Abstract

The main goal of the CLIC Test Facility (CTF) is to study the generation of a drive beam with high charge in short bunches. One of the limitations is the space charge effect at low energy which were experimentally verified. In order to balance this effect, it is proposed to produce the requested high charges with a long pulse length, accelerate them and shorten the pulses at the desired value when the energy is high enough.

This note describes the design of a magnetic bunch compressor. The main objective is to produce bunches in the range of 10 nC with a σ, below 3 ps at the output of the bunch compressor. An optics is also implemented in order to get the beam performances in the CLIC transfer structure. A recall of the theory is given before presenting the results of the beam dynamic simulations.
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1 Introduction

For the CLIC machine, the nominal accelerating gradient is 80 MV/m. In order to generate such an electric field at 30 GHz, it would be necessary to produce a single bunch of 54 nC with $\sigma_t = 3$ ps crossing the RF CLIC structure [1]. Since such a high charge in a single short bunch would be rather difficult to produce and transport, a proposal [2] using a train of 16 bunches has been made. It corresponds to 7 nC/bunch with the same bunch length $\sigma_t = 1$ mm.

Experiments done in the 1993 CTF run [3] are the following (for single bunch):

- Laser pulse length: $\sigma_l = 3.5$ ps
- $e^-$ pulse length at CLIC structure: $\sigma_t = 5.5$ ps
- Maximum charge at the gun exit: $q = 14$ nC
- Maximum charge at the CLIC structure: $q = 7$ nC

Experiments done with different trains (8 bunches, 16 bunches, 24 bunches) show that the charge is always below 2nC/bunch. A proposal [4] was made in order to produce high charges at the RF gun with long laser pulses ($\sigma_l = 8$ ps). They will be accelerated up to 10 MeV/c (or even 20 MeV/c later on) and then longitudinally compressed down to $\sigma_t = 3$ ps.

This note describes the principle of the magnetic bunch compressor based on 3 dipoles. The optics and the settings of the whole CTF line are given. Finally the beam dynamics simulations are analysed and show that the bunch characteristics at the compressor output can be conserved up to the CLIC structure with a good efficiency.

2 Analytical model

2.1 Variable definitions

A group of particles are described by two sets of canonically conjugate variables $\dot{q}$ and $\dot{p}$. If the system is conservative, one can derive the classical particle motion from the Hamiltonian function $H(q,p,t)$

$$\dot{q} = \frac{\partial H}{\partial p} \quad (1)$$

$$\dot{p} = -\frac{\partial H}{\partial q} \quad (2)$$

Under these conditions the particles move in the phase space as in an incompressible fluid. The Hamiltonian function for a charged particle of mass, $m$, and charge, $e$, in a magnetic vector potential $\vec{A}$, and scalar potential, $\phi$, is:

$$H = c\Phi + c\sqrt{(\vec{p} - e\vec{A})^2 + m^2c^2} \quad (3)$$

where

$\Phi$ and $\vec{A}$ are function of space and time,
$c$ is the velocity of the light,
$\vec{q} = q_x, q_y, q_z$ is the space coordinate,
$\vec{p} = p_x, p_y, p_z$ is the momentum conjugate to the space coordinate.
From (1) and (2) and expanding the equation (3) one obtains:

\[ q_i = \frac{c(p_i - eA_i)}{\sqrt{(\overline{p} - e\overline{A})^2 + m^2c^2}} \]  

(4)

and

\[ p_i = -e\frac{\partial \Phi}{\partial q_i} + ec \sum_j \frac{p_j - eA_j}{\sqrt{(\overline{p} - e\overline{A})^2 + m^2c^2}} \frac{\partial A_j}{\partial q_i} \]  

(5)

which gives

\[ p_i - eA_i = -e\frac{\partial \Phi}{\partial q_i} - e\frac{\partial A_i}{\partial t} + e \sum_j (q_j \frac{\partial A_j}{\partial q_i} - q_j \frac{\partial A_i}{\partial q_j}) \]  

(6)

From equation (4), the normalized velocity \( \beta_c = \frac{q_i}{c} \) can be written as:

\[ \beta^2 = \frac{(\overline{p} - e\overline{A})^2}{(\overline{p} - e\overline{A})^2 + m^2c^2} \]  

(7)

that one develops to get:

\[ p_i - eA_i = \beta_i \gamma mc \]  

(8)

Only the longitudinal plane will be discussed here. Additionally, the equation (8) will be considered where \( A_x = A_z = 0 \) [5]. Under this hypothesis (8) becomes:

\[ p_i = \beta_i \gamma mc \]  

(9)

where \( \beta_i = \frac{q_i}{c} \)

This transformation shows that the behaviour of the longitudinal plane is the same as the transverse plane in a sense that if the system is conservative then there exists a phase space described by a set of two conjugate variables \( (q_i, \beta_i \gamma) \) in which the longitudinal emittance is conserved (Liouville’s theorem).

2.2 Equivalence between particle phase \( \Phi \) and longitudinal position \( z \)

The bunch compression studies are simulated with the code PARMELA [6] in which the accessible longitudinal variables are \( (\Phi, \beta_i \gamma) \). The linear relation between \( \Phi \) and \( z \) is recalled below. The phase of the particle \( i \) is usually defined as \( \Phi_i = -\omega(t_i - t_0) + \Phi_0 \) as the phase of a particle \( i \) relativistic or not [7], where

\[ t_i = \frac{z_i}{v_i}, \]
\[ \omega = 2\pi c/\lambda, \]
\[ \lambda \text{ is the wavelength associated to the RF,} \]
\[ v_i \text{ is the velocity of the particle,} \]
\[ t_0 \text{ is the time of the reference particle,} \]
\[ \Phi_0 \text{ is the phase of the reference particle.} \]

\(^1\)For simplicity the variable \( q_z \) from the Hamiltonian formalism is renamed \( z \).
2.3 Principle of the longitudinal compression

This yields to:

$$\Phi_i = -\frac{2\pi}{\lambda} \frac{z_i}{v_i} (\Phi_0 - \frac{x_0}{\beta_0}) + \Phi_0$$

(10)

If \( z_0 \) is the longitudinal position of the reference particle in the bunch, then the longitudinal position of the particle \( i \) becomes \( z_i = z_0 + \Delta z \). The expansion of (10) provides:

$$\Phi_i = -\frac{2\pi}{\lambda} (\frac{\Delta z}{\beta_i} - 2(z_0 (\frac{1}{\beta_0} - \frac{1}{\beta_i}))) + \Phi_0$$

(11)

The bunch compressor will work, at least, at 11 MeV, then particles will be relativistic: \( \beta = \beta_0 \approx 1 \) and

$$\Delta \Phi = -\frac{2\pi \Delta z}{\lambda}$$

(12)

Finally, the variables \( (\Phi, \beta, \gamma) \) are also a set of conjugate variables and the particle behaviour is the same as in \( (z, \beta, \gamma) \).

2.3 Principle of the longitudinal compression

The previous paragraphs demonstrated that the longitudinal emittance is conserved either in the \( (z, \beta, \gamma) \) or \( (\Phi, \beta, \gamma) \) phase spaces. A general formalism of the longitudinal compression is given below.

First, let us consider an ellipse in one of those phase spaces containing ninety per cent of particles for example, where their coordinates and momentum are taken as a function of the reference particle: \( z_0 = 0, t_0 = 0 \) and \( (\beta, \gamma)_0 \).

In all the following figures the phase spaces are centred in phase and momentum on the reference particle.

Therefore \( \Delta z = z_i - z_0 = z_i, \Delta \phi = \phi_i - \phi_0 = \phi_i \) and \( \delta p = ((\beta, \gamma)_i - (\beta, \gamma)_0). \)

The area \( \epsilon \) of the ellipse, which also represents the beam emittance, is described by a linear combination of a generalisation of the Twiss parameters \( (\alpha, \beta, \gamma) \) as it is done for the transverse plane:

$$\gamma_1 z_i^2 + 2\alpha_1 z_i (\beta, \gamma)_i + \beta_1 (\beta, \gamma)_i^2 = \epsilon_i$$

(13)

Let \( \eta = -2\pi/\lambda \) in (12). Then (13) can be written as:

$$\gamma_1 \frac{\Phi_i^2}{\eta^2} + 2\alpha_1 \Phi_i (\beta, \gamma)_i + \beta_1 (\beta, \gamma)_i^2 = \epsilon_i$$

(14)

One can compare both emittances by comparing the surfaces of the straight ellipses (coupling term \( \alpha_1 = 0 \)).

$$S_x = \pi \beta_1 \gamma_1$$

$$S_y = \pi \beta_1 \gamma_1$$

and

$$S_x = \frac{S_x}{\eta^2}$$

$$S_y = \frac{S_y}{\eta^2}$$
The emittance being proportional to the surfaces, one obtains:

\[ \epsilon \Phi = \frac{\epsilon_s}{\eta^2} \]  

(15)

From now on, the phase space \((\phi, \beta, \gamma)\) will be used. Let us apply to the ellipse the following adiabatic transformation (Fig. 1):

\[
\begin{align*}
    \Phi_s &= \Phi - K(\beta_s \gamma)_s \\
    (\beta_s \gamma)_s &= (\beta_s \gamma)_c
\end{align*}
\]  

(16)

where the index, \(c\), refers to the quantities before the transformation and the index, \(s\), refers to the quantities after the transformation. \(K\) is an arbitrary constant (positive or negative). This transformation conserves the momentum of the particle but modifies its phase. It is also a linear transformation which implies a correlation between \(\Phi\) and \(\beta, \gamma\). For a given correlation, \(K\) should be determined in such a way that the change in phase is proportional to the momentum. Therefore the phase spread in the bunch will tend to a minimum.

The equation (14) of the ellipse after the compression process becomes:

\[
\gamma_1 \Phi_s + 2(\alpha_t + \gamma_1 K)\Phi_s(\beta_s \gamma) + \left( \frac{\gamma_1 K}{\eta} + 2 \frac{\alpha_t K}{\eta} + \beta_t \right)(\beta_s \gamma)^2 = \epsilon
\]  

(17)

For a more readable equation let put \(\gamma_1/\eta^2 \rightarrow \gamma_1, \alpha_t/\eta \rightarrow \alpha_t\) and \(\epsilon \rightarrow \epsilon\), so the equation (17) becomes:

\[
\gamma_1 \Phi_s + 2(\alpha_t + \gamma_1 K)\Phi_s(\beta_s \gamma) + (\gamma_1 K + 2\alpha_t K + \beta_t)(\beta_s \gamma)^2 = \epsilon
\]  

(18)

The optimum compression is reached when the ellipse has a horizontal waist. This condition gives immediately a unique value of \(K\):

\[ K = -\frac{\alpha_t}{\gamma_1} \]  

(19)

Figure 1: Compression process in the \((\Phi, \delta p)\) phase space
2.4 Minimum bunch length

The ellipse parameters (Fig. 2) for the longitudinal phase plane are derived from [8]. The relation between $K$ and these parameters is given below.

\[ \beta \gamma \]

\[ -\frac{a}{\sqrt{\beta \gamma}} \phi_{\text{max}} \]

\[ \phi_{\text{int}} = \sqrt{\frac{\varepsilon}{\gamma}} \]

\[ \phi_{\text{max}} = \sqrt{\varepsilon} \]

\[ \text{slope} = -\frac{\gamma}{\alpha} \]

\[ \text{slope} = -\frac{a}{\beta} \]

\[ \gamma \]

Figure 2: Ellipse parameters for the longitudinal phase plane.

Assuming that $K$ depends on the position of $(\beta \gamma)_{\text{max}}$, the transformation (16) yields:

\[ \Phi_z = \Phi_z - K(\beta \gamma)_{\text{max}} = 0 \] (20)

The phase associated to $(\beta \gamma)_{\text{max}}$ is $\Phi_z$ which can be developed into:

\[ \Phi_z = -\frac{\alpha_1}{\sqrt{\beta \gamma}} \Phi_{\text{max}} \Rightarrow \Phi_z = -\alpha_1 \sqrt{\frac{\varepsilon}{\gamma_1}} \]

and

\[ (\beta \gamma)_{\text{max}} = \sqrt{\gamma_1 \varepsilon} \]

By substituting the expression of $\Phi_z$ into (20), one obtains:

\[ -\alpha_1 \sqrt{\frac{\varepsilon}{\gamma_1}} - K \sqrt{\gamma_1 \varepsilon} = 0 \Rightarrow K = -\frac{\alpha_1}{\gamma_1} \] (21)

Therefore, $(\beta \gamma)_{\text{max}}$ is the ellipse reference point for an optimum compression and every time this point will change, so will $K$. Similarly, two points will determine, theoretically, the minimum phase spread of the bunch: $\phi_{\text{int}}$ and its symmetric from the vertical axis. Then the minimum bunch length is:

\[ \Delta \phi = 2 \phi_{\text{int}} = 2 \sqrt{\frac{\varepsilon}{\gamma}} \] (22)
Because of the Liouville's theorem the positions of $\phi_{\text{int}}$ can still be reduced by increasing the momentum spread ($\sim \gamma_1$ increases) for a constant emittance. Then, ideally, $\phi_{\text{int}}$ would be reduced to zero if $\delta p/p \to \infty$.

2.5 Magnetic compression with three dipoles

For the reasons explained in Section 2.9.5, the choice for the CTF line is settled for a system of three dipoles of inverse polarity. A study of such system is given below.

2.5.1 Optical design

This layout allows to keep the same momentum spread before and after the compression process. The following analytical study will not integrate the effect of the dipole fringe fields, only hard edge field is assumed. In the general case, a beam enters into the bunch compressor system with an angle $\epsilon$ (Fig. 3). Its trajectory through those dipoles depends of eleven quantities:

- $l_{i=1,3}$: the length of each dipole,
- $\alpha, \beta, \gamma$: the curvature angle of each dipole,
- $\rho_{i=1,3}$: the curvature radius of the dipole,
- $\lambda_{i=1,3}$: the drift between the dipoles.

Figure 3: Basic geometry for a 3 dipole bunch compressor.

Magnet lengths (Fig. 4 and 5).

$$l_1 = \rho_1[\sin(\epsilon + \alpha) - \sin \epsilon]$$  \hspace{1cm} (23)

$$l_2 = \rho_2[\sin(\epsilon + \alpha) - \sin(\epsilon + \alpha + \beta)]$$  \hspace{1cm} (24)
2.5 Magnetic compression with three dipoles

\[ l_3 = \rho_3 [\sin(\epsilon + \alpha + \beta + \gamma) - \sin(\epsilon + \alpha + \beta)] \]  

(25)

The total length of the bunch compressor is:

\[ L = l_1 + l_2 + l_3 + \lambda_1 + \lambda_2 \]  

(26)

- In the transverse plane: \( d_i \) = offset in position between the input and the output of the dipoles.

\[ d_1 = \rho_1 [\cos \epsilon - \cos(\epsilon + \alpha)] \]  

(27)

\[ d_2 = \rho_2 [\cos(\epsilon + \alpha + \beta) - \cos(\epsilon + \alpha)] \]  

(28)

\[ d_3 = \rho_3 [\cos(\epsilon + \alpha + \beta) - \cos(\epsilon + \alpha + \beta + \gamma)] \]  

(29)

The total offset in position between the input and the output of the bunch compressor in the transverse plane is:

\[ d = d_1 + d_2 + d_3 + \lambda_1 \tan(\epsilon + \alpha) + \lambda_2 \tan(\epsilon + \alpha + \beta) \]

The problem is simplified as follow:

\[ \epsilon = 0 \text{ and } \epsilon + \alpha + \beta + \gamma = 0 \]

assuming the beam to be parallel to the z-axis at the entrance and the exit of the bunch compressor system. Then

\[ \beta = -(\alpha + \gamma) \implies \gamma = \alpha \implies \beta = -2\alpha \]  

(30)

Additionally, we settle \( d \) to zero for reasons of symmetry:

\[ d = (\rho_1 + \rho_2)(1 - \cos \alpha) + (\lambda_1 + \lambda_2) \tan \alpha = 0 \]  

(31)

Still willing to keep a symmetrical system we take:

\[ \rho_1 = \rho_2 = \rho \text{ and } \lambda_1 = \lambda_2 = \lambda \]  

(32)

- Maximum transverse displacement:

\[ D = 2\rho(1 - \cos \alpha) + \lambda \tan \alpha \]  

(33)

- Longitudinal position associated to the maximum transverse deflection:

\[ L_M = 2\rho \sin \alpha + \lambda \]  

(34)

With the mentioned simplifications, the expressions of the lengths become:

\[ l_i = \rho \sin \alpha \]  

(35)
Figure 4: First dipole parameters.
(The third dipole is the same.)

Figure 5: Second dipole parameters
2.5 Magnetic compression with three dipoles

Figure 6: Basic requirements for a simplified bunch compressor.

\[
l_2 = \rho [\sin \alpha - \sin(-\alpha)] = 2\rho \sin \alpha
\]

\[
l_3 = \rho [\sin(\alpha + \beta + \gamma) - \sin(\alpha + \beta)] = \rho \sin \alpha
\]

Therefore:

\[
2l_1 = 2l_3 = l_2 = 2l
\]

Since \( \rho = l/\sin \alpha \) and \( B_{[T]} \rho_{[m]} \approx P_{[GeV/c]} / 0.299 \), there is the following relations between the fields:

\[
B_1 = B_2 = B_3 = B
\]

Figure 6 gives the simplified scheme.

2.5.2 Horizontal matrix for beam optics

The symmetry conditions for the lengths and magnetic field (Fig. 6) are used to develop the matrix formalism. The bunch compressor is composed of three elementary matrices: a dipole \([B]\), an edge focusing \([F]\) and a drift \([D]\). Each of them will describe the motion in a 4x4 matrix formalism for the horizontal plane \([8]\).

\[
\begin{bmatrix}
z \\
z' \\
\delta l_p \\
\delta p/p
\end{bmatrix} = [MATRIX] \begin{bmatrix}
z \\
z' \\
\delta l_p \\
\delta p/p
\end{bmatrix}
\]
The [MATRIX] elements are:

\[
[B] = \begin{bmatrix}
\cos \alpha & \rho \sin \alpha & 0 & \rho(1 - \cos \alpha) \\
-\sin \alpha/\rho & \cos \alpha & 0 & \sin \alpha \\
-\sin \alpha & -\rho(1 - \cos \alpha) & 1 & -\rho(\alpha - \sin \alpha) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[F] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
\tan \alpha/\rho & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[D] = \begin{bmatrix}
1 & \lambda & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

The variables are:

- \( z, z' \): horizontal position and divergence,
- \( \delta l_x \): path length difference between the arbitrary ray and the central trajectory,
- \( \delta p/p \): relative momentum spread.

We will use the following notations to lighten the matrix expressions:

- \( C \) as \( \cos \alpha \)
- \( S \) as \( \sin \alpha \)
- \( T \) as \( \tan \alpha \)

The edge focusing has no effect on a beam perpendicular to the dipole edge, then the matrix calculation will begin and end with one dipole matrix.

The central magnet \([FBBF]\) will be composed of two identical magnets of curvature angle, \(-\alpha\), and curvature radius, \(\rho\), giving a total curvature angle of \(-2\alpha\). Because of their reversed sign, the matrix of the central magnet will be taken as if it were positive and reversed after calculation.

Calculation of \([DFB]\) for the first dipole:

\[
[FB] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
T/\rho & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C & \rho S & 0 & \rho(1 - C) \\
-S/\rho & C & 0 & S \\
0 & -S & -\rho(1 - C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[FB] = \begin{bmatrix}
C & \rho S & 0 & \rho(1 - C) \\
0 & TS + C & 0 & T(1 - C) + S \\
-S & -\rho(1 - C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C & \rho S & 0 & \rho(1 - C) \\
0 & 1/C & 0 & T \\
-S & -\rho(1 - C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[DFB] = \begin{bmatrix}
1 & \lambda & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C & \rho S + \lambda/C & 0 & \rho(1 - C) + \lambda T \\
0 & 1/C & 0 & T \\
-S & -\rho(1 - C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(40)
Calculation of [FBBF] for the second dipole:

\[
[FBBF] = \begin{bmatrix}
C & \rho S & 0 & \rho(1-C) \\
0 & 1/C & 0 & T \\
-S & -\rho(1-C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C & \rho S & 0 & \rho(1-C) \\
-S/\rho & C & 0 & S \\
-S - T(1-C) & -\rho(1-C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 \\
T/\rho & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[FBBF] = \begin{bmatrix}
C + S^2/C & \rho S & 0 & \rho(1-C) \\
-S/\rho + S/\rho & C & 0 & S \\
-S - T(1-C) & -\rho(1-C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[FBBF] = \begin{bmatrix}
1/C & \rho S & 0 & \rho(1-C) \\
0 & C & 0 & S \\
-\rho(1-C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Finally,

\[
[FBBF] = \begin{bmatrix}
1 & 2\rho CS & 0 & 2\rho S^2 \\
0 & 1 & 0 & 2T \\
-2T & -2\rho S^2 & 1 & -2\rho(\alpha - SC) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

We apply now the transformation due to the reversed angle and reverse curvature radius:

\[
[FBBF]_{\text{trans.}} = \begin{bmatrix}
1 & 2\rho CS & 0 & -2\rho S^2 \\
0 & 1 & 0 & -2T \\
2T & 2\rho S^2 & 1 & 2\rho(-\alpha + SC) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Calculation of [FBD] for the third dipole:

\[
[BFD] = \begin{bmatrix}
1/C & \rho S & 0 & \rho(1-C) \\
0 & C & 0 & S \\
-\rho(1-C) & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \lambda & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
[BFD] = \begin{bmatrix}
1/C & \rho S + \lambda/C & 0 & \rho(1-C) \\
0 & C & 0 & S \\
-\rho(1-C) - \lambda T & 1 & -\rho(\alpha - S) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Calculation of the whole matrix transformation:

\[
[BFD][FBBF]_{\text{trans.}}[DFB] =
\]
Table 1 gives numerical values of these quantities for $l=150\text{ mm}$ and $\lambda=100\text{ mm}$:
2.5 Magnetic compression with three dipoles

<table>
<thead>
<tr>
<th>$\alpha$ [degree]</th>
<th>$\frac{d_\alpha}{d \rho}$ [mm/%]</th>
<th>$\frac{d\phi}{\rho}$ [degree/%]</th>
<th>$B[T]$ at 11MeV/c</th>
<th>$B[T]$ at 20 MeV/c</th>
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<tr>
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<td>0.077</td>
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<td>20</td>
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<td>1.89</td>
<td>0.084</td>
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<tr>
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<td>3.09</td>
<td>0.104</td>
<td>0.188</td>
</tr>
<tr>
<td>30</td>
<td>1.31</td>
<td>4.72</td>
<td>0.123</td>
<td>0.223</td>
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<td>6.89</td>
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<td>65</td>
<td>15.88</td>
<td>57.18</td>
<td>0.222</td>
<td>0.404</td>
</tr>
</tbody>
</table>

Table 1: $\alpha$-dependence of main parameters

2.5.3 Vertical matrix for beam optics

The same matrix transformation $[BFD][FBBF]_{\text{trans}}[DFB]$ for the vertical plane is computed.

$y, y':$ vertical position and divergence.

$$[BF] = \begin{bmatrix} 1 & \rho \alpha \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -T/\rho & 1 \end{bmatrix} = \begin{bmatrix} 1 - \alpha T & \rho \alpha \\ -T/\rho & 1 \end{bmatrix}$$

$$[FB] = \begin{bmatrix} 1 & 0 \\ -T/\rho & 1 \end{bmatrix} \begin{bmatrix} 1 & \rho \alpha \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & \rho \alpha \\ -T/\rho & 1 - \alpha T \end{bmatrix}$$

$$[BFD] = \begin{bmatrix} 1 - \alpha T & \rho \alpha \\ -T/\rho & 1 \end{bmatrix} \begin{bmatrix} 1 & \lambda \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 - \alpha T & \lambda(1 - \alpha T) + \rho \alpha \\ -T/\rho & 1 - \lambda T/\rho \end{bmatrix}$$

$$[DFB] = \begin{bmatrix} 1 & \lambda \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 - \alpha T & \rho \alpha \\ -T/\rho & 1 \end{bmatrix} = \begin{bmatrix} 1 - \lambda T/\rho & \lambda(1 - \alpha T) + \rho \alpha \\ -T/\rho & 1 - \alpha T \end{bmatrix}$$

$$[FBBF] = \begin{bmatrix} 1 & \rho \alpha \\ -T/\rho & 1 - \alpha T \end{bmatrix} \begin{bmatrix} 1 & \alpha T & \rho \alpha \\ -T/\rho & 1 \end{bmatrix} = \begin{bmatrix} 1 & 2\alpha T & 2\rho \alpha \\ -2T(1 - \alpha T)/\rho & 1 - 2\alpha T \end{bmatrix}$$
Finally, the matrix transformation for the vertical plane is:

\[
\begin{bmatrix}
   1 + 8(\alpha T)^2 - 8\alpha T & 4\rho \alpha (1 - \alpha T)(1 - 2\alpha T) \\
   +2\lambda \theta^2(T/\rho)^2(1\alpha T)^2 & -2\lambda^2 T/\rho(1 - \alpha T)^2 \\
   -4\lambda(T/\rho)(1 - \alpha T)(1 - 2\alpha T) & +2\lambda(1 - \alpha T)^3(1 - 4\alpha T)
\end{bmatrix}
\]

\[\text{[BFD]}[[FBBF]]_{\text{trans}}[[DFB]]\]

In the vertical plane, the focusing effect is given by:

\[f = \frac{1}{4(T/\rho)(2\alpha T - 1) - 2\lambda^2 T/\rho(1 - \alpha T) + 2\lambda T/\rho(3 - 4\alpha T)}\]  \hspace{1cm} (48)

### 2.6 Spectrometer optics

With the bunch compressor design, a spectrometer line will be implemented. The first dipole is switched on while the two others are off. From (40), the horizontal beam size at the exit of the first dipole is:

\[z_1 = z_0 \cos \alpha + z'_0(\rho \sin \alpha + \frac{\lambda}{\cos \alpha}) + [\rho(1 - \cos \alpha) + \lambda \tan \alpha] \frac{\delta p}{p} \]  \hspace{1cm} (49)

The first two terms are the emittance contribution (\(\text{Sigma}_e\)). The third term is the dispersion contribution (\(\text{Disp}\)). From both quantities, the resolution of the spectrometer is derived:

\[f(\lambda) = \frac{[\rho(1 - \cos \alpha) + \lambda \tan \alpha] \frac{\delta p}{p}}{z_0 \cos \alpha + z'_0(\rho \sin \alpha + \frac{\lambda}{\cos \alpha})} \]  \hspace{1cm} (50)

Figure 7 shows the evolution of \(f(\lambda)\) for a beam with the following characteristics taken from the output data of PARMELA at the exit of the first dipole magnet at 0 nC:

- Momentum spread: \(\frac{\delta p}{p} = 3.8\%\),
- one-half of the horizontal beam extent: \(z_0 = 1.3\) mm,
- one-half of the horizontal beam divergence: \(z'_0 = 2.4\) mrad,
- the curvature angle of the spectrometer: \(\alpha = 30\) degrees.

From this figure a possible position of the screen around 1 m is possible since the resolution curve \(f(\lambda)\) starts to saturate.
2.7 Ellipse parameters in the longitudinal phase space

From (46) and (47):

$$\phi_1 - \phi_0 = \frac{360}{100} \left[ 4 \rho (\tan \alpha - \alpha) + 2 \lambda \tan^2 \alpha \right] \frac{\delta p}{p} \quad [\text{deg.}].$$  \hspace{1cm} (51)

As written previously for the path length (see 2.5), $\phi_1 - \phi_0$ represents the relative lengthening or shortening of the phase extension of the bunch. Once the momentum spread known one can vary the relative phase extension by changing the parameters of the bunch compressor: $\alpha, \rho, \lambda$.

An optimum compression is obtained for $\phi_1 = 0$, the two particles have the same phase. Then, one has to know the initial value $\phi_0$ to calculate (51). (20) gives this information. One can note that both quantities $\phi_0$ and $\phi_1$ are the same and with (20), one has:

$$K = \frac{\phi_e}{(\beta_s \gamma)_{\max}}$$  \hspace{1cm} (52)

We have now to establish a relation between (52) and (51) at $(\delta p/p)_{\max}$ to determine the expression of $\alpha$ and the magnetic field. For this purpose and since $(\beta_s \gamma)_{\max}$ is the point
for an optimum compression (Fig. 1), we express the momentum spread function of this particular point of the ellipse:

\[
\frac{\delta p}{p}_{\text{max}} = \frac{p_{\text{max}} - p_0}{p_0} = \frac{((\beta_s \gamma)_{\text{max}} - (\beta_s \gamma)_0)/(\beta_s \gamma)_0 = \delta(\beta_s \gamma)_{\text{max}}/(\beta_s \gamma)_0}
\]

Using the equations (35) and (52), and since the ellipse is centred around the reference particle \(\delta(\beta_s \gamma)_{\text{max}} = (\beta_s \gamma)_{\text{max}}\), the equation (51) becomes:

\[
\frac{\phi_1 - \phi_0}{(\beta_s \gamma)_{\text{max}}/(\beta_s \gamma)_0} = \frac{4l}{360} = \frac{4l}{360} = K(\beta_s \gamma)_0
\]

To resolve this equation where \(\alpha\) is unknown, a numerical method is used. Finally, another computation will be required to extract the \(\alpha\) value from (53). Figure 8 shows \(\alpha\) versus \(K(\beta_s \gamma)_0\). Each different value of \(K\) is determined by the initial conditions of the bunch. For example, at 0 nC, \(K(\beta_s \gamma)_0 = 298.0\) then a curvature angle of \(\alpha = 30\) degrees would have to be applied to this bunch, corresponding to a magnetic field of \(B = 0.222\) Tesla for a 20 MeV beam.
2.8 RMS beam emittance

PARMELA code gives an arbitrary longitudinal particle distribution before the bunch compressor system. An ellipse fitting the rms values of the distribution can be deduced. The description of this ellipse is the same as in paragraph 2.3. The rms emittance $\epsilon_{RMS}$ [9] is described as follow:

\[
\begin{align*}
\langle \beta_x \gamma \rangle^2 &= \eta_1^2 \epsilon_{RMS} \\
\langle \phi(\beta_x \gamma) \rangle &= -\alpha_1 \epsilon_{RMS} \\
\langle \phi^2 \rangle &= \beta_1 \epsilon_{RMS}
\end{align*}
\]

\[
\epsilon_{RMS} = \sqrt{\langle \phi^2 \rangle - \langle \beta_x \gamma \rangle^2 - \langle \phi(\beta_x \gamma) \rangle^2}
\]

where angle brackets indicate averages of the bracketed quantities over the entire bunch. One can express them with the help of the variable $z$ for simplicity. The mean of the values $z_1, \cdots, z_N$ is:

\[
\langle z \rangle = \frac{1}{N} \sum_{j=1}^{N} z_j
\]

and the variance:

\[
Var(z_1 \cdots z_N) = \langle z^2 \rangle = \frac{1}{N-1} \sum_{j=1}^{N} (z_j - \langle z \rangle)^2
\]

or its square root, the standard deviation:

\[
\sigma(z_1 \cdots z_N) = \sqrt{Var(z_1 \cdots z_N)}
\]

2.9 Review of other magnetic compressions

There exists numerous ways and systems to compress an electron bunch [10], [11] and [12]. Three of them are mentioned here as possible bunch compressors for CTF: planar wiggler, helical wiggler, alpha-magnet. The two wigglers are similar to the magnetic chicane and will be quantitatively compare to it.

2.9.1 Chicane

Under the paraxial condition [13], $\beta_\parallel \approx c$, the difference of path length is given by:

\[
\Delta l_c \propto \frac{l^3}{p^2 (eB_0)^2} \frac{\delta p}{p}
\]  \hspace{1cm} (54)

2.9.2 Planar wiggler

With the same assumption, one has:

\[
\Delta l_{wp} \propto \frac{l^3}{Nw^2 p^3 (eB_0)^2} \frac{\delta p}{p}
\]  \hspace{1cm} (55)
2.9.3 Helical wiggler

\[ \Delta l_{wa} \propto 2 \frac{f}{N_w^2 p^2} (eB_0)^2 \frac{\delta p}{p} \]  

(56)

for a wiggler with \( N_w \) period. Therefore,

\[ \frac{\Delta l_c}{\Delta l_{wp}} = N_w^2 \]  

(57)

which means that for similar values of the magnetic field, the chicane gives a compression proportional to the cube of the length, while when adding cells as a planar wiggler, the compression stays proportional to the cube of the length of the unit of cell, but is only proportional to the number of cells. Then the chicane is more efficient.

2.9.4 Alpha-magnet

Alpha-magnet is a generic term describing a range of achromatic mirrors [14]. The length of the particle trajectory, \( l_p \), scales with momentum, \( p \), as:

\[ l_p \propto p^{1+n} \]  

(58)

In the particular case of a quadrupolar field, \( n=1 \), and for small bunch momentum spread, one can approximate the gradient to:

\[ G \simeq \frac{K^2 (\frac{1}{p_0} \frac{dp}{dx})^2}{c^2} \]  

(59)

This system has to be used for bunches in which the particle momentum decreases monotonically from head to tail of the bunch contrary to the chicane and wiggler systems. With typical parameters of the CTF gun, we reach a 25 to 30 Tesla/m gradient. This implies a superconducting device.

2.9.5 Choice for the CTF

The choice of 3 dipoles with inverse polarity as a bunch compressor for CTF has been made with the following arguments:

- A system of three dipoles can be switched off if no compression is desired while the beam passes through the bunch compressor without seeing any field, contrary to the \( \alpha \)-magnet compressor.
- The fields involved in those dipoles are weak, about 0.222 T at 20 MeV/c, versus superconducting quadrupoles needed for \( \alpha \)-magnet. Accordingly, the size of the magnets can be very conservative, reducing the manufacturing and power supplies costs.
- The compression factor per unit of length is higher than the other methods. This characteristic is essential for the CTF line having a strong limitation in space.
3 Design of the CTF bunch compressor

3.1 Definition of the optics

As mentioned above, the bunch compressor chosen for the CTF is based on 3 dipoles with inverted polarity and full symmetry with respect to the central magnet axis. Table 2 summarises the characteristics discussed in the paragraph 2.5 for \( \lambda = 100\) mm.

For a bunch compression at a maximum momentum of 20 MeV/c, the maximum magnetic field will be: \( B = 0.223 \) T. The good field region covers the maximum requirements. Under these conditions, the trajectory of the reference particle in the bunch compressor is plotted (Fig. 9). Uppsala University participated in the design of the bunch compressor and provided stimulating discussions [15].
3 DESIGN OF THE CTF BUNCH COMPRESSOR

### Table 2: Magnet characteristics

<table>
<thead>
<tr>
<th>Good field region</th>
<th>Central Magnet</th>
<th>End Magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective length</td>
<td>170 mm</td>
<td>75 mm</td>
</tr>
<tr>
<td>Aperture</td>
<td>300 mm</td>
<td>150 mm</td>
</tr>
<tr>
<td>Max. deflection angle</td>
<td>60°</td>
<td>30°</td>
</tr>
<tr>
<td>Curvature radius $\rho$</td>
<td>70 mm</td>
<td>70 mm</td>
</tr>
<tr>
<td>Max. horizontal deviation D</td>
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<td>300 mm</td>
</tr>
<tr>
<td></td>
<td>138 mm</td>
<td>40 mm</td>
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</table>

3.2 Layout of simplified CTF line for simulations

Fig. 10 gives the layout of the optics from the RF gun up to the travelling wave section and including the bunch compression region. Figure 11 shows the layout of the CTF up to the first CLIC structure (TRS) as foreseen for 1995. It is composed of an RF gun (one and half cell S-band) at 4 MeV [16] with a photo-cathode ($C_{S1Tc}$); a booster structure (4 cells) providing a 7 MeV beam [17]; the bunch compressor, four quadrupoles to match the beam emittances to the entrance of LAS (LIL Accelerating Section). At the exit of LAS the beam energy is 68 MeV. A quadrupole triplet focuses the beam into the TRS (Transfer Structure). The rest of the line is not simulated with PARMELA code since it is not necessary for the design optimisation of the bunch compressor.

3.3 Optimisation of the phases.

Two phases are free parameters and are of great importance for the bunch compressor optimisation:

- $\Phi_{\text{gun}}$ is the phase when the center of the laser pulse hits the photo-cathode in respect with the 3 GHz RF voltage in the gun.
- $\Phi_{\text{booster}}$ is the phase of the 3 GHz RF voltage in the booster in respect with the same RF in the gun.

To achieve a compression with the magnetic chicane it is necessary to get a correlation between the phase and the energy of the particles as linear as possible. This correlation has to create bunches with momentum distribution that increases from head to tail. Otherwise the bunches would be lengthening instead of shortening. This correlation is obtained by an adjustment of the $\Phi_{\text{gun}}$ and $\Phi_{\text{booster}}$. The momentum and the momentum spread are plotted versus $\Phi_{\text{gun}}$ (Fig. 12 (a)) from PARMELA simulations. Two extrema appear for the momentum spread:

- $\Phi_{\text{gun}} = 25^\circ$: the momentum spread is maximum and the correlation is rather good but the momentum is around 4.4 MeV/c.
- $\Phi_{\text{gun}} = 50^\circ$: The momentum is maximum, 4.8 MeV/c, and the energy spread is minimum. As a consequence, the linear correlation is not good enough between the phase and the energy.
3.4 Results from PARMELA simulations

For these two extrema of $\Phi_{\text{pwn}}$, the momentum and the momentum spread are plotted versus $\Phi_{\text{booster}}$ (Fig. 12 (b),(c)). One can notice that at the maximum momentum, the momentum spread is close to its minimum.

A compromise has to be found between the maximum momentum spread and a minimum energy loss. According to the Figure 12, the following set of phases is chosen, for a 0 nC beam:

$\phi_{\text{pwn}} = 25^\circ$

$\phi_{\text{booster}} = 264^\circ$

Giving,

$\frac{\delta p}{p} = 3.8\%$

3.4 Results from PARMELA simulations

Series of simulations are done to investigate the bunch compression for different beam charges: 0 nC, 1 nC, 3 nC, 5 nC and 10 nC. The simulations without space charge will allow to set up the element parameters to obtain a maximum transmission all through the CTF line (Fig. 11). This fitting is done by using the code TRANSPORT [8]. Nevertheless, TRANSPORT does not take into account the effect of the space charge, making the matching of the beam envelope more critical. To understand how evolves this effect, one can characterise this space charge force $F_s$ in the simple case of a beam with a uniform particle density $\rho_0$ moving with the velocity $v$ along the z-axis:

$$F_s = e(E_r - \frac{v}{c}B_{\phi}) = \frac{2\pi e \rho_0}{\gamma^2} r$$

where

$E_r$ is the radial electrical field from Coulomb's law $\nabla E = 4\pi \rho_0$ at the distance $r$ from the beam axis,

$B_{\phi}$ is the azimuthal magnetic field derived from Ampere's law $\nabla \times B = \frac{4\pi}{c} \rho_0 v$.

Then the repelling electrostatic force is increasingly compensated by the magnetic force when $\gamma$ increases.

The space charge effect has to be limited as much as possible because in the case of the bunch compression the distance between each particle becoming smaller, $\rho_0$ increases causing a growing repelling effect of this force. The induced beam divergence at the exit of the bunch compressor would be difficult to compensate needing strong quadrupoles. Two modifications were required to improve the compression process:

- Increase the bunch length at the input of the bunch compressor.
- Increase the beam energy.

By lengthening the electron bunch one decreases the particle density $\rho_0$, so is the space charge force. This is achieved by working on the natural length of the laser pulse, $\sigma_{\text{max}} = 16$ ps, hitting on the photo-cathode.

Additionally, the booster will increase $\gamma$ up to 21.5 corresponding to $\beta$ equal to 0.9989. The possibility to add another identical booster is still open. We rely on these two modifications to improve the transport of high charged beam toward the compressor system. After
compression, one has to minimise the distance between the exit of the bunch compressor
and the entrance of LAS in which the bunch length will be frozen when the beam becomes
completely ultra-relativistic.

3.4.1 Momentum spread function of the charge

The optimum $\delta p/p=3.8\%$ corresponds to a beam without space charge effects. However this
value depends on the charge.

The momentum spread versus the charge is plotted, for $\phi_{\text{gun}} = 25^\circ$ and $\phi_{\text{booster}} = 264^\circ$:

- At the gun exit (Fig. 13 (a))
- At the booster exit (Fig. 13 (b))
- At the LAS exit (Fig. 13 (c))

At the exit of the booster (entrance of the bunch compressor), $\delta p/p$ drops from 3.84 % for
0 nC down to 3.55 % for 10 nC. The consequence will be a bunch compressor less efficient at
high charge. However at the exit of LAS, the effect is inverted. $\delta p/p$ increases from 0.55% for
0 nC, up to 1 % for 10 nC.

Fortunately this value is still acceptable to keep a minimum beam loss through the CTF
line.

3.4.2 Beam envelopes and emittances

The beam envelopes from the RF gun until the entrance of LAS are reported in the horizontal
plane (Fig. 14) and in the vertical plane (Fig. 15) for the following initial charges:
0, 1, 3, 5, 10 nC.

These envelopes are restricted to the LAS input in order to analyse with better accuracy
the region of the bunch compressor. On the same graphs, the aperture limitations of each
element are drawn.

The only solenoid SNF350 allows to focus as good as possible the beam at the booster input.
Its effect is clearly seen in the various plots. The optimised value found for the charge 10 nC
is kept for all lower charges.

The settings of the four quadrupoles are optimised in order to have a minimum divergence at
the entrance of LAS with a beam radius equal or less than 12 mm (iris aperture at the LAS
input). As shown on Figures 14 and 15, these conditions are reached for a beam of 0 nC but
not completely for a beam of 10 nC (particularly for the vertical plane).

Table 3 gives the input data which are independent of the charge and Table 4 those which
are dependent of the charge. Table 5 and 6 give the output data.

The Appendix A gives the files which are used as input files for PARMELA simulations
and the distribution of the magnetic field along LAS. The electric fields in the RF gun and
the booster are described as ideal cosine functions. The number of macro particles is 300.

The results of the simulations show that a transmission of 100% is possible through the
whole CTF line for a charge below 10 nC. For this latter value, the transmission drops to
87%.

The beam envelopes are now plotted from the RF gun until TRS in the horizontal plane
(Fig. 16) and in the vertical plane (Fig. 17) for the same set of initial charges. One can see
that the main losses, for 10 nC, are due to LAS aperture, mainly in the vertical plane.
3.4 Results from PARMELA simulations

Table 3: Input data (independent of the charge)

<table>
<thead>
<tr>
<th>Laser pulse length:</th>
<th>( \sigma_L ) [( \text{ps} )]</th>
<th>8.</th>
</tr>
</thead>
<tbody>
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<td>( \sigma_{\text{rms}} ) [( \text{ps} )]</td>
<td>16.</td>
<td></td>
</tr>
<tr>
<td>Laser pulse transverse size:</td>
<td>( \sigma_r ) [( \text{mm} )]</td>
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</tr>
<tr>
<td>( \sigma_{\text{rms}} ) [( \text{mm} )]</td>
<td>5.</td>
<td></td>
</tr>
<tr>
<td>( \Phi_{\text{ran}} ) [( \text{deg} )]</td>
<td>25.</td>
<td></td>
</tr>
<tr>
<td>( \Phi_{\text{booster}} ) [( \text{deg} )]</td>
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<td></td>
</tr>
<tr>
<td>SNF350 [T]</td>
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</tr>
<tr>
<td>QD410 [T/m]</td>
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</tr>
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<td>QF415 [T/m]</td>
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</tr>
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<td>QD420 [T/m]</td>
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</table>

Table 4: Input data and transmission results (charge-dependent)

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<td>0.34</td>
<td>-0.37</td>
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</tr>
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<td>100</td>
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<td>100</td>
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<td>0.39</td>
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### Table 5: Output data for 0 nC

<table>
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<th>Metric</th>
<th>Unit</th>
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<th>Booster</th>
<th>Compressor</th>
<th>Exit</th>
</tr>
</thead>
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<tr>
<td>Momentum: P [MeV/c]</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the gun:</td>
<td></td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td></td>
<td>10.67</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of TRS:</td>
<td></td>
<td>68.3</td>
<td></td>
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<td></td>
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<tr>
<td>Momentum spread: $\delta p/p$ [%]</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the gun:</td>
<td></td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td></td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of TRS:</td>
<td></td>
<td>0.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS transverse sizes [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the gun:</td>
<td></td>
<td>$x=y=3.6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td></td>
<td>$x=y=3.0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the compressor:</td>
<td></td>
<td>$x=2.8, y=1.8$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of TRS:</td>
<td></td>
<td>$x=0.4, y=0.8$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS transverse divergences [mrad]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the gun:</td>
<td></td>
<td>$x'=y'=22.5$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td></td>
<td>$x'=y'=2.4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the compressor:</td>
<td></td>
<td>$x'=2.4, y'=1.6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of TRS:</td>
<td></td>
<td>$x'=0.9, y'=0.7$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS normalized beam emittances $\epsilon$ [mm.mrad]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the gun:</td>
<td></td>
<td>$\epsilon_H=\epsilon_V=44.$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td></td>
<td>$\epsilon_H=\epsilon_V=53.$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of the compressor:</td>
<td></td>
<td>$\epsilon_H=\epsilon_V=61.$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the exit of TRS:</td>
<td></td>
<td>$\epsilon_H=57., \epsilon_V=63.$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 DESIGN OF THE CTF BUNCH COMPRESSOR
## 3.4 Results from PARMELA simulations

<table>
<thead>
<tr>
<th>Momentum: $P$ [MeV/c]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>At the exit of the gun:</td>
<td>4.5</td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td>10.8</td>
</tr>
<tr>
<td>At the exit of the bunch compressor:</td>
<td>10.8</td>
</tr>
<tr>
<td>At the entrance of TRS:</td>
<td>64.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Momentum spread: $\delta p/p$ [%]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>At the exit of the gun:</td>
<td>1.6</td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td>3.6</td>
</tr>
<tr>
<td>At the exit of the bunch compressor:</td>
<td>2.6</td>
</tr>
<tr>
<td>At the entrance of TRS:</td>
<td>1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RMS transverse sizes [mm]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>At the exit of the gun:</td>
<td>$x'=y'=4.5$</td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td>$x'=y'=4.7$</td>
</tr>
<tr>
<td>At the exit of the bunch compressor:</td>
<td>$x=4.5$, $y=1.0$</td>
</tr>
<tr>
<td>At the entrance of TRS:</td>
<td>$x=1.4$, $y=1.3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RMS transverse divergences [mrad]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>At the exit of the gun:</td>
<td>$x'=y'=31.0$</td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td>$x'=y'=1.0$</td>
</tr>
<tr>
<td>At the exit of the bunch compressor:</td>
<td>$x'=2.0$, $y'=6.8$</td>
</tr>
<tr>
<td>At the entrance of TRS:</td>
<td>$x'=0.9$, $y'=1.6$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RMS normalised beam emittances $\epsilon$ [mm.mrad]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>At the exit of the gun:</td>
<td>$\epsilon_H=\epsilon_V=64.$</td>
</tr>
<tr>
<td>At the exit of the booster:</td>
<td>$\epsilon_H=\epsilon_V=70.$</td>
</tr>
<tr>
<td>At the exit of the bunch compressor:</td>
<td>$\epsilon_H=132.0$, $\epsilon_V=60.0$</td>
</tr>
<tr>
<td>At the entrance of TRS:</td>
<td>$\epsilon_H=167.0$, $\epsilon_V=190.$</td>
</tr>
</tbody>
</table>

Table 6: Output data for 10 nC
However, 100% of particles can be focused correctly in the TRS for all charges which is one of the goals of this study.

Finally, the transverse phase spaces are characterised at 0 nC (Fig. 18) and at 10 nC (Fig. 19) at three different critical places of the CTF.

- At 0 nC, only the RF fields and the magnetic fields contribute to this particular distribution (butterfly shape). After the bunch compressor the horizontal beam dimensions are increased, due to the fact that the horizontal dispersion is not completely cancelled. Although both transverse planes are not completely similar, with the proposed optic settings (Table 4), it has been possible to obtain the same emittances for the horizontal and vertical planes at the exit of the bunch compressor (Fig. 19). In TRS, the butterfly shape is recovered in both planes and with acceptable values.

- At 10 nC, the space charge effects are predominant and with a minimum divergence at the bunch compressor input in both planes, there is a tremendous effect for the vertical divergence at the bunch compressor exit. The consequence is that the quadruplet cannot compensate this effect before entering in LAS and therefore 13% losses are produced in LAS. However at TRS, both transverse phase spaces have decent values for such high charges.

### 3.4.3 Longitudinal phase space

In order to optimise the bunch compressor, the longitudinal phase space is analysed in four particular places of the CTF (Fig. 11):

- At the bunch compressor input: element 17.
- At the bunch compressor output: element 23.
- At the entrance of LAS: element 37.
- At the entrance of TRS: element 61.

The longitudinal phase spaces are plotted at the 4 elements mentioned above:

- elements 17, 23, 37
  - 0 nC (Fig. 20)
  - 1 nC (Fig. 21)
  - 3 nC (Fig. 22)
  - 5 nC (Fig. 23)
  - 10 nC (Fig. 24)

- element 61
  - 0, 1, 3 nC (Fig. 25)
  - 5, 10 nC (Fig. 26)
3.4 Results from PARMELA simulations

<table>
<thead>
<tr>
<th>Charge [nC]</th>
<th>$\alpha$ [deg]</th>
<th>$\Delta \Phi_{21}$ (FWHH) [deg]</th>
<th>$\Delta \Phi_{23}$ (FWHH) [deg]</th>
<th>$\Delta \Phi_{81}$ (FWHH) [deg]</th>
<th>Compression rate 17/23</th>
<th>Compression rate 17/61</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.</td>
<td>11.25</td>
<td>1.5</td>
<td>1.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>1</td>
<td>14.</td>
<td>11.25</td>
<td>1.5</td>
<td>1.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>14.5</td>
<td>12.</td>
<td>3.</td>
<td>3.</td>
<td>4.</td>
<td>4.</td>
</tr>
<tr>
<td>5</td>
<td>15.</td>
<td>13.</td>
<td>3.2</td>
<td>5.</td>
<td>4.</td>
<td>2.6</td>
</tr>
<tr>
<td>10</td>
<td>17.5</td>
<td>13.</td>
<td>3.2</td>
<td>7.</td>
<td>4.</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 7: Simulation results in phase

<table>
<thead>
<tr>
<th>Charge [nC]</th>
<th>$\alpha$ [deg]</th>
<th>$\sigma_{17RMS}$ [mm]</th>
<th>$\sigma_{23RMS}$ [mm]</th>
<th>$\sigma_{61RMS}$ [mm]</th>
<th>Compression rate 17/23</th>
<th>Compression rate 17/61</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.</td>
<td>1.04</td>
<td>.25</td>
<td>.23</td>
<td>4.2</td>
<td>4.5</td>
</tr>
<tr>
<td>1</td>
<td>14.</td>
<td>1.07</td>
<td>.25</td>
<td>.25</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>14.5</td>
<td>1.13</td>
<td>.32</td>
<td>.42</td>
<td>3.5</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>15.</td>
<td>1.18</td>
<td>.38</td>
<td>.51</td>
<td>3.1</td>
<td>2.3</td>
</tr>
<tr>
<td>10</td>
<td>17.5</td>
<td>1.3</td>
<td>.35</td>
<td>.68</td>
<td>3.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 8: Simulation results in RMS

For each Figure, the longitudinal phase space is given with the coordinates $(y, \beta_x, \phi)$ and a corresponding histogram is given with the coordinates (number of particles, $\phi$).

In the table 7, the bunch lengths are reported in $\Delta \phi$ (degrees) according to the histogram plots (Fig. 20 to 26). In the Table 8, the same bunch lengths are reported in $\sigma$ (mm) according to the PARMELA output.

The fact that the bunch compressor factor is not the same according to the tables 7 and 8 (mainly at low charge) is due to the sharp edge of the distribution in phase. Therefore the $\sigma$ value does not represent correctly this non-symmetric distribution.

- At 0 nC: An optimum compression is calculated without space charge effect. The compression rate (Table 7) obtained at the element 23 is 7.5. The shape of the bunch is slightly curved due to the sine shape of the RF wave. Then the compression gives to a "moon-shape" in the longitudinal phase space reducing the compression rate, because the compression process is based on a perfect elliptical longitudinal phase space (Fig. 1). It is impossible to have the ideal straight ellipse before compression. Additionally the simulations show that most of the particles lay in the front of the bunch. Then one has to take into account the head of the bunch as reference for the compression, taking care to compress enough to place all the front particles almost in phase with the reference particle. The position of the bunch tail is of less importance.

The transmission through all the CTF line is 100%.

The bunch length is conserved until the entrance of TRS. Its value is 1.4 ps (FWHH) or 0.83 ps (RMS) or 1.5 degree (FWHH).
The 30 GHz RF power generated in TRS is sent to the CAS (CLIC Accelerating Structure).

The complete layout of the CTF as foreseen for 1995 is given (Fig. 28).

Gradients equal to 80 MV/m.

Another objective is to check that an acceleration with such RF power is possible with pulses in order to check the generation of 30 GHz RF power.

As already mentioned, one of the CTF objectives is to produce short and intense electron pulses in order to check the generation of 30 GHz RF power.

Another objective is to check that an acceleration with such RF power is possible with gradients equal to 80 MV/m.

The complete layout of the CTF as foreseen for 1995 is given (Fig. 28).

The 30 GHz RF power generated in TRS is sent to the CAS (CLIC Accelerating Structure).
4.2 Bunch compressor off

From the simulations, one can expect to produce 60 MW peak in TRS, with the compressed bunches, corresponding to an electric field of 113 MV/m in TRS. Taking into account the efficiency factor, it would be possible to get 80 MV/m in the CAS.

Fig. 29 shows the mechanical layout of the bunch compressor region.

It is now designed and mechanical pieces are ordered according to this configuration.

4.2 Bunch compressor off

Up to now, design and simulations have been presented assuming that the bunch compressor was working continuously. However, the option to accelerate beam in LAS without any compression is strongly recommended.

For the set-up of the CTF, at least at low energy and for specific studies, in single bunch and with a train of bunches, one should transport the beam through the bunch compressor system without any loss when this latter is off.

PARMELA simulations have been performed under this hypothesis.

Fig. 30 and 31 show respectively the horizontal and vertical beam envelopes from the RF gun up to TRS input.

According to the simulations, the 1995 CTF line could work without the bunch compressor.

4.3 Spectrometer line

In order to measure some beam characteristics, a spectrometer line is implemented (see 2.6 and Fig. 29). A scintillator screen will be installed in the line and the optimised position is derived from Fig. 7. The vacuum chamber is 60 mm in the horizontal plane. The aperture of the Faraday cup is 35 mm. In order to transport all the beam to the Faraday cup, the simulations with TRANSPORT code give a distance for a screen, followed by a Faraday cup, of 700 mm downstream the exit of the first dipole.

The beam characteristics at this point and at 0 nC are:

\[ x_1 = 34.6 \text{ mm} \]
\[ x'_1 = 22.3 \text{ mrad} \]
\[ y_1 = 1.4 \text{ mm} \]
\[ y'_1 = 2.3 \text{ mrad} \]

These values are optimised for a good matching in the Faraday cup and a good resolution as spectrometer line.
### 4.4 Proposed settings for the 1995 CTF

(At low charges)

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>pulse length</td>
<td>19 ps (FWHH)</td>
</tr>
<tr>
<td></td>
<td>energy</td>
<td>0.2 mJ</td>
</tr>
<tr>
<td>RF gun</td>
<td>$\phi_{\text{gun}}$</td>
<td>25°</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{gun}}$</td>
<td>100 MV/m</td>
</tr>
<tr>
<td></td>
<td>RF power</td>
<td>6.0 MW</td>
</tr>
<tr>
<td>SNF350</td>
<td>B</td>
<td>0.24 T</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>69. A</td>
</tr>
<tr>
<td>Booster</td>
<td>$\phi_{\text{booster}}$</td>
<td>264°</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{booster}}$</td>
<td>70 MV/m</td>
</tr>
<tr>
<td></td>
<td>RF power</td>
<td>8.3 MW</td>
</tr>
<tr>
<td>Bunch compressor</td>
<td>$\alpha$</td>
<td>14.5°</td>
</tr>
<tr>
<td></td>
<td>$\beta$</td>
<td>0.056 T</td>
</tr>
<tr>
<td></td>
<td>$I_1$</td>
<td>22.6 A</td>
</tr>
<tr>
<td></td>
<td>$I_2$</td>
<td>22.6 A</td>
</tr>
<tr>
<td>Quadruplet</td>
<td>$G_1$</td>
<td>0.70 T/m</td>
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<tr>
<td></td>
<td>$G_2$</td>
<td>-0.19 T/m</td>
</tr>
<tr>
<td></td>
<td>$G_3$</td>
<td>0.34 T/m</td>
</tr>
<tr>
<td></td>
<td>$G_4$</td>
<td>-0.59 T/m</td>
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<td>$I_1$</td>
<td>2.8 A</td>
</tr>
<tr>
<td></td>
<td>$I_2$</td>
<td>0.8 A</td>
</tr>
<tr>
<td></td>
<td>$I_3$</td>
<td>1.4 A</td>
</tr>
<tr>
<td></td>
<td>$I_4$</td>
<td>2.4 A</td>
</tr>
<tr>
<td>LAS</td>
<td>$\phi_{\text{LAS}}$</td>
<td>350°</td>
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<td></td>
<td>$E_{\text{LAS}}$</td>
<td>17 MV/m</td>
</tr>
<tr>
<td></td>
<td>RF power</td>
<td>30 MW</td>
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<tr>
<td></td>
<td>$B_{\text{LAS}}$</td>
<td>0.1 T</td>
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<tr>
<td>Triplet</td>
<td>$G_1$</td>
<td>1. T/m</td>
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<tr>
<td></td>
<td>$G_2$</td>
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<td>$G_3$</td>
<td>1.45 T/m</td>
</tr>
<tr>
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<td>$I_1$</td>
<td>4. A</td>
</tr>
<tr>
<td></td>
<td>$I_2$</td>
<td>9.2 A</td>
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<tr>
<td></td>
<td>$I_3$</td>
<td>5.8 A</td>
</tr>
<tr>
<td>TRS</td>
<td>$e^-$ pulse length</td>
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</tr>
<tr>
<td></td>
<td>$\sigma_z$</td>
<td>0.42 mm</td>
</tr>
<tr>
<td></td>
<td>$\sigma_t$</td>
<td>1.4 ps</td>
</tr>
<tr>
<td></td>
<td>$\Delta t$ (FWHH)</td>
<td>3.3 ps</td>
</tr>
<tr>
<td></td>
<td>charge Q</td>
<td>3 nC</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{dec}}$</td>
<td>113 MV/m</td>
</tr>
</tbody>
</table>
5 Conclusion

This note is the first step in the design of the bunch compressor for the CTF. The sensitivity of the system to the geometric aberrations and chromatic effects is in progress. The main objective to produce and accelerate single bunches of 10 nC and \( \sigma_t \leq 3 \) ps is reached.

Under these conditions, the total transmission is close to 90\% until the CLIC structure TRS. In consequence and based on these simulation results, the mechanical design of the bunch compressor has been finalised and the order has been placed. It is foreseen to receive the entire system before the end of the year in order to do the magnetic measurements and install the bunch compressor in the CTF at the beginning of 1995.

6 Acknowledgements

A number of people made very useful comments and suggestions to this study. In particular the CTF beam dynamics working group: H. Braun, J.P. Delahaye, G. Guignard, J.H.B. Madsen, A. Riche, B. Mouton and W. Remmer provided a great help for the improvements of the code PARMELA. D. Reistad (Uppsala University) gave a valuable contribution to the design of the bunch compressor.
Appendices

A  PARMELA input files

A.1  PARMELA input listing

The following input file has been used for a 0 nC beam. The cards used are fully described in [6].

```
TITLE
Gun 100 MV/m, Booster 70 MV/m, Optics for 1995
RUN /NO= 6 / 1 /FREQ= 2998.55 MHz /Z0= 0. CM
/E0= 2.0e+12 MeV / 1
OUTPUT 6
FOCLAL /ZMIN= 342.3 /ZMAX= 912.3 /DZZ= 10.
/NPCBH= 58 /COEFF= 1.0 /OPT= 0
bfield
CELL /L=2.5 /APER=1.0 /IOUT=1 /phi0= 0.0 /E0=63.657
/CELL=1 /DWTMAX=1 /SYM= -1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=1 /VV=1 /NECR=1
1.5708
CELL /L=2.5 /APER=1.5 /IOUT=1 /phi0= 180.0 /E0=63.657
/CELL=2 /DWTMAX=2 /SYM= 1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=1 /VV=1 /NECR=1
1.5708
CELL /L=5.0 /APER=1.5 /IOUT=1 /phi0= 180.0 /E0=56.586
/CELL=3 /DWTMAX=2 /SYM= -1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=2 /VV=1 /NECR=2
1.5708,0.5236
DRIFT /L= 2.33 /APER= 1.5 /IOUT=1
SOLENOID /L= 5.34 /A=1.5 /IOUT=1 /B= 2400. /SNF 350
CELL /L=5.0 /APER=1.5 /IOUT=1 /phi0= 260.0 /E0=39.61
/CELL=4 /DWTMAX=3 /SYM= 1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=2 /VV=1 /NECR=2
1.5708,0.5236
CELL /L=2.5 /APER=1.5 /IOUT=1 /phi0= 260.0 /E0=44.56
/CELL=5 /DWTMAX=3 /SYM= -1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=1 /VV=1 /NECR=1
1.5708
CELL /L=5.0 /APER=1.5 /IOUT=1 /phi0= 80.0 /E0=44.56
/CELL=6 /DWTMAX=3 /SYM=0 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=1 /VV=1 /NECR=1
1.5708
CELL /L=5.0 /APER=1.5 /IOUT=1 /phi0= 260.0 /E0=44.56
/CELL=7 /DWTMAX=3 /SYM=0 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=1 /VV=1 /NECR=1
1.5708
CELL /L=2.5 /APER=1.5 /IOUT=1 /phi0= 80.0 /E0=44.56
/CELL=8 /DWTMAX=3 /SYM= 1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=1 /VV=1 /NECR=1
1.5708
CELL /L=5.0 /APER=1.5 /IOUT=1 /phi0= 80.0 /E0=39.61
/CELL=9 /DWTMAX=3 /SYM= -1 /CFREQ=0 /CTYPE=1
/BZ=0. /NFC=2 /VV=1 /NECR=2
1.5708,0.5236
DRIFT /L= 157.0 /APER= 2.0 /IOUT= 1
BEND /L=15.130 /A=20.0 /IOUT=1 /WR=10.102 /AL=13.00
```
A.1 PARMELA input listing

/ B1=0.0 / B2=13.00 / PSI1=0.0 / PSI2=0.0 / R1=0.0 / R2=0.0
DRIFT / L=10.0 / APER= 2.0 / IOUT= 1
BEND / L=30.26 / A=20.0 / IOUT= 1 / WR=10.102 / AL= -26.00
/ B1= 13.00 / B2= 13.00 / PSI1= 0.0 / PSI2= 0.0 / R1= 0.0
/ R2= 0.0
DRIFT / L= 10.0 / APER= 2.0 / IOUT= 1
BEND / L=15.13 / A=20.0 / IOUT= 1 / WR=10.102 / AL=13.00
/ B1=13.00 / B2=0.00 / PSI1=0.0 / PSI2=0.0 / R1=0.0 / R2=0.0
DRIFT / L= 9.50 / APER= 2.0 / IOUT= 1
QUAD / L= 10.4 / APER= 2.9 / IOUT= 1 / BP= 54.0
DRIFT / L= 9.00 / APER= 2.0 / IOUT= 1
QUAD / L= 10.4 / APER= 2.9 / IOUT= 1 / BP= -34.5
DRIFT / L= 9.00 / APER= 2.0 / IOUT= 1
QUAD / L= 10.4 / APER= 2.9 / IOUT= 1 / BP= 34.5
DRIFT / L= 9.00 / APER= 2.0 / IOUT= 1
QUAD / L= 10.4 / APER= 2.9 / IOUT= 1 / BP= -37.0
DRIFT / L= 4.50 / APER= 2.0 / IOUT= 1
DRIFT / L= 74.10 / APER= 2.0 / IOUT= 1
CELL / L=3.3333 / APER=1.25 / IOUT= 1 / PHI0= 20.
/ E0=6.6054 / NC=10 / DWT=2. / SYM=1 / CFREQ= 2998.55
/ CTYPE=1 / BZ=0. / NFC=14 / COS=1 / NECR=14
0.1704634+0.1340474+0.1232453+0.56985169-0.1234567+0.8976543
0.165716+0.3410586+0.345687+0.2345678-0.2345678
0.2683355-0.50.322212E-07-0.9270728E-08-0.6640441E-07,
-9.901188E-07-7.171031E-07
TRWAVE / L= 1.6667 / APER= 1.250 / IOUT= 1
/ PHI= 290.00 / E0= 13.6 / NC= 11 / DWTMAX= 1.
/ CFREQ = 2998.55 / GAP= 0. / NMIN = 5 / NMAX = 5
/ PSHIT = .6667 / NW = 138 / NPRINT = 0
/ Z1 = 129.3 / Z2 = 138.1 / R1 = 0. / R2 = .5 / DPHI = 800.
TRWAVE 3.3333 1.250 1 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 1.250 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 1.250 0 290.00 13.6 11 1. 2998.55 0.0
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TRWAVE 3.3333 1.250 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 1.250 0 290.00 13.6 11 1. 2998.55 0.0

120×(TRWAVE 3.3333 1.250 0 290.00 13.6 11 1. 2998.55 0.0)

TRWAVE 3.3333 0.900 1 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 0.900 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 0.900 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 0.900 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 0.900 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 0.900 0 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 3.3333 0.900 1 290.00 13.6 11 1. 2998.55 0.0
TRWAVE 1.6667 0.900 1 290.00 13.6 11 1. 2998.55 0.0
DRIFT / L= 55.4 / APER= 2.0 / IOUT= 1
QUAD / L= 20.0 / APER= 2.0 / IOUT= 1 / GR= 105.25
DRIFT / L= 9.80 / APER= 2.0 / IOUT= 1
A.2 Magnetic field along LAS

A magnetic field along LAS, represented by the TRWAVE cards, can be switched on and off by the use of a FOCLAL card. This card calls the file 'bsfield' given below. Additionally, the value of this field can be modulated by a factor 'COEFF' in FOCLAL.

\$ champ chp=

10.0,
50.0,
200.0,
400.0,
600.0,
800.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
1000.0,
B Graphics
SNF: Solenoid    LAS: LIL Accelerating Structure
QF, QD: Quadrupoles   TRS: Transfer Structure

Figure 11: Simplified CTF layout for simulations
Figure 12: Phase scannings at 0 nC.
At the exit of the gun

At the exit of the booster

At the exit of LAS

Figure 13: Momentum spread function of the charge
Figure 14: Horizontal beam envelopes in the bunch compressor region. 
(. . .): 100% particles. (-): rms value.
Figure 15: Vertical beam envelopes in the bunch compressor region. 
(...) : 100% particles. (-) : rms value.
Figure 16: Horizontal beam envelopes for the simplified CTF line.

- (a) 0 nC
- (b) 1 nC
- (c) 3 nC
- (d) 5 nC
- (e) 10 nC

(...): 100% particles. (-): rms value.
Figure 17: Vertical beam envelopes for the simplified CTF line.
(\ldots): 100% particles. (-): rms value.
Figure 18: $(4, x')$ and $(y', y')$ phase space evolutions through the CTF line for a 0 nC beam.
Figure 19: $(x', y')$ and $(x' y')$ phase space evolutions through the CTF line for a 10 nC beam.
Figure 20: Longitudinal phase space evolution through the CTF line for a GC beam.
Figure 21: Longitudinal phase space evolution through the CTF line for a 1 nC beam.
Figure 22. Longitudinal phase space evolution through the CTF line for a 3 nC beam.
Figure 23: Longitudinal phase space evolution through the CTF line for a 5 nC beam.
Figure 26: Longitudinal phase space evolution through the CTE line for a 10 nC beam.
Figure 25: Longitudinal phase space at the TRS (0, 1, 3 nC).
Figure 26: Longitudinal phase space at the TRS (5, 10 nC).
Figure 27: Space charge effect.
Figure 28: Complete CTF line (1995).

SNF: Solenoid   LAS: LIL Accelerating Structure   QF, QD: Quadrupoles
TRS: Transfer Structure   CAS: CLIC Accelerating Structure
Figure 26: Mechanical layout of the bunch compressor region.
Figure 30: Horizontal beam envelopes with bunch compressor off.

(...): 100% particles. (-): rms value.
Figure 31: Vertical beam envelopes with bunch compressor off.

(...): 100% particles. (-): rms value.
References

[1] J.P. Delahaye. A simplified scheme for 30 GHz RF generation in CTF. *CLIC note 175*


