AN UPDATED ASSESSMENT OF THE ELECTRON CLOUD EFFECTS IN THE DAMPING RING OF THE FCC-ee INJECTOR COMPLEX

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Abstract

The new FCC-ee injector complex design, as outlined in the feasibility report, consists of an electron source, two separate linacs for electron and positron beams to accelerate beams up to 2.86 GeV, a positron production target, a damping ring at 2.86 GeV energy for emittance cooling, a bunch compressor, a high energy linac to accelerate the beam up to 20 GeV, and an energy compressor. The primary function of the damping ring design is to accept the 2.86 GeV positron and electron beams coming from the electron linacs, reduce their beam emittances, and deliver the required beam quality for injection into the subsequent high-energy linac. It is essential for decreasing the emittance of the incoming positron beam from 2.36×10^{-6} m·rad to about 1.8×10^{-9} m·rad. Among the collective effects that may limit the performance of the positron rings, the electron cloud (e-cloud) effect remains one of the most significant challenges. This paper presents the results of updated studies of the e-cloud impact on various damping ring design options for the FCC-ee, including the latest version.

INTRODUCTION

The Future Circular Collider e^+e^- (FCC-ee) is a proposed high-luminosity precision frontier collider aiming to perform detailed studies of the Higgs boson, the electroweak sector through precision measurements of the W and Z bosons, and the top quark. The FCC-ee injector complex relies on a 2.86 GeV damping ring (DR) to achieve the low beam emittances required prior to acceleration in the high-energy linac and booster synchrotron, in order to satisfy the stringent luminosity requirements of the collider ring. Several DR lattice configurations have been investigated during the FCC conceptual design and feasibility study phases of the project [1–7].

The e-cloud effects constitute one of the major collective limitations in high-intensity positron storage rings. Electrons present in the vacuum pipe can be trapped by the fields of the positively charged circulating particles. When free electrons in the vacuum chamber get accelerated in the electromagnetic field of the beam and hit the chamber walls, electron amplification can occur through the multipacting effect. In this context, analytical threshold estimations, build-up simulations, and heat-load calculations have been carried out for the considered DR design options [8–12].

Two alternative DR designs are considered: six-fold symmetry featuring a circumference of 373.78 m (baseline option) and three-fold symmetry (alternative option) with 384.87 m circumference. The beam parameters used in the analytical and numerical calculations for the DR design options are summarized in Table 1. The e-cloud formation depends on beam and machine parameters. Among these, the Secondary Electron Yield (SEY) of the vacuum chamber surface constitutes one of the most critical inputs for e-cloud simulations. The SEY is defined as the ratio between the emitted and impacted electron current as a function of the energy of the impacting electrons. Since the vacuum chamber material and surface treatment have not yet been finalized, a range of SEY values has been considered in the simulations.

Table 1: Beam Parameters for Both Damping Ring Options: Six-fold and Three-fold Symmetry

Parameter	**Six-fold**	**Three-fold**
Circumference [m]	373.78	384.87
Beam energy [GeV]	2.86	2.86
Eq. hor. emit. [nm·rad]	3.37	1.76
Damping time (hor.) [ms]	6.0	6.46
Mom. compaction fac. (10^{-2})	0.16	0.17
Eq. bunch length [mm]	6.83	8.26
Energy spread (10^{-2})	0.08	0.08
Energy loss/turn [MeV]	1.18	1.13
Harmonic number	499	513
Number of bunches	20 (or 28)	20 (or 28)
Beam current [mA]	83.83	78.57
Bunch spacing [ns]	25	25
Bunch intensity (10^{10})	3.15	3.15
Bending magnet field in the arc [T]	0.98	0.94
Assumed chamber radius (x/y) [mm]	25/9	25/9

ELECTRON CLOUD CALCULATIONS

Analytical Estimates

The electron build-up saturates when the attractive beam field is compensated by the field of the electrons, at a neutralization density, given by [11]:

$$\rho_{\mathrm{neutr}} = \frac{N_b}{L_{\mathrm{sep}} \pi b_x b_y}, \qquad (1)$$

where L_{sep} [m] is the bunch spacing, N_b is the bunch intensity, $b_{x/y}$ are the horizontal and vertical vacuum chamber radii, respectively. The single bunch e-cloud instability (ECI) occurs above the electron density threshold estimated by [11,

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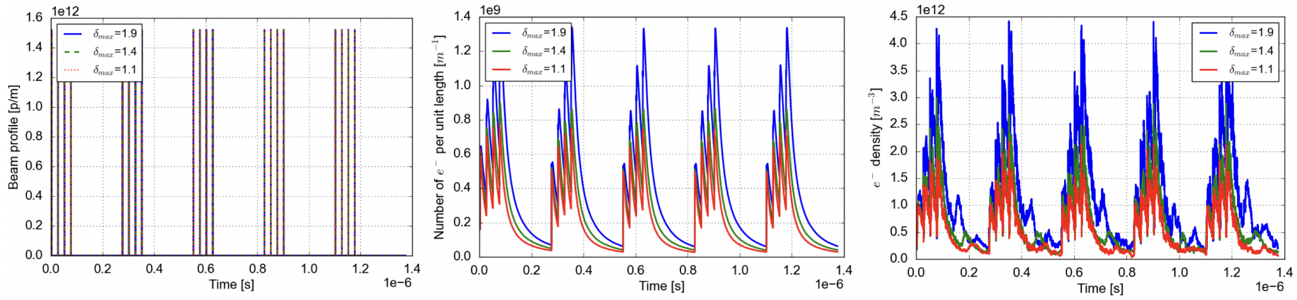

Figure 1: The electron cloud build-up simulation results for the three-fold DR design option: Beam profile (left), e-cloud build-up line density (middle), and central e-cloud volume density (right) for maximum SEY of 1.9 (blue), 1.4 (green), and 1.1 (red).

13, 14]:

$$\rho_{\text{th}} = \frac{2\gamma Q_s}{\sqrt{3} Q r_e \beta_y C}, \tag{2}$$

where $Q = \min(7, \frac{w_e \sigma_z}{c})$ is the angular oscillation frequency of the electrons interacting with the beam, with ${w_e}^2 = \frac{N_b r_e c^2}{2\sigma_z \sigma_y (\sigma_x + \sigma_y)}$. The relation between the e-cloud density (ρ_e) and the tune shift (ΔQ) is given by [15] (with a simple model of a uniform cloud):

$$\rho_{\text{e}} = \frac{2\gamma \Delta Q}{r_e C < \beta >}. \tag{3}$$

Accordingly, the neutralization density was calculated as $5.94 \times 10^{12}/\text{m}^3$, ECI density threshold (ρ_{th}) $0.79 \times 10^{12}/\text{m}^3$ and $1.81 \times 10^{12}/\text{m}^3$ at equilibrium state (see Table 2) for six-fold and three-fold option, respectively. The neutralization density exceeds the threshold at the equilibrium state for both options. In this regard, we have investigated e-cloud formation with detailed simulations.

Build-up Simulations

In addition to the analytical estimates, e-cloud build-up simulations were performed using the PyECLOUD simulation code [16] in order to investigate the formation and evolution of the e-cloud in the vacuum chamber, and compare the numerical results with analytical predictions. Initially, the simulations were carried out for the dipole magnets in the arc sections for both DR configurations under equilibrium conditions.

Table 2: The e-cloud Calculations for the DR Options

Analytical estimates	**Three-fold**	**Six-fold**
Neutr. density [$10^{12}/\text{m}^3$]	5.94	5.94
ΔQ (h) @neutr. density	0.0023	0.0044
ΔQ (v) @neutr. density	0.0032	0.0073
ECI dens. th. @inj. [$10^{12}/\text{m}^3$]	117.1	802
ECI dens. th. @eq. [$10^{12}/\text{m}^3$]	1.81	0.79
Numerical results @eq.		
ρ_{central} @δ_{max}=1.9 [$10^{12}/\text{m}^3$]	4.3	4.1
ρ_{central} @δ_{max}=1.4 [$10^{12}/\text{m}^3$]	3.0	2.7
ρ_{central} @δ_{max}=1.1 [$10^{12}/\text{m}^3$]	2.2	1.8

For the three-fold DR design, parameters used in the simulation are the following: initial number of electrons is 1.6×10^8, bunch population is 3.15×10^{10}, maximum SEY (δ_{max}) is 1.9 (additional simulations were also performed for δ_{max}=1.4 and δ_{max}=1.1), energy at maximum SEY (E_{max}) is 332 eV, external magnetic field is 0.94 T, bunch length is 8.26 mm, vacuum chamber radii are 25 mm/9 mm in the horizontal and vertical planes, respectively, and a total bunch number is 20 with 25 ns bunch spacing. The e-cloud formation obtained from the simulations is presented in Figure 1. The beam structure, as each line symbolizes a bunch, consists of four consecutive bunches followed by seven empty RF buckets, repeated five times, corresponding to the total of 20 bunches, i.e. 5×(4×[1.]+7×[0]) (see Fig. 1, left). The simulated e-cloud line density evolution (number of electron per unit length vs time) is shown in the middle plot of Fig. 1. Accordingly, the e-cloud builds up step by step after each bunch passage and it decreases dramatically between bunch trains, it reaches up to 1.35×10^9 m^{-1} at δ_{max}=1.9. The e-cloud central volume density rises after each bunch reaches values of approximately 4.3×10^{12} m^{-3} (see Fig. 1 on right) at δ_{max}=1.9. The volume density becomes 3.0×10^{12} m^{-3} and 2.2×10^{12} m^{-3} for δ_{max}=1.4 and δ_{max}=1.1, respectively. Thus, the simulated central electron density is therefore of the same order as, and in several time intervals exceeds, the analytical instability threshold reported in Table 2. This indicates that the machine may operate in a regime susceptible to electron-cloud-induced effects, motivating subsequent beam-dynamics studies.

For the six-fold DR design, same initial number of electrons, bunch population, δ_{max}, E_{max}, vacuum chamber radius, bunch filling pattern with the three-fold option are used in the simulation. In addition, external magnetic field is 0.98 T, bunch length is 6.83 mm, geometrical equilibrium emittance is around 3.37 nm·rad which is almost two times larger than three-fold option. The e-cloud formation obtained from the simulations is presented in Fig. 2. The e-cloud builds up after each bunch passage up to 1.30×10^9 m^{-1} at δ_{max}=1.9 and it decreases dramatically between bunch trains (see in the middle of Fig. 2). The e-cloud central volume density reaches values of approximately 4.1×10^{12} m^{-3} (see Fig. 2 on right) at δ_{max}=1.9. The volume density becomes 2.7×10^{12} m^{-3} and 1.8×10^{12} m^{-3} for δ_{max}=1.4 and

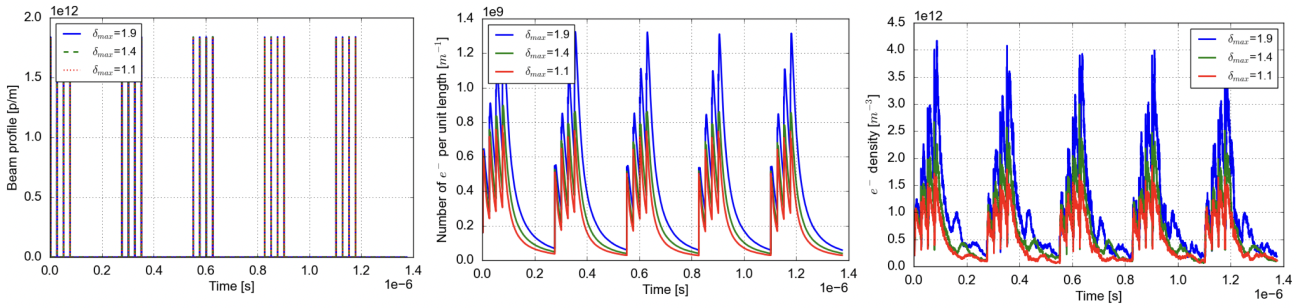

Figure 2: The electron cloud build-up simulation results for the six-fold DR design option: Beam profile (left), e-cloud build-up line density (middle), and central e-cloud volume density (right) for maximum SEY of 1.9 (blue), 1.4 (green), and 1.1 (red).

δ_{max}=1.1, respectively. Thus, similarly to the three-fold option's results, further instability simulations using PyHEADTAIL will be performed to assess the impact of the accumulated e-cloud on beam stability for the DR in the following process.

Heat Load Calculations

The heat load has also been simulated for both DR options. For this simulation, the following two different bunch populations (ppb) were evaluated: $3.15{\times}10^{10}$ and $4.70{\times}10^{10}$ for different SEY values varying between 1.1 and 1.9. Consequently, heat load in the dipole magnet corresponding to the beam parameters presented in the Table 1 remains below 0.05 W/m for the considered SEY values and bunch-intensities for both options. The heat-load calculations are shown in Fig. 3 for the six-fold DR option. This value is well below heat-load levels usually considered critical in accelerators. Therefore, heat load is not expected to be the limiting electron-cloud effect. The results for the three-fold option, although not presented here, are comparable.

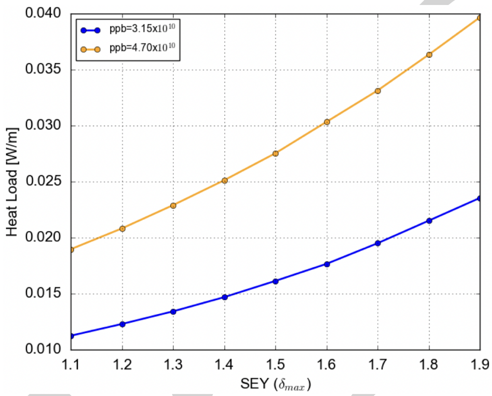

Figure 3: Heat load calculation for different bunch intensities for various SEY in the dipole magnet for six-fold DR option.

Further Simulations

Additional simulations were performed for the six-fold symmetry DR configuration using a filling pattern consisting of 28 consecutive bunches with 50 ns bunch spacing in order to further assess the electron cloud formation. In this configuration, the bunches are uniformly distributed around the DR circumference, with a bunch population of 3.15×10^{10}. As expected, the simulated electron cloud build-up level is significantly reduced compared with the case employing shorter bunch spacing (see Fig. 4).

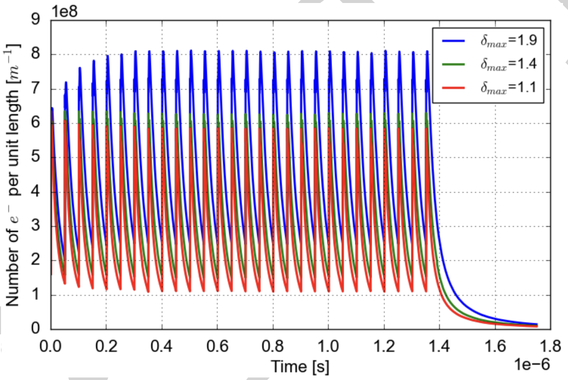

Figure 4: The e-cloud build-up line density for the six-fold DR option with a filling pattern of 28 consecutive bunches and 50 ns bunch spacing, for maximum SEY of 1.9 (blue), 1.4 (green), and 1.1 (red).

CONCLUSION

The e-cloud build-up simulations have been performed for the FCC-ee damping ring design options, namely the six-fold symmetry (baseline) and three-fold symmetry (alternative) configurations. The simulated electron cloud densities for both options are found to be comparable to the analytically estimated instability threshold values. In several time intervals, the simulated densities exceed the analytical thresholds, indicating that the machine may operate in a regime susceptible to electron-cloud-induced effects. The obtained results therefore motivate further beam-dynamics investigations using PyHEADTAIL in order to evaluate the impact of the electron cloud on beam stability. On the other hand, the estimated heat load associated with the electron cloud is not expected to constitute the dominant limiting effect for the considered operating conditions. Future work will include additional build-up studies for different bunch filling patterns and detailed instability simulations.

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