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ENERGY DEPOSITION AND RADIATION LEVEL STUDIES FOR THE FCC-ee EXPERIMENTAL INSERTIONS

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Abstract

The Future Circular Collider (FCC) study foresees the construction of a 90.7 km underground ring where, as a first stage, a high-luminosity e^+e^- collider (FCC-ee) is envisaged, operating at beam energies from 45.6 GeV (Z pole) to 182.5 GeV (ttbar). In the FCC-ee experimental interaction regions, various physical processes give rise to particle showers that can be detrimental to machine components as well as equipment in the tunnel, such as cables and electronics. In this work, we evaluate the impact of the synchrotron radiation (SR) emitted in the magnets and the beamstrahlung (BS) radiation from the interaction point (IP). The Monte Carlo code FLUKA is used to quantify the power deposited in key machine elements, such as the BS dump, as well as the cumulative radiation levels in the tunnel. We also examine the effect of SR absorbers in the vacuum chamber and of external tungsten shielding. The results are presented for the different operation modes, namely Z pole and ttbar.

INTRODUCTION

The Future Circular Collider (FCC) is an ambitious new accelerator project at CERN, which proposes the construction of a 90.7-km-long tunnel. It is articulated in two stages: first a high-luminosity e^+e^- collider providing precision measurements, the FCC-ee [1], and then an energy-frontier hadron collider, the FCC-hh [2]. The FCC-ee is expected to start operating in the 2040s, providing collisions at four interaction points (IPs) in four operation modes, for which the main beam parameters are reported in Table 1.

During the FCC-ee operation, several physical processes trigger radiation showers that can compromise the lifetime and the performance of machine equipment. As a circular lepton machine, high fluxes of photons are produced via synchrotron radiation (SR), particularly within the arc dipole magnets. In the experimental insertions, the incoming beamlines towards the IPs are designed without significant bending to limit the associated SR, which can impact on the detector, to about 1 kW emitted within 500 m of the IP. To accommodate the 30 mrad crossing angle, the outgoing beamlines are more strongly bent, implying that more than 60 kW are radiated already within the first 250 m [3]. While this SR does not affect the experiments, it can give rise to significant radiation levels in the tunnel. To avoid the direct impact of SR photons on the vacuum chamber, copper absorbers will be installed along the outgoing beamline as in the FCC-ee arcs [4].

Table 1: FCC-ee Beam Parameters for the Four Operation Modes Presented at 2021 Snowmass Summer Study [10]

Operation Mode	**Z**	**WW**	**ZH**	**ttbar**
Beam energy [GeV]	45.6	80	120	182.5
Bunches/beam	10000	880	248	36
Bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
σ_x^{bunch} at the IP [μm]	8	21	14	39
σ_y^{bunch} at the IP [nm]	34	66	36	69

In addition, intense photon fluxes emerge at the IPs from a process called beamstrahlung (BS) [5]. In BS, bunch particles curve their trajectory during bunch crossings under the influence of the electromagnetic (EM) field of the opposite colliding bunch, emitting photons in a manner similar to SR, but concentrated at the IPs. The high bunch populations and small beam spot sizes cause each beam to radiate a few hundred kW of power as BS photons. The aperture of the photon emission cone is inversely proportional to the energy of the emitting particles, so it is very narrow. As a result, two high-power photon beams exit each IP directed as the outgoing beams, requiring dedicated dumps for their disposal located 500 m downstream [6]. To design the dump, it is necessary to quantify the power that its core must withstand when absorbing BS photons at steady state, as well as the radiation levels generated in its surroundings.

In this paper we use the Monte Carlo code FLUKA [7–9] to compute the power deposition inside the BS dump and the total ionizing dose (TID) caused by BS and SR from the outgoing beam up to 500 m from the IP. This study considers only the operation mode with the highest beam current, at Z pole, and with the highest beam energy, at ttbar.

SIMULATION SETUP

FLUKA is a Monte Carlo code that simulates the transport and interaction of particles in matter, with state-of-the-art physics models reproducing the propagation of EM and hadronic showers in user-defined 3D geometries.

Given the symmetry of FCC-ee tunnel around the IP, only the geometry model of its right side up to ≈520 m has been implemented in FLUKA (Fig. 1). It includes the concrete tunnel, the surrounding soil, the outgoing beamline, and the BS dump with its extraction line. The tunnel is divided

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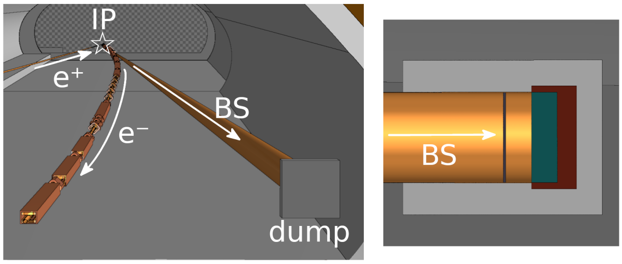

Figure 1: FLUKA geometry model of the first 520 m from the IP (left) and longitudinal cross section of BS dump (right).

into two different straight segments, to reproduce its curvature and variable section. Since a full design of the BS extraction line is not yet available, in this work we chose to model it as a 3-mm-thick copper conical vacuum chamber directed tangentially along the direction of the outgoing beam (15 mrad with respect to the tunnel longitudinal axis). The BS photons and the outgoing beam overlap for several tens of metres before gradually separating due to bending of the beamline. A several meter long extraction window is required on the beam pipe to allow photons to pass to the BS extraction line. At 500 m, where the photon dump is placed, its radius reaches 35 cm to contain around 8 σ of the BS beam spot size. For the BS dump core, we studied a compact solution consisting of a liquid lead curtain with a thickness of 20 cm, modeled as a 35x35x20 cm^3 box in lead (ρ=10.678 g/cm^3). A 2-cm-thick carbon fiber composite (CFC) window (ρ=1.7 g/cm^3), which would preserve the vacuum, is placed before it inside the extraction line. We propose a dump shielding composed of two layers of 5-cm thick iron and 20-cm thick concrete, where the latter extends up to 1 m upstream of the dump to contain back-scattered particles. The outgoing beamline consists of the copper beam pipe and of the magnets, including their respective magnetic fields. The dipole and quadrupole prototypes are modelled with the iron yoke and copper coils. The few sextupoles present in the lattice are currently neglected. The vacuum chamber has a radius of 35 mm and a thickness of 2 mm, and features two horizontal winglets to host the localised SR absorbers in CuCrZr alloy proposed in [4]. The absorbers are 30-cm long and disposed in order to intercept all SR fans. Part of the SR from the first dipole after the IP passes through the BS extraction window and impinges downstream on the internal wall of the extraction line. To partially absorb this energy, a lead absorber with a thickness of about 1 cm is placed outside of the impacted region.

In the FLUKA simulations BS photons are sourced from a sample generated with GUINEA-PIG++ [6], injected at the IP and propagated from there into the geometry. As for the SR, FLUKA can simulate run-time the emission of photons when transporting a charged particle in a vacuum region with a magnetic field. In this study, e^- at nominal energy, sampled from a Gaussian beam with the dimensions reported in Table 1, have been transported from the IP.

Table 2: Beamstrahlung emission characteristics from GUINEA-PIG++ (positions given with respect to the outgoing-beam axis) [6] and fractions of power absorbed simulated with FLUKA.

Operation Mode	**Z Pole**	**ttbar**
Mean energy [MeV]	1.7	62.3
Hor. distr. at 500 m [cm]	2.27 ± 4.59	0.473 ± 2.23
Ver. distr. at 500 m [cm]	0.00 ± 2.46	0.00 ± 2.52
Power (one beam) [kW]	370.0	77.2
Power abs. in window	4.01%	0.41%
Power abs. in dump	93.62%	98.67%
Power abs. in shielding	1.38%	0.62%

BEAMSTRAHLUNG RADIATION

A full characterisation of the BS radiation at FCC-ee is given in [6], including the energy spectra for the four operation modes. In Table 2 we report the single-photon mean energy, the spatial distribution (mean±RMS) of BS photons at 500 m from the IP (i.e. impacting on the dump), the total power and the absorbed fractions calculated with FLUKA. A non-zero angle of emission of BS photons with respect to the outgoing e^- beam axis is observed. It is more pronounced at Z pole, resulting in a horizontal shift of over 2 cm with respect to the outgoing beam axis (with which the centre of the dump is aligned). At Z pole, the softer BS photon spectrum causes the CFC window to absorb 4% of the total power, ten times more than at ttbar. The 20 cm of liquid lead are very efficient in absorbing the impacting energy, letting only a few percentage of it escape. The plot in Fig. 2 shows the longitudinal maximum of power density deposition inside the lead dump core, which reaches peaks of 2.16 kW cm^{-3} and 0.52 kW cm^{-3} at Z pole and ttbar, respectively. The resulting temperature increase must be carefully evaluated, as the liquid lead must be kept at 400–500 °C to avoid solidification and corrosion. The proposed shielding blocks 58% and 67% of the power leaking beyond the dump core at Z pole and ttbar, respectively. This results in 3.7 kW and 0.2 kW of prompt radiation hitting the vicinity of the dump. Figure 3 depicts a top view of the radiation levels around the dump in terms of TID accumulated in one year of operation (approximately 10^7 s) at Z pole. This conceptual shielding

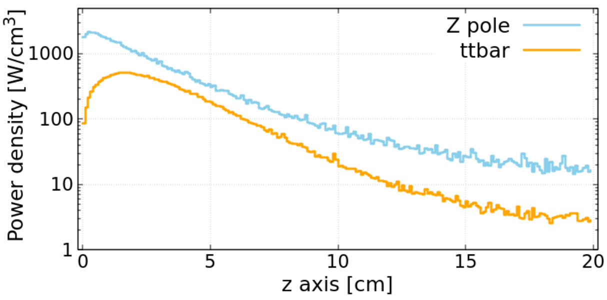

Figure 2: Longitudinal maximum power density deposition inside the BS dump in liquid lead, calculated with FLUKA for the two operation modes at Z pole and ttbar.

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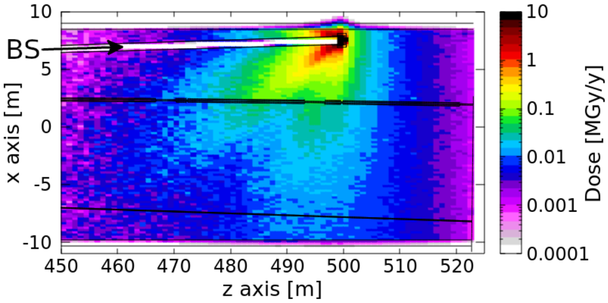

Figure 3: Top view at beamline height (average for y in ±20 cm) of the annual dose caused by BS photons interacting with the liquid lead dump at Z pole, simulated with FLUKA.

design results in TID levels of a few tens of kGy/y on the closest beamline. Further optimization of the shielding can be performed if it is deemed necessary.

These results demonstrate that, concerning the BS dump, the highest power deposition and tunnel dose levels are reached at Z pole operation mode. Nonetheless, this is not the full picture, because the harder BS photon spectrum at ttbar can lead to enhanced neutron production, with possible consequences on sensitive equipment such as electronics.

SYNCHROTRON RADIATION

The SR emitted in the 13 dipoles along the first 520 m of the beamline outgoing from the IP has been characterized with FLUKA. The total power radiated amounts to 164 kW for both Z pole and ttbar, as imposed by design through the beam parameters. Nevertheless, the different SR spectra at the two beam energies determine two distinct scenarios: the SR critical energies in the different dipoles range from 2.14 keV to 23.23 keV at Z pole, and from 0.14 MeV to 1.49 MeV at ttbar. This entails a huge difference in the efficiency of SR absorbers, which can stop 95.0% of the SR power at Z pole but just 67.9 % at ttbar. As a result, the tunnel radiation levels are basically unaffected by SR at Z pole, therefore in this paper we focus on the results of ttbar case. A top view of the annual TID in the region of interest is given in Fig. 4. It contains both the contributions from BS and SR at ttbar, with the SR dominating everywhere except in the closest vicinity to the BS dump. Hotspots of TID of the order of 0.1–1 MGy/y are observed in close proximity of SR absorbers. Thanks to the iron yoke of the magnets hosting the absorbers, most of these hotspots are well contained in 1 m around the beamline. More extended hotspots are found where the absorbers are surrounded by less material budget, such as at drifts or at the magnets allowing the passage of the BS extraction line. Absorbers alone are less efficient in suppressing the radiation leakage in the tunnel, hence additional shielding may be needed to mitigate the TID. In this regard, preliminary FLUKA simulations showed that 1 cm of tungsten, placed around the beam pipe at the drifts in the absence of absorbers, can locally reduce the dose levels by 1–2 orders of magnitude. Finally, the absence of the sextupoles in the geometry has an impact on the material budget and, therefore, on the radiation levels themselves.

CONCLUSION

At FCC-ee different physical processes produce radiation showers around the IPs. The impact of BS and SR has been studied with FLUKA from the point of view of power deposition and tunnel radiation levels for the operation modes at Z pole and ttbar. A geometry representative of the first 520 m after the IP has been modeled, including a 20-cm thick liquid lead curtain with a conceptual shielding of iron and concrete for the BS dump and CuCrZr absorbers for SR. Simulations show that the proposed combination of BS dump and shielding can absorb 99% of the power at steady state operation. The highest BS power is reached at Z pole, causing a peak power density inside the lead of 2.16 kW cm^{-3} and the release of 3.7 kW of power in its vicinity. However, the dump shielding reduces the BS-driven dose on the most exposed point of the beamline to a few tens of kGy/y. Further optimization will be performed also considering other radiation level quantities (e.g. neutron fluences), final beam parameters and beam adjustment transients, during which separation between colliding bunches can increase BS power. At Z pole and ttbar, absorbers stop 95% and 68% of the SR radiation power, respectively. This results in significant radiation levels only at ttbar, where hotspots of dose of the 0.1–1 MGy/y level are found along the beamline. Additional shielding can be considered to obtain further reduction of the tunnel dose from SR. Other sources, like radiative Bhabha, are expected to be relevant for tunnel radiation levels, particularly in the vicinity of the IP, and need to be studied.

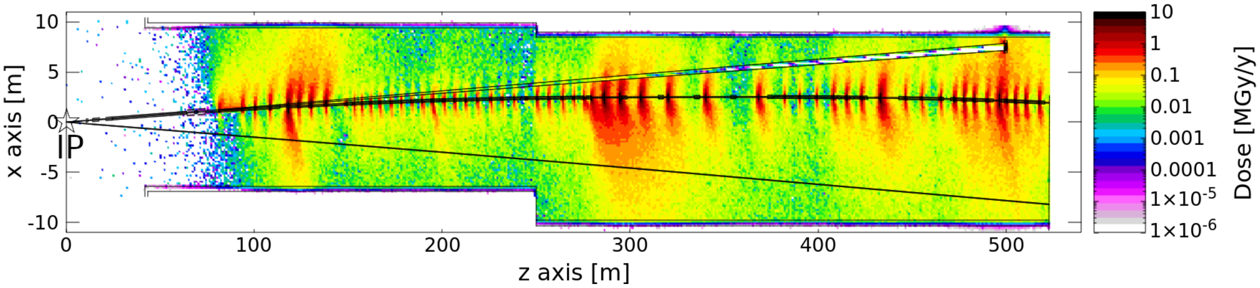

Figure 4: Top view at beamline height (average for y in ±20 cm) of the annual dose caused by SR from the beam outgoing from the IP and BS photons interacting with the liquid lead dump at ttbar, simulated with FLUKA.

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