Preliminary Design of a Bunch Compressor for CLIC

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Abstract

All the variants of the injector complex for the CERN Linear Collider (CLIC) necessarily include the bunch compression needed to reduce the bunch length from its value at the damping-ring extraction to the required value at the main linac injection. In order to learn more on this issue, a preliminary design of a CLIC bunch compressor as a two-stage device was initialized. The main parameters of this device are presented, including the RF voltage required to generate the necessary rotation in the synchrotron phase space, the bending and focusing power essential to produce the needed momentum compaction, and the energy-spread and length of the bunch at the different stages. Design issues are discussed and results show that the system considered, without imperfections, is likely to do the job of transmitting the beam and producing the bunch characteristics desired for injecting into the main linac.

1. INTRODUCTION

The damping rings of the CERN Linear Collider (CLIC) are designed to provide a bunch length at their exit of 2.34 mm with a beam energy spread of 0.135% [1]. The required bunch length at the entrance of the main linac should be of the order of 0.17 mm with an r.m.s energy spread lower than 0.5%. A bunch compressor is then needed. Moreover, to reduce the transverse emittance dilution in the main linac due to the wakefields, it is advisable to shape the beam to obtain more steeply rising flanks [2]. This can be achieved by taking advantage of the important dispersion required inside the bunch compressor. The overall compression factor is around 14 which implies a relative increase of the energy spread to around 1.9% which cannot be accepted in a one-stage compressor and in the injection system because of non-linear effects and dilution of the transverse emittance. To reduce this large increase in the energy spread, a two-stage bunch compressor was chosen to take advantage of the adiabatic damping during acceleration. Thus a first stage will work at the same momentum as the damping ring, i.e. 1.8 GeV/c and a second one at a higher momentum that was chosen to be 6.12 GeV/c owing to the special acceleration scheme of the injector [1] as will be explained later. The bunch shaping will be obtained through a beam collimator inside the first compressor. To reduce the requirement for a large RF rotator in the first compressor, the latter has been designed to give a small compression factor of 2.5 obtained with a voltage of 91 MV. The energy spread of the beam at the exit of the first compressor is 0.34%, which we think is small enough to avoid strong second-order effects on the transverse emittance. The acceleration adiabatic damping up to 6.12 GeV/c will reduce the energy spread to 0.1%, while the bunch length is 0.94 mm. The second compressor will take advantage of the 1.44 GV superconducting linac which will increase the beam momentum from 1.8 GeV/c up to 9 GeV/c through recirculation [1]. The bunch length will be compressed to 0.16 mm while the energy spread will rise to 0.59% which we consider is still acceptable in the isochronous arcs of the injection complex and of the main linac.

2. BASICS OF BUNCH COMPRESSION

The principles of bunch compression have been explained in many papers [3], [4]. Let us consider the longitudinal phase space $\{z, \Delta p/p_0\}$ where z is the relative position inside the bunch. When the beam centre is synchronous with the zero phase of the RF voltage, its energy spread will be increased by a quantity which is at first approximation proportional to z if the beam length is much smaller than $c/2\pi f_{RF}$ with f_{RF} being the RF frequency. Assuming a bidimensional Gaussian for the beam distribution in the longitudinal phase space, it will be modified as follows after the beam has passed through the RF system:

$$f(z, \Delta p/p_0) = \frac{1}{2\pi\sigma_z\sigma_{\Delta p/p_0}} \exp\left[-\frac{z^2}{2\sigma_z^2} - \frac{(\Delta p/p_0 - az)^2}{2\sigma^2_{\Delta p/p_0}}\right] \quad (1)$$

where $a = 2\pi f_{RF} V_{RF}/Ec$, V_{RF} being the RF voltage and E the energy. When the beam passes through a dispersive section the path length will be correlated with the energy through the R_{56} matrix element. Higher energy particles will follow longer paths and the relative position inside the bunch will be decreased accordingly by a quantity which is proportional to the energy spread. The beam distribution becomes

$$f(z, \Delta p/p_0) = \frac{1}{2\pi\sigma_z\sigma_{\Delta p/p_0}} \exp\left[-\frac{(z + R_{56}\,\Delta p/p_0)^2}{2\sigma_z^2}\right] \times$$
$$\times \exp\left[-\frac{(\Delta p/p_0 - az - aR_{56}\,\Delta p/p_0)^2}{2\sigma^2_{\Delta p/p_0}}\right]. \quad (2)$$

After some manipulations it can be proved that the r.m.s. bunch length is minimized for:

$$R_{56} = \frac{a}{\sigma^2_{\Delta p/p_0}/\sigma_z^2 + a^2}. \quad (3)$$

Introducing the compression rate c_R as the ratio of the r.m.s. bunch length before the described process over the r.m.s. bunch length after it, the minimum is reached for:

$$a = \frac{\sigma_{\Delta p/p_0}}{\sigma_z}\sqrt{c_R^2 - 1} \quad \text{and} \quad R_{56} = \frac{1}{a}\left(1 - 1/c_R^2\right) . \quad (4)$$

These relations are used to compute the RF voltage and R_{56} needed to achieve a given compression rate.

The compression rate may also be written as:

$$c_R = \sqrt{1 + a^2\sigma_z^2 / \sigma_{\Delta p/p_0}^2} \; . \quad (5)$$

It is important to note that the quantity a is proportional to the inverse of the energy. Because of the adiabatic damping during the acceleration, the r.m.s. energy spread at the entrance of the second compressor is also inversely proportional to the energy when expressed as a function of the r.m.s. energy spread at the exit of the first compressor. Thus relation (5) shows that the compression rate of the second compressor does not depend on the energy. As a consequence, in designing the second compressor, one should choose the lowest energy compatible with the required energy spread at its entrance, in order to minimize the dilution of the transverse emittance due to synchrotron radiation.

3. PROPOSED DESIGN

The suggested value of 9 GeV for the injection energy in the main linac is a compromise between the transverse emittance dilution in the arcs due to the synchrotron radiation and wakefield effects. An injection energy of 15 GeV would reduce the latter by 30%, but the increase of the transverse emittance being proportional to the sixth power of energy and to the inverse of the square of the radius of curvature, the 360° isochronous arc should have a radius of curvature of the order of 1 km to limit the emittance growth of a 15 GeV/c beam to the same value it would have at 9 GeV/c with a radius of curvature of 220 m.

The injector complex consists of a superconducting linac which will raise the beam energy from 1.8 GeV to 9 GeV by letting the beam recirculate through four loops [1]. We propose to insert the two bunch compressors in this complex as described in the following sections.

3.1 Low-energy compressor with bunch collimator

The low-energy compressor (Fig. 1) consists of an RF rotator and of a double chicane placed at the exit of the damping rings. The RF rotator at 1.25 GHz will provide a voltage of 91 MV. The electron and positron beams will then pass through the two arms of a chicane consisting of three rectangular magnets separated by a distance of 6.61 m. The first and last magnets are 2 m long while the length of the central one is 4 m. The R_{56} needed to obtain the required longitudinal phase space rotation is 0.64 m and is obtained by a deflection angle of 200 mrad according to formula (2) in Ref. [4]. The transverse emittance growth has been computed using the expressions in Refs. [4] and [5] and amounts to 3.88×10^{-9} m·rad. The small compression rate of 2.5 and low energy-spread inside the chicane of 0.34% let us think that the transverse emittance dilution due to non-linearities or alignment errors will be negligible compared with the transverse emittances at the exit of the damping rings.

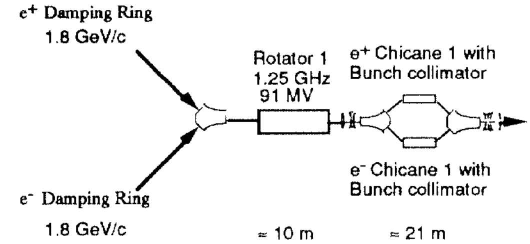

Figure 1. Low-energy bunch compressor.

To reduce the wakefield effect in the main linac, the front edge of the longitudinal distribution of the bunch should be steeper than a Gaussian [2]. In the centre of the middle magnet of the chicane the horizontal dispersion reaches a maximum of about 1.8 m (see Fig. 2) with an energy spread of 0.34%. Particles with energies greater than 1.806 GeV will be displaced transversally by more than 6 mm which is much larger than the displacement due to betatron motion (of the order of 70 µm). A simple collimator will remove those particles. The 90° rotation of the longitudinal phase space obtained by the second compressor will then transfer the sharp edge from the energy spread distribution to the distribution of relative position inside the bunch.

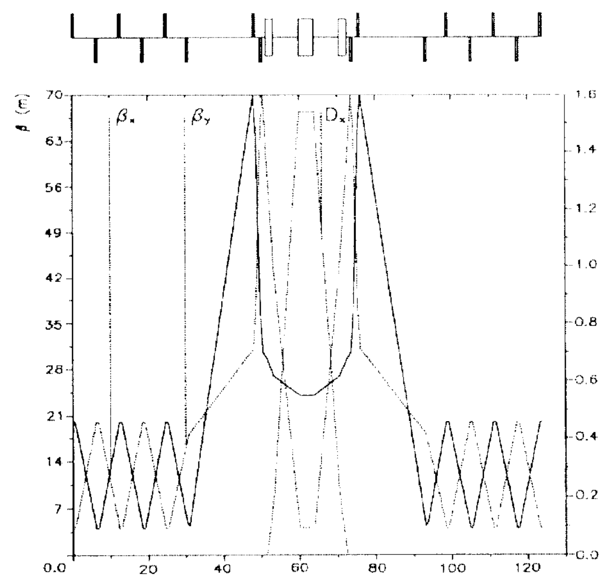

Figure 2. Optics functions of the low-energy compressor.

3.2 High-energy compressor

The proposed acceleration scheme [1] with its recirculation loops suggests a way to economize the high-energy RF rotator. The same superconducting linac used for acceleration will also provide the energy-spread increase proportional to the relative position inside the bunch. The 6.12 GeV/c loop (Fig. 3) was selected to obtain a low energy-spread (of the order of 0.1%). Coming from the 4.68 GeV/c

loop the beam will pass through the superconducting linac and be accelerated to 6.12 GeV/c. All the loops have a length which is a multiple of 0.24 m corresponding to an increase of the RF phase by a multiple of 2π. The length of the loop containing the compressor is chosen to accommodate different synchronizations with the RF phase. Two kickers placed before and after the chicane will be fired before the beam enters the loop. They will create an alternative path by deviating the beam on a closed sinusoidal oscillation. The length of the resulting loop is chosen to be 0.18 m plus a multiple of 0.24 m so that the beam will enter the superconducting linac when the RF phase is shifted by $3\pi/2$ and the RF voltage is nearly zero. Thus the next passage in the superconducting linac will only increase the energy spread proportionally to the relative position inside the bunch, and the beam will still have an energy of 6.12 GeV. The kickers being switched off, the beam will follow another loop which has a length of 0.06 m plus a multiple of 0.24 m in order to enter the superconducting linac when the RF phase is shifted by $\pi/2$ and the RF voltage is maximum. Along this path the beam will pass through the chicane where it will experience the required rotation in the longitudinal phase space. This chicane is similar to that described earlier but with different parameters: the end magnets and the middle one are, respectively, 6 m and 12 m long and they are separated by a distance of 3.9 m. The deflection angle is 105 mrad which gives a value of 0.16 m for R_{56}. The resulting compression rate is 5.9 bringing the overall compression rate to 14.7. The transverse emittance growth is 3.52×10^{-8} m·rad. Inside the linac the beam will be accelerated to 7.56 GeV/c and at the end of the linac it will enter the 7.56 GeV/c loop. Finally, it will exit from the superconducting linac for the last time with a momentum of 9 GeV/c, a bunch length of 0.16 mm and an energy spread of 0.4%. Possible optics of the low- and high-energy bunch compressors have been calculated and matched to a standard FODO lattice. They are illustrated respectively in Fig. 2 and Fig. 4. Table 1 summarizes the parameters of the preliminary bunch compressors.

Table 1
Parameters of the preliminary bunch compressor

Parameter	1st Stage	2nd Stage
Energy	1.8 GeV	6.12 GeV
RF voltage	91 MV	1440 MV
RF frequency	1.25 GHz	1.25 GHz
Chicane length	21.22 m	31.8 m
Chicane deflection angle	200 mrad	105 mrad
Chicane bending field	0.6 T	0.36 T
Chicane radius of curvature	10 m	57.4 m
R_{56}	0.64 m	0.16 m
Compression rate	2.5	5.9
Bunch length at entrance	2.34 mm	0.94 mm
Bunch length at exit	0.94 mm	0.16 mm
Energy spread at entrance	0.135%	0.1%
Energy spread at exit	0.34%	0.59%
Transv. emittance incr. (m·rad)	3.88×10^{-9}	3.52×10^{-8}

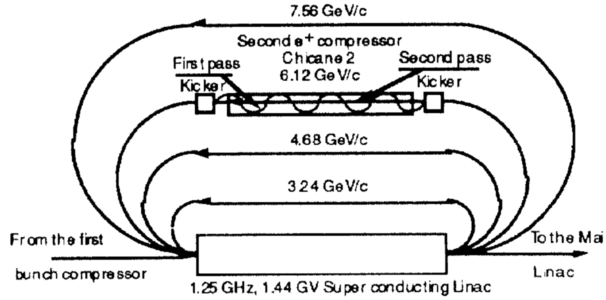

Figure 3. High-energy bunch compressor for positrons which should be duplicated for electrons.

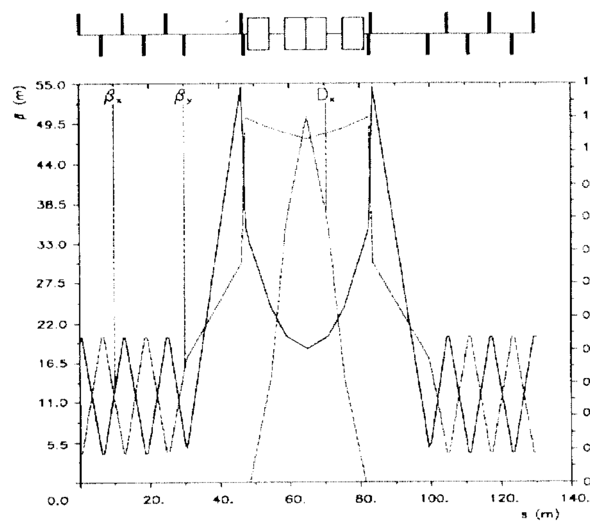

Figure 4. Optics functions of the high-energy bunch compressor.

4. DISCUSSION

A proposal for a bunch compressor for CLIC has been described that fits nicely in the current scheme of the injector. Its main features are the reusability of the superconducting linac, the possibility of achieving bunch shaping, its central location, and the separation of functions which avoids including the final 360° arc in the bunch compressor. First-order calculations show its validity. However, further studies are needed to assess the effect of high-order contributions and the robustness of the design in the presence of magnet errors or orbit distortions. These studies should lead to the optimization of the parameters. Finally, the design of the isochronous arc should be completed to demonstrate its ability to accept the required energy spread.

5. REFERENCES

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