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POWER DEPOSITION STUDIES FOR THE FCC-ee HALO COLLIMATION SYSTEM

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Abstract

The Future Circular Collider (FCC-ee) at CERN requires a betatron and momentum collimation system for reducing particle backgrounds in the detectors, and for protecting the machine in case of excessive beam losses. The system is composed of primary and secondary collimators, which will be housed in one of the technical insertions of the 91 km ring. In this paper, we present a first assessment of the beam-induced power deposition in the collimators using FLUKA Monte Carlo simulations. We show that dedicated shower absorbers are needed in the collimation insertion, which intercept secondary particles from the halo collimators and reduce the energy leakage to the environment. A first optimization of the shower absorber configuration is presented, considering different absorber positions and absorber lengths. We demonstrate that the power absorption of the betatron collimation system can be increased from about 50 % to over 80 % by adding two shower absorbers between primary and secondary collimators.

INTRODUCTION

The FCC-ee is a proposed high-luminosity electron-positron collider with a circumference of about 91 km [1]. Four modes of operation are envisioned, tuned to particle-production resonances. In order of increasing energy, these are Z (45.6 GeV), W^+W^- (80 GeV), ZH (120 GeV), and $t\bar{t}$ (182.5 GeV). The beam current strongly decreases between the different operation modes since the emitted synchrotron radiation power is kept constant at 50 MW/beam. At the Z-pole, the stored beam energy is the highest and reaches about 17.5 MJ per beam, which is sufficient to damage the machine if the beam is lost in an uncontrolled way. To protect equipment and detectors in case of accidental beam losses and to reduce the background in the experiments, a dedicated betatron and momentum collimation system is essential [2–4]. The primary and secondary collimators will be housed in one of the straight sections of the collider ring, whereas additional collimators are foreseen near the experiments.

The impact of high-energy halo electrons and positrons on collimators produces electromagnetic showers propagating down the beamline. The secondary particles can give rise to radiation damage in equipment, and they contribute to the activation of the machine and the environment following the production of neutrons in photo-nuclear interactions. The purpose of this study is to quantify the radiation leakage from the collimation system and limit the resulting radiation effects by adding dedicated shower absorbers, which can enhance the overall energy absorption of the system. In addition, we quantify the power deposition in collimators, which is essential for the collimator design. We focus on the betatron collimation section of the positron beam, a straight section of approximately 700 m consisting of primary and secondary collimators, as well as quadrupole magnets.

We analyze the worst-case scenario (Z-mode), which operates at the lowest beam energy but at the highest beam intensity and the highest beam power across the four different operation modes. The beam parameters and optics are still in development [1]; we use lattice version v23 and the beam parameters from the final FCC Feasibility Study Report [5]. Simulating the positron beam only, we assume a bunch intensity of 2.16×10^{11} positrons, and 11,200 bunches per beam. We assume a beam halo-loss beam lifetime of 5 min and a beam top-up occurring after each lifetime has elapsed, resulting in a power loss of 37.2 kW.

SIMULATION MODEL

For this study, we use the FLUKA code [6–9], developed by the FLUKA.CERN collaboration. FLUKA is a Monte Carlo code designed to study the effects of high-energy beams on matter, taking into account the interaction of low energy charged particles down to the keV scale, and a significantly lower threshold of 0.01 meV for neutrons.

Table 1: Collimator Half-Gaps Δ and Positions s

	Δ (mm)	***s* (m)**		**Δ (mm)**	***s* (m)**
TCP.V	2.413	39.17	TCS.V1	2.480	382.53
TCP.H	6.526	46.17	TCS.H2	6.914	429.07
TCS.H1	4.965	194.43	TCS.V2	2.931	622.78

The geometry of the simulation consists of a concrete tunnel of 5.5 m inner-bore diameter, two 6 cm diameter vacuum chambers, whose centers are separated by 35 cm, and whose copper wall is 2 mm thick. In the collimation layout, the two primary collimators, first vertical then horizontal, are followed by four secondary collimators, alternating horizontal and vertical ones [4]. Quadrupole magnets are positioned throughout the entire section. Table 1 summarizes the position and gaps of vertical (V) and horizontal (H) collimators, on the positron beamline . The primary collimators (TCP) consist of a graphite absorber, 25 cm in length, and a cross section of 6 cm in width by 2.5 cm height. The absorber is tapered at an angle of 12.5° both upstream and downstream. The absorber is covered by a frame, a support structure on the sides not facing the beam enveloping the entire absorber jaw, made of TZM, a dense (10.22 g/cm^3) alloy of molybdenum with 0.08 % titanium and 0.5 % zirconium. The design of the secondary collimators (TCS) is identical to the primary

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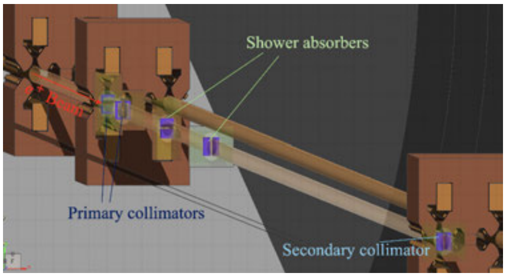

Figure 1: FLUKA geometry model of the betatron cleaning system including primary and secondary collimators, as well as shower absorbers.

ones, with the exception that the absorber is 30 cm in length and it is entirely made of TZM, both absorber and frame. The gaps of the secondary collimators, 12 and 75 σ in the x and y planes, respectively, are slightly larger than the 11 and 65 σ of the primary collimator gap. However, the showers generated during the interactions rapidly expand in the transverse plane, and can thus deposit energy in the vacuum chamber, the magnets, and the tunnel, before reaching the first secondary collimator.

We study the use of absorbers, positioned after the primary collimators, to absorb the generated showers. For the shower absorbers, we adopt a design identical to the secondary collimators. However, a stringent requirement for the shower absorbers is that they may not interfere with the collimation hierarchy. The jaw gap is selected to be larger than the secondary collimator gap, 15 and 91 σ in x and y, respectively. Because the beam Twiss parameters vary in the region where the shower absorbers are placed, the half-gap of the jaws vary between 6.2 and 8.8 mm in x and 2.8 and 3.3 mm in y. A rendering of the betatron collimation section, spanning from the primary collimators up until the first secondary collimators, including two shower absorbers in between, is shown in Fig. 1.

As source in the FLUKA model, we simulate a positron pencil beam impacting the middle point of the primary collimator jaws, with an impact parameter with respect to the jaw's edge of 1 μm; we also investigate the dependence of the power deposition on the impact parameter. We evenly sample impacts on the upper jaw of the vertical and right jaw of the horizontal primary collimators.

EFFECT OF SHOWER ABSORBERS

The first row of Table 2 summarizes the power loss distribution along the beamline. In the environment, we account for everything that is not included in the other categories, notably including the vacuum chamber, the tunnel, and the surrounding earth. We see that the power to primary collimators and quadrupole magnets is a small fraction of the total, below 1 kW, whereas the vast majority is absorbed by the secondary collimators and the environment. The losses to the environment (almost 50 %) are especially important, both from a radiation protection perspective as well as a source of radiation damage in equipment if not intercepted by dedicated devices. For these reasons, we look to minimize the power absorbed by the environment by inserting shower absorbers.

The optimal configuration of shower absorbers is determined using a Bayesian optimization of parameters: the orientation and position of n shower absorbers is analyzed. Since we lack a cost function for adding additional shower absorbers, n is used as a control variable, and the optimization is performed within each group. Ultimately, it is found that the optimal configuration with n =2 reduced the power to the environment by ≈70 %, and more absorbers have diminishing returns; in particular for n =4 the power to the environment is reduced only by an additional ≈30 % compared to n =2, while also increasing the overall impedance.

The length of the shower absorbed is optimized independently of the other model parameters, by exploring lengths from 15 to 60 cm. We found that above 30 cm the reduction of the power leaking to the environment levels off, thus with a length identical to the secondary collimator.

The optimization procedure indicates that two shower absorbers, 30 cm in length, with the first placed 20 m from the primary collimators, and the second 20 m after the first, can significantly reduce power leakage to the environment from almost 50 % to 15 %; the corresponding results are reported in Table 2. A part of the optimization procedure results are presented in Fig. 2, which shows the position optimization. The triangular shape results from the constraint that both shower absorbers (or all n of them, in the general case) need to fit in the 180 m straight section between primary and secondary collimators. The comparison of the power losses fractions can be made with the LHC values [10]. In particular we find that the fraction of the power in the magnets is an order of magnitude lower in this work; the power absorbed in the environment is similar, in the absence of shower absorbers. Thus, using shower absorbers can significantly improve on the LHC performance.

We present in Fig. 3 the linear power deposition along the beamline. The figure shows that the most prominent effect of shower absorbers is to reduce the continuum of power absorbed (mostly by the vacuum chamber walls, not distinguished in the figure), focusing the power losses at the two absorbers, thus collimating the showers.

Table 2: Energy Absorption With and Without Shower Absorbers

	Primary collimators		**Shower absorbers**		**Secondary collimators**		**Quadrupole magnets**		**Environment**	
	kW	**% of total**	**kW**	**% of total**	**kW**	**% of total**	**kW**	**% of total**	**kW**	**% of total**
Without absorbers	0.17	0.45	—	—	19.30	50.80	0.76	1.99	17.70	46.58
With absorbers	0.20	0.52	15.85	41.70	15.88	41.78	0.30	0.78	5.74	15.10
Change (%)	16.52	—	—	—	−17.75	—	−60.80	—	−67.58	—

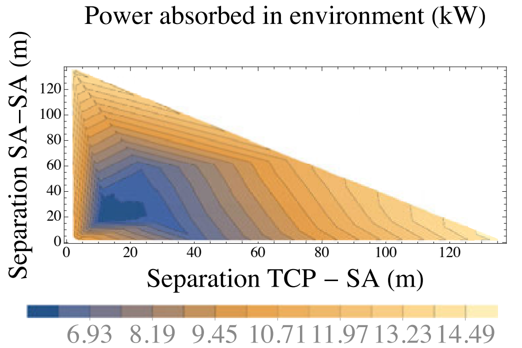

Figure 2: Optimization landscape of power deposition to environment for a configuration with two shower absorbers (SA), as a function of the distance of the first SA to the primary collimators (TCP-SA) and relative distance (SA-SA).

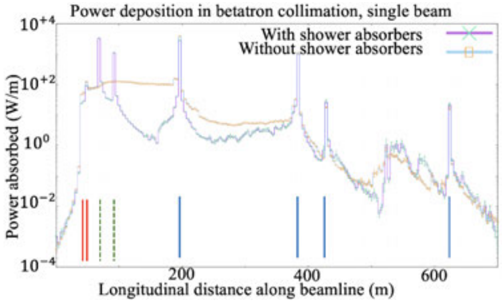

Figure 3: Power deposition along beamline in the betatron collimation section. Vertical lines indicate the position of the primary (blue), secondary (red) collimators, and shower absorbers (green, dotted)

The impact parameter, assumed as 1 μm to obtain the results above, could potentially have an impact on the power distribution observed. In real operation, we expect the impact parameter to be distributed, with this distribution not being precisely known due to uncertainties concerning the beam loss mechanisms, surface imperfections, and beam dynamics. We studied the dependence of power deposition as a function of the impact parameter, and show the results in Fig. 4. With increasing depth of the interactions in the primary collimator, we observe a large relative increase in the power absorbed by the impacted jaw; however, it should be verified if this is still the case in multiturn simulations where particles escaping the local FLUKA geometry could come back and impact again on a later turn. At the same time, the power absorbed in the environment grows, while the power absorbed by the secondary collimator jaws decreases. This tradeoff between environment and collimators, in the absence of shower absorbers, can be explained as a broadening of the shower transverse profile with deeper impacts. Broader showers are lost on the beam pipe and surrounding equipment earlier, before reaching the secondary collimators.

While the focus of the optimization process is to minimize the power absorbed in the environment, we see from Table 2 that a significant portion of the power is absorbed by the secondary collimators, with the majority going to the first one, even in the presence of shower absorbers. The power absorbed by secondary collimators could pose a challenge for the device lifetime. We present in Fig. 5 a horizontal slice of average power absorption density in the jaws of the first horizontal primary collimator. The power distribution is asymmetric because the assumed source is itself asymmetric.

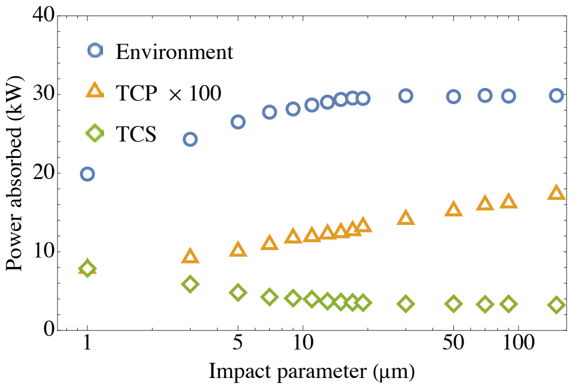

Figure 4: Effects of impact parameter, with respect to edge of collimator jaw, on power absorbed on the impacted primary collimator (TCP, scaled for clarity), on the most impacted secondary collimator jaw (TCS), and in the environment. No shower absorbers are used for this study.

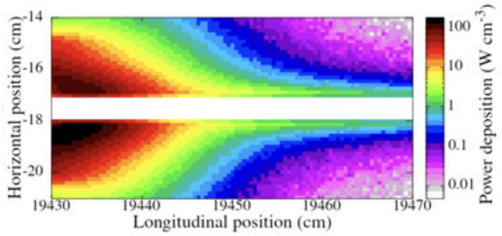

Figure 5: Average power absorption density in the most impacted secondary collimator, the first secondary collimator. The average is performed on a narrow 4 mm slice around the region of highest energy deposition. Two optimized shower absorbers are included in the model.

CONCLUSION

We have explored the secondary radiation leakage from the betatron collimation system of the FCC-ee collider. Our results suggest that magnets in the betatron insertion are not at risk of receiving excessive instantaneous radiation load, even in the absence of prevention measures. Long term radiation effects will be assessed in future studies. The results still indicate that, when unmitigated, almost half of the halo power-losses are not stopped by the primary and secondary collimators, but are rather absorbed by the surrounding, including vacuum chambers, tunnel walls, or the surrounding earth. However, the use of shower absorbers, when strategically positioned, can significantly reduce the power escaping the system. The study was performed for the present FCC-ee collimation lattice layout (v23), which is expected to evolve further. Nevertheless, the general findings of this study will remain approximately valid and will provide the basis for evaluating future layouts of the collimation system.

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