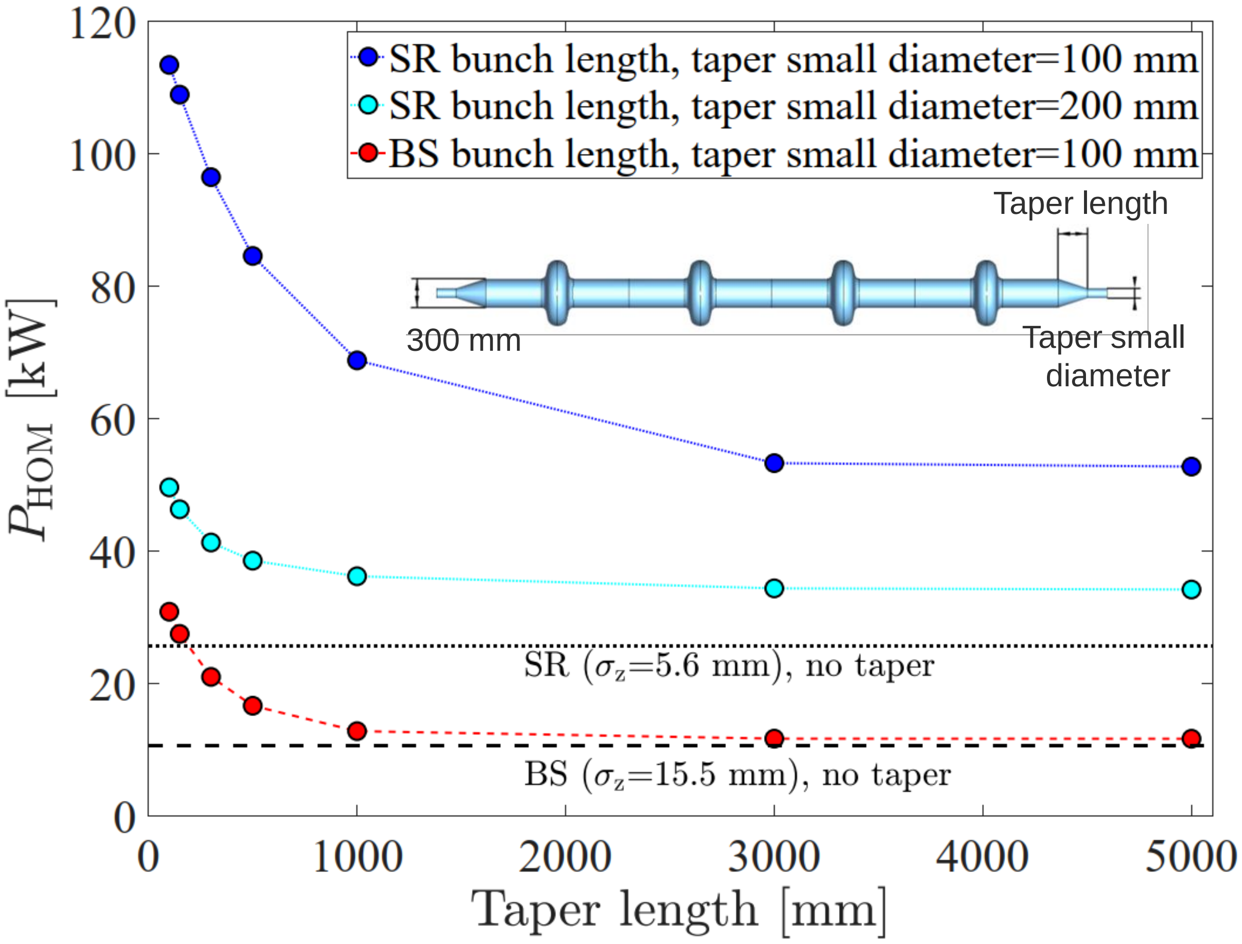


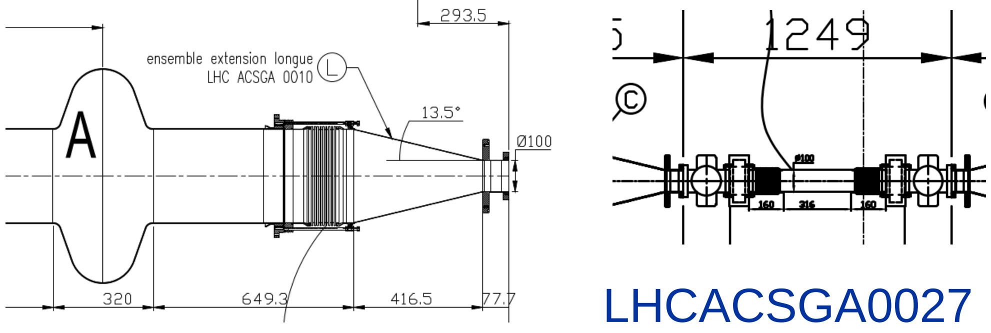
W: $P_{\text{HOM-tot}} \approx 15.4$ kW



- In beam spectrum calculation, it is assumed that all bunches are uniformly distributed within the beam
- BS bunch length is considered
- The tapers are assumed to transition from a 100 mm diameter to 300 mm, similar to those used in the LHC cavities (not ideal for the FCC-ee cavities, see next slide)

Taper size and HOM power at the Z working point





LHC cavity taper size. Due to the large bunch length in the LHC cavities, the tapers have a small impact on the total loss factor.

- The taper dimensions have a significant impact on the total HOM power at the Z working point, especially with the SR bunch length
- A taper size like the LHC's is not suitable for FCC-ee. Increasing the smaller radius is recommended (ideally avoiding tapers between cryomodules in the RF section), but compatibility with other components between cavities must be ensured

Summary

- **Cavity designs**
  - 1-cell and 2-cell 400 MHz cavities designed to avoids modes with high $Z_{\parallel}$
- **HOM couplers**
  - Two hook-type couplers near the cavity for dipole mode damping and two bigger coaxial couplers between cavities for HOM power extraction
- **HOM power analysis**
  - At Z working point: tens of watts propagate through hook-type coupler and a few kWs pass through each FPC-size coaxial coupler
  - Large difference in HOM power between SR and BS at Z working point due to large change in bunch length. Avoid full beam current operation at SR
  - HOM power calculations for the Z and W working points. Breakdown of each component's contribution
- **Taper Impact**
  - Crucial influence of taper dimension on total HOM power. Avoid a taper dimension similar to the one used in LHC

appendix

HOM power calculation methods

- From loss factor:
  - $P_{\mathrm{HOM}} = (k_{\parallel} - k_0)q^2/t_{\mathrm{b}} = (k_{\parallel} - k_0)qI_0$ → single bunch excitation assuming HOMs field decay before next bunch arrives
- From the real part of longitudinal impedance
  - $P_{\mathrm{HOM}} = I_0^2 \sum_{n=-\infty}^{n=\infty} |\hat{I}_n|^2 \Re[Z_{\parallel}(n\omega_{\mathrm{rev}})]$
  - Short bench lengths of a few mm at FCC-ee working points generate beam spectral lines up to tens of GHz . Computational expenses limit the calculation of beam impedance up to such values in large 3D structures. The total HOM power can be approximated from the loss factor of the 2D axisymmetric part of the structure

$k_{\parallel}$: total longitudinal loss factor
k_0: FM loss factor
q: bunch charge
I_0: average beam current
t_{b}: bunch spacing

$Z_{\parallel}$: longitudinal impedance
ω_{rev}: revolution harmonic
$\widehat{I_n}$: normalized Fourier harmonic of the beam current at nth revolution harmonic
I_0: average beam current

$$P_{\mathrm{HOM}} = P_{\mathrm{L}} + P_{\mathrm{M}} + P_{\mathrm{H}} \rightarrow P_{\mathrm{HOM}} \approx P_{\mathrm{L}} + P_{\mathrm{M}} + \frac{\sum_{\mathrm{in\ H}} k_{\parallel}}{\sum_{\mathrm{in\ M}} k_{\parallel}} P_{\mathrm{M}}$$