

# BEAM TRANSVERSE STABILITY IN THE CLIC COMBINER RINGS

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## Abstract

The Compact Linear Collider (CLIC) RF power source is based on a new scheme of electron pulse compression and bunch frequency multiplication. In this scheme the drive beam time structure is obtained by the combination of electron bunch trains in isochronous rings using RF deflectors. One of the potential problems is the drive beam transverse stability in the rings, arising from beam resonant excitation of the electric field in the RF deflectors. In this paper numerical simulations are used to evaluate the effect and to show that the instability can be minimised by a proper choice of the tune of the ring, and of the parameters of the deflector and of the injection region lattice.

## 1 INTRODUCTION

In CLIC a high intensity electron beam, the drive beam, is decelerated in order to produce 30 GHz RF power for the acceleration of the main beams. The drive beam time structure is obtained in isochronous rings, by interleaving electron bunch trains in order to increase the beam current and the bunch repetition frequency [1]. A time-dependent closed bump is obtained in the combiner ring by using two transverse RF deflectors with a relative betatron phase advance of  $\pi$ . The septum is located half-way between the deflectors. At injection, each bunch train has a phase corresponding to the maximum deflection and is kicked onto the closed orbit. On the other hand, the phase of the circulating bunch trains is such that they see either a zero or a negative bump amplitude. Thus they avoid the septum and are kept circulating in the ring until the combination process is complete. The combined trains are then extracted using a conventional fast kicker.

The proposed deflectors, scaled from an existing design [2], are short traveling wave structures with negative group velocity working on a  $\text{EH}_{11}$  hybrid mode, with a phase advance of  $2\pi/3$  per cell. A potential concern is the beam loading effect on the fundamental mode. A bunch train passing through the structure couples to the mode through both the transverse and the longitudinal velocity. The transverse coupling in most practical cases is negligible, due to the small value of the transverse velocity. The longitudinal coupling takes place when the train is displaced with respect to the deflector axis (where the longitudinal field component is zero). In the case of perfect injection, the beam offset inside the deflector is in general very small, and the longitudinal coupling can also be neglected. However, if an injection error is present, it can induce a strong excitation of the fundamental mode (wake-field), in quadrature with the externally generated deflecting field. Since it is out of phase, such component does

not have a direct influence on the exciting train, but when the different trains are interleaved during combination, the bunch pattern is such that a mutual perturbation between trains can lead to an amplification of the injection errors.

A previous analysis in the case of the CLIC Test Facility CTF3, under construction at CERN, has shown that a proper choice of the ring betatron tune can minimize the effect [3]. In this paper we study the case of the CLIC RF power source, where two combiner rings are used. We will mainly concentrate on the second ring, whose deflectors have the higher RF frequency (3.75 GHz) and therefore the stronger coupling.

## 2 SIMULATIONS

### 2.1 Simulation Model

The single-pass wake-field from an electron bunch is evaluated using a linearization of the dispersion curve of the structure over an unlimited frequency range. This approximation is sufficient to model the multi-bunch wake-field when the bunch distance is small with respect to the filling time of the structure [3]. In fact in this case the excitation is virtually monochromatic, and therefore the details of the dispersion curve out of resonance are not relevant.

The approximation allows us to efficiently evaluate the multi-bunch wake build-up, including propagation effects. A tracking program is used to model the beam-deflector interactions during combination, over several turns in the ring. The bunches are treated like point-like charges. The  $\beta$ -function at the deflector locations is taken into account and the phase advance between them is kept fixed at  $\pi$ . The phase advance in the rest of the ring, described by a first-order transfer matrix, can be chosen independently.

The simulations confirm that the systematic effects, for perfect injection, are small. When considering beam jitter, they show that after an initial transient, the final position and angle of the bunches after combination reaches a steady state value, different for each train. Considering the maximum values of the final position and angle of all bunches and all trains, the effect can be described in terms of amplification of the initial error.

### 2.2 Simulation Results - Second Combiner Ring

In the second combiner ring of CLIC, the 130 ns long drive beam pulses are combined four by four; they have an energy of 2 GeV and each one is composed by bunches of 10 nC each, spaced by 8 cm. Initially, we have considered the injection parameters given in reference [1]. In particular, the horizontal  $\beta$ -function in the deflector is  $\beta_x = 10$  m

and the deflection angle is  $\theta = 2$  mrad. The deflector parameters are given in Table 1.

Frequency	3.75 GHz
Number of cells	10
Iris diameter	3.4 cm
Total length	26.6 cm
Group velocity	$-0.0233 c$
Filling time	38 ns
Deflection angle	2 mrad
Input power	40 MW
Wakefield amplitude	1.65 V/(pC m mm)

The amplification of an initial beam jitter has been evaluated for different ring tunes. The simulation results are summarized in Fig. 1. Even for an optimum phase advance, the amplification was found to be well above one. However, if the horizontal  $\beta$ -function is decreased, the beam offsets in the deflector are reduced, and a stable tune region appear, in particular, for  $\beta_x \simeq 3$ , (see Fig. 2).

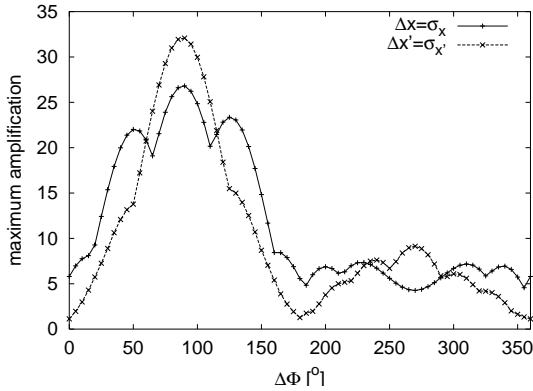


Figure 1: Amplification of an initial error (position and angle) as a function of the betatron phase advance in the ring, for  $\beta_x = 10$  m

In reference [1] the choice of the  $\beta$ -function was not optimised for beam stability, since a complete model of the multi-turn beam-deflector interaction was not yet available. It is clear that, for a given injection angle  $\theta$ , one must minimize  $\beta_x$ . The value of the  $\beta$ -function is linked to the injection region parameters by the formula:

$$\theta \geq \frac{n\sqrt{\beta_{x,s}\epsilon_{x,r}} + x_s}{\sqrt{\beta_x\beta_{x,s}}} \quad (1)$$

where  $\beta_{x,s}$  is the  $\beta$ -function at the level of the septum,  $x_s$  is the effective septum thickness,  $\epsilon_{x,r} = \epsilon_{x,n}/\gamma$  is the horizontal rms real emittance and  $n$  is a margin for beam clearance. For instance, in the simple case of a FODO lattice, for which  $\beta_{x,s} = \beta_x = 3$  m, considering  $\epsilon_{x,n} = 150\pi$  mm mrad, an angle  $\theta = 2$  mrad gives a maximum septum thickness of 2.6 mm with a clearance factor  $n = 10$ .

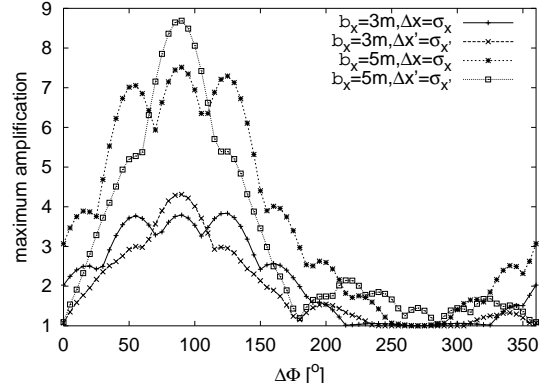


Figure 2: Amplification of an initial error as a function of the betatron phase advance in the ring, for  $\beta_x = 3$  m and  $\beta_x = 5$  m

An additional margin for the septum thickness can be obtained by using a less straightforward optics and increasing  $\beta_{x,s}$  while keeping  $\beta_x$  constant. It must be noted that, with respect to the parameter set given in [1], the drive beam energy has been increased from 1.23 GeV to 2 GeV, therefore the RF power needed for the same deflector parameters and deflection angle was increased from 15 MW to 40 MW. Such a value seems to be reasonable for power sources in this frequency range, as is the corresponding peak surface field in the deflector (55 MV/m) [4]. Therefore, by choosing  $\beta_x \leq 3$ , the beam appears to be stable, and a realistic set of parameters has been found.

### 3 SCALING CONSIDERATIONS

#### 3.1 Dependence from the $\beta$ -function

So far we have shown that, for a fixed injection angle,  $\beta_x$  must be minimum in order to improve beam stability. In view of a more general optimization we present some simple scaling laws, which help to better understand the constraints of the design. For simplicity it is assumed that the systematic beam displacement (for perfect injection) inside the deflector can be neglected compared to the initial offsets. For the deflector length  $L_D$  considered here, the fill time is much smaller than the train length. Therefore a bunch at the end of the train sees a wakefield created by  $N \propto L_D$  preceding bunches. Since the wakefield kick due to a single bunch is also proportional to the structure length, the total deflection one finds for a constant offset of all bunches is  $\delta x' \propto L_D^2$ .

The main source of position error at the RF-deflector is expected to be beam jitter. A static offset can be corrected using beam-based alignment; this will need to be studied in detail in the future. The beam jitter scales as the beam size, so for the same relative error the wakefield kick in the RF deflector is proportional to  $\sqrt{\beta_x}$ . The normalised kick is thus  $\delta x'/\sigma_{x'} \propto \beta_x$ . The overall dependence of the deflection is consequently  $\delta x'/\sigma_{x'} \propto L_D^2 \beta_x$ .

The necessary RF deflector length is proportional to the deflection angle  $\theta$ . If one neglects details of the combiner ring lattice, the minimum acceptable deflection angle is proportional to the divergence of the beam at the deflector, because the different incoming beams have to be well separated in phase space. This can be seen from Eq. 1, assuming  $n\sqrt{\beta_x s \epsilon_{x,r}} \gg x_s$ , and leads to  $L_D \propto \theta \propto \sqrt{1/\beta_x}$ . Using this proportionality in the expression for the wakefield kick results in  $\delta x' / \sigma_{x'} \propto L_D^2 \beta_x = \text{const.}$

In spite of the approximations used in its derivation, such simple scaling seems to be remarkably correct, as can be seen from the simulation results shown in Fig. 3. One can thus conclude that the choice of the injection angle should be based on practical considerations.

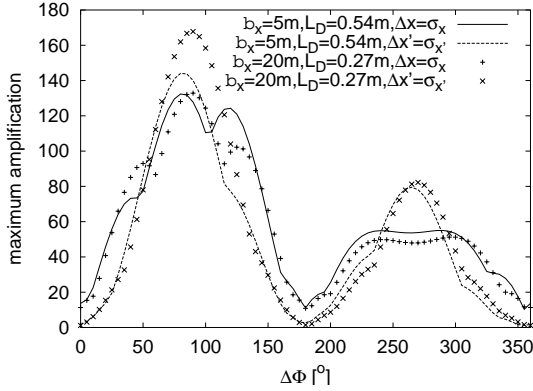


Figure 3: Amplification of an initial error as a function of betatron phase advance in the ring, for two different values of  $\beta_x$  and of the deflector length. The amplification is very similar in both cases, when  $L_D^2 \beta_x$  is kept constant.

### 3.2 Scaling with the RF frequency

In the first CLIC combiner ring, the combination factor is also four; the 10 nC bunches are spaced by 32 cm at injection, and the deflector frequency is 937.5 MHz. We have already mentioned that the beam stability in this ring is of less concern, since the coupling is weaker. In the following we will give a justification for this statement, based on scaling arguments. The total deflection corresponding to an RF power input  $P_{in}$  is:

$$\theta = \frac{\sqrt{1/v_g \omega r' P_{in} L_D}}{E_{beam}} \quad (2)$$

where  $\omega = 2\pi\nu$ ,  $r'$  is the shunt impedance per meter,  $v_g$  is the group velocity and  $E_{beam}$  the beam voltage. If the deflector geometry is scaled linearly with the frequency,  $v_g = \text{const.}$ ,  $L_D \propto 1/\nu$  and  $r' \propto \nu$ . In this case the RF power needed to obtain a given deflection angle is independent from the frequency. On the other hand, the maximum integrated wakefield kick due to an offset bunch train in such a structure is given by:

$$\delta x' = \frac{\omega^3}{4\pi c^2} \frac{r' L_D^2}{E_{beam}} q_b \Delta x \quad (3)$$

where  $\Delta x$  is the train offset and  $q_b$  is the bunch charge. Using Eqs. 2 and 3, one then get  $\delta x' \propto \nu^2$ . Therefore, when following a simple linear scaling of the deflector, and keeping the injection angle and the  $\beta$ -function constant, the stability in the first ring is improved with respect to the second ring. It must be noted that an even more favourable scaling can be obtained by increasing the power in the first ring deflectors and reducing their length, if the limiting factor is the peak surface field (which scales as  $\sqrt{c^2/v_g \omega r' P_{in}} \propto \nu \sqrt{P_{in}}$ ), rather than the available power.

## 4 CONCLUSIONS

A tracking simulation code has been used to evaluate the beam transverse stability in the combiner rings of the CLIC RF power source. It has been shown that a proper choice of the ring tune and of the  $\beta$ -function in the RF deflectors minimises the effect of wakefields. Scaling arguments have also shown that the injection angle has a small influence on the beam stability if the minimum  $\beta$ -function compatible with the injection angle is adopted. The choice of the injection angle can then be based on practical considerations.

The beam has been found to be stable in the second combiner ring for a realistic set of parameters. The stability in the first combiner ring, whose deflectors operate at an RF frequency four times lower (937.5 MHz rather than 3.75 GHz) can then be deduced from scaling considerations.

## 5 ACKNOWLEDGMENTS

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## 6 REFERENCES

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