Electron cloud build-up studies for FCC-ee

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Abstract. The Future Circular Collider (FCC) study is developing designs for a new research infrastructure to host the next generation of higher performance particle colliders to extend the research currently being conducted at the LHC. In particular, FCC-ee is an electron-positron collider, which is the first stage towards a 100 TeV proton-proton collider FCC-hh. FCC-ee may be affected by electron cloud (e-cloud) and the strongest effects are foreseen for the Z configuration, due to the highest number of bunches, which corresponds to the smallest bunch spacing. The presence of a large electron density in the beam pipe can limit the achievable performance of the accelerator through different effects like transverse instabilities, transverse emittance growth, particle losses, vacuum degradation and additional heat loads of the inner surface of the vacuum chambers. In the design phase, the goal is to suppress the e-cloud effects in FCC-ee and, therefore, a preliminary study to identify the parameters, which play a significant role in the e-cloud formation has been performed. In this paper, an extensive e-cloud simulation study is presented. In particular, the impact of the e-cloud is studied for different configurations, for example: for the electron and the positron beam; in the different elements of the particle accelerator; changing the beam chamber geometry; for different values of the Secondary Emission Yield (SEY); and for different beam parameters.

1. Introduction

FCC-ee is an electron-positron collider, which is the first stage towards a 100 TeV proton-proton collider FCC-hh. In a circular particle accelerator, mainly machines operating with positively charged particles, e-cloud build-up may occur [1, 2]. In this case, the trailing bunches of each train pass through a dense electron distribution that can lead to unwanted effects: transverse instabilities, transverse emittance blow-up, particle losses, heat loads on the beam chambers, vacuum degradation (as observed in several accelerators all over the world [3, 4, 5, 6, 7]). For these reasons, the e-cloud mitigation strategy is a fundamental task at the design stage of a circular particle accelerator (e.g., synchrotron, cyclotron) [8]. The process of the electron cloud formation is complex and depends on several parameters [9].

Studies of the beam stability in the presence of such cloud of electrons can be performed by means of self-consistent simulations for realistic e-cloud distributions obtained from build-up simulations [10, 11] at the different lattice elements. The simulation results can be compared to the theoretical stability limit [12]. The limit of this approach is that the self-consistent beam stability simulations are heavy from a computational point of view. Moreover, at the design stage of the FCC-ee it is important to understand and identify the machine and beam parameters, which play a significant role in the e-cloud formation to guide the machine design.

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In this paper, we present an extensive e-cloud build-up simulation study, in order to investigate a broad range of parameters and to gather the relevant electron densities required to perform a self-consistent beam stability simulation study for the FCC-ee. In particular, using the PyECLOUD code [13] we have characterised the electron cloud formation at different elements of the FCC-ee ring and for different machine and beam properties. In this paper, we will first present the main parameters involved in the study and their impact on the electron cloud formation and the main FCC-ee parameters are discussed. Secondly, the simulation results are discussed.

2. E-Cloud Formation Process and FCC-ee Parameters

The process of the electron cloud formation is complex and depends on several parameters and in the following a summary of the main parameters involved in this process is discussed. Electron trajectories are strongly influenced by externally applied magnetic fields, because the electrons spin around the field lines. Moreover, the bunch spacing determines how many electrons survive between consecutive bunch passages. The bunch intensity and bunch length also have an important effect as they affect the acceleration received by the electrons. The chamber geometry influences electron acceleration and time of flight and the surface properties have a primary role in the electron multiplication process [14]. The main quantity involved is the Secondary Electron Yield (SEY), which is defined as the ratio between emitted and impacting electron current as a function of the energy of the impinging electrons [9]. The SEY plays a key role in the e-cloud formation and, therefore, the goal is to reduce this surface parameter [15, 2, 16]. The SEY depends on surface chemical properties and on the accumulated electron dose. The main strategies to reduce the SEY are: (i) to design the FCC vacuum chambers in terms of material, coating or surface treatment by means of extensive simulation studies; (ii) to reduce accumulated electron dose by means of beam induced scrubbing runs [17].

Among the different FCC-ee operational configurations we have concentrated on the so called Z-mode configuration, because the strongest e-cloud effects are foreseen for this configuration due to the very high number of bunches foreseen approximately 10,000 resulting in an effective bunch spacing of around 30 ns. In the study, the collider optics version *V22.2* has been used [18]. The FCC-ee will be operated in top-up injection mode, therefore we have used collision configuration parameters with the longest bunch length (rms 14.5 mm), where the synchrotron radiation and beamstrahlung effects are considered, is analysed. In this study, 9,450 simulations have been carried out with the following investigated parameters:

- bunch particle species: positron beams, electron beam;
- beam chamber geometry, winglet height (see Fig. 1): from 9 mm to 11 mm, with a step of 1 mm;
- accelerator lattice elements: drift space, focusing and defocusing quadrupole, dipole close to a focusing and defocusing quadrupole;
- bunch spacing: from 10 ns to 30 ns, with a step of 5 ns;
- bunch population: from $2.0 \cdot 10^{11}$ particle per bunch (ppb) to $2.8 \cdot 10^{11}$ ppb, with a step of $0.1 \cdot 10^{11}$ ppb;
- SEY: from 1.0 to 1.6, with a step of 0.1.

3. Simulation Results

All simulations have been performed using the PyECLOUD 2D macro-particle code [13]. The code models the electron cloud effects in particle accelerators and provides a linear e-cloud density in the output files. In order to obtain the total e-cloud distribution in an element, the linear e-cloud density has to be multiplied by the length of the element (neglecting the edge

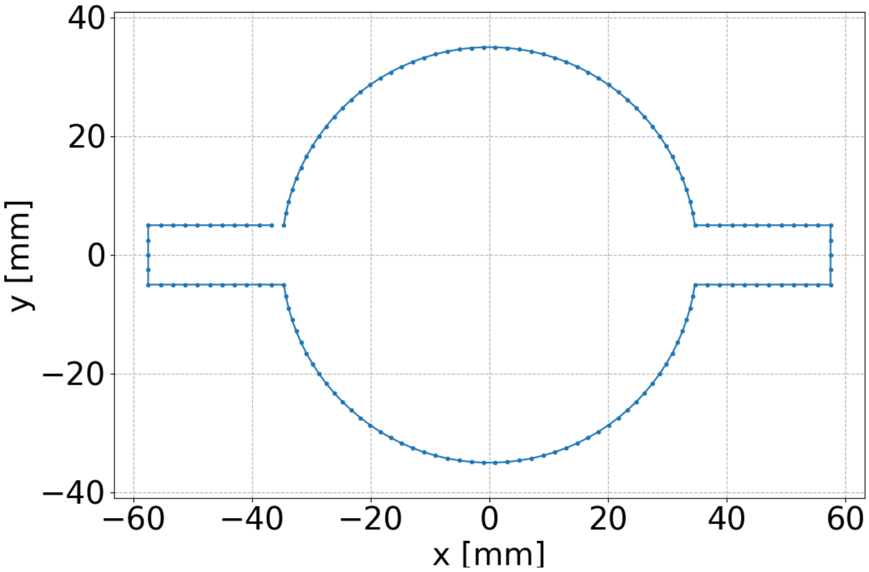

Figure 1. FCC-ee vacuum chamber transverse section.

effects). In the analysis of the simulation results, firstly, the e-cloud density versus the bunch passage (see Fig. 2) has been analysed in order to check if the multipacting occurs in every simulation (by the simulated bunch passages) and a synthetic parameter has been used for the global analysis. The synthetic parameter is defined as the average of the e-cloud density after the e-cloud build-up has reached the saturation (red line in Fig. 2). In the simulations, we have simulated a finite number of bunch passages, which would have been feasible from the computational point of view. In particular, we have decided to simulate 500 bunch passages.

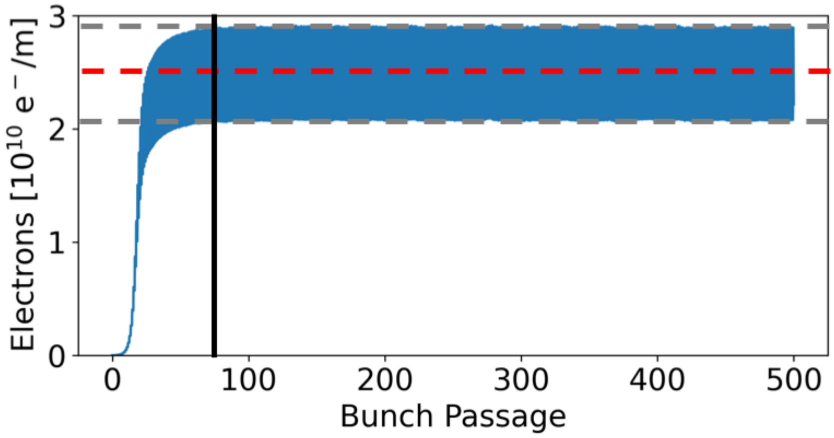

Figure 2. Example of e-cloud density versus bunch passage. The bunch passage, after that there is multipacting, is in solid black line; the minimum and the maximum values of the e-cloud density after multipacting are in dashed grey line; the average e-cloud density after multipacting is in dashed red line.

3.1. Vacuum Chamber Winglet and β-functions

Based on the simulation results, the variation of the beam chamber winglet height has a negligible effect on the e-cloud density within the considered range. In the different machine elements, the configuration of the magnetic field is different: in the drift space, there is no magnetic field; the magnetic field in the dipole is 1.415 mT; and, in the quadrupole, there is a quadrupolar gradient of 5.65 $\mathrm{T\,m^{-1}}$. In the focusing and defocusing quadrupole, the only quantities that change are the horizontal and vertical β-functions (see Fig. 3). In the FCC-ee, the beam is flat (the horizontal and vertical emittance are $\epsilon_{g_x} = 0.71$ nm, $\epsilon_{g_y} = 1.42$ pm, respectively) and, therefore, only the flatness of the beam changes among the different elements. The simulation results have shown a negligible effect of the β-functions, in the range of the FCC-ee parameters, on the e-cloud build-up process.

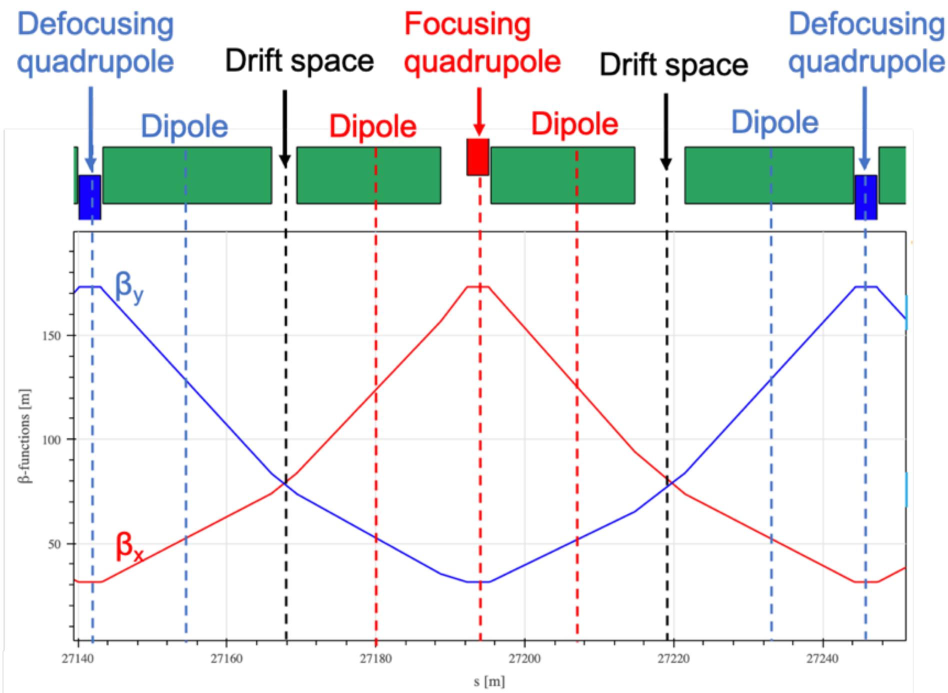

Figure 3. Horizontal (β_x), red, and vertical (β_y), blue, β-functions along a typical FCC-ee FODO cell.

3.2. Accelerator Lattice Elements, SEY, Bunch Intensity, Bunch Particle Species

In Fig. 4, the e-cloud density versus SEY for different bunch intensity (in different colours) in the elements is shown: drift space on the left, dipole in the centre, quadrupole on the right. The value of the bunch spacing is 10 ns. In the drift space and dipole, the electron density has a similar behaviour with respect to the bunch intensity: smaller bunch intensity means larger e-cloud density. In the quadrupole, the electron density is smaller than in the dipole and drift space case for lower bunch intensity, and the bunch intensity has a negligible effect on the e-cloud density. In all elements, when increasing the bunch spacing, the electron density decreases. In particular, the dependence on the bunch spacing is stronger in the drift space and dipole and for some cases there is no multipacting by the simulated 500 bunch passages. Increasing the bunch spacing, the dependence of the e-cloud density on the bunch intensity is weaker. Moreover, in the drift space and the dipole, the SEY threshold for multipacting increases with the bunch spacing more than in the quadrupole case. In the case of electron bunches, the multipacting

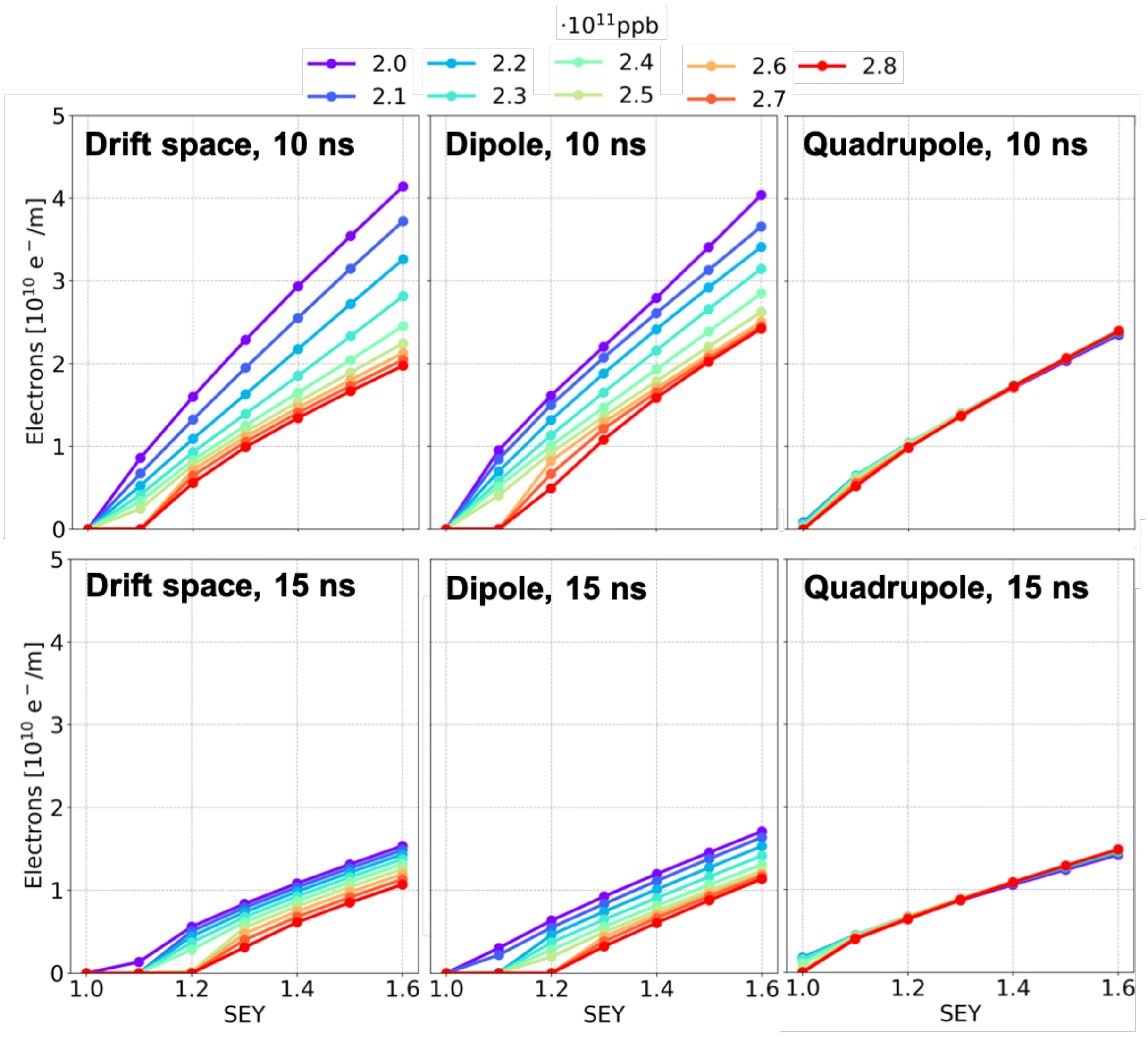

Figure 4. E-cloud density versus SEY for different bunch intensities (in different colours) in the different lattice elements: drift space on the left, dipole in the centre, quadrupole on the right; and for different bunch spacing: in first row 10 ns and in the second row 15 ns.

occurs in a few cases, but the e-cloud density is smaller than in the positron bunch cases and the electrons of the e-cloud are mainly located far from the beam chamber centre (as shown in Fig. 5).

3.3. Bunch Spacing

The bunch spacing is a key parameter for the e-cloud formation process. In order to minimise the e-cloud, the bunch spacing has to be maximised (as shown in Fig. 4), taking into account the other constraints. Considering for the FCC-ee collider a circumference of 91.1 km and a number of bunches per beam of 10,000, the maximum bunch spacing reachable is 30.4 ns, when all the bunches are equally spaced. In this filling scheme, there is no space to put any gaps between bunch trains in order to "clean" the e-cloud between two consecutive bunch train passages and, therefore, even in the case of large bunch spacing and small SEY, multipacting could occur after a large number of bunch passages. In the simulation results, a finite number of bunch passages

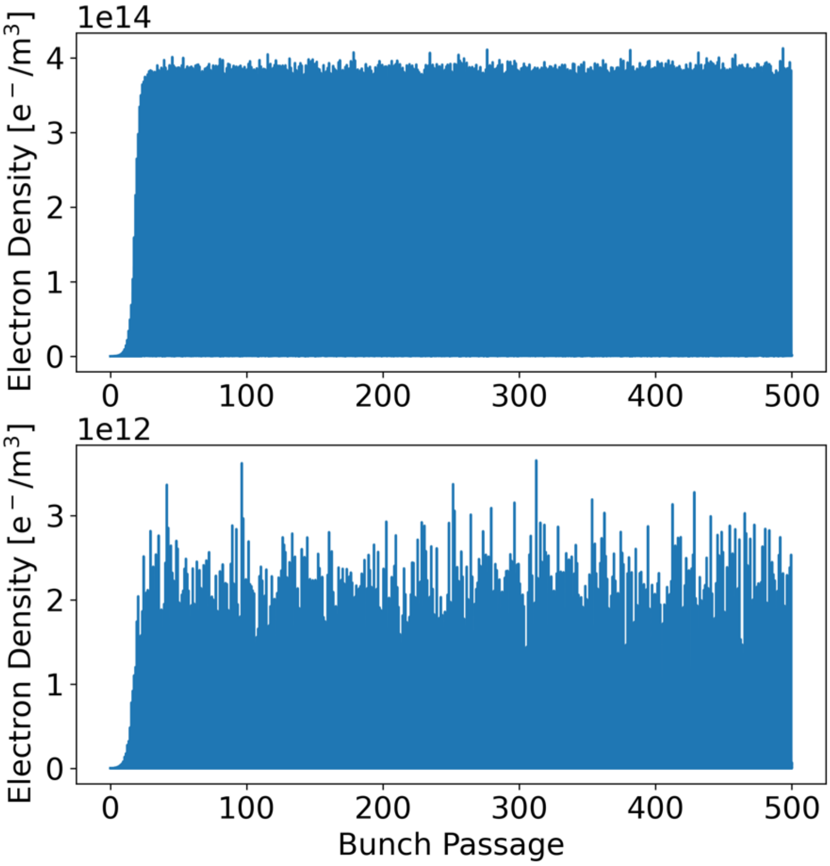

Figure 5. E-cloud central volumetric density versus bunch passages for the positron bunches on top and electron bunches on bottom.

(500) has been simulated, but multipacting could occur in the next bunch passages and the saturation value of the e-cloud density could be reached after 500 bunches and, therefore, the e-cloud density could be higher. To simulate the e-cloud formation process in the case of particular filling schemes (e.g., no gaps between bunch trains), a large number of bunch passages has to be used and it is not feasible from the computational point of view.

4. Conclusion

An extensive e-cloud build-up simulation study has been carried out using the PyECLOUD code for the FCC-ee Z configuration case and the simulation results have been shown in this paper. Based on the results, the variation of the beam chamber winglet height and of the β-function have a negligible effect on the e-cloud build-up process within the considered range. Moreover, in the drift space and dipole, the electron density has a similar behaviour with respect to the bunch intensity: smaller bunch intensity means larger e-cloud density. In the quadrupole, the electron density is smaller than in the dipole and drift space case for lower bunch intensity, and the bunch intensity has a negligible effect on the e-cloud density. In all elements, when increasing the bunch spacing, the electron density decreases. In the case of electron bunches, the multipacting occurs in a few cases, but the e-cloud density is smaller than in the positron bunch cases and the electrons of the e-cloud are mainly located far from the beam chamber centre.

As future development, studies of the beam stability in the presence of e-cloud can be performed by means of self-consistent simulations for realistic e-cloud distributions obtained from build-up simulations [10, 11] at the different lattice elements in the most critical cases highlighted from the studies summarised in this paper. Furthermore, a comparison with the theoretical stability limit can be carried out. Moreover, the injection configuration also has to be analysed with the shortest bunch length, where only the synchrotron radiation effects are considered. These simulations need a smaller time step and, therefore, they are heavier from the computation point of view.

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