

# LAYOUT AND PERFORMANCE OF THE FCC-ee PRE-INJECTOR CHAIN

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## Abstract

The Future Circular  $e^+e^-$  Collider pre-injector chain consists of a 6 GeV S-Band linac, a damping ring at 1.54 GeV and pre-booster ring to reach 20 GeV for injection to the main booster. The electron and positron beams use the same accelerator chain alternatively. The  $e^-$  beam is generated from a novel low level RF-gun providing 6.5 nC charge at 11 MeV with 0.5 micron geometric emittance. The  $e^+$  beam is produced by the impact of a 4.46 GeV  $e^-$  beam onto a hybrid target, accelerated in the linac up to 1.54 GeV, and injected to the damping ring for emittance cooling. Simulations on the performance of the DR are presented for reaching the required equilibrium emittances at the required damping time. As an alternative option, a 20 GeV linac is considered utilising C-Band cavities and simulations studies have been undertaken regarding the beam transport and transmission efficiency up to that energy.

## INTRODUCTION

The Future Circular Collider's luminosity frontier the FCC-ee will require very high charge flux and a very fast top-up injection to keep the luminosity around  $2 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$  throughout the operation at the resonance energy of the  $Z$  boson. There will be 4 operational modes of the FCC-ee, namely  $Z$ ,  $W$ ,  $H$ , and  $t\bar{t}$  operations. Amongst those, the  $Z$  mode is the main focus of the pre-injectors since it requires the highest charge with the lowest equilibrium emittance compared to the other 3 modes. Therefore, once the  $Z$ -operation requirements are satisfied, the other parameters for the other collider flavors will be within the reach. The updated baseline parameters of the FCC-ee modes can be found in [1], and some  $Z$ -pole parameters are presented in Table 1.

Table 1: Baseline Parameters on the  $Z$  Pole

parameter	value
beam energy	45.6 GeV
no. bunches / beam	16640
bunch population	$1.7 \times 10^{11}$
horiz., vert. emittance	270, 1 pm

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The main layout to provide the necessary beams consists of a linac up to 6 GeV, a damping ring at 1.54 GeV, then a pre-booster synchrotron of 6-20 GeV [2], then 98 km top-up booster [3] to accelerate from 20 GeV up to the final energies. The DR will cool the emittance of both  $e^-$  and  $e^+$  beams. As an alternative to the pre-booster, a longer linac accelerating up to 20 GeV is being designed. The bunch population at the collider will be reached by accumulating for around 10 injections the current in every collider bunch, at each injection. For this reason,  $2 \times 10^{10}$  particles per bunch have been considered for the pre-injectors taking into account some transmission loss.

## LINAC

The normal conducting linac will be fed by two different electron sources, one will be the RF gun for low emittance  $e^-$  beam, and the second is the thermionic gun to provide higher charge for creating enough positrons by impinging on a hybrid target [4,5]. The linac consists of S-Band structures up to 6 GeV, and C-band high gradient accelerating structures between 6-20 GeV, which is the option of direct injection into the top up booster. The specifications of the accelerating structures are presented in Table 2.

Table 2: Linac Structures

Cavities	S-Band	C-Band
frequency (MHz)	2855.98	5711.96
length (m)	2.97	1.80
cavity mode	$2\pi/3$	$2\pi/3$
aperture diameter (mm)	20	14
unloaded cavity gradient (MV/m)	25	50

The wakefields in linac simulations have been included [6], together with the misalignments and offsets as their root mean square values are presented in Table 3. The Beam Position Monitor (BPM) errors tabulated are with respect to the cavity center, where one BPM is attached to the cavity entrance and another one to the exit. The preservation of emittance and charge is provided via an automatic orbit steering code. Basically, the script sets the strengths of two preceding steerers to direct the beam orbit near to the cavity centers, in order to provide cross cancellation of the kicks on the beam's tail due to wakes. The impact of misalignments is perfectly cancelled for the case of ideal BPMs. Nevertheless, the response matrix calculations are needed to be further optimised when the BPM's offset and/or accuracy are included.

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Apart from this, some simulations with different charge and randomization have been performed to study the reliability of the linac. The effect of the random misalignments was left uncorrected in the simulations, which dilutes the nominal emittance few times, yet leaves the current transmission almost intact. Actually, it can be cured in a real machine by performing a beam-based alignment [7].

Table 3: Misalignments and offsets applied to linac elements distributed as a Gaussian distribution with no truncation.

Parameter	Simulated Error
spatial injection offsets (h/v)	0.1 mm
angular injection offset (h/v)	0.1 mrad
quadrupole misalignment (h/v)	0.1 mm
cavity misalignment (h/v)	0.1 mm
BPM's misalig. w.r.t. cavity (h/v)	30 $\mu\text{m}$

### RF Gun

The RF gun is custom designed to have  $\leq 10 \pi$ .mm.mrad normalised transverse emittance with 6.5 nC of charge at 11 MeV. The charge is intentionally higher than the required one taking into account probable high charge injection for the first fill of the collider from scratch. Briefly, the RF gun is based on the parallel coupled accelerating structure [8, 9], and has permanent magnets in the irises to reduce the size and the emittance dilution. As photocathode for such high intense beam, it is planned to use material based on IrCe alloy [10, 11]. Such material provides acceptable life time with high charge extraction and high repetition rate mode.

### Linac Up to 1.54 GeV

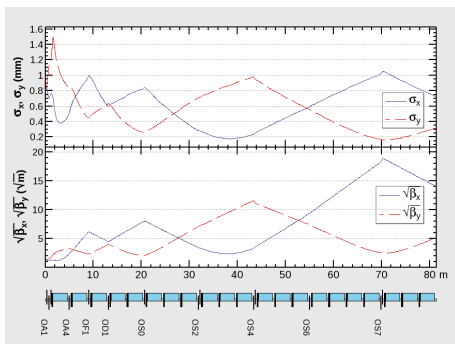


Figure 1: Optics of 1.54 GeV linac.

The low energy part of the linac starts with the beam from the RF gun at 11 MeV. The optics shown in Fig. 1 contains singlets, doublets, and triplets which are intentionally set to low gradients to reduce the impact of the kick due to the misaligned quadrupoles. This choice has brought to the results presented in Table 4.

### Linac 1.54-6 GeV

The linac at 1.54 GeV has a branching point for  $e^-$  beam cooling in the DR during  $e^-$  beam delivery to the collider.

Table 4: Some Parameters of the Linac up to 1.54 GeV

Parameter	Result
length	79.1 m
number of cavities, quadrupoles	21, 14
injected emittance (h/v)	0.35/0.5 $\mu\text{m}$
average extracted emit. (h/v)	6.4/5.0 nm
transmission for 3.2 nC	100%

The usage of DR is to cure the probable emittance dilution due to misalignments and space charge. Electrons will be stored for 25 ms in the DR that time is adequate to cool the emittance dilution even if it would be 100 times of the no blow-up emittance. Thus, the injected emittance to 1.54 GeV linac is determined by the beam cooled in the DR, which is then transferred back to the linac via the turnaround loops and bunch compressor [12].

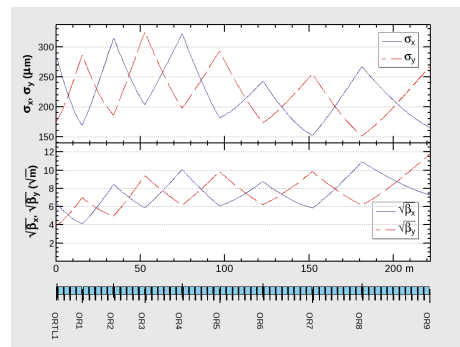


Figure 2: Optics of 1.54-6 GeV linac.

Some parameters of the 1.5-6 GeV part of the linac are presented in Table 5; optics are shown in Fig. 2. In the 6 GeV linac option, the beam will be injected to a pre-booster damping ring or in the Super Proton Synchrotron (SPS) which would be slightly modified for the FCC-ee [2]. The injected geometric emittance in the SPS can be as big as 10/100 nm (h/v), which leaves a very large safety margin to the linac for the extracted emittance.

Table 5: Some Parameters of the 1.54-6 GeV Linac

Parameter	Value
length	221.9 m
injection-extraction energy	1.54 GeV-6 GeV
injected emittance (h/v)	1.9/0.4 nm
average extracted emit. (h/v)	1.1/0.4 nm
transmission for 3.2 nC	100%

### Linac 1.54-20 GeV

The 20 GeV linac optics presented in Fig. 3 is not just an extended version of the S-band linac, but it is re-optimised in order to increase the transmission. The length of the drift spaces (i.e.  $L$ ) between the cavities and steerers are increased in order to reduce the impact of BPM offset ( $\sigma_{BPM}$ ) which is proportional to  $\sigma_{BPM}/L$ . Consequently, the emittance di-

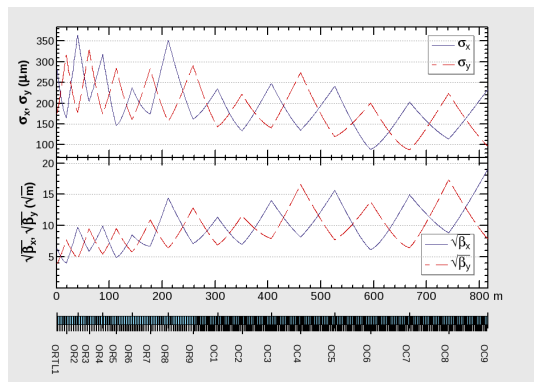


Figure 3: Optics of 1.54-20 GeV linac. Notice that the C-band structures starts after QR9.

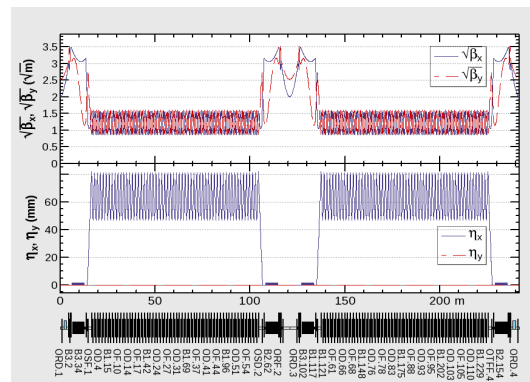


Figure 4: Damping ring optics.

lution is decreased, however it nearly meets the requirement of the booster which is 3.4/0.3 (h/v) for 15  $\sigma$  acceptance. Some parameters of the high-energy linac are presented in Table 6.

Table 6: Some Parameters of the 1.54-20 GeV Linac

Parameter	Value
length	858 m
injection-extraction energy	1.54 GeV-20 GeV
injected emittance (h/v)	1.9/0.4 nm
average extracted emit. (h/v)	4.0/0.3 nm
Transmission for 3.2 nC	92%

### 1.54 GeV DAMPING RING

The DR has been updated [13] to accommodate the changes in the FCC-ee baseline. The 200 Hz repetition has led us to host 5 trains, each with 2 bunches per RF pulse. Concerning the longitudinal wakefields in the linac, the bunch to bunch spacing is chosen as 60 ns [14]. 2 bunches per RF pulse in the linac will become a train in the DR. All in all, 5 trains spaced by 100 ns due to kicker rise/fall time, and bunch-to-bunch spacing of 60 ns in linac have resulted in designing a damping ring with at least a perimeter of 240 m (i.e.  $\sim 800$  ns for  $\beta_{rel} = 1$ ). The  $e^+$  beam used is simulated from the conversion target up to the end of the linac [15]. This  $e^+$  beam has been injected into the DR, where its optics shown in Fig. 4, for a store time of 45 ms, which stems from the interleaved injection/extraction of the 5 trains. Consequently, the beam profile of the ideal machine is shown in Fig. 5, and the results are tabulated in Table 7, in which no beam loss has seen for an aperture of 15 mm.

### CONCLUSIONS

The emittance and charge requirements of the all FCC-ee modes can be met with perfect transmission and a factor of ten safety margin in transverse emittance at 6 GeV. In addition, an alternative full-energy 20 GeV linac is also being studied. The orbit steering for this linac may be improved via dispersion free steering and BNS damping [16], to reduce

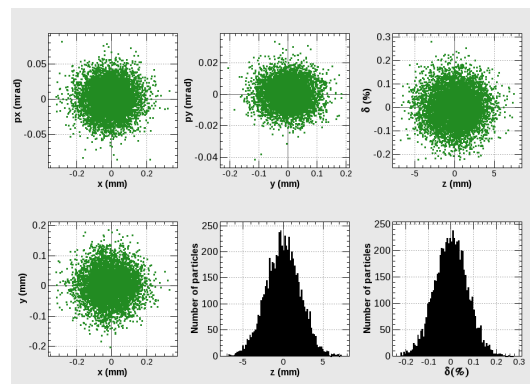


Figure 5: Positron tracking in the ideal DR for 45 ms.

Table 7: 1.54 GeV Damping Ring Parameters

parameter	value
circumference	241.8 m
FODO cell phase advance (h/v)	69.5/66.1 deg
betatron tune (h/v)	24.19/23.58
natural emittance (h/v)	1.16/- nm
damping time (h/v)	10.6/11.0 ms
bending radius, wiggler field	15.5 m, 1.8 T
energy loss per turn	0.22 MeV
RF voltage, frequency	4 MV, 400 MHz
transv., long. acceptance	22.4 $\mu$ m, 14.7 mm
energy spread	$7.09 \times 10^{-4}$
bucket height	8.0 %
energy acceptance	$\pm 7.8$ %
injected emittance (h/v/l)	1.29/1.22/75.5 $\mu$ m
extracted emittance (h/v/l)	1.81/0.37 nm/1.52 $\mu$ m

the emittance blow-up, and to increase the already quite good transmission of 92 %.

The DR requires misalignment and instability studies, such as intrabeam scattering and coherent synchrotron radiation. The  $\pm 7.8\%$  energy acceptance of the DR may be reduced to  $\pm 3.5\%$  by lowering voltage in order to increase bunch length so that the possible emittance dilution due to CSR is avoided. For this reason, we may either collimate the incoming  $e^+$  beam at the end of the linac at  $\pm 3.5\%$  or deploy an energy compressor.

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