FCC-ee HYBRID RF SCHEME
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Abstract
For FCC-ee, the range of beam energies and beam currents is large between each mode of operation, all scaled to an available 50 MW maximum power per beam. The two limiting scenarios for the RF system design are at low energy (45 GeV) with high beam current (1.39 A) and the highest energy (182.5 GeV) with a radiation loss reaching 9.2 GeV per turn. In this paper, RF staging with a hybrid scheme using both 400 MHz and 800 MHz is proposed to mitigate the requirements on the two extremes. Relevant comparisons are made with respect to using only a single frequency for all modes.

INTRODUCTION
In order to accelerate the particles in FCC-ee to the required energy, an RF system is needed to provide the accelerating voltage for the four machine setups. Generally speaking, these four energy setups can be divided into two categories: high current setups which are characterized by low voltage and high current, i.e. Z and W, and high energy setups which are characterized by lower beam current but high accelerating voltage (see Table 1). Based on the RF design studies, a single design which can serve all four cases is not efficient [1]. The high current of the Z option can lead to very high HOM power and beam instabilities. Its design therefore favors a cavity with lower number of cells, lower frequency and larger aperture. The design of the Z option on the other hand, favors higher frequency and higher number of cells per cavity in order to get higher acceleration per unit length. The other two operating modes fall between these two extremes in terms of voltage and current.

Table 1: Some machine parameters as of April 2018 [2]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>Beam RF voltage [GV]</td>
<td>0.1</td>
<td>0.75</td>
<td>2.0</td>
<td>10.93</td>
</tr>
<tr>
<td>SR loss/turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>No. of bunches/beam</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>48</td>
</tr>
<tr>
<td>Bunch intensity [10^{11}]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Bunch SR length [mm]</td>
<td>3.5</td>
<td>3.0</td>
<td>3.15</td>
<td>1.97</td>
</tr>
<tr>
<td>Bunch BS length [mm]</td>
<td>12.1</td>
<td>6.0</td>
<td>5.3</td>
<td>2.54</td>
</tr>
<tr>
<td>Lumin. [10^{34} cm^{-2} s^{-1}]</td>
<td>230</td>
<td>28</td>
<td>8.5</td>
<td>1.55</td>
</tr>
</tbody>
</table>

RF SYSTEM
A comparison of the number of cavities per beam, input power and higher order mode (HOM) power for different energy options (at 400 MHz) with respect to the number of cells per cavity is shown in Figure 1. By using one cell per cavity for the Z energy, and assuming operating each cavity with a field of 10 MV/m, 26 cavities are needed to provide the total voltage of 100 MV. Therefore, an input power of around 1.925 MW is required for each cavity to compensate the total 50 MW synchrotron radiation loss. With the existing technology and the experience of LHC, 500 kW CW power per coupler is feasible at 400 MHz [3].

It is directly evident that the use of multi-cell cavities for the Z-pole energy is fundamentally limited by the maximum input power. The input power for each cavity is reduced by lowering the accelerating gradient and using more cavities to be compatible with the 1 MW limit. Assuming the BS bunch length (Table 1), the beam deposits an average HOM...
power of 3.7 kW and 7.4 kW into a 1-cell and 2-cell cavity, respectively. The input and HOM power restrictions prevent us from using a higher number of cells per cavity or using higher frequency for the Z-pole energy option. An operating frequency of 800 MHz, increases the HOM power by around 20-30%. Furthermore, providing the high CW input power is more challenging at higher frequencies. Therefore, for the Z-pole a single-cell Nb/Cu cavity at 400 MHz similar to that of the LHC is chosen as a baseline. This design is also compatible with the FCC-hh including a large part of RF hardware and other infrastructure.

At the high energy end (t1), multiple cells per cavity and higher frequency are preferred to reach higher acceleration per length and optimize the equipment cost. Due to small number of bunches per beam, a common RF system for both beams is possible. This is achieved by realigning and combining the cavities used for the two beams of the H (4 GV) machine and adding additional cavities to provide the remaining voltage (6.93 GV). Two possibilities are considered for providing the 6.93 GV for the t1 operation, i.e. 4-cell cavity at 400 MHz (Nb/Cu at 4.5 K) or 5-cell cavity at 800 MHz (bulk Nb at 2 K). Frequencies above 800 MHz are not considered due to input power limitation for CW operation. The 400 MHz option allows for a single frequency operation and better compatibility across all modes of operation. However, the 5-cell cavity at 800 MHz provides better acceleration efficiency and therefore fewer cavities.

Input Power
The RF power for each of the four energy options with optimum detuning is shown in Figure 2 as a function of the loaded quality factor $Q_L$. Four-cell cavities at 400 MHz are assumed for W, H and t1 and single-cell cavity at 400 MHz is assumed for Z. The input power of all cavities has to compensate the synchrotron radiation losses, i.e. 50 MW per beam. For optimum operation, the cavity should be operated at minimum $Q_L$ of each curve. With a fixed $E_{acc}$, changing the number of cells has insignificant influence on optimum $Q_L$ because $Q_L\min \propto V_{cav}/(R/Q)$ [4] and numerator ($V_{cav}$) and denominator ($R/Q$) change almost linearly with the number of cells. Minimum $Q_L$ points of H and t1 are close to each other, therefore a fixed input coupler could be used with only a few percent increase in total power. A variable input coupler is required for cavities used by W and H that can change its $Q_L$ roughly between $0.5 \times 10^6$ to $1.5 \times 10^6$. Therefore, the use of the same 4-cell 400 MHz concept for both the W and H options is also not optimum from the perspective of high power and the use of variable coupler.

HOM Damping
A detailed analysis of the cavity higher order mode (HOM) damping and HOM power was performed for the four operating points of the FCC-ee machine with different cavity designs. A 4-cell cavity at 400 MHz and a 5-cell cavity at 800 MHz were proposed as potential candidates for their use in the different FCC-ee machines. The longitudinal and transverse impedance spectrum of a 4-cell cavity at 400 MHz and a 5-cell cavity at 800 MHz. A similar coaxial HOM coupler is used in both cases. The impedance thresholds set by synchrotron radiation for different energy options is plotted and normalized to the number of cavities for each case.

Three possible staging scenarios are given in Table 2. Single cell cavity at 400 MHz is considered in all three scenarios for the Z machine. Research and development is needed to push forward the available CW power with a tar-
### Table 2: Three possible scenarios for FCC-ee. HOM power is calculated for both BS and SR bunch length.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>No. cells / cavity</th>
<th>No. cavities per beam</th>
<th>$E_{acc}$ [MV/m]</th>
<th>$P_{cav}$ [kW]</th>
<th>$Q_{ext}$ [10^6]</th>
<th>$P_{HOM}$ (SR / BS) [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>1</td>
<td>52</td>
<td>5</td>
<td>962</td>
<td>0.045</td>
<td>1.16 / 0.76</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>2</td>
<td>52</td>
<td>100</td>
<td>962</td>
<td>0.045</td>
<td>1.16 / 0.76</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>2</td>
<td>52</td>
<td>100</td>
<td>962</td>
<td>0.045</td>
<td>1.16 / 0.76</td>
</tr>
</tbody>
</table>

CONCLUSION

Several multi-harmonic scenarios for FCC-ee were studied in this paper. In these scenarios Z, W and H are operated at 400 MHz, each. Due to high HOM power, single-cell cavity is considered for the Z-pole machine. The 400 MHz cavities are used also for $t_f$ and the remaining voltage is provided with five-cell cavities at 800 MHz.

REFERENCES


