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OPTIMIZING THE BEAM INTENSITY CONTROL BY COMPTON BACK-SCATTERING IN e+/e- FUTURE CIRCULAR COLLIDER

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Abstract

In this paper, we present the possible use of laser Compton back scattering (CBS) to adjust and tune the bunch intensity. In the future circular electron-positron collider "FCC-ee", the intensity of the colliding bunches should be tightly controlled, with a maximum charge imbalance between collision partner bunches of less than 3 – 5%. The control of such tolerance is necessary due to the strong effect of beamstrahlung on the bunch length and "flip-flop" instability. We show a realistic beam optical line and simulation results of CBS in the "FCC-ee", including the distribution of scattered positrons.

INTRODUCTION

The future circular electron-positron collider FCC-ee aims to achieve tightly controlled colliding bunches, where the maximum charge imbalance between collision partner bunches is less than 5% on the Z pole and less than 3% at other collision energies [1–4]. Maintaining this tolerance is crucial due to the impact of beamstrahlung on the bunch length and the resulting "flip-flop" instability [5]. To address this challenge, a "bootstrapping" injection scheme [4] has been proposed, involving alternate injections of small portions of the design intensity into the RF buckets that accommodate a colliding pair of electrons and positrons.

Adjusting and fine-tuning the intensity of colliding bunches between top-up injections is also critical. In this paper, we investigate the use of laser Compton back scattering (CBS) to achieve this. By leveraging CBS, we can pre-adjust the intensity of colliding bunches to match the needs of the collider before each beam extraction from the booster and top-up injection in the collider.

Moreover, CBS could be used to remove single bunch pairs from the stored fill pattern in the collider as a last resort, enabling the injection of fresh pair of bunches and restarting at zero bunch current.

Compton Back Scattering

Compton Back Scattering is a phenomenon in which a photon collides with a charged particle, such as an electron or positron, and is scattered off in a different direction with a changed wavelength or energy. During this process, energy is exchanged between the photon and the charged particle, leading to a change in their respective energies. The energy gain from electrons to photons can be expressed as $E_{max\,phot} \approx 4\gamma^2 E_{las}$. At a beam energy of 45.6 GeV, this corresponds to $E_{max\,phot} \approx 23$ GeV, and for 182.5 GeV ($t\bar{t}$) collisions, $E_{max\,phot} \approx 148$ GeV for the FCC. This means that in the first case, the electron or positron loses almost half of its energy, while in the second case it loses almost 80% of its energy. Given that the ring's acceptance is only 1.3%, all particles that undergo collision with laser photons will be extracted from the bunch.

The number of scattered particles in head-on collisions is given by the luminosity formula:

$$N = \frac{\sigma_C N_e N_L}{2\pi\sqrt{(\sigma_{y,e}^2 + \sigma_{y,L}^2)(\sigma_{x,e}^2 + \sigma_{x,L}^2)}} \quad (1)$$

where σ_C is the Compton cross section [6], N_e, N_L are the number of interacting electrons and laser photons, σ_x ($\sigma_{e,L}$) and σ_y ($\sigma_{e,L}$) are the rms electron (laser) transverse dimensions at waist.

The actual number of scattered particles and their energy distribution in an experiment will depend on a variety of factors, including the beam energy, beam emittance, and the specific interaction process being studied. It is important to perform realistic Monte Carlo simulations to accurately predict the experimental results and to optimize the experimental parameters.

Laser

As an example for this study, we consider a Ti:sapphire J-class kHz laser system that is currently available for construction [7–9]. Specifically, we focus on a laser system operating with 1 J pulses at a frequency of 3 kHz, which corresponds to the revolution frequency in the ring. The average power of this laser system is 3 kW, which is equivalent to the average power of the k-BELLA initiative at the LBNL, where a 3 J laser system operates at a frequency of 1 kHz [10]. This laser system operates at a wavelength of 800 nm, which is obtainable from a Ti:sapphire laser and corresponds to a photon energy of 1.5 eV.

Interaction Point

As shown in the luminosity Eq. (1), the number of scattered particles is inversely proportional to the transverse spot sizes of the collided bunches. Therefore, we should identify a position with a small electron spot size and focus the laser at that point for maximum scattering efficiency.

As interaction point (IP) was chosen middle of the dipole magnet located in upstream of the collimator system, the layout of collimation section presented on Fig. 1 together with the optics for the Z-operation mode, as presented in [11]. It should be noted that at the given location, the optics function are the same for both the Z and $t\bar{t}$ operation modes.

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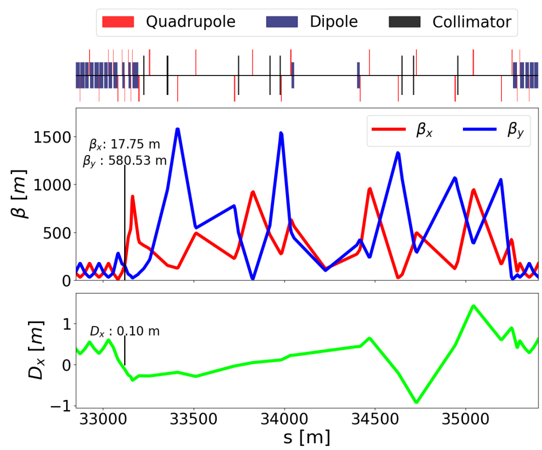

Figure 1: Layout of the collimation section under study for the FCC-ee at the Z operation mode. The location of the laser interaction is indicated by black bars, together with the optics functions.

The beamsize at the laser interaction point together with the beam parameters can be found in Tab. 1. The reasoning for

Table 1: Parameters for the Z and $t\bar{t}$ operation mode [12], together with the beamsize at the Laser interaction point.

Operation mode	Z	$t\bar{t}$
Beam Energy [GeV]	45.6	182.5
ϵ_x [nm]	0.71	1.49
ϵ_y [pm]	1.42	2.98
σ_x [mm] at IP	0.11	0.16
σ_y [mm] at IP	0.02	0.04

this choice is the low value of the beta function and, as a consequence, the small transverse beam size, as well as the rapid removal of particles knocked out of the beam from the orbit.

We should also take into account that the efficiency of the collision is maximized at the head-on collision [13]. It is also necessary to install mirrors and lenses outside the electron orbit, at a distance of at least 3 cm, for the input and output of the laser pulse.

To focus the laser pulse at IP we propose simple scheme using optical length and plain mirror as shown on Fig 2. Using the proposed scheme offers the advantage of allowing

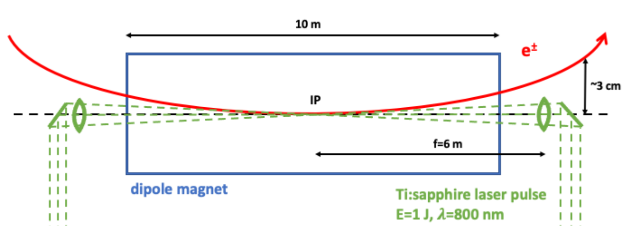

Figure 2: Sketch of the Compton collision inside a single 10 m long dipole, as described in the text.

for a large spot size on the lens, up to 8 mm to reach safety factor of 2 with 1 J/cm^2 for pulse length $\sigma_{t,las} = 300$ ps, which eliminates the risk of damage to the lens even when using a 1 Joule pulse. By applying

$$W_0 = \frac{\lambda f}{\pi W}, \quad (2)$$

it can be determined that such a pulse, with a wavelength of 800 nm, can be focused to a pulse waist of $\sigma_{las} = W_0/2 = 100$ µm at the midpoint of the bending magnet at $f = 6$ m.

BEAM DYNAMICS SIMULATIONS

To study the efficacy with which particles can be removed, as well as the loss location of scattered particles and the emittance evolution, a number of tracking studies have been performed. The XSuite tracking code [14] has been selected for tracking in the magnetic lattice given its speed and possibility to track with synchrotron radiation in a tapered lattice. The interaction with the laser photons is modelled using code CAIN [15], and a small wrapper has been developed to provide an interface between the two codes. Moreover, a framework called collimasim [16] has been used to link the tracking code with a particle-matter interaction code. Here, scattered particles interacting with a collimator will be handed to the Geant4 code [17, 18], with BDSIM [19] used to prepare the Geant4 models and input. After scattering, the primary particle and potential secondary particles are then handed back to the XSuite tracking code for further tracking. In the tracking studies, the collimators of the betatron and momentum collimation sections are included, as well as masks to absorb synchrotron radiation upstream of the experiments. For elements other than these, particle hitting the aperture will be assumed lost. The same setup is being used to study a collimation system in the FCC-ee [20, 21]. For the tracking, a particle bunch with 10^6 particles has been tracked, initialized with the transverse emittance given in Tab. 1. The particles were tracked for 500 and 250 turns in the Z and $t\bar{t}$ lattice, respectively. Note that for the Z operation mode, the transverse damping time is around 2500 turns, whereas for the $t\bar{t}$ operation mode, it is around 45 turns. For these initial studies, based on the laser parameter mentioned above, the initial conservative assumption was made that the bunch undergoes laser interaction every 3$^{\text{rd}}$ turn, corresponding to a laser frequency of 1 kHz and assuming a pulse energy of 1 J.

In Fig. 3, the fraction of surviving initial particles over the number of tracked turns is presented. As expected, the rate with which particles are removed increases with decreasing laser spot size.

In Fig. 4, the distribution of the losses around the ring is shown as a loss map in s. The loss map shown represents the binned energy of particle losses on the aperture and collimators, normalised to the bin size, which is $\Delta s = 10$ cm for losses on the aperture. The case presented is for a single bunch at the Z mode, tracked for 500 turns with laser interaction on and a 100 µm spot size (corresponding to the blue dashed line in Fig. 3), where an intensity loss of around 12 % is found. This represents the worst case scenario out of

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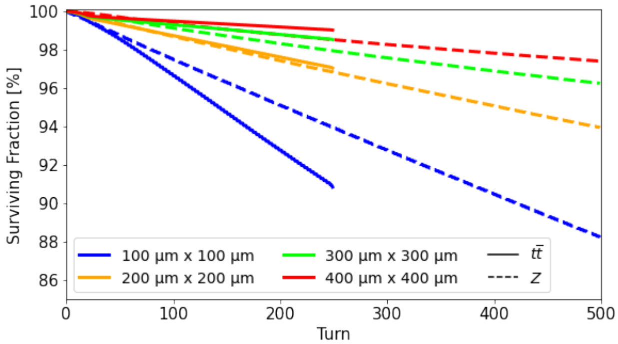

Figure 3: Surviving fraction of the initial particle bunch of 10^6 particles for different laser spot size. The dashed line indicates the results for the Z operation mode, whereas the solid line is for tracking with $t\bar{t}$ parameters.

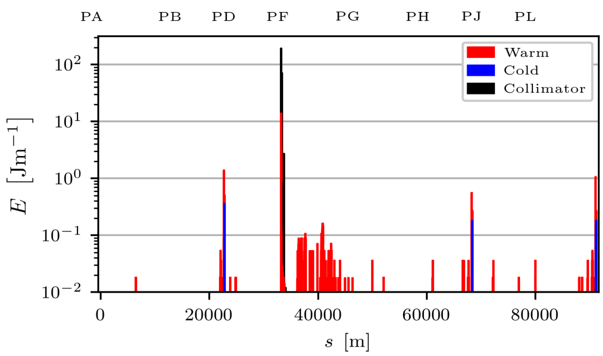

Figure 4: Single-bunch loss map after 500 turns with laser interaction for the Z operation mode and a laser spot size of 100 μm. Aperture losses in normal conducting magnets are shown in red, and losses on superconducting magnets are shown in blue.

the 8 studied cases, both in terms of absolute energy loss and relative losses on the aperture. For the current parameter set, the Z mode has 10000 bunches with a bunch population of 2.43×10^{11} at 45.6 GeV [12], giving 1.8 kJ energy per bunch. The majority of the scattered particles are absorbed by the betatron collimation system in PF, but notable losses occur in the experimental insertions, where up to around 1.1 J/m is observed at the dispersion peaks at the start of the insertions. The regions ±100 m from the collision points, where sensitive equipment like the experiment detectors and superconducting final focus quadrupoles are located, receive up to an integrated total of 0.35 J, corresponding to a power loss of 2.27 W. It should be noted that this is the power load per bunch only during the intensity trimming, not a continuous power load during operation. A full assessment of the risks from the loss power load will be carried out in the future, when the specifications for the required intensity trim and the number of bunches trimmed simultaneously are established.

In Fig. 5, the RMS emittance evolution for the tracking with the Laser interaction every 3rd turn is compared with a reference tracking without any Laser interaction. It is

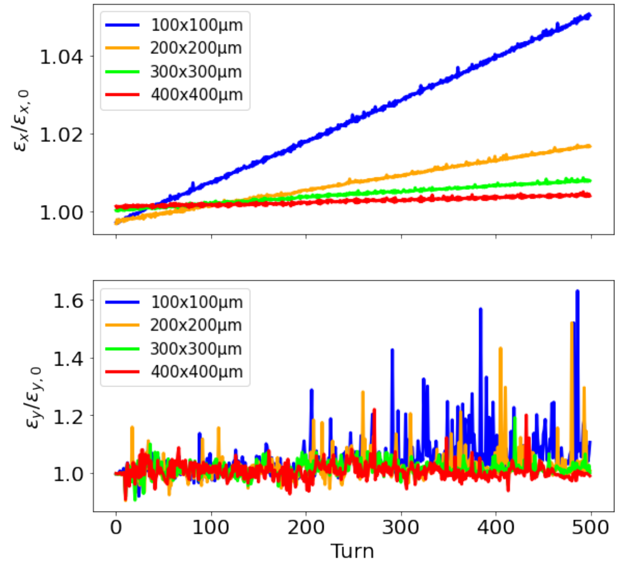

Figure 5: Emittance evolution of the particle bunch for different laser spot size and for the Z operation mode.

found that for the smallest spot size, the horizontal emittance increases by about 5 % after 500 turns compared to the reference case, both initialized with emittances following Tab. 1. As expected, the emittance blow-up decreases with increasing Laser spot size, with the largest spot size of 400 μm showing basically no increase in the horizontal emittance. For the vertical plane, emittance spikes occur after particles interacting with Laser pulse but before being lost and no reliable conclusion on the emittance increase can be made at this point. It should be noted that in these first tracking studies, synchrotron radiation damping has been treated as an average energy loss in each element, rather than the discrete emission of photons with the energy sampled from the spectrum of the synchrotron radiation process. As such, the horizontal emittance of tracked distribution will tend towards 0 rather than the equilibrium emittance. While more time-consuming, future tracking aim to better study the emittance evolution by modelling the emission of synchrotron radiation as a stochastic fluctuation process. Moreover, coupling should be introduced in the lattice to generate a nonzero vertical emittance. Lastly, for the case of the $t\bar{t}$, no emittance increase was found.

CONCLUSION

This paper presents simulation of dynamics in the FCC-ee ring including CBS for the fine tuning of individual single-bunch intensities to avoid the beam-beam flip-flop instability. The effectiveness of the proposed scheme is demonstrated and various collision parameters are proposed for subsequent use in more systematical studies of beam dynamics in the FCC-ee ring.

It is interesting to note that during the CBS, high-energy photons are produced, with energy 23 GeV for the Z-operation mode and 148 GeV for the $t\bar{t}$-operation mode, forming bundles with low divergence $\theta \approx 1/\gamma$. These photons could be of interest for additional experiments.

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