

Radiation environment at FCC-ee experimental insertion regions

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The future circular electron-positron collider will provide collisions at four interaction points (IPs) along a 91-km ring, with beam energies ranging from 45.6 GeV (Z pole) to 182.5 GeV ($t\bar{t}$ threshold). Several processes, induced by both the collisions at the IPs and the circulating beams, contribute to the radiation environment of the experimental insertion regions, exposing the detector, machine equipment, and electronics. Quantifying these radiation fields and their effects is essential to guide design strategies. In this work, the Monte Carlo code FLUKA is employed to simulate the propagation of radiation showers from both IP-driven and beam-driven sources, including radiative Bhabha scattering, incoherent pair creation, beamstrahlung, synchrotron radiation, and beam-gas interactions. Power deposition, equivalent fluences, and total ionizing dose are estimated to assess the exposure of sensitive components and to characterize tunnel radiation levels at the Z-pole and $t\bar{t}$ -threshold modes. The results show that incoherent pairs dominate the detector environment, particularly in the tracker, while radiative Bhabha losses in the superconducting final-focus quadrupoles (FFQs) require shielding to ensure safe magnet operation. Tunnel radiation levels exceed the tolerance of standard equipment at both operational modes, being dominated by radiative Bhabha and collimation losses at the Z pole, and by synchrotron radiation at the $t\bar{t}$ threshold. While a tungsten layer is shown to effectively protect the FFQs, the high radiation levels elsewhere indicate the need for additional shielding in dipoles and drifts, as well as dedicated absorbers downstream of the IPs and collimators.

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I. INTRODUCTION

The future circular collider (FCC) study at CERN proposes a next-generation accelerator infrastructure based on a new 91-km underground tunnel. A two-stage integrated programme is envisioned: the first stage features a luminosity-frontier electron-positron collider (FCC-ee) [1], expected to begin operation in the 2040s, followed by a second stage hosting an energy-frontier hadron collider (FCC-hh) [2]. The FCC-ee is designed to deliver collisions at four interaction points (IPs) over a wide range of center-of-mass energies, serving as an electroweak, Higgs, and top

factory. The current baseline foresees operation at beam energies of 45.6 GeV (Z pole), 80 GeV (WW threshold), 120 GeV (ZH production), and 182.5 GeV ($t\bar{t}$ threshold). The physics programme targets precision measurements and rare processes, requiring extremely high integrated luminosities and continuous operation over more than a decade. In the interaction regions (IRs) hosting the experiments [3], multiple processes contribute to the development of radiation showers that can be detrimental to accelerator and detector operation, impacting the performance and longevity of the exposed equipment. They may degrade material properties through instantaneous or cumulative damage, induce quenches in superconducting magnets via power deposition, and compromise the functioning of detectors and electronics. A precise characterization of the radiation fields at the FCC-ee IR is therefore essential for multiple aspects of its design.

Most FCC-ee accelerator-related studies are based on the collider Global Hybrid Correction (GHC) lattice [4], which

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TABLE I. FCC-ee beam parameters used in version 24.4 of the GHC lattice [4–6] for the four operational modes.

Operational mode	Z	WW	ZH	$\bar{t}\bar{t}$
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1852	300	64
Bunch intensity (10^{11})	2.18	1.38	1.69	1.50
Beam current (mA)	1294	135	26.8	5.1
Luminosity/IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	145	20	7.5	1.41
Run time (yr)	4	2	3	5

is still under development. This work uses version 24.4 [5,6], released in late 2024, the year before the publication of the FCC Feasibility Study Report [7–9]. The main beam parameters for this lattice version are summarized in Table I for the planned 15-yr running scenario. For each operational mode, the beam current is adjusted according to the beam energy in order to limit the synchrotron radiation (SR) power loss to 50 MW per beam. At the Z pole, the beam current reaches 1294 mA, yielding a luminosity per IP of $1.45 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$, while at the $\bar{t}\bar{t}$ threshold the current is reduced to 5.1 mA and the luminosity drops to $1.41 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The unprecedented combination of beam intensities, luminosities, and energies at the FCC-ee creates a challenging radiation environment. In this work, the IR is defined as the 725 m longitudinal region extending on each side of the IP, encompassing all elements associated with the experimental insertion. Within this region, some of the radiation sources originate from the collisions at the IPs (IP-driven), such as beamstrahlung (BS) [10], radiative Bhabha (RB) scattering [11], and incoherent pair creation (IPC) [12]; others are intrinsic to the circulating beams (beam-driven), including synchrotron radiation (SR) [13,14], beam-gas (BG) interactions [15], and collimation losses [16,17]. The detectors, and in particular their silicon trackers, must withstand high fluxes of low-energy e^+e^- pairs, which influence layout and technology choices. The superconducting final-focus quadrupoles (FFQs) are highly sensitive to localized losses of RB particles, requiring dedicated shielding to avoid quenches and coil degradation. Other critical components, such as beam dumps and absorbers, have to be designed based on the power deposition they are expected to withstand. Furthermore, the tunnel radiation environment must be characterized to provide the necessary input for defining tolerance levels and potential shielding requirements for distributed components like cables or in-tunnel electronics.

Previous studies have addressed some of these topics individually, focusing, for example, on the performance of the BS dump and photon stoppers [18], RB-induced losses in the FFQs [19], or general tunnel radiation levels [20]. In this work, we present a comprehensive study that integrates both IP-driven and beam-driven sources in the FCC-ee IRs. Using the Monte Carlo transport code FLUKA [21–23], we quantify power deposition, equivalent particle fluences, and

total ionizing dose for the Z-pole and $\bar{t}\bar{t}$ -threshold operational points, thereby covering the extremes of the machine parameter space. While the present work focuses on FCC-ee operation, it is worth noting that the more demanding radiation environment expected during FCC-hh operation has important implications for the design of the underground infrastructure, which is foreseen to host both machines. Radiation studies for FCC-hh are available in Refs. [24–26].

The paper is organized as follows. Section II describes the simulation setup, emphasizing the modeling of IR layout and radiation sources, as well as the evaluated quantities. Section III presents the results for IP-driven sources (RB, IPC, and BS), while Sec. IV addresses beam-driven sources (SR, BG, and collimation losses). Section V provides an overall view of the radiation environment produced by both types of sources and discusses its implications for mitigation and shielding strategies. Section VI concludes with the main findings and their broader impact on the FCC-ee design.

II. SIMULATION SETUP

The Monte Carlo code FLUKA [21–23] simulates the transport and interaction of neutral and charged particles in matter across a wide range of particle types and energies. It incorporates state-of-the-art physics models that reproduce the propagation of hadronic and electromagnetic showers within user-defined three-dimensional geometries and magnetic fields. This capability makes FLUKA particularly well-suited for evaluating the radiation environment in the complex geometries of the FCC-ee IRs. This section describes the implementation of the FLUKA model used in this work. The model combines a detailed description of the IR geometry with radiation sources representing the main IP-driven and beam-driven processes. Quantities relevant for the design of machine components and detectors are defined to quantify the radiation-induced effects.

A. FCC-ee IR layout

The FCC-ee IP design foresees the use of flat beams, a large crossing angle of 30 mrad, and a crab-waist scheme [3] to maximize the luminosity production. The incoming beamlines, which enter the IP from the inner rings and exit into the outer ones, are designed to minimize the SR photons that can reach the detector by avoiding significant bending close to the IP, thereby limiting the SR power radiated within 500 m upstream of the IP to about 1 kW [27]. Additional protection is provided by SR masks and SR collimators [14]. Two tertiary collimators, one vertical (TCTV) and one horizontal (TCTH), are placed in the incoming beamline at $s = 456$ m and 706 m from the IP, respectively, to protect the experiment [28]. To accommodate the large crossing angle, the outgoing beamlines are more strongly bent, radiating significantly more SR power.

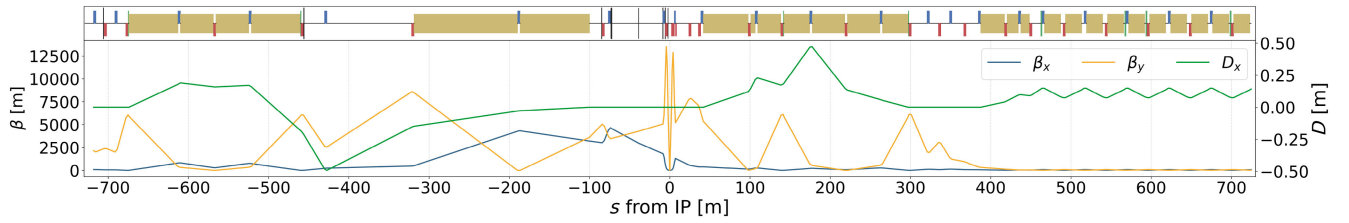


FIG. 1. Lattice and optical functions of the FCC-ee IR from version 24.4 of the collider GHC optics. Shown are the horizontal and vertical betatron functions (β_x and β_y) and the horizontal dispersion D_x . The beam travels from left to right. Dipoles, focusing quadrupoles, defocusing quadrupoles, and sextupoles are indicated in yellow, blue, red, and green, respectively, while collimators and masks are shown in black.

Direct impact of SR photons on the vacuum chamber is prevented by discrete photon stoppers embedded in the horizontal winglets of the beam pipe [29–32]. Throughout the IR, the lateral beam separation is of the order of meters, requiring single-beam magnets. All magnets except the FFQs are normal conducting. The current design foresees a final-focus doublet of NbTi superconducting canted-cosine-theta quadrupoles, QC1 and QC2, consisting of three (QC1R1, QC1R2, QC1R3) and two segments (QC2R1, QC2R2), respectively [33]. The QC1 quadrupoles, located 2.2 m from the IP, are housed in liquid-helium cryostats placed on either side of the detector, each cryostat accommodating both the incoming and outgoing beamline elements. QC2 follows further downstream, with two magnet segments placed outside the detector volume. The orbit distortion induced by the 2 T detector solenoid and the crossing angle is compensated locally by a 5 T antisolenoid and a screening solenoid around the QC1 magnets [3]. The IR also features an extraction line to transport BS photons produced at the IP to a dedicated dump, currently foreseen at 500 m downstream of the IP [10].

The FLUKA model of the IR incorporates a simplified yet representative description of all the main beamline elements, tunnel infrastructure, and detector-related structures relevant for radiation transport. This includes the magnetic fields of both the detector and beamline elements. The beamline geometries are assembled using auxiliary tools [34,35], adopting a modeling strategy validated by benchmarking studies at existing facilities, such as Ref. [36]. The setup is based on version 24.4 of the GHC lattice [4–6]. Owing to the periodicity of the lattice, all four IRs share identical optics. Figure 1 shows the lattice and optics of the IR in Z-pole mode as functions of the curvilinear coordinate s measured from the IP, such that $s < 0$ denotes the beamline incoming to the experiment and $s > 0$ the beamline outgoing from it. In what follows, the positron beam is assumed to circulate clockwise and the electron beam counterclockwise, referred to as beam 1 (B1) and beam 2 (B2), respectively. Because B2 is assumed to follow the same optics as B1, only one side of the IR is explicitly modeled in FLUKA for reasons of symmetry (see Fig. 2). Consequently, the geometry features the outgoing section of B1 ($-5.56 \text{ m} < s < 723 \text{ m}$ in Fig. 1) and the incoming

section of B2 ($-723 \text{ m} < s < 5.56 \text{ m}$ in Fig. 1). The modeled infrastructure consists of the detector cavern and the long straight section (LSS) tunnel, both composed of concrete and surrounded by soil. The LSS is represented by three straight segments to approximate its curvature and varying cross section.

A 2 mm-thick copper beam pipe with a radius of 30 mm and horizontal winglets is implemented. Photon stoppers made of CuCrZr, 37 cm in length and based on the bulkier design presented in Ref. [37], are installed along the beamline bends. Their placement, currently limited to the dipoles, has been chosen to intercept the majority of the SR fans, but their exact configuration in the IR is expected to be further optimized in the future.

Room-temperature magnets are modeled with an iron yoke and copper coils. The FFQs, QC1 and QC2, are based on the current design featuring a water-cooled stainless steel beam pipe, represented by a 1.4 mm-thick water layer sandwiched between two 0.8 mm-thick steel layers. The FFQ magnet, separated from the beam pipe by 2 mm of vacuum, is represented by four alternating layers (2 mm Al and 4 mm coil material) for a total thickness of 12 mm (see Fig. 3). The coils are modeled using an equivalent homogenized material composed of Al, NbTi, and Cu, with an effective density of 5.09 g cm^{-3} . The inner radii of the beam pipes in QC1 and QC2 are 1.5 and 2 cm, respectively.

The BS extraction line is modeled here as a 3 mm-thick conical copper vacuum chamber branching from the first dipole downstream of the IP. Dedicated open-geometry dipoles and quadrupoles provide lateral clearance for the

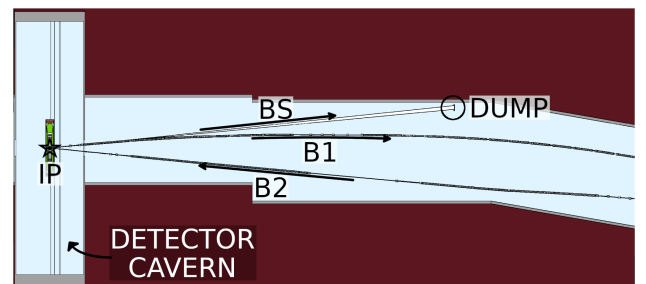


FIG. 2. Top view of FLUKA geometry of FCC-ee IR.

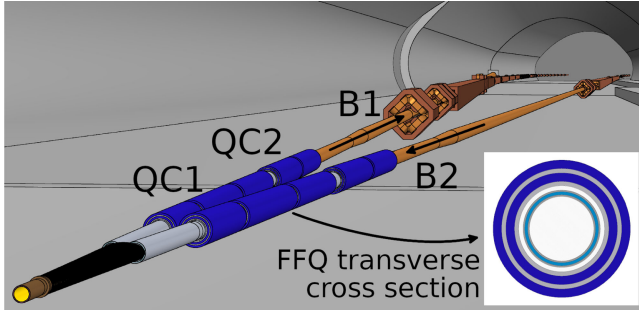


FIG. 3. FLUKA model of FCC-ee FFQs.

extraction line, allowing the photons to reach the dump [38]. Several design proposals based on liquid lead flows are currently under study for the BS dump core. Here a conceptual model is assumed, consisting of a liquid lead box with a cross section of $70 \times 70 \text{ cm}^2$ and a depth of 20 cm. A simplistic shielding featuring a 5 cm-thick iron layer enclosed in 20 cm-thick concrete is included [18].

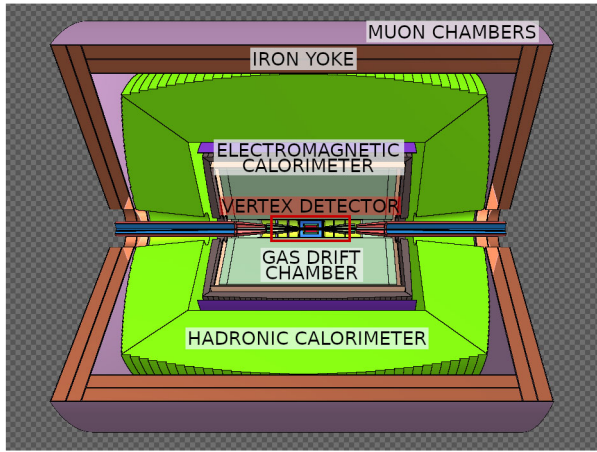
The detector model implemented in the FLUKA geometry is based on IDEA [39]. It features the main components and subdetectors, specifically the vertex (VTX) detector, the gas drift chamber, the electromagnetic crystal (PbWO_4) calorimeter (ECAL), the hadronic iron calorimeter (HCAL), the solenoid, the iron yoke, and the muon chambers [see Fig. 4(a)]. The VTX detector consists of several barrel layers, inner (consisting of three layers), middle, and outer,

and three endcap disks on each side, each featuring silicon layers on both faces [see Fig. 4(c)]. Two luminosity calorimeters (LumiCals) [3,40], aligned with the outgoing beams, are also implemented. A magnetic-field map covering the entire detector is included (see Fig. 4), accounting for the detector solenoid, compensating and screening antisolenoids.

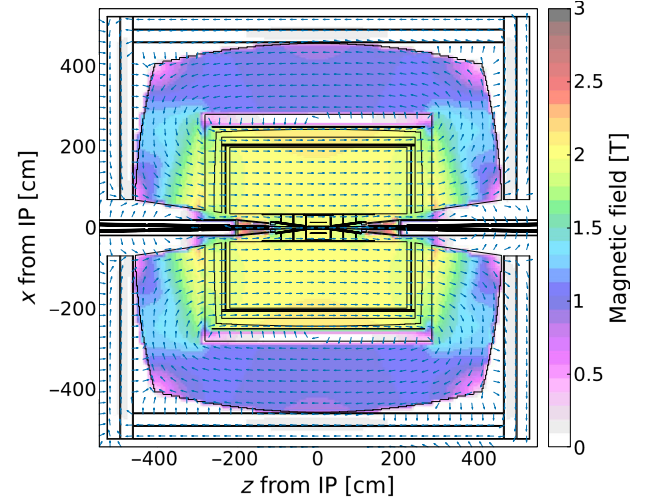
B. Sources of radiation

1. IP-driven sources

Beamstrahlung radiation (BS). Beamstrahlung radiation is the emission of photons by particles of one bunch in the electromagnetic field of the opposing bunch at the IP. The resulting beam-beam kicks bend particle trajectories, inducing the emission of electromagnetic radiation in a manner analogous to SR. Its characteristics depend on the beam energy, bunch population, and transverse beam sizes at collision [41]. At FCC-ee, the combination of very high bunch intensities and extremely small transverse dimensions leads to BS powers of up to a few hundred kW per beam. The photons are emitted within a cone of opening angle $\propto 1/\gamma$ [42], with γ the Lorentz factor, aligned with the outgoing beams. As a result, two intense and highly collimated photon beams emerge from each IP, requiring dedicated extraction lines and dumps for their safe disposal. While BS is the main driver of the energy spread and bunch



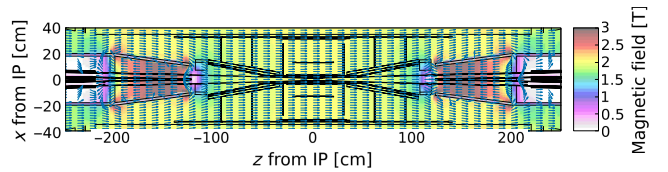
(a)



(b)



(c)



(d)

FIG. 4. FLUKA geometry of the IDEA detector and the corresponding magnetic-field maps on the horizontal midplane, shown for the full detector (a),(b) and for an enlarged view of the VTX region (c),(d).

TABLE II. Main BS radiation properties for Z and $t\bar{t}$ operation, as obtained from GUINEA-PIG++ simulations [10].

Quantity	Z	$t\bar{t}$
Power (per beam) (kW)	370	77.2
Mean photon energy (MeV)	1.7	62.3
Horizontal divergence (μrad)	91.8	44.6
Vertical divergence (μrad)	49.2	50.3
Horizontal spot size @500 m (μm)	4.59	2.23
Vertical spot size @500 m (μm)	2.46	2.51

length, its average energy loss remains a small fraction of the beam energy. As a result, BS-induced losses are expected to occur mainly in the collimation system, with no significant primary beam losses in the IR under nominal operating conditions. The exact power of the photon beams depends strongly on the bunch population, and therefore varies with the operational mode and the optics version. In particular, GHC optics version 22 assumes the highest bunch population, resulting in the highest BS power per beam: approximately 370 kW at the Z pole and 77 kW at $t\bar{t}$ operation. Since the optics are still evolving, here the parameters of version 22 are considered to provide conservative estimates for BS-related results. Table II summarizes the main BS properties, calculated in a previous study [10] based on optics version 22 of the GHC lattice, which also reports the corresponding BS radiation spectra. That study used GUINEA-PIG++ [43], a particle-in-cell simulation code designed to model the beam-beam interactions.

In the present simulations, BS photons were sampled at the IP from GUINEA-PIG++ samples and then propagated in the FLUKA geometry.

Radiative Bhabha scattering (RB). Radiative Bhabha scattering, $e^+e^- \rightarrow e^+e^-\gamma$ [44], is one of the processes with the highest cross section in e^+e^- collisions [11] and constitutes the dominant contribution to beam lifetime at all FCC-ee operational modes [8]. In this work, RB refers to the small-angle regime of the process, historically also referred to as single bremsstrahlung, which dominates the total cross section at FCC-ee energies. In this process, either the electron or the positron emits a photon and loses up to nearly all of its kinetic energy, possibly exiting the machine energy acceptance and being lost downstream of the IP. Lower-energy RB particles are typically lost within the FFQs, while higher-energy ones may be lost further downstream in the IR and beyond. Others within the energy acceptance of the machine can remain in orbit, most likely contributing to the beam halo. The photons radiated in RB scattering are emitted within the same narrow cone as BS radiation and are thus directed toward the same dump. However, their overall intensity is several orders of magnitude lower than that of BS [10], so their contribution to power deposition in the dump and tunnel

radiation levels is negligible and has been neglected in this study.

Radiative Bhabha particles were sampled at the IP from externally generated distributions and transported in the FLUKA geometry. Event samples were produced with BBBrem and GUINEA-PIG++. BBBrem [45] is a Monte Carlo generator for RB scattering in the very forward direction based on the matrix element and kinematics of Bhabha scattering with single-photon emission of Ref. [46]. Events are generated for a given center-of-mass energy with a specified cutoff on the minimum energy of the radiated photon. An additional cutoff on the minimum momentum transfer can be applied to account for the maximum impact parameter imposed by the field screening due to bunch particles. This so-called beam-size effect [47] was first observed at the VEPP-4, where a reduction of the cross section from the finite beam size and its enhancement from beam offsets at the IP were measured [48,49]. It was later confirmed at LEP, where BBBrem could reproduce the reduction of approximately 30% in the measured cross section once the bunch dimensions were taken into account [11,45]. Accordingly, a cutoff of $1\sigma_y^*$, corresponding to the vertical rms beam size at the IP (40.1 nm at the Z pole and 43.6 nm at the $t\bar{t}$ threshold), was applied to all RB samples used in this work. For slightly separated beams, the luminosity decreases much faster than the increase in cross section associated with the beam-size effect. The estimates presented here therefore remain valid as an upper limit, as they are expected to correspond to the worst-case scenario of smallest beam size and highest luminosity. Preliminary studies indicated that RB particles lost up to QC2 typically carry less than 50% of the nominal beam energy, while those lost within 725 m seldom exceed 93%. Photon-energy cutoffs of 50% and 7% of the nominal beam energy were therefore adopted to improve simulation efficiency for machine-detector interface and tunnel analyses, respectively. Table III lists the RB cross sections, σ_{RB} , computed with BBBrem for the two operational modes and the different photon-energy cutoffs. The generated RB events are then processed by GUINEA-PIG++ to embed them into a realistic bunch-crossing simulation, accounting for the beam phase-space distributions at the IP and for electromagnetic beam-beam deflections at the nominal crossing angle. The resulting distortions of the angular distributions of low-angle Bhabha products due to beam-beam

TABLE III. Radiative Bhabha cross sections σ_{RB} for different photon-energy cutoffs, expressed as a fraction of the nominal beam energy E_{beam} .

$E_\gamma^{\text{min}}/E_{\text{beam}}$	$\sigma_{\text{RB}}^{\text{Z}}$ (mb)	$\sigma_{\text{RB}}^{t\bar{t}}$ (mb)
0.01%	335	337
7%	82.0	82.5
50%	18.5	18.6

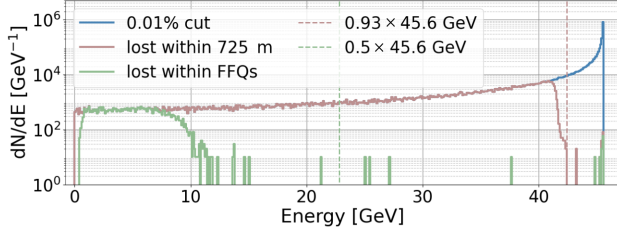


FIG. 5. Energy spectrum of a RB sample at the Z pole (photon-energy cutoff 0.01%), compared with the energy distributions of the particles lost within the FFQs and within 725 m downstream of the IP.

interactions have been extensively discussed in the context of precision luminosity measurements at LEP and future linear colliders [50–52]. Figure 5 shows the spectrum of a complete RB sample (photon-energy cutoff 0.01% of beam energy) at the Z pole, along with the energy distributions of the particles lost within QC2 and within 725 m downstream of the IP.

Incoherent pair creation (IPC). Copious e^+e^- pairs are produced at the IP through interactions of real and virtual photons originating from the colliding beams. These particles are typically of low energy and, under the influence of the detector solenoid field, follow spiraling trajectories until they are absorbed by the nearby elements, contributing significantly to the detector radiation load.

As for the other IP-induced processes, incoherent pairs are sampled from GUINEA-PIG++ event distributions and then transported in the FLUKA geometry. Figure 6 shows the spectrum of a complete sample of incoherent pairs at the Z pole, along with the energy distributions of the particles lost within the detector region ($-5.26 \text{ m} < z < 5.26 \text{ m}$).

Other processes. Additional physical processes occur at the IP in e^+e^- collisions. Nonetheless, their cross sections are much smaller than those of the processes discussed above, and thus they do not significantly contribute to the radiation environment in the FCC-ee IR. For example, the production of a Z boson followed by its decay, $e^+e^- \rightarrow Z \rightarrow \text{hadrons}$, reaches a maximum cross section of $\approx 41.5 \text{ nb}$ at the Z pole [53]. This is roughly 7 orders of magnitude lower than σ_{RB} ,

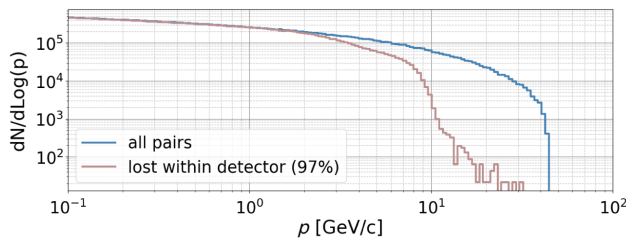


FIG. 6. Distribution of momentum p of an IPC sample at the Z pole, compared with the energy distribution of the pairs lost in the detector region.

illustrating the negligible impact of such processes on the overall radiation levels.

2. Beam-driven sources

Synchrotron radiation (SR). Synchrotron radiation is the electromagnetic radiation emitted by relativistic charged particles accelerated along curved trajectories by magnetic fields. The radiated power for a charged particle in circular motion of radius ρ scales as $P \propto \gamma^4/\rho^2$, making SR one of the dominant radiation sources in circular lepton machines such as FCC-ee. It is characterized by strong forward collimation within a cone of opening angle $\sim 1/\gamma$ and by a broad spectrum that falls off rapidly above the critical energy $E_c \propto E_{\text{beam}}^3/\rho$, which sets the hardness scale of the radiation. The critical energy is defined so that the integrated spectral power is split equally above and below E_c [54].

By design choice, the SR power emitted in the dipole magnets of FCC-ee IR is constant across all operational modes. In the region under study, about 96 kW are generated in the B2 dipoles (less than 1 kW within 500 m upstream of the IP, the rest in the three dipoles between 566 and 674 m) and 311 kW in the B1 dipole, along the more strongly bent outgoing line. Although the SR power is fixed by design across FCC-ee operational modes, the photon spectra vary significantly. At the Z pole, critical energies are in the range of a few to a few tens of keV, resulting in short attenuation lengths and photon absorption in the vacuum chamber with negligible tunnel leakage. At the $t\bar{t}$ threshold, instead, critical energies reach up to about 1.6 MeV, producing harder spectra that initiate electromagnetic showers propagating beyond the chamber, making SR the dominant contributor to tunnel radiation. A representative SR photon spectrum from the dipole with the highest E_c in this mode is shown in Fig. 7, where the dashed red line indicates the corresponding E_c . Additional SR photon spectra from arc dipoles at different operating points are presented in Ref. [55].

Synchrotron radiation generated by magnetic fields in the machine-detector interface—including the detector

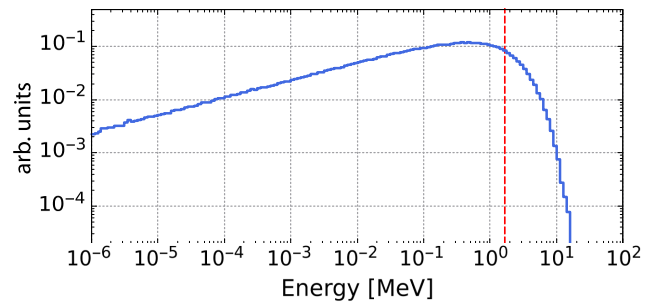


FIG. 7. Photon energy spectrum of SR generated by the dipole magnet with the largest E_c in the IR at the $t\bar{t}$ mode. The vertical axis is in arbitrary units (arb. units), and the dashed red line marks the corresponding E_c .

solenoid, compensating antisolenoids, and screening solenoids—is not included in this study, as its evaluation is planned for future work.

In FLUKA, SR photons can be generated directly during particle transport in vacuum regions within magnetic fields [23]. Emission from all beamline magnets, including dipoles and quadrupoles, is naturally accounted for during the transport. In this study, SR from optics-matched beams was simulated, with primary particles sampled from the Gaussian phase space defined by the Twiss parameters at the lattice location where the simulation starts. The SR emission was evaluated for both the positron beam (B1, outgoing clockwise) and the electron beam (B2, incoming anticlockwise). This nominal scenario does not include additional SR contributions arising from beam tails, orbit distortions, or optics mismatches. Such deviations are not expected to significantly affect the dipole radiation, which provides the dominant contribution to tunnel radiation levels. They may, however, enhance the SR produced in quadrupoles and are therefore particularly relevant for MDI and detector-background studies. These effects will be addressed in future dedicated work.

Beam–gas interactions (BG). Beam-gas interactions arise from collisions of beam particles with residual gas molecules in the vacuum chamber. For lepton beams, like at the FCC-ee, the relevant electromagnetic processes are bremsstrahlung on nuclei, elastic Coulomb scattering, and atomic ionization or excitation. Beam-gas bremsstrahlung constitutes a distributed source of high-energy photons that can carry a substantial fraction of the beam-particle energy, initiating electromagnetic showers upon leaving the vacuum chamber. The resulting off-momentum particles follow dispersive trajectories and are lost if their energy deviation exceeds the machine momentum acceptance. Among BG interactions, bremsstrahlung is expected to be the dominant contributor to beam-lifetime degradation. Under conditions of limited dynamic aperture, however, angular deflections from Coulomb scattering can drive beam particles beyond it, leading to losses within a few turns, typically at collimators. Although ionization and excitation dominate in terms of cross section, they induce only soft energy losses and negligible angular deflections, and thus do not contribute significantly to the radiation environment. Current FCC-ee studies indicate that, even under pessimistic assumptions on the residual gas pressure, beam-gas interactions lead to longer lifetimes than radiative Bhabha scattering and are therefore not expected to limit machine operation [15,56]. Due to the limited dynamic aperture of the GHC optics, Coulomb scattering may still drive important localized losses, with impacts on tertiary collimators in the IR comparable to those observed at primary collimators. For a given gas pressure profile, the overall BG interaction rate scales with beam current, peaking at the Z pole and reaching a minimum at the $\bar{\tau}$

threshold. Due to the presence of collimators upstream of the IP, BG interactions are expected to generate increased radiation along the incoming beam lines, which may eventually affect the detector.

In this work, BG losses have been simulated in two conceptually different ways, exclusively for the Z-pole operational mode. Local interactions were studied only for bremsstrahlung, as this process is expected to have the strongest local impact. For both B1 and B2, a dedicated FLUKA routine was employed to sample photon emission and update the momentum of the emitting particle. Events were sampled along the nominal trajectories according to a realistic gas pressure profile, while considering the matched transverse distribution. As a different approach, losses on the IR collimators induced by BG Coulomb scattering and bremsstrahlung occurring along the full ring were considered. Multiturn tracking simulations were performed with Xsuite [57] in another study [15], inserting discrete lumped scattering centers for BG interactions along the FCC-ee lattice. The resulting collimator hit data were recorded and used in this work to sample losses in the IR FLUKA model. Only hits in the collimators of the IR furthest from the collimation insertion were considered, as these represent the most critical case. Both approaches relied on the same pressure profile calculated with Synrad+ and Molflow+ [58,59], based on the FCC-ee vacuum design assumptions, including NEG-coated chambers, distributed pumps, discrete photon stoppers, and the nominal vacuum chamber geometry [8]. The target pressure range of FCC-ee is driven by beam-lifetime considerations and builds on experience from SR-dominated storage rings and colliders, which indicates that pressures of the order of 1×10^{-9} mbar ensure beam-gas lifetimes of several tens of hours [8]. A pessimistic scenario corresponding to only 1 h of beam conditioning at the nominal beam current of the Z mode was adopted, although further operation is expected to reduce the pressure by a couple of orders of magnitude. Such simulations typically carry an uncertainty of about 50% [60], which remains acceptable for radiation studies where the order of magnitude is the relevant figure and is small compared to the expected improvement from vacuum conditioning during operation. A gas mixture of 85% H₂, 10% CO, and 5% CO₂ was assumed, consistent with the conditions commonly observed at synchrotron light sources [61]. Figure 8 shows a representative portion of the adopted pressure profile along the IR.

Other processes. Several additional beam-driven mechanisms can cause losses in the ring, generating radiation cascades. Typically, these losses arise from multiturn effects, such as generic halo population, beam instabilities, or injection inefficiencies. As expected, Touschek scattering is negligible at FCC-ee energies [56]. Losses arising from beam halo [16,17,56,62], also populated by beam-beam effects and nonlinear optics, are expected to have a

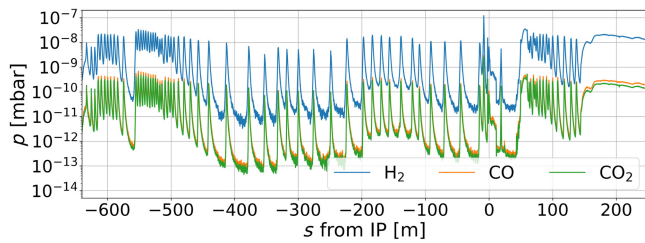


FIG. 8. Residual gas pressure profile along the IR, obtained from Synrad+ and Molflow+ simulations. The shown region is representative of the profile adopted in the simulations; local peaks correspond to areas of enhanced SR impact, such as photon-stopper locations and regions of reduced geometric aperture near the IP.

limited direct impact on the IR, as they are mainly intercepted by the dedicated collimation system. Losses associated with beam instabilities are typically related to transient or accidental scenarios [28] rather than steady-state operation and are therefore beyond the scope of the present study. Injection-related losses may represent an additional contribution, as observed at existing facilities such as SuperKEKB [63]. Their quantitative assessment will be addressed in future dedicated studies based on quantitative loss maps, analogous to those used for BG interactions, once the machine configuration is more accurately established.

C. Quantities of interest

The FLUKA simulations provide the quantities most relevant for assessing the radiation-induced effects on the machine equipment. These can be grouped into three main categories:

(i) Cumulative damage includes two main types of radiation effects, ionization damage and displacement damage. Ionization damage refers to the degradation of material properties in organic materials, such as insulators, as well as the aging of electronics. It is quantified through the total ionizing dose (TID), defined as the ionization energy deposited per unit mass. Displacement damage, on the other hand, occurs mainly in inorganic materials and results from nonionizing energy deposition, which produces lattice defects in the form of interstitial atoms and vacancies. This effect is quantified through the cumulative silicon 1 MeV-neutron equivalent fluence ($\Phi_{\text{eq}}^{1 \text{ MeV}}$), obtained by weighting the fluence of all particles and energies with the appropriate displacement-damage function, normalized to the effect of a 1 MeV neutron in silicon [64,65].

(ii) Stochastic failures of electronics are caused by single-event effects (SEEs), i.e., energy-deposition events triggered by individual energetic particles inducing transient or permanent malfunctioning of active components. To quantify the associated risk, this paper relies on a quantity originally developed at CERN to characterize SEE effects at the LHC, i.e., the cumulative high-energy hadron equivalent fluence ($\Phi_{\text{eq}}^{\text{HEH}}$), defined as the fluence of all

hadrons above 20 MeV plus a weighted contribution from lower-energy neutrons according to their SEE effectiveness [66,67]. At the FCC-ee, neutrons are effectively the only hadrons in the radiation field, produced via photonuclear reactions. While SEEs may also be induced by electrons, positrons, or photons with energies of a few MeV or above, the associated cross sections are substantially lower [68], so the analysis in this paper is focused on the $\Phi_{\text{eq}}^{\text{HEH}}$ only.

Thermal neutrons are also not examined in the present paper even though they can induce soft SEEs, because (unlike higher-energy neutrons) they can be locally shielded with thin layers of materials, so the detailed assessment of the $\Phi_{\text{eq}}^{\text{HEH}}$ shall be prioritized at the current stage of the FCC-ee project. (iii) Operational failures and machine protection include quench and thermo-mechanical effects. Beam losses can induce local heating, causing superconducting magnet coils to transition to the normal-conducting state (i.e., a quench), or generating critical thermo-mechanical stresses in absorbers and other beam-intercepting devices. These effects are assessed by quantifying the local power density deposition (P_V) in the exposed elements.

In this work, instantaneous quantities are normalized to the relevant nominal operational parameters, while all cumulative quantities are normalized to 1 yr of operation, following the annual integrated luminosity estimate given in Ref. [69]. This estimate assumes 185 days of running at 75% efficiency (corresponding to approximately 1.27×10^7 s), with nominal beam currents and luminosities. In the following radiation maps, coordinates are defined in the detector reference frame, with the origin at the IP: z denotes the longitudinal coordinate, x the horizontal coordinate pointing outward from the collider center, and y the vertical coordinate pointing upward.

III. RESULTS ON IP-DRIVEN LOSSES

Processes taking place at the IP are among the most critical radiation sources for the IR. In particular, RB, IPC, and BS generate large fluxes of secondary particles that can directly impact the detector, the FFQs, and the tunnel environment. The radiation load from these IP-driven processes is assessed separately for these three areas of concern. Due to its highest luminosity, Z-pole operation is found to be the most critical scenario for radiation from these sources and is therefore the main focus of the following studies. Between the Z and $\bar{t}t$ modes, the luminosity decreases by a factor of ≈ 100 , while the energy available in a single e^+e^- collision increases by only about a factor of 4, highlighting luminosity as the dominant driver of radiation effects.

A. Detector region

Among the IP-driven sources considered in this study, RB and IPC contribute to the detector radiation load, while

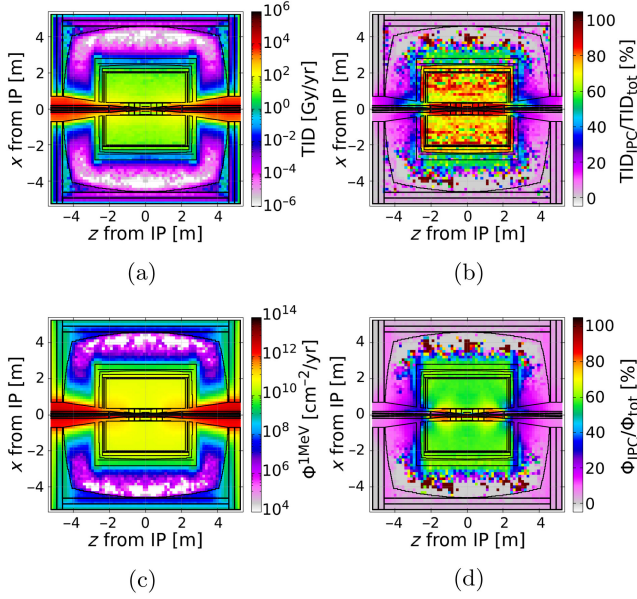


FIG. 9. Top-view distributions at beam height (average for y in ± 15 cm) for 1 yr of Z-pole operation. (a) Total TID, (b) IPC contribution to TID, (c) total $\Phi_{eq}^{1 \text{ MeV}}$, (d) IPC contribution to $\Phi_{eq}^{1 \text{ MeV}}$.

BS photons, emitted strictly collinear with the outgoing beams, do not enter the detector volume and are therefore not relevant in this context. Figures 9(a) and 9(c) show the top-view distributions of cumulative TID and $\Phi_{eq}^{1 \text{ MeV}}$ at beam height (averaged over ± 20 cm in y) for 1 yr of Z-pole operation. The innermost regions, closest to the machine, reach levels of 10 kGy yr^{-1} and $1 \times 10^{13} \text{ cm}^{-2} \text{ yr}^{-1}$, while subdetectors beyond the VTX detector experience values below 10 Gy yr^{-1} and $1 \times 10^{11} \text{ cm}^{-2} \text{ yr}^{-1}$. Table IV summarizes the orders of magnitude of these quantities for

TABLE IV. Orders of magnitude of radiation load in selected IDEA subcomponents from IPC and RB at the Z pole.

	TID (Gy yr^{-1})	$\Phi_{eq}^{1 \text{ MeV}}$ ($\text{cm}^{-2} \text{ yr}^{-1}$)
VTX detector	$10\text{--}10^4$	$10^{10}\text{--}10^{13}$
Y-pipe	10^5	$10^{14}\text{--}10^{15}$
LumiCal	$10^1\text{--}10^4$	$10^{11}\text{--}10^{13}$
Drift chamber	10	1×10^{11}
ECAL	1	1×10^{10}
HCAL	<1	$<1 \times 10^{10}$

several detector subcomponents, including the gas drift chamber, the ECAL, and the HCAL. The relative contribution of IPC to the total load is illustrated in Figs. 9(b) and 9(d). IPC dominates up to the drift chamber (70%–80% for TID and 60% for $\Phi_{eq}^{1 \text{ MeV}}$), whereas RB becomes dominant in the forward direction, contributing up to 80% of the load in the HCAL endcaps.

A closer view of the radiation load on the VTX detector region is presented in Figs. 10(a) and 10(c). Local TID values on the VTX layers range from a few tens of Gy yr^{-1} up to tens of kGy yr^{-1} , while $\Phi_{eq}^{1 \text{ MeV}}$ spans over 3 orders of magnitude, from 1×10^{10} to $1 \times 10^{13} \text{ cm}^{-2} \text{ yr}^{-1}$. Even higher values, reaching $1 \times 10^5 \text{ Gy yr}^{-1}$ and $1 \times 10^{15} \text{ cm}^{-2} \text{ yr}^{-1}$, occur near the Y-pipes, where IPC particles predominantly impact, and close to the FFQs, where RB losses dominate. The relative contribution maps [Figs. 10(b) and 10(d)] show that IPC accounts for 80%–100% of the TID in all VTX layers. For the $\Phi_{eq}^{1 \text{ MeV}}$, IPC dominates in the inner layers (above 80%) but its contribution decreases to about 60% in the disk, middle, and outer layers, due to neutron backscattering induced by energetic RB particles. The average values of the two quantities on each VTX detector layer are reported in

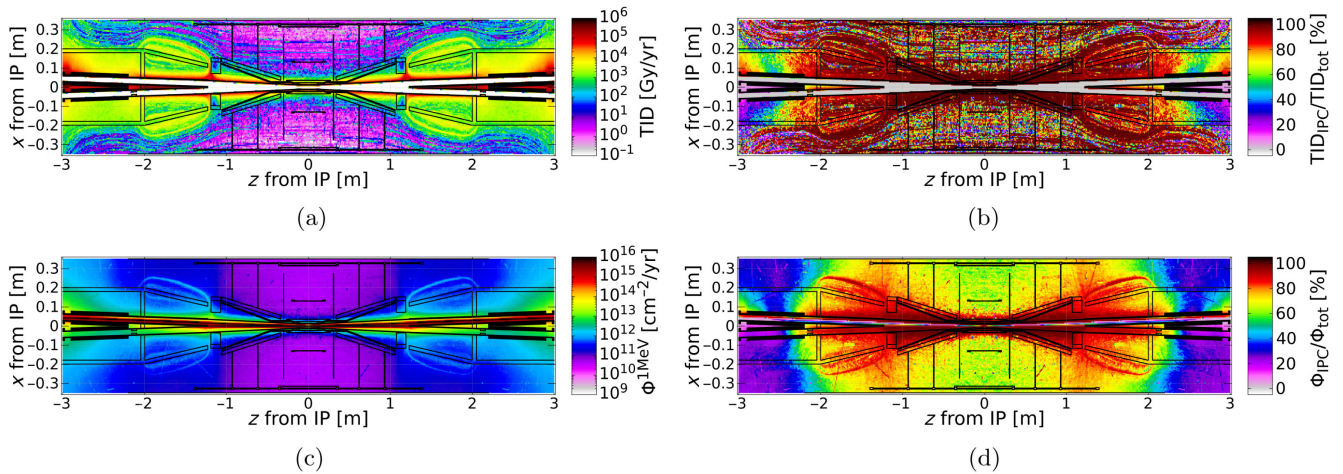


FIG. 10. Radiation load on the FCC-ee VTX detector region at beam height (average for y in ± 0.5 cm) for 1 yr of Z-pole operation. See Fig. 12 for the corresponding asymmetry at the sides of the FFQs. (a) Total TID, (b) relative IPC contribution to TID, (c) total $\Phi_{eq}^{1 \text{ MeV}}$, (d) relative IPC contribution to $\Phi_{eq}^{1 \text{ MeV}}$.

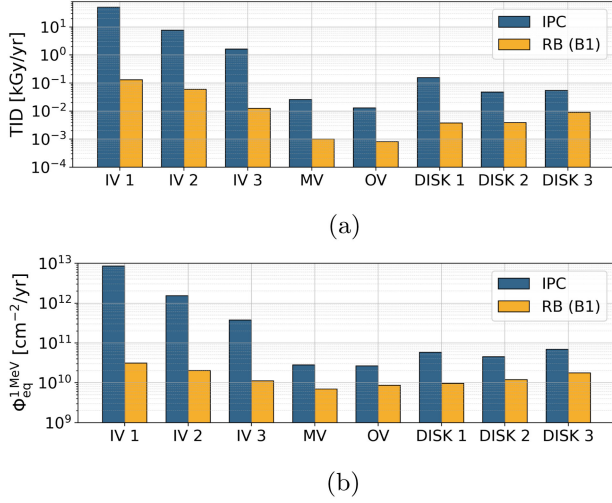


FIG. 11. Average radiation load on the FCC-ee VTX Silicon layers for 1 yr of Z-pole operation. Here, IV stands for inner vertex, MV for middle vertex, and OV for outer vertex. (a) TID and (b) Φ_{eq}^{1MeV} .

Fig. 11 for the two separated sources. The plots indicate that IPC dominates the radiation levels in the VTX detector, with a relative contribution from RB which becomes larger in the disk layers.

Concerning the LumiCals, IPC produces peak values up to about 50 kGy yr^{-1} and $1 \times 10^{13} \text{ cm}^{-2} \text{ yr}^{-1}$, while the RB contribution is smaller, with maxima of the order of 1 Gy yr^{-1} and $5 \times 10^{11} \text{ cm}^{-2} \text{ yr}^{-1}$.

B. Final-focus quadrupoles

Similarly to the detector studies, also for the FFQs the only IP-driven sources considered are IPC and RB. The power deposition in the different layers of QC1 and QC2 downstream of the IP is summarized in Table V for both Z-pole and $\bar{t}\bar{t}$ -threshold operation. The values range from a few tens to several hundreds of mW per segment at the Z pole, reaching up to 1.4 W in QC1R3. At the $\bar{t}\bar{t}$ threshold, the power deposition is about 2 orders of magnitude lower.

TABLE V. Power deposition in FFQ layers (mW) from RB and IPC at Z and $\bar{t}\bar{t}$ modes simulated with FLUKA. For QC1 segments at the Z pole, values in parentheses represent power deposition with 2 mm-thick W shielding in place.

Magnet segment	QC1						QC2			
	QC1R1		QC1R2		QC1R3		QC2R1		QC2R2	
	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$
Operational mode	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$	Z pole	$\bar{t}\bar{t}$
Gradient (T/m)	-40.8	-97.3	-29.5	-82.7	-19.4	-94.3	39.4	14.8	-0.00632	76.5
Al (I)	17 (4.9)	0.17	140 (30)	1.3	300 (55)	3.4	63	2.8	9.8	0.58
Coils (I)	42 (13)	0.51	350 (81)	3.5	690 (150)	8.5	160	6.6	23	1.5
Al (II)	7.7 (2.6)	0.1	61 (16)	0.66	120 (30)	1.5	32	1.2	4.1	0.29
Coils (II)	19 (7.5)	0.28	150 (46)	1.6	290 (88)	3.7	86	2.9	10	0.78
Total	86 (28)	1.1	710 (170)	7.0	1400 (320)	17	340	14	47	3.1
RB fraction (%)	72 (70)	26	82 (82)	51	92 (93)	75	94	87	57	89

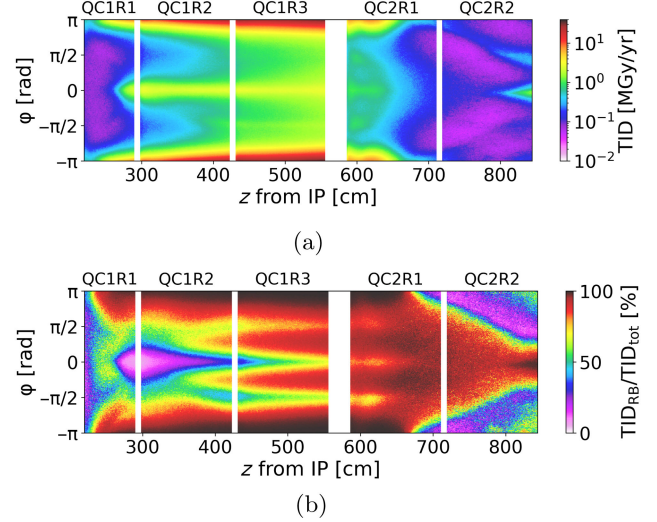


FIG. 12. Peak TID in the innermost superconducting layer of the FFQs for 1 yr of Z-pole operation. (a) Total TID and (b) relative RB contribution to TID.

The total power deposited in the FFQs is not a concern, as it is negligible compared to the contribution from impedance, preliminarily estimated to be on the order of 100 W [70]. Consequently, the RB-induced power deposition does not pose any challenge to the cryogenic system. However, the local peak values of TID and power density are more critical. Figure 12(a) shows the peak values of TID in the innermost layer of superconducting coils for 1 yr of Z-pole operation as a z - ϕ map, where $\phi = 0$ and $\phi = \pm\pi$ correspond to the horizontal plane. The relative contribution of RB to these peak values is displayed in Fig. 12(b), showing that the observed hotspots are almost entirely RB-driven. A pronounced asymmetric hotspot of the order of 10 MGy yr^{-1} appears toward the internal side of the collider ($\phi = \pm\pi$). This asymmetry arises from the combined effect of the reduced magnetic rigidity of RB particles, asymmetric beam-beam kicks, and the strong horizontal defocusing fields of QC1. The horizontal

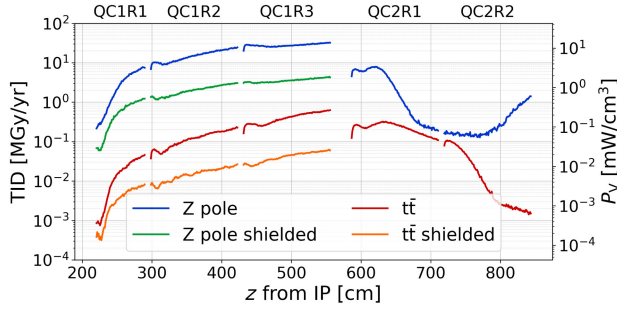


FIG. 13. Peak values of TID and P_V in the innermost superconducting layer of the FFQs due to RB scattering.

angular distributions simulated by GUINEA-PIG++ show an asymmetric tail at negative angles (toward the internal side of the collider) [50–52], leading to an average negative offset of RB particles at the QC1 entrance. The lower magnetic rigidity at the Z pole makes the offset (−1.0 mm) more pronounced than at the $t\bar{t}$ -threshold (−0.2 mm), resulting in most RB particles being defocused toward and lost on the internal side of QC1. Incoherent pairs, while contributing to the total load, follow a broader angular and energy distribution, and their impact on local peaks in the coils is negligible compared with RB.

Figure 13 shows the peak TID and the peak P_V produced by RB in the innermost layer of FFQ superconducting coils, evaluated at nominal luminosity. At the Z pole, QC1R3 is identified as the most critical case, with RB-induced values reaching 32 MGy yr^{-1} and 14 mW cm^{-3} , both above the LHC cold-magnet design limits of 30 MGy [71] over the full lifetime and 4 mW cm^{-3} [72]. Based on these figures, the addition of a shielding layer is recommended, to ensure the safe FFQ operation. Given the tight space constraints of the MDI design, Tungsten (W) is a natural choice, as its high density results in effective shielding efficiency over short distances [73]. FLUKA simulations including a 2 mm-thick W layer between the beam pipe and QC1 show a significant reduction in the power absorbed by QC1 at the Z pole (Table V), ranging from around 67% to 77%. Local peak values (Fig. 13) show even greater improvement, with reductions of about 86% for Z-pole operation. The proposed shielding lowers peak TID to 4.4 MGy yr^{-1} and P_V to 1.9 mW cm^{-3} . These levels comply with the LHC design limits given above and provide a comfortable margin to account for uncertainties or additional radiation sources.

C. Tunnel environment

The IP-driven sources contributing most significantly to the radiation environment in the tunnel surrounding the experiment cavern are RB and BS. The higher-energy off-momentum RB particles are lost within the first few hundred meters downstream of the IP, whereas BS photons propagate along the dedicated extraction line and interact

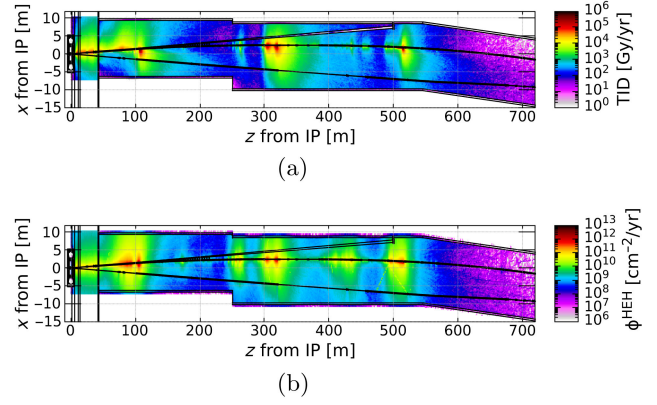


FIG. 14. Top view of tunnel radiation levels at beam height (average for y in $\pm 20 \text{ cm}$) from RB at Z-pole operation. (a) TID and (b) $\Phi_{\text{eq}}^{\text{HEH}}$.

with the dump system located about 500 m downstream, producing secondary radiation fields in its vicinity. Incoherent pairs are not included in this analysis of the tunnel environment because, while they dominate the radiation levels in the detector, they give a relatively small contribution to the radiation showers developing in the forward direction.

Figure 14 shows the top-view distributions of cumulative TID and $\Phi_{\text{eq}}^{\text{HEH}}$ from RB at beam height (averaged over $y = \pm 20 \text{ cm}$) for 1 yr of operation at the Z pole. Several radiation hotspots are observed along the outgoing beamline, with TID ranging from 10 to 100 kGy yr^{-1} and cumulative $\Phi_{\text{eq}}^{\text{HEH}}$ of 10^{11} – $10^{12} \text{ cm}^{-2} \text{ yr}^{-1}$. They are mainly concentrated within the first 150 m from the IP and in isolated regions near 300 and 515 m downstream. These hotspots correspond to areas with reduced material budget around the vacuum chamber, such as drifts and magnets hosting the branching of the BS extraction line. The precise location of the peaks follow the RB loss pattern, which is strongly dependent on the machine optics. At the $t\bar{t}$ threshold, a similar spatial distribution is obtained, but with radiation levels approximately 2 orders of magnitude lower due to the reduced luminosity.

Figure 15 presents the corresponding TID and $\Phi_{\text{eq}}^{\text{HEH}}$ distributions in the vicinity of the BS dump for both Z-pole and $t\bar{t}$ -threshold operation. Owing to the higher beam power, the Z-pole operation yields the largest TID, with values of a few MGy yr^{-1} near the dump and 100 kGy yr^{-1} along the adjacent beamline. The conceptual shielding only partially contains the radiation leakage, resulting in a hotspot that exposes the tunnel section between 460 and 515 m from the IP to up to 10 kGy yr^{-1} . A strong backscattering component characterizes the radiation field in this region. At $t\bar{t}$ operation, the TID hotspot is much more contained, producing less than 10 Gy yr^{-1} at the B1 beamline. The behavior of $\Phi_{\text{eq}}^{\text{HEH}}$ differs from that of TID. Although the BS power at the $t\bar{t}$ threshold is lower by about

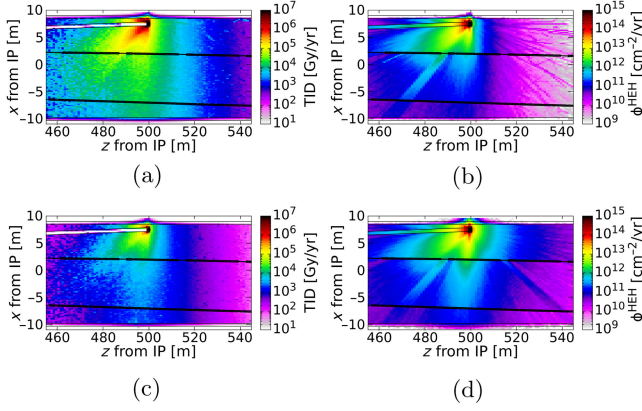


FIG. 15. Top-view radiation levels at beam height (average for y in ± 20 cm) in the vicinity of the BS dump. (a) TID at the Z pole, (b) $\Phi_{\text{eq}}^{\text{HEH}}$ at the Z pole, (c) TID at the $\bar{t}\bar{t}$ threshold, (d) $\Phi_{\text{eq}}^{\text{HEH}}$ at the $\bar{t}\bar{t}$ threshold.

a factor of 5, the $\Phi_{\text{eq}}^{\text{HEH}}$ levels are comparable to or even higher than those at the Z pole. The annual equivalent fluence reaches $1 \times 10^{13} \text{ cm}^{-2} \text{ yr}^{-1}$ near the dump and about $1 \times 10^{12} \text{ cm}^{-2} \text{ yr}^{-1}$ along the B1 beamline. This is due to the harder photon spectrum at $\bar{t}\bar{t}$ mode, which produces a significantly larger number of neutrons above 20 MeV, despite the lower overall beam intensity. The shielding is less effective at containing these high-energy neutrons, which also contribute more to $\Phi_{\text{eq}}^{\text{HEH}}$.

IV. RESULTS ON BEAM-DRIVEN LOSSES

Beam-driven sources of radiation originate from the circulating beams and are therefore present throughout the entire accelerator. They include both secondary particles produced by the beam, and primary beam particles that are lost either along the vacuum chamber or at collimators. Following this distinction, in this section the tunnel radiation levels are presented separately for SR and beam losses from BG interactions. Because of their different nature, these two sources exhibit distinct dependences on the operational mode and lead to different concerns and criticalities.

A. Synchrotron radiation

The impact of SR on the radiation environment is primarily driven by the beam energy. While the SR power loss is fixed across the operational modes, the different beam energies produce different photon spectra and, therefore, distinct radiation scenarios.

At the Z pole, the SR photon energies remain well below the MeV-scale, resulting in almost complete absorption within the photon stoppers inside the vacuum chamber. For the preliminary photon-stopper configuration considered in this study, 86.5% and 94.9% of the SR power from the B1 and B2 beamlines, respectively, are dissipated inside the

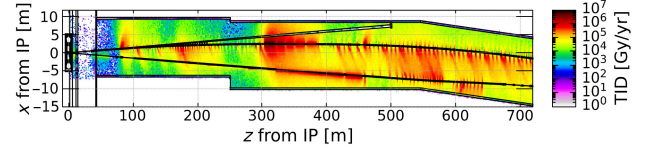


FIG. 16. Top view of tunnel TID levels at beam height (average for y in ± 20 cm) from SR at $\bar{t}\bar{t}$ operation.

absorbers. Consequently, SR contributes negligibly to the tunnel radiation levels at the Z pole, and the main concern shifts to the thermo-mechanical design and cooling of the photon stoppers themselves.

For $\bar{t}\bar{t}$ operation, however, the harder SR photon spectra extend above 1 MeV, enough to generate showers that propagate beyond the vacuum chamber. At these energies, photonuclear interaction channels become accessible, introducing a non-negligible neutron component to the radiation field that is entirely absent at the Z pole. Under the same configuration, the power fraction absorbed in the photon stoppers decreases to 71.8% and 76.7% for the B1 and B2 beamlines, respectively. As a result, SR becomes a major contributor to the tunnel radiation environment at the $\bar{t}\bar{t}$ threshold, as shown by the cumulative TID distribution in Fig. 16. Hotspots of the order of $0.1\text{--}1 \text{ MGy yr}^{-1}$ are observed near the SR absorbers, with even higher values in unshadowed drifts.

Unlike for the other radiation sources considered in this study, the $\Phi_{\text{eq}}^{\text{HEH}}$ levels are not reported for SR. This choice is motivated by the characteristics of the SR-induced neutron spectra, which are confined to the intermediate energy range (0.1–20 MeV) (see Fig. 17). In particular, the spectra contain essentially no neutrons above 20 MeV, i.e., beyond the energy threshold where the SEE response of electronic devices becomes approximately flat and largely device-independent—an assumption that underpins the definition of $\Phi_{\text{eq}}^{\text{HEH}}$. Although the contribution of intermediate-energy neutrons is formally included in $\Phi_{\text{eq}}^{\text{HEH}}$, their weighting factors are strongly device-dependent and vary significantly [74]. For this reason, SR-induced SEE risk estimates based on a single $\Phi_{\text{eq}}^{\text{HEH}}$ quantity can differ substantially. A more detailed analysis of this limitation is

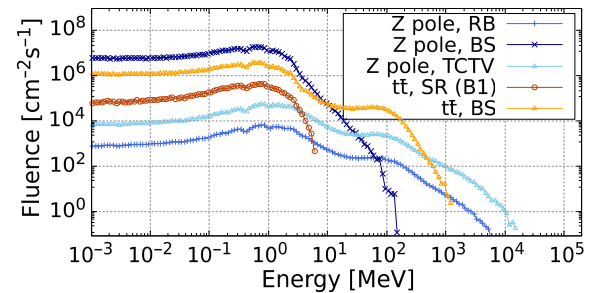


FIG. 17. Neutron fluences from the main radiation sources at Z and $\bar{t}\bar{t}$ modes, calculated in air near the respective hotspots.

beyond the scope of the present work, but dedicated studies are required to identify an optimal metric for SEE risk prediction in environments dominated by MeV-scale neutrons.

B. Beam losses

Losses of primary beam particles impacting the aperture or collimators represent a major contribution to the radiation environment, particularly in the IR, where aperture bottlenecks and protective collimators are located. Unlike SR, whose total power remains constant across operational modes, the power associated with beam losses scales (to a first approximation) with the total stored beam energy. At the Z pole, the stored beam energy is roughly 60 times higher than at the $\bar{t}\bar{t}$ threshold. This difference has a stronger impact on radiation levels than the change in beam particle energy, making the contribution of beam losses to the FCC-ee radiation environment primarily driven by beam intensity. For this reason, the present study focuses on Z-pole operation, regarded as the most critical scenario.

Beam losses in a given region are not solely determined by local processes but rather by the cumulative history of beam particles over many revolutions. In particular, losses at the collimators mainly arise from multiturn effects that populate the beam halo. In this work, we study as a representative case the contribution from BG interactions, occurring both locally in the IR and throughout the entire ring.

In the IR, which hosts the SR (TCRs) and tertiary (TCTs) collimators introduced in Sec. II, the radiation levels produced by off-momentum particles and photons from local BG bremsstrahlung interactions simulated along B1 and B2 are found to be significantly lower than those from multiturn losses. Even under the conservative assumption of a gas pressure corresponding to only 1 h of beam conditioning maintained for the entire year, the TID hotspots around the drifts from local BG bremsstrahlung reach only a few tens of Gy yr^{-1} . They peak at about 100 Gy yr^{-1} near the beamline, well below the levels reached by other radiation sources, and can therefore be neglected in first approximation. For comparison, the TID distribution from impacts on the TCRs and TCTs due to multiturn BG Coulomb and bremsstrahlung is shown in Fig. 18, where the the same vacuum conditions are assumed. The most pronounced hotspot appears at the TCTV, dominated by losses from Coulomb scattering, exposing the tunnel section up to 200 m upstream of the IP to cumulative doses above 1 kGy yr^{-1} , and reaching fractions of a MGy yr^{-1} around the drift downstream of the collimator. The hotspot associated with the TCTH, to which Coulomb and bremsstrahlung contribute comparably, is more contained and peaks at about 10 kGy yr^{-1} close to the beamline, while that from the TCRs remains below 10 kGy yr^{-1} .

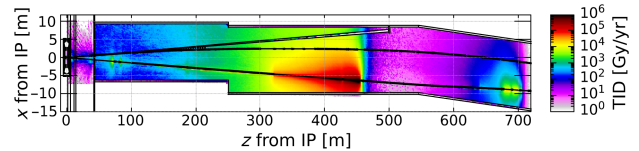


FIG. 18. Top view of tunnel TID levels at beam height (average for y in ± 20 cm) from beam losses due to BG Coulomb and bremsstrahlung on IR collimators at Z-pole operation.

The impact of TCR losses from BG on the VTX detector layers was estimated to produce an average TID of at most $\approx 1 \text{ kGy yr}^{-1}$ when considering both incoming beamlines, under the aforementioned pessimistic conditions. The contribution from more distant TCTs, which however experience a higher hit rate, has not yet been assessed due to the difficulty of obtaining statistically meaningful results. Nevertheless, this preliminary estimate confirms that the radiation load on the VTX detector is driven by IPC.

This radiation level assessment of BG losses should still be regarded as preliminary, as it relies on assumptions that are still carrying significant uncertainties, such as optics, collimation design, and vacuum pressure profiles. Nevertheless, the previous estimates are conservative and likely overstate the actual radiation levels, since the vacuum would be better conditioned over a full year of operation.

V. GLOBAL VIEW

The overall radiation environment in the tunnel surrounding the experimental cavern results from the superposition of the effects from all IP-driven and beam-driven sources. Figure 19 presents the top-view distributions of annual TID for both Z and $\bar{t}\bar{t}$ modes, providing a comprehensive picture of the expected conditions along the IR. The relative importance of the different sources varies markedly across operating points. This overview highlights the dominant contributors and identifies the main hotspots of radiation, supporting the definition of design guidelines for shielding and equipment placement.

At the Z pole, the radiation environment is dominated by off-momentum losses of RB products generated at the IP, BS photons, and showers from collimator losses. Within the first 200 m from the IP, RB losses prevail, with an additional contribution from BS photons lost at the branching of the extraction line. Between 200 and 460 m, radiation showers from the TCTV dominate, while the region from 460 to 530 m is dominated by the BS dump and a localized RB hotspot. Further away from the IP, the TCTH becomes by far the most significant radiation source. These radiation-level peaks create a harsh radiation environment that exceeds the operational limits of commercial components. Consequently, reliable operation requires the use of radiation-hard devices or sufficient shielding to protect standard hardware. Preliminary

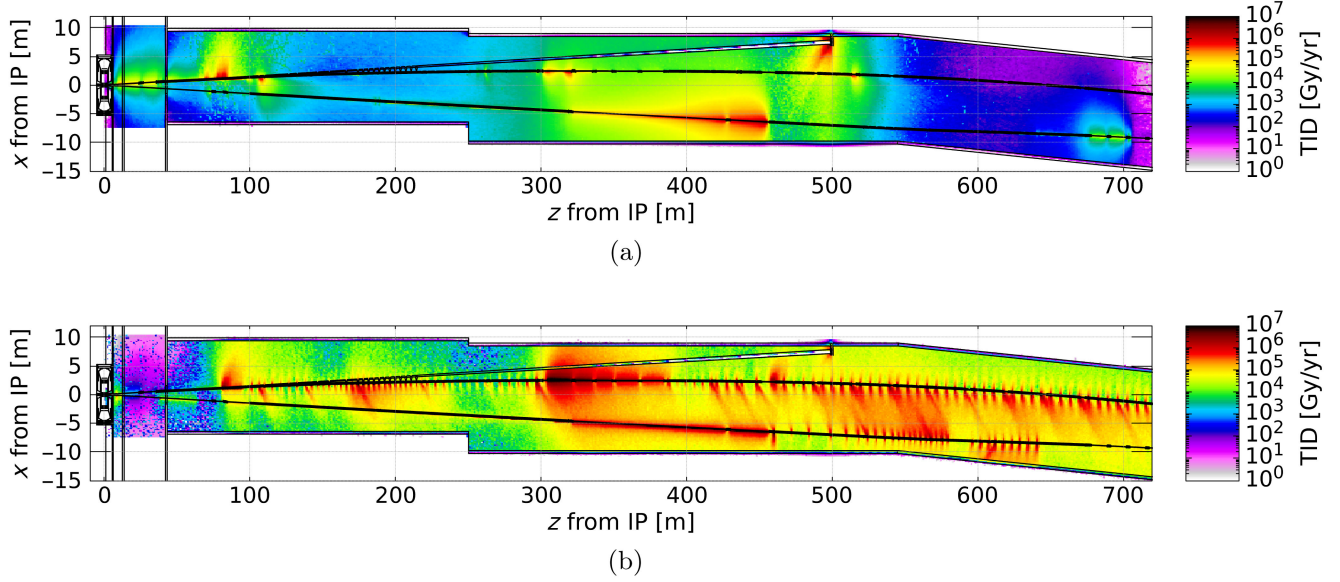


FIG. 19. Comparison of annual TID distributions in a symmetric half of the IR at Z (a) and $t\bar{t}$ (b) operational modes. (a) Top view (average over +20 cm in y) of annual TID from RB, BS and BG losses on collimators at the Z pole as simulated with FLUKA and (b) Top view (average over +20 cm in y) of annual TID from RB, BS and SR at the $t\bar{t}$ threshold as simulated with FLUKA.

radiological studies on the BS dump indicate that its shielding design is driven by radiation-protection criteria to limit neutron leakage and activation, which are beyond the scope of this work. A dump shielding that satisfies these criteria is expected to be effective also against prompt radiation. Absorbers for RB products and localized shielding at their loss locations should be designed once the optics is finalized. Given that many additional losses will occur at the TCTs, shower absorbers downstream of these collimators will also be necessary.

At the $t\bar{t}$ threshold, the situation changes completely. The harder SR spectrum becomes the dominant source of tunnel radiation, producing extended dose distributions along both beamlines and overshadowing the RB contribution. The hotspot around the BS dump is comparable in magnitude to the weaker ones at the photon stoppers and is expected to be mostly contained by the future dump shielding. Dose levels at $t\bar{t}$ operation exceed those at the Z pole, calling for a shielding strategy similar to the one being studied for the arcs [13,37,55], employing lead blocks around the dipoles at photon-stopper locations. The different dipole geometry in the IR (single-beam configuration) compared with the arcs (dual-beam) will require a dedicated integration design. Additional shielding solutions should also be implemented for exposed drifts that do not host SR absorbers. Preliminary FLUKA simulations show that a 1 cm-thick tungsten layer placed around such drifts can locally reduce dose levels by 1 to 2 orders of magnitude.

In all operating modes, radiation levels in the IR tunnel exceed the tolerance of conventional accelerator equipment. Shielding designs must therefore follow a source-specific optimization, accounting for the different particle

spectra involved: up to the GeV scale for RB and beam losses, and up to the MeV scale for SR. Once the mitigation strategy is defined, further design studies should identify suitable locations for in-tunnel electronics and develop protection schemes enabling the safe deployment of radiation-tolerant systems. This may include the design of dedicated electronics bunkers, analogous to that being studied for the FCC-ee arcs [55].

VI. CONCLUSION

A detailed FLUKA model of the FCC-ee IR has been developed, providing a unified framework for simulating the radiation shower propagation from both IP-driven backgrounds and beam losses. It relies on external Monte Carlo event generators, particle-in-cell codes, or multitrack tracking studies to generate the radiation sources. This model, based on version 24.4 of GHC lattice, will serve as a reference tool for future optimization studies on shielding, component qualification, and radiation protection. Although alternative optics configurations may modify the machine layout and alter the pattern of individual losses, thereby shifting the location of radiation hot spots, the dominant radiation sources and the overall scale of the resulting radiation fields are not expected to vary substantially. Therefore, the conclusions of this study remain broadly valid even as the optics and machine design continue to evolve.

This work has focused on the two extremes of FCC-ee operation, namely the Z pole and the $t\bar{t}$ threshold, in order to bracket the expected range of machine parameters and resulting radiation environments. Radiation in the IR results from a combination of IP-driven and beam-driven sources,

whose relative importance varies across operational modes. At the Z pole, the dominant contributions arise from RB losses, BS photons, and local collimation losses. At the $t\bar{t}$ threshold, the harder SR spectrum becomes the main driver of tunnel radiation, overshadowing all other sources.

Close to the IP, radiation loads on the detector and FFQs are dominated by IPC and RB processes, with Z-pole operation representing the most critical scenario due to its higher luminosity. Incoherent pairs are the main contributor to the radiation load on the VTX detector and dominate dose levels up to the ECAL, while fast neutrons from photonuclear reactions induced by RB particles contribute comparably to the cumulative $\Phi_{\text{eq}}^{1\text{ MeV}}$. Off-momentum RB products primarily affect the forward regions, dominating the radiation load in the HCAL endcaps. In the FFQs, radiation showers from localized RB losses at the Z pole produce TID peaks up to 34 MGy yr^{-1} and P_V around 14 mW cm^{-3} , exceeding the design limits adopted for the LHC. Simulations indicate that safe operation can be ensured by installing a 2 mm tungsten liner between the beam pipe and QC1. The contribution from IPC is several orders of magnitude smaller and does not alter the shielding requirements.

The tunnel surrounding the experimental cavern presents a challenging radiation environment at all operating modes, dominated by electromagnetic showers and accompanied by neutronic fields from photonuclear reactions. At the Z pole, radiation is driven mainly by collimation losses in the incoming lines, RB off-momentum losses along the outgoing beamlines, and leakage from the BS dump. At the $t\bar{t}$ threshold, SR photons from both beams dominate the tunnel environment. Consequently, the neutron spectra differ between modes, featuring a dominant high-energy component at the Z pole and an intermediate-energy one at the $t\bar{t}$ threshold. Their impact on electronics performance depends on the specific device technology.

The results of tunnel radiation levels highlight the need for dedicated shielding measures, including absorbers for RB products, shower absorbers downstream of TCTs, dipole shielding at photon-stopper locations, and additional shielding to prevent radiation leakage through exposed drifts. Shielding design must account for the different radiation spectra, with GeV-scale particles originating from non-SR processes and MeV-scale photons from SR at the $t\bar{t}$ threshold. A dedicated BS dump shielding will be designed to minimize neutron leakage and prevent activation of surrounding materials, while also containing prompt electromagnetic showers. Given these findings, the definition and implementation of the primary shielding solutions must be prioritized, whereas the evaluation of suitable locations for in-tunnel electronics and their protection strategies should follow only once the main mitigation measures are established.

Even though the radiation environment at the other operational modes, WW and ZH, is expected to follow

the trends defined by the two extreme scenarios, the combination of intermediate beam currents and SR critical energies may introduce specific challenges, for instance an enhanced outgassing. Dedicated studies are therefore required to assess their impact on the MDI and on tunnel radiation levels. The FLUKA model developed in this work will continue to be refined as the optics, collimation system, vacuum design, and overall layout of FCC-ee evolve.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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