FCC-ee RADIATION ENVIRONMENT AND SHIELDING

A. Lechner*, B. Humann, J. Bauche, J.P. Burnet, M. Calviani, F. Carra, F. Cerutti, A. Frasca[1],
R. Garcia Alia, C. Garion, K. Hanke, C. Jaermyr Eriksson, R. Kersevan, G. Lavezzari, G. Lerner,
J. Manczak, M. Morrone, A. Perillo Marcone, A. Piccini, A. Romero Francia, R. Seidenbinder,
L. Von Freeden, M. Widorski, CERN, Geneva, Switzerland
F. Valchkova-Georgieva, CEGELEC SA, Carouge, Switzerland
[1]also at University of Liverpool, Liverpool, UK

Abstract

The secondary radiation fields generated by synchrotron photons pose a significant challenge for equipment in high energy electron and positron storage rings like the Future Circular Collider (FCC-ee) at CERN. The annual ionizing dose can reach MGy-levels in the FCC-ee tunnel and requires the design of a dedicated radiation shielding enclosing the photon stoppers in dipoles. In this paper, we present a first optimization of the shielding design, taking into account different aspects such as shielding efficiency, engineering and integration constraints, raw material costs, and radiological considerations. We demonstrate that the proposed shielding solution can decrease the dose in the tunnel by about two orders of magnitude, which considerably reduces the need of expensive radiation-hard equipment. In addition, we explore the option of housing accelerator electronics in a dedicated bunker near lattice quadrupoles, which can possibly allow for commercial-off-the-shelf-based radiation tolerant electronics systems. We quantify the expected radiation levels in this bunker, which are driven by photo-neutron production by the high-energy component of the synchrotron spectrum.

INTRODUCTION

Synchrotron radiation (SR) is the dominant source of radiation in high-energy electron-positron colliders like the FCC-ee [1]. The FCC-ee will operate at different working points ranging from 45.6 GeV (Z pole) to 182.5 GeV (above the $t\bar{t}$ threshold). The SR-induced energy loss is proportional to $E^4/(m^4\rho)$, where E is the beam energy, m the electron mass, and ρ the bending radius (about 10 km for FCC-ee). The emitted synchrotron power in FCC-ee is limited by design to 50 MW/beam for all working points, which corresponds to 0.65 kW/m/beam in the arcs. In the present FCC-ee layout, the synchrotron radiation fan is intercepted by localized photon stoppers embedded in horizontal winglets of the dipole vacuum chambers [2–4]. Although the power emission is kept constant for all working points, the radiation levels in the tunnel increase for higher beam energies due to the harder SR photon spectrum. The SR spectra for the different working points are illustrated in Fig. 1. The critical energy ($E_c \propto E^3/\rho$) is 0.02 MeV at the Z pole (45.6 GeV) and reaches 1.3 MeV for $t\bar{t}$ (182.5 GeV).

Previous studies [5, 6] showed that the dose in the tunnel can reach MGy-levels, which can severely affect the lifetime of equipment and would require expensive radiation-hard solutions. Although the annual dose levels are dominated by the $t\bar{t}$ mode, they are also significant for ZH (about 2–3× less than for $t\bar{t}$) and $W^{\pm}$ operation (about 4–5× less than for $t\bar{t}$). The radiation exposure of equipment can be significantly reduced by means of a dedicated radiation shielding. In this paper, we present a preliminary shielding concept for the arc dipoles, together with a possible electronics bunker near the arc quadrupoles. Based on FLUKA Monte Carlo simulations [7–10], we explore the required material budget for the shielding and bunker. The dipole shielding is an evolution of an earlier design presented in Ref. [6]. The studies are carried out for a representative ZH/$t\bar{t}$ FODO cell, which is about 52 m long (see Fig. 2). The shielding and bunker are only first concepts developed for the FCC Feasibility Study [11], with the goal to assess the achievable reduction of dose levels and fluences. Detailed engineering and integration studies are needed to increase the maturity of the design.

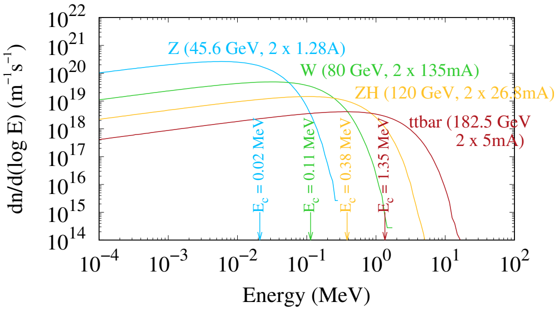

Figure 1: Synchrotron radiation spectra emitted by the FCC-ee beams at different working points.

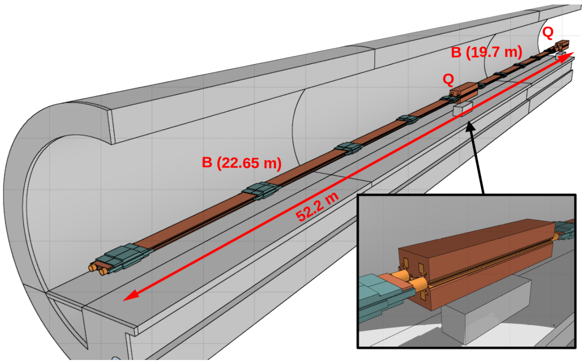

Figure 2: FLUKA geometry model of a representative FODO cell of the ZH and $t\bar{t}$ lattice.

---

* Anton.Lechner@cern.ch

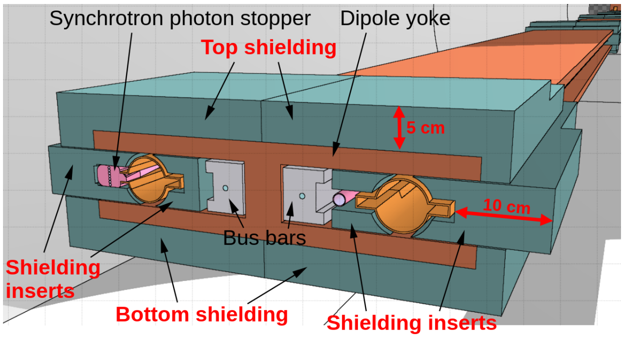

Figure 3: First shielding concept for the FCC-ee collider. The PbSb shielding must enclose the CuCrZr photon stoppers to reduce the radation leakage to the tunnel.

DIPOLE SHIELDING AROUND STOPPERS

The distance between SR photon stoppers in the dipoles is about 5 m, and they also shadow the short straight sections. The stoppers have a length of about 35 cm and are made of a copper alloy (CuCrZr) [3, 4]. In order to contain the radiation leakage from the stoppers, the stoppers need to be tightly enclosed by a heavy shielding assembly. When selecting a suitable shielding material, economic aspects such as raw material and fabrication costs, and the availability of sufficient material quantities in industry play an important role due to the large number of required shielding units (>20000 for the full ring). Tungsten heavy alloys (17–18.5 g/cm^3) provide a very good shielding efficiency, but have been discarded for cost reasons. A much cheaper alternative is antimonial lead, which is a common shielding material for gammas. In the present study, we assume an antimony content of 6%, which gives a density of 10.88 g/cm^3 and is primarily needed for structural reasons; the antimony hardens the material, which improves the mechanical stability and the machining of the shielding. The shielding might need to be covered by a casing or coating in order to allow for a safe handling of shielding components.

Table 1: Relative power deposition by SR in the machine and the tunnel, with and without radiation shielding around the photon stoppers. The last row (environment) includes the power deposition in air, tunnel walls and earth or rock.

	ZH		$t\bar{t}$	
	w/o	**with**	**w/o**	**with**
Photon stoppers	69.9%	69.7%	68.3%	68.1%
Shielding	-	19.1%	-	20.4%
Vac. chambers	9.0%	8.9%	8.1%	8.0%
Dipoles	16.7%	2.3%	17.4%	3.5%
Quad.+Sext.	<0.04%	<0.02%	<0.2%	<0.04%
Environment	4.3%	<0.01%	6.1%	<0.03%

A first optimization of the required PbSb shielding topology has been performed using radiation transport simulations. The resulting shielding assembly (see Fig. 3) consists of shielding plates above and below the dipole yoke, as well as horizontal shielding inserts. The shielding is assumed to be about four times longer (130 cm) than the photon stoppers to reduce the backscattering of photons into the tunnel. With a shielding thickness of 5 cm vertically and 10 cm horizontally, the flux of secondary photons and electrons in the tunnel can be reduced by several orders of magnitude, even at the $t\bar{t}$ working point (182.5 GeV). The resulting shielding weight is about 400 kg per photon stopper (roughly 11 kt for the full machine). As shown in Table 1, the shielding dissipates about 20% of the SR power at the ZH and $t\bar{t}$ working points. This corresponds to 20 MW for the full ring, or 2.5 MW per arc. For a single shielding element, the power load can reach up to several hundreds of Watts, which have to be dissipated by a dedicated cooling circuit. A first thermo-mechanical assessment of the shielding assembly is presented in Ref. [12].

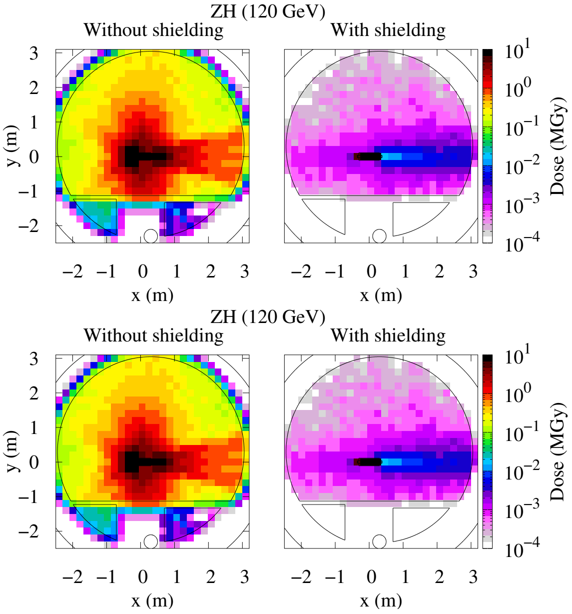

Figure 4: SR-induced annual dose in the FCC-ee arc tunnel at the ZH (top) and $t\bar{t}$ (bottom) working points (left - without shielding, right - with shielding).

The shielding decreases significantly the radiation leakage to the environment (see the last row in Table 1). Figure 4 illustrates the corresponding reduction of the annual dose levels in the arc tunnel. The dose maps correspond to the ZH and $t\bar{t}$ working points, which contribute the largest fraction of the dose received by equipment. The figure assumes 185 days/year, 75% operational efficiency, and beam currents of 26.8 mA (ZH) and 5.1 mA ($t\bar{t}$). Particular attention has to be paid to the radiation exposure of cable trays, considering the large amount of cables and optical fibres which need to be routed in the tunnel. At the location of the upper cable trays on the walls (>2 m above floor level), the dose can reach hundreds of kGy/year if no shielding is installed. With the present shielding concept, the dose at cable trays can be reduced to <1 kGy/year for the ZH working point, and to <10 kGy/year for the $t\bar{t}$ working point. It seems feasible that most cables accumulate less than 100 kGy/year in the full FCC-ee era, which would allow for general-purpose cables according to the criteria presently adopted at CERN. In the vicinity of the machine, radiation-hard cables and connectors which can sustain MGy dose levels can likely not be avoided even with the shielding in place.

The design of the shielding must also account for radiological considerations due to photo-neutron production by SR photons at higher beam energies. A first study indicates that the PbSb assembly can be classified as non-radioactive after one to two years once $t\bar{t}$ operation has concluded. The exact period depends on the antimony content, which dominates the resulting radionuclide inventory in the initial cool-down phase. Possible contributions of beam losses, mainly due to beam-gas scattering, still have to be assessed.

ELECTRONICS BUNKER

Several FCC-ee accelerator systems, in particular beam position monitors, beam loss monitors and vacuum equipment, require electronics near the machine. Even with the dipole shielding introduced in the previous section, the cumulative dose in the tunnel poses a concern for the lifetime of electronics. Furthermore, secondary neutrons can give rise to single event effects and increase the risk of displacement damage. Electronics systems based on commercial-off-the-shelf (COTS) components can be made radiation-tolerant through careful selection and testing of components, and by applying radiation effects mitigation measures at different design levels; but their use is typically restricted to locations, where the cumulative dose remains below 0.5–1 kGy. For higher dose values, radiation-hardened components need to be procured and, in some cases, even developed, requiring an additional investment in time and resources.

A possible option for reducing the radiation exposure of electronics is to house the racks in dedicated bunkers near lattice quadrupoles. A first concept of such a bunker is shown in Fig. 5. The bunker is assumed to be made of concrete walls (10–20 cm thick), which are very effective in reducing the SR-induced flux of secondary electrons and photons, even at the $t\bar{t}$ working point. Radiation effects in the bunker are hence dominated by neutrons, which can still penetrate the walls. The neutrons can be partially moderated and captured by covering the inner bunker walls with sheets of borated polyethylene (here assumed to be 2 cm thick, with a 10% boron content). Figure 6 presents the calculated neutron spectra for $t\bar{t}$ operation in the concrete walls, as well as inside the bunker. The presence of borated polyethylene suppresses the thermal peak in the spectrum and reduces the flux.

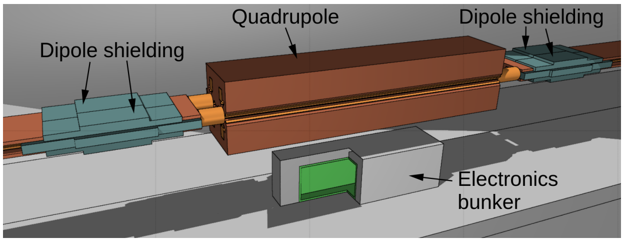

Figure 5: Concept of an electronics bunker near the lattice quadrupoles in the FCC-ee arcs. The bunker is assumed to be made of concrete and borated polyethylene sheets (green).

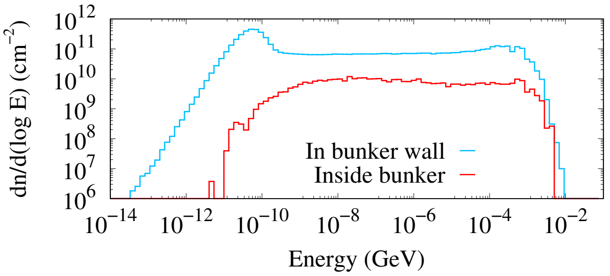

Figure 6: SR-induced neutron fluence spectra in the concrete walls of the electronics bunker and inside the bunker. The curves correspond to one year of $t\bar{t}$ operation (185 days).

Table 2: Radiation environment inside and outside the FCC-ee electronics bunker, normalized to one year of $t\bar{t}$ operation (185 days). The last column shows the radiation level specifications for the HL-LHC arcs (one year) [13].

	FCC-ee $t\bar{t}$ (outside bunker)	**FCC-ee $t\bar{t}$ (inside bunker)**	**HL-LHC arcs (below magnets)**
D	few kGy	<10 Gy	1.4 Gy
$\Phi_{eq}^{1\,\mathrm{MeV}}$	6×10^{11} cm^{-2}	2×10^{10} cm^{-2}	1.6×10^{10} cm^{-2}
Φ_{eq}^{HEH}	8×10^{8} cm^{-2}	2×10^{7} cm^{-2}	2.4×10^{9} cm^{-2}
Φ_{eq}^{THN}	5×10^{11} cm^{-2}	4×10^{9} cm^{-2}	1.2×10^{10} cm^{-2}

Table 2 compares the predicted dose and fluence values inside and outside the bunker for one year of $t\bar{t}$ operation. The table shows quantities related to cumulative radiation effects in electronics (dose - D, 1 MeV-neutron-equivalent fluence in Silicon - $\Phi_{eq}^{1\,\mathrm{MeV}}$) and to single event effects (high-energy hadron-equivalent fluence - Φ_{eq}^{HEH}, thermal neutron-equivalent fluence - Φ_{eq}^{THN}). The radiation levels inside the bunker are similar or even lower than for the HL-LHC arcs (see last column), with the exception of the total ionizing dose which nevertheless remains acceptable. The results demonstrate that a bunker possibly enables the use of custom radiation-tolerant electronics systems based on COTS semiconductor devices. The technical design and the integration of such a bunker in the arc tunnel still needs to be elaborated. The electronics must remain accessible in case of human or robotic interventions. Another important aspect is the ventilation of the bunker in order to dissipate the heat generated by the electronics.

CONCLUSIONS

This paper presented a shielding and bunker concept for the FCC-ee arcs, which significantly lowers the radiation exposure of sensitive equipment like cables, optical fibres and electronics. The studies demonstrate that the amount of resource-intensive radiation-hard equipment can be substantially reduced. The shielding and bunker need to be developed into a realistic technical design, which requires detailed engineering and integration studies.

REFERENCES

[1] A. Abada *et al.*, “FCC-ee: The Lepton Collider”, *Eur. Phys. J. Spec. Top.*, vol. 228, pp. 261–623, 2019. `doi:10.1140/epjst/e2019-900045-4`

[2] R. Kersevan and C. Garion, “Conceptual design of the vacuum system for the Future Circular Collider FCC-ee main rings”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 2438–2440. `doi:10.18429/JACoW-IPAC2021-TUPAB392`

[3] R. Kersevan, “The FCC-ee vacuum system, from conceptual to prototyping”, *EPJ Tech. Instrum.*, vol. 9, 2022. `doi:10.1140/epjti/s40485-022-00087-w`

[4] M. Morrone *et al.*, “Preliminary design of the FCC-ee vacuum chamber absorbers”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 382–385. `doi:10.18429/JACoW-IPAC2023-MOPA141`

[5] B. Humann, F. Cerutti, and R. Kersevan, “Synchrotron radiation impact on the FCC-ee arcs”, in *Proc. IPAC’22*, Bangkok, Thailand, 2022, pp. 1675–1678. `doi:10.18429/JACoW-IPAC2022-WEPOST002`

[6] B. Humann *et al.*, “Challenges and mitigation measures for synchrotron radiation on the FCC-ee arcs”, in *Proc. IPAC’24*, Nashville, TN, USA, 2024, pp. 292–295. `doi:10.18429/JACoW-IPAC2024-MOPG04`

[7] C. Ahdida *et al.*, “New Capabilities of the FLUKA Multi-Purpose Code”, *Front. Phys.*, vol. 9, 2022. `doi:10.3389/fphy.2021.788253`

[8] G. Battistoni et al., “Overview of the FLUKA code”, *Ann. Nucl. Energy*, vol. 82, pp. 10–18, 2015. `doi:10.1016/j.anucene.2014.11.007`

[9] G. Hugo *et al.*, “Latest FLUKA developments”, *EPJ Nuclear Sci. Technol.*, vol. 10, p. 20, 2024. `doi:10.1051/epjn/2024023`

[10] CERN, *FLUKA Website*, `https://fluka.cern`.

[11] M. Benedikt *et al.*, “Future Circular Collider Feasibility Study Report Volume 2: Accelerators, technical infrastructure and safety”, CERN, Geneva, Switzerland, Tech. Rep. CERN-FCC-ACC-2025-0004, 2025. `doi:10.17181/CERN.EBAY.7W4X`

[12] A. Romero Francia *et al.*, “Mechanical design and challenges of the FCC-ee arc radiation shielding”, presented at IPAC’25, Taipei, Taiwan, Jun. 2025, paper THPB060, this conference.

[13] G. Lerner *et al.*, “HL-LHC Radiation level specification document”, CERN, Geneva, Switzerland, Tech. Rep., 2024.