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# DAMPING RING AND TRANSFER LINES OF FCC-$e^+e^-$ INJECTOR COMPLEX

S. Spampinati*, C. Milardi, A. De Santis, O. Etisken [1], Laboratori LNF-INFN, Frascati, Italy
Y. Dutheil, R. Ramjiawan, CERN, Geneva, Switzerland
[1] also at Kirikkale University, Kirikkale, Turkey

## *Abstract*

The Future Circular Collider Project is built around two main pillars: the construction of around 91 km lepton collider running at increasing energies from the Z-pole to the $t-\bar{t}$ threshold (FCC-$e^+e^-$) followed by a hadron collider in the same tunnel (FCC-*hh*) to explore unprecedented energy frontier. The realization of FCC-$e^+e^-$ relies on a very challenging injector complex that should provide the highest ever realized source of positrons, which will serve the first phase of the collider operations (Z-pole). In this contribution, the relevant aspects related to the damping of the high-emittance beam coming from the positron source and the transport of the damped beam within the different LINAC of the injector complex are presented and discussed.

## INTRODUCTION

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

On the other hand, the positron beam is generated by hitting the electron beam on a positron target, then it is accelerated up to 1.54 GeV into the positron LINAC (pLINAC) and injected in the Damping Ring (DR) for emittance cooling. A complex system of Transfer Lines (TL) is needed to bring back the positron beam to the common LINAC (cLINAC) from the DR in order to accelerate them up to 6 GeV. TL include doglegs to implement DR injection and extraction, and arcs to bring back the cooled positron beam to the entrance of the cLINAC. An Energy pre-Compressor (ECS) system is installed between the pLINAC and the DR 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 keep the RMS bunch length of the incoming beam under control. The cLINAC duty cycle has recently been increased from 200 to 400 Hz, with two bunches per RF pulse. This new configuration implies revising the DR injection-extraction timing in order to account for the additional time necessary to avoid the presence of two different kinds of particles in the same LINAC RF pulse. A timing revision compatible with the latest pre-injector layout is presented in [2]. This paper aims at presenting the status of the DR, TL, the ECS before the DR, the BC before the cLINAC.

## DAMPING RING

The purpose of the DR design is to accept the 1.54 GeV positron beam coming from the pLINAC, damp the emittance, and provide the required beam parameters for injection into the cLINAC, see Fig. 1. In this regard, the DR has quite challenging design requirements. DR should reduce by orders of magnitude the beam emittance, and should provide large beam acceptance in order to catch the beam from the pLINAC, which has a large distribution in the 6D phase space. The DR is about 240 m long and its energy is selected to avoid spin resonances. According to the current design, a FODO-type cell is chosen, the DR is made up by two arcs and two straight sections housing the damping wiggler magnets, RF cavity, and injection/extraction equipment. The injection will be done by using on-axis scheme. The DR beam structure foreseen a sequence of a maximum of 9 bunch trains, each of them including two bunches. Single bunch current is planned to reach a rather high intensity as it varies in the range of 0.6 ÷ 5.7 mA. The injected beam must reach the nominal extraction emittance of 1.9 nm·rad in a store time of about 40 ms. High currents stored in rather short bunches require a careful evaluation of beam lifetime and a comprehensive analysis of collective effects taking into account a realistic impedance budget, and considering beam coupling with the RF system. Preliminary analytical estimations of various collective effects such as space charge (SC), intra-beam scattering (IBS), longitudinal micro-wave instability, transverse mode coupling instability (TMCI), ion effects, electron cloud, and coherent synchrotron radiation (CSR), have been performed for an intermediate version of the DR optics [3]. No major limitations are expected from IBS, TMCI, and CSR. Concerning the SC, the tune shift at the equilibrium state might be an issue. It was shown that the neutralization density exceeds the e-cloud instability threshold for the equilibrium state. The fast rise times of the fast ion instability can be compensated with a feedback system, provided a vacuum pressure of $10^{-9}$ mbar is achieved in the DR. Similar studies must be repeated for the latest DR optics, and considering a realistic model for the beam pipe and vacuum equipment. The Dynamic Aperture (DA) has been evaluated using the PTC tracking code embedded in the MAD-X simulation code [4, 5].

At first, tracking has been performed starting in the transverse plane on a random position within a box of 4x4 cm$^2$. The particles have been tracked up for 2000 turns without radiation damping. The initial energy deviation has been considered up to ±5%. The result of this tracking is shown in Fig. 2. At the nominal energy, the stable region normalized

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[*] simone.spampinati@lnf.infn.it

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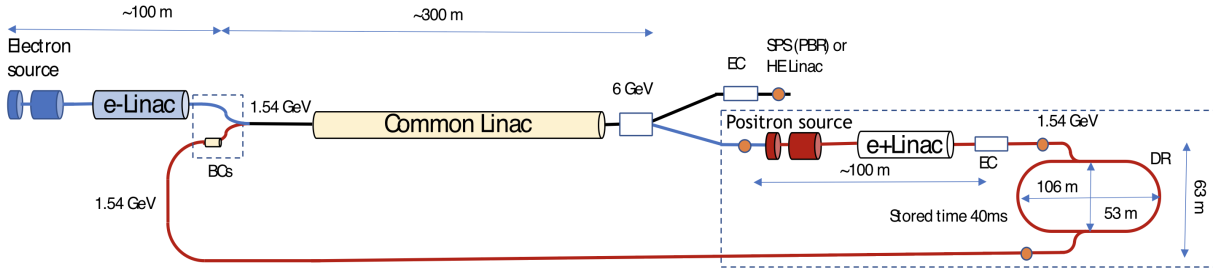

Figure 1: A schematic baseline layout of the FCC-$e^+e^-$ pre-injector complex [2, 8].

as a function of beam width is of the order of three $\sigma_{h,v} = \sqrt{\beta_{h,v}\epsilon_{h,v} + (D_{h,v}\delta_E)^2} \simeq 3$ mm, in both planes. The CDR nominal 6D beam envelope ($\epsilon^{geo}_{h,v} = 1.29, 1.22$ mm·mrad and $\delta_E \simeq 5\%$) at the injection has been tracked with radiation damping for 10000 turns, corresponding to a store time equal to one DR damping time. The DR acceptance resulting from this tracking is: $\epsilon_{ACC} \simeq 47\%$, thus implying a factor of two of reduction in the positron yield without using the ECS.

The Radio Frequency (RF) cavity is fundamental to define the DR longitudinal beam dynamics and should provide a large energy acceptance compliant with the large energy spread of the incoming positron beam. Presently the plan is to use as RF cavity the LHC type SC device operating at the frequency of 400 MHz, as already proposed in the CDR [6]. This cavity consists of two RF modules housed in the same cryostat. It is worth reminding, that in the following we will indicate as RF voltage the total voltage of the two RF modules. High RF voltage determines rather short bunch length values, which can represent an issue for beam lifetime and for collective effects in general. This aspect, together with the result obtained from tracking studies about transverse beam acceptance, led us to fix $V_{RF} = 4$ MV as a reference value for the RF cavity voltage.

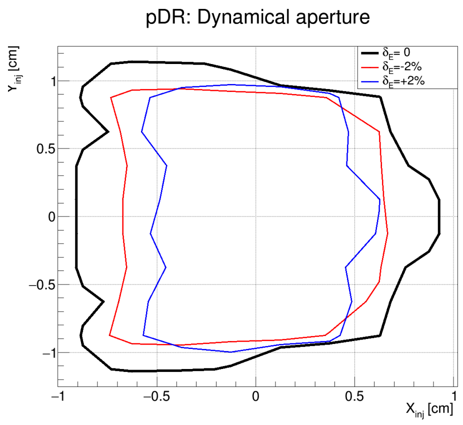

Figure 2: Dynamic aperture. The transverse stable region is shown for the nominal beam energy (1.54 GeV - black) and for ±2% energy relative deviation (blue and red, respectively). While the stable region is kept quite constant within 2% energy spread is observed to drop significantly for higher deviations.

### *DR Layout upgrades*

The current DR design uses 232 dipole magnets, which requires high number of components such as: quadrupoles, sextupoles, octupoles, steering magnets, and beam diagnostics. In parallel to this design, a new DR layout study has been started, in order to avoid high realization costs, complicate installation, and alignment procedures [1, 7]. Moreover, higher energy damping ring option (at 2.86 GeV) is considered, which could lead to a remarkable simplification in the general pre-injector layout maintaining or even reducing the LINACs total accelerating lenght [2].

Preliminary optics studies shows that required beam parameters (2 nm·rad horizontal emittance, and 8 ms damping time) could be achieved by using much less electromagnetic elements compared to the current DR version with the same ring circumference, and the same nominal energy of 1.54 GeV. Furthermore, it is also shown that design parameters meet the prerequisite of the pre-injector complex with a DR working at the energy of 2.86 GeV, and having larger circumference (around 380 m) [7, 8].

## TRANSFER LINES

The design of the FCC-ee TL is inspired by criteria of high modularity, suitable to deal with a project in constant evolution, and, as a consequence, requiring frequent modifications.

The optics for the electron beam TL, eTL, was also designed, even though at the moment it does not represent a priority. The eTL includes a long 180 degrees arc turning around the DR. Preliminary studies to evaluate a possible contribution of the CSR to the beam emittance dilution were performed by using the ELEGANT [9, 10] simulation code, which did not outline any harmful issue.

Presently the positron beam TL, pTL, include a line driving particles from the pLINAC to the DR injection section, pTLi, and an extraction line bringing the damped beam back to the cLINAC, pTLe. The pTLe relies on two 90 degrees arcs based on Triple Bend Achromat (TBA) cell having optics function presented in Fig. 3. The pTLi is very demanding in terms of beam transport efficiency as the beam from the pLINAC features rather broad distributions both in the transverse and in the longitudinal phase space. A design of pTLi

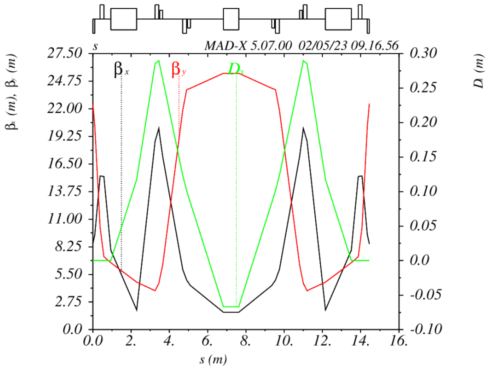

Figure 3: pTLe optics function: betatron amplitudes and dispersion.

and of the DR injection section has been presented at [11]. To improve positron beam injection efficiency in the DR an ECS has been added just after the pLINAC. The pTLe is based on a combination of periodical straight section modules, implemented by a FODO magnetic structure, and arcs built by combining basic cells providing 30 degrees of deflection each. The arcs in the pTLe are periodic structures based on isomagnetic TBA. The bends are rectangular magnets providing 10 degrees deflection angle each, but having asymmetric lengths, with the central being the shorter one.

Each cell is achromatic, isochronous, has moderate betatron oscillation amplitude both in the horizontal and in the vertical plane, and moderate maximum horizontal dispersion excursion, $|\eta_x| < 0.3$ m. The cell also features very low $\mathcal{H}$ function values suitable to avoid possible beam quality degradation induced by CSR emission.

## ENERGY COMPRESSOR

Preliminary studies of the DR dynamic aperture show that the stability region shrinks to almost the incoming beam size as the relative energy variation exceeds ±2%. The RMS energy spectrum of the incoming positron beam is approximately ±4%, and only the 77% of these particles lie within ±2% the nominal energy. The number of particles accepted by the DR can be increased placing an ECS [12, 13], in the pTLi. The ECS consists of a c-shape chicane with $R_{56}$<0, and by two RF cavities tuned on the zero crossing. The combination of the coordinates transformation associated with this elements permits to rotate the bunch in the longitudinal plane compressing the energy distribution. The ECS uses the same type of cavity foreseen for the pLINAC working at the frequency of 2 GHz and optimized to handle the big transverse dimensions of the beam. Two cavities of this type can provide an accelerating voltage of 120 MV. The chicane includes four dipoles 1.39 m long separated by 1 m long drifts. The ECS parameters, R56 and RF voltage, have been evaluated analytically applying first order transformation to the simulated bunch particle distribution at the end of the pLINAC. Extensive ECS simulations confirmed the design assumptions. In the simulations, dipole bending angles of 12.9°, corresponding to a magnetic field of 0.9 T, and resulting in a $R_{56}$ = 0.205 m, plus a RF voltage of 99 MV were considered. Fig. 4 shows how the positron energy distribution modifies after the ECS: blue and brown histograms represent the initial and final energy distribution respectively. Thanks to the ECS 94% of the particles lies within ±2% of the nominal energy.

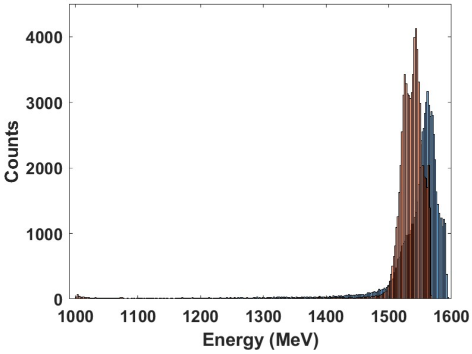

Figure 4: Histogram of the beam energy distribution before(blue) and after(red) the energy compressor.

## BUNCH COMPRESSOR

The bunch compressor has to compress the bunch length, expected to be in the range 3-5 mm, of the beam coming from the damping ring down to 1 mm. The relative beam energy spread at the exit of the bunch compressor has to be <0.7 % to ensure the compatibility with the cLINAC. This limits the maximum relative energy chirp $(d\gamma/\gamma/dz)$ that can be used to compress the beam to 1.3 m$^{-1}$. Consequently, the $R_{56}$ needed to compress the beam by a factor 5 is $|R_{56}|$>0.6 m. It is possible to increase the energy chirp used to compress the beam and reduce the needed $R_{56}$ by placing two RF cavities, phased at the opposite zero crossing, just after the compressor. Several options can be considered for the design of the bunch compressor.

## CONCLUSION

We have presented the status of the WP4 of the pre-injector of the FCC-ee project. The dynamic aperture of the damping ring has been evaluated for the expected positron beam parameters. The acceptance of the damping ring is improved by the energy compressor, here presented, and has expected to be above the 85% for the ideal case. The design of the bunch compressor has started. Further integration of the elements and an analysis of the effects of errors and imperfections will be applied in the near future.

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# REFERENCES

[1] A. Abada *et al.* “FCC-ee: The Lepton Collider”, *Eur. Phys. J. Spec. Top.*, 228, 261–623 (2019), `https://doi.org/10.1140/epjst/e2019-900045-4`.

[2] S. Bettoni *et al.* “FCC-ee Injector Study and the P3 Project at PSI”, *CHART Scientific Report 2022*, January, 2023.

[3] Eisken, O. et al. "Collective Effects Estimates for the Damping Ring Design of the FCC-ee" in*Proc. of IPAC2022*, Bangkock, THI, 2022, paper THPOST003, `doi:10.18429/JACoW-IPAC2022-THPOST003`

[4] Forest, E. and Schmidt, F. and McIntosh, E, “Introduction to the Polymorphic Tracking Code”, *"Technical Report KEK" 2002-3, 2002.*

[5] Deniau, L et al., “The MAD-X Program: User’s Reference Manual (v.5.08.01)”, *CERN ADS.* 2000.

[6] Boussard, D. and Linnecar, T., “THE LHC SUPERCONDUCTING RF SYSTEM”, *"LHC Project Report" 316, 1999.*

[7] O. Etisken *et al.* ‘“New consideration for the damping ring design of the FCC e+e- injector complex”, presented at the IPAC’23, Venice, Italy, May 2023, paper MOPL175, this conference.

[8] P. Craievich *et al.* “FCCee: Pre-Injector complex overview”, *FCC-ee Pre-injector: CHART Collabration Meeting*, 20 and 21, April (2023).

[9] G. Borland *et al.*, “ELEGANT, A Flexible SDDS-Compliant Code for Accelerator Simulation”, *Advanced Photon Source.* LS-287, 2000.

[10] G. Borland *et al.*, “Modeling of the microbunching instability”, *Physical review accelerators and beam*, vol. 15, p. 112804, 2008.

[11] C. Milardi *et al.*, “FCC-ee pre-injector WP4 Damping ring, and transfer lines general status”, *FCC-ee Pre-injector: CHART Collabration Meeting*, 20 and 21, April (2023).

[12] H. Herminghaus and K.H. Kaiser, “Design, construction and performance of the energy compressing system of the Mainz 300 MeV electron linac”, *Nuclear instruments and methods*, Volume 113, Issue 2, 15 November 1973, Pages 189-194.

[13] T. Asaka *et al.*, "Stabilization of the rf system at the SPring-8 linac", *Nuclear instruments and methods*, Volume 488, Issues 1–2, 1 August 2002, Pages 26-41.