13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST010

CONTROLLING e^+/e^- CIRCULAR COLLIDER BUNCH INTENSITY BY LASER COMPTON SCATTERING*

F. Zimmermann†, European Organization for Nuclear Research (CERN), Meyrin, Switzerland
T.O. Raubenheimer, SLAC National Accelerator Laboratory, Menlo Park, CA, U.S.A.

Abstract

In the future circular electron-positron collider “FCC-ee”, the intensity of colliding bunches must be tightly controlled, with a maximum charge imbalance between collision partner bunches of less than 3–5%. Laser Compton back scattering could be used to adjust and fine-tune the bunch intensity. We discuss a possible implementation and suitable laser parameters.

INTRODUCTION

In the future circular electron-positron collider FCC-ee, the intensity of colliding bunches must be tightly controlled, through frequent top-up injections, with a maximum charge imbalance between collision partner bunches of less than 5% on the Z pole and less than 3% at the other collision energies [1–3]. If the charge imbalance exceeds this tolerance, due to the strong effect of beamstrahlung on the bunch length, a “flip-flop” effect [4] results, with the more intense bunch shrunk and the weaker bunch blown up. This is the reason why, when filling the machine from zero, a “bootstrapping” injection scheme [3] is proposed with alternate injections of small portions of the design intensity into the RF buckets accommodating a colliding pair of electrons and positrons.

In this paper, we consider the possible use of laser Compton back scattering to adjust and fine-tune the bunch intensity, in one or both collider rings, between subsequent top-up injections. The laser of the Compton polarimeter [5] could be used for this purpose, provided that its laser power is increased to a sufficiently high value.

The same approach could be applied with a dedicated laser in the full-energy booster (which alternatingly serves as injector to both collider rings), in order to pre-adjust the bunch intensity to the instantaneous needs of the collider, prior to each beam extraction from the booster and top-up injection in the collider. This could be particularly interesting if the pre-injector linac operates in a multi-bunch mode, which may require precise intensity adjustments downstream, before top-up injection, to accord with the respective intensity pattern of the collider at that moment in time.

Finally, the laser Compton back scattering could also be used, as a last resort, to remove single bunch pairs from the stored fill pattern in the collider, after experiencing a beam-beam flip-flop effect, so as to make space for injecting a fresh pair of bunches, restarting at zero bunch current.

BEAM PARAMETERS

We consider FCC-ee Z pole operation where the beam size is largest, the beam energy lowest, and the number of bunches the highest. In several respects, this represents the most difficult case.

At a beam energy of 45.6 GeV the geometric emittances, according to the FCC Conceptual Design Report [1], are $\varepsilon_x = 0.27$ nm, and $\varepsilon_y = 1$ pm. With local beta functions of $\beta_x^{\rm CP} = 140$ m and $\beta_y^{\rm CP} = 30$ m at the polarimeter [6], we obtain the rms beam sizes $\sigma_x^{\rm CP} \approx 200$ μm and $\sigma_y^{\rm CP} \approx 5$ μm. The vertical beam size considered in an earlier study [5] was about 5 times larger.

Other beam energies of interest relate to the FCC-ee operation at the WW threshold (80 GeV), or at the ZH production peak (120 GeV), and the $\mathrm{t\bar{t}}$ running (182.5 GeV).

LASER PARAMETERS

The laser pulse length is not critical for our application, as long as the trajectory of electrons or positrons overlaps with the path of the full laser pulse. A pulse duration of order 1 ns or higher would be acceptable. Long pulse lengths imply a lower instantaneous peak power and may, thereby, avoid damage to optical mirrors and other components.

A Ti:sapphire J-class kHz laser system is ready to be built today [7–9]. Specifically, we consider a laser system operating with 1 J pulses at 3 kHz (the revolution frequency), with an average power of 3 kW, which translates to the same average laser power as for LBNL’s k-BELLA initiative (3 J at 1 kHz) [10]. A wavelength of 800 nm, obtainable from a Ti:sapphire laser, corresponds to a photon energy of 1.5 eV. We note that, instead, previously [5] considered a laser wavelength λ of 532 nm, as could be provided by a frequency-doubled Nd:YAG laser. As an encouraging example, in 2021, a 1 J laser with 1 kHz repetition rate at $\lambda = 515$ nm was demonstrated by frequency doubling temporally shaped square 2 ns pulses from a cryogenically cooled Yb:YAG laser in LBO crystals [11].

While a laser system like k-BELLA’s appears sufficient for an application targeting single or few bunches, we were informed that LLNL is in the process of developing extremely high average-power laser concepts with Tm-based materials [12]. Such a Tm:YLF laser, operating at a wavelength of 2 μm, could potentially provide much higher energy, photon intensity, and average power, which would render the proposed technique more flexible, and which would, in particular, allow the intensity of many bunches to be controlled simultaneously.

---

* Work partially supported by the European Union’s H2020 Framework Programme under grant agreement no. 951754 (FCCIS).

† frank.zimmermann@cern.ch

COMPTON CROSS SECTION

The energy spectrum of the Compton scattered electrons is characterized by the parameter x defined as

$$x = \frac{4E_bE_\gamma}{m_e^2c^4}\cos^2\frac{\alpha_0}{2}\ , \tag{1}$$

where E_b denotes the beam energy, m_e the electron mass, c the speed of light, α_0 the full crossing angle between laser pulse and electron beam, E_γ the photon energy, or $E_\gamma = hc/\lambda_\gamma$ with $hc = 1.24$ eV μm and λ_γ the laser wavelength. Considering the case of head-on collision ($\alpha_0 = 0$) and the Ti:sapphire laser wavelength of $\lambda_\gamma = 800$ nm, the scattering parameter evaluates to $x = 15.3 \times 0.046 \times 1.5 \approx 1.08$ at the Z pole, 1.9 at the WW threshold, 2.8 at the ZH production peak, and 4.3 at the $\mathrm{t\bar{t}}$ energy. At $x > 4.8$, $\mathrm{e^+e^-}$ pairs would be created in the collisions of high-energy photons with laser photons. This regime is avoided for all beam energies of the FCC-ee at the assumed 800 nm wavelength; see Table 1.

The maximum energy of the Compton scattered photons (or energy lost by the electrons) is $\sim x/(1+x)E_b$, which varies from 51% (Z) to 81% of the electron energy ($\mathrm{t\bar{t}}$). This high a peak value, in combination with the rather flat cross section, suggests that almost all the Compton scattered electrons will be outside the ring momentum acceptance (at most 3%) and be lost from the beam.

The total Compton cross section depends on x as [13]

$$\begin{aligned}\sigma_0(x) \quad = \quad & \frac{2\pi r_e^2}{x}\left(\left[1-\frac{4}{x}-\frac{8}{x^2}\right]\ln(1+x)\right. \\ & \left.+\frac{1}{2}\left[1-\frac{1}{(1+x)^2}\right]+\frac{8}{x}\right)\ . \end{aligned} \tag{2}$$

Values for the four different operation energies of FCC-ee are compiled in Table 1.

Table 1: Compton x Parameter and Total Unpolarized Scattering Cross Section for Different FCC-ee Beam Energies, Assuming a Laser Wavelength of 800 nm and head-on Collision

beam energy [GeV]	x	σ_0 [mbarn]
45.6	1.08	360
80	1.9	289
120	2.8	244
182.5	4.3	199

BEAM LOSS RATE

The number of photons in a 1 J Ti:sapphire laser pulse is $N_\gamma \approx 4 \times 10^{18}$. Assuming a round laser spot with an rms size $\sigma_0 = 400$ μm (two times the horizontal particle beam size), we find an integrated transverse density at the center of the collision equal to

$$n_{\gamma,\perp} = \frac{N_\gamma}{2\pi\sigma_0^2} \approx 4 \times 10^{24}\ \mathrm{m}^{-2}\ . \tag{3}$$

The scattering probability per electron or positron and per passage through the laser pulse then becomes $n_{\gamma,\perp}\sigma_0 \sim 10^{-4}$, implying a ~1% reduction in bunch intensity over 100 turns (30 ms).

Figures 1 and 2 show an example simulation, where an electron beam of size $\sigma_x^{\mathrm{CP}} = 200$ μm and $\sigma_y^{\mathrm{CP}} = 5$ μm, represented by 30,000 macroparticles, collides with a round laser spot of $\sigma_0 = 400$ μm, over 3000 turns, based on the polarimeter set up.

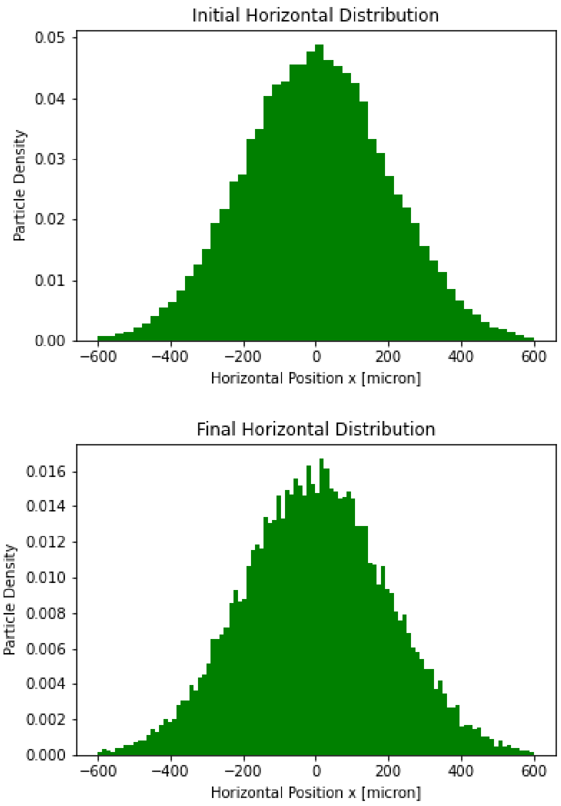

Figure 1: Simulated initial (top) and final horizontal distribution (bottom) of 30,000 macroparticles representing an electron beam of $\sigma_x^{\mathrm{CP}} = 200$ μm and $\sigma_y^{\mathrm{CP}} = 5$ μm, colliding with an 1-J laser pulse at 800 nm wavelength and $\sigma_0 = 400$ μm, on each of 3000 turns. The initial distribution is normalized to a total charge of 1.

COMPTON COLLISION

The FCC-ee polarimeter configuration proposed in [5] realizes near-head-on collision $\alpha_0 = 1$ mrad using a dipole that deflects the unperturbed electrons after collision and also serves as a spectrometer for the scattered electrons. More precisely, this polarimeter design assumes collision at the upstream end of a 24 m long dipole magnet with a field of 13.5 mT.

The detailed polarimeter layout would set specifications on the Rayleigh length, spot size, laser pulse length, etc.

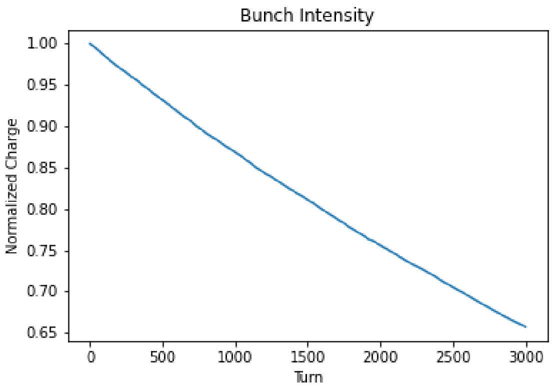

Figure 2: Controlled decrease of bunch charge over 3000 turns, for the simulation of Fig. 1, where 30,000 macroparticles represent an electron beam of $\sigma_x^{\mathrm{CP}} = 200\ \mu$m, $\sigma_y^{\mathrm{CP}} = 5\ \mu$m, colliding with an 1-J laser pulse at 800 nm wavelength and $\sigma_0 = 400\ \mu$m, once per revolution. The initial bunch charge was normalized to 1.

For an ideal Gaussian laser beam, the rms laser beam spot size varies with the longitudinal distance from the focal point, s, as

$$\sigma(s) = \sqrt{\frac{\lambda Z_R}{4\pi}\left(1+\frac{s^2}{Z_R^2}\right)} = \sigma_0\sqrt{1+\frac{s^2}{Z_R^2}} \qquad (4)$$

with λ the laser wavelength, $Z_R = (4\pi\sigma_0^2)/\lambda$ the Rayleigh length, and $\sigma_0 = (Z_R\lambda/(4\pi))^{1/2}$ the rms laser spot size at the Compton collision point (CP), taken to coincide with the laser focal point.

Reference [5] considered $Z_R = 1.48$ m, $\lambda = 532$ nm, and an rms laser spot size of $\sigma_\gamma = 250\ \mu$m. Here, at our chosen laser wavelength of $\lambda = 800$ nm, the laser spot size $\sigma_0 = 400\ \mu$m, which we require, implies a Rayleigh length $Z_R = 2.5$ m. Even with this larger value of Z_R at a distance s of 10 m from the CP the rms laser size amounts to 1.6 mm, and at a distance of 25 m to 8 mm, in case of a Gaussian laser beam. A laser beam rms width of 8 mm is quite large.

Additionally, and in reality, the laser beam is likely not to be a pure Gaussian, but it may feature a larger divergence or an enlarged focal spot. The deviation from a Gaussian is characterized by the M^2 number, as

$$\sigma_M^2(s) = \sigma_{M,0}^2 + M^4\frac{\lambda^2}{16\pi^2\sigma_{M,0}^2}s^2\ , \qquad (5)$$

where $\sigma_{M,0} \geq \sigma_0$. Equality is reached for a pure Gaussian beam, characterized by $M^2 = 1$.

To limit the laser spot size on the mirrors of the surrounding optical cavity set up, we could consider a head-on collision at the center of a 10 m long dipole. The mirrors could then be situated about ±5 m from the IP with the center offset by ~3 cm from the beam assuming a 4 kG dipole field and 50 GeV beam energy. Again selecting a Rayleigh length of 2.5 m, to obtain the assumed 400 μm rms spot size at the Compton collision point for the Ti:sapphire laser wavelength of $\lambda \approx 800$ nm, the rms laser spot size on a mirror at a distance of 5 m from the CP would be less than 1 mm, for $M^2 = 1$. This configuration is depicted in Figure 3.

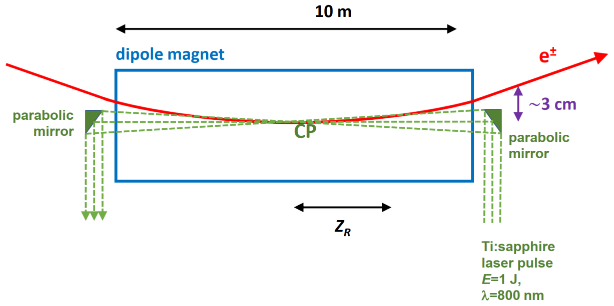

Figure 3: Sketch of the Compton collision inside a single 10 m long dipole, as described in the text.

Alternatively, a simple low-field chicane in a straight might be even easier and less invasive. We also note that a uniform spot across the beam may actually not be needed. If we just focused on the core, the effective emittance would increase by a small amount due the resulting removal of particles preferentially from the center of the beam, similar to the mechanism discussed in [14], but a small, transient emittance increase might not be a problem. This hypothesis could be confirmed in beam-beam simulations.

SUMMARY

Fine tuning of individual single-bunch intensities in the two FCC-ee collider rings and in the FCC-ee full-energy booster, at the sub-percent level, can be accomplished by laser-Compton scattering with a state-of-the-art or near state-of-the-art laser system at a few kW average power. Our study suggests that this approach may provide the necessary level of control of charge equality in colliding bunch pairs, so as to avoid beam-beam flip-flop effects [4]. Tailoring the intensity of many bunches simultaneously would, however, require a more advanced laser system, capable of providing 100 kHz laser pulses with an average power of 10s to 100s of kW, during a fraction of a second.

The same technique of laser-Compton scattering could also be employed to gradually eliminate, from the collider rings, any individual spoilt bunches or bunch pairs, e.g. ones for which a beam-beam flip-flop effect has unwantedly occurred. Until now, for FCC-ee, the only known solution for recovering from such a flip-flop phenomenon had been dumping both beams by firing pulsed kicker magnets.

ACKNOWLEDGEMENTS

We thank A. Fry, M. Hofer, K. Oide, D. Shatilov and T. Spinka for helpful discussions, and Y. Papaphilippou for a careful reading of the manuscript.

REFERENCES

[1] A. Abada, M. Abbrescia, S. S. AbdusSalam, et al., M. Benedikt et al. (eds.), “Fcc-ee: The lepton collider,” *Eur. Phys. J. Spec. Top.*, vol. 228, 2019, `doi:10.1140/epjst/e2019-900045-4`

[2] S. Ogur, K. Oide, Y. Papaphilippou, D. Shatilov, and F. Zimmermann, “Bunch Schedules for the FCC-ee Pre-injector,” in *Proc. 9th International Particle Accelerator Conference (IPAC’18), Vancouver, BC, Canada, April 29-May 4, 2018*, Vancouver, BC, Canada, 2018, pp. 79–82, `doi:doi:10.18429/JACoW-IPAC2018-MOPMF001`

[3] D. Shatilov, “Beam-beam effects at high energy e^+e^- colliders,” in *62nd ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders*, 2019, TUYBA02, `doi:10.18429/JACoW-eeFACT2018-TUYBA02`

[4] D. Shatilov, “How to increase the physics output per MW.h for fcc-ee? - parameter optimization for maximum luminosity,” *Eur. Phys. J. Plus*, vol. 137, no. 1, p. 159, 2022, `doi:10.1140/epjp/s13360-022-02346-x`

[5] N. Muchnoi, “Fcc-ee polarimeter,” arXiv: 1803.09595, 2018, `doi:10.48550/arXiv.1803.09595`

[6] e. a. K. Oide M. Hofer, “Fcc-ee lattice, v18.1,” https://doi.org/10.5281/zenodo.6344457, 2022, `doi:10.5281/zenodo.6344457`

[7] D. Schroeder, “Lasers for plasma accelerators,” APS April Meeting, 19 April 2021,

[8] “Report of workshop on laser technology for k-bella and beyond, (may 9-11, 2017); kbella workshop report,” 2017, `http://www2.lbl.gov/LBL-Programs/atap/Report_Workshop_kBELLA_laser_tech_final.pdf`

[9] L. Kiani *et al.*, “High average power ultrafast laser technologies for driving future advanced accelerators,” arXiv: 2204.10774, 2022, `doi:10.48550/arXiv.2204.10774`

[10] W. Leemans, “Laser technology for k-bella and beyond,” Technical Report, Lawrence Berkeley National Laboratory, Tech. Rep., 2017.

[11] H. Chi, Y. Wang, A. Davenport, C. S. Menoni, and J. J. Rocca, “Demonstration of a kilowatt average power, 1 joule, green laser,” in *Conference on Lasers and Electro-Optics*, 2021, SF2N.1, `doi:10.1364/CLEO_SI.2021.SF2N.1`

[12] A. Fry and T. Spinka, Private communication, 2021.

[13] I. F. Ginzburg, G. L. Kotkin, S. L. Panfil, V. G. Serbo, and V. I. Telnov, “Colliding gamma e and gamma gamma beams based on the single pass e+ e- accelerators II. Polarization effects. monochromatization improvement,” *Nucl. Instrum. Methods Phys. Res.*, vol. 219, pp. 5–24, 1984, `doi:10.1016/0167-5087(84)90128-5`

[14] R. Bruce, “Emittance increase caused by core depletion in collisions,” arXiv: 0911.5627, 2009, `doi:10.48550/arxiv.0911.5627`