THE CLIC MAIN LINAC BUNCH COMPRESSOR

T. E. d'Amico, G. Guignard, CERN, Geneva, Switzerland
T. Raubenheimer, SLAC, Stanford, USA

Abstract

The latest version of the CLIC parameters implies the acceleration in the main linac of a train of bunches with a very short bunch length, around 50 μm rms and an uncorrelated fractional energy spread at injection of about 1 %. On the other hand, the damping ring design imposes a starting bunch length of 3 mm and a fractional energy spread of about 0.08 %. This paper describes the bunch compression chain which achieves the required compression for both positrons and electrons. Criteria taken into account in the choice of the compression ratios at different stages are outlined as well as the main parameters for the first order design. Results of tracking in the longitudinal plane including high order magnetic effects and wakefields are reported. Finally, multibunching is considered and its consequences studied. This analysis shows that the proposed system is able to provide the beam with the required characteristics at the entrance to the main linac .

1 INTRODUCTION

The CLIC study covers a decade-wide range of the centre-of-mass energy obtained in the Final Focus Region [1]. As a result of general scaling laws [2], one of the conditions to reduce the dilution effect of transverse wakefields on the vertical emittance is to accelerate in the main linac a very short bunch. The parameters table of ref. [1] shows that for centre-of-mass energies between 0.5 and 5 TeV the length of the bunch should be between 50 μm and 25 μm respectively. The damping ring of the CLIC main linac is designed to deliver a beam at the energy of 1.98 GeV, bunched at the RF frequency of 3 GHz, of relative energy spread $\sigma_E = \frac{\Delta E}{E_0} = 0.082$ % (rms) and of length $\sigma_z = 3.0$ mm (rms). Thus a compression rate between 60 and 120 has to be achieved. A bunch compressor should be placed before the acceleration of the injector linac which brings the beam from the energy of 1.98 Gev up to that of 9 GeV, in order to reduce the effect of inhomogenous acceleration inside the beam due to its finite bunch length. It cannot be used for the full compression because the relative energy spread at its exit would be too high (4.92 % and 9.84 % respectively) to be accepted in the following optics. As a compromise a compression factor of 12 is chosen which brings the relative energy spread up to an acceptable value of 0.98 % while squeezing the bunch to a length of 250 μm to be compared with the RF wavelength of 0.1 m. At the same RF frequency of 3 GHz, the RF voltage required by the second stage becomes prohibitive.

To benefit from both higher gradients and a larger RF frequency it was decided to place the second stage of bunch compression at the very beginning of the main linac. Its compression rate will vary from 5 to 10 to obtain the required bunch lengths at 500 GeV and 5 TeV respectively. This paper will be limited to the two values 5 and 8.33 (corresponding to the energies of 500 GeV and 1 TeV for the first value and of 3 TeV for the second one which is the energy chosen to optimise the CLIC design [1]). Thus the first compressor will not change when the collision energy is increased which is coherent with the fact that the injector complex should not be modified during an energy upgrade. The presence of many bunches per pulse introduces shifts in the bunch position due to the effect of long range longitudinal wakefields generated in the 30 GHz RF cavities of the second bunch compressor. Several mechanisms have been proposed to compensate this effect [3],[4],[5]. It will be shown in Section 4 that they can be dealt with in CLIC. As a consequence it is no longer necessary to consider complicated schemes like "180 degrees" compression [4] and the well known $\frac{\pi}{2}$-type bunch compression which can easily be modeled analytically to first order is chosen. Its principle is described in Section 2. Section 3 deals with the magnetic chicane which implements the second pseudo-rotation in the longitudinal phase space. Section 4 describes the multibunch effect and Section 5 gives the results of the tracking program .

2 THE BUNCH COMPRESSOR MODEL

The first order analytical model of a $\pi/2$-bunch compressor is well documented in the literature and only the main results will be reported in this section. Basically a $\pi/2$-bunch compressor consists of two pseudo-rotations in the longitudinal phase space. The first one is obtained through an RF system working at an RF phase $\phi = k\pi$, which linearly correlates the relative momentum of a slice inside the bunch, with its distance from the centre. The second pseudo-rotation is achieved by a magnetic system which according to the sign of its parameter R_{56} forces high momentum slices of the bunch to travel longer ($R_{56} > 0$) or shorter paths ($R_{56} < 0$). The beam being ultra-relativistic the speed of each slice is nearly the same and very close to the speed of light c. Thus a slice which travels a longer path will be caught up by the other slices which travel shorter paths. A magnetic chicane, which has a negative R_{56}, has been selected for its simplicity and the availability of closed form expressions for its most important parameters. Thus the RF phase should be $\phi = k\pi$ with k odd. Assuming that the RF frequency f_{RF} is much larger than $\frac{c}{2\pi\sigma_z}$ and that the beam distribution in the longitudinal phase space is a bi-dimensional Gaussian. The standard deviations of the bunch length and relative energy spread are σ_z and $\sigma_{\Delta E/E}$ respectively. To simplify notations let us write σ_E instead

of $\sigma_{\Delta E/E}$.
Then we obtain the following expressions for the RF voltage V and R_{56} [6],[7] :

$$V = a\frac{\sigma_E}{\sigma_z}c_R\sqrt{1-1/c_R^2}$$
$$R_{56} = \frac{\sigma_z}{\sigma_E c_R}\sqrt{1-1/c_R^2}$$

where $a = Ec/2\pi f_{RF}$ and $c_R = \sigma_{z,i}/\sigma_{z,f}$ is the compression rate. Similar expressions can be obtained for the subsequent stages [7]. Inserting the numerical values for an overall compression rate of 100, we get $V_1 = 103$ MV, $R_{56,1} = 0.304$ m, $V_2 = 1026$ MV and $R_{56,2} = 0.014$ m.

The finite length of the bunch will create a small distortion of the relative energy spread during the subsequent acceleration. This effect has been evaluated because it will translate into a distortion of the longitudinal profile after the second compression. It is negligible with the bunch lengths considered [7].

3 CHICANE OPTICS

The chicane retained in this paper contains no quadrupoles and consists of two parts, one being the mirror image of the other. Each part is composed of two rectangular dipoles, of length L_m and bending angle θ, separated by a drift space of length L. Thus the lattice is also symmetric from the optics point of view [7].

The horizontal transfer matrix of the chicane M_h is [7] :

$$M_h = \begin{pmatrix} 1 & 4\rho\tan\theta + 2\frac{L}{\cos^2\theta} \\ 0 & 1 \end{pmatrix}$$

Notice that the chicane is optically equivalent to a drift of length l :

$$l = 2\left(2L_m\frac{\tan\theta}{\theta} + \frac{L}{\cos\theta^2}\right) > l_c$$

where $l_c = 4L_m + 2L$ is the chicane length. The horizontal β-functions at the entry and exit of the chicane are given as equal for symmetry reasons. In this case we get [7] $\beta_i = \frac{1+\alpha_i^2}{2\alpha_i}l$. The minimum value of β_i is obtained for $\alpha_i = 1$ and is equal to l.

The dispersion is of course symmetric around the middle point of the central dipole where it reaches its maximum D_{max}. For small values of θ we obtain the following approximations $D_{max} \approx \theta(L_m + L)$ and $R_{56} \approx -2\theta^2\left(2L_m/3 + L\right)$. Finally expression (5) of [4] provides the growth of the normalised emittance (in mm·mrad) due to the chicane, for the minimum $\beta_i = l$:

$$\Delta\gamma\epsilon_x \approx 8.0\,10^{-2}E^6\frac{\theta^5}{L_m^2}\left(L + L_m + \frac{l}{2}\right)$$

The aim of chicane design is to minimise the magnetic field and the chicane length in order to reduce the effects of synchrotron radiation and the chromaticity perturbations due to high values of the β-function. It can be seen that the bending angle θ should be less than θ_0, defined by :

$$\tan\theta_0 - \theta_0 = -R_{56}B_{max}/(13.3424\,E)$$

where B_{max} and E are the maximum acceptable magnetic field (in Tesla) and the energy (in GeV) respectively. The minimum acceptable chicane length is then $13.3424E\theta_0/B_{max}$ which can be approximated for small θ by $8.1133\cdot\sqrt[3]{R_{56}E^2/B_{max}^2}$ [8]. Using these relationships we could optimise the two chicanes for the low energy bunch compressor (LEBC) and the high energy bunch compressor (HEBC) respectively. Their parameters are listed in Table 1 and their optical functions are shown in Fig. 1 and Fig. 2 respectively where they are matched to a typical FODO lattice by a triplet on each side.

Table 1: Parameters of the two chicanes

Parameter	Unit	1st Stage (LEBC)	2nd Stage (HEBC)
Energy	GeV	1.98	9
R56	m	-0.304	-0.014
Drift length	m	0.58	0.96
Dipole length	m	3.46	7.02
Overall length	m	15	30
Deflection angle	degrees	13	2
Bending field	T	0.433	0.149
$\Delta\gamma\epsilon_x$	mm · mrad	0.003	0.001

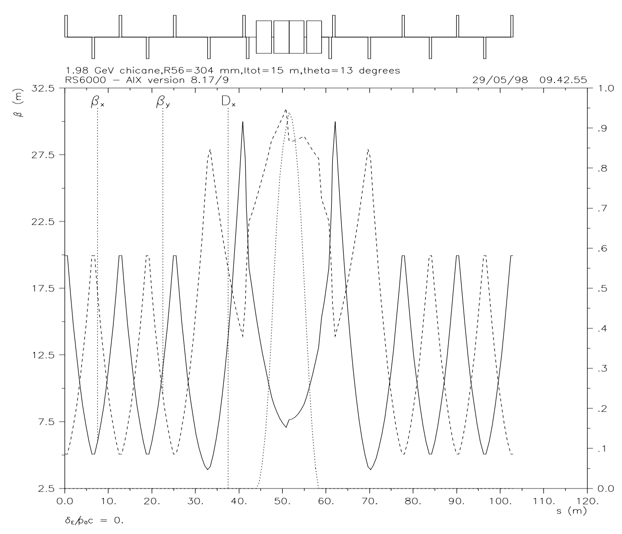

Figure 1: Optical functions of the LEBC chicane.

4 MULTI-BUNCH EFFECTS

The LEBC will not be significantly affected by the longitudinal wakes because the RF frequency is low (3 GHz). The situation is different for the HEBC where the RF frequency is very high (30 GHz). To rotate the bunch in the longitudinal phase space we use the standard main linac accelerating cavity TDS [1] working at phase π. The high modes of the longitudinal wakefield are rapidly damped and will not disturb the following bunches 20 RF periods apart [1].

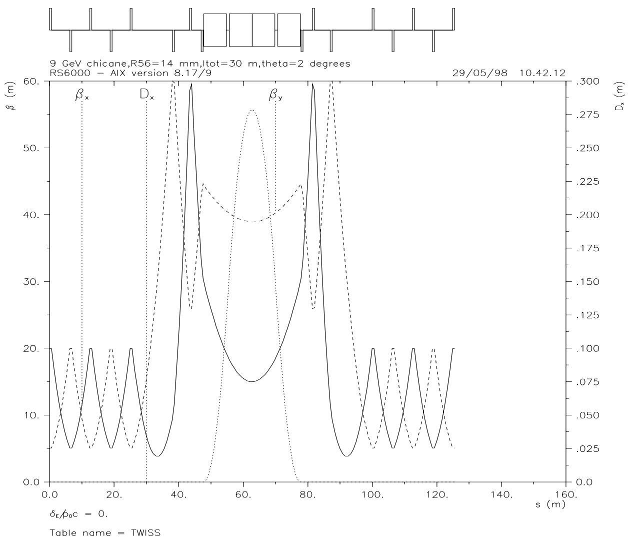

Figure 2: Optical functions of the HEBC chicane.

Unfortunately the main mode is not damped and will add up along the RF cavities used for the rotation. The relative beam loading is of the order of 22 MeV/m in the steady state regime which is reached after about 30 bunches [9]. This number corresponds to the filling time of the cavities. Hence the energy of the first 30 bunches decreases linearly. The largest decrease of the central energy of the bunch in steady state will be 150 MV which will cause a maximum displacement of the bunch after compression about 234 μm. This displacement has two effects. The collision rate is no more periodic and the bunches are accelerated slightly off crest. The first effect can be neglected because it affects the two beams of electrons and positrons in the same way . The second one is more serious because it adds an energy spread which can be estimated about 1.5 %. Possible cures could be to shorten the RF cavity or to adjust the phase of the accelerating RF for the steady state. As an example dividing the length of the cavity by two may reduce to 117 μm the bunch displacement and the energy spread to 0.38 %.

5 RESULTS OF TRACKING

The parameters of the two bunch compressors obtained to first order have been inserted into a longitudinal tracking program to investigate how the beam will behave when the higher order magnetic effects (of the chicane) and the strong wakefields are taken in account.

Fig. 3 and Fig. 4 show the longitudinal phase space before the compressor (horizontal scatter plot), after the RF pseudo-rotation (oblique scatter plot) and at the exit of the chicane (vertical scatter plot) for LEBC and HEBC respectively. The high order effects are small, only slightly lengthening the bunch by one micron.

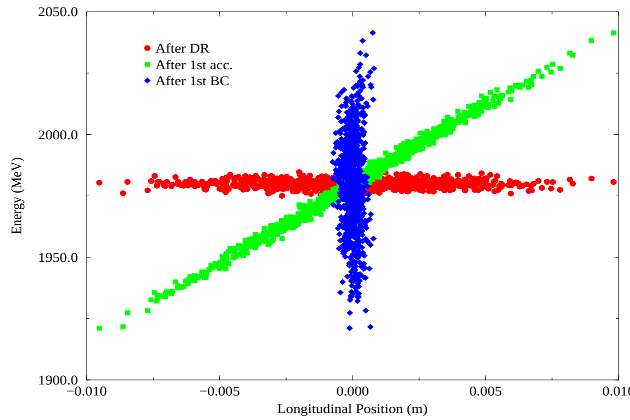

Figure 3: Longitudinal phase space during first stage (compression rate = 12).

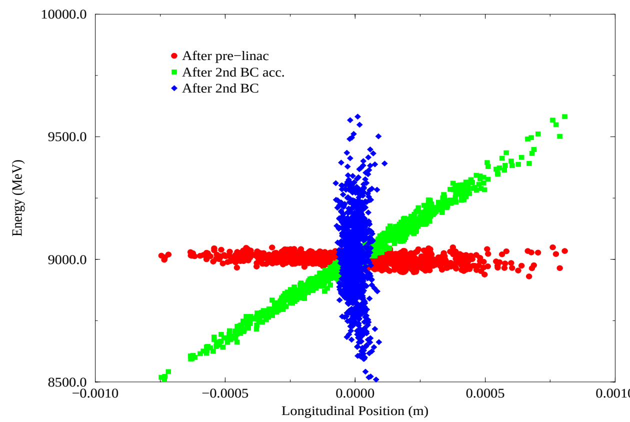

Figure 4: Longitudinal phase space during second stage (compression rate = 8.33).

6 REFERENCES

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