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Status and Perspectives of Detector Background Studies for FCC-ee

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We present the status and prospects of beam-induced background studies for the Future Circular Collider in its electron–positron configuration (FCC-ee). The simulation workflow established within the Machine-Detector Interface (MDI) group is described, together with progress on the modelling of the interaction region, beam-pipe geometry, collimation system, and detector impacts. The main background sources are reviewed—Incoherent Pair Creation (IPC), synchrotron radiation, injection losses, beam-gas interactions, Touschek scattering, and radiative Bhabha processes. Detailed simulation results are presented for the most affected subdetectors, including vertex detector occupancies, drift chamber and TPC distortions, calorimeter backgrounds, and LumiCal performance. An outlook on ongoing and future work in preparation for the FCC-ee pre-TDR is provided.

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1. Introduction

The electron–positron Future Circular Collider (FCC-ee) [1, 2] is a 91 km, double-ring collider designed to deliver very high luminosities from the Z pole up to the $t\bar{t}$ threshold. Key features include a crab-waist collision scheme, a crossing angle of 30 mrad, and final-focus quadrupoles placed inside the detectors ($L^* = 2.2$ m or, recently updated to 2.4 m). These choices maximise luminosity but introduce significant challenges at the MDI [3–5], particularly regarding beam-induced backgrounds. Understanding and mitigating these backgrounds is essential for detector design, occupancy optimisation, and radiation protection.

2. Beam-Induced Background Sources

The main background processes at FCC-ee which are likely to impact detectors and have been simulated so far are briefly described in this section.

- **Incoherent Pair Creation (IPC)**: Low-p_T e^+e^- pairs produced by interactions of beamstrahlung photons with real/virtual photons. While IPC is large in linear colliders due to beam disruption at the beam–beam limit, FCC-ee operates slightly below this regime, keeping the bunches stable across four IPs. Nevertheless, IPC is the leading source of detector occupancy close to the interaction point (IP) [6]. This process is simulated with GuineaPig++ [7]. It is an irreducible process, and only mitigation at the data acquisition level is possible. In the next Sec. 3 their effects on various subdetectors are discussed. Their effects on various subdetectors are discussed in Sec. 3.
- **Synchrotron Radiation (SR)**: SR produced by the last weak dipoles upstream of the MDI area is mostly intercepted by SR collimators and masks at the exit of the final focus quadrupoles, QC1 and QC2. When considering optics imperfections and transverse beam tails, SR is generated also in the final-focus quadrupoles and fringing fields of the IR solenoids. This radiation can be dangerous for detectors if not properly handled. SR emitted by the combination of the detector solenoid and anti-solenoid is collinear with the beam, so it can be properly transported to a dedicated dump after the first dipole magnet that will collect also the intense Beamstrahlung radiation produced at the IP [8], contributing significantly to the radiation levels in the tunnel around the IP. SR reaching masks at the exits of QC1 and QC2 and sensitive regions can produce backscattering and secondary particles that must be tracked in subdetectors. Data samples for various pessimistic conditions are produced to study effects on the detectors for detector studies. An optimisation of the SR masks will be performed as a trade-off between efficiency and beam impedance [9].
- **Injection backgrounds**: Top-up injection, on-axis and off-energy, is foreseen to maintain high luminosity by continuously replenishing beam particles in the main rings with a top-up injection frequency into the collider of about 0.05 Hz at the Z, but also introducing losses of off-energy particles. Simulation is performed with XSuite [10], particle losses are then tracked to detector boundaries in FLUKA [11] according to the workflow shown in Fig. 1. These studies allow the evaluation of the injection efficiency, the location of circulating and

injected beam losses, and the impact on detectors. Off-axis injection proved to be problematic for the SR background induced by the injected beam, an hybrid scheme is under study. First data samples are ready to be tracked in subdetectors for computing hit occupancies and data rates.

- **Beam-gas interactions**: Beam–gas interactions degrade beam quality by reducing lifetime and luminosity, increasing emittance, and generating beam losses that may produce backgrounds in the IR. Simulations assume a typical light-source residual-gas composition (85% H_2, 10% CO, 5% CO_2). Bremsstrahlung and Coulomb scattering have been modelled with Xsuite-BDSIM [12, 13] and FLUKA, distinguishing non-local interactions in the arcs from local ones near the experiments. Non-local losses are largely intercepted by the collimation system, while local contributions require detailed modelling and must be tracked through the detector (see Fig. 1). Initial datasets, corresponding to conservative vacuum conditions at early operation, have been produced and are ready for subdetector-level occupancy and data-rate evaluation.

- **Halo Losses**: During operation, a variety of processes such as space-charge effects, intra-beam scattering, Touschek scattering, magnet misalignment, and magnetic field errors can lead to the population of the beam halo, potentially leading to beam losses. In high-intensity machines, such as the FCC-ee at the Z, beam halo losses must be safely disposed of to avoid damage to sensitive equipment and keep the detector backgrounds to tolerable levels. For these reasons, a beam halo collimation system is being designed and optimized[14, 15]. Particle losses that might impact the detectors are tracked in Fluka up to the detector interface and are ready to be studied by the subdetectors.

- **Radiative Bhabha scattering**: During bunch crossings, beam particles may lose energy through Radiative Bhabha scattering,

$$e^+e^- \to e^+e^-\gamma, \tag{1}$$

with the photon emitted in either the initial or final state. The resulting off-energy beam particles can fall outside the lattice acceptance already in the first quadrupoles. Radiative Bhabha events are generated with BBBrem [18], with GuineaPig++ [7] providing beam–beam smearing. The off-energy particles are then tracked with FLUKA to evaluate power deposition on downstream elements. This is crucial for assessing the load on the superconducting final-focus quadrupoles, which may require internal shielding to avoid quenching or long-term damage. Radiation levels from Radiative Bhabhas in the detectors have also been evaluated with FLUKA.

Touschek effect has also been evaluated, while thermal photons, relevant at LEP, will be studied as a next step.

3. Detector background studies

The background workflow integrates accelerator particle tracking Xsuite-BDSIM simulation tool, which combines particle tracking in the FCC-ee magnetic lattice performed with Xsuite and

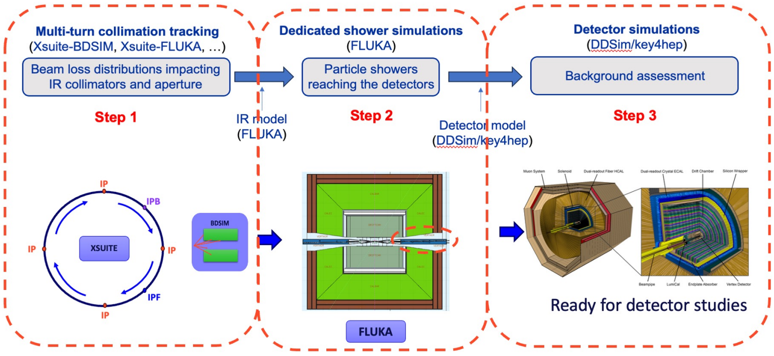

Figure 1: Beam background simulation framework.

full Monte Carlo particle-matter interaction simulations in the collimators performed with BDSIM (based on GEANT4); FLUKA for material interactions and shower development; a standardised HEPEVT-based interface for detector studies, and Key4hep for importing realistic CAD geometries of the IR. Fig. 1 shows this simulation workflow. Detector simulations use Key4hep and subdetector-specific digitisation.

We now summarise the main beam-induced backgrounds in the subdetectors studied so far.

IPC dominates the occupancy in the innermost layer of the vertex detector at a distance of 13.7 mm from the beam. Two sensor concepts are studied: ARCADIA MAPS staves and ALICE ITS3-inspired bent-sensor layout [3]. A study using the V23 FCC-ee lattice and the IDEA vertex detector resulted in an occupancy of up to 20×10^{-6} in the first vertex detector layer, with a safety factor of 3 and cluster size of 5, and this equals a total hit rate of up to 170 MHz/cm^2. Assuming a more realistic average cluster size of 1.5–2.5, a hit rate requirement of around 100 MHz/cm^2 for FCC-ee vertex detectors is derived.

Occupancy levels imply data rates up to $\sim$100 Gb/s per ladder. In the innermost vertex layers, an average total ionising dose (TID) of several tens of kGy per year and a 1-MeV neutron-equivalent fluence of up to a few 10^{12} cm^{-2}/year are expected. These levels are high but still compatible with the capabilities of current MAPS technologies.

In the IDEA detector concept drift chamber, IPC produces a "bare" hit occupancy of about 7% at SIM-hit level when integrating 20 bunch crossings, corresponding to 400 ns drift time given the cell size of about 1 cm. A digitisation algorithm is being simulated, and is expected to reduce this number.

IPC may also reach larger radii, and their effects have been studied for the ALLEGRO liquid argon electromagnetic calorimeter (ECAL). IPC secondaries interact with the sampling structure, and shielding strategies are being evaluated. The energy deposit of these pairs are quite small and can be suppressed by applying an energy threshold between 20 and 30 percent of a minimum ionizing particle (MIP), as shown in Fig. 2.

The TPC is particularly affected by large ion production from IPC, leading to distortions up to $\sim$1 cm [16]. The correction can be implemented using the same techniques currently employed for the ALICE TPC, but no study had been done yet. On the other hand, mitigation strategies have been proposed. The first one is adding additional masking around the TPC; a second solution is adding a transverse B-field component to let the electron-positron pairs spiralising along the magnetic field lines parallel the beam, however, this solution is difficult to implement in a circular collider.

Located in the fringing field of the −5 T compensating solenoid, the luminosity calorimeter (LumiCal) is affected by low-p_T particles that spiral into its acceptance, as illustrated in Fig. 3. Dedicated shielding may therefore be required. We note that adopting the non-local solenoid compensation scheme [17] would substantially mitigate this issue.

Low-p_T IPC particles produce abundant photons and electrons when striking the copper Y-pipe. Replacing copper with a lighter material reduces secondaries equivalently to a 2 cm tungsten shield while significantly reducing mass. An optimization of the shape, material, and possibly shielding of this Y-pipe to minimise scattering of off-particles and photons is one of the next steps.

4. Radiation Levels in the detector

Radiation maps calculated with FLUKA indicate that IPC dominates TID and fluences near the IP at the Z pole. At 15 cm radius, radiation drops by three orders of magnitude.

A representative geometry of the IDEA detector baseline has been modelled in FLUKA, including the vertex detector, the drift chamber, the solenoid, the dual-readout calorimeter, the μRwells and the iron yoke. The complex structure of the vertex detector has been simplified through equivalent layers made of equivalent materials condensing all of the main components. Similarly, the active Si pixels have been condensed into single Si layers. This simplification process has been done keeping the total mass and volume of the several parts unchanged. For what concerns the IR, the central chamber, the ellipto-conical chambers, the support and service cones, the support tube, the LumiCals and the final focus cryostats filled with liquid helium have been integrated as well. The magnetic fields from the detector, the compensation, and the screening solenoids are incorporated in the model through a 3D field map extending from -3 m to +3 m longitudinally and from -0.5 m to 0.5 m transversely.

The summary of the radiation levels in the subdetectors is reported in Table 1.

In the innermost layers of the vertex, an average TID of the level of tens of kGy/year and an average 1-MeV neutron equivalent fluence of up to a few 10^{12} cm^{-2}/year are reached.

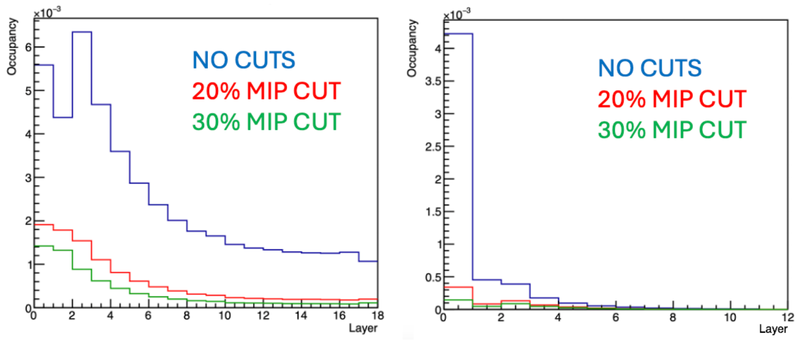

Figure 2: Occupancy per bunch crossing for each layer of ALLEGRO ECAL endcaps (left) and barrel (right), using different cuts on the energy deposition per cell.

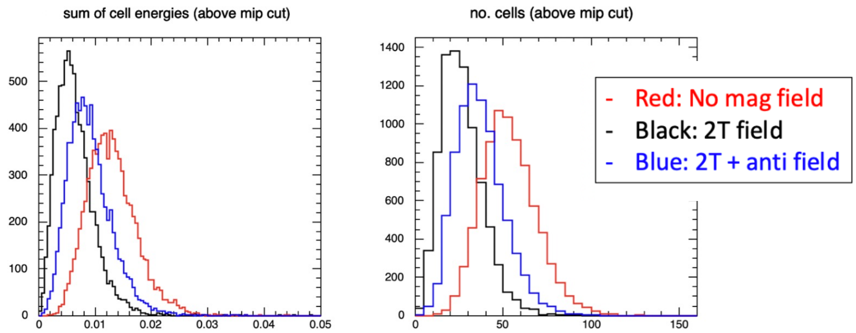

Figure 3: IPC in the LumiCal for Z. Left plot: Average = 9.0 MeV; 1.7% of 510 MeV ; Right: Average=36 cells; 5.3% of 680.

The values of TID and 1-MeV neutron equivalent fluence have been computed for each layer of the vertex.

The results confirm that the inner vertex layer is the most exposed to radiation, and that IPC dominates the radiation levels in the vertex, with a relatively larger share of dose and fluence from RB in the forward disks.

Table 1: Detector radiation levels.

	TID [Gy/yr]	**Fluence [cm^{-2}/yr]**
Vertex	40 k	10^{13}
Drift chamber	10	10^{11}
ECAL	1	10^{10}
HCAL	<1	$<10^{10}$
Lumical	10 k	5×10^{12}

5. Outlook

Beam-induced background studies for FCC-ee have progressed significantly during the Feasibility Study, as various background sources have been added in new tracking tools and data samples produced to study effects on the detectors. IPC remains the dominant background at the Z pole, with important implications for vertex and tracking detectors. SR, injection, beam-gas and Touschek effects have been modelled and are being integrated in full-detector simulations. The established workflow provides a solid basis for the upcoming pre-TDR studies and design optimisation.

Next steps include full tracking of all background particles into each subdetector, occupancy and data-rate evaluation, optimisation of the IR geometry (beam pipe, Y-pipe, shielding), refinement of collimation schemes, integration with detector R&D in the pre-TDR phase.

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