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INTERACTION POINT BEAM OFFSET TOLERANCES FOR LUMINOSITY PERFORMANCE AT FCC-ee *

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Abstract

To achieve physics performance at the Future Circular electron-positron Collider (FCC-ee), luminosity and beam lifetime must be maintained at close to design specifications. Alongside global feedbacks, a fast feedback system is proposed to mitigate beam offset errors at the interaction points (IP), caused by magnet vibrations or other time-varying errors. In this paper, the FCC-ee luminosity performance is simulated for beam-beam interactions including beam offsets, providing performance requirements for the fast feedback system.

INTRODUCTION

The Future Circular electron-positron Collider (FCC-ee) [1–3] is a design study for a 91 km electron-positron collider based at CERN, Geneva. The machine aims to operate at the luminosity-frontier for precision physics at four beam energies: 45.6 GeV (Z), 90 GeV (WW), 120 GeV (ZH) and 182.5 GeV ($t\bar{t}$). The collider is foreseen to operate with four experimental Interaction Points (IPs). Due to the adoption of the nano-beam scheme [4], the vertical beam sizes at the IPs are on the nano-metre scale. Therefore, to maintain luminosity, beams must be kept in collision to high accuracy in the presence of machine errors. An IP feedback system is proposed to mitigate these errors. Parameters relevant for the IP feedback design of the FCC-ee Global Hybrid Correction [5] (GHC) lattice version v24.3 used for most simulations presented are listed in Table 1.

Table 1: FCC-ee GHC v24.3 Parameters

Running mode	**Z**	**WW**	**ZH**	**$t\bar{t}$**
Beam energy [GeV]	45.6	80	120	182.5
Bunch pop. [10^{11}]	2.16	1.38	1.69	1.48
Bunches /beam	11200	1852	300	64
Hor. emit. (BS) ε_x [nm]	0.70	2.16	0.66	1.51
Vert. emit. (BS) ε_y [pm]	1.9	2.0	1.0	1.36
Hor. IP beta β_x^* [mm]	110	220	240	900
Vert. IP beta β_y^* [mm]	0.7	1	1	1.4
σ_z (BS) [mm]	15.6	5.28	5.59	2.32
Hor. BB ξ_x [10^{-3}]	2.2	13	10.8	65
Vert. BB ξ_y [10^{-3}]	97.7	129	130	136
Crab waist k_{CW} [%]	70	55	50	40
Lumi. /IP [10^{34} cm^{-2} s^{-1}]	143	20	7.5	1.38

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Interaction Point Feedback

IP Feedback is an orbit feedback, local to the IP, to ensure maximal overlap of the colliding beams and thereby maximise luminosity. Closed orbit bumps are created in one or both beams at the IP. To close all of orbit, dispersion and coupling, multiple bending correctors per plane, per beam being corrected, on each side of the IP are required [6].

The feedback loop involves: IP offset detection, correction calculation, and correction application. A discussion of the proposed IP feedback signals for FCC-ee is presented in [7]. At FCC-ee, it is proposed to utilise both beam-beam deflection feedback and luminosity dithering feedback [3].

CONTRIBUTING FACTORS

Machine Stability

Offsets at the IPs result in strong beam-beam forces. These forces induce orbit errors, bunch lengthening (due to increased beamstrahlung radiation emission) and tune errors. The combination of these effects results in loss of luminosity, excitation of resonances, increased tune diffusion and eventually emittance growth and particle losses.

Physics Performance

FCC-ee is designed to be a precision physics machine. To achieve this, systematic errors must be minimised. One key systematic error is the measurement of the beam energy. The beam energy measurement precision is influenced by offsets at the IP. For beams with a vertical dispersion difference of 1 µm and a vertical offset of 1 nm, the average collision energy shifts by 100 keV , which is the target energy precision [8]. Thus, the maximum vertical offset should not exceed 1 nm. Offsets also directly degrade luminosity, reducing the volume of data for physics analysis.

Error Sources

Colliders are subject to a range of errors, such as ground motion, mechanical vibration and power converter noise. Previous studies have indicated that the motion of the Final Focus Quadrupoles (FFQs) will be a dominant error source due to the large beta functions [9]. Studies at SuperKEKB support this [10]. The dynamics of the FCC-ee final focus system are under study. The amplitude and frequency of the FFQ resonant modes are expected to dictate the required frequency of the IP feedback, and the maximum strengths of the correctors.

Interplay with other feedbacks

The IP feedback system will not exist in isolation. In particular, the interplay with global orbit feedback systems will

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be key. It is expected that large, low frequency oscillations will be addressed by the global feedback over the full ring, reducing the required closed orbit bumps at the IP. Furthermore, feedbacks such as the transverse damper will have interplay with regards to the bunch length. The design of these other feedbacks is also currently under study [3].

TOLERANCE STUDIES

Tracking simulations are performed to study machine stability with IP offsets. Due to the nano-beam optics at the IP, the dominant errors are in the vertical plane: vertical position and vertical angle. As such, simulations have been focussed on these tolerances.

Simulation Setup

New simulations with GHC v24.3 parameters have been performed using Xsuite [11]. Simulations were performed using linearised lattices, composed of: a beam-beam element, transfer map IP to Crab Sextupole (CS), CS Multipole, Arc transfer map, CS multipole and transfer map CS to IP. Longitudinal and transverse apertures are also included for momentum acceptance and beam-pipe apertures.

The full lattice uses imperfect cancellation of sextupole pairs to produce the crab waist effect. Single thin multipoles are used to represent the crab waist effect. These multipoles have phase advances from the IP of $(1.0, 1.25)$ $[2\pi]$ in the horizontal and vertical plane respectively. The integrated strengths, $\pm k_2 l_{CW}$, are calculated according to

$$k_2 l_{CW} = k_{CW} \frac{1}{2\theta_c \beta_y^* \beta_y^{CW}} \sqrt{\frac{\beta_x^*}{\beta_x^{CW}}}, \quad (1)$$

where θ_c is the half crossing angle and β is the twiss beta function, taken from the full non-linear lattice.

Beam-beam simulations are performed in 'weak-strong' mode. The 'strong' beam is held offset and the distribution of the 'weak' beam is then analysed. The linear lattice represents one super-period (IP to IP). The strong beam at each IP is therefore identically offset. Monitoring occurs outside of the CS region to remove the impact of the non-linear effects.

Previous Studies and Benchmarking

Previous studies were performed using a linearised Conceptual Design Report (CDR) lattice at the Z working point. Simulations were performed using the tracking code LIFETRAK [12]. A linearised lattice with 4 IPs but the same phase advance per super-period as the then baseline 2IP lattice was analysed. A vertical offset tolerance of 0.05 $_y$ was found [13]. This lattice was not optimised for operation with four IPs. The previous LIFETRAK studies were reproduced in Xsuite and good agreement was found, shown in Fig. 1.

Gaussian Beam Tracking Studies

To study the dynamics of realistic bunches, Gaussian bunches with equilibrium collision parameters were initialised and tracked with various beam-beam offsets. Luminosity, beamstrahlung and BhaBha scattering were enabled.

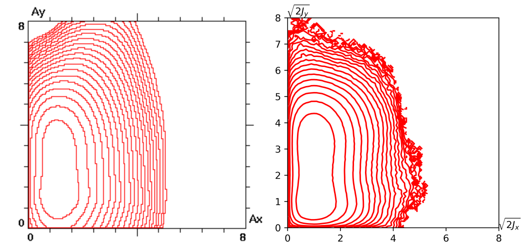

Figure 1: Benchmark normalised action space density contour plots for the CDR 4IP Z lattice with LIFETRACK (left) and Xsuite (right).

Synchrotron radiation damping and excitation was applied in the arc transfer map. Particles were tracked for ~ 8 longitudinal damping times. At the WW, ZH and tt̄ working points 10 000 macroparticles were tracked. Due to the long damping time at the Z working point, only 1 000 macroparticles were tracked, resulting in greater noise.

Relative emittance blow-up, compared to the equilibrium emittance with no-offset, was analysed. The impact of offsets in vertical position and angle are shown in Fig. 2. In all cases, the horizontal plane is largely unaffected. On the other hand, significant emittance blow-up is observed in the vertical plane with beam-beam offsets, most notably for tt̄ with position offset and WW with angle offset. Bunch lengthening is also observed due to the increase in beamstrahlung radiation with offset, most notably at the Z working point.

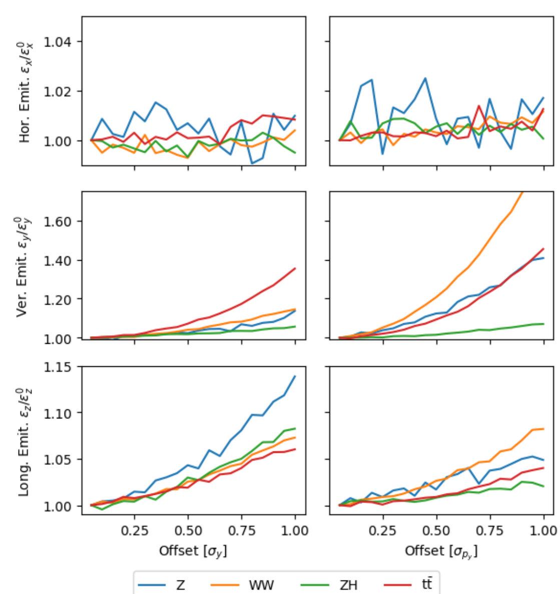

Figure 2: Emittance in the horizontal, vertical and longitudinal planes with beam-beam offsets up to 1σ in y and p_y for the Z, WW, ZH, and tt̄ working points of the GHC 24.3 lattice.

Luminosity degradation is significant with both vertical angle and vertical offsets. To maintain high luminosity, tight tolerances must therefore remain on the vertical position and

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angle offsets. Beamstrahlung increases are most apparent at the Z working point. This is concerning for machine protection as the beamstrahlung radiation power, per IP, per direction is ~ 300 kW [7]. Luminosity and beamstrahlung evolution over the tracking is shown in Fig. 3.

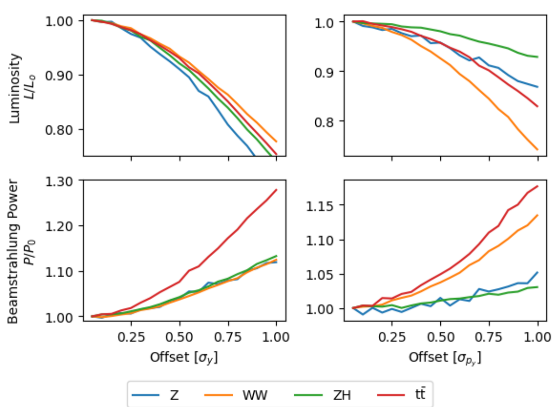

Figure 3: Luminosity and beamstrahlung for beam-beam offsets up to 1σ in y and p_y for the Z, WW, ZH, and $\mathrm{t\bar{t}}$ working points of the GHC 24.3 lattice.

The bunch distributions are also analysed in action space. At each turn, particles are binned based on their action amplitude, taken as

$$J_a = \frac{a^2 + p_a^2}{2}, \qquad a \in x, y, \tag{2}$$

where a and p_a are the position and momentum coordinate in a given plane. This enables analysis into the cause of the emittance changes, distinguishing between the impact of the beam core and beam halo.

Significant blow-up of the beam core is observed with offset. Example contours are shown in Fig. 4. The GHC 24.3 lattice shows greater tolerances to offsets, likely due to the more optimised tune working point.

Frequency Map Analysis

To study at which oscillation amplitudes resonances are encountered, the phase space was analysed by tracking a grid of particles. Particle grids were initialised for $\sqrt{2J}$ in the interval 0 to $8\sqrt{\varepsilon_{RMS}}$ across four test phases $[0, \pi/4, \pi/2, 3\pi/4]$. Luminosity, beamstrahlung, BhaBha scattering and synchrotron radiation were disabled. This allows analysis of the impact of the beam offset, without stochastic processes obscuring the results. Increases in the tune diffusion parameter with beam offsets are observed to be stronger at the CDR working point, as shown in Fig. 5.

CONCLUSION

IP feedback systems are required at FCC-ee to maintain the ambitious luminosity goals. Machine tolerances have been studied with weak-strong beam-beam particle tracking simulations using linearised lattices. Further studies

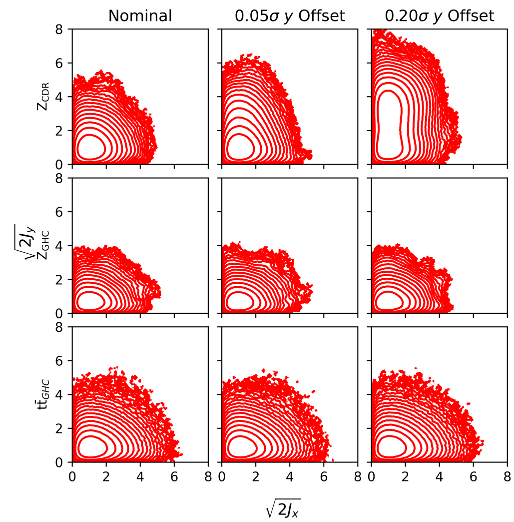

Figure 4: Normalised action space density contour plots for the CDR 4IP Lattice at the Z working point, and the GHC 24.3 lattice at the Z and $\mathrm{t\bar{t}}$ working points with beam-beam offsets of 0, 0.05 and 0.20 σ_y.

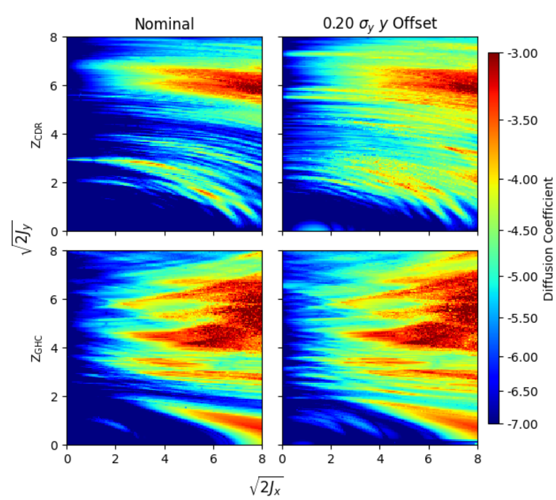

Figure 5: Diffusion Maps for the CDR 4IP Lattice and the GHC 24.3 lattice at the Z working point with beam-beam offsets of 0 and 0.20 σ_y.

are planned, including the full non-linear lattice, and moving towards self-consistent strong-strong beam-beam particle tracking simulations. The current tightest offset tolerance stems from the beam energy measurement tolerance of 100 keV, corresponding to a 1 nm vertical offset with 1 µm dispersion, and not from the loss of performance due to beam dynamics.

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