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The RF system for FCC-ee

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The FCC-ee is a high-luminosity, high-precision e^+e^- circular collider, envisioned in a new 80-100 km tunnel in the Geneva area. It is envisaged to operate the collider with centre of mass energies ranging from 90 GeV for Z production to 350 GeV at the $t\bar{t}$ threshold. With a constant power budget for synchrotron radiation, the FCC-ee RF system must meet the requirements for both the highest possible accelerating voltage and very high beam currents with the same machine, albeit possibly at different stages. Beam-induced higher order mode power will be a major issue for running at the Z pole, and will have a strong impact on the RF system design. Iterations are ongoing on RF scenarios and staging, choice of cavities and cryomodule layout, RF frequency and cryogenic temperature.

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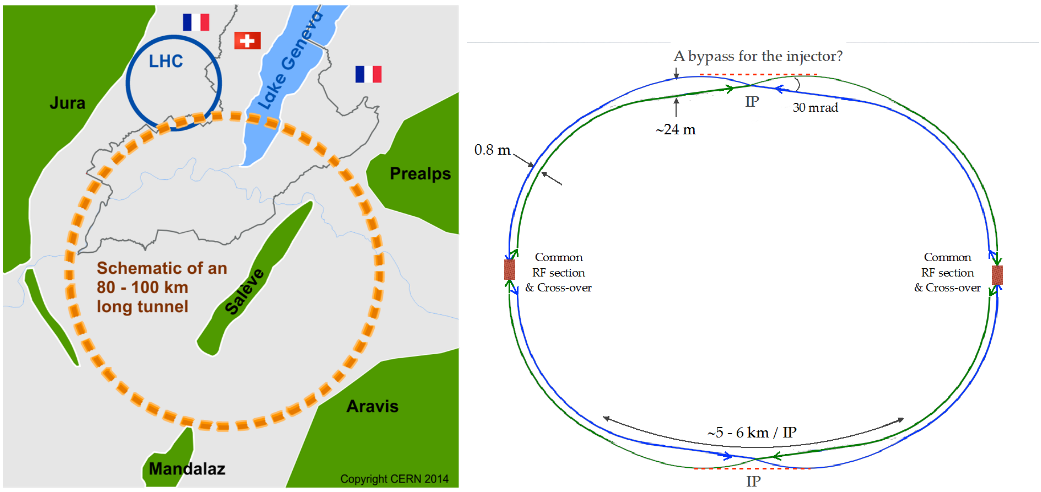
1. Introduction

The FCC-ee [1] is a proposed high-energy e^+e^- collider to be constructed in the 100km circumference tunnel in the Geneva area (Fig. 1) which would subsequently house the FCC-hh proton-proton collider of the Future Circular Accelerators (FCC) study [2]. The highest priority for the FCC-ee is Higgs production ($e^+e^- \rightarrow ZH$) at a centre-of-mass (c.m.) energy of about 240 GeV [3]. The second priority would be operation at the Z-pole (91 GeV c.m.) with extremely high luminosity in order to produce upwards of $10^{12}Z$'s over a couple of years. Further FCC-ee collision energies will be at the WW threshold, and with an ultimate energy upgrade at the $t\bar{t}$ threshold ($\sim$350 GeV c.m.).

With a constant synchrotron radiation (SR) power budget of 50 MW per beam, and radiative losses varying as the fourth power of energy, the maximum beam current is about 1.5 A at the Z-pole where the energy loss per turn is only 35 MeV. Conversely, for operation at the ZH peak or at the $t\bar{t}$ threshold, the loss per turn is about 1700 MeV or 7600 MeV respectively, requiring a total accelerating voltage of up to 11 GV, and limiting the beam current to 30 or 7mA [4]. The parameters related to power and beam current for the different operation modes are shown in Table 1.



(a) Geographical location (b) One possible FCC-ee layout (K. Oide [5])

Figure 1: Schematic of the 80-100 km future circular collider tunnel at CERN (FCC study group).

2. Cavity choice

The scenario currently being considered for the FCC-ee RF consists of a main system at 400 MHz covering operation energies up to 120 GeV, which could be completed by additional 800 MHz cavities to reach the very highest energy point where the beam current is much lower. The need for high accelerating gradients would suggest going towards higher frequency, but the lower longitudinal and transverse loss factors of the 400 MHz cavities make them more suitable for the high beam intensities foreseen at the lower energies. The 800 MHz cavities would be installed only for high energy operation with low beam currents where their higher loss factors are not a problem.

Table 1: Beam and RF parameters for the different operation modes.

Parameter	Unit	FCC-ee operation mode			
		Z	W	H	t
Beam energy	[GeV]	45	80	120	175
SR loss per turn U_0	[GeV]	0.03	0.33	1.67	7.55
Total RF voltage	[GV]	2.5	4	5.5	7.55
Beam current	[mA]	1450	152	30	6.6
Radiative beam power	[MW]	50	50	50	50
Bunch length	[mm]	2.3	1.49	1.17	1.49

Niobium film on copper technology has been shown to be a reliable option in LHC and in LEP, where the mean accelerating gradient was 7.3 MV/m, operating at 4.5 K. Preliminary design studies have been undertaken [6] where 400 MHz cavities from one to four cells were considered for comparison (Fig. 2 and Table 2). A four-cell LEP-like layout [7] is optimal for "real estate" gradient (voltage per unit length of beam line), whereas a single cell has the lowest higher-order-mode (HOM) loss factor, but is approximately a factor two worse in real-estate gradient. A 2+2 cells hybrid layout appears to be an interesting compromise. Further detailed studies are necessary to determine the final number of cells based on the efficiency for acceleration, RF power, HOM losses and layout constraints.

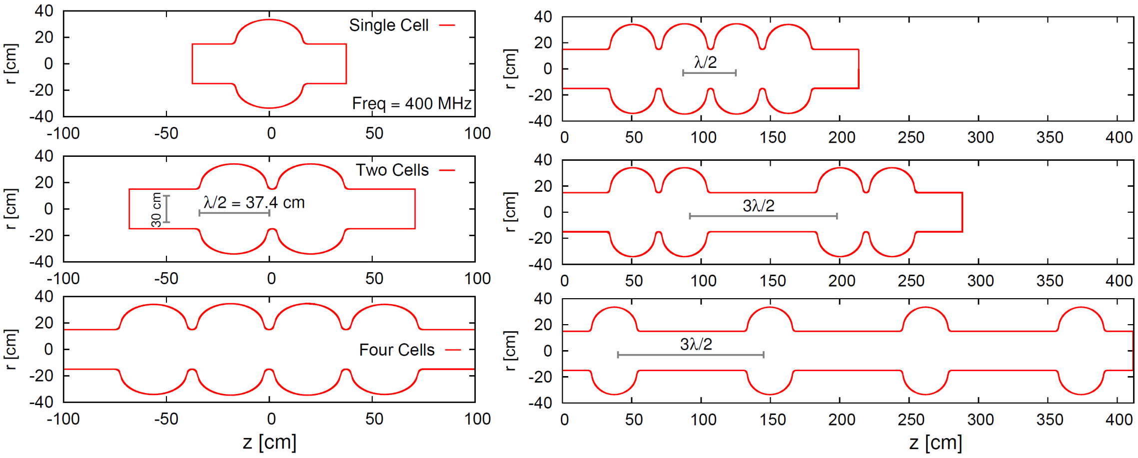


Figure 2: Preliminary design of 1, 2 and 4-cell cavity options and schematic of the different cavity layouts to compare to an effective 4-cell LEP cavity at 400 Mhz [6].

3. Parasitic losses and higher order mode power

The large beam current in the *Z*-pole operation mode coupled with the short bunch length leads to large parasitic losses and high levels of HOM power which must be removed from the cavities.

Table 2: Principal RF characteristics of the one-, two-, and four-cell geometries at 400 Mhz. The nominal operating temperature is assumed to be 4.5 K with Nb film cavities. A five-cell 800 Mhz bulk Nb cavity is listed for comparison, assumed to be operating at 2 K.

Parameter	Unit	1-cell	2-cell	4-cell	5-cell
Frequency	[MHz]	400			800
Active length	[cm]	37.4	74.8	150	93.5
Voltage	[MV]	3.75	7.5	15	11
R/Q	[Ω]	87	169	310	393
Q_0		3×10^9			1×10^9
Cavity losses	[W]	53	124	253	508

Figure 3 shows the longitudinal loss factor versus bunch length σ_z for a single cell at three different frequencies. The bunch length of 2.3 mm, assuming a loss factor of 0.7 V/pC, gives an HOM power of around 29 kW per cell, which is comparable to the input fundamental power, and will therefore have a significant impact on the power budget.

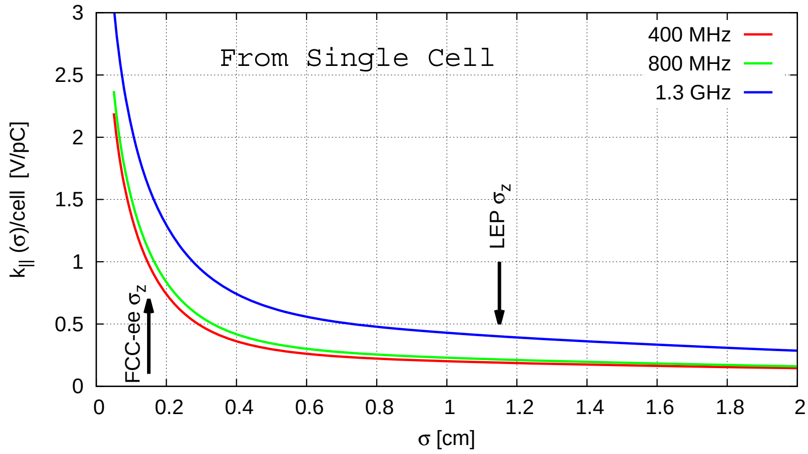


Figure 3: Longitudinal loss factor as a function of bunch length for three different frequencies [6].

The integrated loss factor scales approximately with the number of cells as shown in Fig. 4, leading to a HOM power of around 100 kW for the four-cell cavity with 1.4 mm bunch length and the nominal Z-pole beam intensity. This would seem to strongly argue against the use of multi-cell cavities in this mode of operation, and suggest the use of single- or two-cell cavities with very strong HOM damping.

The HOM damper designs currently available fall into the categories shown in Fig. 5: cryogenic loop (a) and waveguide (b) couplers which evacuate HOM power from the cold cavity, or

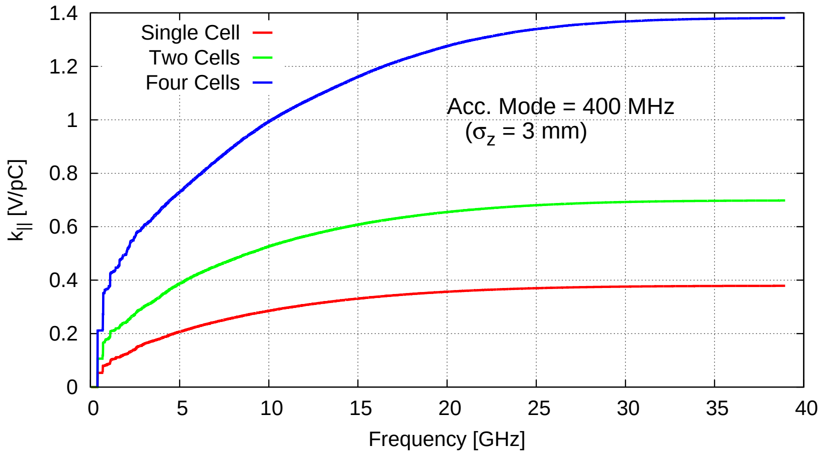


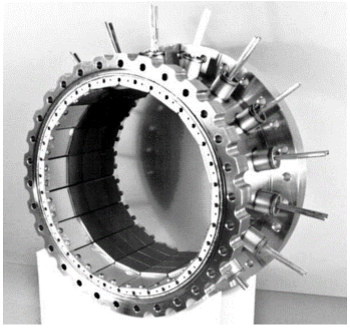
Figure 4: Longitudinal loss factor integrated over frequency for one-, two- and four-cell 400 MHz cavities for a bunch length of 3 mm [6].

warm beam line absorbers (c) which are mounted outside the cryostat. The LHC loop-type couplers are rated at 1 kW [8], while warm absorbers currently provide the highest HOM power handling capability, up to about 15 kW [9]. This is nevertheless insufficient for the levels expected in Z-pole operation. Moreover, the warm beam line sections between cryostats increase the overall cryogenic heat load and take up significant amounts of space; taking as an example the KEKB 509 MHz single-cell cavity module with ferrite absorbers [10], the overall length is 3.7 m, which for 1468 cavities in each of the two beam pipes would lead to extremely long RF sections of over 10 km total length. An extensive research and development program will be required to refine the cavity and HOM damping system design.

4. Fundamental power and cavity coupling

Table 3 shows the parameters related to RF voltage and fundamental power for the two-cell cavities at the Z-pole and ZH. The power transfer to the beam is dependent on the external quality factor Q_{ext} of the cavity which is determined by the fundamental power coupler. A variable coupler allows the Q_{ext} to be tuned so as to optimize power transfer for different beam loading situations. A fixed coupler, on the other hand, must be optimized at installation time for a chosen beam loading. Figure 6 shows how the power delivered to the cavity varies with Q_{ext} for the different FC-ee operation modes. The minimum of each curve corresponds to the matched condition where all power is transferred to the beam. It can be seen that optimizing the Q_{ext} for the Z-pole results in substantial wasted power when running at the ZH. This can be avoided by the use of a variable coupler; however, there is a penalty in complexity and cost, and the trade-off needs to be evaluated.

(a) LHC loop type coupler (b) Waveguide couplers (JLab)



(c) Broadband ferrite-based room-temperature absorber (Cornell)

Figure 5: Different types of HOM damper: cryogenic (a) and (b), warm (c).

Table 3: RF system parameters for the two-cell cavities in H and Z operation modes.

Operation mode	H	Z
Beam energy [GeV]	120	45.5
RF voltage [MV]	5500	2500
SR power/beam [MW]	50	50
Synchronous phase [deg]	162.3	179.2
Accelerating gradient [MV/m]	10	10
Cavity voltage [MV]	7.5	3.4
Number of cavities	734	734
Total cryomodule length [m]	1468	1468
RF power per cavity [kW]	68.1	68.1
Matched Q_{ext}	4.9×10^6	1.0×10^6
Bandwidth [Hz]	81.9	397
Optimal detune [Hz]	-128.8	-14388

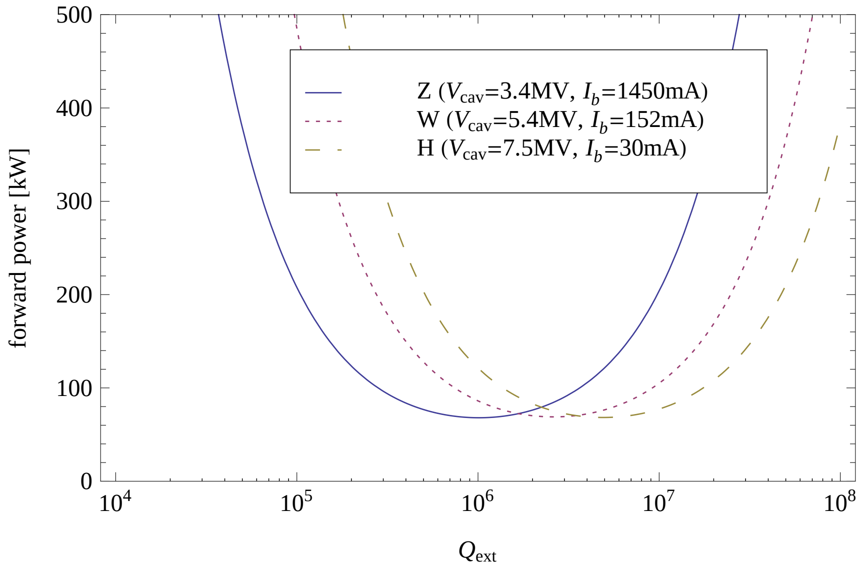


Figure 6: Forward power per cavity as a function of cavity coupling (Q_{ext}) for three different FCC-ee operating modes. Assumes 734 2-cell cavities with an R/Q of 84 Ω and a total SR power of 50 MW, neglecting beam-induced parasitic losses.

5. Cavity tuning and RF feedback

At the Z-pole the high beam current and small energy loss per turn lead to high reactive beam-loading which needs to be compensated by cavity detuning. The optimal detune of over 14 kHz in this operation mode is large compared with the revolution frequency and will tend to drive coupled bunch modes. Fast RF feedback around the cavities will be required to ensure beam stability under these conditions. This is not the case at the ZH and higher energies, where the detune is small. Further studies are needed to determine the exact requirements.

At the ZH and $t\bar{t}$ with optimal Q_{ext} the cavity bandwidth is rather small at around 80 Hz, which will require careful design of the tuning system.

6. Staging of installation

The staged physics program of FCC-ee leads naturally to a staged installation of the RF system, with an increase in installed RF power and total voltage at each step. As Higgs production at the ZH peak is considered the highest physics priority, it is envisaged in a first stage to install half the RF power with enough RF voltage to reach a beam energy of 120 GeV with a moderate beam current, allowing physics with moderate luminosity at the Z-pole, WW threshold and ZH. In a second stage the installation of the full 50 MW RF power per beam would give access to high-luminosity operation at these three energies. In the final stage, to reach the $t\bar{t}$ threshold, the RF voltage must be approximately doubled, either with the installation of additional 800 MHz cavities, or in an alternative scenario by reconfiguring the RF sections to share the cavities between the two beams, thus doubling the RF voltage available to each beam. The latter option is possible only due to the small number of bunches at 175 GeV, and the former will limit the beam intensity due to the high loss factors of the 800 MHz cavities. Thus either of these two scenarios will rule out any further running at the Z-pole with high luminosity.

7. Top-up injection and injector ring

Due to the short beam-beam lifetime of the order of some tens of minutes in collision, a top-up injection scheme is required using a separate ring in the same tunnel. The injector ring must deliver beam at the full energy of the collider ring with a repetition rate of the order of 0.1 Hz, but at only about 1% of the circulating intensity. The highest beam intensity will thus be 14.5 mA at the Z-pole, which assuming a 1.6 s ramp length gives a peak acceleration power of 77 kW. Combined with the peak SR power of 500 kW at the extraction plateau this gives a total maximum RF power of below 600 kW. The injector ring RF system can therefore be optimized principally for high gradient in order to minimize size and cost.

8. Conclusions

The conceptual design of the RF system for FCC-ee is in an initial stage. A proposal currently being considered for the main acceleration system consists of around 700 2-cell 400 MHz elliptical Nb film superconducting cavities per beam at operating at 4.5 K. This will allow operation up to a beam energy of 120 GeV for Higgs production. Reaching the highest design beam energy of 175 GeV is envisaged either with the installation of additional 800 MHz bulk Nb cavities at 2 K or by rearranging the 400 MHz cavities so that they are shared between the two beams, effectively doubling the RF voltage. The biggest challenges are linked to the high beam intensity required for running at the 45.5 GeV Z-pole, where the tens of kW of HOM power produced per cavity will require research and development on cavities with reduced loss factors and strong HOM damping and will ultimately define the limit on beam current. Strong RF feedback will be also be necessary in order to suppress coupled bunch modes driven by the cavity impedance. The separate RF system for the top-up injector ring is required to accelerate relatively small beam currents of around 1% of the collider ring intensity and can therefore be optimized for high gradient.

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