ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP002

LINAC AND DAMPING RING DESIGNS FOR THE FCC-ee

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Abstract

We report the design of the pre-injector chain for the Future Circular e^+ e^- Collider (FCC-ee) system. The electron beam from a low-emittance RF gun is accelerated by an S-band linac up to 6 GeV. A damping ring at 1.54 GeV is required for emittance cooling of the positron beam. The intermediate energy step from the exit of the S-band linac at 6 GeV to the 20 GeV injection energy of the top-up booster can be provided by the modified Super Proton Synchrotron (SPS), serving as a pre-booster ring (PBR). An alternative option to reach 20 GeV energy would be to extend the S-band linac with a C- or X-band linac. An overall cost optimisation will determine the choice of the final configuration. Beam loss and emittance dilution in the linac due to space charge effects, wakefields, and misalignment of accelerator components can be mitigated by RF phasing and orbit steering. Start-to-end simulations examine the beam transport through the linac up to either 6 GeV or 20 GeV. The results indicate large design margins. Simulations of the beam dynamics in the damping ring (DR) demonstrate a sufficiently large momentum acceptance. Effects of intrabeam scattering and electron cloud instability in the DR are also studied.

INTRODUCTION

The FCC collaboration has submitted the conceptual design report in December 2018 [1]. The potential first step of the global project is the positron-electron collider: the FCC-ee which will serve as a precision machine. Its design has been continuously evolving to overcome the technological difficulties as well as to ensure the realization of the best achievable lepton collider [2]. Further optimization of the extremely high luminosities have also brought about an improvement of the injectors in comparison with the earlier design [3]. The linac operation is increased to 200 Hz with 2 bunches per RF pulse. Furthermore, 4 bunches per RF pulse consisting of 2 e^+ followed by 2 e^- bunches are needed during positron beam delivery to collider. The first 2 e^+ bunches will be put into the DR and the subsequent 2 e^- bunches will hit the positron converter and the positrons generated will be injected into the DR after acceleration to 1.54 GeV by a linac. The layout of the positron production and acceleration is presented in Fig. 1.

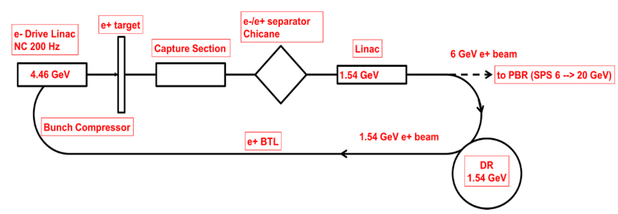

Figure 1: Layout of the positron production, capture, and acceleration.

The switch from 100 Hz to 200 Hz will also change the timing of the DR. The 241.8 meter long DR, which used to host 5 trains, consisting of a bunch pair, would provide 25 ms of beam store time in 200 Hz operation, which does not guarantee the emittance reduction needed in view of the approximately 10 ms transverse damping times. Thus, we have switched to hosting 16 trains in the same DR such that the circulating bunches can be cooled for 40 ms. The linac, DR and PBR schedule for the positron injection into top-up booster is presented in Table 1. The positron bunches extracted from the DR are those which were injected 40 ms earlier. The 2 electron bunches in the linac are those impinging on the positron converter.

Table 1: The Bunch Schedules of the FCC-e^+e^- Pre-Injectors During Positron Beam Delivery

RF time [ms]	linac	DR	PBR
0-5	2 e^-	2 e^+	empty
5-10	2 e^-	4 e^+	empty
10-15	2 e^-	6 e^+	empty
15-20	2 e^-	8 e^+	empty
20-25	2 e^-	10 e^+	empty
25-30	2 e^-	12 e^+	empty
30-35	2 e^-	14 e^+	empty
35-40	2 e^-	16 e^+	empty
40-45	2 e^- & 2 e^+	16 e^+	2 e^+
45-50	2 e^- & 2 e^+	16 e^+	4 e^+
50-55	2 e^- & 2 e^+	16 e^+	6 e^+

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10th Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia JACoW Publishing
ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP002

Apart from e^+ cooling in the DR, we can also cool the emittance of the electrons. However, considering a custom-designed low emittance RF-gun as electron source, we can also directly inject the electrons from the 6 GeV linac into the PBR, which would likely be the SPS. The emittance damping of the electrons can be provided by the already existing SPS by deploying wigglers and changing its phase advance [4, 5].

LINAC

The normal-conducting linac will be fed from two different electron sources, one will be the RF gun for the low-emittance e^- beam, and the second is the thermionic gun for providing higher charge for creating more positrons by impinging on a target. The thermionic gun is a conventional electron source which can be similar to KEK's gun [6]. On the other hand, the aforementioned RF gun can provide a low emittance beam by suppressing the emittance blow up due to space charge using permanent magnets in the irises. Not only the magnetic field adjustment, but also the electric field needed for acceleration can be accomplished by coupling parallel cavities [7–9]. Some of the RF-gun parameters are listed in Table 2.

Table 2: RF Gun Parameters

Parameter	Value
total charge	6.5 nC
laser pulse duration	8 ps
peak accelerating field	100 MV/m
focusing solenoid field	0.5 T
beam length (σ_z)	1.5 mm
normalized transverse emittance	3 μm
energy	9.8 MeV
energy spread	0.6 %

The RF gun can, therefore, provide a normalised emittance of 3 μm even for 6.5 nC. Moreover, the rms bunch length of 1.5 mm and the rms energy spread of 0.6% will be converted into 1 mm bunch length and 1% via a bunch compressor before the linac, leaving some safety margin. Therefore, these longitudinal parameters and 3 μm normalised transverse emittance for 3.5 nC bunch charge are fed into the following linac optics and dynamics simulations. The 1.54 GeV sector linac is presented in Fig. 2 [10]. The accelerating structures used in the linac up to 6 GeV are S-band cavities of 2.97 m length with a resonance frequency of 2856 MHz.

The orbit correction is done via 2 steerers before each cavity [10]. The tracking results with 10^4 macro particles including misalignments, injection errors, as well as space charge effect are presented in Table 3 [10]. The space charge is introduced in the RF gun simulations and in the first cavity of the linac which corresponds to 85 MeV and neglected afterwards since it fades away as $1/\gamma^2$.

The acceleration up to 1.54 GeV may, optionally, have a breakpoint for the electrons for emittance cooling in the DR; afterwards the extracted beam from the DR goes through a

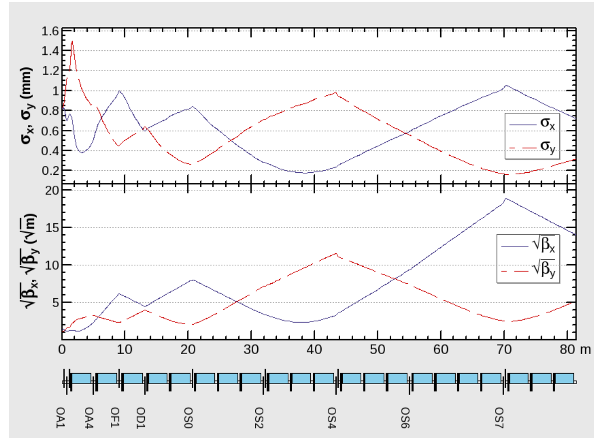

Figure 2: Optics of 1.54 GeV linac.

Table 3: Main Parameters of the Linac up to 1.54 GeV

Parameter	Result
length	79.1 m
number of cavities and quadrupoles	21 and 14
final emittance without errors (x/y)	2.7/3.8 nm
average extracted emittance (x/y)	5.5/6.0 nm
average longitudinal emittance	1.9 μm
final rms bunch length, en. spread	1 mm, 0.2%

bunch compressor [11] is then injected back into the linac at 1.54 GeV to be accelerated to 6 GeV. The beam optics of 1.54-6 GeV linac is shown in Fig. 3 and some of its parameters are presented in Table 4.

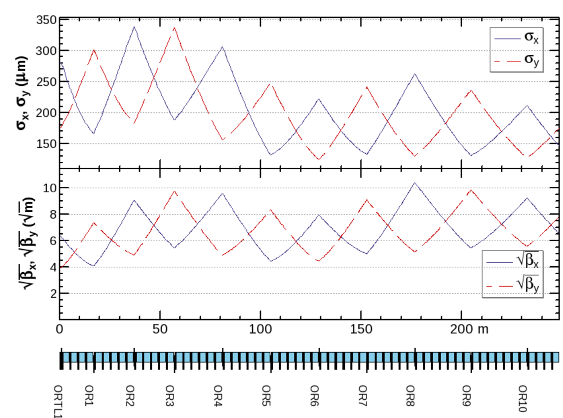

Figure 3: Optics of 1.54-6 GeV linac.

The 20 GeV linac presented in Fig. 4 actually contains the S-band linac presented in Fig. 3 up to the quadrupole named $QC0$. The extended part can be distinguished since the blue boxes representing the accelerating structures up to 248.5 m of the accelerator are larger than the downstream ones, since the earlier part makes use of 2.97 m-long S-band whereas the later ones are 1.8 m-long C-band structures.

The C-band extension of 437.4m is an alternative option to designing a new synchrotron of 2.9 km in circumference

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Table 4: Main Parameters of the 1.54-6 GeV Linac (*During Positron Beam Delivery)

Parameter	Value
length of the accelerator	248.5 m
number of cavities and quadrupoles	60 and 12
bunches per RF pulse	2 (4*)
injected emittance (x/y)	1.9/0.4 nm
final emittance w/o errors (x/y)	0.48/0.10 nm
average extracted emit. (x/y)	0.55/0.11 nm
average extracted emit. (long.)	1.1 μm
final rms bunch length, spread	0.4 mm, 0.5%

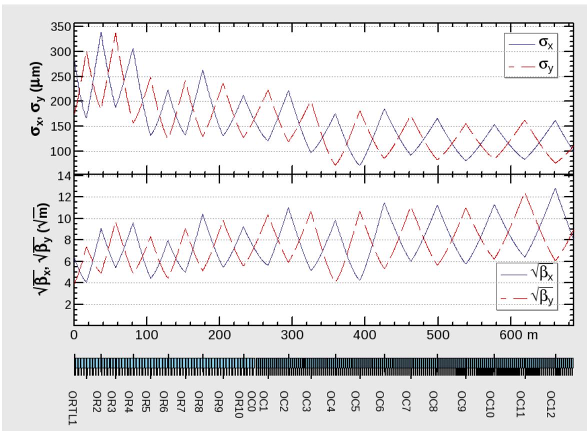

Figure 4: Optics of 1.54-20 GeV linac. Notice that the C-band structures start at QC0 where the S-band structures end.

or to using a slightly modified SPS [12]. C-band accelerating structures are 1.8 meter long with a 5712 MHz operating frequency and an equal repetition of 200 Hz. Tracking results starting from 1.54 GeV up to the end of 20 GeV are presented in Table 5. The 0.1 mm quadrupole misalignment, spatial and angular injection errors of 0.1 mm and 0.1 mrad, respectively, together with a BPM positioning error of 30 μm have been assumed. Within the given rms errors which have a Gaussian distribution with no truncation, the orbit correctors turn out to have a magnetic field less than 13 G which allows air-cooled core magnet. Moreover, all the quadrupoles deployed along the 20 GeV linac have a magnetic field less than 0.8 T. The transmission from the RF gun to the end of any sector (i.e. 1.54 or 6 or 20 GeV) of the linac is calculated to be 100% for 3.5 nC bunch charge.

Table 5: Main Parameters of the 6-20 GeV C-Band Extension Linac

Parameter	Value
length	437.4 m
number of cavities and quads	156 and 13
bunches per RF pulse	2
final emittance w/o errors (x/y)	0.15/0.03 nm
average extracted emittance (x/y)	1.18/0.05 nm

1.54 GeV DAMPING RING

The DR optics design has been kept intact as presented in [12]. However, the DR needs to host 16 bunches with 50 ns bunch-to-bunch spacing, as discussed in the introduction section. Therefore, an electron-cloud build up study has been initiated to determine the impact of this close spacing [13]. Moreover, the intrabeam scattering (IBS) has been studied. In the ideal case, the equilibrium emittance was 0.96 nm in horizontal plane and practically zero in vertical plane. The equilibrium emittance has become 2.3/0.23 nm (x/y) due to IBS. In order to overcome this blow up, we intentionally introduced a 20% emittance coupling in the machine. Therefore, the values presented in Table 6 include IBS and 20% coupling.

Table 6: 1.54 GeV Damping Ring Main Parameters

parameter	value
circumference	241.8 m
no. trains, bunches/train	8, 2
bunch charge	3.5 nC
train, and bunch spacings	51 ns, 50 ns
train store time	40 ms
energy loss per turn	0.225 MeV
RF voltage, frequency	4 MV, 400 MHz
no. of cells in an arc, cell length	57, 1.54 m
FODO cell phase advance (x, y)	69.5/66.1 deg
betatron tune (x, y)	24.19/23.58 rad
momentum compaction α_c	1.5 $\times 10^{-3}$
natural emittance (x, y)	1.39, 0.28 nm
natural emittance (z)	1.75 μm
damping time (τ_x, τ_y, τ_z)	10.6/11.0/5.6 ms
bending radius, wiggler field	7.75 m, 1.8 T
acceptance (x, y)	22.4, 22.4 μm
acceptance (z)	14.7 mm
energy spread	7.7×10^{-4}
bucket height	8.0 %
energy acceptance	$\pm$7.8 %
injected emittance (x, y)	1.29, 1.22 μm
extracted emittance (x, y)	1.62, 0.99 nm
inj. and ext. emittance (z)	75.5 μm, 1.47 μm

CONCLUSIONS

The FCC-ee CDR has been submitted [1] in which the injectors safely provide the necessary charge and low emittance. The linac design up to 20 GeV demonstrates satisfying results. The output beam can be directly accepted by the top up booster [14]. Similarly, the beam extracted from the 6 GeV linac can be safely accepted by the SPS, even off-axis injection into the SPS is considered [5]. The positron capture and pre-injector system is omitted in this paper due to the ongoing parallel positron work [15]. On the other hand, the damping ring optics design is kept intact as [12] and it ideally satisfies the FCC-ee requirements; yet some of the collective effects are still being studied.

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