NONLINEAR POST-LINAC ENERGY COLLIMATION SYSTEM FOR THE COMPACT LINEAR COLLIDER*

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Abstract

The post-linac energy collimation system of the Compact Linear Collider (CLIC) has been designed to provide protection of the Beam Delivery System (BDS) against off-energy and miss-steered beams. The conventional baseline design consists of a two stage spoiler-absorber scheme. The CLIC energy collimators are required to withstand the impact of a full bunch train. This condition makes the energy collimator design very challenging, since the collimators have to deal with a total beam power of 14 MW at nominal energy and intensity. The increase of the transverse spot size at the collimators using nonlinear magnets could be a potential solution to guarantee the survivability of the collimators. In this paper we present an alternative nonlinear optics for the CLIC energy collimation system. Possibilities for its optimisation are discussed in view of performance simulation results.

INTRODUCTION

The energy collimation system is dedicated to collimate beam particles with large energy deviation. In addition, it can fulfil a very important protection function intercepting miss-steered or errant beams with energy offset generated in the main linac. This protection function is crucial for multi-TeV colliders, such as the Compact Linear Collider (CLIC), where energy errors generated by failure modes in the main linac are expected to be much more frequent than large betatron oscillations with small emittance beams.

The conventional collimation schemes are based on mechanical collimation using spoilers (scrapers) and absorbers. It could include several stages. For CLIC the energy collimation system includes a single spoiler-absorber scheme located in a region with horizontal dispersion. The nominal CLIC beam parameters and a complete description of the CLIC baseline linear collimation system can be found in [1].

For CLIC the self-protection of the energy collimators is desirable, i.e. the energy collimators (spoiler and absorber) are required to withstand the impact of a full bunch train. In order to guarantee the collimator survival, the following issues are currently being investigated: the study of novel materials with suitable electrical and thermo-mechanical properties, and the design of alternative optical layouts.

In this paper we present an alternative optics design including nonlinear magnets to increase the spot size at the collimator position. This optical layout has been adapted to the CLIC energy collimation requirements. Performance simulation results are presented and discussed.

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NONLINEAR PASSIVE PROTECTION

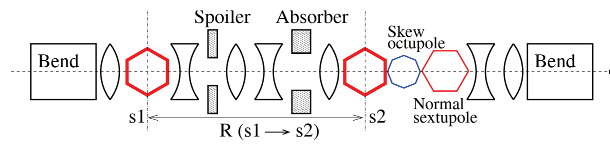

Figure 1: Schematic of a nonlinear collimation system using a pair of skew sextupoles ($s1$ and $s2$) of the same family, and adding a skew octupole and a normal sextupole for local correction of high order optical aberrations.

By nonlinear passive protection we mean the use of a nonlinear magnet (e.g. sextupole, octupole) to increase the beam spot size at downstream mechanical collimators. Somehow this nonlinear element would play the role of a primary spoiler. A second nonlinear magnet of the same family is located downstream of the collimators to cancel the optical aberrations introduced by the former nonlinear element. Figure 1 shows a basic scheme $s1$-$R(s1 \to s2)$-$s2$ of this nonlinear collimation concept based on two skew sextupoles $s1$ and $s2$, where R is the transfer matrix between them.

Optics Design

Using the transport formalism, in order to cancel geometric nonlinear terms between two skew sextupoles, the following optical constraints can be established:

$$R_{12} = 0,\ R_{34} = 0,\ |R_{11}| = |R_{33}|,\ |R_{22}| = |R_{44}|\ , \quad (1)$$

where R_{ij} $(i, j = 1, 2, 3, 4)$ are elements of the transverse first order transport matrix between the two sextupoles. In terms of beta functions and transverse phase advance, from condition (1) one obtains $\mu_x(s1 \to s2) = n_x\pi,\ \mu_y(s1 \to s2) = n_y\pi$, where n_x and n_y are integers, and $\beta_{x2}/\beta_{x1} = \beta_{y2}/\beta_{y1}$. Here $\beta_{x,y1}$ and $\beta_{x,y2}$ are the betatron functions at the sextupoles $s1$ and $s2$, respectively, and $\mu_{x,y}(s1 \to s2)$ the betatronic phase advance between the sextupoles.

The normalised integrated strength of the first skew sextupole, K_{s1}, is selected to get enough transverse beam spot size at the spoiler position for spoiler survivability in case of direct beam impact. For cancellation of geometric aberrations the second skew sextupole strength, K_{s2}, must satisfy [2]

$$K_{s2} = (-1)^{1+n_y} K_{s1} \left(\beta_{x1}/\beta_{x2}\right)^{3/2}\ . \quad (2)$$

For simplicity we use the $-I$ transfer matrix in both x and y planes between the sextupoles, which is a special case of the previous conditions. In this case, n_x and n_y are odd integers (for simplicity we select $n_x = n_y = 1$), and $\beta_{x1} = \beta_{x2}$, $\beta_{y1} = \beta_{y2}$, $\alpha_{x1} = \alpha_{x2}$, $\alpha_{y1} = \alpha_{y2}$, $\mu_{x,y}(s1 \rightarrow s2) = \pi$. From these conditions and Eq. (2) one obtains $K_{s1} = K_{s2}$. In addition, to cancel chromatic and chromo-geometric aberrations between the sextupole pair: $D_{x1} = -D_{x2}$, with D_{x1} and D_{x2} the first order horizontal dispersion at the first and second skew sextupole respectively.

Figure 2 shows an optics solution for the nonlinear energy collimation system. We use a mechanical spoiler and an absorber in between the two sextupoles. Two matching sections are included at the beginning and the end of the lattice.

The collimation depth has been set to intercept beams with energy deviation larger than 1.3% of the nominal energy. A horizontal spoiler and a horizontal absorber are used with half gap aperture ≈ 1 mm.

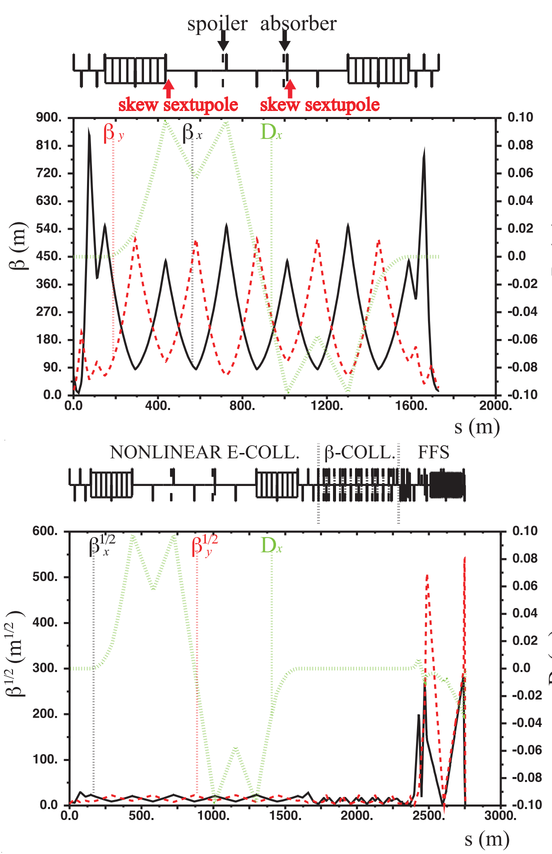

Figure 2: Top: layout and optical functions of a nonlinear energy collimation system for CLIC. Bottom: layout and optical functions of the CLIC BDS including the nonlinear energy collimation section.

Remnant higher order optical aberrations, mainly second and third order chromatic and chromo-geometric aberrations, are not effectively cancelled by the previous skew sextupole pair scheme ($s1$-$R(s1 \rightarrow s2)$-$s2$, $R(s1 \rightarrow s2) = -I$). This limits the luminosity performance. For the optimisation of the system, in order to cancel higher order aberrations we have added a skew octupole and a normal sextupole downstream of the second skew sextupole. Figure 1 shows the schematic of the optimised lattice configuration. The strengths of the two additional nonlinear magnets have been calculated using the optimisation code MAPCLASS [3], a simplex based algorithm to minimise the beam spot size in transfer lines.

In order to look for the optimal nonlinear magnet strengths we have to take into account the balance between the increase of the beam spot size for spoiler survival in case of beam impact, and an acceptable luminosity performance during normal beam operation. As condition, the luminosity loss $\Delta\mathcal{L}/\mathcal{L}_0 \lesssim 2\%$, with $\mathcal{L}_0 \simeq 6\times10^{34}$ cm^{-2}s^{-1} the nominal CLIC total luminosity. An optimal solution was found for skew sextupole strength $K_s = 8$ m^{-2}.

Synchrotron Radiation Limits

The emittance growth due to synchrotron radiation (SR) emission must be constrained within tolerable levels.

For a given lattice the horizontal emittance growth due to incoherent SR can be evaluated using the following expression [4]:

$$\Delta(\gamma\epsilon_x) \simeq (4.13\times10^{-8}\ \mathrm{m^2GeV^{-6}})E^6 I_5\ , \qquad (3)$$

as a function of the beam energy E and the so-called radiation integral I_5, which is defined in [5].

The beam core luminosity loss can be estimated from:

$$\Delta\mathcal{L}/\mathcal{L}_0 = 1 - 1/\sqrt{1+\Delta(\gamma\epsilon_x)/(\gamma\epsilon_x)}\ . \qquad (4)$$

For the design of the nonlinear collimation lattice we consider the following condition for the luminosity loss due to SR effects: $\Delta\mathcal{L}/\mathcal{L}_0 \lesssim 2\%$. This translates into the limit $I_5 \lesssim 6\times10^{-20}$ m^{-1}.

BEAMLINE PERFORMANCE

Multiparticle tracking simulations have been performed to study the beam transport in the CLIC BDS with the nonlinear energy collimation system. For this study 50000 macroparticles were tracked through the BDS, simulating a beam with zero mean energy offset and with a uniform energy distribution (centred at the nominal beam energy 1500 GeV) with 1% full energy spread (uniform distribution). For the transverse phase space Gaussian beam distributions have been assumed. The code MAD [6] has been used for this tracking study.

Figure 3 shows the transverse phase space at the Interaction Point (IP) for the cases with and without nonlinear optimisation (MAPCLASS). After optimisation the beam tails are reduced and the beam core is more compact and much less distorted.

Luminosity

The luminosity has been computed at the IP using the beam-beam interaction code GUINEA-PIG [7]. It is necessary to point out that to evaluate the luminosity perfor-

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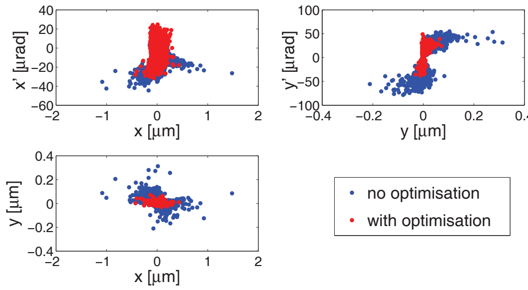

Figure 3: Transverse phase space of a CLIC beam at the IP, with and without optical optimisation.

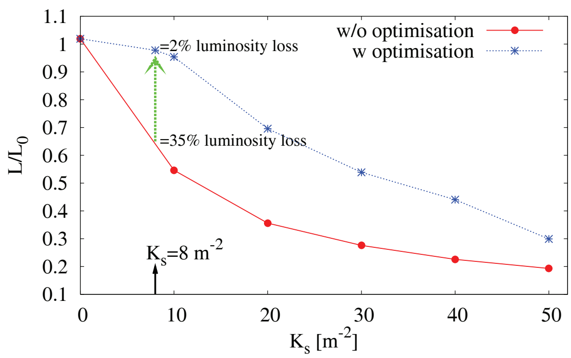

Figure 4: Relative luminosity as a function of the skew sextupole strength for the cases with and without optical optimisation.

mance of the lattice we have removed the aperture limitation in tracking to allow all particles reach the IP. Figure 4 shows the relative total luminosity as a function of the integrated strength of the skew sextupoles. The cases with and without optimisation are compared. The luminosity is degraded quickly as the skew sextupole strength increases. The cancellation of high order aberrations using two additional nonlinear magnets (a skew octupole and a normal sextupole) helps to significantly improve the luminosity. For $K_s = 8$ m^{-2}, without nonlinear optimisation, we obtain $\Delta\mathcal{L}/\mathcal{L}_0 \approx 35\%$. For $K_s = 8$ m^{-2}, in the case of nonlinear optimisation with K(skew octupole)$=$ -2400 m^{-3} and K(normal sextupole)$= -0.4$ m^{-2}, we obtain $\Delta\mathcal{L}/\mathcal{L}_0 \approx 2\%$, i.e. $\mathcal{L} = 5.88 \times 10^{34}$ cm^{-2}s^{-1}.

Beam Size at Spoiler Position

From tracking simulations we have evaluated the transverse spot size, $\sqrt{\sigma_x\sigma_y}$, and the corresponding beam peak density (per bunch) at the spoiler position, $\rho = N/(2\pi\sigma_x\sigma_y)$, with N the number of particles per bunch.

Figure 5 shows the transverse beam peak density at spoiler position as a function of the skew sextupole strength for different mean energy offsets. The results are compared with the values for the case of the baseline linear collimation system (black solid line): $\sqrt{\sigma_x\sigma_y} = 130.8$ μm and $\rho = 3.5 \times 10^{10}$ electrons (positrons) mm^{-2} per bunch. For instance, in the case of 1.5% mean energy offset, the

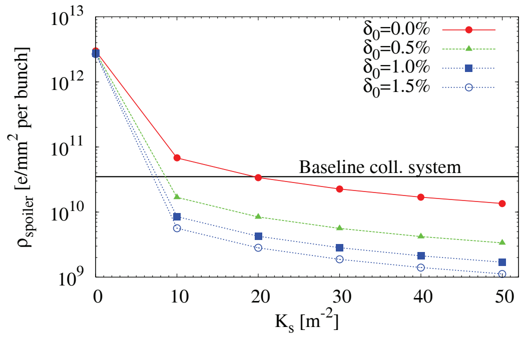

Figure 5: Transverse beam peak density at the spoiler position versus the integrated skew sextupole strength, for different mean beam energy offsets from the nominal energy: $\delta_0 \equiv \Delta E/E_0 = 0\%, 0.5\%, 1.0\%, 1.5\%$.

nonlinear collimation system reduces 4 times the transverse beam peak density at the energy spoiler with respect to the baseline linear collimation system.

CONCLUSIONS

The increase of the transverse beam size at the collimators using nonlinear elements is a potential solution to guarantee the survival of the CLIC energy collimators in case of impact by a full bunch train.

For CLIC we have presented the design of an alternative nonlinear energy collimation system based on a skew sextupole pair. Conditions for effective cancellation of optical aberrations of the lattice have been discussed. After beamline optics optimisation, beam tracking simulations have shown an acceptable luminosity performance. Simulations have also shown a significant decrease of the transverse beam peak density at the spoiler position for beam energy offset $> 1\%$, thus reducing the risk of material damage to the mechanical spoiler and absorber due to direct beam impact.

In this paper we have presented a nonlinear energy collimation system for CLIC. However, this system is based on a general nonlinear optical scheme and could be adapted to other high energy colliders.

Further studies include the investigation of a more compact optics design.

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