ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF036

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 $t\bar{t}$ on the other hand, favors higher frequency and higher number of cells per cavity in order to get higher acceleration per unit length. The $t\bar{t}$ option requires the longest accelerating structure. 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]

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

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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].

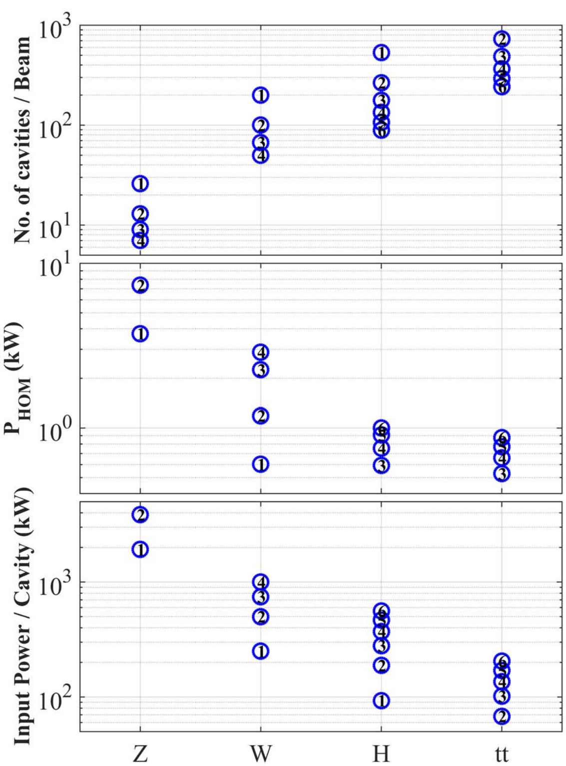

Figure 1: Dependency of number of cavities, HOM power and input power on the number of cells per cavity at 400 MHz (number of cells are shown in the circle markers). The number of cavities are calculated for E_{acc}=10 MV/m. The HOM power is calculated for the BS bunch lengths of Table 1.

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

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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 ($t\bar{t}$), 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 $t\bar{t}$ 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 $t\bar{t}$ 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 $t\bar{t}$ 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 0.5×10^6 to 1.5×10^6. 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

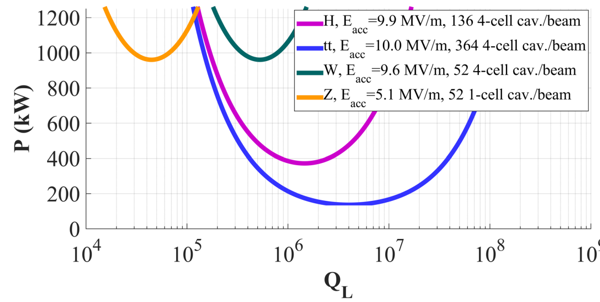

Figure 2: Forward power as a function of Q_L with optimal detuning for each energy option.

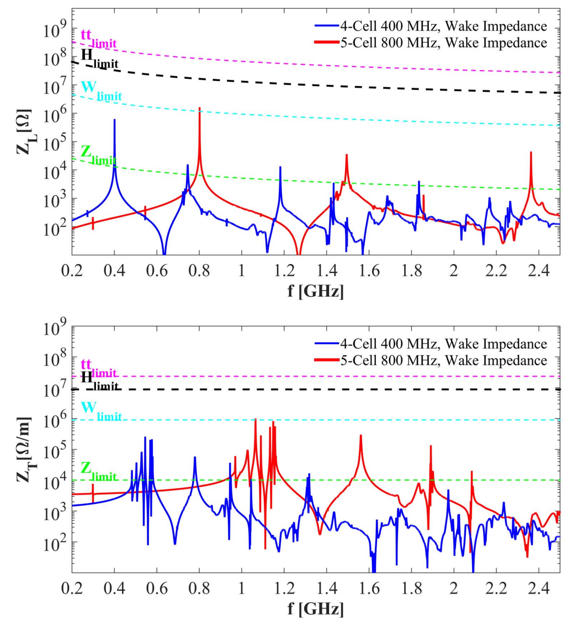

Figure 3: Comparison between the longitudinal and transversal impedance spectrum of a 4-cell cavity at 400 MHz and a 5-cell cavity at 800 MHz. A similar coaxial HOM coupler is used in both cases. The impedance thresholds set by synchrotron radiation for different energy options is plotted and normalized to the number of cavities for each case.

use in the different FCC-ee machines. The longitudinal and transverse impedance of a cavity at 400 MHz and 800 MHz using LHC-like broad-band coaxial couplers are compared in Figure 3. The impedance threshold set by the synchrotron radiation for the different operating energies is used as the impedance budget limit. For both designs, the impedances are well below the thresholds for the H and $t\bar{t}$ while close to the threshold of the W operating point. The low stability threshold for the Z-pole confines the choice to a heavily damped single cell 400 MHz cavity.

LAYOUT

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-

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Table 2: Three possible scenarios for FCC-ee. HOM power is calculated for both BS and SR bunch length.

		Z	W	H		$t\bar{t}$		
Total beam voltage [GV]		0.1	0.75	2.0		5.465		10.93
Scenario 1	Voltage [GV]	0.1	0.75	2.0		2.0 (5.465)	3.465	reorder and align both rings for the rest
	f [MHz]	400	400	400		400	800	
	No. cells / cavity	1	4	4		4	5	
	No. cavities per beam	52	52	136		136 (364)	186	
	E_{acc} [MV/m]	5.1	9.6	9.8		9.8 (10.0)	19.9	
	P_{cav} [kW]	962	962	367		150 (137)	158	
	Q_{ext} [10^6]	0.045	0.53	1.44		3.51 (4.01)	4.22	
	P_{HOM} (SR / BS) [kW]	9.5 / 3.7	5.09 / 2.89	1.16 / 0.76		0.81 / 0.66	1.09 / 0.89	
Scenario 2	Voltage [GV]	0.1	0.75	2.0		2.0 (5.465)	3.465	reorder and align both rings for the rest
	f [MHz]	400	400	400		400	800	
	No. cells / cavity	1	2	2		2	5	
	No. cavities per beam	52	100	268		268 (732)	186	
	E_{acc} [MV/m]	5.1	10.0	10.0		10.0 (10.0)	19.9	
	P_{cav} [kW]	962	500	186		76 (68)	158	
	Q_{ext} [10^6]	0.045	0.59	1.58		3.86 (4.33)	4.22	
	P_{HOM} (SR / BS) [kW]	9.5 / 3.7	1.91 / 1.19	0.44 / 0.31		0.28 / 0.24	1.09 / 0.89	
Scenario 3	Voltage [GV]	0.1	0.75	0.75	1.25	0.75	4.715	reorder and align both rings for the rest
	f [MHz]	400	400	400	800	400	800	
	No. cells / cavity	1	2	2	5	2	5	
	No. cavities per beam	52	100	100	68	100	252	
	E_{acc} [MV/m]	5.1	10.0	10.0	19.7	10.0	20.0	
	P_{cav} [kW]	962	500	207	430	77	167	
	Q_{ext} [10^6]	0.045	0.59	1.44	1.51	3.84	4.03	
	P_{HOM} (SR / BS) [kW]	9.5 / 3.7	1.91 / 1.19	0.44 / 0.31	1.59 / 1.06	0.28 / 0.24	1.09 / 0.89	

get value of 1 MW. The HOM couplers of Z have to cope with around 4 kW. The performance of 2-cell and 4-cell cavities at 400 MHz for W and H machines is also compared. Five-cell cavities at 800 MHz are considered in all scenarios for the remaining voltage of $t\bar{t}$.

Some challenges and obstacles in each scenario, apart from Z machine, are:

- Scenario 1: requires 136 4-cell (400 MHz) and 186 5-cell (800 MHz) cavities per beam for W, H and $t\bar{t}$. High HOM power, high transverse impedance (close to threshold) and high input power with variable input coupler for W machine are to be tackled.
- Scenario 2: requires 268 2-cell (400 MHz) and 186 5-cell (800 MHz) cavities per beam for W, H and $t\bar{t}$. The HOM power, impedance and input power of the W machine are decreased by using 2-cell cavities at the cost of doubling the number of 400 MHz cavities in comparison with the first scenario.
- Scenario 3: requires 100 2-cell (400 MHz) and 252 5-cell (800 MHz) cavities per beam for W, H and $t\bar{t}$. It is similar to scenario 2. A multi-harmonic system is also considered for H in order to lower the number of cavities. It requires high input power of 430 kW at 800 MHz for H machine. The HOM power of the H machine is higher than that in the other two scenarios. Upgrading from the W machine to H demands more time as infrastructure for two frequencies has to be installed.

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 $t\bar{t}$ and the remaining voltage is provided with five-cell cavities at 800 MHz.

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