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EMITTANCE AND ENERGY DISTRIBUTION REDUCTION IN THE POSITRON INJECTOR OF FCC-e^+e^-

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Abstract

The FCC-e^+e^- project foresees the realization of the most intense ever realized source of positrons providing a bunch charge of the order of 5 nC. This large number of positrons ($\approx 3.12\times10^{10}$) is produced by pair conversion following a 6 GeV electron beam bremsstrahlung on a target, and as a consequence has large divergence and energy spread. The actual design of the positron injector includes a damping ring, and a bunch compressor to reduce the beam particle distributions in the longitudinal and transverse phase spaces to values appropriate for the injection in the common LINAC, which accelerates both electron, and positron beams from 1.54 to 6 GeV. An energy compressor installed after the positron LINAC improves the positron acceptance in the damping ring. This contribution presents relevant aspects related to the damping used for the positron beam including the evaluation of transmission efficiency through the whole transfer line from the positron source to the common LINAC, the energy compressor, and the bunch compressor installed in the injection and extraction branches of the Damping Ring.

INTRODUCTION

In the present FCC-ee pre-injector configuration, see Fig. 1, an e^- beam from a low-emittance RF gun is accelerated by an S-band LINAC up to 6 GeV, and it is directly injected into a pre-booster ring or high energy LINAC [1].

Differently, the e^+ beam is generated by hitting the electron beam (at the energy of 6 GeV) on a positron target, and it is accelerated up to 1.54 GeV in the positron LINAC (pLINAC). The e^+ beam at this point is characterized by a large transverse and longitudinal emittance, which is not suited for injection in the common LINAC (cLINAC). A complex system is dedicated to reduce the 6D-emittance of the beam and to trade it back to the cLINAC.

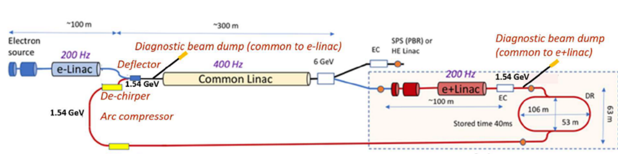

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Figure 1: A schematic baseline layout of the FCC-e^+e^- pre-injector complex [4, 17].

The Damping Ring (DR) cools down by several orders of magnitude the transverse emittance of the beam and strongly reduces its energy spread. An Energy Compressor (ECS) [2, 3], and a transfer line (pTLi) are installed between the pLINAC and the DR. The ECS is needed to reduce the incoming beam energy spread in order to maximize the injection efficiency. A Bunch Compressor (BC) at the entrance of the cLINAC is used to adjust the RMS bunch length of the incoming beam according to the needs of the cLINAC. A long transfer line (pTLe), and a matching section transport the beam from the DR into the BC. Two diagnostic lines (cBD, and pBD), both equipped with a beam damp, complete the system. The ECS, the DR, the transfer, and the matching section were already described in [4–6].

In the last year these different parts have been integrated in a single MAD-X [7] layout, reproduced graphically by using the SIREPO [8] application as shown in Fig.2. Such MAD-X layout has been used to evaluate the e^+ transport efficiency in the whole system. The BC has been designed, and validated by using the ELEGANT [9, 10] simulation code. The current version of the BC was included in the MAD-X file, too.

The preliminary work done to evaluate the impact of collective effects using parametric considerations, see [11], has been further developed addressing the influence of the e-cloud effects in the DR. The results of the simulation of the e-cloud in the DR are reported in [12]. The present injector configuration, foresees the use of a DR operating at 1.54 GeV for the e^+ beam only. Such layout has been used as a reference for the project feasibility evaluation, and cost estimation prepared for the midterm review report [13]. Eventually, we will present a possible layout of the injector complex with a DR at beam energy of 2.86 GeV.

DAMPING RING ACCEPTANCE

The capacity of the systems, so far described, to accept the beam coming from the pLINAC has been evaluated based by start-to-end simulations including ECS, pTLi and DR. The particle beam distribution coming from pLINAC, prepared with the code RF track, has been tracked with ELEGANT through ECS, and pTLi. These simulations confirmed the effectiveness of the energy compressor to reduce the positron energy distribution. Thanks to the ECS, 94% of the particles lie within ±2% of the nominal energy acceptance of the DR. The pTLi permits the injection and the matching to DR. The transverse emittance of the beam is preserved in ECS and pTLi. The beam distribution prepared in this way has been used as input for the tracking through DR done with PTC-MAD-X [14]. The 83% of the beam survived after the first 10k turns, which corresponds to 75% of a damping time. This time is more than enough to esteem the acceptance as most of the particle losses come up in

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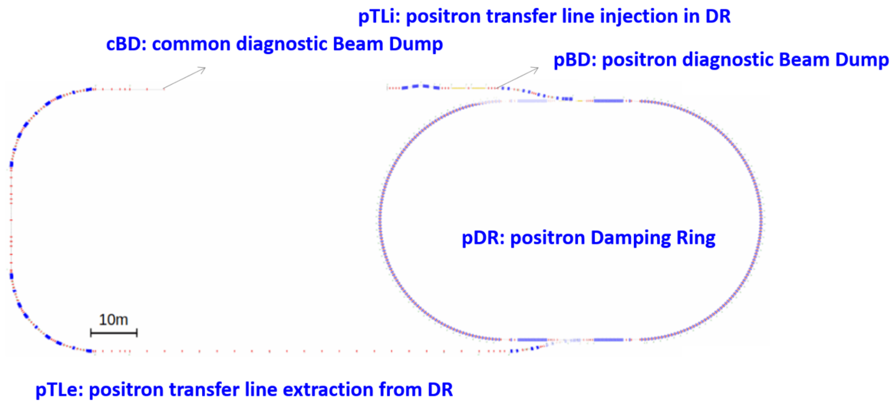

Figure 2: DR and pTLi/e transfer lines layout. The longitudinal size of the extraction line is not in scale.

the first turn. Fig. 3 shows the distribution of the survived particles according to their transverse positions at the exit of the pLINAC. The coordinates of the accepted and rejected particles can be used to design a possible collimation system capable of cleaning away all those particles that would not be accepted in the DR, to alleviate the problems related to the machine radiation protection.

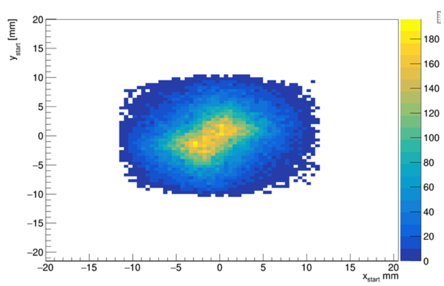

Figure 3: Distribution of the survived particles according to their transverse positions at the exit of pLINAC.

BUNCH COMPRESSOR

The BC has to compress the bunch length of the beam coming from the DR, expected to be in the range 3-5 mm, down to 1 mm. The BC is composed of a RF section in which the beam acquires a correlated energy spread, and by a dispersive section in which the particles move on different paths according to their energy. Several options can be considered for the design of the dispersive BC section. In the actual FCC injector design the return arc of the pTLe is used to produce the required R_{56} by using several cells instead of a single chicane. This helps to avoid emittance dilution contributions due to Coherent Synchrotron Radiation (CSR). The returning arc is composed by two equal 90-degree halves, connected by a matching section. Each of the two halves consists of three Triple Bend Achromat (TBA) cells, each of them providing a R_{56} of the order of 6.49. Hence, the total R_{56} of the arc compressor is about 40 cm. For the present R_{56} value a linear energy chirp of the order of -2/m is required in order to achieve the necessary compression factor (3-5). This linear chirp corresponds, for an RSM bunch length of 5 mm, to $\approx 1\%$ RSM energy spread. The cell also features a low $\mathcal{H}$ function ≤ 0.1, suitable to avoid possible beam quality degradation induced by CSR emission. Each cell is equipped with four sextupoles that allow zero second-order dispersion at both cell ends, and linearize the compression reducing the T_{566} term. The value of horizontal phase advance between the third and the fourth TBA is set to π to simplify the optics layout. The main parameters of the single TBA cell are listed in the figf. 4.

Parameter	Value	Unit
Bending angle (1&3)	0. 2094396 (12)	Rad (deg)
Bending length (1&3)	1.2676	m
Bending angle (2)	0.1047198 (6)	Rad (deg)
Bending length (2)	0.63	m
Cel total length	10.09	m
Sextupoles K2	-12.65	
R56	0.06748	m
Max dispersion (abs. value)	0.5	m
H	0.1	m

Figure 4: Mean parameters of each of the 6 equal TBA cells composing the arc.

One cavity of the same type used in cLINAC is sufficient to give the required chirp when operating at 0- phase, and with an RF peak voltage of 54 MV. The relative beam energy spread at the exit of the bunch compressor has to be <0.7% to ensure compatibility with the cLINAC. Other two cavities of the same type operating at 180 deg, are placed after the bunch compressor to reduce the residual energy chirp on the beam at the required level. The total accelerating voltage of these two cavities is 99 MV. The BC design has been extensively tested and optimized by using the ELEGANT simulation code. These simulations include a 1-D model of CSR. The input beam has been prepared assuming that the beam coming from the damping ring has Gaussian distribution in the 6-D phase space coordinates. The beam, 4M macro-particles, is supposed to have a transverse emittance equal to 0.96 nm in both planes, a relative energy spread equal to 0.1% and a RMS bunch length of 5 mm. The main results of the simulations concerning the longitudinal dynamic in BC are reproduced in Fig. 5 which shows the phase

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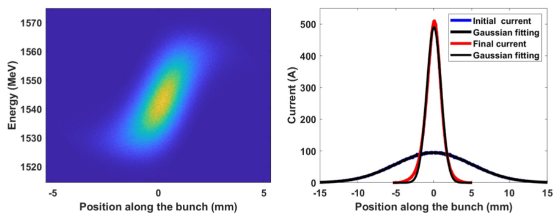

Figure 5: Left: phase space of the compressed beam. Right: Uncompressed and Compressed bunch current with the Gaussian fitting of both the profiles.

space at the end of the bunch compressors and the evolution of the bunch current. The phase space at the end of the bunch compressor is dominated by the linear energy spread. The bunch current is increased by a factor of 5, and the Gaussian shape is preserved. The compression is almost linear, and the final bunch duration is one-fifth of the initial one as required. The total relative energy spread at the end of BC is $\approx 0.7\%$.

The diagnostic station cBD placed after BC allows the measurement of the longitudinal phase space and the current profile of the beam. It comprises a small RF deflector, 0.5 m long, working at the same frequency of the cLINAC 2.8 GhZ, six quadrupoles, one bending dipole, and two screens for optics control. The electron beam is deflected vertically by the deflecting cavity. This deflection maps the electron beam longitudinal coordinate to the vertical coordinate on the first diagnostic screen where the current profile of the beam can be reconstructed. The first four quadrupoles of the screen are placed between the deflector and the first screen. They are used to increase the beam deflection, and minimize the vertical beam size on the screen. Fig. 6 shows the results of the simulation done to validate the performance of this diagnostic station. On the left, the vertical profiles of the deflected and of the un-deflected beam on the screen are reproduced. The right-plot of the picture reproduce the expected and measured bunch current by the screen image. The spectrometer dipole magnet converts the particle's energy to the horizontal coordinate on the screen. Consequently, the electron beam energy distribution is imaged on the second screen. Other two quadrupoles are placed between the dipole and the screen for tuning purposes.

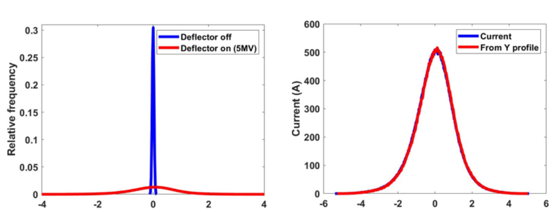

Figure 6: Left: Vertical profiles of the beam on the first diagnostic screen of cBD with the deflector switched on and off. Right: comparison between expected and measured current profiles at the screen.

OPTIONAL LAYOUT WITH HIGHER ENERGY DR

An alternative FCCee injector layout was also proposed including a damping ring at higher beam energy of 2.86 GeV based on FCC Feasibility Study Mid-Term Review [13].

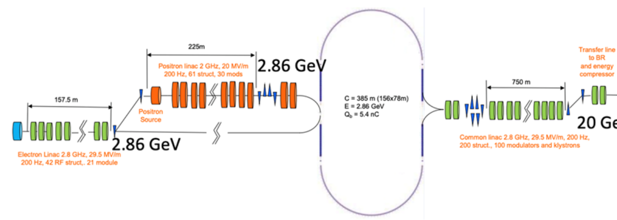

Figure 7: Optional layout with the damping ring operating at 2.86 GeV.

This option could lead to a remarkable simplification in the general pre-injector layout maintaining or even reducing the LINACs total accelerating length, and relaxing the challenges related to the 400 Hz cLINAC design requirements [4]. The positron yield at the source is large enough to lower the energy of the primary electron beam used for positron production. The layout for this option, shown in Fig. 7, allows to use DR for both particle species. In this scheme the cLINAC can work at 200 hz instead of 400 Hz repetion rate and can be built using a structure at a higher accelerating gradient reducing the length, the overage RF power used, and the operative costs. Currently two alternative proposal for the High-Energy DR are under study: CLIC-PDR which uses TME cell in the arc, and a new ring design relying on FODO cell lattice having a larger circumference [15]. For the CLIC-PDR, existing design parameters do not meet the horizontal emittance requirement. However, this can be arranged by properly tuning the phase advance in the cells. In this case, the acceptance of the CLIC-PDR must be carefully evaluated again. For the new design option with FODO lattice, a preliminary optics study shows that design parameters meet the prerequisite of the pre-injector complex with a DR working at the energy of 2.86 GeV, having larger circumference (around 380 m) [16, 17]. We are also exploring the possibility of realizing a more compact high-energy DR by using combined function magnets. In the following process, all options will be evaluated and the chosen one will be detailed with non-linear optimization.

CONCLUSIONS

We have presented the status of the WP4 of the pre-injector of the FCC-ee project including possible upgrades. Start-to-end simulations having as input the particle distribution coming from the pLINAC, improved by the ECS, outlined a very satisfactory DR acceptance over 80%. The design, and the expected performances of the bunch compressor, and its dedicated diagnostics have been also evaluated in detail.

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