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Collimation for CLIC

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The collimation system of the Compact Linear Collider (CLIC) must fulfil a number of conflicting requirements, namely it should (1) remove beam halo to reduce the detector background, (2) provide a minimum distance between collimators and collision point for muon suppression, (3) ensure collimator survival and machine protection against errand beam pulses, (4) not be excessively long, and (5) not amplify incoming trajectory fluctuations via the collimator wake fields. Two optical systems have been designed — the first linear, the second non-linear —, which promise to meet all these requirements for the design beam energy of 1.5 TeV. We describe the various design criteria, a preliminary performance assessment, and outstanding questions.

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Abstract. The collimation system of the Compact Linear Collider (CLIC) must fulfil a number of conflicting requirements, namely it should (1) remove beam halo to reduce the detector background, (2) provide a minimum distance between collimators and collision point for muon suppression, (3) ensure collimator survival and machine protection against errand beam pulses, (4) not be excessively long, and (5) not amplify incoming trajectory fluctuations via the collimator wake fields. Two optical systems have been designed — the first linear, the second non-linear —, which promise to meet all these requirements for the design beam energy of 1.5 TeV. We describe the various design criteria, a preliminary performance assessment, and outstanding questions.

INTRODUCTION

CLIC is designed to deliver electron-positron collisions of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ luminosity at a centre-of-mass energy of 3 TeV. Its total length is about 35 km. The CLIC rf power source is based on two-beam acceleration comprising 22 drive beams for each of the two main linacs. The beam-delivery system (BDS) includes collimation and final focus, and it occupies a total length of about 5 km (counting both sides). The CLIC BDS can be scaled to 500 GeV by varying the strengths of sextupoles and bending magnets, while maintaining the same total length. Table 1 compiles key parameters for the 500-GeV and 3-TeV systems. The BDS accommodates a single-stage momentum collimation, followed by betatron collimation and a 500-m long compact final focus with nonzero dispersion in the final low-beta quadrupoles. A comprehensive review of the CLIC BDS can be found in Ref. [1]. The five conflicting design requirements for the collimation system were listed in the abstract.

COLLIMATION DEPTH AND FAILURES

The transverse collimation depth for CLIC is set by synchrotron radiation and beam loss in the final quadrupoles on the incoming side of the IP. The rms IP divergence for a single beam is less than $10 \mu\text{rad}$. After the collision the outgoing spent beam and the generated electron-positron

TABLE 1. Parameters of final focus (FF), collimation system (CS), and the beam for 3 TeV and 500 GeV cm energy. Emittance numbers refer to the entrance of the BDS. The spot sizes at the interaction point (IP) are rms values obtained by particle tracking and are up to 3 times larger than the ‘effective’ beam sizes which determine the luminosity

parameter	symbol	3 TeV	500 GeV
FF, CS length [km]		0.5, 2.0	0.5, 2.0
tot. BDS length [km]		2.5	2.5
emittances [μm]	$\gamma\epsilon_{x,y}$	0.68, 0.01	2.0, 0.01
beta functions [mm]	$\beta_{x,y}^*$	6.0, 0.07	3.0, 0.05
rms spot sizes [nm]	$\sigma_{x,y}^*$	67, 2.1	180, 4.2
bunch length [μm]	σ_z^*	35	35
crossing angle [mrad]	θ_c	20	20
repetition rate [Hz]	f_{rep}	100	200
no. bunches/train	n_b	154	154
particles per bunch	N_b	4×10^9	4×10^9
lum. w/o pinch [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	L_0	4.0	1.9

pairs extend up to 10 mrad [2], *i.e.*, to 1000 times larger angles. Therefore, the much narrower cone of photons emitted by the incoming beam is of no concern for the exit line. Computing synchrotron-radiation fans at 3 TeV shows that the available beam stay-clear, limited by the aperture of the final permanent-magnet quadrupoles, is about $14\sigma_x$ and $83\sigma_y$ in the two transverse planes [1]. Since the dispersive component of the horizontal beam divergence is about equal to the betatron component, the

actual limiting envelope for horizontal betatron oscillations is about $\sqrt{2}$ smaller, or $10\sigma_x$.

If the beam impacts on a collimator, the latter can be destroyed either by melting or by surface fracture. Already at the SLC, the beam damaged the gold-plated Ti-alloy collimators located at the end of the SLAC linac [3]. The particle flux of the CLIC beam is about 10^5 times more intense. All proposed linear colliders envision a sequence of thin spoilers (0.5–1.0 radiation length), which are followed in some distance by thick absorbers (10 r.l.). The purpose of the spoilers is to increase the beam angular spread due to multiple scattering, in case of beam impact due to a failure. This increases the beam size at the absorbers and reduces the risk of melting. The spoiler-absorber scheme has been employed in the SLAC linac since many years [4]. The acceptable spot size at the spoilers is limited by surface fracture due to beam impact. This limit can roughly be estimated from the local temperature rise $\Delta T = (1/C_p)(\Delta E/\Delta m)$, where C_p denotes the heat capacity and $\Delta E/\Delta m$ the ionization-energy deposition per unit mass, which is $(\Delta E/\Delta m) = (dE/dx)/(2\pi\sigma_x\sigma_y\rho)$. Comparing the ensuing tension $\sigma = E\alpha\Delta T$ (where E denotes the Young's modulus and α the thermal expansion coefficient) with the ultimate tensile strength σ_{UTS} yields the minimum spot size required to avoid surface fracture: $\sigma_x\sigma_y > (1/2\pi\rho)(dE/dx)N_b n_b E\alpha/(C_p\sigma_{UTS})$. The stability limit obtained from a more precise calculation [5] is displayed in Fig. 1. For carbon, the computation was done twice, with and without the additional heating due to beam image currents (i.c.). The plotting symbols superposed on the stability curves indicate the nominal design beam sizes at the spoilers for the momentum collimation, for the betatron collimation, and for a 2nd collimation stage in the final focus proper, respectively. The momentum spoiler will survive, if it is made from carbon, and possibly in the case of beryllium. The dedicated betatron collimators will always be destroyed, in case they are directly hit by the nominal beam. Most of the final-focus collimators survive, if made from carbon. Copper and titanium cannot withstand the beam impact anywhere.

TABLE 2. Collimator parameters

cm energy	3 TeV	500 GeV
δ spoiler gap	± 4 mm	± 4.8 mm
β_x spoiler gap	± 80 μ m (10 σ_x)	± 300 μ m (9 σ_x)
β_y spoiler gap	± 104 μ m (80 σ_y)	± 215 μ m (69 σ_y)
spoiler material	Be	Be
spoiler length	177 mm (0.5 r.l.)	177 mm (0.5 r.l.)
absorber mat.	Ti (Cu coated)	Ti (Cu coated)
absorber length	712 mm (10 r.l.)	712 mm (10 r.l.)
no. $\delta, \beta_{x,y}$ spoil.	1, 4, 4	1, 4, 4

FIGURE 1. Nominal beam sizes at the CLIC spoilers superposed on a damage threshold diagram according to [5]

Large betatron oscillations are not easily generated from pulse to pulse. In addition, such oscillations filament rapidly in the linac due to the beam energy spread (partly unavoidable and partly introduced for BNS damping), increasing the beam emittance by at least two orders of magnitude [6]. Momentum errors are expected to occur much more frequently. Our design philosophy has been to demand passive survival for momentum errors, but to allow for sacrificial betatron collimators (which saves length). The likelihood of beam impact on the betatron collimators must then be minimized. Momentum errors in the linac can be caused, *e.g.*, if one of the 22 drive beams is missing, or if the beam is injected at the wrong phase, or with the wrong charge. Simulations using PLACET and MAD show that every energy error likely generates significant tails, at the 1% level, in the beam distribution incident on the momentum collimator [7]. Most of the momentum errors studied result in a beam-size increase by not more than a factor 2 or 3 [7]. Therefore, only carbon and possibly beryllium can withstand the beam impact on the momentum collimators for these failures, confirming our earlier finding for the nominal beam. The momentum errors may be accompanied by significant horizontal betatron oscillations. Indeed, failures which cause momentum errors smaller than 4% can induce betatron amplitudes of 10–45 σ_x [7]. Therefore, in order to protect the horizontal betatron spoilers, the momentum collimation was tightened to $\pm 1.5\%$, so that all dangerous beam pulses are intercepted by the momentum spoiler. Table 2 summarizes the collimator parameters. The slightly marginal Be was chosen as spoiler material in view of its better wake-field properties (see below). At 3 TeV the rms beam size at the momentum absorber for a beam scattered by the spoiler is 1.1 mm.

HALO AND MUON BACKGROUND

Muons are generated at a rate of roughly 10^{-4} per lost electron. GEANT-3 and GEANT-4 simulations for CLIC [8] have shown that 1–10% of the muons produced by beam loss on the collimators reach a detector at the IP of 7.5 radius. If the halo amounts to 10^{-3} of the beam, about 25000 muons may pass through the detector per bunch train. Simulations performed by the CLIC physics study group suggest that even with this magnitude of background it is still possible, and in fact straightforward, to discern supersymmetric events emerging from the primary IP [9]. Details of the muon simulations are important. For example, increasing the size of the magnets from 20 cm to 50 cm reduces the number of muons by an order of magnitude. Also the full shower evolution needs to be considered [8].

The wave length required for beam-size measurements by a laser wire depends not only on the size to be measured, but also on the beam size in the orthogonal plane, as [10] $\lambda < \pi\sigma_y^2/(2\sigma_x)$. Inserting, for example, $\sigma_y \approx 2 \mu\text{m}$, $\sigma_x \approx 8 \mu\text{m}$, we obtain $\lambda < 800 \text{ nm}$, which is easily achieved. However, a severe concern is the magnitude of the laser-wire signal compared with the background from lost halo particles. Detailed simulations with the code BDSIM for an older version of the CLIC beam delivery show that at most locations downstream of the collimators, the background from beam loss is up to 7 orders of magnitude higher than the laser-wire signal [11]. This may imply the need for a dedicated diagnostics section upstream of the first collimator.

Simulations of the beam particle transport at large amplitudes are important for estimating the expected background levels. A comparison of tracking results for the nominal Gaussian beam by the four codes DIMAD, MAD, MERLIN and PLACET has revealed significant differences in the rms IP spot sizes, especially if a nonzero energy spread or synchrotron radiation are also included [12].

WAKE FIELDS

The collimators consist of a central flat part and they are tapered at a shallow angle on either side. The flat part at the centre gives rise to a resistive wall wake field, the two tapers to a combination of resistive-wall and geometric wakes. The beam centroid deflection by a tapered circular collimator is [13, 14]: $\Delta y' = (2N_b r_e / (\gamma \sigma_z)) \left[\frac{(4\lambda \sigma_z)^{1/4}}{g^{3/2}} + L_F \frac{(\lambda \sigma_z)^{1/2}}{2\sqrt{\pi} g^3} \right] y$, with $\lambda[\text{m}] = \rho[\Omega\text{m}] / (120\pi)$, and assuming the optimum taper angle at which the wake is minimum [14]: $\theta_{\text{opt}} \approx 1.1(\lambda \sigma_z / g^2)^{1/4}$. The above formula is applicable for $\sqrt{\sigma_z \lambda} \ll g \ll \sqrt{\sigma_z \lambda} \sigma_z / \lambda$ [14]. For example consid-

ering a resistivity of $\rho \approx 6 \times 10^{-8} \Omega\text{m}$ (beryllium), it is valid for half gaps g between 70 nm and 13 mm. Taking again Be and a gap $g = 100 \mu\text{m}$, the optimum taper angle is 30 mrad. However, for the CLIC rms bunch length of $35 \mu\text{m}$ the anomalous skin effect may become important [15]. This has not yet been accounted for.

FIGURE 2. Maximum vertical jitter enhancement due to collimator wake fields for 4 vertical spoilers and 4 absorbers made from a variety of materials

Assuming the wake field for circular collimators, and considering the combined effect of 4 spoilers and 4 absorbers, we can compute the vertical centroid jitter enhancement due to the wake field. For an incoming betatron oscillation of a certain amplitude, the maximum position offset at the IP (*i.e.*, maximum as a function of the oscillation phase) equals the initial amplitude multiplied by a jitter enhancement factor. This enhancement is computed after normalizing both the initial amplitude and the final IP position to the ideal (linear) rms beam sizes at either position. The jitter enhancement due to wakes in the CLIC collimation system is displayed in Fig. 2 as a function of bunch intensity, for a few absorber and spoiler materials. We observe that a carbon spoiler is ruled out by its enormous wake field. A beryllium spoiler promises an acceptable performance, and so do absorbers consisting either of Cu-coated Ti or pure Cu. So far we have treated circular collimators only. This may be a good approximation also for square collimators. A theory for rectangular collimators of half width h and half height g was developed by G. Stupakov in 1996 [16] and 2001 [17]. According to [17], for $\sqrt{\theta h^2 / (g \sigma_z)} < 3.1$, the deflection from the geometric wake field of two rectangular shallow tapers is $\Delta y'_G = (N_b r_p / \gamma) \sqrt{\pi} \theta h / (2 \sigma_z g^2) y$. This contains an additional factor h/b , which can be significant. For comparison, the deflection by two circular tapers of radius g is $\Delta y'_G = (N_b r_p / \gamma) 2\theta / (\sqrt{\pi} \sigma_z g) y$, which is $4/\pi \approx 1.27$ times larger than that for a square aperture with half gaps $h = g$. At SLAC, wake fields of four different prototype collimators were measured [18], but,

unfortunately, none of these has probed the regime which is relevant for CLIC.

ALTERNATIVE NONLINEAR SYSTEM

As an alternative to the conventional linear collimation system described above, we have designed a nonlinear system, which employs three skew sextupoles. The main skew sextupole is placed at a position with large dispersion and blows up the vertical beam size at a single spoiler downstream, profiting from the large beam energy spread. This ensures a large beam size at the spoiler and, thus, its survival in case of a failure. Also the collimator gaps are much increased, and the strength of the wake fields is reduced. The vertical beam size at the spoiler is controlled by the dispersion and by the strength of the skew sextupole. The value of the dispersion is limited by the desired maximum length of the system and by emittance growth from synchrotron radiation. A second skew sextupole separated by an optical $-I$ transform from the first and located behind the spoiler cancels the nonlinear aberrations induced by its upstream counterpart. This pair of skew sextupoles is positioned so as to remove large-amplitude particles in the final-doublet (FD) phase. To take care of the orthogonal IP phase, where we may collimate at much larger amplitudes, we place a weak (pre-)skew sextupole upstream of the entire system, at an appropriate betatron phase. This pre-sextupole will nonlinearly deflect IP-phase particles, entering at large amplitudes, into the final-doublet phase, so that they will be deflected by the following much stronger FD-phase skew sextupole and impact on the same spoiler as the FD-phase particles. The horizontal and vertical rms beam sizes at the spoiler are $69\text{ }\mu\text{m}$ and $209\text{ }\mu\text{m}$, respectively, which should be compared with the corresponding much smaller values of $8\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m}$ for the conventional linear system. Likewise, the vertical spoiler half gap is 16.7 mm for the nonlinear system, instead of about $100\text{ }\mu\text{m}$ for the linear one. However, the collimation in the nonlinear system is not perfect. ‘Holes’ exist in the 6-dimensional phase space, where particles may escape collimation. More details on this system can be found in reference [19].

CONCLUSIONS AND THANKS

Two collimation systems for CLIC at 3 TeV were presented. Both have a reasonable length of about 2 km. Simulations so far indicate a promising performance. Only minor changes are required to lower the centre-of-energy from 3 TeV to 500 GeV. On the other hand, the collimation depths and collimator materials are heavily

constrained by various requirements. The nonlinear system is a promising alternative to the conventional system, with several potential advantages, but also a few drawbacks. A modified version of the nonlinear system could be applied in storage rings, which might be a possible solution for collimation at a future LHC upgrade.

A number of open questions remain: (1) Do the codes accurately describe the particle transport at large amplitudes? (2) Do we believe the predicted wake field for flat collimators? (3) How important is the anomalous skin effect for CLIC bunch lengths? (4) What is the best material for spoilers or collimators? (5) Do the absorbers survive the full beam impact? (6) Are ‘holes’ in phase space a showstopper for the nonlinear system? (7) Should we devote time and resources to study more exotic schemes, like crystals, plasmas, lasers, liquid metals, or wake-free collimators? Many of these questions could be addressed in a dedicated test facility.

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