ELECTRON BEAM COMBINATION BY RF DEFLECTORS: TOLERANCE AND REQUIREMENTS

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Abstract

In the framework of the new Compact Linear Collider (CLIC) Test Facility CTF3, it is planned to perform a demonstration of the bunch frequency multiplication process on which the CLIC drive beam generation scheme is based. This process relies on the combination of electron bunch trains in isochronous rings using RF deflecting cavities. Specific requirements are imposed on both the beam characteristics and the RF amplitude and phase in the deflectors. In this paper, we study and specify these requirements in the case of the Preliminary Phase of CTF3.

1 INTRODUCTION

The CLIC [1] RF power source is based on a two beam acceleration scheme which requires electron pulse compression and bunch frequency multiplication [2]. The goal of the new CLIC Test Facility CTF3 is to demonstrate the technical feasibility of this scheme. The first phase of this facility (Preliminary Phase) aims at testing the bunch combination scheme at low charge, for a multiplication factor from three to five [3]. The principle relies on the injection of short electron bunches into an isochronous ring using transverse RF deflecting cavities in order to achieve the frequency multiplication. Firstly, this injection mode imposes specific requirements on the beam characteristics and especially on the bunch length. Secondly, the amplitude and phase of the RF wave in the deflectors must be stable enough to avoid beam losses and instabilities. After a short description of the RF deflectors, all these requirements are analysed and the tolerances are specified according to simulations of the injection process using the RF deflectors.

2 RF DEFLECTING CAVITIES

For the Preliminary Phase of CTF3, it is planned to use existing RF deflectors. They are short, travelling wave, iris-loaded structures for which the fundamental mode is a deflecting mode, with a phase advance of $\pi/2$ per cell and a negative group velocity. Each deflector has an overall length of 27 cm, with six regular cells (and the two couplers) and an iris diameter of 2.3 cm (2.1 cm in the coupler cells). In this type of cavity, the deflecting force is uniform in strength and direction over the aperture [4]. The voltage attenuation along the structure is characterised by the constant α and the deflection angle is given by

$$\phi = \frac{\sqrt{ZP}}{E}\left(\frac{1-e^{-\alpha L}}{\alpha}\right)$$

where P is the input power, L is the total active length, E is the electron beam energy, and Z is the series impedance defined as

$$Z = \frac{R}{Q}\frac{2\pi}{\lambda_0}\frac{1}{\beta_g}$$

where R is the shunt impedance, λ_0 is the RF wavelength, Q is the quality factor, and β_g is the normalised group velocity.

When using the RF deflector parameters given in [5], a reference injection angle of 4.5 mrad at 350 MeV is found for a 7 MW input power. The two deflectors will be powered by the same klystron. A phase shifter and a variable attenuator allow relative phase and amplitude adjustments.

New deflectors with a larger aperture will be used in the following phases of CTF3. Two prototypes [6], build by INFN-Frascati, should be ready in 2002 for testing in the Preliminary Phase.

3 BEAM REQUIREMENTS

3.1 The Injection scheme

The deflectors are located in the ring with a betatron phase advance of π between them, so that they produce a time-dependent closed bump of the reference orbit, allowing the interleaving of the bunch trains.

The angle required for injection is given by both the geometry of the injection region and the optics. If μ_x is the horizontal phase advance between the deflector and the septum, if β_s and β_d are the values of the horizontal β-function at the septum and the deflector locations, then the angular kick is

$$\theta = \frac{x}{\sqrt{\beta_s\beta_d}\sin\mu_x} \qquad (1)$$

where x is the distance between the centre of the injected beam and the centre of the machine aperture at the location of the septum. Given the geometry of the vacuum chamber in this region and the septum thickness, equation (1) gives a nominal deflection angle of the order of 4.5 mrad.

3.2 Bunch Length Tolerances

For the injected beam, the angular kick is maximum and the centre of the injected bunch is located on the crest of the RF wave in the deflectors. For the nominal frequency multiplication factor of five, the centres of the four circulating bunches are located on the RF wave with phases of $\frac{2\pi}{5}$, $\frac{4\pi}{5}$, $\frac{6\pi}{5}$, $\frac{8\pi}{5}$ from the crest. The variation of the kick with the location of the bunches on the cosine curve is shown in Figure 1.

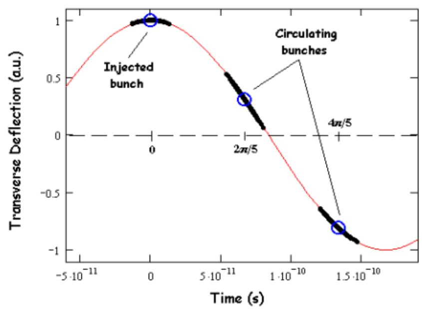

Figure 1: Kick amplitudes for injected and circulating bunches for a combination factor of five. The next two circulating bunches are symmetrically located on the curve with respect to the minimum of the cosine. The longitudinal extension corresponds to $\pm 2\sigma$ Gaussian distribution with a length of 4.5 ps rms.

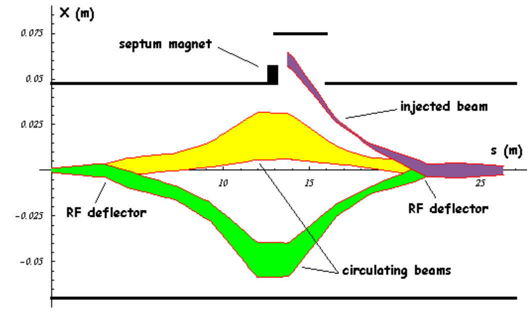

Figure 2: Beam envelopes of the bunches of Figure 1. From top to bottom: injected bunch, circulating bunches with phase $\frac{2\pi}{5}$ and $\frac{4\pi}{5}$. The lines are the limits of the vacuum chamber and the rectangle stands for the injection septum.

As a consequence of the phase extension, the head and the tail of the circulating bunches experience different deflection angles. This enlarges the transverse size of the circulating beam in the region between the two RF deflectors. This effect represents the dominant contribution to the beam size at the level of the septum. The main constraints on the size of the beam are the limit of the vacuum chamber and the thickness of the septum in the chamber. In order to limit the phase extension, short bunches are essential, and simulations have shown that the maximum acceptable bunch length is around 6.5 ps rms for a combination factor of five. Figure 2 shows the envelopes of Gaussian bunches of length 4.5 ps rms (truncated longitudinally at $\pm 2\sigma$, with a 2σ extension in the transverse plane) in the injection region. The deflection angle on the crest corresponds to 4.5 mrad.

4 RF DEFLECTORS REQUIREMENTS

4.1 RF Deflector Model

In order to study the tolerances on the RF deflectors, a simple analytic model of the deflecting cavities was elaborated within the framework of the MAD program [8]. The RF deflector is described as a thin element with transfer matrix elements up to the second order such that, if x denotes the horizontal particle position,

$$\begin{aligned} x' = & - A\cos(\phi) \\ & + [2\pi\nu A\sin(\phi)]\,t + [A\cos(\phi)]\,\frac{\Delta p}{p} \\ & + [2\pi^2\nu^2 A\cos(\phi)]\,t^2 \end{aligned} \quad (2)$$

where A is the kick amplitude, ϕ the RF phase, ν the RF frequency of 2.99855 GHz, t the time coordinate of the particle and $\frac{\Delta p}{p}$ its energy spread. The zero order term represents the horizontal kick received by the beam in the transverse deflector. The sign is negative since the beam is injected from inside the ring [3]. The first and second order terms in time give the dependence of the kick with respect to the bunch length. The first order term in energy describes the dependence of the kick on the energy.

A constant phase shift is added turn after turn to compensate for the time delay introduced by the bump between the two deflectors. This delay varies from one turn to the next (depending on the bump in the deflectors), so that only a correction of the mean value is experimentally feasible.

In order to take into account the restricted aperture of 23 mm in the deflectors, circular collimators are added at the deflector locations. Another restriction is set around the septum where the amplitude of the bump is maximum and where possible particle losses might occur.

4.2 Tracking with RF deflectors

The initial conditions for the tracking correspond to a transverse matched beam at the end of the injection line with transverse normalised rms emittances of 15 π mm mrad and with a nominal bunch length of 3 ps rms (Gaussian distribution truncated at $\pm 2\sigma$), corresponding to the measured value in 2001 [7]. The main contribution to the energy spread is taken into account by calculating the phase extension of the bunches on the 3 GHz RF wave during the acceleration in the linac. The tracking is done for 1000 particles at the nominal energy of 350 MeV and for the nominal injection angle of 4.5 mrad. All graphs sketch the beam coordinates at the ejection point in the ring.

By tracking the bunches turn by turn, it is possible to simulate the bunch combination factor of five. Figure 3 shows the reference situation without and with the energy spread. In this latter case, about 5% of the particles are lost in the last turn, mainly in the restricted aperture of the deflectors. Chromatic effects are visible when adding the initial energy spread. However, the beam stays within the vacuum chamber acceptance (diameter of 10 cm).

Figure 4 compares the phase space of a beam injected using the standard injection kicker with the final phase space after a bunch combination of factor five. The statistical calculation of the emittance indicates an emittance growth by 40%, which is still acceptable for the demonstration of the combination.

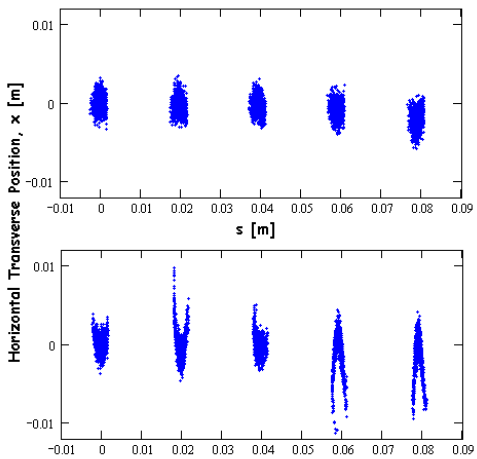

Figure 3: Simulated bunch combination factor of five: horizontal transverse position versus longitudinal abscissa. Top: without energy spread. Bottom: with energy spread.

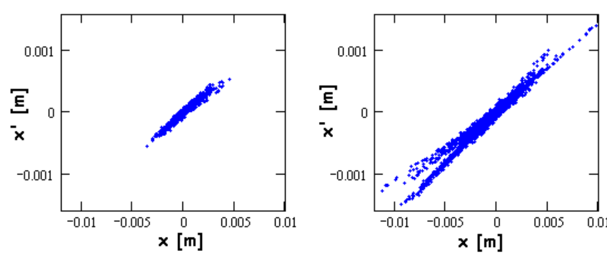

Figure 4: Simulated phase space at the ejection point. Left: using standard injection with kickers. Right: after bunch combination factor of five.

4.3 Tolerances Studies

The model described above was used to study the tolerances on the phases and the amplitudes in the deflectors. These parameters are related to the stability of the RF power produced by the klystron-modulator.

Figure 5 shows the two different types of phase errors that were studied. A relative systematic error of five degrees in the second deflector produces important losses of the order of 40% on the second deflector aperture restriction. These losses are reduced to less than 1% if the aperture is increased from 23 mm to 40 mm, as foreseen for the new RF deflectors. This kind of relative error can easily be corrected. On the other hand, a phase error on both deflectors does not have an important effect on the bunch position and the bunches are still within the physical acceptance of the machine with losses below 5% for a ± 5 degree variation, which is much larger than the measured phase stability at the klystron exit ($\pm 2°$).

Simulations with kick errors show that a variation of $\pm 3\%$ on the nominal amplitude on both the RF deflectors would lead to losses between 28% for a negative variation and 3% for a positive one. The positions of the bunches are affected by less than one centimetre, which is acceptable for our experiment.

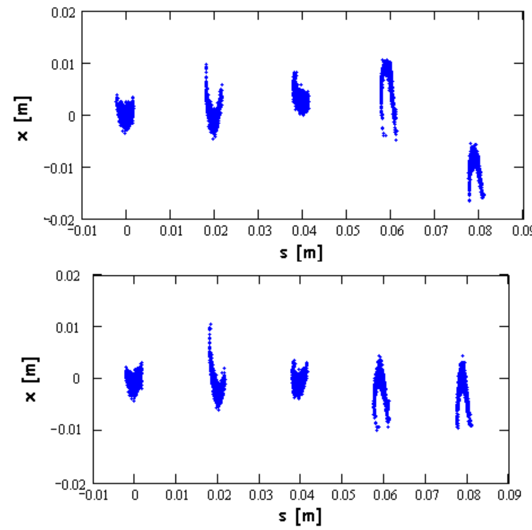

Figure 5: Simulated bunch combination factor of five with phase errors on the RF deflectors. Top: Relative phase error of $5°$ between the first and the second deflector, losses are close to 40%. Bottom: Phase jitter of $-5°$ in both deflectors, losses are below 5%.

5 CONCLUSION

The studies on electron beam combination have shown that the use of the existing RF deflectors in the Preliminary Phase of CTF3 is possible. For the beam, the main constraint is the bunch length which must be shorter than 6.5 ps rms to minimise the bunch transverse extension in between the two deflectors. In the deflectors, the restricted aperture of 23 mm induces important losses for amplitude variations above $\pm 3\%$ of 4.5 mrad, whereas phase variations of $\pm 5°$ are still acceptable.

6 REFERENCES

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