

THE DRIVE BEAM DECELERATOR OF CLIC

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Abstract

In the Compact Linear Collider (CLIC) a high-current, low-energy beam will be decelerated in a chain of power extraction structures to produce the RF-power necessary to accelerate a low-current, high-energy beam in the main linac. The transverse dynamics of the decelerated beam is discussed, based on results of the programs WAKE [1] and PLACET [2]. The very large energy spread and strong transverse wakefields as well as the high group velocity of these fields and the considerable length of the bunch train are important factors. Static and dynamic imperfections are considered including ground motion. The choice of parameters for the structures is investigated. A promising beam-based alignment technique is presented that makes use of a low emittance beam.

1 INTRODUCTION

CLIC [3] is based on a two-beam scheme. The RF power used to accelerate the main beam (at 30 GHz) is produced by a second high-current low-energy beam (drive beam) running parallel to the main one [4], which is decelerated in power extraction structures, to produce the RF power.

Each drive beam decelerator is on average 767 m long and contains 550 power extraction structures. The train producing the power consists of 1824 bunches. Along the train the bunch charge increases over the first 320 bunches and then stays constant (at 17.6 nC). This charge ramp is necessary to compensate the beam-loading in the main linac [5]. In the following simulations, the charge of the first bunch is assumed to be half of the charge of a bunch on the flat top. Within the ramp the bunch charge increases linearly with the bunch number.

Depending on the beam-loading compensation in the drive beam accelerator, the ramp may be different from the model used and the flat top may be followed by a tail of bunches with decreasing charge. However, first simulations indicate that the different ramps have little influence.

The bunches are separated by a distance of 2 cm, have a length of $\sigma_z = 400 \mu\text{m}$ and have normalised transverse emittances of $\gamma\epsilon_x = \gamma\epsilon_y = 150 \mu\text{m}$. The initial energy is $E = 1.2 \text{ GeV}$ and the initial energy spread is assumed to be $\sigma_E/E \approx 1\%$ RMS [6]. During deceleration the energy spread increases to about 90% of the initial energy.

2 MODULE LAYOUT

To simplify the longitudinal matching of the drive beam decelerators and the main linac they both consist of modules of equal length. A main linac module contains up to four structures—one to four of which can be replaced by quadrupoles if necessary. A drive beam decelerator module consists of two structures, quadrupoles and beam position monitors (BPMs) forming a FODO-cell. Each drive beam structure has an active length of 0.8 m and feeds two main linac structures, its total power is 512 MW.

In modules where main linac structures are replaced by quadrupoles, decelerator structures will be replaced by drifts or special types that feed one structure only.

3 STRUCTURE MODEL

Here, only on the so-called four-waveguide structure [7] is considered. The inner bore of the structures is cylindrically symmetric, except for the four longitudinal waveguides that are cut into the surface.

The longitudinal and transverse wakefields can each be described very well by a single mode. These modes have almost the same frequency—longitudinally it is 30 GHz, transversely it is 24 MHz lower.

In contrast to most structures in accelerators, the group velocities of the longitudinal and transverse modes $\beta_{\parallel,\perp}$ are comparable to the speed of light—e.g. $\beta_{\parallel} \approx \beta_{\perp} \approx 0.44c$.

The maximum, minimum and mean energy of each bunch is shown in Fig. 1 at the end of the decelerator.

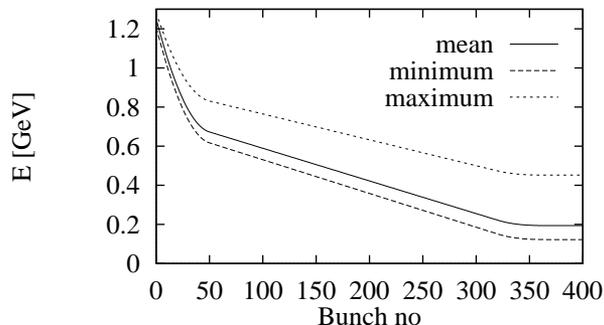


Figure 1: The final minimum, maximum and mean energy of each bunch as a function of the bunch number. Only the first 400 bunches are shown, on the flat top the values are constant.

4 LATTICE

The lattice consists of simple FODO-cells with a quadrupole spacing of half a girder length or 1.115 m. Ignoring the additional drifts or special structures, each decelerator consists of 275 modules supporting 550 structures. For the same normalised emittance the maximum envelope in a periodic lattice is given by the particles with the lowest energy [8]. The lattice is scaled to have constant beta-functions for the lowest energy. The dependence of the final envelope on the final energy is shown in Fig. 2. A phase advance of $\Delta\Phi = 88^\circ$ per cell was chosen. Larger phase advances reduce the sensitivity to transverse wakefields but increase the maximum transverse beam size. The three-sigma envelope of the beam is shown in Fig. 3. It shows the adiabatic undamping due to the decreasing energy.

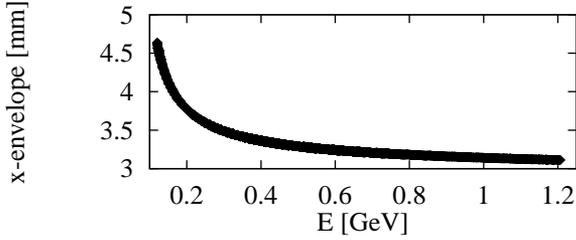


Figure 2: Final beam size versus final energy in the drive beam.

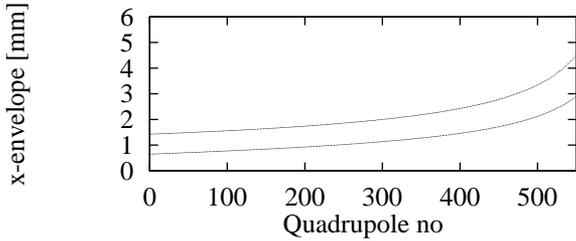


Figure 3: The envelope of a three-sigma beam along the decelerator in the focusing and defocusing quadrupoles.

5 STABILITY

In order to find the optimum iris radius a of the decelerating structures a scaling law for the longitudinal and transverse wakefields was derived using three different structures with $a = 10, 12$ and 20 mm. The wakefields were found to scale as $\hat{W}_\perp \propto a^{-5}$ and $\hat{W}_L \propto a^{-3}$. The group velocity remains about constant.

Simulations were performed for different values of a and Q , ignoring the field non-uniformity. The layout of the decelerator was kept constant. In order to achieve the same power and initial-to-final energy ratio, the charge per bunch and initial energy were adjusted. Figure 4 shows the maximum amplitude reached by a three-sigma particle. The initial beam offset was $\Delta x = \sigma_x$. As can be seen, larger radii

lead to a more stable beam. For very small values of Q , the envelope is larger at large radii, just because the emittance is larger due to the smaller energy.

The maximum charge per bunch is fixed by the drive beam injector to about 20 nC. The parameters are thus chosen to be $a = 12$ mm corresponding to $R/Q = 31 \Omega/\text{m}$. The necessary output power of $P = 512$ MW can then be provided by $q \approx 17.6$ nC. The achievable Q is 50 [5].

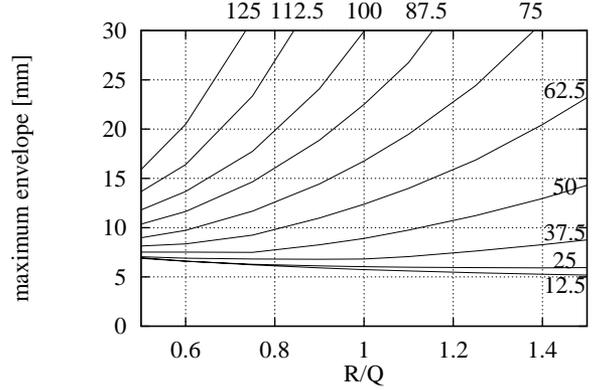


Figure 4: The maximum envelope of a three sigma beam with an initial offset of one sigma for different four-waveguide structures. The radius was varied to achieve different values of R/Q . The curves correspond to different Q -values.

6 NON-UNIFORMITY OF THE FIELD

The waveguides lead to a variation of the longitudinal field with the transverse offset r and ϕ . This in turn gives rise to a transverse kick

$$\Delta p_\perp(r, \phi) = \Delta p_{z,0} \sum_{k=1}^{\infty} 4k \frac{r^{4k-1}}{a^{4k}} \frac{\lambda}{2\pi} \sin(2\pi s/\lambda) c_k [-\vec{e}_r \cos(4k\phi) + \vec{e}_\phi \sin(4k\phi)]$$

Here, $\phi = 0$ lies in a symmetry plane in the centre of a waveguide.

In the simulation only $k = 1$ and $k = 2$ are taken into account. The higher-order terms will cause a significant field only at large radii due to the $(r/a)^{4k}$ dependence.

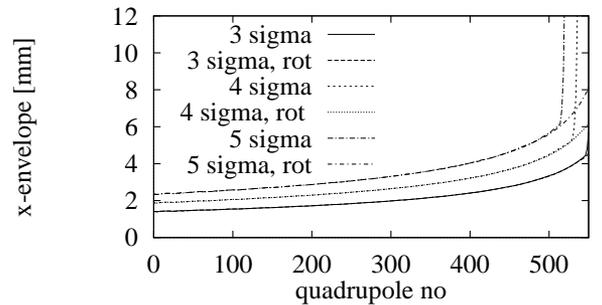


Figure 5: The envelope of an on-axis beam with and without rotating the structures at the focusing quadrupoles.

Figure 5 shows the envelopes for on-axis beams for particles with Courant-Snyder invariants $A_x^2 = c^2 \epsilon_x$ and $A_y^2 = 0$. In this symmetry plane the forces are purely radial. The three-sigma particles barely pass. The situation improves significantly if every second structure is turned by 45° to get a cancellation of focusing and defocusing deflections. Here, the term with $k = 2$ may become important since it is not cancelled, but even the five-sigma particles turn out to be stable.

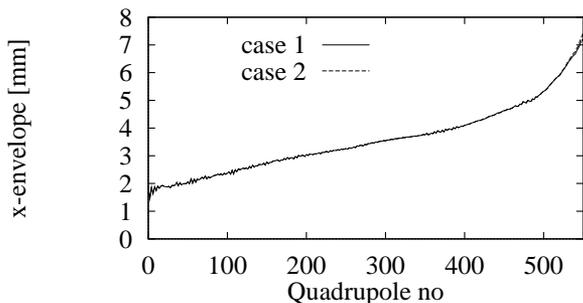


Figure 6: The envelope for a three sigma beam with an initial offset of $\delta_x = \sigma_x$ with (case 2) and without (case 1) taking into account the non-uniformity of the field.

To see the effect of the non-uniformity in the presence of beam jitter, the envelope for particles starting with $A_x^2 = 3^2 \epsilon_x$ and $A_y^2 = 0$ for a beam with an initial offset $\delta_x = \sigma_x$ is calculated, with and without taking the non-uniformity into account. If the structures are rotated as described before, the difference is negligible, see Fig. 6. The same behaviour is expected for $A_x^2/\epsilon_x + A_y^2/\epsilon_y \leq 3^2$, but this needs more investigation.

7 ALIGNMENT AND STEERING

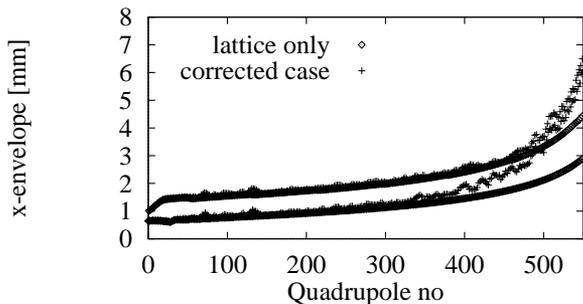


Figure 7: The envelope along the beamline after applying the ballistic correction.

Beam-based alignment is used to reduce the effect of the initial position errors of the beamline elements. One such method is the so-called “ballistic correction” [9], in which the beamline is divided into bins containing a number of quadrupoles and BPMs. The bins are aligned one after another in two steps that can be iterated if necessary. In the first step the quadrupoles in the bin are switched off. The

beam is steered into the last BPM of the bin using a correction coil. The centres of the other BPMs are then shifted onto the beam trajectory—either using software or hardware. In the second step the quadrupoles are switched on and a few-to-few steering is performed. In this method, the beam has to be transported over some distance without focusing. This is not possible with the large emittance drive beam without major beam loss. Therefore it is necessary to use a low emittance beam such as, for example, the main beam after the damping ring. This beam has a bunch length of $\sigma_z = 300 \mu\text{m}$ and an energy of $E = 1.98 \text{ GeV}$. Its emittance is less than $\gamma \epsilon_x \leq 2 \mu\text{m}$ in the horizontal plane. After aligning the BPMs, a simple one-to-one steering can be performed using the whole bunch train. The resulting envelope in a test case—not taking the non-uniformity into account—is shown in Fig. 7.

8 CONCLUSIONS

For a given type of power extraction structure it was found that increasing the aperture, and simultaneously decreasing the initial beam energy and increasing the bunch charge, improves the stability. Therefore the maximum beam current achievable by the injector has been chosen. The required output power then defines the structure aperture.

The non-uniformity of the longitudinal field effectively reduces the available aperture since particles at large radii are lost rapidly. Rotating every second structure improves the situation considerably, using a structure with a higher order of symmetry solves the problem. For example six-waveguide and eight-waveguide structures are under investigation.

With the present parameters a three-sigma beam is expected to pass the whole decelerator even if it has an uncorrected offset of one sigma at the beamline entry.

Further studies are necessary to understand the effect of the field non-uniformity on the correction scheme.

9 REFERENCES

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