FINAL FOCUS SYSTEMS AT 550 AND 1500 GEV

L. Kennedy*[,1,2], C. Caliari[2], R. Tomás[2], P. N. Burrows[1]
[1]John Adams Institute, University of Oxford, Oxford, United Kingdom
[2]European Organization for Nuclear Research (CERN), Meyrin, Switzerland

Abstract

The Final Focus System (FFS) results for CLIC at 1.5 TeV have thus far been estimated using a 3 TeV system operated at reduced energy. Here, we present a dedicated design for the 1.5 TeV stage, where we exploit reduced radiation effects to allow stronger dispersion and weaker chromaticity-correcting sextupoles, thereby mitigating beam transport nonlinearities. The resulting design is 220 m shorter and offers a 50% luminosity gain. The performance of both normal-conducting and superconducting beams at 550 GeV are evaluated using the CLIC FFS, addressing the goals defined by the CLIC and Linear Collider Facility at CERN inputs to the European Strategy for Particle Physics Update.

CLIC 1.5 TeV FINAL FOCUS

The 1.5 TeV Final Focus System (FFS) baseline reported in the CLIC Readiness Report (CRR) [1] offers an estimated total luminosity of 3.7×10^{34} cm$^{-2}s^{-1}$, based on the transport of a 1.5 TeV beam in a lattice designed for 3 TeV [2,3]. At 3 TeV, synchrotron radiation induced beam size growth is more significant and must be mitigated by reducing the average dispersion in the system. The resulting reduction in dispersion requires stronger sextupole magnets for chromaticity correction, thereby introducing strong chromatic aberrations and luminosity loss. At 1.5 TeV, we can afford to adopt a more compact FFS featuring shorter and stronger bending dipoles, allowing increased dispersion and weaker sextupoles to reduce chromatic and geometric aberrations. Figure 1 demonstrates the reduction in sextupole strengths k_2 with the increase in average horizontal dispersion η_x and the subsequent improvement in total luminosity $\mathscr{L}_{Tot}$. The resulting lattice features 78% increased dispersion and provides a 220 m shorter FFS relative to the CRR design.

Using MADX [4], the linear optics in the FFS were matched and scanned to find the horizontal and vertical IP beta functions, β_x^* and β_y^*, which best minimise the beam size. The beam is then tracked using PLACET [5,6] and the luminosity is computed using GUINEA-PIG [7]. Figure 2 shows the total and peak luminosity vs β_y^* and the corresponding higher-order beam sizes computed semi-analytically in MAPCLASS [8,9].

Including radiation effects generated by the dipoles, quadrupoles and higher-order multipoles, a total luminosity of 5.5×10^{34} cm$^{-2}s^{-1}$ is found when $\beta_x^*/\beta_y^* = 5/0.07$ mm. In this configuration, 10% of the luminosity is lost to synchrotron radiation while 33% of the luminosity resides in the 1% peak of the beam energy distribution. Reducing β_x^* from 6 mm (as in the CRR) to 5 mm improves the total luminosity

* lewis.kennedy@cern.ch

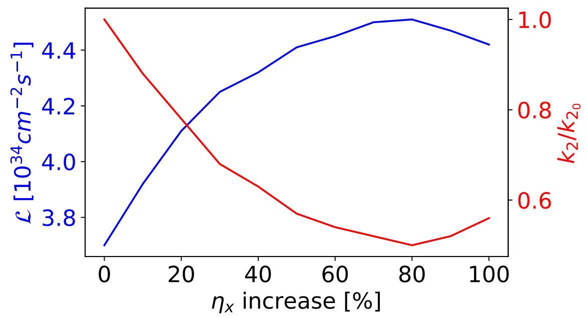

Figure 1: Blue: total luminosity of the 1.5 TeV final focus as a function of average dispersion, η_x. Red: the reduction in sextupole strengths, k_2, as bending angles are increased.

by approximately 10%, while the absolute peak luminosity remains constant. However, the ratio of the total and peak luminosities, $\mathscr{L}_{1\%}/\mathscr{L}_{Tot}$ is reduced by approximately 3% due to enhanced disruption at lower β_x^*, leading to increased background. At $\beta_y^* < 0.07$ mm, we see a decrease in luminosity dominated by an increase in aberrations, along with a more pronounced hourglass effect as we approach $\beta_y^*/\sigma_z < 1$ [10]. Figure 3 shows the resulting linear optics with final drift length $L^* = 6$ m [11].

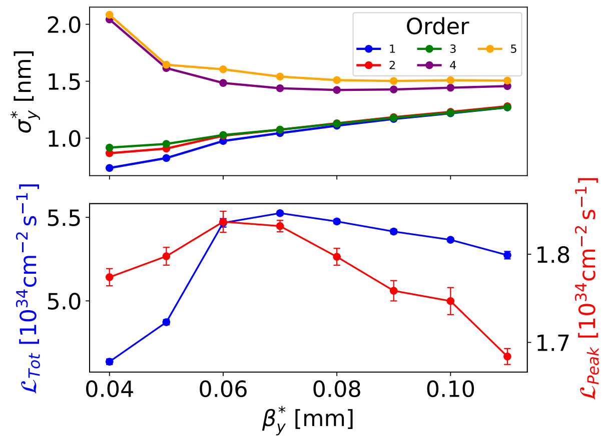

Figure 2: Bottom: total luminosity vs the vertical IP beta function, β_y^*, computed in GUINEA-PIG for a CLIC-type beam at 1.5 TeV. Top: higher-order analytic beam sizes computed using MAPCLASS as a function of β_y^*.

In addition to scaling sextupole strengths with the inverse of the dipole bending angles, MAPCLASS was used to optimise the sextupole, octupole and decapole strengths, targeting further reduction of the higher-order aberrations. In a recent study at 7 TeV [12], we demonstrated that the Gaussian core of the beam is strongly correlated with the lumi-

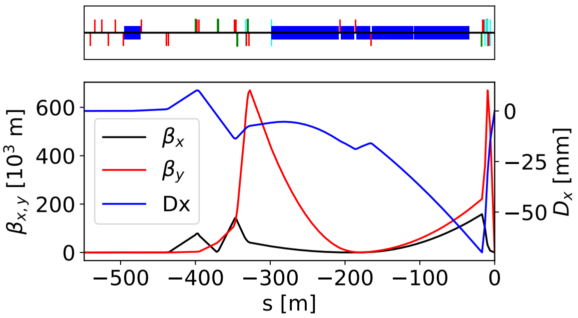

Figure 3: Top: lattice survey of the 1.5 TeV CLIC final focus system showing dipoles (blue), quadrupoles (red), sextupoles (green) and octupoles (cyan). Bottom: linear optics functions β_x, β_y, and horizontal dispersion D_x (blue). The interaction point is located at S = 0 m.

nosity performance, and is primarily driven by the second- and third-order aberrations. An increased weighting was therefore applied to the second- and third-order beam sizes when minimising the beam size in MAPCLASS. Figure 4 compares the aberrations present in the baseline CRR design with the optimised design, showing improved suppression of the vertical beam size in the weighted optimisation case.

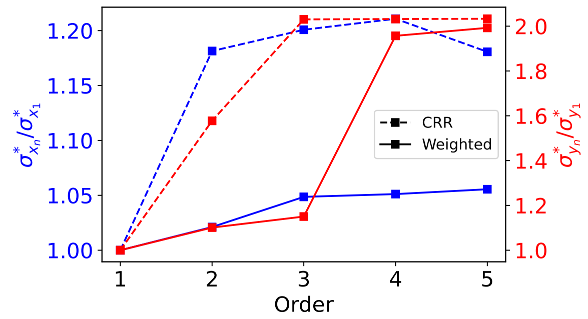

Figure 4: Comparison of the aberrations to the fifth-order, normalised to the first-order beam size, for the CRR design and the optimised design focusing on mitigation of second- and third-order aberrations.

The optical functions for the off-momentum particles were evaluated by scanning the relative momentum deviation, $\delta = dp/p$. Figure 5 shows that the variation in optics is negligible across the considered range between -0.3% to 0.3%, indicating a weak chromatic dependence of the lattice. The new 1.5 TeV design offers a 30% shorter FFS with a total luminosity of 5.5×10^{34} $cm^{-2}s^{-1}$, with 1.8×10^{34} $cm^{-2}s^{-1}$ in the 1% energy peak, offering a 48% performance upgrade over the CRR design proposal. The horizontal and vertical beam sizes, σ_x and σ_y, were calculated to be 55 nm and 1.3 nm, respectively, by taking the RMS of the tracked particle distribution. A summary of the design parameters is given in Table 1.

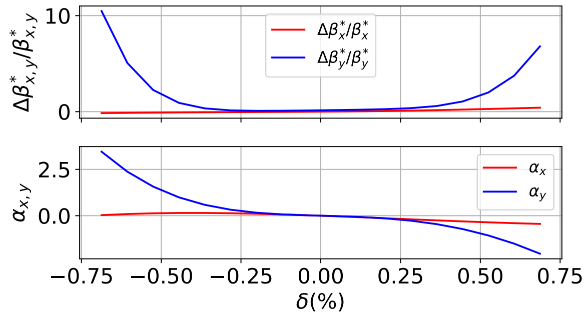

Figure 5: Change in linear optics functions evaluated for off-momentum particles, dp/p, in the range ±0.75% at 1.5 TeV.

Table 1: Parameters for the 1.5 TeV Stage, Comparing Values from the CLIC Readiness Report with the Optimised Design

Parameter	**CRR**	**Current**
Energy [TeV]	1.5	1.5
Repetition frequency [Hz]	50	50
Bunches per train	312	312
Energy spread [%]	0.3	0.3
Final drift length [m]	6	6
FFS length [m]	770	550
Norm. emittance [nm]	660 / 20	660 / 20
β^*_x/β^*_y [mm]	8 / 0.11	5 / 0.07
RMS beam size (IP) [nm]	60 / 1.5	55 / 2.0
Bunch length [μm]	44	44
Crossing angle [mrad]	21.2	21.2
Total luminosity [10^{34} $cm^{-2}s^{-1}$]	3.7	5.5
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.4	1.8

550 GeV FINAL FOCUS

The proposed CLIC facility features a main linac based on normal-conducting accelerating structures with the novel CLIC technology [1]. However, recent developments within the linear collider community highlighted the possibility of an alternative configuration in which the accelerator would use superconducting RF cavities, as in the ILC [13], combined with the CLIC BDS to form a new Linear Collider Facility at CERN (LCF) [14, 15]. At 550 GeV, the same optimisation strategy as at 1.5 TeV is applied.

Figure 6 shows the luminosity vs the vertical beta function for the CLIC case with parameters given in Table 2. The total and peak luminosities were 8.4×10^{34} $cm^{-2}s^{-1}$ and 3.5×10^{34} $cm^{-2}s^{-1}$, respectively, when β^*_x/β^*_y = 7/0.07 mm, exceeding the performance targets set out in the CRR. The RMS beam sizes σ_x and σ_y are 117 nm and 2.9 nm respectively, with aberrations computed in MAPCLASS up to the fifth-order shown in Fig. 7.

Figure 8 shows the proposed layouts of the 1.5 TeV and 550 GeV designs with crossing angles of 21.2 mrad and 21.0 mrad, respectively. The layouts align with both the main linac and the preceding 380 GeV stage, demonstrating a feasible upgrade path to the TeV scale.

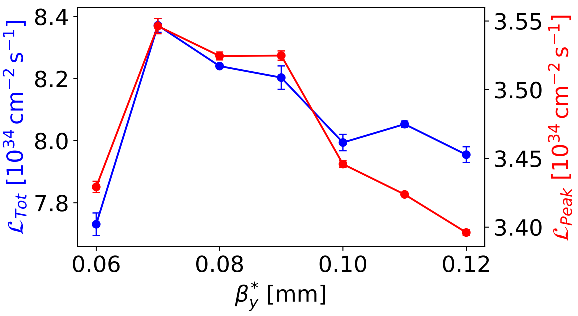

Figure 6: Luminosity vs the IP beta function β_y, computed with GUINEA-PIG for a CLIC-type beam.

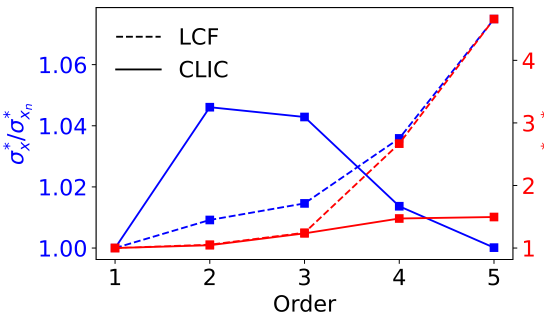

Figure 7: Aberrations up to the fifth-order, normalised to the first-order beam size, computed in MAPCLASS for the LCF and CLIC FFS designs.

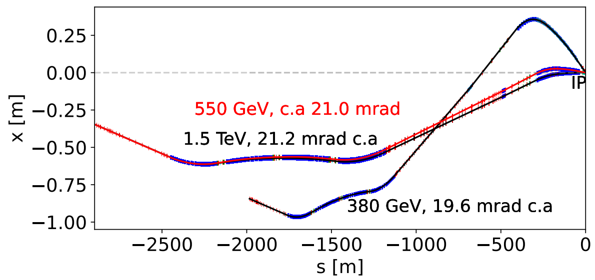

Figure 8: Layout of the 1.5 TeV, 550 GeV and 380 GeV lines aligned to the main linac and the interaction point, with crossing angles 21.2 mrad and 21.0 mrad respectively.

For the LCF case, where $\beta_x^*/\beta_y^* = 13/0.41$ mm, total and peak luminosities of $4.1{\times}10^{34}\,\text{cm}^{-2}s^{-1}$ and $2.6{\times}10^{34}\,\text{cm}^{-2}s^{-1}$ were found, respectively, with RMS IP beam sizes $\sigma_x/\sigma_y = 1045/58$ nm. For the LCF beam, the ratio of the normalised transverse emittances ϵ_x/ϵ_y is notably larger, leading to a reduction in beamstrahlung effects at the IP [16], thereby improving the fraction of the luminosity in the 1% energy peak. However, due to the large horizontal emittance and stronger aberrations of the compact CLIC FFS, as shown in Figure 7, the total and peak luminosities fall short of the LCF targets. A reduction in the horizontal emittance of more than 50% would be required to meet the luminosity targets using the current CLIC FFS. A comparison of the designs with the respective performance estimates reported in both the CLIC Readiness Report (CRR) and the Linear Collider Facility at CERN report is made in Table 2 [17].

Table 2: Parameters for the 550 GeV Designs, where † Denotes the Design Estimates, * the Current optimisation Status, and ^{a} the Luminosity Obtained with GUINEA-PIG

Parameter	**CLIC†**	**CLIC***	**LCF†**	**LCF***
Energy [GeV]	550	550	550	550
Repetition frequency [Hz]	100	100	10	10
Bunches per train	352	352	2625	2625
Energy spread [%]	0.3	0.3	0.15/0.19	0.15
Final drift length [m]	6	6	6	6
FFS length [m]	–	550	-	550
Norm. emittance [nm]	930 / 15	930 / 15	10000 / 35	10000 / 35
β_x^*/β_y^* [mm]	–	7 / 0.07	13 / 0.41	13 / 0.41
RMS beam size (IP) [nm]	124 / 1.7	117 / 2.9	452/5.6	1045/58
Bunch length [μm]	70	70	300	300
Total luminosity [10^{34} cm^{-2}s^{-1}]	~6.5	8.4	7.7	4.1
Peak luminosity [10^{34} cm^{-2}s^{-1}]	~3.2	3.5	4.5	2.6

CONCLUSION

Dedicated final focus systems have been developed for the 550 GeV and 1.5 TeV stages of CLIC, adopting a more compact layout with increased dispersion, weaker sextupoles, and reduced aberrations. The 1.5 TeV design delivers total and peak luminosities of 5.5×10^{34} cm^{-2}s^{-1} and 1.8×10^{34} cm^{-2}s^{-1}, respectively. The new design provides a 50% luminosity upgrade and a 220 m length reduction relative to the CLIC Readiness Report baseline values. With a 550 GeV CLIC beam, the design delivers total and peak luminosities of 8.4×10^{34} cm^{-2}s^{-1} and 3.5×10^{34} cm^{-2}s^{-1}, exceeding the design targets in the CLIC Readiness Report. For the 550 GeV LCF configuration, the luminosity falls short of the design target by approximately 50% due to the large horizontal emittance and aberrations of the compact CLIC FFS with $L^* = 6$ m. Further improvements could be made by further optimising the optics and lowering the horizontal emittance, such as in the 250 GeV LCF design, to reduce the impact of aberrations. Additionally, both the collimation system and the final doublet configurations should be evaluated and optimised, with particular emphasis placed on mitigating the impact of the large radiation cone of the LCF beam at 550 GeV.

REFERENCES

[1] E. Adli *et al.*, “Clic readiness report”, *The European Physical Journal Special Topics*, vol. 234, no. 22, pp. 6473–6652, Feb. 2026. doi:10.1140/epjs/s11734-025-02016-w

[2] P. Raimondi and A. Seryi, “Novel final focus design for future linear colliders”, *Phys. Rev. Lett.*, vol. 86, no. 17, pp. 3779–3782, Apr. 2001. doi:10.1103/PhysRevLett.86.3779

[3] F. Plassard, “Optics optimization of longer l* beam delivery system designs for clic and tuning of the atf2 final focus system at ultra-low β^* using octupoles”, Ph.D. thesis, Univ. Paris-Saclay, 2018. https://cds.cern.ch/record/2646086

[4] H. Grote and F. Schmidt, "MAD-X: An Upgrade from MAD8", CERN, Geneva, Switzerland, Rep. CERN-AB-2003-024-ABP, 2003.

[5] D. Pellegrini, A. Latina, and D. Schulte, "PLACET2: A Novel Code for Beam Dynamics in Recirculating Machines", in *Proc. 6th Int. Part. Accel. Conf. (IPAC'15)*, pp. 465–467, 2015. doi:10.18429/JACoW-IPAC2015-MOPJE068

[6] A. Latina, Y. Levinsen, D. Schulte, and J. Snuverink, "Evolution of the Tracking Code PLACET", CERN, Geneva, Switzerland, Rep. CERN-ACC-2013-0083, 2013.

[7] D. Schulte, "Study of Electromagnetic and Hadronic Background in the Interaction Region of the TESLA Collider", Ph.D. thesis, Hamburg Univ., 1997.

[8] R. Tomás, "MAPCLASS: a code to optimize high order aberrations", CERN, Geneva, Switzerland, Rep. AB-Note-2006-017, CERN-AB-Note-2006-017, 2006.

[9] R. Tomás, "Nonlinear optimization of beam lines", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 9, no. 8, p. 081001, Aug. 2006. doi:10.1103/PhysRevSTAB.9.081001

[10] K. Yokoya and P. Chen, "Beam-beam phenomena in linear colliders", *Lect. Notes Phys.*, vol. 400, pp. 415–445, 1992. doi:10.1007/3-540-55250-2_37

[11] F. Plassard, A. Latina, E. Marin, R. Tomás, and P. Bambade, "Quadrupole-free detector optics design for the compact linear collider final focus system at 3 tev", *Phys. Rev. Accel. Beams*, vol. 21, no. 1, p. 011002, Jan. 2018. doi:10.1103/PhysRevAccelBeams.21.011002

[12] L. Kennedy, C. Caliari, V. Cilento, R. Tomás García, and P. Burrows, "Design and performance evaluation of the CLIC beam delivery system at 7 TeV".

[13] C. Adolphsen *et al.*, "The International Linear Collider Technical Design Report - Volume 3.I: Accelerator R&D in the Technical Design Phase", 2013, arXiv: 1306.6353 [physics.acc-ph],

[14] H. Abramowicz *et al.*, "A linear collider vision for the future of particle physics", *EPJ Spec. Top.*, Mar. 2026. doi:10.1140/epjs/s11734-026-02153-w

[15] R. Tomás García and A. Faus-Golfe, "Beam delivery system for a linear collider at cern", presented at the Linear Collider Workshop, CERN, Geneva, Switzerland, Jan. 2026, 2026, https://indico.cern.ch/event/1602105/contributions/6836128/,

[16] *Handbook of Accelerator Physics and Engineering*, A. W. Chao, K. H. Mess, M. Tigner, and F. Zimmermann, Eds. Singapore: World Scientific, 2013. doi:10.1142/8543

[17] H. Abramowicz *et al.*, "The Linear Collider Facility (LCF) at CERN", 2025, arXiv: 2503.24049 [hep-ex],