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DESIGN OF CLIC BEAM DELIVERY SYSTEM AT 7 TeV

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Abstract

The Compact Linear Collider (CLIC) is a proposed linear accelerator designed to collide electrons and positrons at energies up to 3 TeV. In order to explore new physics and to be more competitive with other collider projects, CLIC is exploring the increase of the center-of-mass energy to 7 TeV. The CLIC Beam Delivery System (BDS) transports the lepton beams from the exit of the Main Linac to the Interaction Point (IP). This paper reports on the studies and the challenges of the new BDS design, such as minimizing the extent of trajectory bending for collimation and chromaticity correction to reduce the effects from synchrotron radiation, ensuring a good transverse aberration control at the IP.

INTRODUCTION

Studies of CLIC with 7 TeV of c.m. energy have never been done so far. To estimate a target design luminosity we extrapolate from previous studies up to a c.m. energy of 3 TeV (Fig. 1). The resulting predicted luminosity for the 7 TeV design is about $10^{35}\text{cm}^{-2}\text{s}^{-1}$. The challenges of this

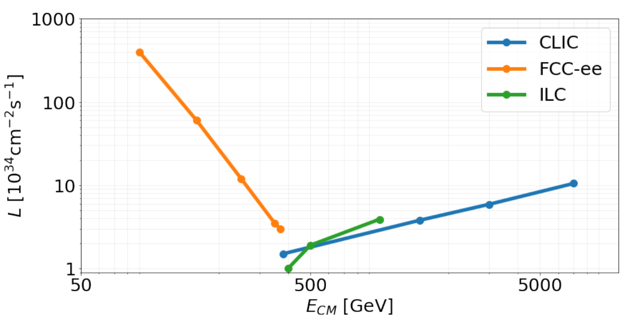

Figure 1: Total luminosity of proposed highest-energy electron-positron colliders as a function of c.m. energy [1].

new design are minimizing the extent of trajectory bending for collimation and chromaticity correction to reduce the effects from synchrotron radiation, ensuring a good transverse aberration control at the IP. The design of a 7 TeV BDS [2] involves the process of scaling up the 3 TeV lattice [3] to accommodate the higher energy level. The scaling factor used in this process is determined by the previous energy level of 3 TeV and the actual energy level of 7 TeV, and it is given by the rescaling factor $\alpha_s = (7/3)^{1/3}$ [4, 5]. This scaling factor is used as a starting point for adjusting the parameters of the BDS elements to make them suitable for use at the higher energy level of 7 TeV. However, to achieve the desired luminosity, discussed above, at this energy level, it may be necessary to increase the length of the line and further optimize the BDS elements beyond what can be achieved by just scaling the 3 TeV lattice with the scaling factor α_s.

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The main sources of synchrotron radiation are the bending magnets in the Collimation section and in the Final Focus System (FFS). The bending magnets in the first part of the Collimation system, called Energy Collimation, are needed to remove the beam halo due to the off-momentum particles. The bending magnets in the FFS are necessary to generate the dispersion for sextupoles to cancel the chromaticity. Synchrotron radiation causes an increase in the square of the beam size proportional to the fifth power of the product of beam energy and bending angle, assuming negligible energy loss [6, 7],

$$\sigma^2_{bend} = C_2 \int_0^{\Theta} \frac{E^5}{\rho^3} \left[\rho(1-\cos\theta)\right]^2 ds \propto E^5(\Theta^5 + O(\Theta^7)) , \quad (1)$$

where $C_2 = \frac{55}{24\sqrt{3}} \frac{r_e \hbar c}{(mc^2)^6} = 4.13 \times 10^{-11}\text{m}^2\text{GeV}^{-5}$ is a constant. For this reason, it is necessary to reduce the bending angle as much as possible to minimize this effect. In the Collimation section, the dispersion must guarantee the collimator (energy spoiler) to remove the particles with an energy shift greater than 1.3%. Reduction of the energy spoiler gap will lead to an increase in wakefield effects [8]. In the FFS, the dispersion must be sufficient to allow the sextupoles to cancel the chromaticity generated by the lattice quadrupoles. At the IP, the main source of the beam size growth is the chromaticity [9],

$$\sigma^{*2} = \epsilon\beta^*(1 + \xi^2\delta_p^2) , \quad (2)$$

where ϵ is the beam emittance, β^* is the beta-function at the IP, δ_p is the relative momentum spread of the beam and ξ is the chromaticity at the IP.

SYNCHROTRON RADIATION IN THE COLLIMATION SYSTEM

Scaling of the Bending Angles

To minimize the radiation generated in the Collimation system, the bending angles of the dipoles must be reduced as much as possible which will lead to a reduction in dispersion. A decrease in dispersion will lead to a reduction in the spoiler gap [10] and, as mentioned above, to a high wakefield effects especially the transverse wakefields can lead to a significant emittance dilution. The kick due to the wakefield effect is proportional to

$$< \Delta y' > \propto \frac{L_{spoiler}}{\gamma\sqrt{\sigma_z \sigma} Z_0 g^3}, \quad (3)$$

where $Z_0 = 377\ \Omega$ is the vacuum impedance, σ_z is the bunch length, γ is the relativistic factor, $L_{spoiler}$ is the length of the spoiler, σ is the conductivity of the spoiler and g is the

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half-gap of the spoiler. Using a spoiler made of the same material and with the same length as for the 3 TeV design, the only variables remaining are the beam energy and the gap:

$$<\Delta y'> \propto (E \cdot g^3)^{-1}. \tag{4}$$

The wakefield effect has been kept the same as the one at 3 TeV, to maintain the same effect on the beam. The half-gap at 3 TeV is equal to 3.51 mm, then, from Eq. (4) we obtain that at 7 TeV the half-gap will be 2.6 mm. With this value, the spoiler gap required to remove beam with energy spread higher than 1.3% is $g = \delta_p \cdot D_x = 2.6$ mm. Using this dispersion value at the spoiler ($D_x = 0.2$ m), it is possible to reduce the bending angles by 58%, compared to the previous 3 TeV design. Under this design, the horizontal beam size growth due to the SR is +27%, at the end of the Collimation system, $\sigma_x^{SR} = 3.65$ µm, compared to the one without SR, $\sigma_x = 2.87$ µm. The beam size with the contribution of the SR is computed using PLACET [11].

Scaling of the Collimation Length

To further reduce the bending angles, keeping the dispersion at the spoiler position of 0.2 m, it is necessary to increase the length of the line. Starting from the bending angles already reduced by 58%, the length has been increased by 50% in steps of 5%. Increasing the length of the Collimation section, just scaling the length of the elements, the beam size with SR will decrease, then the aberration not corrected will dominate and the beam size will increase. For this reason it is necessary to correct this effect for each step of the scaling, with the sextupoles and the octupoles in the Collimation section. As shown in Fig. 2, after the correction, the beam size with no radiation contribution remains constant and that which includes the effect of synchrotron radiation decreases as the length increases. This scaling will be used to increase the length of the BDS achieving the target luminosity.

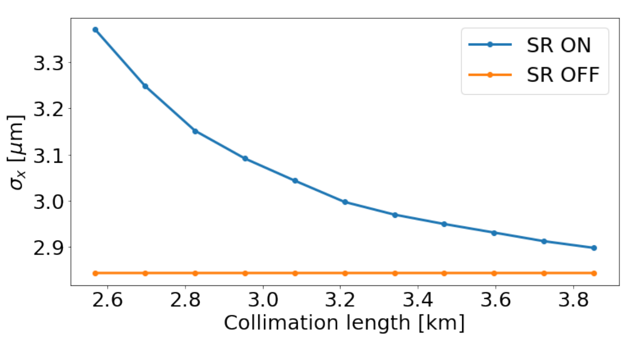

Figure 2: Horizontal beam size, at the end of the Collimation line, with SR (blue) and without SR (orange) for different lengths. Sextupoles and octupoles are optimized.

SYNCHROTRON RADIATION IN THE FINAL FOCUS SYSTEM

The reduction of the bending angles in the FFS leads to a lower dispersion at the sextupoles. On the other hand, the relevant sources of beam size growth are the chromaticity and the higher order aberrations. In Fig. 3, it is shown the beam size with and without the SR as a function of the bending factor in steps of 10%. The minimum value of σ_x on the plot is an approximation based on the step size used in the simulation. To obtain the actual minimum value of σ_x, the results were extrapolated from MADX by making incremental adjustments to the scale factor in steps of 1% until the smallest value of σ_x and the highest value for the luminosity ware achieved. Based on this extrapolation, the bending factor for which σ_x is minimized, and the luminosity is maximized, is estimated to be -64%.

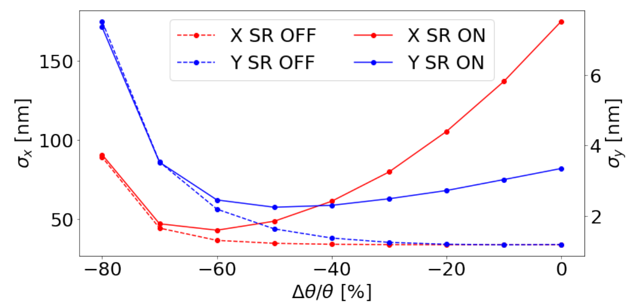

Figure 3: Horizontal and vertical beam size at the IP for step of 10% of scaling factors of the bending magnets with and without the effect of the synchrotron radiation.

The minimum value of σ_y (around -50% bending factor) was not taken into consideration, as the bending magnets only act in the horizontal plane and therefore it was necessary to focus on reducing the effects of SR in that plane.

OPTIMIZATION OF THE FINAL FOCUS SYSTEM

After reducing the synchrotron radiation effects in the beam line, the focus shifted to optimizing the FFS to reduce aberrations affecting the beam sizes at the interaction point (IP). Due to the scaling of the line from 3 TeV to 7 TeV, the value of L^* increased from the design value of 6 m to approximately 8 m. The first step in the optimization process was to bring L^* back to the design value of 6 m. Next, the positions and strengths of quadrupoles and sextupoles were adjusted to minimize the discrepancy of the phase advances between the sextupoles from the nominal value of π (Table 1). After scaling the FFS by 64% to reduce the SR effects, the β functions and dispersion have been rematched to achieve

Table 1: Phase Advance Discrepancy from the Nominal Value Between Sextupoles

	$\lvert 0.5-\Delta\mu_{SD0-SD4}\rvert$ [$10^{-6}2\pi$]		$\lvert 0.5-\Delta\mu_{SF1-SF5}\rvert$ [$10^{-6}2\pi$]	
	X	Y	X	Y
7 TeV	4.6	2.1	3.7	8.6
3 TeV	8.2	2.8	3.7	10

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the shape obtained before the elements were moved. This rematching process is shown in Fig. 4. Sextupoles were then used to cancel chromaticity, and octupoles and decapoles were added to reduce higher order aberrations. To evaluate the horizontal and vertical beam sizes without SR, the transfer map was computed using Mapclass [12–15]. The

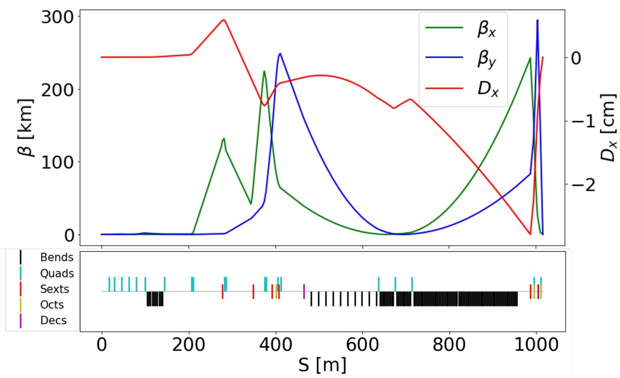

Figure 4: β_x, β_y and D_x along the FFS (top). Element position along the FFS (bottom).

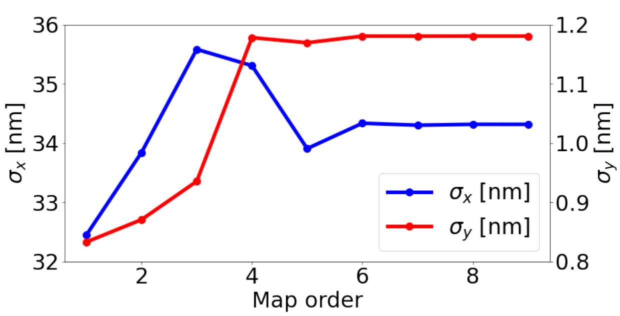

Figure 5: Horizontal and vertical beam size at the IP as a function of the map order.

Table 2: FFS Parameters at 7 TeV and at 3 TeV

Parameters	**7 TeV**	**3 TeV**
L_{FFS} [m]	1016	770
L^* [m]	6	6
β^*_x/β^*_y [mm]	11/0.24	7/0.12
$\epsilon^n_x/\epsilon^n_y$ [nm]	660/20	660/30
σ^*_x/σ^*_y [nm]	32.4/0.83	40/0.9
$\sigma^*_{x,SR}/\sigma^*_{y,SR}$ [nm]	39.4/1.8	50/1.5
$\delta_{p,rms}$ [%]	0.3	0.3

results are shown in Fig. 5, where the beam size is shown as a function of the order of the transfer map considered. Finally, the optimized FFS parameters at 7 TeV were determined and are shown in Table 2, along with the design parameters at 3 TeV for comparison.

FULL BDS

The full BDS is obtained assembling in order the Diagnostics section, Collimation and FFS. In Fig. 6, four possible lengths of the BDS have been proposed to achieve a target luminosity of approximately 10^{35} cm^{-2}s^{-1} at 7 TeV. It has been found that increasing the length of the BDS up to 6 km can achieve this target (see Table 3). The luminosity values presented in the figure have been calculated using Guinea-Pig [16].

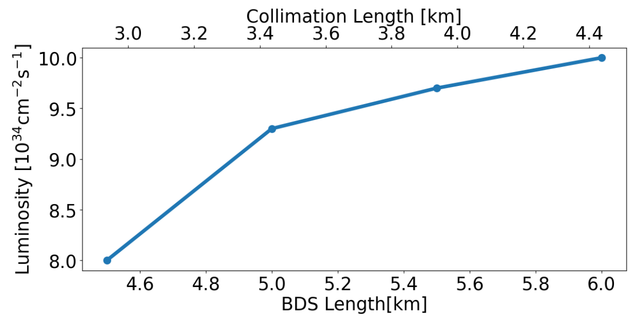

Figure 6: 7 TeV BDS luminosity for different BDS and Collimations lengths.

Table 3: 7 TeV BDS Luminosity for Different BDS and Collimations Lengths. FFS and Diagnostics Length are Kept Constant, L_{FFS} = 1016 m, $L_{Diagnostics}$ = 547 m

L_{BDS} [km]	4.5	5.0	5.5	6.0
$L_{Collimation}$ [m]	2937	3437	3937	4437
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	8.0	9.3	9.7	10.1
$\mathcal{L}_{1\%}$ [10^{34}cm^{-2}s^{-1}]	2.68	2.87	2.89	2.97

CONCLUSIONS

The new BDS at 7 TeV was developed by scaling up the previous design used for 3 TeV. To mitigate the effects of SR, the bending angles in Collimation and FFS were reduced by 86% and 64%, respectively, for a BDS of 6 km length. Further extending the Collimation section will not improve luminosity significantly. The FFS has been optimized by bringing L^* from 8 m to 6 m, rematching the Twiss parameters at the IP and optimizing higher-order aberrations using sextupoles, octupoles, and decapoles. Combining all systems together results in a luminosity of 10^{35}cm^{-2}s^{-1}. Further optimization of the systems can be achieved through additional studies. For the Collimation section, the length of the betatron collimation could be reduced as it has no bends. Regarding the FFS, it has been observed that increasing the length of the system can further reduce the SR effects. However, a preliminary study did not produce better results, indicating that further investigations are required to improve its performance. One approach under development is through the exploitation of the new MAD-NG code [17], which could offer additional tools and faster speed to optimize the FFS design.

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REFERENCES

[1] F. Zimmermann, Y. Aharonov, L. Bravina, and S. Kabana, "Accelerators in the 21st Century", *EPJ Web Conf.*, vol. 182, p. 02134, 2018. doi:10.1051/epjconf/201818202134

[2] M. Aicheler *et al.*, "A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report", CERN, Geneva, Switzerland, Rep. CERN-2012-007, 2012. doi:10.5170/CERN-2012-007

[3] F. Plassard, "Optics optimization of longer L^* BDS designs for CLIC and tuning of the ATF2 final focus system at ultra-low β^* using octupoles", Ph.D. thesis, U. Paris-Saclay, France, CERN-THESIS-2018-223, 2018. https://cds.cern.ch/record/2646086

[4] M. Roman *et al.*, "Interaction region design driven by energy deposition", *Phys. Rev. Accel. Beams*, vol. 20, 2017. doi:10.1103/PhysRevAccelBeams.20.081005

[5] P. Raimondi and A. Seryi, "Novel Final Focus Design for Future Linear Colliders", *Phys. Rev. Lett.*, vol. 86, 2001. doi:10.1103/PhysRevLett.86.3779

[6] O. Blanco, R. Tomás, and P. Bambade, "Oide Effect and Radiation in Bending Magnets", CERN, Geneva, Switzerland, CERN-OPEN-2014-051, CLIC-Note-1049, 2014. https://cds.cern.ch/record/1967497

[7] O. Blanco, R. Tomás, and P. Bambade, "Beam focusing limitation from synchrotron radiation in two dimensions", *Phys. Rev. Accel. Beams*, vol. 19, 2016. doi:10.1103/PhysRevAccelBeams.19.021002

[8] M. Seidel, D. Onoprienko, and P. Tenenbaum, "Measurement of Resistivity Dominated Collimator Wakefield Kicks at the SLC", in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper WEAGB002. https://cds.cern.ch/record/1344632

[9] A. W. Chao *et al.*, *Handbook of accelerator physics and engineering; 2nd ed.*, World Scientific, 2013. doi:10.1142/8543,

[10] J. Resta-Lopez *et al.*, "Status report of the baseline collimation system of CLIC. Part II. Status report of the baseline collimation system of the compact linear collider", 2011. doi:10.48550/arXiv.1104.2431

[11] PLACET, https://twiki.cern.ch/twiki/bin/view/ABPComputing/Placet

[12] *MAPCLASS*, https://twiki.cern.ch/twiki/bin/view/ABPComputing/MapClass

[13] R. Tomás, "Nonlinear optimization of beam lines", Phys. Rev. Spec. Top. Accel. Beams, vol. 9, 2006. doi:10.1103/PhysRevSTAB.9.081001

[14] R. Tomás, "MAPCLASS: a code to optimize high order aberrations", CERN, Geneva, Switzerland, AB-Note-2006-017, CERN-AB-Note-2006-017, 2006. https://cds.cern.ch/record/944769

[15] D. Martinez, A. Rosam, R. Tomás, and R. De Maria, "MAPCLASS2: a code to aid the optimisation of lattice design", CERN, Geneva, Switzerland, CERN-ATS-Note-2012-087, 2012. https://cds.cern.ch/record/1491228

[16] GUINEA-PIG, https://twiki.cern.ch/twiki/bin/view/ABPComputing/Guinea-Pig

[17] E. Manosperti, L. Deniau, J. M. Gray, R. Tomás, and A. Pastushenko, "MAD-NG for Final Focus Design", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL112, this conference.