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2.12 Proposed RF Staging Scenario for FCC-ee

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2.12.1 **Introduction**

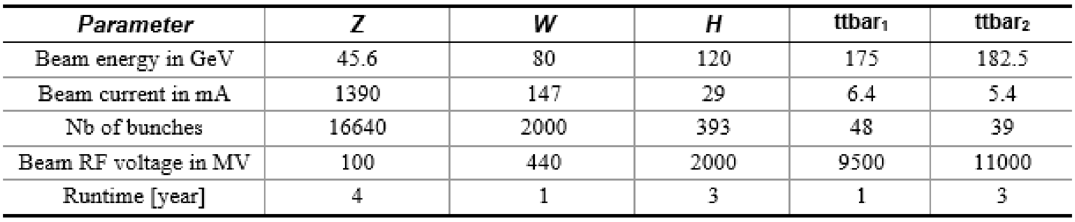
FCC-ee is a proposed high-energy electron positron circular collider that could initially occupy the 100-km tunnel of the future 100 TeV FCC-hh hadron collider. The parameter range for the e+e− collider is large, operating at center-of-mass energies from 90 GeV to 365 GeV with beam currents ranging between 1.39 A and 5.4 mA, at fixed synchrotron radiation power of 50 MW per beam. These are challenging parameters for the radiofrequency (RF) system because of the extreme voltage requirements and beam loading conditions. This document details a scenario for gradual evolution of the FCC-ee complex by step-wise expansion and reconfiguration of the superconducting RF system.

2.12.2 **Operation model**

The main center-of-mass operating points with large physics interest are around 91 GeV (Z-pole), 160 GeV (W pair production threshold), 240 GeV (Higgs resonance) and 365 GeV (above top-antitop (ttbar) threshold). The construction of FCC-ee will therefore proceed in five steps, combining eight months of operation periods with four months of interleaved winter shutdowns during which the hardware upgrades for energy increase can take place.

In order to collect the required luminosity and allow for interesting physics at each energy step, it is planned to run the machine four years at the Z-pole, one year at the W pair production threshold, three years at the Higgs resonance and finally four years at the highest energy, one year at the ttbar threshold, followed by three years at 182.5 GeV per beam. The main machine parameters are summarized in Table 1 [1].

Table 1: FCC_ee machine parameters



Parameter	*Z*	*W*	*H*	ttbar$_1$	ttbar$_2$
Beam energy in GeV	45.6	80	120	175	182.5
Beam current in mA	1390	147	29	6.4	5.4
Nb of bunches	16640	2000	393	48	39
Beam RF voltage in MV	100	440	2000	9500	11000
Runtime [year]	4	1	3	1	3

2.12.3 **RF configurations**

As shown in table 1, the RF voltage requirement is very broad, spanning from 0.1 to 11GV. Running at the Z-pole the FCC-ee is an ampere class, heavy beam loaded machine, while at the ttbar threshold it becomes an extremely high energy machine.

For the Z-pole machine, the cavity shape must be carefully optimized with regard to higher order modes (HOM). This favours low frequency, low shunt resistance and low number of cells per cavity. For this energy step, a 400 MHz continuous wave (CW) RF system made up of fifty-two single-cell Nb/Cu cavities per beam is considered. This frequency is indeed the natural choice for the FCC-hh, which will profit from the LHC as injector. The LHC also employs a 400 MHz RF system. The 400 MHz choice offers good perspectives for the FCC-ee low energy machines, and thus the opportunity to re-use a large part of the hardware and infrastructure for later use in FCC-hh.

High acceleration efficiency is necessary to optimize the total size and cost of the highest energy point, for which about 2600 cells are required to produce the total RF voltage of 11 GV. At this energy, the small number of bunches and the low beam loading suggest looking into the possibility of a common RF system for both beams. This can be accomplished by re-aligning the cavities used for the Higgs production on a common beam axis, and installing additional cavities to produce the extra 7 GV. For this, the relatively modest CW RF power per cavity offers the possibility to use 800 MHz bulk Nb five-cell cavities. Although these cavities must be operated at 2 K, this choice provides a better acceleration efficiency and a significantly reduced overall footprint, hence potentially significant cost savings, considering the overall size of the ttbar RF system.

Higher frequencies have been eliminated due to transverse impedance considerations and power coupler limitation for CW operation.

2.12.4 **Cavity material options**

A detailed analysis of SRF performance data for different RF frequencies, temperatures and materials and the perspective for future R&D is presented in [2]. Although the cavity material decision vs frequency is clear, it is demonstrated that a sustained and concerted R&D program on Nb/Cu films could potentially decrease the surface resistance by a factor two to three, and as a result making the Nb/Cu technology operated at 4.5 K competitive with bulk Nb, operated at 2 K.

This is very attractive, in particular, for the H machine, which requires a high RF acceleration efficiency with several hundreds of kW power input per cavity, and for which a lower transverse impedance is certainly beneficial. This choice also facilitates the re-use of the existing RF power system.

The A15 compounds potentially show great promise for the future. They could offer even more cryogenic cost savings, but require a much longer R&D effort [3].

2.12.5 **Beam-cavity interaction and beam dynamic issues**

In order to maximize the luminosity of the FCC-ee at the different energy steps, sufficient current must be stored in both beams. Higher-order mode (HOM) losses, single- and coupled-bunch instabilities that might seriously affect the final performance of the machines, have been studied in detail. Most of these issues appear to be more prominent in the high-current "low-energy" operation at the Z pole.

The microwave instability thresholds have been calculated with the BLonD code, a macro-particle tracking code developed at CERN for longitudinal beam dynamics simulations [4]. Its latest release supports new functions to accurately compute synchrotron radiation effects in leptons and very high energy hadron synchrotrons [5]. At nominal beam current, the machine impedance leads to increased energy spread and bunch length, despite the strong synchrotron radiation damping, but does not result in unstable growth [6]. This is consistent with previous analysis [7, 8].

The coupled-bunch instability thresholds were calculated using an analytical approach [9]. Although the single-cell cavity for the Z-pole machine must be further optimized, its longitudinal impedance spectrum above the cut-off frequency of the pipe sits well inside the coupled-bunch stability zone. For the impedance spectrum below the cut-off frequency, HOMs should be damped according to the calculated limit. The further analysis needs to focus on the cavity fundamental-driven coupled-bunch instabilities and on the potential impact of the large detuning angle.

A detailed analysis of the HOM power and damping requirements has been performed for all FCC-ee machines [10]. Power losses were evaluated for different cavity designs, cryomodule arrangements, including beam pipes and tapers, and various filling schemes. Proper bunch spacing selection and carefully designed cavities help to keep the HOM power per cavity below a few kilowatts, and LHC-like superconducting hook couplers are appropriate for this.

2.12.6 **A flavor of other R&D challenges**

The challenges ahead are numerous, and the important R&D areas have been carefully identified. In addition to those already addressed in the previous paragraphs, we may note the impressive 2 x 50 MW of continuous RF power; this sets the overall scale of the RF power system. Improving energy efficiency and reducing energy demand is absolutely crucial for future big accelerators such as FCC, and the development of high-efficiency RF power sources must be at the core of the R&D program [11].

For the proposed configuration of the Z-pole and W-threshold machines to be realized, the RF coupler technology must also be pushed forward to increase their CW power transfer capability: the higher order mode couplers will have to deal with high beam loading and must effectively extract kW's of RF power, while progress on the fundamental power couplers (FPC) will be decisive for limiting the cost and size of the RF system. The target value is 1 MW CW per power coupler at 400 MHz [12]. FPC design must ensure easy adaptation of their coupling coefficient to the different machines.

2.12.7 **Installation and staging plan**

The RF system will be expanded in steps, with rising maximum voltage, as shown in Figure 1. First of all, twenty-six four single-cavity cryomodules will be installed for the Z-pole machine. Each cavity will be fed by about 1 MW CW RF power for supplying the 2x50MW beam power. A number of possible solutions exist to produce the required RF power, but in any case, as the space in the tunnel is restricted, the large, bulky power equipment will be installed on the surface. The underground areas will only accommodate the RF power amplification, the D.C power distribution, the fast servos & control and protection systems. In the perspective of the different energy upgrades, using a combination of two or four medium-size RF power sources seems very attractive.

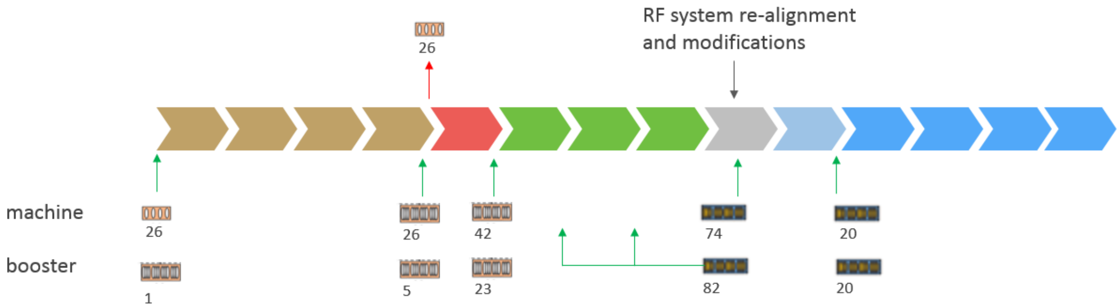


Figure 1: Proposed FCC-ee staging schedule. The figures underneath indicate the numbers of cryomodules to be newly installed during the various winter shutdowns.

During the winter shutdown at the end of the Z-pole campaign, these cryomodules will be replaced by twenty-six four-cell cavity cryomodules to allow for the W-threshold machine operation. The RF power sources, the control systems and the RF power distribution will remain unchanged.

The step between the W and H machines requires the installation of forty-two additional four-cell four-cavity cryomodules to produce the necessary RF voltage of 2 GV/beam. The fast RF feedback requirements and the still large number of bunches favor a single cavity per power source. The RF power system initially installed for the Z machine will be reconfigured to adapt to the new power requirement per cavity, and additional new RF power stations will complete the installation. The detailed powering scheme and the associated workload must be carefully studied to be in line with the available timeframe, and the pre-installation effort must be spread over several annual winter shutdowns (e.g. cabling and installation campaigns).

When transiting towards the highest beam energy of 182.5 GeV, it is attractive to rearrange the existing RF system and to share it between the two beams, so as to double the RF voltage available for either beam. The sharing of cavities by the two beams is possible thanks to the small number of bunches in this mode of operation. The sixty-eight RF cryomodules will be moved transversally and separators will be installed at the entrance and exit of each RF straight section. The system will be completed by ninety-four additional 800 MHz five-cell four-cavity cryomodules installed in series to produce the extra 7 GV. These 2 K cryomodules will be connected to form long cold segments in order to minimize the warm beamline sections, and the relatively modest power requirement per cavity will allow for the gradual introduction of less powerful and less expensive RF power sources. A one-year shutdown will be necessary to cope with this major intervention. It will be followed by one-year intermediate operation stage at 175 GeV, as requested by the particle physicists.

The main changes to the RF unit's configuration in tandem with the required beam-energy changes are depicted in Figure 2. The RF parameters for each stage are detailed in Table 2.

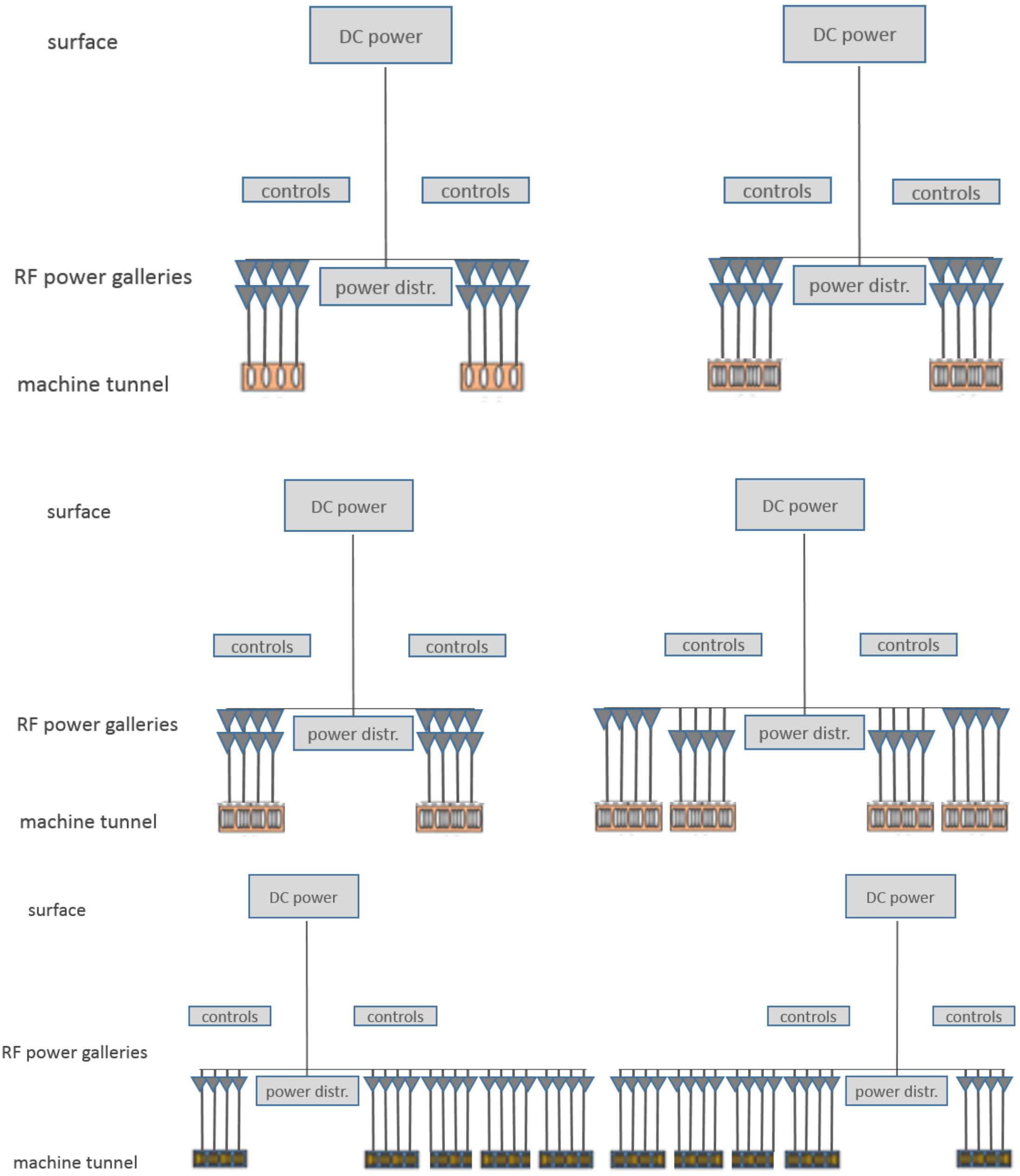
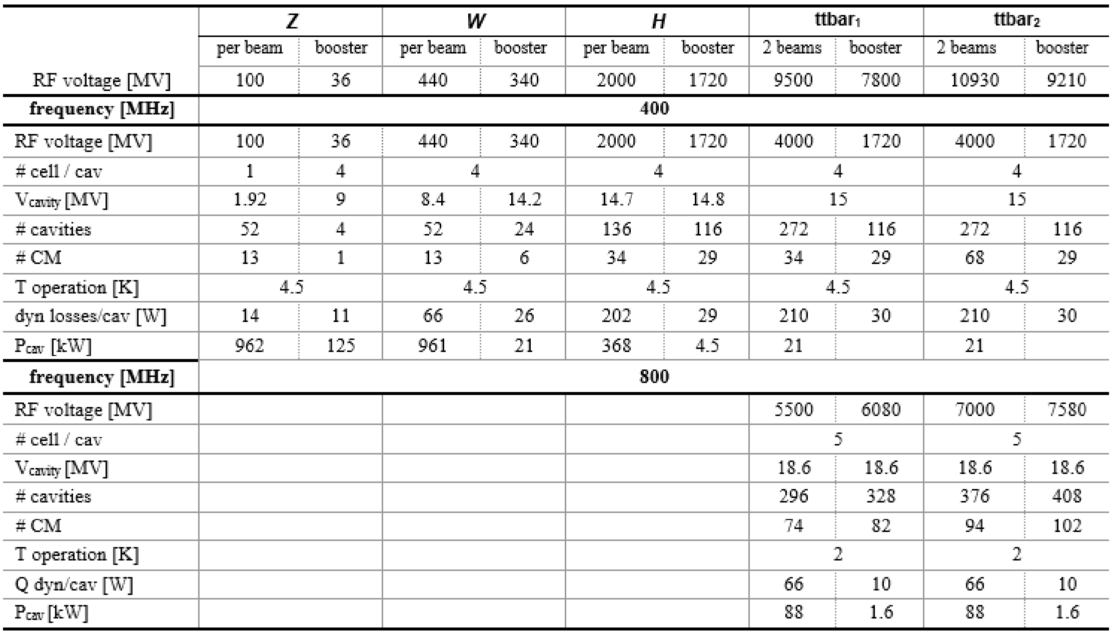


Figure 2: Schematic view of the RF unit evolution.
Top: Z => W: Single-cell cavity CM are replaced by 4-cell cavity CM
Centre: W => H: existing RF power units (triangles) are split and moved to power new cryomodules. New RF units are installed.

Bottom: New 800 MHz RF units are installed. The modest RF power per cavity allows each power distribution unit to power several cryomodules, which will be connected to form long cold segments.

Table 2: Detailed RF configuration of each machine and booster ring



	Z		***W***		***H***		**ttbar$_1$**		**ttbar$_2$**	
	per beam	booster	per beam	booster	per beam	booster	2 beams	booster	2 beams	booster
RF voltage [MV]	100	36	440	340	2000	1720	9500	7800	10930	9210
frequency [MHz]	**400**									
RF voltage [MV]	100	36	440	340	2000	1720	4000	1720	4000	1720
# cell / cav	1	4	4		4		4		4	
V_{cavity} [MV]	1.92	9	8.4	14.2	14.7	14.8	15		15	
# cavities	52	4	52	24	136	116	272	116	272	116
# CM	13	1	13	6	34	29	34	29	68	29
T operation [K]	4.5		4.5		4.5		4.5		4.5	
dyn losses/cav [W]	14	11	66	26	202	29	210	30	210	30
P_{cav} [kW]	962	125	961	21	368	4.5	21		21	
frequency [MHz]	**800**									
RF voltage [MV]							5500	6080	7000	7580
# cell / cav							5		5	
V_{cavity} [MV]							18.6	18.6	18.6	18.6
# cavities							296	328	376	408
# CM							74	82	94	102
T operation [K]							2		2	
Q dyn/cav [W]							66	10	66	10
P_{cav} [kW]							88	1.6	88	1.6

2.12.8 The booster ring

Beside the collider rings, a fast repetition rate booster [13] of the same size must provide beams for top-up injection at collision energy to sustain the extremely high luminosity. The booster's rated voltage corresponds to the energy loss per turn via synchrotron radiation emission. The RF configuration of the booster ring for each running step is shown in Table 2. In order to optimize the cryogenic system and distribution, it is proposed to use the same technology as for the collider-ring itself. The relatively modest duty cycle of the booster (~10%) offers the possibility to use compact RF power systems.

The low beam loading allows for multi-cell cavities at all energies and for a staged installation distributed between all winter shutdowns.

2.12.9 Summary

We have presented a baseline scenario for gradual evolution of the FCC-ee complex by step-wise expansion and reconfiguration of the superconducting RF system. This scenario matches the latest FCC-ee parameter and timeline. While a 400 MHz RF system for the Z, W, H and FCC-hh maximizes the re-use of the existing hardware, a hybrid 400/800 MHz system offers the best perspectives for the highest energy ttbar machine, in terms of cost, diversity of technology and integration constraints. Each of the energy stages requires extensive preparatory and pre-installation work to be carried out within the available short time frame. Although it is deemed to be feasible, the management and organization of the shutdown workload remains a major challenge.

2.12.10 **Acknowledgments**

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