

Design and optimization of the CLIC beam delivery system at 7 TeV

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A new beam delivery system has been developed to explore the feasibility of extending the energy reach of Compact Linear Collider (CLIC) to 7 TeV, either through an extension of existing CLIC linacs or by integrating novel acceleration technologies. This study provides key insights for the design of future multi-TeV collider concepts, including a potential 10 TeV plasma-wakefield acceleration-based collider. Particular emphasis is placed on developing a more compact final focus system capable of achieving a luminosity higher than that of previous designs. An in-depth analysis of higher-order optical aberrations and their impact on beam size and luminosity performance is presented.

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I. INTRODUCTION

The Compact Linear Collider (CLIC) is a proposed multi-TeV linear e^+e^- collider designed to operate at c.m. energies of 380 GeV, 1.5 TeV, and 3 TeV [1–5]. Among the possible upgrade scenarios is an extension of the energy reach to 7 TeV, either by extending the existing CLIC linacs or by integrating novel acceleration technologies such as plasma wakefield acceleration modules. The current CLIC beam delivery system (BDS) designs can deliver c.m. collisions up to 3 TeV; thus, a new BDS capable of transporting higher energy beams is required. BDS designs at these energy scales are particularly relevant as input for concepts such as the 10 TeV plasma-based collider [6–8], where the BDS would constitute a significant fraction of the overall accelerator footprint. Located downstream from the main linac, the BDS comprises three sections: the diagnostics section, for beam measurements and corrections; the collimation section, for removing particles with large energy offsets and betatron amplitudes; and the final focus system (FFS), which focuses the beam at the interaction point (IP) and corrects chromatic effects using a local chromaticity

correction scheme [9]. The 3 TeV CLIC BDS layout is shown in Fig. 1 with the design parameters given in Table I.

The BDS design is primarily driven by the need to collimate the beam halo and correct nonlinear aberrations while minimizing synchrotron-radiation-induced beam-size growth, which becomes particularly significant at 7 TeV. Synchrotron radiation (SR) is introduced by the bending dipoles, which generate the dispersion required to remove off-energy particles in the collimation section and to correct chromatic aberrations in the FFS. In addition, the strong quadrupoles in the final doublet (FD) generate synchrotron radiation, resulting in beam-size growth and luminosity loss at the IP [10–12].

Figure 2 compares the CLIC luminosity with the FCC-ee, ILC, LCF, and HALHF design luminosities [13–17]. A target luminosity for 7 TeV is derived by fitting a power law to luminosity results for earlier CLIC designs [18]

$$\mathcal{L}_{\text{tot}}(E) = A \left(\frac{E}{E_0} \right)^{0.42}, \quad (1)$$

where $A = 0.196 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $E_0 = 1 \text{ GeV}$. Therefore, the estimated target luminosity for 7 TeV c.m. collision energy is $\mathcal{L}_{\text{tot}} = 8.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Earlier design efforts exceeded the extrapolated target, reaching a total luminosity of $\mathcal{L}_{\text{tot}} = 10.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ using a 1 km long FFS [19].

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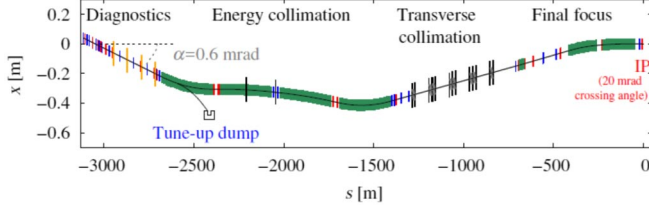


FIG. 1. Schematic of the 3 TeV CLIC BDS [2].

During collisions, beamstrahlung radiation reduces particle energies, leading to a lower c.m. collision energy. This effect is typically mitigated by using flat beam profiles, where β_x^* is much greater than β_y^* . The total luminosity and the 1% energy-peak luminosity are computed at 7 TeV for ideal Gaussian beams using the parameters listed in Table I for various β^* configurations. Figure 3 shows that for flat beams with the β^* values given in Table I, a total luminosity of about $\mathcal{L}_{\text{tot}} = 16.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ can be achieved, although only a fraction resides in the energy peak, with $\mathcal{L}_{1\%} \approx 0.23 \mathcal{L}_{\text{tot}}$. The operational parameter space is constrained, as reducing β_x^* and β_y^* may increase total luminosity $\mathcal{L}_{\text{tot}}$ while decreasing the ratio $\mathcal{L}_{1\%}/\mathcal{L}_{\text{tot}}$. An interesting region appears at currently unattainable values of β_y^* of 1 μm , offering improved ideal performance in both $\mathcal{L}_{1\%}$ and $\mathcal{L}_{\text{tot}}$.

In the following, a beam delivery system suited for a linear e^+e^- collider operating at 7 TeV c.m. energy is designed. Section II describes the energy-dependent scaling laws and optimization of the collimation system. Section III focuses on the development of the final focus system, including the mitigation of synchrotron radiation

TABLE I. Overview of the newly developed 7 TeV beam delivery system compared with the 3 TeV design [2].

Energy (c.m.)	3 TeV	7 TeV
L^* (m)	6	6
BDS length (m)	3117	6400
FFS length (m)	768	768
L_{QD0} (m)	4.7	4.7
L_{QF1} (m)	5.6	6.5
D_x at spoiler (m)	0.27	0.12
Energy spoiler gap (mm)	2.5	1.57
Normalized emittance $\gamma\epsilon_x/\gamma\epsilon_y$ (nm)	660/20	660/20
IP beta function β_x^*/β_y^* (mm)	7/0.12	7/0.16
rms IP beam size σ_x^*/σ_y^* (nm)	—/—	41/3.0
Bunch length σ_z^* (μm)	44	44
rms energy spread (%)	0.3	0.3
Bunch population N_e (1×10^9)	3.72	3.72
Number of bunches n_b	312	312
Repetition rate f_{rep} (Hz)	50	50
Crossing angle (mrad)	20	16.5
Total luminosity $\mathcal{L}_{\text{tot}}$ ($1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	5.9	12.8
Peak luminosity $\mathcal{L}_{1\%}$ ($1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	2	3.5

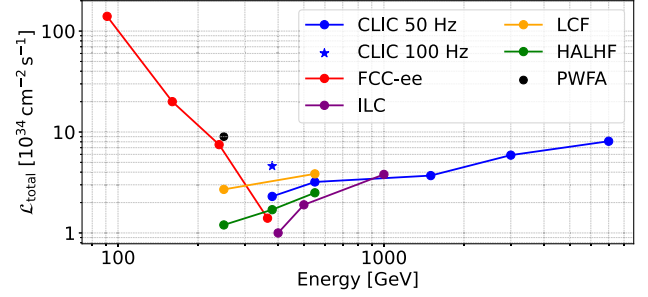


FIG. 2. Total luminosity per IP of proposed electron-positron colliders as a function of c.m. energy. The CLIC 7 TeV luminosity value is extrapolated from the lower energies.

effects and the correction of nonlinear aberrations. Section IV examines the collimation depth and its effectiveness in protecting the final doublet, while Sec. V discusses practical implementation challenges and integration aspects of the 7 TeV design. Finally, Sec. VI summarizes the main findings and outlines directions for future studies.

II. COLLIMATION SYSTEM OPTIMIZATION

The collimation system employs a spoiler-absorber scheme. For the 7 TeV design, the 3 TeV collimation system is used as a baseline and is then optimized for the higher energy, with the energy collimation and transverse collimation systems (TCSs) treated independently.

A. Transverse collimation system

To satisfy aperture and magnet-strength constraints, it is sufficient to scale the length of the beamline proportionally to the cubic root of the beam energy ($\gamma^{1/3}$) [20]. However, the TCS must be scaled to maintain a constant normalized vertical wakefield kick from collimators, $\Delta y'/\sigma_{py}$, and the emission angle from multiple Coulomb scattering, $\phi_{\text{MCS}}/\sigma_{py}$. The minimum spoiler half-gap, g , is assumed to be $55\sigma_y$. These quantities scale as follows [21],

$$\frac{\Delta y'}{\sigma_{py}} \propto \frac{L_s}{\gamma g^3} / \sqrt{\frac{\epsilon_n}{\gamma \beta_y}} \propto \frac{L_s \sqrt{\beta_y}}{\sqrt{\gamma} g^3} \propto \frac{L_s \gamma}{\beta_y}, \quad (2)$$

$$\frac{\phi_{\text{MCS}}}{\sigma_{py}} \propto \frac{\sqrt{L_s}}{\gamma} / \sqrt{\frac{\epsilon_n}{\gamma \beta_y}} \propto \sqrt{\frac{L_s \beta_y}{\gamma}}, \quad (3)$$

where γ is the relativistic Lorentz factor, L_s is the length of the spoiler, and β_y is the beta function at the spoiler location. To keep the quantities in Eqs. (2) and (3) constant, it is necessary to keep both the spoiler length and the ratio β_y/γ constant. The latter can be achieved by scaling the length of the transverse collimation system, L_{TCS} , proportionally to the energy, helping to ensure the aperture and pole-tip field

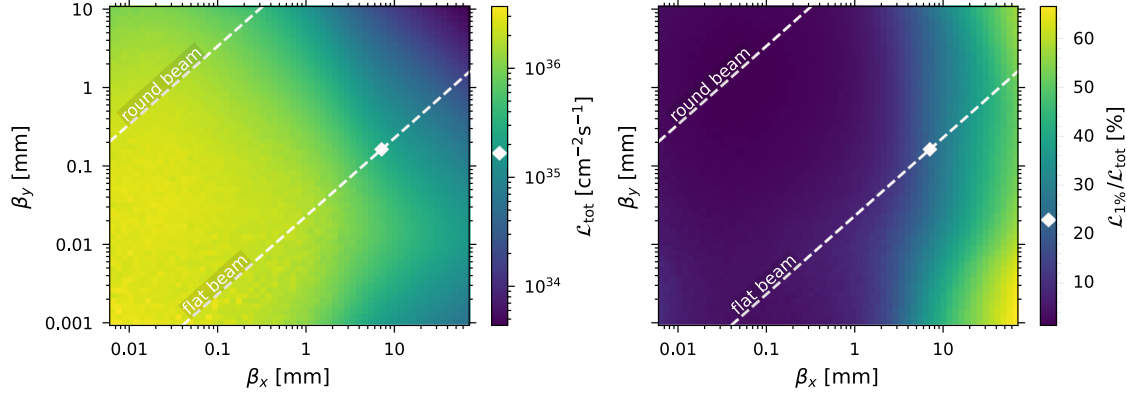


FIG. 3. Total luminosity, $\mathcal{L}_{\text{tot}}$ (left), and the relative fraction of collisions with an energy deviation within 1% of the nominal 7 TeV c.m. energy (right), as functions of the β -function value at the IP. Luminosities are calculated using GUINEA-PIG, assuming normally distributed beams with their waists located at the IP. The marker denotes the β -function values corresponding to the 7 TeV lattice.

strength constraints are satisfied [22], as follows

$$L_{\text{TCS}} \propto \gamma, \quad \beta_{x,y} \propto \gamma. \quad (4)$$

B. Energy collimation system

For the energy collimation system (ECS), both the total length and the bending angles must be scaled, with the bending angles reduced to minimize the impact of synchrotron radiation. The transverse collimation system length scaling given by Eq. (4) is extended to the energy collimation system,

$$L_{\text{ECS}} \propto \gamma. \quad (5)$$

The minimum energy spoiler gap must satisfy the beam-clearance condition, defined by $15\sigma_x = 15\sqrt{\epsilon_x \beta_x}$ and $\delta_p = 0.5\%$, leading to the following relation,

$$g_{\text{min}} = 15\sigma_x + D_x \delta_p, \quad (6)$$

where $\beta_x = 3281$ m at the spoiler location after scaling the length according to Eq. (5). On the other hand, the largest possible gap has to remove particles with a relative energy deviation larger than 1.3% ($\delta_{p,1.3\%}$) as follows

$$g_{\text{max}} = D_x \delta_{p,1.3\%}, \quad (7)$$

to protect the system from particles with large energy errors. The minimum possible dispersion would require that $g_{\text{min}} = g_{\text{max}}$. Combining both Eqs. (6) and (7) results in

$$D_{x,\text{min}} = \frac{15\sigma_x}{\delta_{p,1.3\%} - \delta_p} = 0.033 \text{ m}, \quad (8)$$

where the 3 TeV β_x value at the spoiler location has been scaled by 7/3. PLACET simulations show that a dispersion

of $D_x = 0.12$ m is sufficient to mitigate emittance growth due to synchrotron radiation to the percent level. This corresponds to a spoiler half-gap of $g_{\text{spoiler}} = 1.57$ mm, which is smaller than the 3 TeV value of 2.5 mm and results in a normalized wakefield kick approximately 4 times greater. This increase is considered acceptable, as the wakefield from the energy spoiler is the weakest among all intercepting devices [23].

However, the higher beam energy and reduced D_x increase the risk of damaging the energy spoiler, an issue that requires further investigation beyond the scope of this study. A potential mitigation approach is the use of a rotatory collimator [24].

III. FINAL FOCUS SYSTEM OPTIMIZATION

The performance of a short FFS at 7 TeV is evaluated using the 3 TeV baseline lattice listed in Table I as the starting point, while ensuring all magnet strengths remain within the 1.5 T iron saturation limit [22]. Tracking the 7 TeV beam in the 3 TeV lattice using PLACET [25,26] and GUINEA-PIG [27] yields a luminosity of $4.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The 45% discrepancy between the achieved luminosity and the extrapolated target is attributed mainly to an increase in beam-size growth from synchrotron radiation and higher-order transport aberrations.

To minimize synchrotron radiation, the dipole bending angles were reduced by a relative amount $\Delta\theta/\theta$ with respect to the 3 TeV baseline. To compensate for the corresponding reduction in dispersion, the sextupole strengths were scaled inversely by the same factor. A 40% reduction in the bending angles yields total and peak luminosities of $\mathcal{L}_{\text{tot}} = 11.75 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $\mathcal{L}_{1\%} = 3.49 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, respectively, as shown in Fig. 4. The change in bending angles corresponds to a 2.1 cm horizontal shift of the FFS layout relative to the 3 TeV design. Layout implementation challenges are discussed in Sec. V. The corresponding linear optics and lattice are illustrated in Fig. 5.

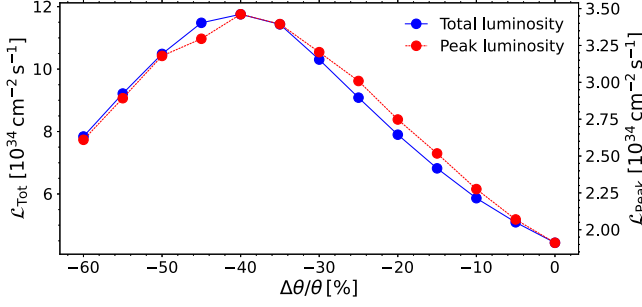


FIG. 4. Total and peak luminosity with variation of the FFS dipole bending angles relative to the reference design at 3 TeV.

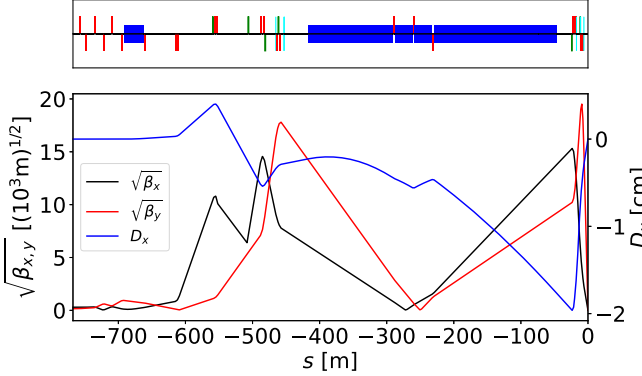


FIG. 5. 7 TeV FFS linear optics (bottom) with lattice (top), including quadrupoles (red), dipoles (blue), sextupoles (green), and octupoles and decapoles (cyan). The IP is at $s = 0$ m.

In general, the luminosity can be increased by reducing the beam size at the IP. A smaller beam size is obtained by decreasing the vertical beta function, β_y , until the required strong focusing introduces nonlinear aberrations that limit further beam-size reduction. The dependence of the vertical beam size on β_y was evaluated using MAPCLASS [28,29], which computes the rms beam size semianalytically by expanding the particle optics in a truncated power series and evaluating the integral definition of the rms.

Figure 6 shows the computed rms beam size for different truncation orders as a function of β_y^* , with β_y^* varied by matching the FFS quadrupole strengths in MADX without nonlinear corrections. The luminosity is obtained from tracking simulations using PLACET and GUINEA-PIG. The optimal luminosity is achieved when $\beta_y^* = 0.16$ mm, where it is sufficiently low to minimize the IP rms beam size before higher-order aberrations and the Oide effect [11] begin to dominate. At $\beta_y^* > 0.16$ mm, the luminosity is reduced as a result of the increasing size of the beam core, which is dominated by lower-order aberrations.

Following the linear optics design, sextupole, octupole, and decapole magnets were introduced as correctors to

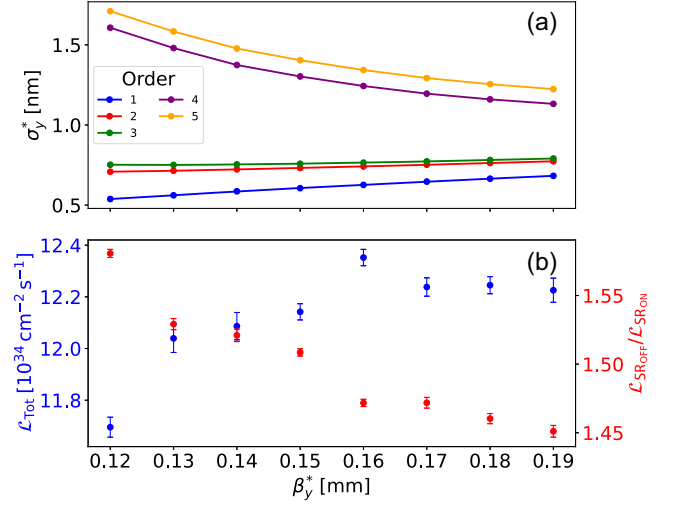


FIG. 6. (a) Vertical beam size at the IP up to the fifth order of the transfer map versus β_y^* . (b) Total luminosity and the ratio between the luminosity with and without synchrotron radiation, as functions of β_y^* for $\beta_x = 7$ mm. Error bars represent the standard deviation over $N = 10$ samples.

minimize nonlinear aberrations. While maximizing luminosity is the primary objective, it was optimized indirectly by minimizing the semianalytic beam size predicted by MAPCLASS. This approach was advantageous because the computation is faster than numerical tracking followed by particle-in-cell (PIC) simulations of the colliding beams, and it is not affected by the noise inherent to PIC codes.

The rms provides a statistical measure of the width of a distribution and is sensitive to its tails. However, extended tails in the beam distribution correspond to regions of low phase-space density and therefore contribute little to the luminosity. As an alternative, the width of the distribution can be estimated using the median absolute deviation (MAD),

$$\Lambda = \text{median}(|x - \text{median}(x)|), \quad (9)$$

which is less influenced by the distribution tails. Both the rms and MAD are model-independent measures used to characterize the width of arbitrary distributions. For a normal distribution, the MAD is related to the standard deviation by $\Lambda = \sigma_{\text{MAD}}/1.4826$ [30].

Figure 7 shows the vertical beam profile at the IP after tracking with PLACET, which exhibits pronounced tails compared to a normally distributed beam. Three Gaussian profiles are compared: one obtained from a least-squares fit and two with standard deviations fixed to the rms and σ_{MAD} values of the distribution, respectively.

Due to the presence of long tails in the beam profile, the rms is significantly larger than the standard deviation of the fitted Gaussian core, with $\sigma_{\text{rms}}/\sigma_{\text{Fit}} \approx 3.6$. In contrast, the Gaussian profile corresponding to the MAD

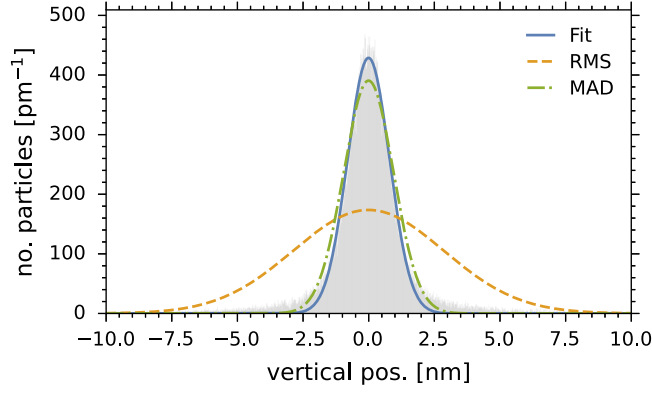


FIG. 7. Optimized vertical beam profile at the IP after tracking (gray). A least-squares Gaussian fit (blue, solid) is compared with two Gaussian functions whose standard deviations are fixed to the beam's rms (orange, dashed) and σ_{MAD} (green, dash-dotted) values.

reproduced both the beam core and the least-squares fit more accurately, with $\sigma_{\text{MAD}}/\sigma_{\text{Fit}} \approx 1.2$.

Pearson correlation coefficients between the tracked beam sizes (rms and MAD) and the rms beam sizes at the IP computed by MAPCLASS for different truncation orders are presented in Table II. The results indicate that the core width of the distribution, represented by the MAD, is mainly determined by lower-order terms, whereas the rms is dominated by fourth-order and higher-order aberrations.

Figure 8 illustrates the correlation between the tracked beam size (rms and MAD) and the luminosity computed by GUINEA-PIG when the nonlinear corrector strengths are varied randomly. The expected anticorrelation between beam size and luminosity is evident. Quantifying the correlation using Pearson correlation coefficients yields $\rho_{\text{rms}} = -0.622$ and $\rho_{\text{MAD}} = -0.939$, indicating that the MAD is more strongly correlated with luminosity, where $\rho = -1$ corresponds to a perfect linear anticorrelation. This observation confirms that nonlinear aberrations strongly influence the rms beam size by generating tails in the beam distribution, whereas the luminosity is primarily determined by the core size.

TABLE II. Pearson correlation coefficients between tracked and semianalytic beam sizes (rms and MAD) from PLACET and MAPCLASS, respectively, for the horizontal (x) and vertical (y) planes at the IP and for different map orders, including synchrotron radiation effects in PLACET.

Order	rms_x	MAD_x	rms_y	MAD_y
2	0.032	0.788	0.099	0.675
3	0.022	0.774	0.099	0.659
4	0.927	0.783	0.985	0.614
5	0.959	0.711	0.976	0.607

Consequently, the rms beam size should be replaced by the MAD beam size as the optimized quantity for luminosity maximization. However, the analytical solution to the rms integral implemented in MAPCLASS cannot be readily adapted to compute the MAD. Instead, the weighted rms beam size is optimized by introducing optimization weights, w_x and w_y , and minimizing the cost function

$$C(\sigma) = \sum_{n=2}^5 \left[w_x^{(n)} (\sigma_x^{(n)} - \sigma_x^{(1)}) + w_y^{(n)} (\sigma_y^{(n)} - \sigma_y^{(1)}) \right], \quad (10)$$

where $\sigma_x^{(1)} = \sqrt{\beta_x \epsilon_x}$ and $\sigma_y^{(1)} = \sqrt{\beta_y \epsilon_y}$ are the linear beam sizes and n is the order up to $n = 5$. These weights encourage solutions in which the contribution of tails caused by higher-order aberrations is minimized. Both the horizontal and vertical beam sizes are minimized using Eq. (10), with optimization weights $w_x^{(n)} = 0.1 \text{MAD}_x^{(n)}$ and $w_y^{(n)} = \text{MAD}_y^{(n)}$ corresponding to the MAD coefficients listed in Table II. Figure 9 shows a clear improvement in the relative order-by-order aberrations when using the weighted cost-function scheme compared with the unweighted case. The optimization gives higher

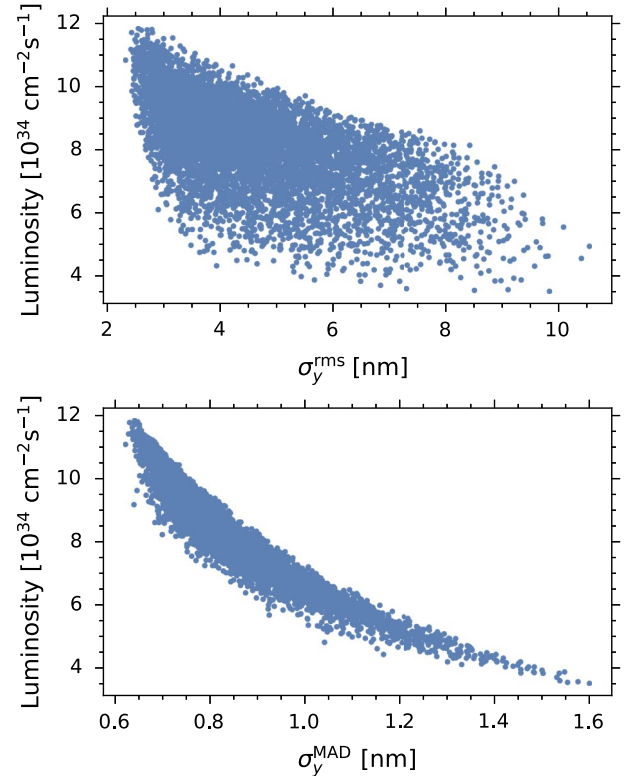


FIG. 8. Luminosity computed by GUINEA-PIG as a function of the beam size at the interaction point (IP), shown for the rms (top) and MAD (bottom) beam-size metrics. The sextupole, octupole, and decapole corrector strengths were randomly varied while keeping the linear optics configuration unchanged.

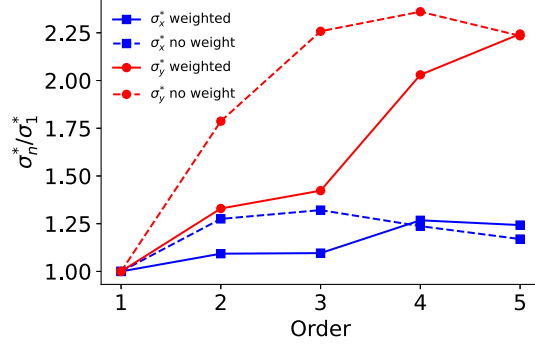


FIG. 9. Horizontal (blue) and vertical (red) rms beam sizes at the IP computed with MAPCLASS for different truncation orders. The beam sizes correspond to the final values obtained after minimizing either the rms beam size (dashed lines) or a weighted cost function (solid lines).

priority to minimizing second- and third-order vertical aberrations and yields a total luminosity of $\mathcal{L}_{\text{tot}} = 12.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. In contrast, omitting the optimization weights results in a considerably lower luminosity of $\mathcal{L}_{\text{tot}} = 11.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

A. Final doublet optimization

The FD quadrupole field strengths should be minimized to mitigate the impact of the Oide effect on the beam size [10,31]. By increasing the length of the FD quadrupoles and reducing their gradients, the beam-size growth due to synchrotron radiation is decreased while maintaining the same integrated focusing strength. Accordingly, the length of QF1, L_{QF1} , was increased from 5.6 m to 6.5 m, which represents the maximum feasible increase while keeping the sextupole position and QF1 center fixed, as shown in Fig. 10. Changing L_{QF1} , the upstream chromaticity, ξ_x^{UP} , no longer matches that generated by the FD, ξ_x^{FD} , as required by the FFS scheme [9]. The optics were therefore rematched using MADX to restore both the linear and nonlinear corrections while ensuring $\xi_x^{\text{UP}} = \xi_x^{\text{FD}}$. With the new FD configuration, the achieved luminosities are $\mathcal{L}_{\text{tot}} = 12.8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $\mathcal{L}_{1\%} = 3.46 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Table III summarizes the luminosity performance for different configurations, with and without synchrotron

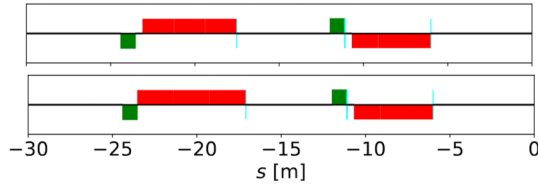


FIG. 10. FD with quadrupoles (red), sextupoles (green), and octupoles (cyan) with a short QF1 (top) and a longer QF1 (bottom) to mitigate the impact of the Oide effect on the IP beam size. The IP is at $s = 0$ m.

TABLE III. Comparison of the total luminosity $\mathcal{L}_{\text{tot}}$ and the IP rms beam sizes σ_x^*/σ_y^* computed with GUINEA-PIG and PLACET, respectively, with synchrotron radiation switched ON or OFF in the final doublet quadrupoles and in the FFS bending dipoles.

Configuration	$\mathcal{L}_{\text{tot}} [10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$	σ_x^*/σ_y^* (nm)
SR ON	12.8	40.7/3.0
SR OFF in QD0 only	13.7	41.0/2.2
SR OFF in QF1 only	14.4	37.7/2.4
SR OFF in FD	15.7	37.6/1.6
SR OFF in FD & dipoles	19.2	35.4/1.5

radiation effects in the FD quadrupoles and bending dipoles. Further lengthening of QF1 could yield up to a 13% luminosity increase, while extending QD0 could provide up to 8%. Although sufficient longitudinal space is available for such modifications, their optimization is left for future studies. Removing synchrotron radiation in the dipoles increases luminosity by an additional 22%, which could be realized by lengthening the FFS. However, previous attempts with a longer system did not produce higher luminosity due to stronger aberrations [19], likely caused by the increased chromaticity when maintaining the same β^* and L^* values in the longer lattice.

B. Detector solenoid impact

Solenoid effects from the CLIC detector have thus far been neglected. Figure 11 shows the longitudinal, B_z , and radial, B_r , magnetic-field components along the beam axis. Synchrotron radiation emitted while traversing the solenoid leads to an increase in emittance at the IP. For the current crossing angle, this results in a 20% reduction in luminosity, yielding a total luminosity of $\mathcal{L}_{\text{tot}} = 10.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Using a smaller crossing angle of 16.5 mrad, as used in the 380 GeV baseline design [32], restores the luminosity performance to $\mathcal{L}_{\text{tot}} = 12.8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. It is assumed that complete compensation of the transverse coupling from the solenoid is achieved with skew quadrupoles or compensation solenoids, thereby mitigating any luminosity loss to coupling [33].

IV. COLLIMATION DEPTH

The primary function of the transverse collimation section is to remove particles with large betatron amplitudes. Such particles pose a risk of hitting the FD or the detector, potentially generating unwanted background radiation in the interaction region. The minimum collimation depth of $15\sigma_x$ and $55\sigma_y$ is set to mitigate the impact of wakefield effects (see Sec. II A). To ensure no loss of large-amplitude particles, a uniform beam distribution with an energy spread of 1.3% and phase space collimated to $15\sigma_x$, $55\sigma_y$, $15\sigma'_x$, and $55\sigma'_y$ at the entrance to the FFS

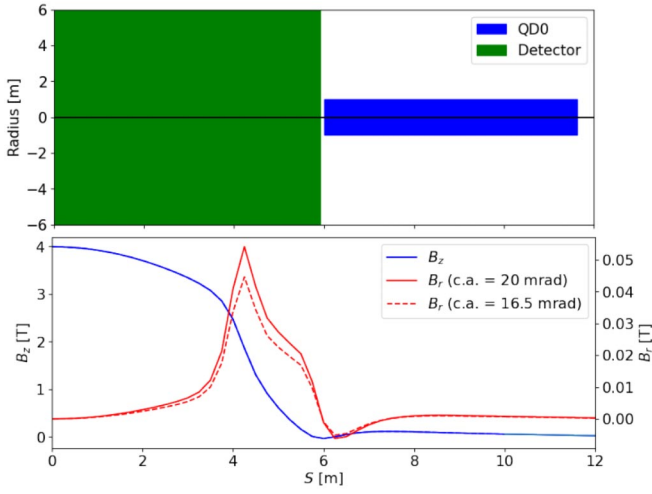


FIG. 11. Interaction region layout (top). Longitudinal B_z and radial magnetic fields B_r (bottom) for 20 mrad and 16.5 mrad crossing angle.

was tracked through the FFS. At each of the upstream dipoles and at the entrance, center, and exit of each FD quadrupole, photons emitted due to synchrotron radiation were assumed to have an emission angle of $\phi \approx 1/\gamma = m_e/E \approx \pm 0.15 \mu\text{rad}$ relative to the trajectory of the particles, where E is the particle energy. Figure 12 shows the emitted photon flux from the FD and from the upstream

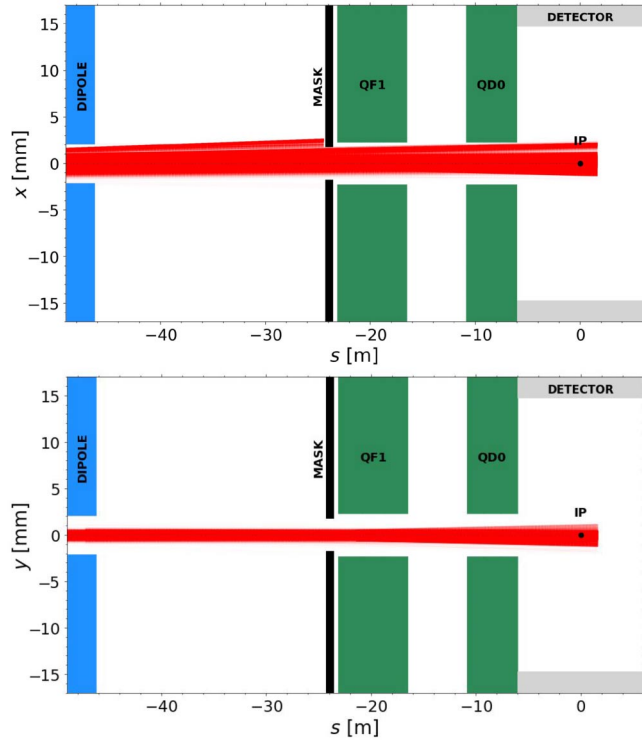


FIG. 12. Trajectories of photons (red) emitted in the FD and the upstream dipoles. The aperture of QF1 has been reduced to match QD0.

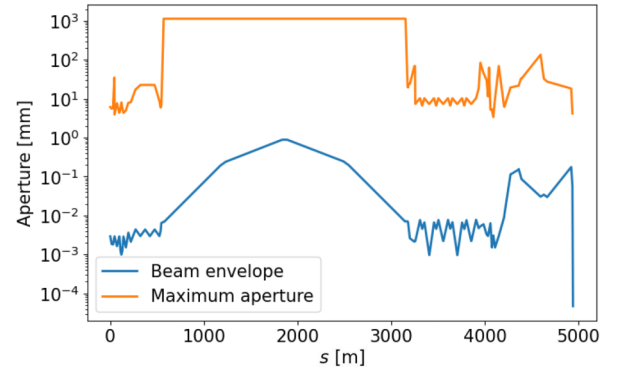


FIG. 13. The maximum feasible aperture imposed by the $B_{\text{quad}} = 1.5 \text{ T}$ limit (orange) compared with the beam envelope (blue), taken as the maximum between the horizontal and vertical beam sizes when collimated to $15\sigma_x$ and $55\sigma_y$, along the beam delivery system.

dipoles. Using an arbitrary photon mask, the FD is shielded from upstream dipole photons to prevent secondary emission, while the detector is naturally shielded due to its large aperture relative to the FD quadrupoles. A photon mask aperture of 3.5 mm proves to be sufficient in protecting the FD without further collimating the beam, which has $15\sigma_x$ and $55\sigma_y$ of 2.4 mm and 0.9 mm, respectively, at the mask location. More detailed descriptions of the geometry and materials of the photon masks are beyond the scope of this work.

The maximum feasible quadrupole aperture is given by Eq. (11), where the pole-tip field, B_{quad} , must not exceed the 1.5 T iron saturation limit:

$$B_{\text{quad}}[\text{T}] = 3.33 \times k_1[\text{m}^{-2}] \times p[\text{GeV}/c] \times Ap[\text{m}]. \quad (11)$$

Figure 13 compares the maximum feasible aperture with the beam envelope, taken as the maximum between the horizontal and vertical size of the beam when collimated to $15\sigma_x$ and $55\sigma_y$, along the BDS, confirming that all magnet strengths and apertures satisfy the 1.5 T constraint. A summary of the final 7 TeV BDS parameters is provided in Table I, and the lattice is available on the CLIC lattice repository [34].

V. IMPLEMENTATION CHALLENGES AT 7 TeV

To be considered a viable upgrade option, the 7 TeV BDS must fit within a 4.5 m diameter tunnel [35] and remain aligned with the preceding energy stage, the main linac, and the IP. Consequently, the IP crossing angle and the bending angles in the 7 TeV design must be adjusted to ensure compatibility with the 3 TeV layout [36]. Specifically, the crossing angle of the 7 TeV design must be reduced from 20 mrad to 19.74 mrad, and the collimation bending angles should be increased by a factor of 2.6, resulting in a 24% reduction in luminosity. Figure 14

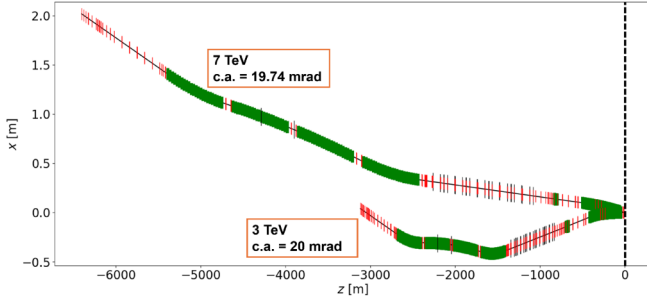


FIG. 14. CLIC 3 TeV BDS and CLIC 7 TeV BDS layouts after alignment with the main linac and the IP.

shows a possible layout configuration in which the systems are properly aligned. This introduces additional challenges at 7 TeV, as it suggests that lower-energy layouts, which are less sensitive to radiation effects, may instead need to be modified to retain compatibility, possibly leading to reduced luminosity at the baseline energies.

Operation of high-energy accelerators that target beam sizes on the tens-of-nanometer scale has proven challenging [37]. To date, these machines have not reached their design beam intensities and often require relaxing the optics design, thereby increasing the horizontal or vertical beam size at the IP. The alignment and magnetic-field quality tolerances of the CLIC FFS have been extensively studied at 380 GeV and 3 TeV [38–40]. Equivalent studies will be necessary for the proposed 7 TeV design, as additional challenges may arise at higher energy.

Additionally, the Earth’s background magnetic field has a significant impact on beam dynamics at 7 TeV [41–43]. To evaluate its effect on the 7 TeV FFS design, all drift spaces were replaced by equivalent dipoles with magnetic fields of 42 μ T, while maintaining the FFS dipole field strengths of 2.2 mT, resulting in a reduction in luminosity of 33%. Mitigation measures such as insulation materials or compensating coils, as discussed in Ref. [43], are therefore essential to reach design performance.

VI. CONCLUSIONS

A new 7 TeV beam delivery system for CLIC has been developed based on the 3 TeV design. Tracking simulations yield a total luminosity of $\mathcal{L}_{\text{tot}} = 12.8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with $\mathcal{L}_{1\%} \approx 0.27 \mathcal{L}_{\text{tot}}$, including solenoid effects for a 16.5 mrad crossing angle. Key properties like the distance between the final doublet and the detector, $L^* = 6 \text{ m}$, and the length of the final focusing system of 768 m are maintained. This represents a 27% improvement over previous designs and exceeds the extrapolated luminosity target.

Synchrotron-radiation-induced beam-size growth is mitigated by reducing the dipole bending angles by 40% and by lengthening the horizontally focusing FD quadrupole to limit the Oide effect. A new optimization

strategy for maximizing luminosity has been implemented, which weights the contribution of nonlinear aberrations based on an analysis of the correlations between luminosity and beam size. The length of the collimation section is approximately doubled to preserve cleaning efficiency while maintaining comparable wakefield effects, resulting in a total BDS length of 6.4 km.

Collimation-depth studies confirm that collimating the beam at $15\sigma_x$ and $55\sigma_y$ is sufficient to protect the final doublet from synchrotron-radiation photons. The design introduces additional challenges, including compatibility with preceding lower-energy configurations and increased sensitivity to the Earth’s magnetic field. The survivability of the energy spoiler is challenged by the reduced dispersion function in the energy-collimation section and may require a redesign based on advanced concepts such as rotatory collimators.

The newly designed beam delivery system enables the extension of the energy reach of CLIC to 7 TeV and may serve as a baseline for future high-energy e^+e^- colliders such as the proposed 10 TeV plasma-wakefield collider [8].

DATA AVAILABILITY

The lattice that supports the findings of this article is openly available on the repository listed in Ref. [34].

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