

A COMPARATIVE STUDY FOR THE CLIC DRIVE BEAM DECELERATOR OPTICS

G. Sterbini*, D. Schulte, CERN, Geneva, Switzerland
 E. Adli, University of Oslo, Oslo, Norway

Abstract

The baseline for the CLIC drive beam decelerator optics consists of a 2 m long FODO cell. This solution was adopted to have strong focusing in order to mitigate the effect of the PETS wake fields and to minimize the drive beam envelope. Taking into account the most recent PETS design, we compare the performance of the baseline FODO cell with a proposal that consider twice longer FODO cell. Despite of the expected cost in terms of performance, the reduction of the complexity of the system due to the halving of the number of quadrupoles can be beneficial for the overall optimization of the decelerator design.

INTRODUCTION

In the Compact Linear Collider (CLIC) the colliding beams will be accelerated by decelerating a high intensity (101 A) drive beam (DB) from 2.4 GeV to 0.24 GeV along the 2×24 decelerator stations [1, 2]. In order to maximize the main figures of merit of the collider (integrated luminosity and peak luminosity versus power consumption)

1. the DB transport has to be efficient (minimization of static losses),
2. reproducible between consecutive beam pulses (minimization of dynamic losses),
3. and the availability of the decelerator has to be maximized (minimization of the machine downtime).

The required pulse-to-pulse stability of the DB current, $\Delta I/I$, is $7.5 \cdot 10^{-4}$ [3]. This specification can be met only with a close synergy between the DB generation complex and the decelerator itself. On one hand, the DB complex has to deliver a good and stable beam in terms of beam current, bunch phase along the pulse, orbit, emittance and energy. On the other hand the decelerator has to preserve the beam quality all along the deceleration process.

In this paper we will focus only on the decelerator: the $\Delta I/I$ specification can be met by minimizing the beam size σ_{beam} (minimization of static and dynamic losses) and by reducing the hardware complexity and the number of total components (minimization of the machine downtime). A trade-off between beam size and system complexity has to be found.

In the following we present a comparative study on the DB performance between the nominal optics [4] (2 m long FODO cell, $\sim 40k$ DB quadrupoles with integrated gradient ($\int Gdl$) from 12 to 1.2 T) and a significantly weaker

optics (4 m long FODO cell, $\sim 20k$ DB quadrupoles with $\int Gdl$ from 6 to 0.6 T). As in the nominal case, the gradient of the quadrupoles will be scaled down along the decelerator to match the energy of the most decelerated particles.

METHODS

Due to the different energy of the beam along the 244 ns pulse induced by the deceleration, the β function, $\beta(s, z)$, depends on the position, s , along the machine and on the longitudinal position, z , along the pulse. We assume the nominal deceleration efficiency along the line (90%, it does not depend on the optics) and the nominal beam emittances ($\epsilon_n|_{x,y} = 150$ mm mrad). The DB size, $\sigma_{beam}(s, z)$, is given by the sum of

- the beam envelope (incoherent oscillations), σ_{env} ,
- the beam orbit (coherent oscillations along the bunch and along the pulse).

The weaker optics has been dimensioned to have $\beta(s, z)$ approximately a factor two larger than the nominal case. The σ_{env} depends of course on the focusing strength of the lattice and scales as $\sqrt{\beta}$ whereas the beam orbit has different contributions:

1. misalignment errors of quadrupoles (static errors): for a given RMS misplacement the induced RMS orbit scales with $\langle\beta\rangle \sqrt{N_{quad}} \int Gdl$ (N_{quad} represents the total number of quadrupoles). In this respect the weaker optics relaxes, for a constant RMS orbit, the pre-alignment requirements for the quadrupole by about $\sqrt{2}$. The effect of the power extraction and transfer structure (PETS) misalignment scales with $\langle\beta\rangle$ but with the present pre-alignment tolerances (100 μm) the PETS effect has a negligible impact. Moreover, after beam based alignment, BBA, all static contributions are expected to be minimized.
2. Orbit error/jitter at the injection (dynamic, i.e. varying pulse-to-pulse): the induced orbit oscillation along the decelerator (neglecting transverse wakes) scales with the $\sqrt{\beta}$.
3. Transverse wake-field instabilities (dynamic): as consequence of the previous point and due to the transverse wake fields of the PETS, an orbit error/jitter at the injection will be amplified along the machine and the pulse.

We can write

$$\sigma_{beam}(s, z) = \sigma_{env}(s, z) + \sum_{i=1}^3 x_i(s, z) \quad (1)$$

* guido.sterbini@cern.ch

where x_i ($i = 1, 2$ and 3) refers to the each of the three aforementioned contributions (for simplicity we will consider in the notation only the horizontal plane). In our model the decelerator is linear and uncoupled: we can consider separately the four effects and the two planes with simulations in the PLACET tracking code [5]. For the wake fields in the PETS we used the model with 8 transverse wake modes summarized in Table 1 and described in [6].

Table 1: The PETS transverse wake expansion. For each mode we report the frequency, f , the group velocity β_t , the amplitude, A , and the effective quality factor, Q .

Mode	f [GHz]	β_t [-]	A [V/(m ² pC)]	Q [-]
1	3.95	0.43	73.73	3.40
2	6.93	0.67	107.83	5.50
3	8.5	0.7	138.85	5.00
4	12.01	0.67	3985.5	6.82
5	16.40	0.56	3369.3	6.30
6	27.41	0.18	63.4	527.00
7	28.00	0.03	22.56	156.0
8	32.82	0.02	33.68	943.00

To be on the conservative side, we always refer to the first decelerator (the longest one, therefore where the beam transport is more challenging).

As already mentioned, the quadrupole strength along the lattice is designed for most decelerated particles, so particles at higher energy will be less focused (adiabatic mismatch). It has been shown ([4], Section 5.3.2) that those particles will smoothly rematch their optics functions to the weaker focusing. This means that the maximum and minimum of the betatron oscillation will still be located very close to the quadrupole for all the different energies, yielding

$$\max_s \beta_{x,y}(s, z) \approx \max\{\beta_x(s_{end}, z), \beta_y(s_{end}, z)\}. \quad (2)$$

Therefore by considering only the end of the line, s_{end} , we can estimate the maximum β -function along the machine. In the tracking code, each bunch is divided into 256 “slices”: this relatively large number is needed to sample the high frequency intra-bunch oscillations. They are produced by the different betatron phases along the bunch induced by the large intra-bunch energy spread. We considered 48 out of the ≈ 3000 bunches in the pulse. This corresponds to tracking only the first 1.2 m of the pulse (the total pulse length is ≈ 75 m). This choice is driven by the computation time of the simulation and its post-processing but it needs further analysis. In fact, as shown in Fig. 1, possible instabilities driven by the high Q modes 6 and 8 (Table 1) could be detected only considering a larger number of bunches.

RESULTS

The mechanical acceptance of the decelerator is limited by the inner radius, R , of the PETS ($R=11.5$ mm). In order

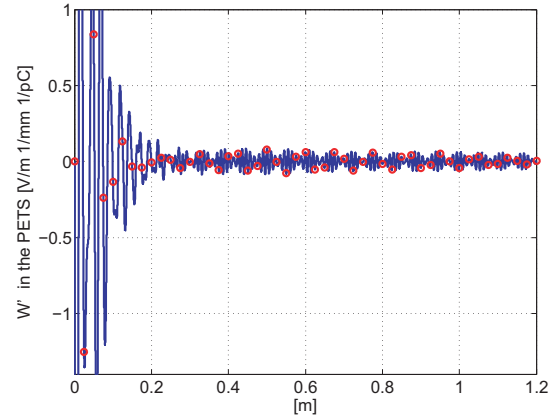


Figure 1: Wake field of the PETS. A beating is clearly visible at ≈ 6 GHz (every 2 bunches) due to the high Q of modes 6 and 8, Table 1.

to maintain the static and the dynamic losses within the specification, the criterium we currently adopt is to limit the 3σ beam size to almost half of the available aperture ($3\sigma_{beam} < 6$ mm). In the following we compare each of the four contributions for the two optics. We refer to the horizontal plane but an identical approach can be extended to the vertical one.

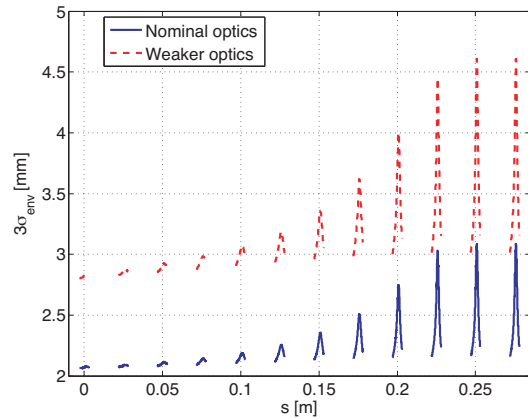


Figure 2: The $3\sigma_{env}$ for the nominal optics (y-plane) and for the weaker optics (x-plane) for the first 12 bunches (red circles) at the end of the decelerator.

The Beam Envelope

Comparing the σ_{env} between the two optics is straightforward: the maximum $3\sigma_{env}$ DB envelope along the machine, $\max_{s,z}(\sigma_{env})$, is ≈ 3.1 mm in the nominal case and becomes ≈ 4.6 mm for the weaker optics.

The Beam Orbit Due to the Misalignment

The x_1 after the BBA is supposed to be negligible with respect to the 6 mm for both optics. Considering only BBA, the weaker optics requires half the number of correctors and BPMs for similar performance.

The Beam Orbit Neglecting the Wakes

We have that

$$x_2(s, z) = \sqrt{\frac{\beta(s, z)\epsilon_{n, err}(z)}{\gamma_r(s, z)}} \cos(\mu(s, z) + \Delta\phi(z)) \quad (3)$$

where $\epsilon_{n, err}(z)$ and $\Delta\phi(z)$ correspond to the injecting error $\{x_2(s_{in}, x), x'_2(s_{in}, z)\}$ and $\gamma_r(s, z)$ represents the relativistic γ related to the adiabatic undamping of the beam. A conservative approximation of the maximum x_2 along the decelerator is $\max_s x_2(s, z) \approx \sqrt{\frac{\beta(s_{end}, z)\epsilon_{n, err}(z)}{\gamma_r(s_{end}, z)}}$. The behavior of this function is the same of that presented in Fig. 2 assuming a 3σ injection error. Assuming 1σ error, we get $\max_{s, z} x_2(s, z) \approx 1$ mm and ≈ 1.6 mm respectively in the two optics under study.

The Transverse Wakes Effect

The contribution of the transverse wakes to the beam orbit can be expressed as

$$\mathbf{x}_3(s) = T_{11}(s) \mathbf{x}_{in} + T_{12}(s) \mathbf{x}'_{in} \quad (4)$$

where \mathbf{x}_3 , \mathbf{x}_{in} and \mathbf{x}'_{in} represent respectively the vector of our sliced beam (48 bunches \times 256 slices per bunch) at the position s and at the injection of the machine (position and angle). T_{11} and T_{12} are strictly lower triangular matrices. Using PLACET we can compute the T's matrices along the machine. In the following we consider $s = s_{end}$. For simplicity we assume that at the entrance of the decelerator the 48 bunches present only rigid modes, that is each of the 256 beam slices belonging to the same bunch has the same x and x' . This working hypothesis needs to be verified addressing with specific studies all possible sources of intra-bunch instabilities in DB generation complex.

Using Eq. 4 we can evaluate the frequency response to the different rigid modes of the $\max_z(x_3(s_{end}, z))$ (Fig. 3). The high frequency part of the spectrum is limited to 6 GHz by the bunch frequency (12 GHz). In the lower part of the spectrum, the resolution on the frequency axis is limited by the number of bunches considered. The frequency response is relatively flat: assuming an injection error of 1σ , $\max_z(x_3(s_{end}, z))$ is ≈ 1 mm and ≈ 5 mm in our two optics. In terms of wake field effect, the drawbacks of the weaker optics are evident.

CONCLUSIONS

In this work we compared the nominal optics of the CLIC drive beam with a weaker lattice that uses half of the number of quadrupoles and half of the nominal integrated

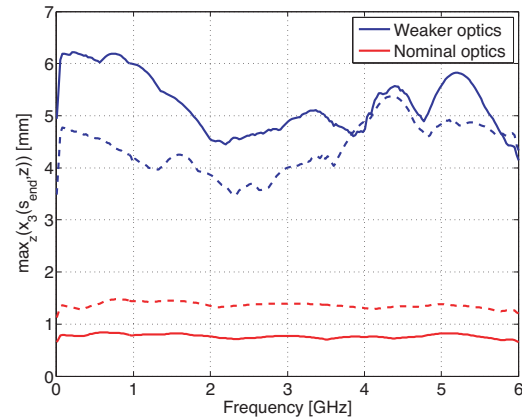


Figure 3: The behavior of $\max_z(x_3(s_{end}, z))$ as function of the position (solid line) and angle (dashed line) of the beam at the entrance of the decelerator. We assume an injection error of 1σ . The different σ between the two optics is already taken into account.

gradient. The β -functions of the weaker lattice are doubled with respect to the nominal one. This impacts the beam envelope, the pre-alignment requirements and the motion of the beam centroids along the bunches induced by steering error at the injection. With conservative approximations, we derived, for both optics, a simplified expression of the maximum σ_{beam}

$$\max_{s, z}(\sigma_{beam}) [mm] \approx 3.1 + (1 + 1) \times n$$

$$\max_{s, z}(\sigma_{beam}) [mm] \approx 4.6 + (1.6 + 5) \times n$$

where n represents the injection error expressed in σ . Only with the ambitious condition $n < 0.2$ the weaker optics option can be considered ($\max_{s, z}(\sigma_{beam}) < 6$ mm). This requires an optimal control of the beam orbit, the machine dispersion and the energy of the beam along the pulse. On one hand, until the feasibility of $n < 0.2$ is not fully demonstrated and the wake field characterization of PETS is not fully assessed, the weaker optics does not appear a viable option for the CLIC decelerator. On the other hand, all efforts in those directions if successful would have an evident impact on the CLIC decelerator.

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