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ELECTRON CLOUD BUILD-UP FOR THE ARC SEXTUPOLE SECTIONS OF THE FCC-ee

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Abstract

In particle accelerators that operate with positrons, an electron cloud may occur due to several mechanism. This work reports preliminary studies on electron cloud build-up for the arc sextupole sections of the positron ring of the FCCe+e- using the code PyECLOUD. We compute the electron cloud evolution while varying strategic parameters and consider three simulation scenarios. We report the values of the central density just before the bunch passage, which is related to the single-bunch instability threshold and the electron density threshold for the three scenarios. In addition, we compare the simulated electron distribution across the central circular cross-section for a chamber with and without winglets.

INTRODUCTION

The electron-cloud (EC) effect is a phenomenon that occurs in high-energy particle accelerators that operate with positrons (or positively charged beams). It consists of the accumulation of electrons inside the machine vacuum chamber produced by a secondary emission process, where seed electrons come from the residual gas ionization or a photoemission process due to the beam-induced synchrotron radiation. Commonly electrons generated by this last mechanism constitute the main source of primary electrons in high-energy accelerators, such as the Future Circular electron-positron Collider (FCC-ee).

In the positron ring of the FCC-ee, it is expected that the electric field of the beam would accelerate these electrons to energies of up to several hundred eV [1]. Once the beam passes, these electrons will collide with the chamber walls and, depending on their speed, position, direction, and the beam pipe surface conditions, can generate new electrons. This process is repeated with each new bunch passage, and, due to the multipactor effect induced by the beam, an avalanche growth of the number of electrons may arise generating an electron cloud [2]. The EC density in the chamber can reach high levels and drive instabilities in the beam, such as the single-bunch head-tail instability [3].

The EC density is a critical aspect in order to avoid this instability. It depends on parameters such as the bunch spacing, the geometry of the vacuum chamber, photoelectron generation rate (n_γ), and the secondary emission yield (SEY) [4]. In this work, we present an analysis of the dependence of the electron density for three different scenarios to determine which presents the broadest range of variation of the aforementioned parameters below the instability threshold.

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ELECTRON DENSITY THRESHOLD AND SIMULATION SCENARIOS

Scenarios

The FCC-ee is a proposed first stage post-LHC particle accelerator with energy significantly above that of previous circular colliders [5]. It is still in the design stage, and its operating parameters are constantly updated. We consider three scenarios for the EC build-up simulations of the main arc sextupole sections. The first one considers the design parameters extracted from the 2019 conceptual design report (CDR) to be used as a reference [6] (named *Scenario A*). In November 2021, a careful review of the parameters presented in the CDR resulted in an update, starting with a smaller circumference and only eight arc sections [7], these updated parameters make up our *Scenario B*; however, this set cause coherent beam instability issued, including high impedances [8], consequently in March 2022 an alternative set of parameters with slight changes was presented, which we named *Scenario C*.

Electron Density Threshold

The electron cloud acts as a short range wake field with frequency [9]:

$$\omega_e = \sqrt{\frac{2\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}} \tag{1}$$

where $\lambda_p = \frac{N}{4\sigma_z}$ is the line charge density, N the bunch population and σ_z bunch length, r_e is the classical electron radius and $\sigma_{x,y}$ are the transverse beam dimensions.

The threshold density for the single-bunch head-tail instability is given by:

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

where Q_s is the synchrotron tune, C the machine circumference, γ the Lorentz factor and $Q = min\left(7, \frac{\omega_e \sigma_z}{c}\right)$.

The electron density threshold and the values used to compute them using Eqs. (1) and (2) are listed in Table 1 for each scenario.

The smallest threshold is found with the data extracted from the CDR with a value of $2.99 \times 10^{10}\ e^-/m^3$, while the threshold for scenarios B and C is essentially the same, with a value of $4.75 \times 10^{10}\ e^-/m^3$.

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Table 1: Single Bunch Head-tail Instability Threshold

Parameter		Scenarios A	B	C
N $\times 10^{11}$		1.76	2.76	2.43
C	km	97.756	91.180	91.174
σ_z	mm	3.5	4.32	4.38
σ_x	μm	120	188.41	188.41
σ_y	μm	7	8.42	8.42
r_e	m		2.817×10^{-15}	
β_y	m		50	
Q_s		0.025	0.0370	0.0370
γ			$\approx 1 \times 10^5$	
$\rho_{\mathbf{th}} \times \mathbf{10^{10}}$	$\frac{1}{m^3}$	**2.99509**	**4.75244**	**4.75275**

SIMULATION PARAMETERS

The FCC-ee vacuum chamber design considers a circular vacuum cross-section with a pair of narrow horizontal winglets to reduce the considerable amount of photons generated due to synchrotron radiation. The simulations were done using this type of chamber and a circular chamber without winglets as a reference to identify the impact of the winglets on the electron cloud build-up. In both cases the radius of the circular cross section of the chambers has been set at 35 mm, while the width of the chamber with winglets is proposed to be 120 mm [10] (see Figs. 4 and 5). For this analysis, the CERN PyECLOUD code was employed varying three strategic parameters n_γ, SEY, and bunch spacing [11].

On the other hand, the number of primary electrons generated by a single positively charged particle per unit length is given by [12],

$$n_\gamma = Y_\gamma \frac{dN_\gamma}{dz} \tag{3}$$

where Y_γ represents the photoelectron yield coefficient, and $\frac{dN_\gamma}{dz}$ the number of electrons emitted per length. This last value is represented by $\frac{dN_\gamma}{dz} = \frac{5\alpha\gamma}{2\sqrt{3}\rho}$, where $\alpha \approx 1/137$ denotes the fine structure constant, $\rho \approx 10000$ m the bending radius for the FCC-ee, and $\gamma \approx 10^5$ the Lorentz factor taking an energy of 45.6 GeV. For the FCC-ee collider arcs, the value of Y_γ is reduced because the antechamber will remove a large fraction of the synchrotron radiation photons from the beam pipe (typically its value is approximately 0.1 photoelectrons emitted per photon absorbed [12]). Therefore, in this study we analyze the photoelectron generation rate from 1×10^{-6} to 1×10^{-3} m^{-1}.

Another strategic parameter is the secondary emission yield, which is defined as the ratio between the number of secondary electrons emitted for each incident primary electron [13],

$$\delta(E) = \frac{I_{sec}}{I_{pri}(E)} \tag{4}$$

where E is the impact energy of the electron, I_{sec} represents the secondary electron current and I_{pri} the current of primary electrons that collide on the wall. The SEY typical scanning starts at 1.1 and ends at 1.5 with increments of 0.1. Finally, the bunch spacing is also varied. We take values previously analyzed in the literature (25 ns and 30 ns) [4] and we proposed a third spacing of 32.25 ns. The complete values using in PyECLOUD are shown in the Table 2.

Table 2: Main Parameters used for the Simulations

Parameter name	Scenarios A	B	C
Beam energy		45.6 GeV	
Bunch spacing		25 ns, 30 ns, 32.25 ns	
N $\times 10^{11}$	1.76	2.76	2.43
Chamber type		Circular, Winglets	
SEY		1.1, 1.2, 1.3, 1.4, 1.5	
n_γ		1e-3, 1e-4, 1e-5, 1e-6	
Filling pattern		150*[1]+200*[0]	
Trains per beam		1	
Beam pipe radius		35 mm	
Sextupole		201.64 T/m^2	

RESULTS AND CONCLUSIONS

Electron Density at the Center of the Chamber

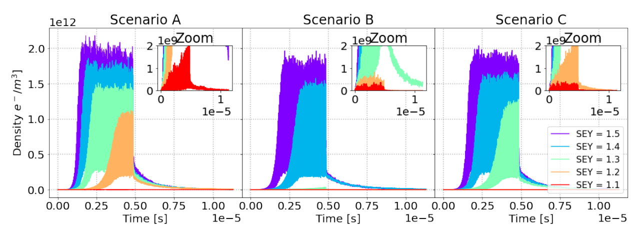

Figure 1: Electron density at the center of a chamber with winglets. Paramaters: n_γ = 1e-6 and 32.25 bunch spacing.

Figure 1 shows the electron density at the center of the chamber with winglets using n_γ =1e-6 and 32.25 ns bunch spacing. The design parameters (scenario A) show the highest densities, while the updated parameters B presents the lowest values for the electron density. For a circular chamber (without winglets), the electron density behaviour is similar to those shown in Fig. 1 for each scenario. However, a slight increase is found for this cross-section, ranging from 0.43 to 5.74%.

Electron Density Contour Plots for Each Scenario

The electron density value prior to the bunch arrival is the critical parameter that drives beam instabilities. To identify the broadest range of the simulation parameters below the instability threshold contour plots were employed. Figure 2 shows contour maps of SEY vs n_γ along with the average densities just prior to bunch arrival for a circular chamber. Each box is divided into a grid of 20 combinations and the threshold is drawn with a white dotted line. We observed

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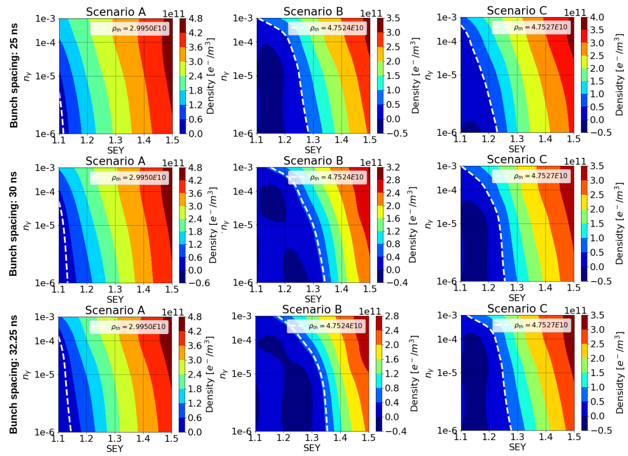

Figure 2: Comparison between contour maps of SEY vs n_γ in a sextupole using a circular chamber and bunch spacing of 25 ns (top), 30 ns (middle) and 32.25 ns (bottom).

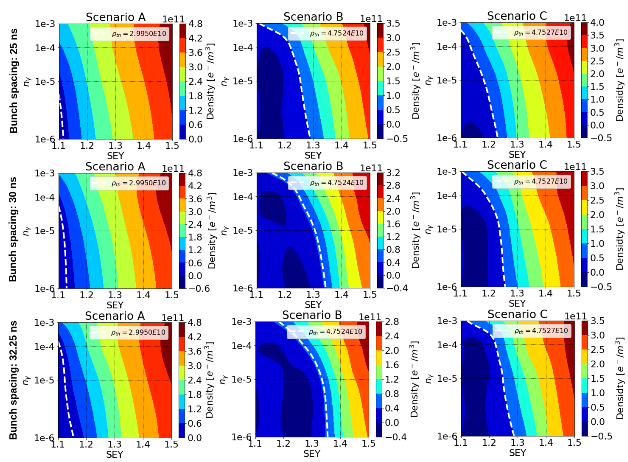

Figure 3: Comparison between contour maps of SEY vs n_γ in a sextupole using a chamber with winglets and bunch spacing of 25 ns (top), 30 ns (middle) and 32.25 ns (bottom).

that scenario B is the most convenient because it presents the broadest range of possible values for n_γ and SEY below the electron density threshold. On the contrary, scenario A is the most restrictive one. For all scenarios, 25 ns is the most restrictive bunch spacing. With a spacing of 32.25 ns, Scenario B is the most flexible and has 45% of the combinations for n_γ and SEY values below the threshold. Overall, bunch spacing that reduces the multipactor effect is 32.25 ns. For all the scenarios and combinations explored, a SEY below 1.4 is recommended to avoid the head-tail instability arising. On the other hand, Fig. 3 shows the same contour maps on a chamber with winglets. We observed that comparing the cross-section chambers, the use of winglets has a negligible impact on the electron density values except in Scenario B, with a bunch spacing of 30 ns. All the other results are the same as when using a circular chamber.

Sequence of EC Build-up along the Bunch Passage

Regarding the influence of the cross-section with winglets, a comparison with the circular chamber as a reference is shown in Figs. 4 and 5; we can observe the electron cloud evolution along a single bunch passage using a chamber without and with winglets, respectively. At the beginning of the passage, the snapshot at 2.934 μs shows the electrons inside the vacuum chamber being attracted to the central region due to the beam's electric field, and the electrons start to accumulate around the central region of the vacuum chamber. During the passage (snapshot at time of 2.903 μs), the accelerated electrons follow the field lines generated by the sextupolar magnet, and hit the chamber wall, where they create new electrons through a secondary emission process. At the end of the passage (snapshot at the time of 2.934 μs) the electron density increases due to the newly generated electrons, and we can observe a typical cloud formation just prior to the next bunch's arrival. When comparing the cross-section chambers, winglets have a negligible impact on the EC during the bunch passage. From the results, we notice a small density inside the winglets and almost negligible, at least two orders of magnitude smaller than the rest of the chamber. Electrons are attracted to the positive charge of the beam, and due to the sextupolar field arrangement they are trapped and do not enter into the winglets.

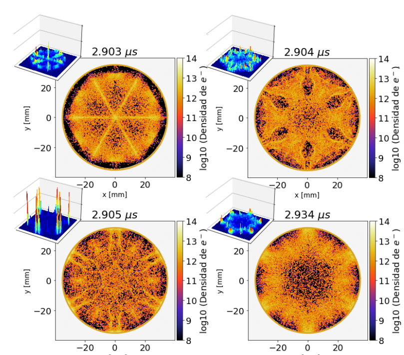

Figure 4: Snapshots of the electron cloud evolution along with a single passage using a circular chamber.

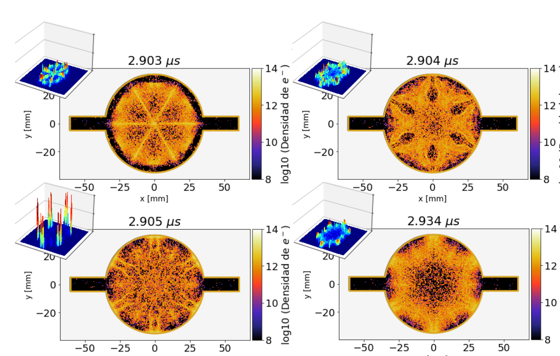

Figure 5: Snapshots of the electron cloud evolution along with a single passage using a chamber with winglets.

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