STUDIES ON BEAM LOADING IN THE CLIC RF DEFLECTORS

David Alesini, Caterina Biscari and Andrea Ghigo, LNF-INFN, Frascati (Italy)

Abstract

After a short description of the Frequency Multiplication Scheme of the CLIC drive beam we present the impact of beam loading in the RF deflectors on the beam dynamics. First order scaling laws for the beam loading have been obtained to compare the effects in CLIC with those in the Test Facility CTF3. A dedicated tracking code has been written to study the multi-bunch multi-turn beam dynamics and the results are presented. Possible solutions to mitigate the beam loading effects such as the use of multiple RF deflectors are shown.

INTRODUCTION

The CLIC Drive Beam is accelerated by the fully loaded 1GHz Linac up to 2.37 GeV in 140 μsec pulses. The average beam current of 4.2 A is multiplied by a factor of 24 along the Frequency Multiplication System (FMS), where the bunch trains are recombined and the 12 GHz time structure is created in 240 nsec trains. Three recombination stages are foreseen: a Turn Around (TA) for the first factor of 2, a first Combiner Ring (CR1) for a factor of 3, and a second one (CR2) for the last factor of 4. The length of these three systems is determined by the temporal structure of the drive beam, and is shown in Table 1, together with the drive beam and FMS main parameters.

The FMS design [1] is optimized to preserve transverse and longitudinal beam emittances: isochronicity, smooth linear optics, low impedance vacuum chambers and diagnostics, HOM free rf active elements are foreseen.

All ring and turn around arcs are based on the same isochronous cell characteristics: three dipoles, with two symmetric quadrupole triplets, based on the structure used in the CTF3 combiner ring. From the single particle dynamics point of view the energy acceptance is the most critical issue: isochronicity is obtained by means of strong horizontal focusing, which implies high chromaticity. Sextupole configuration, used both to correct the non linear momentum compaction and the chromaticity, is optimized not to limit the energy acceptance and not to produce loss of isochronicity for off-energy particles.

In each ring the arc length, the dipole length and angle are set taking into account the optimization based on the available space and on the minimization of coherent synchrotron radiation effects on the bunch longitudinal emittance.

The bunch recombination is obtained by using RF deflectors, whose frequency can be chosen as the minimum dictated by the bunch frequency and recombination factor or as one of its multiples. Both standing wave (SW) and travelling wave (TW) structures can in principle been used. The beam loading due to the high current through the rf structures must be carefully considered to define the deflector parameters, and is the subject of this paper. In particular we will analyze the beam loading effects in the CR1 and CR2 assuming TW rf deflectors.

Table 1: Drive beam and FMS main parameters

	TA	CR1	CR2
Beam energy E [GeV]	2.37		
Emittance [mm mrad]	<100		
Bunch charge [nC]	8.4		
Energy spread [%]	< 1.		
Multiplication factor	2	3	4
Length L [m]	146	292	438
Final bunch distance [cm]	30	10	2.5
Final average current [A]	8.4	25	100
Deflector RF frequency [GHz]	t.b.d.	2	3

SCALING LAWS OF BEAM LOADING IN TW RF DEFLECTORS

The beam loading in RF deflectors is generated by the interaction between the beam current and the longitudinal electric field component of the deflecting off-axis modes. The unwanted deflecting field can be excited by the beam if it passes off-axis into the deflectors both in the horizontal and in the vertical planes. Beam loading in RF deflectors of both CR and DL of CTF3 has been widely studied [2,3].

Let us consider the case of a TW RF deflector. Fig. 1 shows as an example the case of a single bunch of charge q injected into the CR (ϕ is the injection angle, x is the horizontal deflection direction). The trajectory, in case of perfect injection and constant deflecting field, is parabolic and the off-axis of the beam at the entrance of the deflector is x_{in}. From the plot it is easy to understand that, due to the off-axis passage of the beam in the deflector, we have beam loading effects in the deflecting plane even in the case of perfect injection.

Let us consider the case of a recombination factor 4. The transverse deflecting field "seen" by a trailing bunch that passes into the deflector after $T_{RF}/4$ is given by [2]:

$$E_T = \frac{1}{2} q \frac{\omega_{RF}^2}{c} \frac{R}{Q} x \left(z - \frac{T_{RF}}{4} v_g \right) \qquad (1)$$

where the R, Q and v_g (*) are the transverse shunt impedance, the quality factor per unit length and the

* In general the TW RF deflectors are backward structures and v_g is negative.

group velocity of the deflector, and *x(z)* is the trajectory of the leading bunch.

Since in general $v_g \ll c$, from eq. (1), it is straightforward to note that the total transverse voltage "seen" by the trailing charge is proportional to the yellow area under the leading particle trajectory of Fig. 1, it means that $V_T \propto \phi L^2_{defl}$. If we consider N bunches injected into the CR with a time distance equal to T_{RF}, the wakes generated by all bunches add each other and we have, after one filling time of the structure, the situation sketched in Fig. 2. Each bunch generates a wake that propagates into the structure according to the negative group velocity. The total deflecting voltage "seen" by a trailing particle is in this case $V_T \propto \phi L^3_{defl}/v_g$.

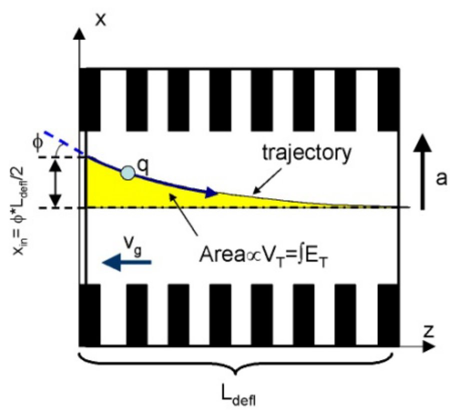

Figure 1: Sketch of a single bunch injected into the CR.

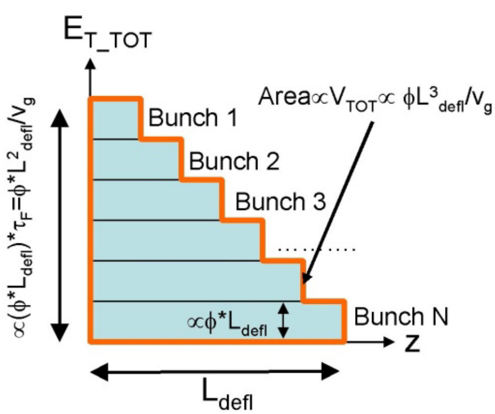

Figure 2: Sketch of a total wake generated by N bunches.

From previous consideration it is possible to find a general scaling law for the beam loading effects. The induced oscillation amplitude ($\langle x_{osc} \rangle$) in the bunch train is proportional to the total induced voltage in the deflectors divided by the beam energy (E_0) and therefore:

$$\langle x_{osc} \rangle \propto \phi \frac{q}{E_0} f_{RF}^2 \frac{R}{Q} \frac{L_{defl}^3}{v_g} = q \phi^4 E_0^2 P_{IN}^{-3/2} f_{RF}^0 \xi(a/\lambda_{RF}) \quad (2)$$

where P_{IN} is the maximum available power to feed the RF deflectors and $\xi(a/\lambda_{RF})$ is a function of the ratio between the deflector iris radius (*a*) and the wavelength. This function takes into account the dependence of the *R/Q* and v_g from the iris radius. Typical behaviours of the ξ function show that it has a broadband maximum in a wide range of a/λ_{RF}.

One interesting results from eq. (2) is that the beam loading effects do not depend on the RF frequency of the deflectors. This is due to the fact that if we increase the frequency we increase both the efficiency and the wakes intensities. Moreover if we consider the CTF3 parameters [4] and the CLIC ones (Table 2) it is easy to verify that, fixing the value of the maximum available input power, the effects of the beam loading in CLIC are three orders of magnitude bigger that in CTF3. This means that in the CLIC case the beam loading is a crucial point even in the case of perfect injection.

To overcome this problem one has to simultaneously increase the input power thus reducing the deflector length and use, instead of a single deflector, N deflectors fed in parallel (with the same total length). In this case, according to the sketch of Fig. 2, we can reduce the effects of the wake as N^2.

DEFLECTOR PARAMETERS AND TRACKING RESULTS

The tracking code already written for the CTF3 beam loading studies [2] has been modified to calculate the effects of the beam loading in CLIC. The code allows studying both the case of perfect injection ("systematic effect") and the case of injection errors, also considering more deflectors.

The final RF deflector parameters are reported in Table 2. In the case of CR1 the recombination factor 3 mitigates the beam loading effects with respect to CR2 because the beam loading is not perfectly 90 deg out-of-phase. For this reason the number of multiple deflectors (*N*) can be limited (for CR1) to 2.

Systematic Effects

The ratio between the output Courant-Snider (CS) invariants of each bunch and the nominal projected emittance has been calculated for different phase advances between the two deflectors and for different horizontal β-function at the deflectors (β_{x_defl}).

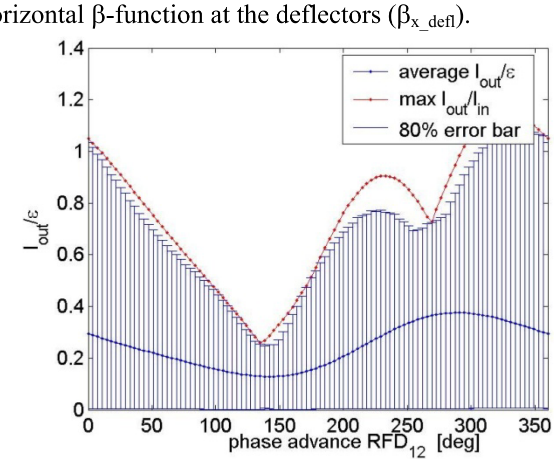

Figure 3: Ratio between the output CS invariants of bunches and the nominal projected emittance for CR1.

Figs. 3 and 4 show this ratio for the CR1 and CR2, without injection errors, assuming β_{x_defl}=4m and 2m, respectively. The results show that the beam loading is controllable even if more critical with respect to the CTF3 case.

Table 2: RFD parameters for CR1 and CR2

	CR1	CR2
Working frequency f_{RF} [GHz]	2	3
Total deflectors length L_{defl} [m]	1.1	1.1
Number of multiple deflector N	2	6
R/Q [Ohm/m]	1450	1350
Total input power P_{IN} [MW]	35	35
Av. diss. Power per unit length [kW/m]	47	62
Iris aperture a [cm]	2	2
Pulse length [μs]	140	140
Repetition rate [Hz]	100	100
Group velocity/c [%]	1.55	2.17

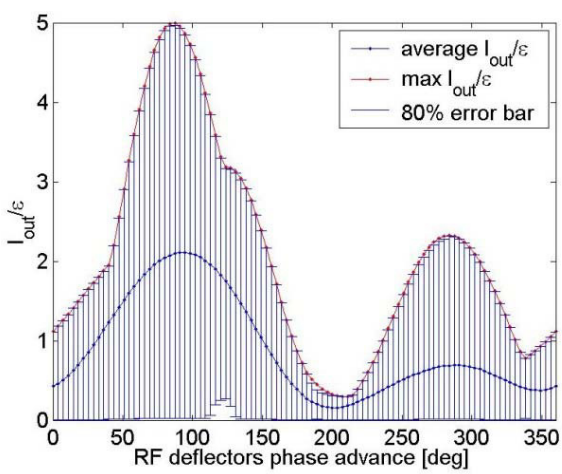

Figure 4: Ratio between the output CS invariants of bunches and the nominal projected emittance for CR2.

Injection Errors

The case of injection errors has also been explored. According to previous beam loading calculations [2,3], in this case, we have considered injection errors in angle and/or in phase located in an ellipse with a CS invariant equal to the projected emittance of the beam. Figs. 5 and 6 show, as example, the amplification factor of an initial error in position as a function of the phase advances between the two deflectors. Similar results can be obtained considering other injection errors. From the plots it is easy to note that the amplification factor can lower than a factor 10 in a wide range of CR tunes.

CONCLUSIONS

First order scaling laws for the beam loading effects in the drive beam RF deflectors have been found. They show the much more criticality in the CLIC CR compared to the CTF3 case. Simulations with the tracking code have confirmed these predictions. Multiple deflectors per ring have to be used to mitigate the BL effects. This is equivalent to use a strongly damped system. The use of multiple deflectors complicates the design from the power distribution and RF points of views since each sub-deflector has to be fed with the nominal input power. Results of the tracking code simulations have been finally illustrated. They show that with a proper choice of the number of multiple deflectors and machine parameters the BL effects can be controlled.

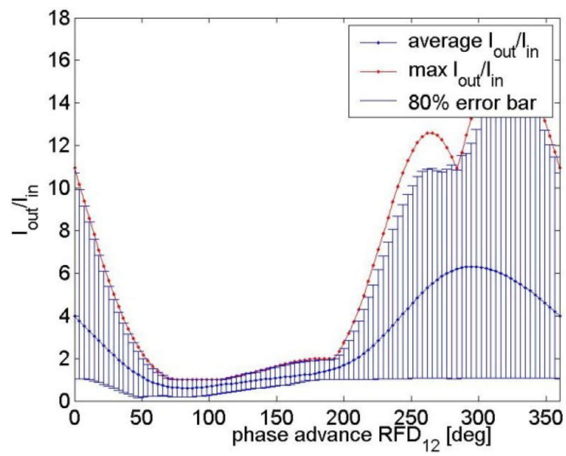

Figure 5: Amplification factor for an initial error in position (CR1).

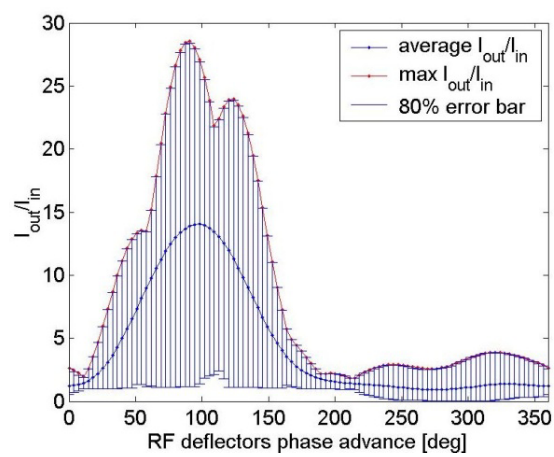

Figure 6: Amplification factor for an initial error in position (CR2).

REFERENCES

[1] C. Biscari et al., "CLIC Drive Beam Frequency Multiplication System design", PAC09 Conference Proceedings.
[2] D. Alesini, et al., "Effects of the beam loading in the rf deflectors of the CLIC test facility CTF3 combiner ring", PRST-AB, **7**, 034403, 2004.
[3] D. Alesini and F. Marcellini., "RF deflector design of the CLIC test facility CTF3 delay loop and beam loading effect analysis", PRST-AB,12,031301 2009.
[4] CERN Report No. PS 2002-008 (RF), Geneve, 2002.