TOWARDS A PRELIMINARY FCC-ee INJECTOR DESIGN

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Abstract

The Future Circular Collider-ee aims to get high luminosity which mainly relies upon high charge and low geometric emittance in the collider. The FCC-ee is a future project of CERN to operate as Z, W, H and tt factories with varying energies between 45.6 to 175 GeV. Among those, the total charge requirement is peaked for Z-operation (i.e. 91500 bunches of electron and positron with 3.3E10 particles per bunch) meanwhile this mode targets the smallest geometric emittance in the Collider. To reach the goal, the normal conducting S-band Linac has been designed to accelerate 4E10 particles in a bunch to 6 GeV and send two bunches per RF pulse within a repetition of 100 Hz. The FCC-ee positrons will also be created inside the linac at 4.46 GeV and accelerated to 1.54 GeV. These positrons are damped at the designed Damping Ring at that energy, and then transferred back to the Linac to meet the same characteristics of electrons. Therefore, in this paper, we'd like to discuss the transmission and robustness of the Linac and the dynamic aperture of the Damping Ring which has to be large enough to accept the incoming beam and cover the probable shrink due to the misalignments.

INTRODUCTION

CERN's leading role over the world in the fields of the particle and accelerator physics has brought about thinking of ambitious post-LHC (Large Hadron Collider) projects. As a 100 km-machine, FCC-ee has been proposed to supply ever increasing demand of high luminosity machines for new physics search and the precision study of the particle physics. Nowadays, FCC-ee is being designed to operate as Z, W, H and tt factories. However, in the design of pre-injectors, the total charge and the equilibrium emittance are determinant. Therefore, we will be following Z-operation which has the highest total charge and lowest final emittance at 45.6 GeV to study pre-injectors, some parameters of Z-operation is tabulated in Table 1.

Table 1: FCC-ee Baseline Parameters for Z-operation Mode

Parameter	Value
Final Energy [GeV]	45.6
Number of Bunches per Beam	91500
Bunch Population	3.3×10^{10}
Horizontal Emittance	0.09 nm
Vertical Emittance	1 pm

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The detailed version of the table and the preliminary design parameters of the pre-injectors are already discussed in details in our earlier proceedings [1] and [2], respectively. In this paper, however, we'd like to discuss the followings: i) improvements on the Linac transmission, and ii) enlargement of dynamic aperture of the Damping Ring.

IMPROVEMENTS ON LINAC

The designed Linac for FCC-ee is an S-band normal conducting accelerator operating at frequency 2.856 GHz. The optics before the correctors were tightly allocated as presented in Fig. 1.

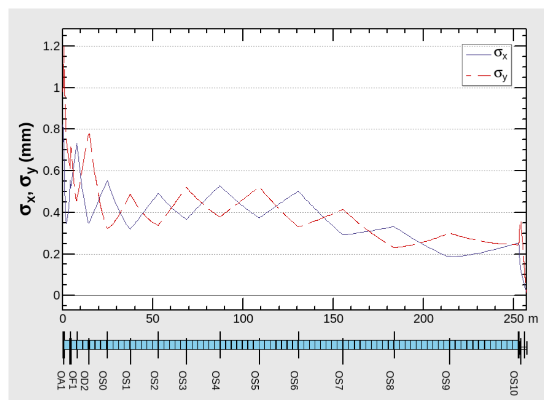

Figure 1: Linac optics before the misalignments.

After the idealistic design of the Linac, the study of errors is crucial in a sense to determine probable and inevitable misalignments through the commissioning of the accelerator. Therefore, we have given some misalignment to the elements both horizontally and vertically as tabulated in Table 2. The study has been done as a Monte-Carlo simulation where the tabulated errors represents one-sigma, and no truncation has been made.

Table 2: Misalignment Study

Element	Simulated Error
Injectional Error (h/v)	0.1 mm
Injectional Momentum Error (h/v)	0.1 mrad
Quadrupole Misalignment (h/v)	0.1 mm
Cavity Misalignment (h/v)	0.1 mm

After introducing errors, the Linac transmission has dropped dramatically down to 33%. The cavities of the Linac are with length of 28 + 1/3 wavelengths which correspond to 3 meters approximately. The wakefields of the cavities are similar to ATF-Linac [3] and the cavity geometry

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is tapered such a way that 11 mm as an entrance aperture and 9 mm at the exit to keep the field uniformity. For the simplicity, yet the simulations are made for a straight aperture of 10 mm for 3 meter long full length cavity.

The orbit correction is fully automatized by a code written. Firstly, we introduce a steerer magnet before each cavity where the gradients are determined by aligning the orbit of the tracked particles back to the cavity center. The performance of the orbit correction can be seen from the orbit oscillations throughout the accelerator as presented in Fig. 2.

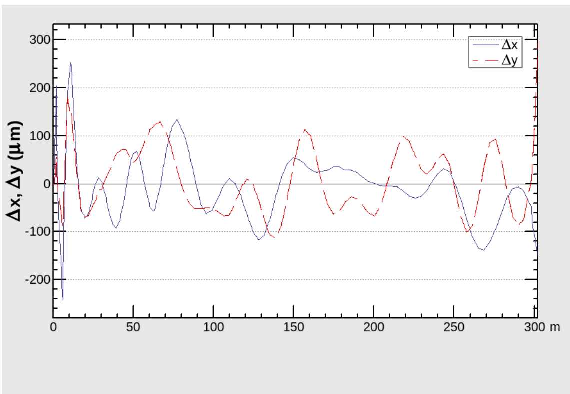

Figure 2: Orbit oscillations.

Actually, this tracking corresponds physically to deploy a Beam Position Monitor before the cavity entrance and the adjusting the steerer magnet accordingly. This adjustment has led the transmission to rise up to 70%, yet the resulting transmission is not sufficient for our requirements. Therefore, we change the optics for the low energy part of the 6 GeV Linac as shown in Fig. 3.

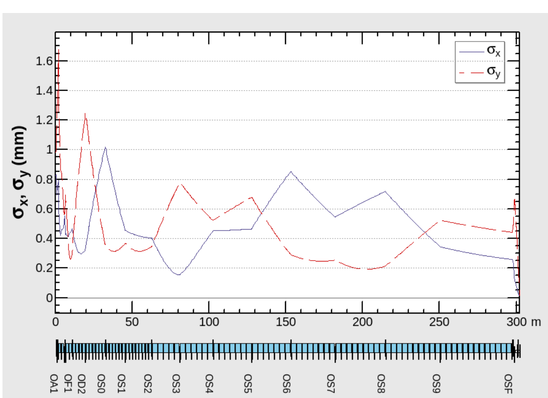

Figure 3: Linac optics after orbit correction elements.

Using the fact that the wakefields are loosen as the cavity aperture widens, we interchange the first 14 full length cavities to 28 half length cavities. The half length cavities are 1.5 m (i.e. 14 + 1/3 wavelengths) such that their transverse aperture is the twice of the full length (i.e. 20 mm), on the other side, the cavity voltage is still kept below 27 MV/m. Therefore the impact of the wakefields is decreased significantly. Also, we have become able to steer the beam more frequently due to higher number of dipoles and shorter length to intervene the beam. As a result, the transmission becomes slightly more than 88%. Nevertheless, the wakefields still affect the beam to shape like *banana* as shown in Fig. 4 which apparently dilates the final emittance.

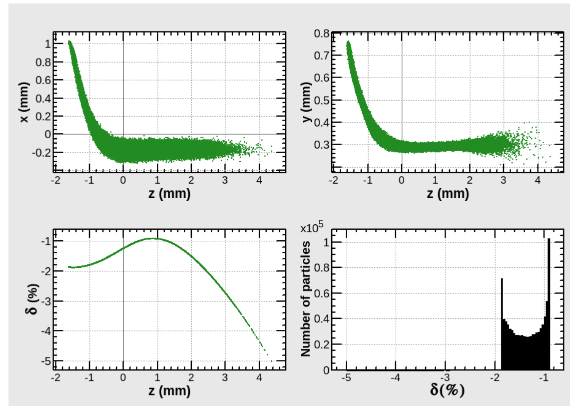

Figure 4: Linac beam profiles after orbit correction.

The overall performance of the orbit correction study can be summarized as in Table 3.

Table 3: Performance of the Misalignment Study

At the end of Linac	Results
Transmission Required	83%
Transmission Provided	88%
Emittance (h/v) Required	0.7/1.0 nm
Emittance (h/v) Provided	60/51 nm

DAMPING RING WITH LARGE DYNAMIC APERTURE

FCC-ee Linac is utilized both for electrons and positrons. The creation of the positrons will be by exposing the electrons at energy of 4.46 GeV to a hybrid (crystal and amorphous) target. Hence, the positrons can be accelerated at 1.54 GeV at the remaining part of the Linac. Yet the positrons do not match the specifications of the electrons at the same energy, this is why they have to be damped. An overview of the damping necessities has been presented in Table 4, in which the positron data of KEK [4] adapted to our parameter selection, and the Booster entrance and exit emittance values are determined by the study of FCC-ee Optics Design team [1].

Table 4: Positron Emittance Evolution

e+ Accelerators	Energy	ϵ_x	ϵ_y
DR Entrance	1.54 GeV	0.76 μm	0.71 μm
DR exit	1.54 GeV	2.66 nm	3.9 nm
Booster exit	45.6 GeV	0.09 nm	0.13 nm

Therefore, the DR is designed to damp μm emittance down to nm level in less than 50 ms, as it is discussed in [2].

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The DR design has been altered in a way to cover FCC-ee targets as demonstrated in Fig. 5. Some parameters of the DR has been presented in Table 5.

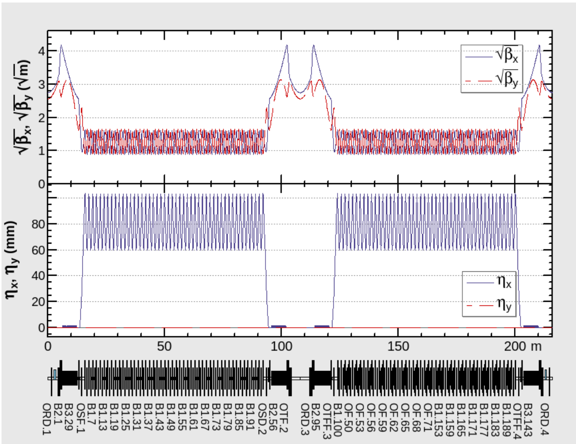


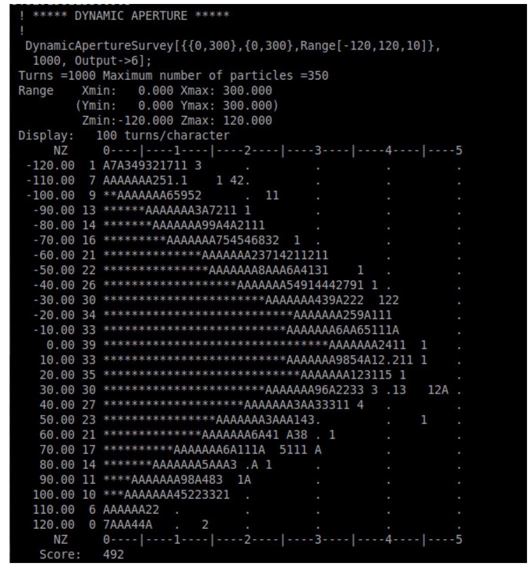
Figure 5: Damping Ring optics.

Table 5: Damping Ring Design Parameters

Parameter	Value
Energy [GeV]	1.54
Number of Trains	3
Bunches/Train	2
Circumference [m]	216
Number of cells	94
Bending Radius [m]	7.7
Bunch Spacing [ns]	120
τ_x [millisecond]	11.0
τ_y [millisecond]	11.4
Horizontal Natural emittance [nm]	1.3
Vertical Natural emittance	-

However, the performance of the Damping Ring is limited by the dynamic aperture provided. The acceptance of a Damping Ring can be calculated as the natural emittance times the square of the dynamic aperture (DA) in that direction. In order to achieve a large DA, we choose lower and closer tune per cells in horizontal and vertical directions, such that we can make the FODO lattice shorter. The DA, presented in Fig. 6, horizontally demonstrates the transverse DA (up to 300 sigmas), whereas the vertical axis shows the longitudinal DA; where each random character should be considered as a flag which indicates that the particle(s) is/are alive for 1000 turns. All in all, we become able to provide 234 sigmas as DA to the on-momentum positrons with respect to the equilibrium emittance of DR.

The resulting performance of DR brings about reaching targets tabulated in Table 4 in 35 milliseconds for horizontal emittance and 29 ms for vertical emittance which both are well-below than the allocated time (i.e. 50 ms) for positrons to spend inside the DR. The acceptance provided for the horizontal direction stated in Table 6.



```
! ***** DYNAMIC APERTURE *****
!
 DynamicApertureSurvey[{{0,300},{0,300},Range[-120,120,10]},
  1000, Output->6];
Turns =1000 Maximum number of particles =350
Range    Xmin:   0.000 Xmax: 300.000
        (Ymin:   0.000 Ymax: 300.000)
         Zmin:-120.000 Zmax: 120.000
Display:   100 turns/character
     NZ     0----|----1----|----2----|----3----|----4----|----5
 -120.00  1 A7A349321711 3      .         .         .         .
 -110.00  7 AAAAAAA251.1    1 42.         .         .         .
 -100.00  9 **AAAAAAA65952      .  11     .         .         .
  -90.00 13 ******AAAAAAA3A7211 1         .         .         .
  -80.00 14 *******AAAAAAA99A4A2111       .         .         .
  -70.00 16 *********AAAAAAA754546832  1  .         .         .
  -60.00 21 **************AAAAAAA23714211211        .         .
  -50.00 22 ***************AAAAAAA8AAA6A4131    1   .         .
  -40.00 26 *******************AAAAAAA54914442791 1 .         .
  -30.00 30 ***********************AAAAAAA439A222  122        .
  -20.00 34 ***************************AAAAAAA259A111         .
  -10.00 33 **************************AAAAAAA6AA65111A        .
    0.00 39 ********************************AAAAAAA2411  1     .
   10.00 33 **************************AAAAAAA9854A12.211 1     .
   20.00 35 ****************************AAAAAAA123115 1        .
   30.00 30 ***********************AAAAAAA96A2233 3 .13   12A .
   40.00 27 ********************AAAAAAA3AA33311 4   .         .
   50.00 23 ****************AAAAAAA3AAA143.         .    1    .
   60.00 21 **************AAAAAAA6A41 A38 . 1       .         .
   70.00 17 **********AAAAAAA6A111A  5111 A         .         .
   80.00 14 *******AAAAAAA5AAA3 .A 1      .         .         .
   90.00 11 ****AAAAAAA98A483  1A         .         .         .
  100.00 10 ***AAAAAAA45223321  .         .         .         .
  110.00  6 AAAAAA22  .         .         .         .         .
  120.00  0 7AAA44A   .   2     .         .         .         .
     NZ     0----|----1----|----2----|----3----|----4----|----5
   Score:   492
```

Figure 6: Transverse and longitudinal Dynamic Aperture of the Damping Ring for 1000 turns.

Table 6: Performance of the Damping Ring Design in Transverse Direction

Parameter	Value
Natural Emittance	1.3 nm
Positron Emittance (1-sigma)	0.76 μm
Acceptance needed (3-sigma)	6.84 μm
DA needed (3-sigma)	73 σ
DA provided	234 σ
Acceptance Provided	69.5 μm

Therefore, we can conclude that the DR designed can provide many times larger acceptance then it is required. Similarly, the longitudinal DA enables a wide acceptance, too, as presented in Table 7.

Table 7: Longitudinal Performance of the Damping Ring

Parameter	Value
Natural Emittance	3.6 μm
Positron Emittance (1-sigma)	1 mm
Acceptance needed (3-sigma)	9 mm
DA needed (3-sigma)	50 σ
DA provided	110 σ
Acceptance Provided	43.6 mm

The bucket height ratio is 8.3% and the energy spread is 6.7×10^{-4} for 2 MV cavity voltage which still comprises the longitudinal DA (i.e. 110 σ). Furthermore, the beta function of DR is calculated as the bunch length square divided by the longitudinal emittance as follows:

$$\beta_z = \frac{\sigma_z^2}{\epsilon_z} = \frac{(5.30\ mm)^2}{3.56\ \mu m} = 7.9\ m. \tag{1}$$

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On the other hand, the beta function for the positron data is:

$$\beta_z = \frac{(0.041\ m)^2}{0.001\ m} = 1.7\ m. \quad (2)$$

Thus, we conclude that we need an energy compressor which compress the incoming positrons energy dispersion more than to its half.

CONCLUSION

The Linac transmission is increased fairly enough to supply Z-operation, that also means fulfilling all operations of FCC-ee in terms of total charge and emittance in the collider. The introduction of 28 half-length cavities in low energy part with bigger aperture of 20 mm and 92 steerer magnets result 88% of transmission. Cumulatively, the 6 GeV Linac has become 299 meter long, yet still with less than 25 MV/m acceleration gradient throughout the Linac. Despite of the fact that the emittance blow at the exit of the Linac diverges from the goal, the FCC-ee aims not to use an intermediate step to shrink electrons' emittance at the moment. In other words, the Linac will inject 6 GeV electrons directly to 100-km top-up Booster for Z-operation. Therefore, the emittance growth due to the wakefields is going to be studied to be suppressed.

On the other side, the designed Damping Ring covers the FCC-ee positron damping requirements totally thanks to the dynamic aperture which is wider than 200 of sigmas transversely and more than 100 sigmas longitudinally. Moreover, we conclude that an energy compressor is needed before the DR to match the beta functions.

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