STUDIES ON NONLINEAR POST-LINAC PROTECTION FOR CLIC*

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Abstract

The post-linac energy collimation system of CLIC is designed to fulfil an essential function of protection of the Beam Delivery System (BDS) against miss-steered beams generated by failure modes in the main linac. Guaranteeing the collimator survivability in case of direct beam impact is very challenging, if we take into account the need to deal with an unprecedented transverse energy density per beam of the order of $\mathrm{GJ/mm^2}$. This translates into a high damage potential of uncontrolled beams. In this paper we present an alternative nonlinear energy collimation system as a potential solution to guarantee the survival of the collimators. The performance and error tolerances of this system are studied by means of beam tracking simulations, and compared with those of the conventional baseline CLIC energy collimation system.

INTRODUCTION

In high-energy physics colliders, energy collimation systems are essential to collimate beam particles with large energy deviation. In addition, they can fulfil a very important protection function intercepting miss-steered or errant beams with energy offsets generated in the main linac. This protection function is crucial for multi-TeV colliders, such as the Compact Linear Collider (CLIC) [1], where miss-phased or unstable off-energy drive beams and the malfunction of some components of the RF accelerating structures in the 21 km long main linac are likely failure modes, and they are expected to be much more frequent than large betatron oscillations with small emittance beams [2].

In this context, where the collimator must dispose of beams with transverse energy density of the order of $\mathrm{GJ/mm^2}$ and full power of ~ 10 MW, the self-protection of the energy collimators is a challenge. For instance, assuming critical scenarios of failures in the CLIC main linac, recent studies of thermo-mechanical features of the baseline energy spoiler of the CLIC BDS have shown that it may be difficult to avoid fracture or there might be a permanent deformation of the spoiler surface after a full beam impact [3]. In order to guarantee the collimator survival, we are investigating the feasibility of using an alternative optics design based on nonlinear magnets to increase the spot size at the primary collimator (or spoiler) position, whilst keeping an acceptable quality of the beam during normal operation. In this paper we present performance simulation studies for a CLIC post-linac energy collimation system, mainly focused on luminosity performance and misalignment tolerances. These results complete previous studies of such a system presented in [4, 5].

OPTICS LAYOUT

The conceptual design of the CLIC nonlinear energy protection system is illustrated in Fig. 1. A first skew sextupole plays the role of a "magnetic primary spoiler", intended to increase the beam spot size at downstream mechanical collimators (spoiler and absorber). In order to cancel the geometric optical aberrations, a second skew sextupole of the same strength ($K_{s1} = K_{s2}$) is placed downstream, setting a $-I$ (minus unit) transfer matrix between the skew sextupoles.

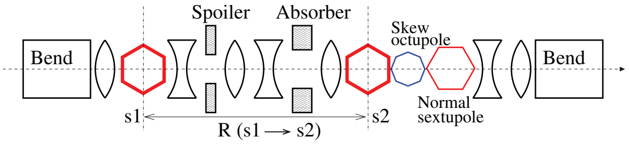

Figure 1: Basic scheme of the nonlinear energy collimation system.

Figure 2 shows an optics solution for this system. It consists of five FODO cells, where the drift space of the first and last cells is occupied by bending magnets to create the necessary horizontal dispersion D_x. The bending angles have been adjusted accordingly to maximise as much as possible D_x at the sextupole and collimator positions, while minimising the emittance growth due to incoherent synchrotron radiation. A mechanical spoiler and an absorber are placed in between the two sextupoles. The spoiler is located at approximately $\pi/2$ phase advance from the first skew sextupole, and the absorber is at $\pi/2$ phase advance from the spoiler. Two matching sections, containing four normal quadrupoles each, are included at the beginning and the end of the lattice.

The criterion for selecting the skew sextupole strength has been a trade-off between minimising the beam peak density of miss-steered beams at the spoiler position and maximising the luminosity during normal operation. For the optimisation of the system, in order to locally cancel higher order aberrations we have added a normal sextupole and an octupole just downstream of the second skew sextupole. Table 1 shows the normalised integrated strengths of the nonlinear elements for this optics solution. More details about the optics design can be found in [5].

The collimation depth has been set to intercept beams with energy deviation larger than $\pm 1.5\%$ of the nominal energy. This energy collimation depth is determined by failure modes in the main linac [2]. The horizontal spoiler and absorber are used with a half gap aperture of about 1 mm. This aperture is 10 times bigger than that of the betatronic

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Table 1: Strengths of the Multipole Magnets of the CLIC Nonlinear Collimation System.

Element	Normalised integrated strength
Skew sextupoles	$8\ \mathrm{m}^{-2}$
Normal sextupole	$-0.4\ \mathrm{m}^{-2}$
Skew octupole	$-2400\ \mathrm{m}^{-3}$

collimators, whose half gap has been set to 100 μm. Therefore, in terms of wakefield effects, the energy collimator contribution is expected to be much smaller than that of the betatronic collimators [6].

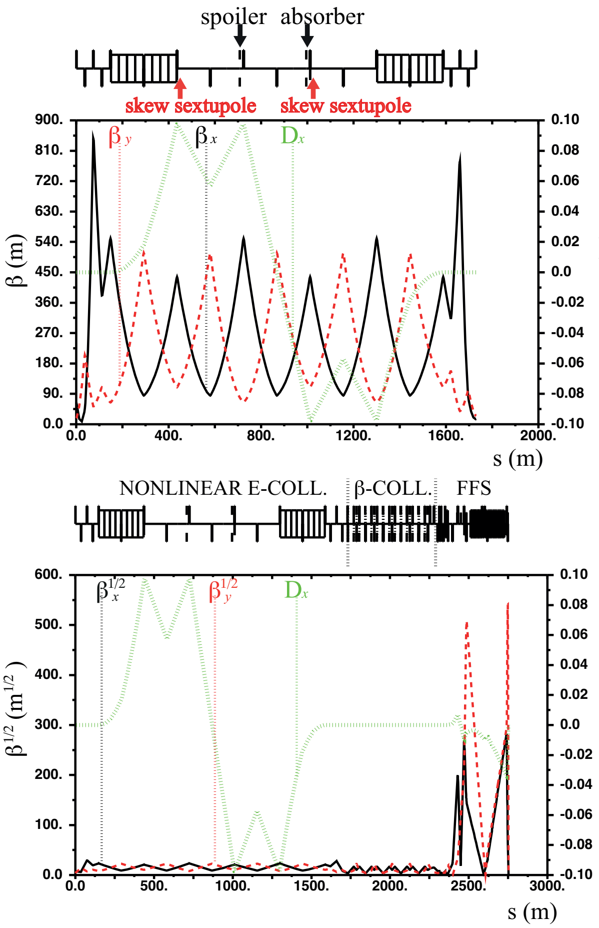

Figure 2: Top: layout and optical functions (betatron functions and first order horizontal dispersion) of a nonlinear energy collimation system for CLIC. Bottom: layout and optical functions (square root of betatron functions and first order horizontal dispersion) of the CLIC BDS integrating the following sections: the nonlinear energy collimation system (NONLINEAR E-COLL.), the betatron collimation system (β-COLL.) and the Final Focus System (FFS).

PERFORMANCE SIMULATIONS

Luminosity

Beam tracking studies have also been performed in order to investigate the energy bandwidth of the BDS. The addition of nonlinear elements further limits the bandwidth, and energy errors can lead to a significant luminosity loss. Figure 3 depicts the energy bandwidth in terms of relative peak luminosity as a function of the mean energy offset of the beam ($\delta_0 \equiv \Delta E/E_0$), comparing the nonlinear collimation based BDS with the baseline BDS. For the reference baseline BDS the energy error tolerance for less than 2% luminosity reduction is $\delta_0 < |\pm 0.2\%|$. The nonlinear system led to a narrower energy bandwidth: $\delta_0 < |\pm 0.1\%|$.

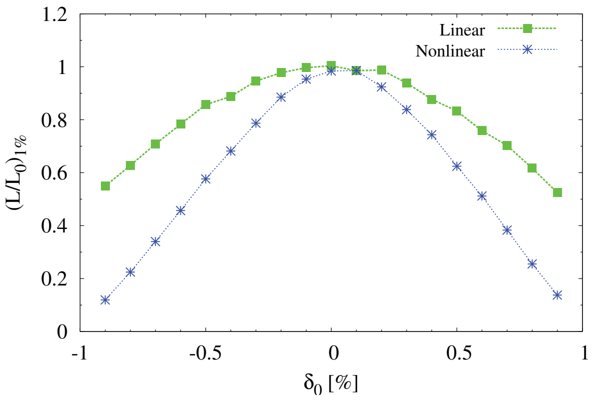

Figure 3: Relative peak luminosity as a function of the beam energy offset, comparing the energy bandwidth of the nonlinear energy collimation based CLIC BDS (asterisk points) with that of the baseline CLIC BDS (square points).

Misalignment Tolerances

Since the beams at the collision point are so small, and since there are strong sextupoles to cancel the chromaticity and geometric aberrations with a high precision the performance of the final focus optics is sensitive to many forms of perturbations.

The misalignment tolerances for a 2% peak luminosity loss have been calculated for each magnet in the nonlinear collimation system: the two skew sextupoles named S1 and S2, the skew octupole, and the normal sextupole. In addition, since the last three magnets are right after each other, the tolerances for this block of three magnets are also calculated, e.g. for the case that these are put on the same girder. The imperfections that are considered are position offsets, both vertically and horizontally, magnetic strength errors and tilts. Simulations are done with PLACET [7] and GUINEA-PIG [8]. It should be noted that the tolerances and luminosity performances presented should be regarded for pulse to pulse stability, since static or low frequency changes can to a large extent be corrected by the orbit feedback, interaction point position feedback and beam tuning with sextupole knobs [9]. Tolerances for a pulse to pulse stability are given, and in every case only one beamline is perturbed while the other is kept unperturbed.

Figure 4 shows the misalignment tolerances for the nonlinear magnets of the collimation system for the horizontal offset versus relative peak luminosity. In this case the tolerance for a 2% peak luminosity loss is about 1.8 μm for S1 and S2. Furthermore, it can be seen that for S1 and S2 the maximum luminosity is achieved when the sextupole is slightly offset from its nominal position.

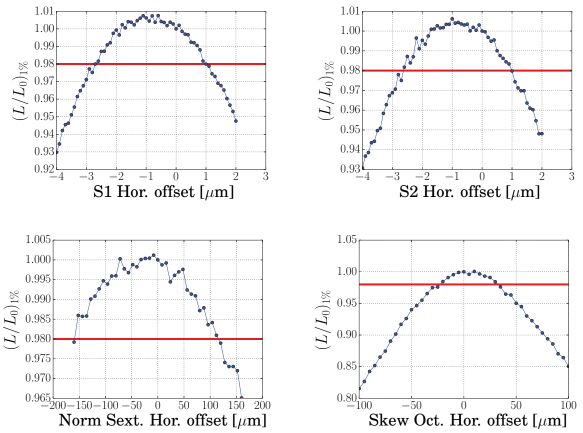

Figure 4: Relative peak luminosity versus horizontal offset of the first skew sextupole S1 (top left), the second skew sextupole S2 (top right), the normal sextupole (bottom left) and the skew octupole (bottom right). The red line indicates the 2% luminosity loss limit.

In Table 2 the tolerances for the 2% peak luminosity loss are shown. It can be noted that the two skew sextupoles, S1 and S2, that have the same properties have also the same tolerances. The normal sextupole, which has 20 times less strength compared to the skew sextupoles is also 20 times less sensitive. And that the tolerances of the combination of the last three magnets are determined by the most sensitive magnet, the skew sextupole S2.

Table 2: Offset tolerances and strength errors (relative) for the magnets in the non-linear collimation system for a relative peak luminosity loss of 2%. Combined is the combination of the S2, normal sextupole and skew octupole for the case that those are placed on the same girder.

Magnet	Hor. [μm]	Vert. [μm]	Roll [mrad]	Strength [relative]
S1	1.8	6	12	0.009
S2	1.8	7	12	0.009
Normal Sextupole	140	40	70	0.75
Skew Octupole	30	110	210	0.28
Combined	1.8	6	13	-

In addition to the magnets in the nonlinear collimation section the tolerances for the final doublet magnets have also been calculated for this lattice. Since the final focus system is the same as the baseline BDS, it was expected that the tolerances for those magnets are comparable to the tolerances of the baseline BDS which were reported in [10]. This expectation was confirmed by simulation.

It can be concluded that the misalignment tolerances for the magnets in the nonlinear collimation section are not very stringent.

CONCLUSIONS

A nonlinear energy collimation system for the CLIC BDS has been designed. This system is based on four multipole magnets (a skew sextupole pair, a normal sextupole and a skew octupole). The optics of this system has been designed to increase as much as possible the transverse spot size on the collimators in order to protect them, and, on the other hand, it must not introduce intolerable optical aberrations which degrade the luminosity performance.

In order to complete previous studies [4, 5], in this paper we have investigated different error tolerances of this system (for less than 2% luminosity loss). Concretely, we have studied the energy error and element misalignment tolerances for pulse to pulse stability. From simulation results it can be concluded that the multipole magnets of the nonlinear collimation system does not induce very stringent tolerances. These results and the fact that the system shows an acceptable luminosity performance make it a serious alternative to the conventional linear energy collimation systems.

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