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CHALLENGES AND MITIGATION MEASURES FOR SYNCHROTRON RADIATION ON THE FCC-ee ARCS

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Abstract

In a high-energy circular electron-positron collider like the Future Circular Collider (FCC-ee) at CERN, synchrotron radiation (SR) presents a significant challenge due to the radiation load on collider magnets and equipment in the tunnel like cables, optical fibres, and electronics. The efficiency of the anticipated photon absorbers in the vacuum chambers depends on the operational beam energy, ranging from 45.6 GeV to 182.5 GeV. Radiation load studies using FLUKA are conducted for the four operation modes to assess the SR impact on various systems and equipment. Particularly at higher energies (120 GeV and 182.5 GeV), the radiation levels in the tunnel environment would likely not be sustainable. The objective is to implement a mitigation strategy that enables the placement of essential components, such as electronics, power converters, and beam instrumentation, in the tunnel, while enduring both instantaneous and long-term radiation effects over multiple years.

INTRODUCTION

The future circular lepton collider (FCC-ee) proposed at CERN will collide electrons and positrons with energies ranging from 45.6 GeV to 182.5 GeV per beam. The circumference of the ring is expected to be 91 km, with the arcs accounting for 77 km, which results in a machine bending radius of approximately 10 km [1]. The main source of radiation originates from synchrotron radiation (SR), electromagnetic radiation emitted by charged particles following a curved trajectory. The energy loss per turn, ΔE, is proportional to $\Delta E \propto \frac{E^4}{m_0^4 \rho}$, with E the energy of the particle, m_0 the rest mass of the particles, and ρ the bending radius of the trajectory. Compared to high-energy hadron colliders like the LHC, the energy loss due to SR emission is much higher in FCC-ee because of the much smaller rest mass of electrons and positrons. At the lowest operational energy of 45.6 GeV (Z mode), the energy loss amounts to 38 MeV/turn, while for the $t\bar{t}$ mode at 182.5 GeV, the energy loss increases to 9.2 GeV/turn. The produced SR power is by design equal for all four operation modes (50 MW/beam), which is achieved by adjusting the stored beam current from 1.28 A for the Z mode to 4.9 mA for the $t\bar{t}$ mode [2].

The FCC-ee vacuum system for the collider arcs includes discrete 30 cm long photon absorbers made of a copper-alloy (CuCrZr), which are placed every five to six meters in the horizontal winglets of a round vacuum chamber [3–6]. The absorbers intercept the primary SR fan, avoiding that SR photons are directly lost on the chamber wall. This approach differs from LEP, where a continuous lead shielding with a thickness of 3–8 mm was bonded to the aluminum vacuum chambers of arc magnets [7]. The FCC-ee SR absorbers will be exclusively placed in dipoles, while the short straight sections with quadrupoles and sextupoles will be in the geometrical shadow of upstream absorbers. The absorber positions are not necessarily equidistant due to the different dipole lengths in the arcs, which range from 19 m to 22 m. The SR absorbers have a weight of about 1 kg and must be actively cooled considering the high power carried by the SR photons (0.63 kW/m per beam). The absorber surfaces, which intercept the SR photons, are slightly tilted to spread the impact of photons over a longer distance [6].

As demonstrated by first radiation studies [8], the leakage of secondary particles from the SR absorbers becomes important at high operational energies (H, $t\bar{t}$). As a consequence, the cumulative ionizing dose in machine equipment and the tunnel infrastructure can be excessively high. This is a particular concern for radiation-sensitive equipment such as cables, cable connectors, optical fibres, magnet insulation, as well as electronics. Another issue is the heat deposited in air, which has to be evacuated by the ventilation system. As a general mitigation strategy, it is therefore envisaged to reduce the overall radiation levels in the tunnel by adding more shielding in the form of high-density blocks around the SR absorbers. As discussed in [9], additional shielding plates have the potential to decrease the dose to equipment in the tunnel by a significant amount. This would reduce the need of expensive radiation-hard equipment, while offering the possibility of using commercial-off-the-shelf (COTS) solutions. On the other hand, a careful optimization of the shielding configuration is essential, due to costs (raw material and machining), structural reasons (weight of the shielding), and space constraints (shielding integration in the magnets). In this paper, we present a first conceptual shielding design and evaluate the shielding efficiency by means of FLUKA [10–12] simulations.

RADIATION SHIELDING IN THE ARCS

The shielding efficiency of the SR absorbers depends on the so-called critical energy of SR photons, E_c, which can be approximated with $E_c\,[\text{MeV}] \approx 2.21 \cdot 10^{-6} \frac{E^3[\text{GeV}]}{\rho[\text{km}]}$ [13]. This quantity splits the SR spectrum in two parts of equal power (see Fig. 1), where half of the power is carried by photons below this energy and the other half is carried by higher-energy photons. Photons undergo different physical processes depending on their energy, which eventually

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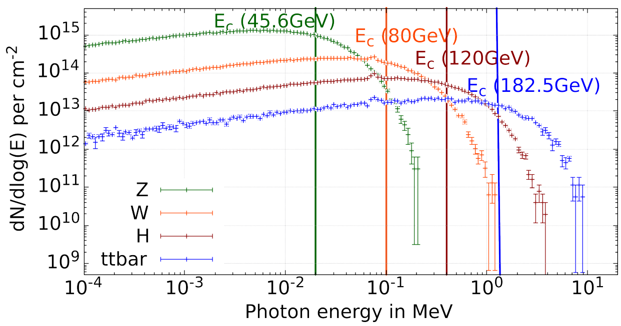

Figure 1: SR spectra for all FCC operation modes, as generated by FLUKA with the critical energy indicated by vertical lines.

determine the amount of energy that is leaking from the SR absorbers. For low-energy photons the photoelectric effect dominates, leading to rapid absorption, while Compton scattering and eventually electron-positron pair production become important at higher energies. Considering the E^3-dependency of the critical energy, the $t\bar{t}$ mode governs the need for additional shielding around the SR absorbers to reduce the radiation levels. Nevertheless, the other beam modes cannot be neglected, in particular the H (Higgs) operation mode at 120 GeV, which features the second highest beam energy with a beam current of 26.7 mA. Here, the combination of a relatively high beam energy and a substantial beam current also results in high radiation load in the tunnel that has to be investigated closely.

In this paper, we evaluate the absorption efficiency of the SR absorbers and develop an additional radiation shielding by means of FLUKA simulations. In order to assess the power deposition and radiation levels in the tunnel, we model a 130 m-long arc cell (see Fig. 2), which includes five dipoles, five quadrupoles with a length of 2.9 m, and two pairs of sextupoles of 1.3 m each. The iron-based magnets are operated at room temperature, with a copper vacuum chamber of 2 mm thickness and a diameter of 60 mm. The beam separation is assumed to be 35 cm. The simulation setup incorporates a simplified model of the SR absorbers in the winglets of the chambers. In total, 25 absorbers are placed in the chambers of the external and internal beam.

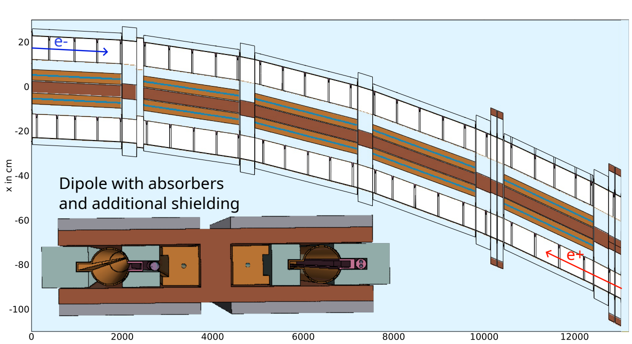

Figure 2: Top view of the geometry and cross section of a dipole with absorbers and additional shielding. Furthermore, the top view of the absorber at the beam level is shown.

As radiation shielding, we consider 60 cm-long tungsten blocks on the outside of the vacuum chamber, which are placed around the SR absorbers (see Fig. 2). The blocks enclose the winglets to enhance the shielding efficieny. The shielding must not be in thermal contact with the vacuum chamber since it would act as a heat sink during the bakeout of the chambers. Detailed integration studies are needed to determine the required tolerances. In this first conceptual study, we assume a gap of 1 mm between shielding and chamber. In addition to the tungsten blocks, additional shielding plates made of lead are added on top and bottom of the dipole yokes at the absorber locations. The plates are assumed to be 2 cm thick and 60 cm long. The total weight of the tungsten blocks and lead plates is about 150 kg per SR absorber, or about 1500 kg per dipole, which has to be taken into account in the support design. For simplicity, we assume pure tungsten and lead in the radiation studies; the final choice of absorber material (likely an alloy) will depend on a variety of aspects, including machining and costs.

POWER DISSIPATION IN ARC CELL

The SR power dissipated in the 130 m-long cell is 164 kW for both beams, which scales to 100 MW of SR power in the full ring [2]. Table 1 summarizes the power deposition in magnets, vacuum chambers, SR absorbers, shielding and the tunnel environment. The latter includes the power deposition in air, concrete walls and surrounding soil. The table shows results for H and $t\bar{t}$ mode without the additional shielding, as well as for the $t\bar{t}$ mode with the additional tungsten blocks and lead plates. For the H operation mode, around 72% of all the power (118.3 kW) is deposited in the CuCrZr absorbers, while this reduces to 69% of the total power (112.8 kW) in the $t\bar{t}$ mode. On average, this results in 2.2 kW per SR absorber for $t\bar{t}$.

The fraction of power dissipated in the tunnel environment is about 5% for H and 7% for $t\bar{t}$ if no additional radiation shielding is used. This represents a significant power load

Table 1: Absorbed power per arc cell for the H and $t\bar{t}$ operation mode with SR absorbers, and $t\bar{t}$ operation mode with SR absorbers and additional shielding.

	H	**$t\bar{t}$**	**$t\bar{t}$**
SR absorbers	yes	yes	yes
W+Pb shield.	no	no	yes
Dipoles	26.8 kW	28.8 kW	5.3 kW
Quadrupoles	1.5 kW	1.7 kW	1.6 kW
Sextupoles	0.01 kW	0.02 kW	0.02 kW
Vac. chamber	8.9 kW	8.7 kW	7.8 kW
SR absorbers	118.3 kW	112.8 kW	111 kW
W+Pb shield.	-	-	36.1 kW
Tunnel	8.7 kW	12.3 kW	1.3 kW
Total	**164 kW**	**164 kW**	**164 kW**

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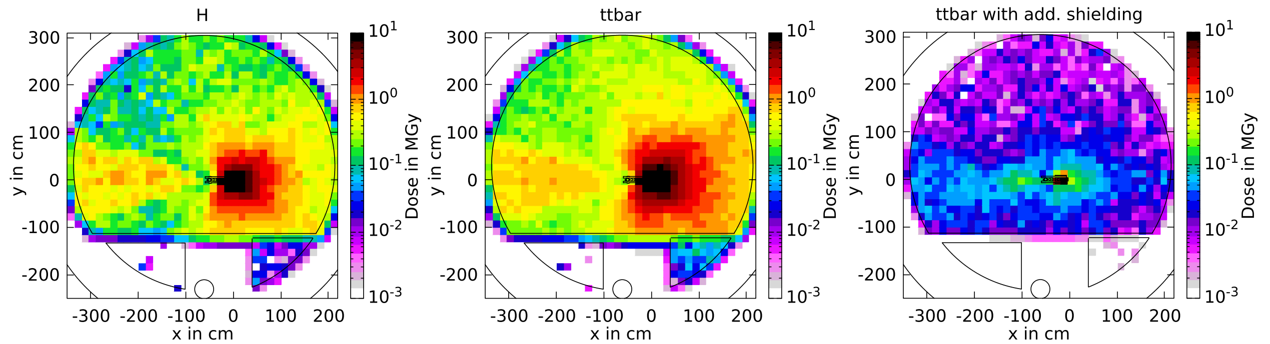

Figure 3: Dose levels in the cross section of the tunnel at a absorber location for H and $t\bar{t}$ operation mode without radiation shielding, and $t\bar{t}$ mode with shielding. The same location is used for all cross-section plots.

of 5 MW and 7 MW, respectively, when scaled to the entire ring. With the proposed tungsten and lead shielding, the power to the environment in $t\bar{t}$ operation can be reduced by about one order of magnitude (from 7% to 0.8%), which relaxes the requirements for heat removal from the tunnel air and also translates into significantly lower dose values in equipment as discussed later. The combination of the SR absorbers and the shielding take a share of approximately 90% of the total power in $t\bar{t}$ operation, which is a significant increase to the 69% beforehand. On average, the shielding around one SR absorber dissipates about 0.75 kW and likely requires active cooling like the SR absorbers themselves.

CUMULATIVE IONISING DOSE

The cumulative ionizing dose can affect mechanical, electrical and optical material properties of organic materials such as magnet insulation, cable insulation, optical fibers, seals, lubricants etc. This can limit the lifetime of equipment, as was already experienced in the synchrotron radiation environment of LEP [14]. The ionizing dose can also lead to the failure of electronics. Considering the size of FCC-ee, it would be very costly if equipment needs to be exchanged frequently or if a large number of components needs to be radiation-hard. The dose levels in the tunnel must therefore be sufficiently reduced such that COTS solutions can be deployed for a good fraction of equipment, although the need of radiation-hard components cannot be avoided for some systems or for some locations in the tunnel.

Figure 3 shows the cumulative ionizing dose in the arc tunnel cross section, comparing the same operating modes and configurations as in the previous section, i.e., H and $t\bar{t}$ operation without radiation shielding, and $t\bar{t}$ operation with shielding. The figures correspond to the location of an SR absorber where the dose level are the highest. The dose levels are normalised to one year of operation, which is assumed to be 1×10^7 s.

The highest dose values are observed in the horizontal plane in the vicinity of the absorbers. Without any radiation shielding, dose values near the machine can reach multiple MGy/year, even in H operation. The dose values are lower but still very significant in the upper half of the tunnel, where most of the cable trays are located on the tunnel walls. In this location, the dose reaches up to 300 kGy/year in H operation and 600 kGy/year in $t\bar{t}$ operation. Such dose levels would require radiation-hard cables in order to avoid premature material failures during the lifetime of the collider, which foresees 3 years of H operation at 5 years of $t\bar{t}$ operation.

The additional shielding leads to a significant reduction of the dose levels in the overall tunnel. In particular, at the level of the cable trays the annual dose in $t\bar{t}$ operation decreases from 600 kGy to 20 kGy. These results look very promising, although a further reduction of at least a factor of two is needed to limit the dose to cables to less than 100 kGy over the full collider lifetime of several years. This tentative target value is based on the experience of cable irradiation studies carried out within the HL-LHC project [15], but might be revised in the future. The resulting dose values are also still too high for COTS electronics. Designing a system with commercial electronics with some level of complexity is considered as unfeasible for a dose above 1 kGy. As a possible solution, locally shielded pits will be investigated.

Another important aspect are the dose levels at the busbars of the dipoles, which need to be insulated. The study shows that it is not possible to use any organic insulation material, as the dose levels reach up to 50 MGy/year near the absorbers even with the additional shielding. Hence, it is mandatory to develop a radiation-hard solution for the busbar insulation in order to avoid premature failures of the insulation within the lifetime of the machine.

CONCLUSION

This paper shows that a dedicated radiation shielding is required in addition to the FCC-ee SR photon absorbers, in order to reduce the dose levels in the tunnel environment to acceptable levels. The shielding is also needed to reduce the heat dissipation in air. The presented shielding needs to be further optimized, but the results demonstrate that dose levels can be reduced by more than one order of magnitude. The final choice of the shielding material will depend on a variety of aspects like costs, machining and cooling efficiency. To achieve a complete picture of the radiation load in the FCC-ee arcs, it is also necessary to include the booster that will be located on top of the collider machine. Due to its operation mode, it will be contributing less, but detailed studies are required as no dedicated SR absorbers are presently foreseen in the booster magnets.

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