INTEGRATED SIMULATION OF COMPTON BACKSCATTERING AND BEAM–BEAM EFFECTS FOR BUNCH INTENSITY CONTROL IN FCC-ee

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Abstract

Precise regulation of the bunch population in FCC-ee is required to maintain the charge imbalance between collision bunches within the 3–5% tolerance that preserves beamstrahlung limits, bunch-length stability, and avoids flip–flop behavior. Laser-driven Compton backscattering (CBS) has been proposed as an active actuator for bunch-by-bunch intensity control. An Xsuite-based simulation framework is employed to track the beam over many turns, while the bunch population is continuously updated according to the CBS-induced particle removal. The modified bunch intensity is then propagated in the presence of the beam–beam interaction model, allowing the resulting impact on beam parameters and overall stability margins to be quantified.

INTRODUCTION

The Future Circular Collider (FCC-ee) project [1, 2] aims to provide unprecedented luminosity for high-energy physics experiments. However, operating at these intensities introduces significant beam dynamics challenges, the among the most critical being beamstrahlung [3, 4]. In collision mode, beamstrahlung strongly influences bunch length and energy spread, creating conditions for the "flip-flop" instability [5]. In this work we focus in the Z operation mode.

This instability occurs in an asymmetric scenario: a "strong" beam (with higher charge) induces more intense beamstrahlung in its "weak" (with low charge) partner bunch, leading to an increase in the latter's vertical emittance and a subsequent loss of luminosity [6]. To mitigate this, the charge imbalance between colliding bunches must be strictly maintained within a tolerance of less than 5% for the Z-pole and less than 3% for higher collision energies [7, 8]. While the standard top-up injection scheme balances intensities, the growth rate of the instability (approximately 10 000 turns) [5] can exceed the injection system's reaction time.

As a solution, Laser Compton Backscattering (CBS) has been proposed as a fast, non-invasive actuator for bunch-by-bunch intensity control [3, 9, 10]. The physics involves colliding high-power laser photons with relativistic electrons or positrons. At a beam energy of 45.6 GeV (Z operation mode), a scattered particle loses nearly 50 % of its energy, while at 182.5 GeV ($t\bar{t}$ operation mode), the loss reaches 80 % [10]. Since the momentum acceptance of the FCC-ee ring is only approximately few %, these scattered particles are immediately extracted from the stable orbit and removed by the collimation system by the smart choice of the laser IP.

Recent progress in high-average-power laser technology has made CBS-based bunch intensity control increasingly realistic for FCC-ee operation. Modern multi-kHz laser systems are capable of delivering pulse energies ranging from hundreds of millijoules up to the joule-class regime [11–13], compatible with the effective FCC-ee bunch circulation frequency of approximately 3.7 kHz. Such systems enable turn-by-turn bunch-by-bunch intensity regulation through CBS.controlled particle removal.

This paper presents the next stage in the design of the intensity control system: the transition from analytical estimates to Integrated Simulation. Using a framework combining Xsuite [14] and CAIN [15] (via the Xcain [16] interface), we track particle distributions through a realistic magnetic lattice including the effects of synchrotron radiation. We quantitatively analyze how the modified bunch intensities evolve in particle tracking in presence of beam-beam effects, evaluating the resulting impact on emittance evolution and the overall stability margins of the collider.

COMPTON BACK SCATTERING

Compton Back Scattering is an interaction in which a photon collides with a relativistic charged particle, such as an electron or positron, and is scattered with altered energy and direction. During this process, energy and momentum are exchanged between the photon and the charged particle, leading to corresponding changes in the kinematic properties of both particles.

The energy E_{ph} of the scattered photons can be calculated using the following formula:

$$E_{\text{ph}} = \frac{4\gamma^2 E_L \cos^2\left(\frac{\alpha_0}{2}\right)}{1 + X\cos^2\left(\frac{\alpha_0}{2}\right)} \tag{1}$$

where E_L is the laser photon energy, γ is the Lorentz factor of the electron at the beam energy E_0, α_0 is the collision angle, mc^2 is the rest energy of the electron, and $X = 4\gamma E_L/mc^2$ is the recoil factor.

Given that the FCC-ee ring has a momentum acceptance of about 1% in the Z operation mode, nearly all electrons or positrons undergoing CBS with such energy loss are expected to be removed from the circulating bunch.

The actual number of scattered particles and their energy distribution depend on several factors, including the beam energy, beam emittance, laser parameters, and the interaction geometry. Therefore, realistic Monte Carlo simulations are

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required to accurately predict scattering yields and optimize the system design.

LASER SYSTEM

The main requirements for the laser system are high pulse energy preferably in the joule class range and a repetition rate compatible with the FCC-ee bunch circulation frequency, ideally matching the effective bunch repetition rate of approximately 3.7 kHz.

Laser systems based on thin-disk technology currently represent the most mature industrial solution satisfying these requirements [11]. Such systems are commercially available today and can deliver pulse energies in the range of 0.2–0.3 J at multi-kHz repetition rates.

As a higher-energy alternative, next-generation fiber-laser systems under development within the kBELLA program [12, 13] are expected to provide pulse energies in the 3–10 J range at comparable repetition rates. These systems could significantly enhance the achievable Compton scattering rate if realized.

The main parameters of the laser options considered in this study are summarized in Table 1. Since the present work focuses primarily on beam dynamics and system performance comparison, all three laser configurations listed in Table 1 are included in the simulations for comparative analysis.

INTERACTION POINT

Taking these considerations into account, the beam-laser interaction point (IP) was chosen at the center of a dipole magnet located just upstream of the FCC-ee momentum collimation section, which is provisionally located in the straight section PL [17]. The layout of the momentum collimation section PL is presented in Fig. 1, together with the optics for the *Z*-operation mode.

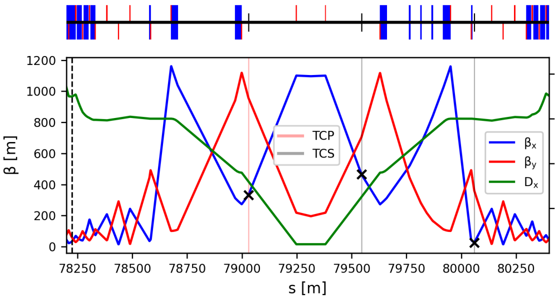


Figure 1: Layout and optics of the FCC-ee momentum collimation section under study at the Z operation mode. The location of the laser IP is indicated by a black dashed line.

The beam size at the laser interaction point together with the beam parameters can be found in Table 2.

The reasoning behind this choice is the low value of the beta functions and consequently the small transverse beam size as well as the rapid removal of particles knocked out of the beam, due to the proximity to the momentum collimation system.

BEAM DYNAMICS SIMULATIONS

In this work, we study beam dynamics in the presence of beam–beam effects and particle removal via Compton backscattering, including the evaluation of loss locations, emittance evolution, and induced beam losses. To this end, dedicated beam dynamics simulations have been performed using a multi-code simulation workflow. Beam-beam effects (Beamstrahlung and beam-beam kicks) were taken into account at each of the 4 interaction points of the FCC-ee using the weak-strong beam-beam models available in Xsuite, in the Xfields package [4]. The lattice tracking was performed with Xsuite [14], including effects of the synchrotron radiation. Laser–particle interactions were simulated with CAIN [15], interfaced to Xsuite through the custom wrapper Xcain [16].

Particle–matter interactions in collimators were modelled using BDSIM [18, 19], a Geant4-based simulation toolkit [20–22], coupled to Xsuite via the Xcoll collimation package [23–26]. Scattered particles are tracked through the lattice, transferred to BDSIM upon impact with collimators, and returned to Xsuite for further tracking if they survive the interaction.

The simulation model includes detailed apertures together with beam halo and synchrotron radiation collimators. Particles reaching the mechanical aperture limits are considered lost. This setup follows the methodology developed for FCC-ee collimation studies [23, 27].

Each simulation was initialized with a bunch of 10^4 macroparticles matched to the equilibrium lattice transverse emittances listed in Table 2. An important extension with respect to previous studies is that the laser is switched off once 5% of the bunch particles have been removed, and the subsequent tracking is performed with constant bunch population. This allows assessment of the residual impact of the CBS process on beam quality after the intensity correction has been completed.

Figure 2 shows the fraction of surviving particles as a function of tracking turns, demonstrating that the particle removal rate depends strongly on the laser pulse energy, with up to 5% of the bunch population removed within only five turns under the most aggressive conditions.

Figure 2 compares the RMS transverse emittance evolution for tracking with laser interaction to a reference case without CBS. No significant emittance growth is observed after 5% bunch depletion, indicating that the CBS process has negligible impact on transverse beam quality. This is primarily because most particles interacting with the laser are intercepted by the collimation system after scattering, while the small fraction remaining in the bunch does not measurably affect the beam core. As a result, beam–beam effects dominate the transverse beam dynamics and mask any residual impact of CBS on the transverse emittances.

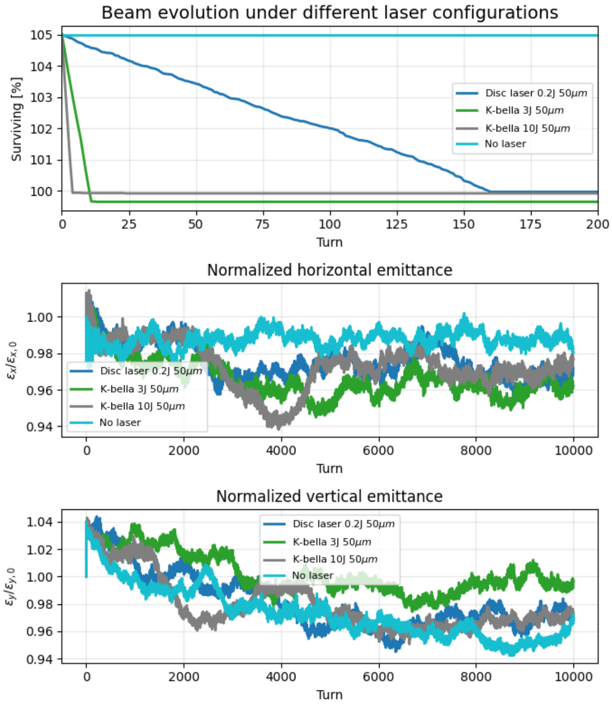
Figure 3 shows the loss map of CBS-induced particle losses around the FCC-ee ring for the kBELLA laser scenario, in which a bunch population excess of 5% is removed within five turns. The simulation tracked 5×10^7 macroparti-

Table 1: Laser Options for FCC-ee CBS

Parameter	**Thin-disk**	**kBELLA type**	**kBELLA upgrade**
Wavelength	969 nm	1015–1090 nm	1015–1090 nm
Pulse energy	200 mJ	3 J	10 J
Repetition rate	3.7 kHz	3.7 kHz	3.7 kHz
Pulse duration	5 ps	40 fs	40 fs
Average power	1 kW	11 kW	37 kW
Technology	Thin-disk	Fiber laser	Fiber laser
Accessibility	already on market	can start building today	can start building in 2 years

Table 2: Parameters for the Z Operation Mode, together with the Beamsize at the Laser Interaction Point.

Operation mode	Z
Beam Energy [GeV]	45.6
ϵ_x [nm]	0.7
ϵ_y [pm]	2.22
σ_x [mm] at IP	0.3
σ_y [mm] at IP	0.01


Beam evolution under different laser configurations

Normalized horizontal emittance

Normalized vertical emittance

Figure 2: Surviving fraction of the initial particle bunch and Emittance evolution for different laser spot size.

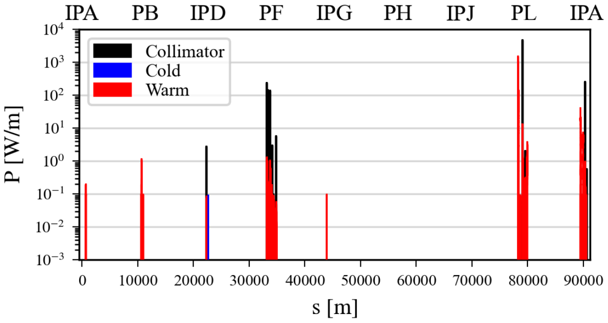


Figure 3: Loss map of CBS-induced losses around the FCC-ee ring for the kBELLA upgrade scenario.

cles through the full FCC-ee lattice, including a detailed aperture model, the complete collimation system, synchrotron radiation effects, and beam–beam effects (beam–beam kicks and beamstrahlung). Losses on the beam-pipe aperture are binned in 10 cm longitudinal intervals, while losses on collimators are accumulated over each collimator's full length. The specific power per unit length is then obtained by weighting each bin by the energy of the lost particles, normalising by the bin width and the CBS removal time. The loss map shows that most CBS-induced losses are efficiently intercepted by the momentum collimation system in PL, just downstream of the laser IP. Residual losses are intercepted by other collimators, namely the IR local protection collimators upstream of IPA and the betatron collimators in PF, with no significant losses on sensitive machine components.

CONCLUSION

A comprehensive simulation framework for studying bunch-by-bunch intensity control in FCC-ee based on Compton backscattering has been developed by integrating beam–beam effects, laser–particle interactions, collimation, and particle-matter interactions into a unified tracking workflow.

The simulations demonstrate that laser-based CBS can remove the required fraction of bunch particles on a timescale significantly shorter than the expected flip–flop instability growth time, with up to 5% bunch depletion achieved within only a few turns for the most aggressive laser configurations considered.

No significant transverse emittance growth is observed after the CBS correction cycle, indicating that the proposed scheme preserves beam quality. This is primarily due to the efficient interception of scattered particles by the collimation system, while the small fraction of particles remaining in the bunch after scattering has negligible impact on the beam core.

These results confirm the feasibility of CBS-based active bunch intensity regulation in FCC-ee and support its potential as a fast actuator for mitigating beam-beam flip-flop instability. Future studies will focus on full self-consistent beam–beam simulations with dynamic bunch population evolution, optimization of laser operating parameters, and evaluation of machine protection and operational integration aspects.

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