EFFECT AND OPTIMISATION OF NON-LINEAR CHROMATIC ABERRATIONS OF THE CLIC DRIVE BEAM RECOMBINATION AT CTF3

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Abstract

The CLIC design relies on the two-beam acceleration principle, i.e. the energy transfer from the so called drive beam to the main colliding beams. At the CLIC Test Facility (CTF3) at CERN the feasibility of this principle is being tested in terms of performance and achievable specifications. The high-current drive beam is generated by recombining its parts in a delay loop and a combiner ring. Preserving the drive beam emittance during the recombination process is crucial to ensure beam-current and power production stability. Present theoretical and experimental studies show that non-linear energy dependence of the transverse optics heavily spoils the quality of the recombined beam. Conventionally these effects are cured by means of non-linear corrections using sextupoles. In this work we propose a mitigation of these effects by optimising the linear lattice, leading to a more robust and easy to operate drive beam recombination complex. The latest results are presented.

INTRODUCTION

The CLIC Test Facility (CTF3) [1] at CERN aims to demonstrate the feasibility of the key technologies of the Compact LInear Collider (CLIC) design [2]. Among others, two are the main peculiarities that are being demonstrated at CTF3: the Drive Beam recombination and the two-beam acceleration [1, 3–5].

This work is focused on the Drive Beam Recombination Complex (DBRC) installed at CTF3. The layout of the DBRC is shown in Figure 1. At the entrance of the DBRC the drive beam is ~1.2 μs-long and is divided into 8 sub-trains, each taking a different path in the DBRC and finally recombined into a single 140 ns-long train that is sent to the CLEX experimental area.

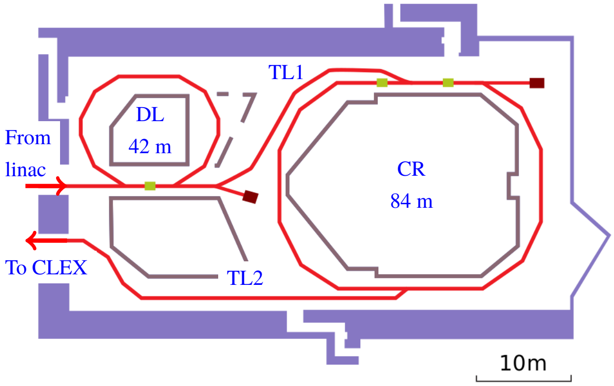

Figure 1: Layout of the DBRC of CTF3 at CERN.

The optics of the Delay Loop (DL) and Combiner Ring (CR) has to ensure that no lengthening nor transverse mismatch occurs between bunches that take different paths in the DBRC. This requires isochronous optics, which is particularly strong and prone to develop non-linearities. Due to the high beam-energy spread of the beam (up to ≈ 1% r.m.s.), non-liner dispersion is one of the main concerns for the operation of CTF3, and this triggered the analysis presented in this work.

SIMULATION PROCEDURE

In order to simplify the treatment of the problem some assumptions are made:

- The transverse dynamics of a monochromatic beam can be treated at first order due to the small dimension of the beam (i.e. less than a few mm), and the relatively short length of the lattice (up to a few hundred metres).
- The beam entering in the DBRC is Gaussian and uncoupled both in the transverse and longitudinal planes.

This allows one not to perform a full tracking of many particles, but only to simulate a discrete number of beam slices of different momenta.

Note that for Gaussian monochromatic beams the relation between Twiss parameters (α, β, γ, ϵ) and statistical covariance of the ensemble of particles (Σ) is expressed by [6]:

$$\Sigma = \begin{bmatrix} \sigma(\mathbf{x},\mathbf{x}) & \sigma(\mathbf{x},\mathbf{p_x}) \\ \sigma(\mathbf{p_x},\mathbf{x}) & \sigma(\mathbf{p_x},\mathbf{p_x}) \end{bmatrix} \quad (1)$$

$$= \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}. \quad (2)$$

The emittance ϵ can then be computed as $\epsilon = \sqrt{\det \Sigma}$.

Given these assumptions, the simulation procedure is:

1. Split the incoming beam into $8 \times n$ slices: one for each of the 8 possible paths in the DBRC each of which is further split into n slices of slightly different energy with respect to the nominal one.
2. Transport each slice through its own path along the DBRC by means of MAD-X [7] TWISS function calls specifying the proper DELTAP parameter.

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3. Compute the covariance matrix of each slice.
4. Combine the covariance matrices and orbits of each slice and so compute the total statistical emittance.

All slices are assumed to be identical at the entrance of the DBRC, with the exception of their momenta. The relevant transverse parameters which have been assumed are reported in Table 1 and are compatible with what is typically measured at the entrance of the DBRC at CTF3.

Table 1: Beam Parameters Assumed at the Entrance of the DBRC at CTF3 for MAD-X Simulations

Beam energy	140 MeV
Energy spread r.m.s. $\sigma_{\Delta p/p_0}$	0.6%
Energy split granularity	0.01%
Energy split range	from -2% to +2%
Hor. Emitt. (Normalised) $\epsilon_{N x_0}$	60 μm
Vert. Emitt. (Normalised) $\epsilon_{N y_0}$	100 μm

FIRST SIMULATIONS

A first simulation of the recombination process has been performed assuming the nominal optics in use at CTF3. Figure 2 shows the final phase-space of a factor-8 combined beam before being extracted from the CR. Note that some of the ellipses representing the slices with the biggest energy deviation are considerably far from the core of the beam. Clearly these ellipses are normally sparsely populated, but they might generate losses and hence affect the overall current stability of the recombined beam.

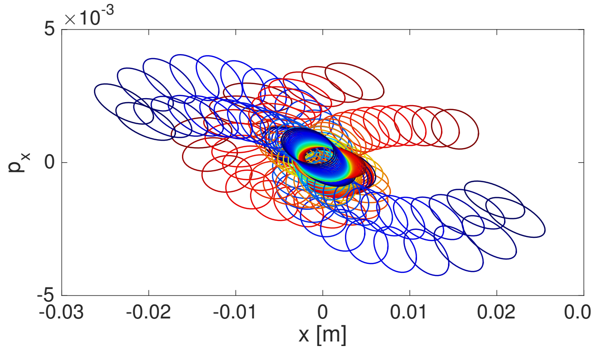

Figure 2: Simulation of the horizontal phase-space of the factor-8 combined beam with nominal optics. Each ellipse identifies the 3σ boundaries of one of the 8×41 simulated monochromatic slices. The colour code represents the momentum deviation from -2% (red) to +2% (blue).

By computing the covariance matrices of each slice and by combining them in the total covariance matrix according to the parameters in Table 1, the statistical emittance of the combined beam is increased by $\Delta\epsilon_x \approx 233\%$ in the horizontal plane. In the vertical plane, here not shown, no dispersion is expected, hence only chromaticity contributes to the emittance growth that turns out to be $\Delta\epsilon_y \approx 2\%$.

By considering individually the 8 possible paths in the DBRC it turns out that the sub-trains that pass through the DL experience the biggest emittance growth, which is mainly due to non-linear dispersion [8].

OPTIMISATION OF DL OPTICS

Normally non-linear dispersion is treated by means of sextupoles. An attempt to implement a sextupolar correction was made, but it was not possible to fully implement it in practice. The main limitation in using sextupoles comes from the alignment error of the magnetic elements and by the limited dynamic aperture of the DL. Indeed even if sextupoles have been foreseen at CTF3 to correct mainly the longitudinal aberrations [1], they were rarely used mainly due to the feed-down effects that they were causing.

An alternative approach is to find a linear optics that limits the production of non-linear dispersion. An optimisation was performed by means of a custom MAD-X match procedure: instead of targeting only zero dispersion at the end of DL, it was required that also 1σ off-momentum particles would arrive at the end of DL with zero orbit error. This is one of the simplest optimisations in the context of more general non-linear optimisations that make use of linear-elements only [9].

A new DL optics fulfilling the new requirement was found [8]. Figure 3 shows the comparison between the old and new optics in terms of emittance growth along the DL path. Chromaticity and non-linear dispersion are the only contributions to the emittance growth shown in Figure 3. Note how the emittance increase is symmetric with respect to the middle of the DL lattice with the new optics.

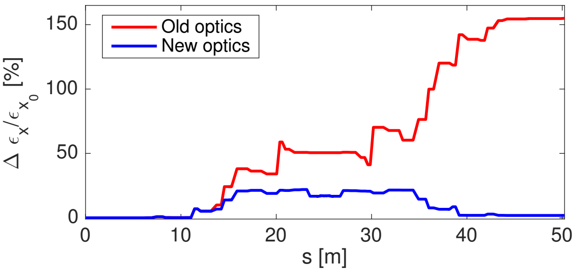

Figure 3: Horizontal emittance growth along the DL with the nominal optics (red) and with the new one (blue).

Figure 4 shows the final phase-space of the factor-8 combined beam assuming the new DL optics, and it has to be compared with the phase-space in Figure 2. Note the different scale of the axes between the two figures and that the area of each ellipse is identical in both plots. In this case the total horizontal emittance growth is $\Delta\epsilon_x \approx 27\%$. In the vertical, without any additional care, the total emittance growth seems to stay confined to $\Delta\epsilon_y \approx 1\%$.

The results are in general consistent with similar simulations performed with PTC_TWISS [7]. In this case the factor-8 horizontal emittance growth goes from $\Delta\epsilon_x \approx 162\%$ with the old optics to $\Delta\epsilon_x \approx 30\%$ considering the new DL

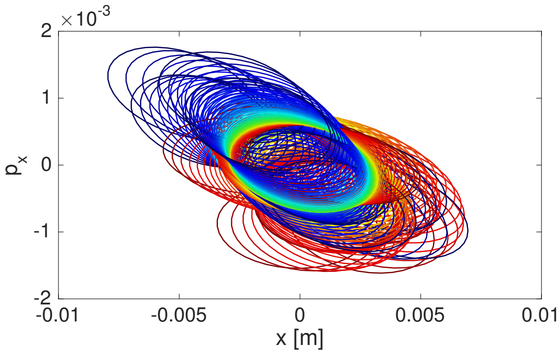

Figure 4: Simulation of the horizontal phase-space of the combined beam after the CR with new DL optics. The ellipses are defined as in Figure 2.

optics. In the vertical plane PTC_TWISS shows slightly worse performance, with a total vertical emittance growth of about $\Delta\epsilon_y \approx 6\%$ for both optics. The main contribution arises in the DL. Figure 5 show the vertical phase-space after a single turn in the DL with new optics simulated with PTC_TWISS. Note the high chromaticity that is principally affecting the off-momentum tails. The vertical emittance growth at this stage is $\Delta\epsilon_y \approx 5\%$ even with the new optics. This is not a concern in itself, but the heavy distortions of the tails, if confirmed, might induce beam losses and hence reduce the stability of the recombined beam.

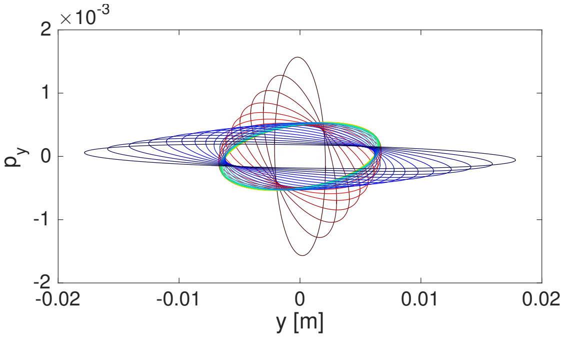

Figure 5: Vertical phase-space of a single sub-train after a single passage in the DL. Each ellipse identifies the 3σ boundaries of one monochromatic slice. The colour represents the momentum deviation from -2% (red) to $+2\%$ (blue).

An attempt to implement the new optics into the actual machine was conducted at the end of the 2015 CTF3 run.

Figure 6 shows the second order dispersion (DD_X) measured at the BPMs installed in TL1 after performing one turn into the DL. Note the overall factor-2 reduction of the measured non-linear dispersion when using the new DL optics.

The result was obtained by switching from the old optics to the new one in a few hours in order to obtain a comparable result. Unfortunately both optics were manually tweaked to improve the beam transmission, and more dedicated time should be given to verify completely the improvement.

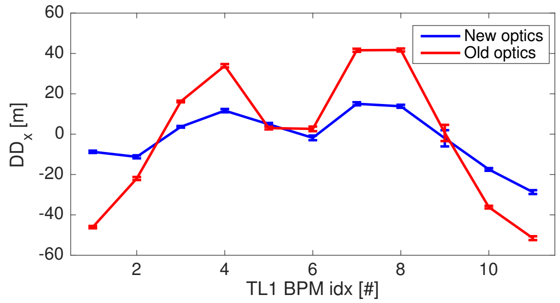

Figure 6: Second order dispersion measured at the TL1 BPMs before (red) and after (blue) implementing the new DL optics.

The new optics allowed easier optimisation of the recombination by improving the dynamic aperture of the DL. It was then used for the last part of the CTF3 run of 2015, and it contributed to advance in scientific program of CTF3 [3].

CONCLUSIONS

The first simulations of the complete drive beam recombination at CTF3 showed that non-linear dispersion in the DL is one of the most critical source of statistical emittance growth in the horizontal plane.

A new optics for the DL that minimises the non-linear dispersion without using sextupoles was found and implemented at CTF3, resulting in improved operation stability.

The simulations with PTC_TWISS revealed that the chromatic aberrations in the vertical plane might be the next issue to attack. This is compatible with the beam-current stability observed [10]. Further investigations are on-going.

ACKNOWLEDGMENT

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