

ELECTRON CLOUD MITIGATION TECHNIQUES FOR THE FCC-ee

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Abstract

The Future Circular Collider (FCC)-ee is a planned electron-positron collider under development. The future collider would be built in an about 91 km ring-shaped underground tunnel located beneath the French departments of Haute-Savoie and Ain, and the Swiss canton of Geneva. The FCC-ee may face challenges from electron cloud (e-cloud). The strongest effects are foreseen for the Z configuration, due to the highest number of bunches, which corresponds to the smallest bunch spacing, which is a key parameter for the e-cloud formation process. A high electron density in the beam pipe could limit the accelerator's achievable performance through various mechanisms, such as transverse instabilities, transverse emittance growth, particle losses, vacuum degradation and additional heat loads on the inner surface of the vacuum chambers. In the design phase, the objective is to suppress the e-cloud effects in the FCC-ee. Therefore, effective e-cloud mitigation techniques, to avoid the e-cloud avalanche multiplication and its deleterious effects, are discussed in the paper.

INTRODUCTION

The Future Circular Collider (FCC)-ee is a proposed electron-positron collider with a circumference of approximately 91 km [1]. Electron cloud (e-cloud) build-up can occur in circular particle accelerators, particularly those operating with positively charged particles. In such instances, the trailing bunches within each train pass through a dense distribution of electrons, potentially causing unwanted effects. These harmful effects of e-cloud formation have been observed in various accelerators worldwide [2–4]. As a result, mitigating e-cloud formation is a critical task for circular accelerators, emphasizing the importance of studying suppression methods during the design phase of a particle accelerator.

The process of electron cloud formation is complex and depends on various parameters. Specialized tools and simulation codes are essential for modelling the physical phenomena occurring within particle accelerators, making them fundamental during the design phase. PyELOUD is a 2D Macro-Particle (MP) code specifically developed to simulate the e-cloud formation process (commonly referred to as e-cloud build-up) in the transverse sections of a particle accelerator [5].

This paper focuses on investigating the impact of e-cloud effects in the FCC-ee to develop effective mitigation strategies. The study is based on the parameters outlined in the mid-term feasible study report [6], with preliminary analyses using earlier FCC-ee parameter configurations presented

in [7]. Firstly, an overview of the FCC-ee parameters is provided, with particular emphasis on the key parameters influencing the e-cloud formation process. The material property constraints necessary to prevent e-cloud build-up, expressed in terms of Secondary Emission Yield (SEY) multipacting thresholds, are presented for the baseline scenario. These constraints are stringent, necessitating the exploration of potential mitigation techniques. Avoiding multipacting is critical to preventing the detrimental effects of e-cloud formation in particle accelerators.

SEY MULTIPACTING THRESHOLDS WITH BASELINE SCENARIO

The process of e-cloud formation is complex and depends on various beam and machine parameters. External magnetic fields strongly influence electron trajectories, causing electrons to spiral around the field lines. Additionally, the spacing between particle bunches determines whether electrons can survive between successive bunch passages. Bunch intensity and length are also crucial factors, as they dictate the acceleration experienced by the electrons. The geometry of the chamber affects both electron acceleration and their time of flight, while surface properties are key to the electron multiplication process. The primary parameter involved in this phenomenon is the SEY, defined as [8]:

$$SEY(E) = \frac{I_{emit}}{I_{imp}(E)}, \quad (1)$$

where I_{emit} is the emitted current and I_{imp} is the impinging current. The SEY depends on the chemical properties of the surface as well as its history, particularly the accumulated electron dose. Additionally, bunch spacing plays a crucial role, as it determines the number of electrons that can survive between consecutive bunch passages. This parameter significantly impacts the multipacting threshold, i.e., the SEY value above which avalanche multiplication is triggered. Bunch intensity and bunch length are also important factors, as they influence the acceleration experienced by the electrons. Furthermore, electron trajectories are strongly affected by externally applied magnetic fields.

FCC-ee is currently in the design stage, with the machine and beam parameters evolving throughout this phase. The FCC feasibility study mid-term report serves as baseline scenario [6], and an investigation on the FCC-ee parameter ranges of interest has been conducted. The FCC-ee vacuum chamber has a circular cross-section with a radius of 30 mm. The vacuum chamber features two horizontal winglets, each with an internal height of 11 mm and a depth of 22.5 mm. The study focused on the Z configuration (beam energy: 45.6 GeV), as this configuration is expected to experience the strongest e-cloud effects due to the largest number of bunches

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Table 1: SEY Multipacting Thresholds per Arc Element for the Baseline Scenario Parameters

Element	Bunch population	Thresholds
Drift space	nominal	1.4
	below nominal	1.2
Dipole (15.2 mT)	nominal	1.4
	below nominal	1.0
Quadrupole (1.45 T/m)	nominal	1.1
	below nominal	1.0
Sextupole (72.5 T/m ²)	nominal	1.1
	below nominal	1.0

and, consequently, the smallest bunch spacing. Additionally, the analysis has been focused on the positron beam, as positively charged beams are more susceptible to the e-cloud effects. Furthermore, FCC-ee operates as a top-up injection accelerator, making it crucial to understand the behaviour of the e-cloud during the charge accumulation phase. For this reason, the bunch intensity has been studied across a range spanning from one tenth of the nominal bunch intensity to the nominal bunch intensity 2.15×10^{11} ppb (positrons per bunch).

The SEY multipacting thresholds have been calculated per arc element: drift spaces, dipole magnets, quadrupole magnets, and sextupole magnets (see Table 1). The constraints for the materials are tight with the baseline scenario parameters. In particular, quadrupoles and sextupoles have the lowest SEY multipacting thresholds. Another important point is that the most demanding constraints in terms of SEY are for bunch intensities lower than the nominal value. In particular, the most critical intensities fall within the range of 1.00 to 1.50×10^{11} ppb as shown in Fig. 1).

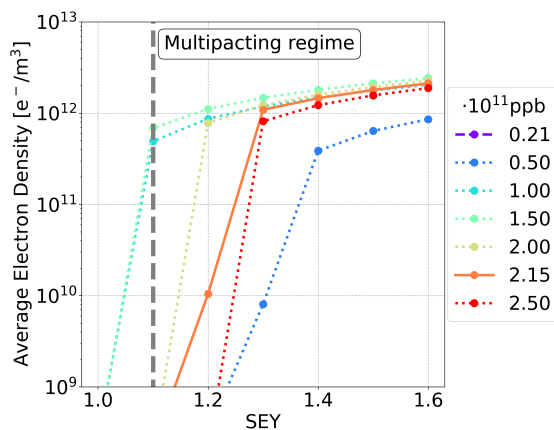


Figure 1: Total e-cloud density in the vacuum chamber versus SEY for different bunch intensities, represented by different colours (with the nominal bunch intensity shown in a solid line). The SEY multipacting threshold, considering different bunch intensities during the charge accumulation phase, is shown by the vertical dashed grey line. The results pertain to the quadrupole magnets.

MITIGATION TECHNIQUES

Multipacting has to be avoided in order to prevent the deleterious effects of the e-cloud in particle accelerators. If e-cloud avalanche multiplication cannot be avoided due to excessively tight material constraints that cannot be met by the properties of the vacuum chamber surface, the side effects of the e-cloud have to be assessed. Firstly, the total additional heat loads in the arcs due to e-cloud are in the order of a percentage of the synchrotron radiation power (50 MW per beam) in case of multipacting, and they are negligible compared to the synchrotron radiation power if there is no multipacting. Secondly, the e-cloud could trigger instabilities, because the e-cloud density exceeds the theoretical stability thresholds [9–11] in different arc elements (drift space, dipole, and quadrupole). Therefore, some e-cloud mitigation techniques are discussed.

Table 2: SEY Multipacting Thresholds per Arc Element for Larger Bunch Spacing

Element	20 ns	25 ns	30 ns	40 ns	50 ns
Drift space	1.1	1.2	1.3	1.5	>1.6
Dipole	1.0	1.0	1.1	1.2	1.3
Quadrupole	1.0	1.0	1.0	1.1	1.3
Sextupole	1.0	1.0	1.1	1.3	1.4

Larger Bunch Spacing

Larger SEY multipacting thresholds could be achieved by employing filling schemes with increased bunch spacing (see Table 2). For instance, a bunch spacing of 50 ns results in SEY multipacting thresholds greater than or equal to 1.3 for all the considered arc elements (see Fig. 2). However, increasing the bunch spacing necessitates a higher bunch intensity to maintain a constant beam current. This increase in bunch intensity could introduce challenges related to other collective effects, such as beam-beam and wake-fields and coupling impedance [12–14].

Special Filling Schemes During the Charge Accumulation Phase

An alternative approach to relax material constraints is to avoid uniformly filling the bunches in the beams. Using this technique, the critical bunch intensities are reached with a larger bunch spacing during the charge accumulation phase avoiding e-cloud build-up, utilising special filling schemes during the charge accumulation phase (see Fig. 3). Two possible options were presented at the FCC week 2024 conference [15]. This strategy allows the SEY multipacting threshold, over the entire charge accumulation phase, to match or approach the SEY multipacting threshold corresponding to the nominal bunch intensity (see Fig. 4 and Table 3). However, a drawback of this method is the presence of bunches with varying intensities coexisting in the collider and, therefore, to find a working point that ensures stability may be difficult.

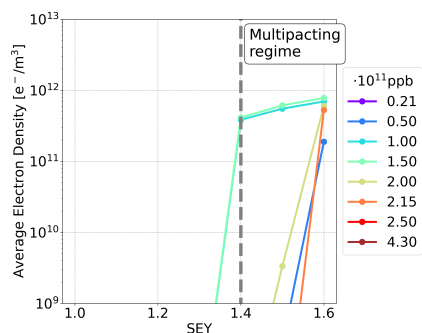


Figure 2: Total e-cloud density in the vacuum chamber versus SEY for different bunch intensities, represented by different colours (with the nominal bunch intensity shown in a solid line). The SEY multipacting threshold, considering different bunch intensities during the charge accumulation phase, is shown by the vertical dashed grey line. The results pertain to the quadrupole magnets and bunch spacing 50 ns.

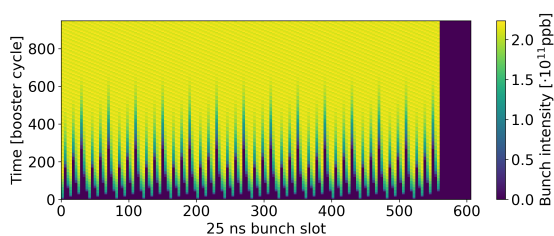


Figure 3: Filling schemes during the charge accumulation phase (vertical axis time in units of booster cycle, horizontal axis time in unit of bunch spacing).

CONCLUSION

An extensive e-cloud study for the FCC-ee has been conducted. Specifically, material constraints required to prevent e-cloud avalanche multiplication have been defined in terms of SEY multipacting thresholds, which are extremely stringent under the baseline parameters. Quadrupoles and sextupoles have the lowest SEY multipacting thresholds. Various methods to relax these material constraints have been explored. One proposed approach involves increasing the bunch spacing, which could allow for less restrictive material constraints. However, this would require increasing the bunch intensity to maintain a constant beam current, potentially leading to challenges with other collective effects. Another suggested solution is to employ special filling schemes during the charge accumulation phase, which could mitigate the tight constraints associated with critical bunch intensities. A downside of this approach is the presence of bunches with varying intensities at the same time in the collider and, therefore, to find a working point that ensures stability may be difficult. Another technique is the use non-uniform bunch spacing, which is extensively discussed in the contribution titled “Filling Pattern with Non-Uniform Bunch Spacing to Mitigate E-Cloud for the FCC-ee” of this conference.

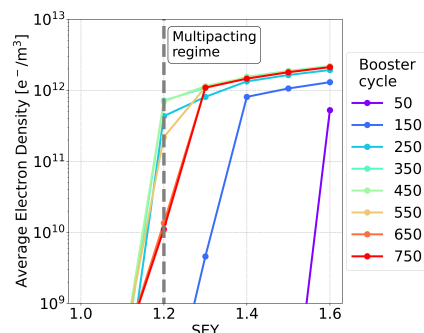


Figure 4: Total e-cloud density in the vacuum chamber versus SEY for different booster cycles during the charge accumulation phase, represented by different colours. The initial e-cloud density is indicated by the horizontal dashed black line. The SEY multipacting threshold, considering different bunch intensities during the charge accumulation phase, is shown by the vertical dashed grey line. The results pertain to the quadrupole magnets.

Table 3: SEY Multipacting Thresholds per Arc Element With Special Filling Schemes During the Charge Accumulation Phase

Element	Special filling schemes during charge accumulation phase
Drift space	1.4
Dipole	1.3
Quadrupole	1.1
Sextupole	1.1

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