OPTIMIZATION OF TWO-CELL CAVITIES FOR THE W AND H WORKING POINTS OF THE FCC-ee CONSIDERING HIGHER-ORDER MODE EFFECTS

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Introduction

• The lepton collider of the Future Circular Collider (FCC-ee) aims at conducting precision measurements on the Z, W, and H bosons and the top quark

• The present RF baseline considers four-cell 400 MHz cavities for the W and H working points

• A detailed study of the W working point has shown strong higher-order mode (HOM) effects in the four-cell cavities [1]

• In this study, a two-cell cavity is designed as an alternative scenario for the current W- and H-RF setups with special attention paid to HOM aspects

Quantities of Interest

- The primary quantities of interest are the impedances of higher-order modes (HOM)
  - HOM Longitudinal Impedance $|Z_L|$ and
  - HOM Transverse Impedance $|Z_T|$

$$Z_L = \frac{1}{c} \int_{-\infty}^{\infty} w_\parallel (r, s) e^{-\frac{j\omega s}{c}} \, ds$$

$$Z_T = \frac{-j}{c} \int_{-\infty}^{\infty} w_\perp (r, s) e^{-\frac{j\omega s}{c}} \, ds$$

- Secondary quantities of interest are these quantities of the fundamental mode (FM):
  - $E_{pk}/E_{acc}$
  - $B_{pk}/E_{acc}$

where $E_{pk}$, $B_{pk}$ and $E_{acc}$ represent the peak electric field on the surface of cavity, peak magnetic field on the surface of the cavity, and accelerating field, respectively
Optimization Method

• In order to reduce the search space for this study, the equator and iris ellipses were assumed to have a circular shape, i.e. $A = B$ and $a = b$

• A parameter sweep in 4D was carried out considering $A \in [50,110], a \in [20,70], L \in [160,190]$, and $R_i \in [150, 160]$, where all dimensions are in mm

• The HOM and FM quantities of interest are combined to form objective functions using the weighted exponential sum method

$$F_{obj} = \left( \sum_{i}^{m} (w_i f_{i,n})^p \right)^{\frac{1}{p}} \quad [2]$$

where $w_i$ represents weights, $p$ represents the norm order and $n$ is used to indicate that the objective functions are normalised. $w$ and $p$ are both set to 1 in this study.

**Objective Functions**

\[
\min_{L,R_i,A,B,a,b} (F_{FM}, F_{HOM})
\]

s.t. \( f_{FM}(R_{eq}) = 400.79 \text{ MHz} \)

\[
F_{FM} = \frac{E_{pk}}{E_{acc}} \cdot \frac{B_{pk}}{E_{acc}} \cdot \frac{mT}{MV/m}
\]

FM frequency tuning

- \( E_{pk}/E_{acc} \) is normalized by 2.2 and \( B_{pk}/E_{acc} \) by 5 \( \frac{mT}{MV/m} \)

- The maximum longitudinal impedance peak above the FM is normalized to 0.3 \( k\Omega \), and the maximum transversal impedance peak above the frequency of the first two dipole passbands is normalized to 3 \( k\Omega/m \), considering a wake length of 50 m
A Pareto distribution of the two objective functions

- The Pareto front of this optimization with the two objective functions $F_{HOM}$ and $F_{FM}$ is highlighted by the blue markers.

- Three geometries are selected from the Pareto front. Geometry 1 ($C_1$) favors $F_{FM}$, Geometry 3 ($C_3$) favors $F_{HOM}$, and Geometry 2 ($C_2$) is a sample in the middle range.

More in favor of $F_{HOM}$

More in favor of $F_{FM}$
The longitudinal wakefield impedance plot shows a strong reduction in the HOM impedance for the selected two-cell cavities, especially for $C_3$. 

$C_1$, $C_2$, $C_3$, $C_{\text{baseline}}$
Transversal Wakefield Impedance Plots for Selected Cavities

From the zoomed area, it can be seen that geometry 3 has less number of peaks which simplifies the design of HOM couplers.
## Result Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$k_{\parallel}^*$ [V/pC]</th>
<th>$k_{\perp}$ [V/pC/m]</th>
<th>$f_{\text{TE}111} - f_{\text{TM}010}$ [MHz]</th>
<th>$R_{sh}/Q_{FM}$ [Ω]</th>
<th>$E_{pk}/E_{acc}^{**}$</th>
<th>$B_{pk}/E_{acc}$ [mT/(MV/m)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>0.02678</td>
<td>0.5401</td>
<td>66.01</td>
<td>165.8</td>
<td>2.03</td>
<td>5.3</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.017582</td>
<td>0.4242</td>
<td>60.21</td>
<td>147.2</td>
<td>2.12</td>
<td>6.2</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0.01504</td>
<td>0.4564</td>
<td>80.51</td>
<td>144.7</td>
<td>2.46</td>
<td>6.6</td>
</tr>
<tr>
<td>$C_{\text{baseline}}$</td>
<td>0.048025</td>
<td>0.82</td>
<td>85.21</td>
<td>411.3</td>
<td>2.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>

* A bunch length of 50 mm was used for the calculation of the HOM loss factors. ** $E_{acc}$ is calculated from $V_{acc}$ with a length of $n_{cell} \times 374$ mm.

The dimensions are given in mm:

<table>
<thead>
<tr>
<th>Var</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_{\text{baseline}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A/A_c$</td>
<td>90</td>
<td>50</td>
<td>50</td>
<td>135.44/133</td>
</tr>
<tr>
<td>$B/B_c$</td>
<td>90</td>
<td>50</td>
<td>50</td>
<td>114.9/102</td>
</tr>
<tr>
<td>$a/a_c$</td>
<td>60</td>
<td>70</td>
<td>60</td>
<td>43.5/34</td>
</tr>
<tr>
<td>$b/b_c$</td>
<td>60</td>
<td>70</td>
<td>60</td>
<td>71.19/46</td>
</tr>
<tr>
<td>$R_t/R_{t,c}$</td>
<td>150</td>
<td>160</td>
<td>155</td>
<td>120/156</td>
</tr>
<tr>
<td>$L/L_c$</td>
<td>190</td>
<td>180</td>
<td>160</td>
<td>187/171.5</td>
</tr>
<tr>
<td>$R_{eq}$</td>
<td>355.042</td>
<td>374.924</td>
<td>372.642</td>
<td>333.182</td>
</tr>
<tr>
<td>$\alpha/\alpha_c$</td>
<td>114.5°</td>
<td>116.1°</td>
<td>111.3°</td>
<td>100°/96.9°</td>
</tr>
</tbody>
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