HOM DAMPING OPTIONS FOR THE Z-POLE OPERATING SCENARIO OF FCC-ee

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Abstract

The Z-pole option of FCC-ee is an Ampere class machine with a beam current of 1.39 A. Due to high HOM power and strong HOM damping requirements, the present baseline of FCC-ee considers a single-cell cavity at 400 MHz. In this paper, different HOM damping schemes are compared for the Z-pole operating scenario with the aim of lowering the parasitic longitudinal and transverse impedance. The HOM power for each damping scheme is also calculated.

INTRODUCTION

The FCC-ee provides collisions in a wide beam energy spectrum, ranging from Z-pole (45.6 GeV) to $t\bar{t}$ (182.5 GeV). As a design choice, the maximum synchrotron radiation (SR) per turn for one beam is fixed to 50 MW, thus the stored beam current ranges from 1.39 A (at Z-pole) to 5.4 mA (at $t\bar{t}$) [1]. The present baseline of the FCC-ee considers a single-cell superconducting cavity for the Z-pole to mitigate the challenges created by the high beam current [1–3]. In this paper, first, we design a single-cell cavity with a focus on its fundamental mode (FM) and higher-order mode (HOM) spectrum at the same time. We then attach different HOM couplers to the cavity and compare the longitudinal and transverse impedance of each geometry. In the HOM power calculation, usually the total power deposited into the cavity by the traversing beam is calculated. However, this does not specify the absorption of power by each HOM coupler. For the proper optimization of the HOM couplers, the contribution of each coupler in absorbing the HOM power have to be determined. Thus, we use a spectral weighting method to approximate the amount of power that propagates into the HOM couplers.

SRF CAVITY DESIGN

The conventional optimization methods of SRF cavities minimize the normalized electric E_{pk}/E_{acc} and normalized magnetic field B_{pk}/E_{acc} on the surface of the cavity to provide room for increasing the accelerating gradient, or maximize the $G \cdot R/Q$ (where G is the geometry factor and R/Q is the geometric shunt impedance) to lower the surface losses of the cavity. For high current storage ring cavities operating at low accelerating fields, special attention should be also given to the HOM damping aspects of the cavity. Particularly, the damping of the first two dipole modes (TE$_{111}$ and TM$_{110}$ modes) that are usually trapped in the cavity is crucial. In order to simplify their damping by using coaxial

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Table 1: RF Parameters of the Optimized Cavity

R/Q [Ω]	G [Ω]	$\frac{E_{pk}}{E_{acc}}$ [-]	$\frac{B_{pk}}{E_{acc}}$ [mT/$\frac{MV}{m}$]	f_1 , f_2 [MHz]	$\frac{R}{Q}_{\perp 1}$, $\frac{R}{Q}_{\perp 2}$ [Ω/m]
78.8	196.1	1.94	4.13	528.7, 529.3	305.8 , 25.5

HOM couplers, we try to minimize the distance $|f_1 - f_2|$ between the frequencies of these two modes and maximize the distance $|f_1 - f_0|$ between the first dipole mode and the FM. Furthermore, the transverse impedances[1] $R/Q_{\perp 1}$ and $R/Q_{\perp 2}$ of the first two dipole modes should be as small as possible. The frequency of the FM should be fixed to 400.79 MHz and the wall angle α of the cavity should be larger than $90°$ to avoid having re-entrant shape with $\alpha > 90°$. Thus, the optimization term to be minimized is

$$\min_{R_i, L, A=B, a=b} \left(- | f_0 - f_1 |, | f_1 - f_2 |, \frac{R}{Q}_{\perp 1} + \frac{R}{Q}_{\perp 2}, \right.$$
$$\left. - G \cdot \frac{R}{Q}, E_{pk}/E_{acc}, B_{pk}/E_{acc} \right)$$

$$\text{subject to} \quad f_0 = 400.79 \text{ MHz and } \alpha \geq 90°. \quad (1)$$

The variables for this optimization are R_i, L, $A = B$ and $a = b$ as shown in Fig. 1. For each geometry, R_{eq} is varied to tune the frequency of FM to 400.79 MHz.
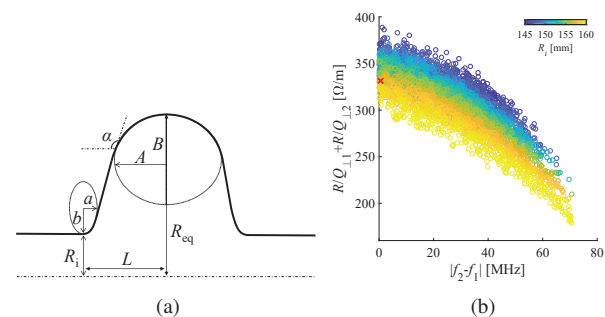

Figure 1: Single-cell parameterization of an elliptical cavity (a) with a plot of two objective functions (b). The red cross sign indicates the chosen geometry with $A = B = 70$ mm, $a = b = 25$ mm, $R_i = 156$ mm, $R_{eq} = 350.574$ mm, $L = 120$ mm and $\alpha = 102.8°$.

Eq. 1 is a multi-objective optimization problem. In order to find the dependency between objective functions and find, if existing, the Pareto front, the genetic algorithm (GA)

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[1] The following definition of $R/Q_\perp$ is used: $R/Q_\perp = \frac{\left(V_{\|(r=r_0)} - V_{\|(r=0)}\right)^2}{k\, r_0^2\, \omega U}$

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A24 Accelerators and Storage Rings, Other

method that is implemented in the optimization toolbox of MATLAB [4] is used. For each sample, SUPERLANS and SLANS2 [5] were called by MATLAB to solve the electromagnetic problem and calculate the quantities of interest. Figure 1 (b) shows the dependency between two objective functions and the location of the chosen geometry. The distance between the frequency of the two dipole modes is decreased at the cost of increase in their shunt impedance. The RF parameters of the selected geometry which is chosen from the Pareto front after 75 generations of GA with a population size of 100 is given in Table 1.

HOM DAMPING SCHEMES

Five damping schemes are compared in this paper as shown in Fig. 2. LHC-type couplers, that are comprised of two hook-type and two probe-type couplers [6, 7], are used in the first damping scheme (referred to as 2H2P). The hook-type couplers are tuned for strong coupling to the first dipole band and the probe-type couplers are used for the damping of high frequency HOMs. In the second scenario, four hook-type couplers (denoted by 4H) are connected to the cavity. Five rectangular waveguide (WG) couplers are used in the third scheme (denoted by 5RecWG). The dimensions of the WGs are set to 292.1 mm × 146.05 mm resulting in a cutoff frequency of 513 MHz for the TE_{10} mode which is below the frequency of the cavity modes in the first dipole band (around 529 MHz). WG couplers provide a broadband transmission at high frequencies, but they are not very efficient in damping the first dipole band. Therefore, a combination of a WG (for high frequency modes) and three hook-type couplers (for low frequency HOMs) is used in the fourth scheme (denoted by 3H1RecWG). The dimensions of the WG coupler are set to 280 mm × 140 mm with a cutoff frequency of 535 MHz and 1071 MHz for the TE_{10} and TE_{01} modes, respectively.

For a fixed value of height and width, the cutoff frequency of the FM of a rectangular WG could be reduced by adding ridges to the WG [8, 9]. In single mode applications, ridges are added in the longer side of the WG to enhance the bandwidth of the FM. If ridges are added to both the short and long sides of the WG, a quad-ridged WG (QRWG) is formed and the cutoff frequencies of both the FM and the second mode could be lowered substantially. This enables us to design a more compact WG HOM coupler with low cutoff frequencies. In the fifth damping scheme, a combination of the hook-type couplers with a QRWG is used. The outer dimension of the cross section of the QRWG is 280 mm × 140 mm and the cutoff frequency of its first two modes (TE_{10} and TE_{01}-like modes) are 494 MHz and 502 MHz, respectively. Thus, the two polarizations of the TE_{11} mode in the beam pipe (which typically couples to the TE_{111} and TM_{110} modes of the cavity) can couple to the QRWG.

Impedance of Cavities

As shown in Fig. 3 (a) no longitudinal mode is trapped in the cavity due to the large beam-pipe radius R_i. In the first
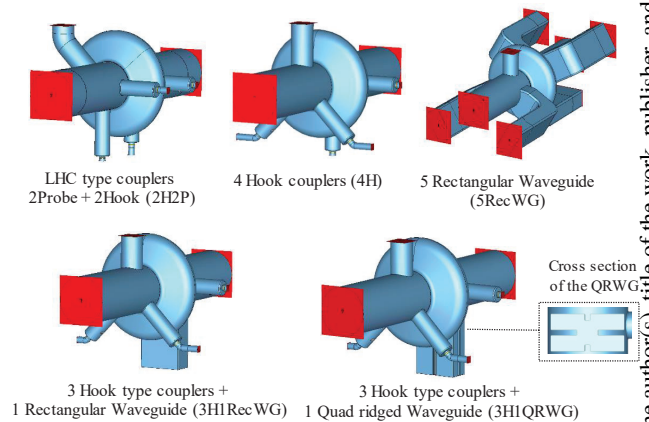

Figure 2: HOM damping schemes.

dipole band, only the 3H1QRWG and 4H damping schemes have a transverse impedance below the stability threshold set by synchrotron radiation. 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.

HOM Power

In order to calculate the propagation of HOM power into the couplers, the power couplers (FPC), HOM couplers and beam pipes (BP) are terminated with ports accounting for multiple modes. The wakefield solver of CST Studio Suite® [10] is then used to excite the cavity with a single Gaussian bunch and calculate the signal scattered into different modes of each port. The resulting port signals correspond to a single bunch excitation of the cavity. The amount of power scattered into the ports depends on the beam filling scheme. In order to account for various beam filling schemes, a spectral weighting method [11, 12] is exploited. This method is a post-processing technique applied to the result obtained from the wakefield solver of CST Studio.

The bunch length of the Z-pole option is 12.1 mm. Thus, the beam has high spectral contributions up to approximately 12 GHz. The numerical determination of the impedance of the cavity up to this frequency is computationally very expensive. Since the HOM power is directly proportional to the square of the beam current, the problem could be simplified by calculating the power up to a certain frequency and approximating the rest. For this purpose, the spectrum is divided into three frequency ranges as shown in Fig. 4. Based on the spectrum of the beam current squared, 53.3% of the power is located between 0 GHz and 2 GHz (denoted by P_L), 32.7% between 2 GHz and 4.1 GHz (denoted by P_M) and 14.0% is located above 4.1 GHz (denoted by P_H). Normally the trapped modes with high narrow-band impedance peaks, are located roughly below three to four times the FM frequency. Above that, the impedance spectrum has rather a broadband behavior. Therefore, the power in the frequency range between 2 GHz to 4.1 GHz is used as a benchmark for

Table 2: HOM Power Propagating Through the Couplers for the Beam Spectrum Shown in Fig. 4

	P_L* [kW]	P_M* [kW]	P_{tot}* [kW]	BPs [%]	FPC [%]	Hooks [%]	Probes [%]	RecWGs [%]	QRWGs [%]
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

* P_L is the power deposited in frequency range 0.45 GHz - 2 GHz, whereas P_M corresponds to the power between 2 GHz - 4.1 GHz and P_{tot} is the total HOM power approximated for the whole spectrum.
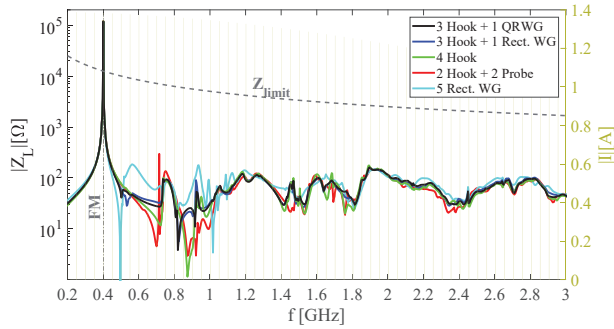
(a) Longitudinal impedance
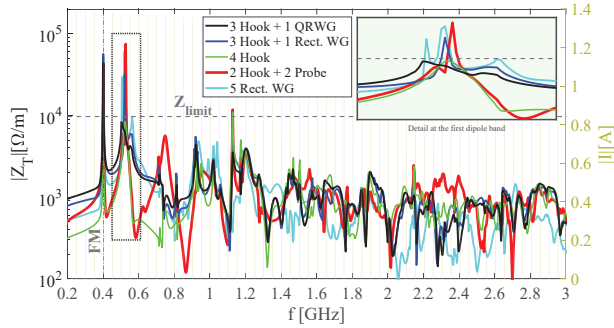
(b) Transverse impedance

Figure 3: Longitudinal and transverse impedance of the cavity using different damping schemes. The wake impedance is calculated from a wakelength of 100 m excited by a beam with 5 mm offset from the center (at $(x, y) = (3.54\,\mathrm{mm}, 3.54\,\mathrm{mm})$). The impedance threshold dictated by SR is normalized to the number of cavities required for the Z-pole. The spectrum of the beam is shown on the right-hand axis.

the calculation of the HOM power above 4.1 GHz. In this study, the spectrum of the cavity is calculated up to 4.1 GHz, thus the total power is approximated by

$$P_{tot} \approx P_L + P_M + \frac{14.0}{32.7} P_M. \qquad (2)$$

The total HOM power and the percentage of power absorbed by each port is given in Table 2. In the waveguides for HOM absorption, TE modes with a comparably large longitudinal electric field on beam axis exist. Thus, the damping schemes with WGs in average have a larger HOM power.
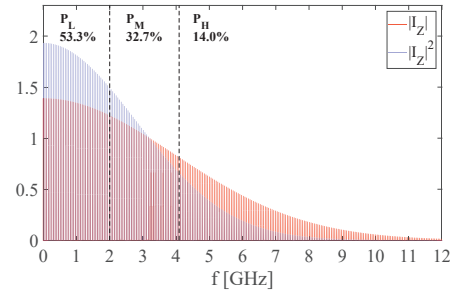

Figure 4: Beam spectrum of the Z-pole option. The spectrum corresponds to a simplistic filling scheme assuming that all the bunches are uniformly distributed in the ring. Note that the beam spectrum is symmetric around $f = 0$ and here the positive frequency side of the spectrum is shown.

The interaction of the large beam current with the field of such modes gives rise to a higher HOM power for such damping schemes. However, the WGs absorb much more HOM power in comparison with coaxial couplers which absorb below 5% of the HOM power. In all damping schemes a large portion of the HOM power propagates out of the BPs. Thus, an additional absorber at the end of the module is required. The amount of power absorbed by the rectangular WG and QRWG is of the same order, but the QRWG has the advantage that it can efficiently damp the modes in the first dipole band at the cost of a more complicated geometry.

CONCLUSION

In this paper, a single-cell cavity was designed for the Z-pole option of FCC-ee with a focus on the FM as well as HOM aspects of the cavity. A comparison between different HOM damping schemes showed that because of the large beam current, the chosen damping scheme also affects the total HOM power. It was shown that coaxial couplers have small ratio of power absorption and BP absorbers at the end of the module are needed to absorb the power that propagates out of the BPs (which is roughly between 3 kW to 4 kW for a single cavity). The damping scheme with three hook-type couplers and a QRWG showed promising results in damping the dipole modes below the stability limit and at the same time absorbing a significant amount of HOM power. Further aspects such as complexity of the design, availability of high power absorbers and multipacting need to be studied to decide for a final design.

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