Failure Modes in CLIC

D. Schulte, F. Zimmermann, CERN, Geneva, Switzerland

Abstract

Several CLIC failure modes may cause beam loss at collimators between the linac and the collision point. Studying sample failures by computer simulation, we derive performance requirements for the CLIC collimation system. In particular, we discuss the effect of energy variations due to rf phase jitter, reduced current, or malfunction of one drive beam sector on the multi-bunch beam emittance.

1 INTRODUCTION

Certain failures in the CLIC accelerator complex [1] may cause a beam loss in the beam delivery system. The beam will first impinge on spoiler elements. These short spoilers constitute the primary part of the collimation system. Their purpose is to widen the beam via scattering so that it can safely be intercepted by downstream absorbers [2, 3]. If an entire bunch train is lost, the beam size at the spoiler must be larger than about $(100\ \mu\mathrm{m})^2$ in order that the collimator not be destroyed by the sudden energy deposition [4, 5]. Assuming the design parameters of the 1.5-TeV CLIC beam, listed in Table 1, beta functions at the betatron spoilers must exceed 1000 km in both transverse planes to guarantee collimator survival. This implies an impressive length of up to 6 km for the collimation systems on each side of the interaction point (IP) [2].

Table 1: Nominal 3-TeV CLIC beam parameters.

variable	symbol	value
beam energy	E	1.5 TeV
bunch population	N_b	4×10^9
number of bunches / train	n_b	154
repetition rate	f_{rep}	100 Hz
full width energy spread	δ_{FW}	1.0%
horizontal emittance	$\gamma\epsilon_x$	$0.68\ \mu$m
vertical emittance	$\gamma\epsilon_y$	5–20 nm
rms bunch length	σ_z	$30\ \mu$m

However, *a priori* it is not clear that the beam will retain the nominal emittance in case of a failure. For example, according to previous simulations [5], a beam which is missteered somewhere in the linac so that it executes a vertical betatron oscillation of amplitude $50\sigma_y$ will suffer a vertical emittance growth by more than two orders of magnitude before it reaches the collimators. This emittance growth is due to the large energy spread and rapid filamentation.

In this paper we study a different set of failure modes which will occur more frequently and result in a significant energy deviation at the end of the linac, namely the effect of a missing drive beam, an injection phase error, and a change in the charge of the main beam.

The required collimation depth, *i.e.*, the transverse distance of the spoilers from the nominal beam in units of rms beam size, is determined from the envelope of synchrotron radiation emitted inside the final quadrupoles upstream of the collision point. Presently, two optical solutions exist for the CLIC final focus at 3 TeV [6]. We here consider the more compact optics, which is a scaled version of the NLC design by Raimondi [7]. For this optics, the collimation depths amount to $10\sigma_x$ and $70\sigma_y$, where we have assumed an energy collimation at $\pm4\%$ and left a margin of $4\sigma_x$ and $13\sigma_y$, respectively, so that all beamline elements are definitely in the shadow of the collimators.

2 SIMULATION PROCEDURE

The beam transport through the linac is simulated using the code PLACET [8]. First, in the simulation, we set up the linac for the nominal beam including misalignments of quadrupoles, structures and position monitors by 100 μm and 10 μm rms, respectively, as well as orbit corrections, beam-based alignment, and emittance tuning bumps. After correction, the residual emittance growth is well contained, and the final normalized vertical emittance at the end of the linac is close to the initial value 5 nm, a factor of 4 below the emittance budgeted for luminosity estimates.

Assuming that a failure occurs between two pulses, we now introduce an error, *e.g.*, a missing drive beam in one of the 22 linac sectors, and then track the main-beam 154-bunch train through the linac, which has previously been optimized for the nominal conditions. The result is an energy error, and possibly a blow up in the single and multi-bunch emittance. The simulation takes into account the effect of multi-bunch beam loading. We track 30 bunches, and assume that all subsequent bunches have the same properties as bunch number 30, since typical transients at the head of the train only extend over about 5 bunches.

From the PLACET simulation we obtain the multi-bunch beam distribution at the end of the linac. Next, we generate a distribution of 10000 test particles whose centroid coordinates and 2nd moments correspond to the PLACET result, also including the correct linear and nonlinear correlations with energy and longitudinal position z. Using either MAD [9] or SIXTRACK90 [10], this distribution is now tracked through the CLIC beam delivery system to the first location of an energy collimator, where we compute the beam distribution and the rms beam size.

We repeat the simulations for10 different random seeds of the initial linac misalignments.

3 RESULTS

We consider (1) the nominal case, (2) a missing drive beam in one of the sectors 9, 16 and 22, respectively, (3) an injection phase error of $-5°$, $+5°$, and $+20°$, and (4) a charge error of -10%.

In all of these failures the beam is still transported to the end of the linac with no losses. Only a failure of sector 1 or 2 would lead to beam loss in the linac, because the beam is over-focused in these cases.

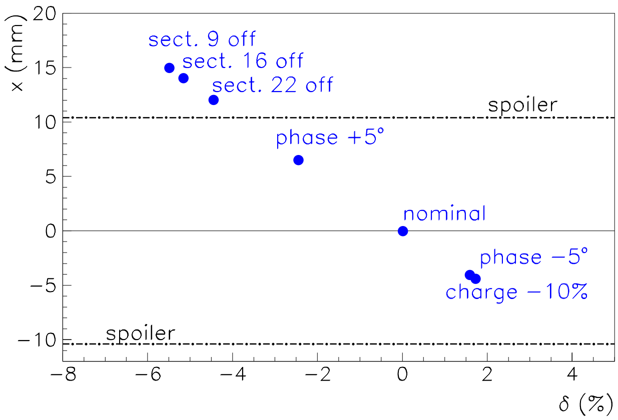

Figure 1: Simulated horizontal beam centroid at the first spoiler vs. centroid energy deviation for various failure modes and for the nominal beam. An average over 154 bunches is shown. Error bars which represent the rms variation over 10 random seeds for the linac are smaller than the size of the circles. Spoiler apertures are indicated.

Figure 1 shows the centroid horizontal position at the first energy spoiler as a function of the beam centroid energy. The amplitude of the spoiler location is also indicated. It corresponds to energy collimation at $\pm 4\%$. In the case of a missing drive beam the energy loss is larger than 4% so that the bunch train hits the spoiler. For an injection phase error of $\pm 5°$ or a 10% charge reduction, the energy deviation is still within the energy acceptance. A larger phase error of $+20°$ causes an energy deviation of -15% and an orbit displacement of 15 cm (outside the scale of the figure).

Typical transverse beam distributions for the nominal conditions and for a failure are shown in Fig. 2. The failure clearly widens the horizontal distribution and, in addition, it induces long tails. Figure 3 displays the horizontal and vertical rms beam sizes at the first energy spoiler as a function of the beam centroid energy. At the spoiler location the horizontal dispersion is large, $D_x \approx 0.26$ m. Therefore, the horizontal beam size is much larger than the vertical, and its increase in case of a failure primarily reflects an increase

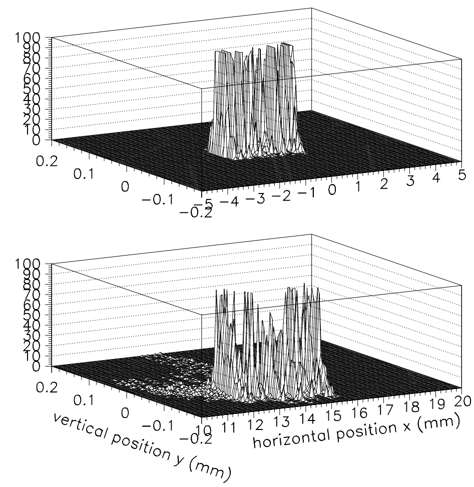

Figure 2: Simulated transverse distribution at the first energy spoiler for the nominal beam (top) and when the 16th drive beam is missing (bottom).

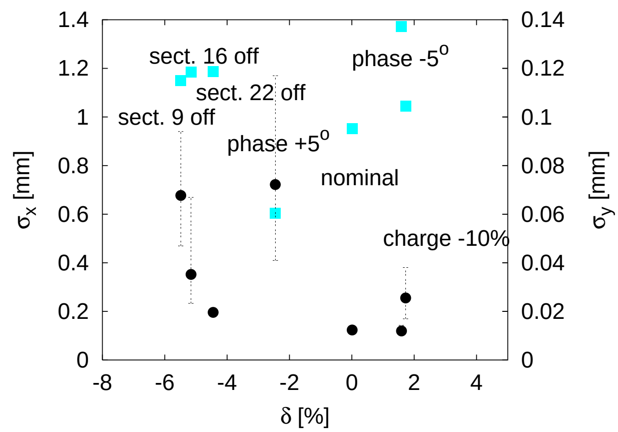

Figure 3: Simulated horizontal (squares) and vertical (circles) beam sizes at the first spoiler vs. centroid energy deviation for various failure modes and for the nominal beam. Error bars show the minimum and maximum of 10 random seeds.

in the beam energy spread.

A relevant parameter for collimator survival is the effective beam size $\sigma_r \equiv \sqrt{\sigma_x \sigma_y}$[4]. This is illustrated in Fig. 4. A spoiler made from carbon survives a beam impact if $\sigma_r \geq 100\,\mu$m; a beryllium spoiler requires $\sigma_r \geq 150\,\mu$m [4].

For most of the failures which cause beam impact on the energy collimator the beam size is large enough such that not only carbon, but also beryllium would survive. The only exception is a missing drive beam in the last sector (22), for which the beam size appears marginal.

For half of the failures considered the resulting momentum deviation is too small for the beam to be caught in the energy collimation section. In such cases, the beam could hit sacrificial spoilers in the betatron collimation section,

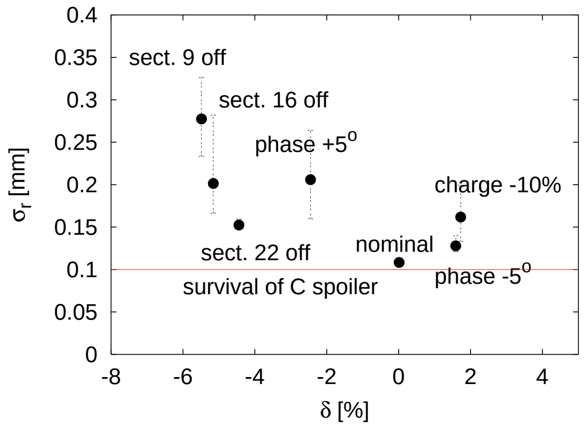

Figure 4: Simulated effective beam size $\sigma_r \equiv \sqrt{\sigma_x \sigma_y}$ at the first spoiler vs. centroid energy deviation for various failure modes and for the nominal beam. Error bars reflect the minimum and maxium value over 10 random seeds. Survival limit of carbon spoiler [4] is indicated.

which is undesirable. We recall that betatron collimation needs to be performed at horizontal and vertical amplitudes of about $10\sigma_{x,\beta}$ and $70\sigma_{y,\beta}$, respectively. This can be compared with the centroid betatron amplitudes for various failure modes displayed in Fig. 5. The horizontal betatron amplitude was computed by subtracting the product of dispersion and relative energy deviation from the horizontal centroid position and slope.

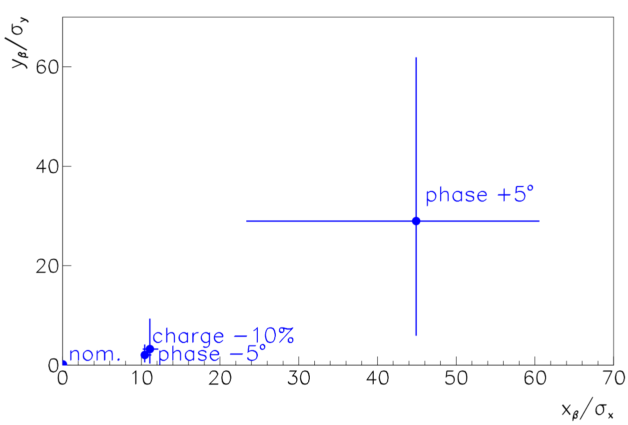

Figure 5: Simulated centroid betatron oscillation amplitudes at the first spoiler, normalized to the unperturbed rms betatron beam sizes, for various failure modes and for the nominal beam. An average over 154 bunches is shown. Error bars reflect the minimum and maximum value over 10 random seeds.

For some failures the energy loss is smaller than 4%. In most of these cases, the betatron motion is slightly larger than the horizontal collimation depth of the downstream sections. The horizontal oscillation amplitude is significantly larger than the $10\sigma_x$ collimation limit only for the $+5^\circ$ phase error. It seems possible to tighten the energy collimation. One would either have to reduce it to about $\pm 1.5\%$ or to about $\pm 2\%$. In the latter case the horizontal collimation must be at a larger amplitude, as it is in the case of the base-line final focus system.

We have repeated the above calculations of beam size and centroid offsets for the first 5 bunches of the train. These bunches experience most of the transient beamloading. However, the results are not much different from those for the full bunch train. Only if the beam current changes, the first few bunches are not affected very much; but the following ones are due to the beamloading.

4 CONCLUSION

Simulation results for likely failure modes in the CLIC linac complex provide requirements for the collimation system. An important observation is that failures which cause a significant energy deviation are not necessarily accompanied by a large beam-size increase at the energy collimators. Therefore, beta functions and dispersion at the energy collimators should be chosen sufficiently large that collimator survival is guaranteed for the impact of the nominal beam. Some of the failures lead to an energy error which is small enough for the beam to pass the energy collimation. The beams still can have significant betatron oscillations, and can thus hit the betatron collimators. As a result either the betatron collimation should be designed to also survive the impact of the full beam, or a tighter energy collimation, probably together with a more relaxed betatron collimation, must be used.

5 ACKNOWLEDGEMENT

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