SRF FOR FUTURE CIRCULAR COLLIDERS

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Abstract

The future circular colliders (FCC) will require superconducting RF (SCRF) systems for the proton-proton, electron-positron and lepton-hadron modes of the collider operation. The SCRF systems will accelerate the protons beams to 50 TeV and the lepton beams from 45.5 to 175 GeV in a staged approach with a possible 60 GeV energy recovery linac for the lepton-hadron to option as an intermediate step. The expected stored beam currents in some modes exceed 1 A with very short bunch lengths. A first conceptual design of the FCC RF system is proposed along with highlights of specific R&D topics to reach the design performance. Challenges related to RF structure design, intensity limitations due to beam loading, RF powering and higher order modes are addressed. Synergies between the different collider modes and the present LHC are identified.

INTRODUCTION

The scope of the FCC design study phase can be highlighted into three main categories [1]:

- FCC-hh: A 50 TeV proton-proton collider as a long term goal
- FCC-ee: A 45-175 GeV e^+e^- collider as an intermediate step
- FCC-he: Integration study to include an electron ring between 60-200 GeV electrons to collide with the 50 TeV protons.

A schematic of the foreseen 80-100 km FCC ring is shown in Fig. 1. A first conceptual design of the RF system for the different collider modes is proposed with highlights on specific SCRF challenges and related R&D to reach the design performance. Synergies between the different options are identified.

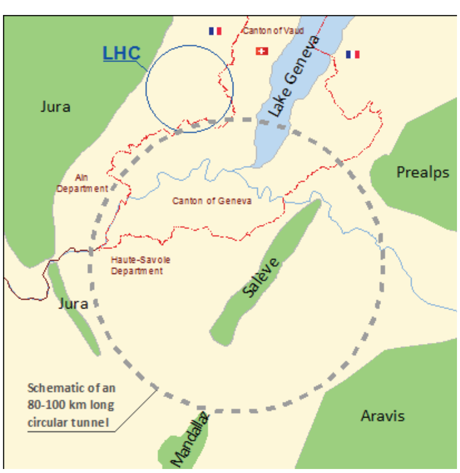

Figure 1: Schematic of the 80-100 km future circular collider tunnel at CERN (courtesy FCC study group).

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SUPERCONDUCTING RF FOR FCC-HH

The FCC-hh collider will become the new energy frontier with a potential for direct discovery of new particles and explore physics well beyond the LHC. The primary function of the RF system for the FCC-hh would be to efficiently capture of up to 0.5 A (10600 bunches) at proposed energy of 3.3 TeV [2], accelerate to 50 TeV in approximately 30 minutes and store the colliding beams at 50 TeV for several hours. The high beam current and the uneven filling scheme, including the long abort gap, will result in transient beam loading that will strongly modulate the voltage vector. The situation is almost identical to that of the present LHC which employs 8 SCRF cavities at 400 MHz with high power RF to compensate for the strong reactive beam loading. Superconducting RF cavities with the large apertures and high stored energy are ideally suited to minimize the transient beam loading and thereby the required RF power for the proposed design voltage. To limit the sharp changes in the demanded power from the RF amplifier and keep the voltage vector constant, a 1/2-detuning scheme [3] similar to the LHC is appropriate.

Table 1: Relevant parameters for the FCC-hh option. The detailed parameter list can be found in Ref. [2].

	Unit	LHC	HL-LHC	FCC-hh
Energy	TeV	7.0	7.0	50.0
p/bunch	10^{11}	1.15	2.2	1.0 (0.2)
Beam current	A	0.55	1.1	0.51
Bun. Spacing	ns	50-25	25	25 (5)
St. Energy	MJ	392	694	8400
SR loss/turn	MeV	7×10^{-3}		3.9
RF Frequency	MHz	400		
Harmonic #		35640		133689
Total voltage	MV	16		32
RF power	kW	300	450	340
Peak Lumi	10^{34}	1.0	8.4	5-29

In this scheme, the cavity detuning is set to value where the RF power required is equal in the segments with and without beam. Only the sign of the generator phase is flipped for the two cases. This ensures that the required instantaneous peak power is kept almost constant. Fig. 2 shows the power requirements as a function of Q_L for injection and top energy parameters assuming the present $\frac{1}{2}$-detuning scheme. The detuning values and the optimum Q_L are listed in Table 2. The detuning at injection is beyond the the revolution frequency and and at top energy is quite close.

Table 2: Detuning, optimum coupling and the required RF power for injection and top energy for FCC-hh option.

	Unit	Injection	Flattop
Energy	[TeV]	3.3	50.0
Total Voltage	[MV]	16.0	32.0
N. of cavities		16	
$Q_{L,opt}$		4.4×10^4	8.5×10^4
Detuning	[kHz]	-4.6	-2.28
RF Power/cav	[kW]	130	325
L. Emittance	[eVs]	2.5	10.0
Bucket Area	[eVs]	6.03	33.2
Sync Frequency	[Hz]	2.93	2.07
Bunch length	[ns]	1.2	1.0
σ_E	[10^{-4}]	0.1	0.4

Very strong feedback will be essential to lower the effective impedance seen by the beam to cure strong instabilities arising from the fundamental mode. A minimum stable voltage is required for optimum bucket filling factor to control losses and ensure stability. Fig. 3 shows the bunch length as a function of emittance for different energies and total RF voltages. During injection, it is vital to preserve the regular bucket spacing to minimize transfer losses between injector and FCC ring. Assuming an maximum injected emittance of 2.5 eVs at 3.3 TeV, 16 MV total voltage would be sufficient to keep the bunch length to 1.2 ns with a filling factor of approximately 0.7. The longitudinal emittance has to be increased by controlled blow up to 10 eVs (Fig. 3) while increasing the voltage to 32 MV to reach the nominal bunch length of 1 ns (see Table 1). The matched voltage voltage can be lower but the higher capture voltage will reduce the transient beam loading at the expense of longitudinal emittance dilution during the capture process. The required RF power per cavity at the optimum coupling is small and the low Q_L will help account for energy and phase errors during the injection process.

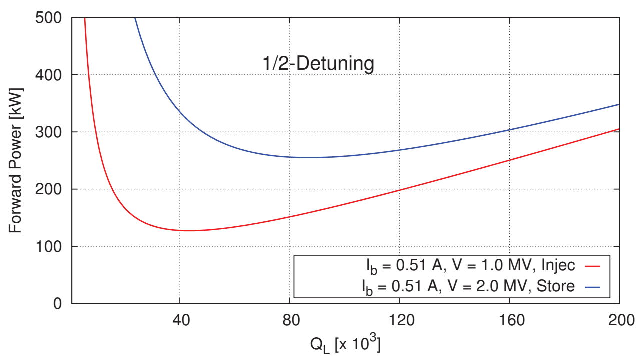

Figure 2: Forward power at injection (top) and flattop (bottom) operated in the $\frac{1}{2}$-detuning scheme for FCC-hh beam parameters and cavity voltage of 2.0 MV.

The energy ramp from 3.3 TeV to 50 TeV is assumed to be approximately 30 min which implies a ramp rate of 9 MeV/turn. This is almost three times the energy lost at top energy due to synchrotron radiation and therefore the most challenging for the RF system. Parasitic losses were assumed to be 800 W assuming a loss factor 0.01 V/pC per cavity. The additional RF power of 4.5 MW must be supplied to the beam to ramp at the specified rate or alternatively increase the ramp time. For example, this translates into an additional RF power of 280 kW/cavity assuming 16 cavities operating at 2.0 MV. Fig. 4 shows the RF power per cavity as a function of beam energy at the optimum coupling. Three different voltages are plotted assuming a total of 16 cavities per beam. At the end of ramp with the 2 MV per cavity, the RF power reaches beyond 500 kW. The required voltage for stability and beam losses during the energy ramp is not discussed. Additional voltage of up to 50 MV might be necessary to minimize losses and preserve stability during the proposed ramp rate. An optimum voltage program during the energy ramp can be developed to minimize the power and any abrupt excursions.

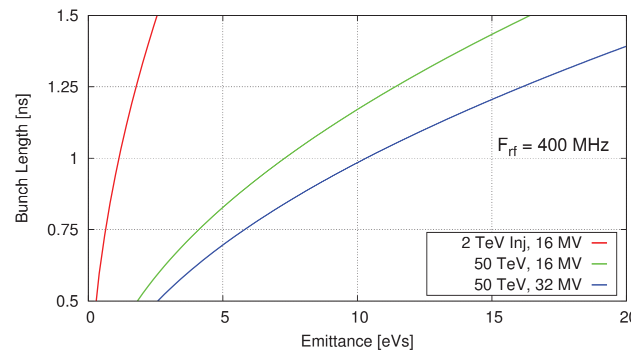

Figure 3: The bunch length as a function of longitudinal emittance for the injection voltage of 16 MV and for flattop voltages of 16-32 MV.

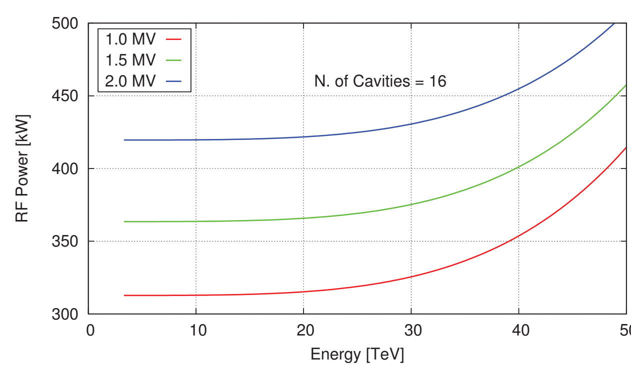

Figure 4: RF Power at the optimized Q_L during the energy ramp of 30 min including synchrotron radiation and parasitic losses. The cavities are operated at $\frac{1}{2} - detuning$.

At top energy, the energy loss due to synchrotron radiation is 3.9 MeV/turn with a required RF power of 325 kW (see Table 2). The threshold for loss of Landau damping as a function of bunch length is shown in Fig. 5 assuming an impedance budget similar to that of the LHC ($ImZ/n = 0.1\Omega$) with a margin of factor of 2 [4]. At a total voltage of only 16 MV, the stability threshold is already

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sufficient. With 32 MV provides another factor 2 for the corresponding emittance at the nominal bunch length of 1 ns. Continuous longitudinal blowup will be necessary during the physics fill to counteract the shrinking of the emittance from synchrotron radiation to ensure stability [4].

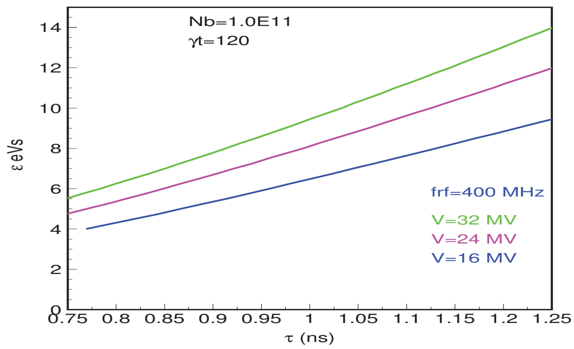

Figure 5: Voltage required for single bunch stability due to loss of Landau damping as a function of bunch length [4].

The RF power chain including the fundamental power couplers, RF amplifiers, circulators, RF loads should be designed to cope with approximately 500 kW. This is primarily driven by the need for the fast energy ramp while allowing for adequate margin to accommodate for future increase in beam currents at top energy. It is feasible to reduce this margin down to 300 kW (LHC specification) by increasing the ramping time by approximately factor 2. Another possibility is use the full detuning scheme [5].

Fig. 6 shows the available RF power sources in the frequency range of interest. At the 400 MHz, CW power sources at 500 kW is feasible with conventional technology. A good promise from solid state amplifiers to be developed in the next two decades. Higher frequencies, on top of the issues related to beam loading, requires significant R&D on high power RF sources.

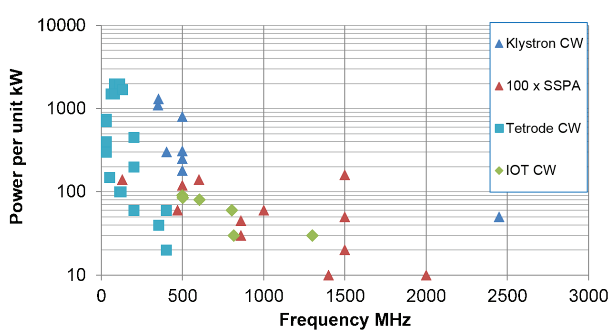

Figure 6: Available RF power sources as a function of frequency. Note the solid state power is scaled up by 100 (courtesy E. Montesinos).

SUPERCONDUCTING RF FOR FCC-EE

The FCC-ee is considered as an intermediate step with the goal of providing high luminosity e^+e^- collisions between 91-350 GeV center of mass. For FCC-ee, the range of beam energies and beam current is large for each mode of operation scaled to maximum synchrotron radiation power to 50 MW [6]. The radiation loss is schematically depicted in Fig. 7 as a function of energy for the FCC rings and compared to the existing LHC/LEP ring. The two limiting scenarios for the RF system design are posed by the Z-nominal at low energy but high beam current of 1.45 A and the $t\bar{t}$-nominal with a radiation loss reaching 7.55 GeV per turn.

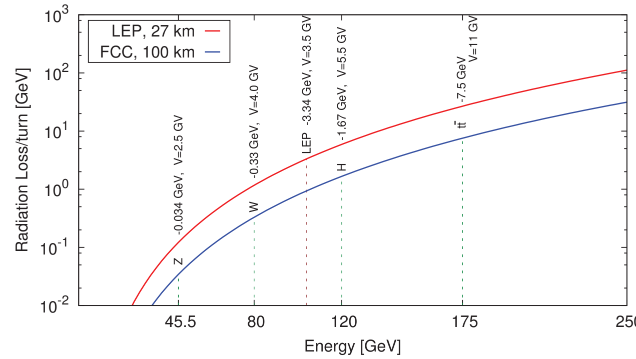

Figure 7: Radiation loss/turn for the FCC rings as a function of beam energy with the specific FCC-ee operation points.

Some relevant parameters for the different energy options are listed in Table 3. A detailed parameter list can be found in Ref. [6]. A RF staging in approximately three phases to increase the available voltage is proposed to reach the final energy of 175 GeV with the maximum voltage reaching 11 GV [6–8]. Alternate scenarios for RF staging to optimize the overall size of the accelerating structure are also under investigation [9]. Fig. 8 shows a selected set of SC cavity types already used in high current storage rings. For large RF systems at low frequencies, Niobium films on Copper cavities have proven to be a reliable option notably from the LEP experience with a maximum operating voltage of 3.5 GV.

Figure 8: A select set of SCRF cavities already used in high current storage ring including LEP (top), LHC, CESRB and KEKB (bottom).

A preliminary design of a 400 MHz cavities from one to four cells were considered for comparison (see Fig. 9). The final number of cells per cavity will be determined after a

Table 3: Relevant beam and RF parameters for the FCC-ee option. The detailed parameter list can be found in Ref. [6, 7].

	Unit	LEP	Z	W	H	T
Energy	[GeV]	104	45.5	80.0	120	175
Beam current	[mA]	3.04	1450	152	30	6.6
Bunch length	[mA]	11.5	2.56	1.49	1.17	1.49
SR loss/turn	[GeV]	3.34	0.03	0.33	1.67	7.55
RF Frequency	[MHz]	352	400			
Total voltage	[GV]	3.5	2.5	4.0	5.5	11.0
Peak Lumi	$[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.012	27-247	35.0	7-11	1.8

detailed analysis on the overall efficiency for acceleration, RF power, HOM losses and layout constraints. Alternative multi-cell cavities with intermediate damping cells are also being investigated [10]. Table 4 lists some relevant parameters for the different numbers of cells along with a five-cell cavity at 800 MHz as a potential alternative excluding the high current option.

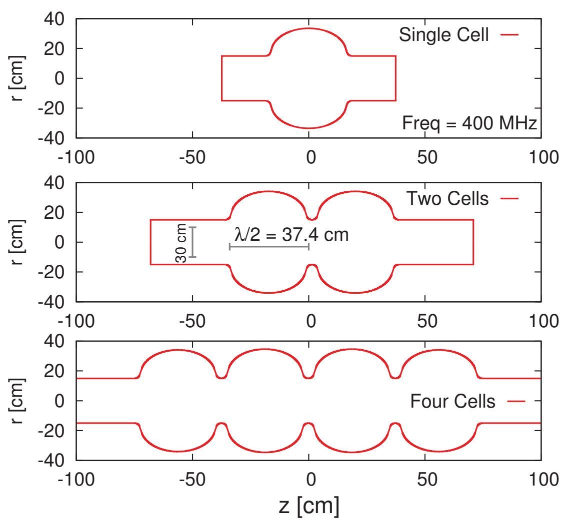

Figure 9: Preliminary design of 1, 2 and 4-cell options considered for the FCC-ee ring.

A first layout for the FCC-ee RF sections include 10 symmetric straight sections with a total available length of 1.2 km [8]. A schematic of the three different cell combinations to compare to an effective 4-cell LEP like layout at 400 MHz cavities is shown in Fig. 10. A single cell layout in a cryomodule is approximately factor 2 or worse in terms of "real estate gradient". A good compromise is a 2+2 cells hybrid which recovers some efficiency while being more compatible for higher currents which will become evident in the later sections.

The statistics from LEP cavities (4-cell, 352 MHz) suggest an accelerating gradient of 7.2 MV/m during the operation at 100 GeV [11]. A 30% increase is considered assumed as modest improvement for the FCC-ee and considered as a reference for options considered for the cavities. The RF characteristics of a 400 MHz single cell, a LEP equivalent 4-cell and a 2-cell are listed in Table 4. At the operating gradient, the Q_0 of 3×10^9 was realized at LEP with Nb-Cu sputtered cavities. This is assumed as the minimum

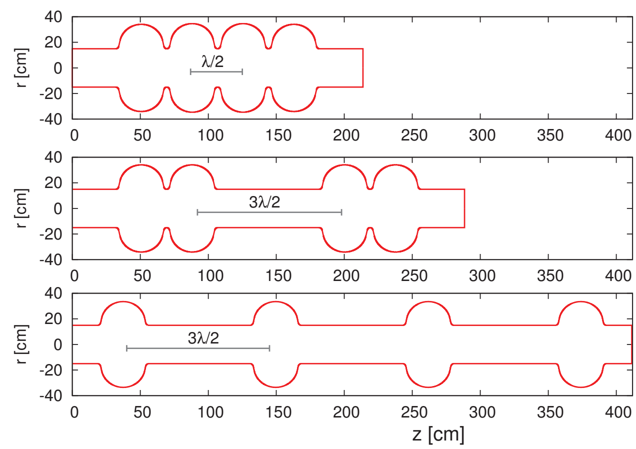

Figure 10: Schematic of the different cavity layouts to compare to an effective 4-cell LEP cavity at 400 MHz.

Q_0 for estimating the dynamic losses from Nb-Cu sputtered cavities in Table 5. The large range of beam currents implies

Table 4: Relevant RF characteristics for the one, two and four cell geometries at 400 MHz. A five-cell 800 MHz cavity is listed for comparison. The nominal operating temperature is assumed to be 4.5 K with Nb-Cu sputtered cavities.

	1-Cell	2-Cell	4-Cell	5-Cell
Freq. [MHz]	400			800
Act. Length [m]	37.4	74.8	150	93.5
Voltage [MV]	3.75	7.5	15.0	11.0
Ep/Ea [MV/m]	3.1	3.3	3.3	2.6
Bp/Ea $[\frac{\mathrm{mT}}{\mathrm{MV.m}}]$	4.2	4.7	4.7	4.9
R/Q [Ω]	87	169	310	393
Geom Factor [Ω]	297	297	297	283
Q_0	3×10^9			1.10^9
Rs [nΩ]	99	99	99	280
Cav. losses [W]	53	124	253	508

a large difference in the reactive beam loading which has to be compensated by appropriate cavity detuning. Fig. 11 shows the detuning as a function of the different operation points. The limiting scenario is clearly the Z-nominal with a very large detuning of -13.6 kHz which is more than 4 times the f_{rev}. For each of the energy options, the RF power is plotted as a function of the Q_L with the appropriate detuning and considering the synchrotron radiation losses at the

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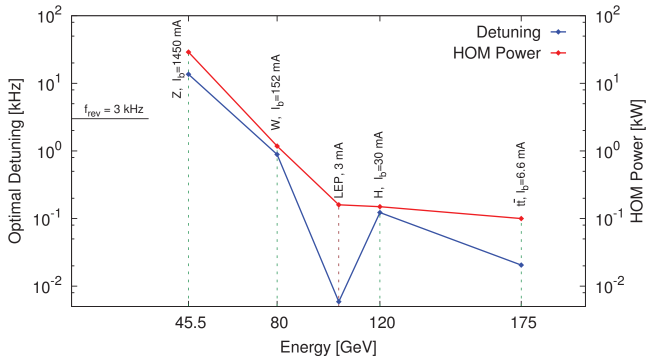

Figure 11: Optimal detuning frequency (left) and the estimated HOM power (right) as a function for the different operation energies.

respective energies (see Fig. 12). The optimum Q_L and the minimum power along with other relevant RF parameters is listed in Table 5. The 2-cell option is used as the baseline for the purpose of further calculations. The input power is dominated by the the Z-nominal with a Q_L that is about a factor 4-10 smaller than the other options. Some optimization on the beam current and the cavity voltage could be performed to avoid the use of variable coupler or operate at the expense of higher RF power.

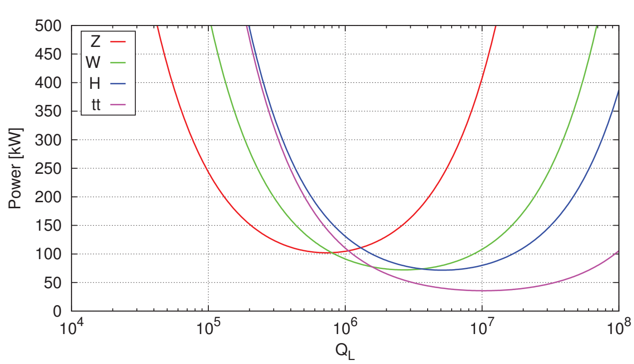

Figure 12: Forward power as a function of cavity coupling (Q_L) for the different FCC-ee options.

The large current at the Z-nominal also induces significant parasitic losses. This is also depicted in Fig. 11 with an assumed loss factor of 0.7 V/pC for a a 2-cell cavity at 400 MHz. In the limiting case (Z-nominal), the HOM power reaches 29 kW for the assumed parameters. Such level of HOM powers are even beyond the limit of the broadband ferrite absorbers successfully used in high current B-factories (see Fig. 13). Loop couplers used in the LHC are rated to a level of 1 kW (see Fig. 13) and could be used for the other options without considering the Z-nominal.

The large detuning likely falls out of the RF system bandwidth, potentially leading to strong coupled bunch instabilities which needs further investigation. The detuning is proportional to the $(R/Q).\omega$ and so is the HOM power leading

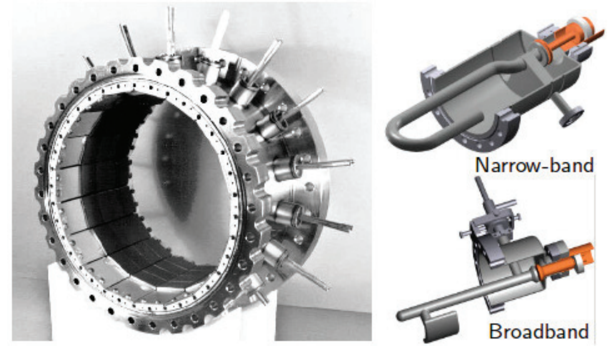

Figure 13: Broadband room temperature ferrite based HOM couplers (left). LHC type broadband and narrow band HOM couplers at 4.5 K (right) [12].

to a frequency choice of 400 MHz which allows to minimize them simultaneously due to the large apertures and high stored energy. One possible cure to decrease the HOM power per cavity would be to increase the bunch lengths. Fig. 14 shows the longitudinal loss factors as a function of bunch length for single cell cavities for three frequencies. The ultra-short bunch length coupled with the high bunch currents leads to large HOM power even with conservative 400 MHz and fewer number of cells per cavity. With higher frequencies, multi-cell cavities become prohibitive and therefore less efficient.

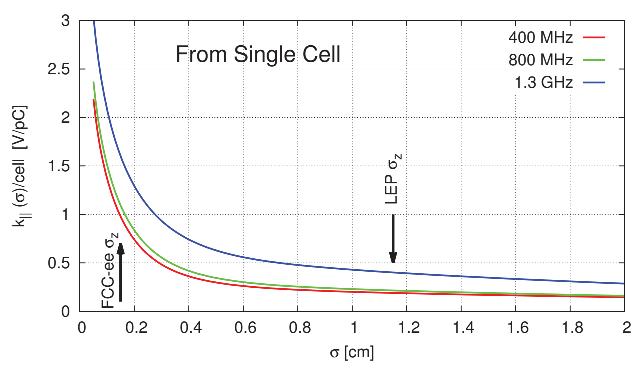

Figure 14: Longitudinal loss factor as a function of bunch length for three different frequencies.

SUPERCONDUCTING RF FOR FCC-HE

The main goal is to reach a luminosity of $1\times10^{34} cm^{-2} s^{-1}$ for the electron-proton collisions which would allow to probe the Higgs self coupling [13]. FCC-he study presently is only considered to investigate integration aspects for the electron ring between 60-200 GeV electrons to collide with the 50 TeV protons. The first detailed study on very high energy electron-proton collisions was on the LHeC [13]. Based on this study, the primary option for the FCC-eh option is to collide 60 GeV electrons using the baseline energy recovery linac (ERL) of LHeC to collide with 50 TeV protons (see Table 6). The second option to use the FCC ring to accelerate the electrons require a detailed integra-

Table 5: Preliminary RF cavity parameters for the FCC-ee option.

	Unit	LEP	Z	W	H	T
RF Frequency	[MHz]	352	400			
# of Cell	-	4	2			
RF Voltage	[MV]	12.0	3.57	5.71	7.85	7.85
# of Cavities	-	288	700			1400
Optimum detuning	[kHZ]	-5.9	-13.6	-0.89	-0.12	-0.02
$Q_{L,opt}$	$[10^6]$	0.9	0.75	2.7	5.3	10.3
RF power	[kW]	35	100	72	72	36
HOM power	[kW]	0.16	29.1	1.18	0.15	0.1

tion study to investigate the feasibility of co-existing e^+e^- and hh rings. Only the 60 GeV ERL option is discussed.

Table 6: Relevant parameters for the FCC-he and electrons accelerated with a LHeC-ERL. The RF power for the ERL assumes 20 Hz detuning with $Q_L = 3 \times 10^7$.

	Unit	LHeC ERL	LHC Ring Protons	FCC Ring Protons
Energy	TeV	0.06	7.0	50
Cur, I_{DC}	A	0.15	1.1	0.51
RF Freq.	MHz	801.58	400.79	
Volt/turn	MV	20000	16	32
# Cavities		1069	8	16
RF Power	kW	25.0	300	340

A 60 GeV superconducting energy recovery linac (SC-ERL) is presently considered as the baseline for a future electron-hadron collider, the LHeC [13]. Fig. 15 shows a schematic of the 6-pass ERL with three acceleration and three deceleration passes. A sketch of a 4-cavity cryomodule assumed as the baseline fundamental unit of the linac is shown in Fig. 15. The details of the 5-cell cavity design can be found in Ref. [14]. The nominal gradient is assumed to be 18.7 MV/cavity.

Due to the large synchrotron radiation especially at the high energy passes (2.88 GeV/pass), the energy recovery can only be efficient up to to 96% (see Fig. 16). This corresponds to 73.6 MW of beam power to be replenished over the 6-passes to allow the main linac to operate in a "zero beam-loading" energy recovery mode. Alternatively, the input power for each cavity could account for the radiation loss by roughly doubling the RF power. An additional RF power of 15 MW is required to maintain the cavity voltage at the proposed $Q_L = 3 \times 10^7$. The cryogenic losses are likely dominated due to the dynamics losses from the cavity which amount to 32 kW at 2 K ($Q_0 = 3 \times 10^{10}$). This is an additional 25.6 MW using a conversion factor of 800 to estimate the wall plug power. The total power is already over the 100 MW limit without accounting for other parasitic and static losses. It should be noted that an ERL tunnel either in the present LHC or in the FCC ring would immediately reduce the synchrotron radiation power by approximately factor 3 to 10 respectively.

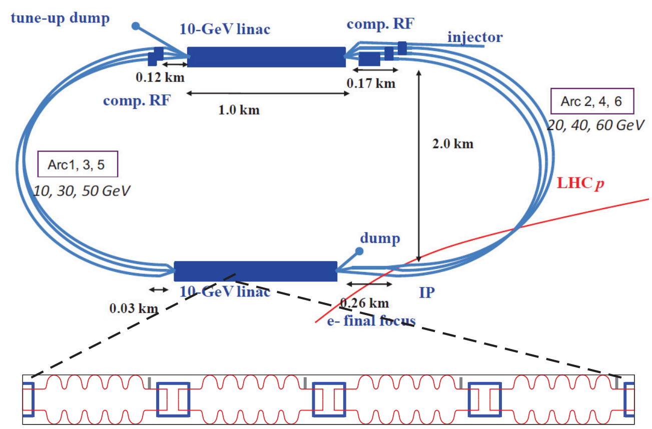

Figure 15: Schematic of the 60 GeV LHeC three-pass energy recovery linac [13]. Two parallel 10 GeV linacs are used to accelerate the electrons to 60 GeV in 3-passes for which a four 5-cell cavity-cryomodule is assumed as the fundamental unit.

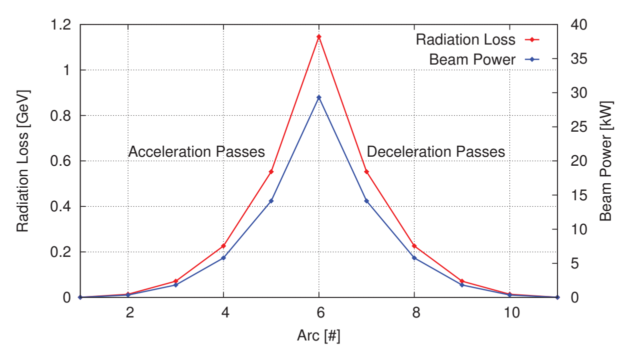

Figure 16: Energy loss due to synchrotron radiation and the corresponding beam power as a function of the passes in the 60 GeV LHeC-ERL.

RF power sources at 800 MHz using IOTs at 60 kW was successfully commissioned in the SPS ring for the 3^{rd} harmonic system. A chain of 8-IOTs powering two cavities is presently in operation. This would be adequate for the LHeC-ERL main linac if operated in the full energy recovery mode. If loss of synchrotron radiation is also to be compensated by the main linac, two IOTs would then be required to power a single cavity. An optimization is required to determine the most efficient compensation method.

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R&D ASPECTS

The R&D aspects for SC RF are summarized for the three FCC options under considerations. The use of the SCRF cavities for high current and high energy proton machines was validated during the Run I experience of the LHC. It is also confirmed the power bottlenecks in the RF chain for increasing beam currents. For the FCC-hh option, a similar type of RF system with approximately two times the present LHC system is sufficient. An upgrade of the RF chain from the amplifiers, circulators, loads and the fundamental power couplers to 500 kW will enable to cope with both the transient beam loading and a fast energy ramp. Improvement in the cavity Q_0 of the thin films and improved cryomodule designs from the ongoing R&D programs at CERN will be beneficial in further reducing the cryogenic consumption. A 2^{nd} harmonic system might inevitably become necessary to provide additional Landau damping to ensure beam stability.

The most challenging of the RF system requirements come from the e^-e^+ rings where compensation of synchrotron radiation and extraction of HOM power reach unprecedented levels. The opposing constraints of high current and high energy in the different FCC-ee options requires R&D on several aspects. Based on the LEP experience, an operating FCC-ee gradient of approximately 15 MV/m is seen as a modest increase. However, this would require that the cavities stably perform well above this gradient. More importantly, the cavity Q_0 should aim for an increase from the LEP performance to approximately 5×10^9 at 4.5 K to minimize the cryogenic losses. Novel materials and coating techniques require special attention to go beyond the present known limits. In the high current case, the FCC-ee will reach a regime where the parasitic beam losses become a substantial part of the input power fed into the cavity. Therefore, the design of the couplers becomes very challenging and similar to that of the input couplers thus playing a driving role in the cavity design. The choice of the frequency, number of cells and novel damping schemes require a substantial R&D to cope with the high HOM power while simultaneously maintaining the high efficiency to maintain the gap voltage. The cavity fundamental and higher order impedance will be the driving component for the instabilities which require strong feedback systems to counteract. Some preliminary studies on the instabilities can be found in Ref. [15]. Appropriate staging will be necessary to progressively increase the energies.

For the FCC-he ERL option with 800 MHz five-cell cavities, a significant reduction in the cryogenic power can be achieved by targeting towards a Q_0 in the 10^{11} range. Coupled with a longer tunnel to reduce the synchrotron radiation losses, the overall power requirements can be substantially reduced to a few 10's of MW instead of the present 100+ MW. Other challenges related to the high efficiency of the ERL operation at high currents should be addressed in a staged demonstration of the different technologies targeting a high Q_L operation to fully benefit from the ERL. It is considered as one of the options for top up injection into the main FCC ring for efficient luminosity production [16].

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