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Tracking studies for the FCC-ee collimation system design

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Summary. — The Future Circular electron-positron Collider (FCC-ee) is being designed for stored beam energies up to 17.8 MJ, a value almost two orders of magnitude higher than any previous lepton collider. In this new regime, collimators are needed not only to control experimental backgrounds, but also to protect the machine from magnet quenches, or even damage. A beam-halo collimation system is therefore under study to protect the most sensitive equipment from unavoidable losses. Tracking simulations are key studies to evaluate the performance of the collimation system and are essential in an iterative process to converge to an optimum performance. In this paper, we present the results of collimation performance studies by means of power load distributions around the collider ring and propose possible optimizations of the halo collimation system.

1. – Introduction

The Future Circular electron-positron Collider, FCC-ee [1], a synchrotron with approximately 91 km circumference, is being designed as a possible luminosity-frontier and highest-energy electron-positron collider. It foresees to operate in four different operation modes, with beam energies 45.6 GeV, 80 GeV, 120 GeV and 182.5 GeV, optimized for the production of different particles (Z, W, H, $t\bar{t}$). The FCC-ee layout [2, 3] considered in this work includes four interaction points (IPA, IPD, IPG, IPJ) and four long straight sections (PB, PF, PH, PL). Given the stored beam energy, reaching 17.8 MJ in the Z operation mode, the FCC-ee beams have an intrinsic damage potential. Therefore, a collimation system is indispensable, not only to reduce experimental backgrounds, as in any lepton collider to date (*e.g.*, SuperKEKB [4], the present state-of-the-art collider for lepton beam intensity), but also to protect sensitive machine components, such as superconducting magnets, from beam losses that will unavoidably occur during operation. This article presents the results of collimation tracking studies to evaluate and optimize the performance of a preliminary collimation system for the FCC-ee. This forms a basis that later collimation studies build upon, as the ones presented in ref. [5].

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2. – FCC-ee collimation system

The FCC-ee collimation system has two main roles, namely, protecting the sensitive machine equipment from unavoidable beam losses and reducing the background in the experiments. A beam halo (or global) collimation system is foreseen to be installed in the PF insertion, as well as Synchrotron Radiation (SR) collimation around each of the IPs. The current design [6] consists of a two-stage, split-function, betatron and off-momentum collimation system. The collimation insertion optics used for the studies presented here is shown in fig. 1, for FCC-ee optics V22 [7]. The current halo collimator design includes 33 cm long Molybdenum carbide-Graphite (MoGr) Target Collimator Primaries (TCPs) and 30 cm long Molybdenum Target Collimator Secondaries (TCSs). This preliminary material choice relies on considerations of robustness, thermal stability and impedance, while the proposal of the collimator lengths draws on the experience developed for the Large Electron-Positron collider (LEP) collimation [8, 9] and on approximated analytical considerations. More details on the selection of these first tentative collimator design parameters can be found in refs. [10, 11]. Research and development on collimator material candidates is ongoing [2], and the choice of the materials will be refined in the future as the FCC-ee design progresses.

3. – Simulation framework

The FCC-ee poses unique challenges for the simulation of collimation processes. Similar to other large-scale accelerators like the LHC [12], it requires a reliable magnetic lattice tracking code to simulate the beam dynamics of a large number of macroparticles, and a detailed aperture model that is used to determine final loss locations of the tracked particles. Additionally, a particle-matter interaction code that can be seamlessly integrated with the tracking code is essential to allow the simulation of the interaction of the beam particles with the accelerator environment, and in particular with collimators. In addition, unlike in other colliders to date, because of SR emission, the FCC-ee beams are subjected to a significant energy loss, of up to 10 GeV in a single turn in the $t\bar{t}$ operation [13]. To account for this, the strength of the magnets has to be locally adjusted, or

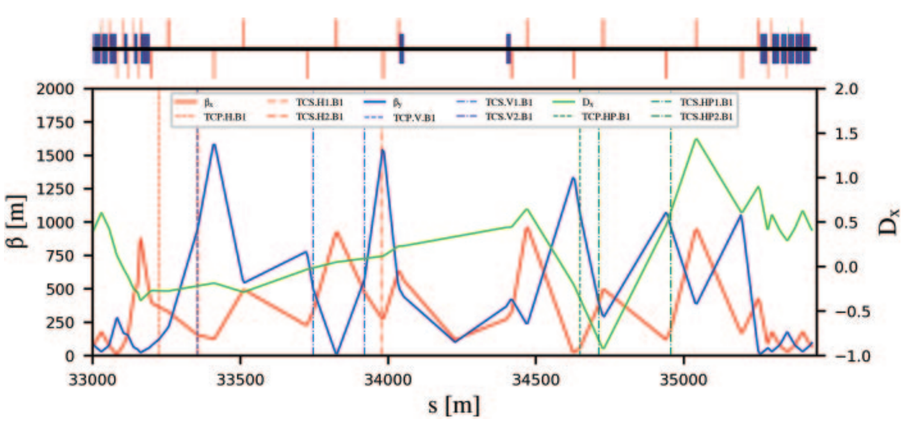

Fig. 1. – Collimation insertion optics. Dashed lines show the TCP locations, dot-dashed lines show the TCS locations. The beam goes from left to right – betatron collimation is achieved in the first half of the insertion, off-momentum collimation in the second half.

tapered. Moreover, accurate modelling of the non-linear dynamics is particularly important given the requirement of tracking particles with large amplitudes and large energy errors. On top of the already complex picture, all these aspects need to be taken into account and simulated over many turns (typically 700) in a 91 km ring.

Xsuite-BDSIM [14], is an integrated simulation tool specifically developed for the FCC-ee collimation simulation needs. Xsuite [15] is a collection of Python packages for beam dynamics simulations in particle accelerators, while BDSIM [16, 17] is a C++ software package based on Geant4 [18-20] to simulate radiation transport in particle accelerators and beamlines. These two codes can be used together for studies including particle tracking and particle-matter interaction. It is of interest for the future to benchmark Xsuite-BDSIM with measurements from an operating lepton collider, like DAΦNE [21] or SuperKEKB [4].

4. – Case study: beam halo losses

There are several beam loss processes that need to be considered for collimation tracking studies, for example, the losses of beam-halo particles due to various diffusion processes, noise, or instabilities, losses due to the collision processes, injection losses, losses from beam-gas interactions or abnormal losses occurring in accidental scenarios. The current focus is on generic beam halo losses —other loss processes are being modelled and will be the subject of future studies. Beam halo losses can be modelled and simulated via a *generic beam halo* (or *direct halo* [22]) approach, which foresees specifying a minimum beam lifetime that must be sustained during normal operation (we use here a preliminary specification of a 5 min minimum lifetime for FCC-ee) and assumes a slow loss process such that the halo particles are always intercepted by a TCP. The diffusion processes, causing particles to reach high enough amplitudes to hit a collimator, are not simulated —the simulations start instead with all the halo particles impacting a TCP at a given transverse depth from the collimator edge, commonly referred to as *impact parameter*, with identical initial conditions. To get conservative performance estimates, and due to the uncertainties on the impact parameters in the real machine, it is common to take the *critical impact parameter*, *i.e.*, the one leading to the highest beam losses along the accelerator ring. The critical impact parameter is determined through *impact parameter scans*, as the ones presented in ref. [23]. In this work, as in previous studies [10, 11], an impact parameter of $1\,\mu$m is used as a standard for FCC-ee collimation studies. The most suitable value might need to be refined in the future as the collimation system design progresses. Once the initial conditions are set according to this approach, the simulation starts with the interaction of the halo particles with a TCP, and the out-scattered particles are tracked for a given number of turns, typically 700. The particles that are lost on the mechanical aperture of the vacuum pipe are recorded, and their distribution along the accelerator ring is represented in terms of *loss maps*. As an example, we show in fig. 2 loss maps simulated for horizontal beam losses for the FCC-ee operation mode with the highest stored beam energy (Z). The results are obtained with 5×10^6 positrons tracked for 700 turns through a lattice without magnetic imperfections or element misalignments, while including SR and tapering. As can be seen in the top plot in fig. 2, the vast majority of losses is shown to be well contained within the collimation insertion in PF. However, a small fraction of the losses occur in other parts of the ring, in particular in the region upstream of IPA. In the next section, we discuss further these results and how the losses outside of the collimation insertion can be reduced.

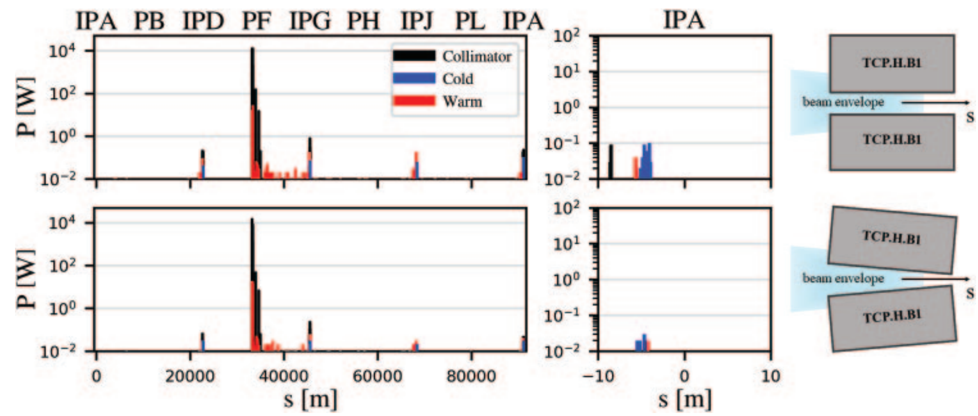

Fig. 2. – Loss maps showing the power load distributions in the FCC-ee (Z mode) for the case with the horizontal TCP parallel to the closed orbit (top) and parallel to beam envelope (bottom). The figure also shows the power load distributions around the most exposed interaction point, IPA.

5. – FCC-ee halo collimators optimization

Halo collimators optimization studies [10, 11], which studied the FCC-ee collimation performance varying the collimator placement, orientation, materials, and length, have already been performed for previous layout versions of the FCC-ee (2IP layout), leading to the collimator design parameters presented in sect. **2**. An important finding was that the effective collimator active length is shorter for particles impacting the TCPs with large angles and small impact parameters. This causes a reduction of the *cleaning potential* of a collimator, *i.e.*, its capability to absorb the incoming halo particles, which translates into a reduction of the collimation performance of the whole system. Therefore, it was concluded that the TCPs must be as parallel as possible to the beam envelope [11], a condition that can be achieved either by tuning the optics in the collimation insertion, or by introducing a tilt to the TCPs. In light of those findings, we simulated the collimation performance with and without tilting the TCPs for the updated FCC-ee model considered in this work. The results are shown in fig. 2. The collimation performance is good even without introducing any collimator tilt —more than 99.95% of the losses are contained within the collimation insertion PF, with only up to 2.4 W of the 59.2 kW incident on the collimation system being lost within 10 m of any experiment, *i.e.*, a reduction of the incoming losses by a factor 25000. Even though the beam loss tolerance of the impacted equipment, still to be designed and built, is not well known, the level of a few W of residual losses is likely by far tolerable. The angular alignment of the horizontal TCP (called TCP.H.B1) to the beam envelope causes a further suppression of the power loads along the whole FCC-ee ring. As a relevant example, the most exposed interaction point, IPA, is subject to a suppression of the *cold power load*, *i.e.*, the power load on superconducting elements, of more than a factor 4, and a comparable suppression is achieved in the other IPs. This loss suppression is not as strong as what was observed in previous studies [10, 11]. This is due to the fact that, with the FCC-ee layout and optics used for the studies presented here, the beam envelope angle at TCP.H.B1 is only $9.69\,\mu$rad —therefore, the worsening of the cleaning potential is minimal.

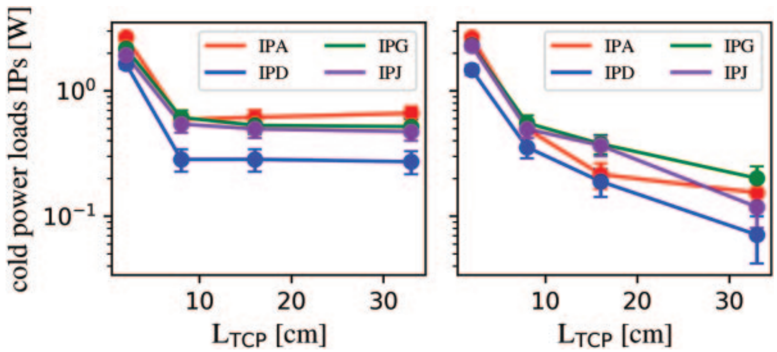

Fig. 3. – Parametric scan of the TCP length for TCP.H.B1 parallel to the closed orbit (left) and aligned to the beam envelope (right). The cold power loads around each IP are used as figures of merit for the collimation performance.

One of the main challenges of TCPs is that they contribute in a significant way to the total impedance budget of an accelerator, since they are the devices closest to the circulating beam and, because of robustness requirements, it might be needed to employ low-Z materials with high radiation length (*e.g.*, MoGr), with typically low electrical conductivity. In addition, if the collimator design criterion requires that a given number of radiation lengths is needed, as it was assumed so far, see ref. [10], this might lead to employ rather long collimators. This causes an overall impedance increase, which could impact the beam stability. For these reasons, we performed a parametric study that aims to assess the collimation performance as a function of the TCP length, with the goal of possibly reducing it without significantly worsening the performance. The results are shown in fig. 3. With TCP.H.B1 parallel to the closed orbit, the performance is constant down to a TCP length, L_{TCP}, of 8 cm. The reason is likely that 8 cm is roughly the distance traversed by particles impacting an untitled collimator jaw with 9.69 μrad angle and 1 μm impact parameter. With TCP.H.B1 aligned to the beam envelope, a monotonic worsening of the collimation performance is observed as L_{TCP} is reduced, with a clear step up at $L_{TCP} = 8$ cm. As the power loads on sensitive elements are low in absolute, it is concluded that there is likely room to decrease the TCP length. Future studies should be performed aiming to find the best compromise between collimator impedance and cleaning performance.

6. – Conclusions

Xsuite-BDSIM collimation tracking studies for FCC-ee beam halo losses have been performed, providing valuable insights for the halo collimation system optimization. Our results show an excellent cleaning performance of the FCC-ee collimation system for beam halo losses, with only a few W of beam loss power leaking to the sensitive regions close to the experiments. The results confirm that keeping TCPs as parallel as possible to the beam envelope decreases the losses around the ring, in particular in the cold elements in the interaction regions. A parametric study of the TCP length highlighted the delicate balance between achieving effective collimation and minimizing impedance-related concerns. In light of the results presented here, we conclude that the TCP length could be reduced from the currently assumed 33 cm to 8 cm without compromising the collimation performance but reducing the impedance generated by the TCPs. Although these results show potential for a significant reduction of the TCP length, input from other studies, including analyzing the energy deposition, must be considered before taking 8 cm as the new baseline length. Selecting a TCP length in the range from 8 to 33 cm as a new baseline would instead ensure adaptability to potential design refinements and enhance the effectiveness of the collimation system as the collider design progresses.

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