# Bunch Compressor Performances at the CLIC Test Facility

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*Abstract*

The Test Facility of the "Compact Linear Collider" (CLIC) at CERN (CTF), has to prove the feasibility of transporting high charge beams through decelerating structures at 30 GHz to create RF power. This RF power is used to supply, in the final scheme, the cavities of the main linac. To optimise this power generation, a bunch compressor has been installed in the test line. This compressor shortens the electron bunches after creation and acceleration in the RF gun. The compressed bunches are then accelerated by a high gradient cavity (50 MV/m) and transported to a 30 GHz cavity. Compressed bunch length measurements showed that lengths of 0.6 mm (rms) were obtained at the entrance of 30 GHz cavity for a 10 nC beam. Compression of electron bunches of charges between 2 and 17 nC have also been measured. Emittance measurements were done to study the transverse effects of the bunch compressor on the beam. The use of the code PARMELA [1] allowed the design and optimisation of the chicane. The simulation results have been compared to the experimental measurements.

## 1 COMPRESSION PROCESS

The use of a magnetic chicane composed of three dipoles to compress bunches implies having bunches with a phase–energy correlation such that the head particles have less energy than the ones from the tail. Thus, the highest energy particles get a shorter path length in the system than the lowest energy particles which tends to reduce the total length of the bunch, (Fig. 1).

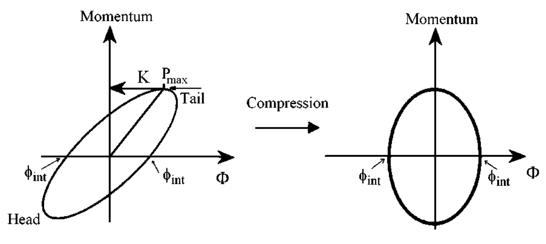



Figure 1: compression process

For a non–isochronous system, the path length difference, $\Delta l$, between an arbitrary particle and the central particle depends of the relative momentum deviation, $\delta p/p$, of the particle from the central one. One finds for the chicane the following relationship :

$$\Delta l = \{4\rho\,[\tan\alpha - \alpha] + 2\lambda\tan^2\alpha\}\,\delta p/p \qquad (1)$$

where $\alpha$ is the bending angle in the first magnet, $\rho$ is the curvature radius of the central trajectory and $\lambda$ is the distance between magnets.

## 2 EXPERIMENTAL SETUP

A scheme of the CTF line in 1995 [2] is given in Figure 2. It is composed of a photo–injector with a 3 GHz RF gun and a 4 cell S–band cavity called *booster*. The gun is equipped with a $Cs_2Te$ photo–cathode which is illuminated by a 8 ps (FWHH) laser pulse at 262 nm. The electron bunch is accelerated from the photo–cathode by a 100 MV/m electric field. The booster accelerates the bunch by a 70 MV/m gradient. In it a longitudinal momentum correlation is obtained. The bunch is adjusted on the slope of the RF wave by changing the phase of this wave ($\phi_{booster}$) with respect to the phase of the beam. The beam energy out of the photo–injector is around 11 MeV. The beam enters into the bunch compressor system. Once the bunch is compressed and to eliminate the space charge effects at low energy ($\propto 1/E^2$), the bunch is accelerated in a 3 GHz structure up to an energy of 65 MeV. Then, it is transported to the instrumentation for measurement.

Although a single pulse of 35 nC was transported through the line [3], the operation of the bunch compressor is only possible up to 17 nC due to the space charge limitations. The longitudinal correlation of the bunch needed at the entrance of the chicane disappears by the effect of the repulsive forces at low energy.

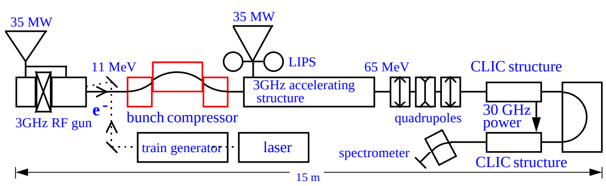



Figure 2: layout of the CTF in 1995

Experimentally, the procedure to measure compressed bunches is the following: the beam is setwith the previously described correlation and by increasing the bunch compressor current from zero, one first compresses the beam, its length is reduced until it has reached the optimum compression (upright ellipse). After this point, the beam is *over–compressed* which means the length increases, the ellipse is rotated counter–clockwise. For the bunch length measurements, a Transition–Cherenkov monitor is used converting the electron pulse into a photon pulse. The light is transported by optical lenses to a streak camera with a 4 ps FWHH resolution. The longitudinal bunch length is measured over 10 measurements to minimise statistical errors.

The emittances were measured by the method of variation of two quadrupoles [4]. They include statistical errors (beam instabilities, errors in the profile measurements) and the systematic errors (beam momentum error, gradient errors).

## 3 SIMULATIONS AND EXPERIMENTS

### *3.1 Bunch lengths*

Three bunch charges (2, 10 and 17 nC) were chosen for the following reasons:

- Below 2 nC, the effect of the space charge is negligible which corresponds to a minimum bunch length.
- At 10 nC, the space charge is important but the simulations still predict a bunch length close to the specification for CLIC ($\sigma_z$ = 0.6 mm rms).
- Finally, at 17 nC, the space charge force (proportional to the particle density $\rho_{bunch}$) is minimised at low energy by using a longer laser pulse on the photo–cathode splitting the incident laser pulse into two 8 ps pulses separated by 9 ps (17 ps FWHH total) which, for a same charge extracted, reduces $\rho_{bunch}$ and then the repulsive force.

All the measurement, $\sigma_{mes}$, are corrected quadratically with the resolution, $\sigma_{res}$, of the streak camera: $\sigma_{cor} = \sqrt{\sigma^2_{mes} - \sigma^2_{res}}$ and used on the figures.

The measurements are started without compression (bending angle $\alpha$ =0) but with an energy to phase correlation along the bunch. At low charge (2 nC), the correlation in the bunch induced by the photo–injector tends to reduce its length due to the difference of velocity between the head and the tail particles. This effect combined with the RF compression in the gun reduced the longitudinal beam extension from 8 ps (laser pulse length) to 6 ps (Fig. 3). On the contrary, at 10 nC (Fig. 4) and 17 nC (Fig. 5), the space charge force counteracts the previous effect and stretches the beam (from 8 ps to 9 ps at 10 nC and from 17 ps to 21 ps at 17 nC). The compressor is then turned on and the beam is deflected in the chicane with increasing bending angles.

At low charge, the bunch length gets shorter than the resolution of the camera, then only 3 characteristic measurements (under–, optimum and over–compression) were done in good agreement with the simulations within measurement errors. The minimum bunch length is 1.8 ps corresponding to a peak current of 1110 A. The compression factor is 4.

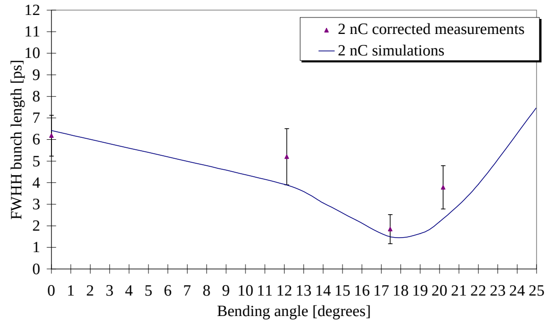



Figure 3: Compression of a 2 nC bunch

At high charge, 10 nC, the minimum length is 4.4 ps for a beam peak current of 2100 A. The compression factor is reduced to 2, mainly due to the space charge effect and the simulations are in good agreement with the measurements. The strong *over–compression* for large bending angles is also observed.

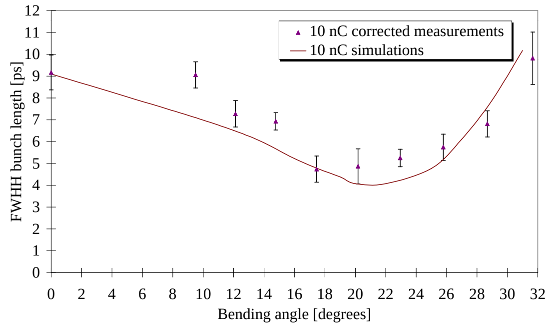



Figure 4: Compression of a 10 nC bunch

Then, at higher charge, 17 nC, starting with longer laser pulse on the photo–cathode, the bunch length after compression is 7.3 ps for a beam current of 2300 A and a compression factor of 3. The figure 5 shows the important effect of the booster phase on the compression

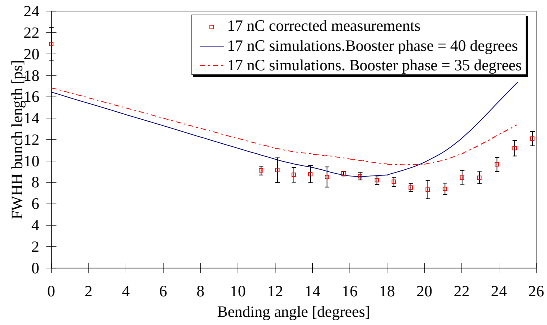



Figure 5: Compression of a 17 nC bunch

The simulation plots for $\Phi_{booster} = 35°$ and 40° from the phase of maximum acceleration are reported. The position of the minimum and the bunch length depend on $\phi_{booster}$ because when $\Phi_{booster}$ increases, $\delta p/p$ also does and the conservation of the emittance (Liouville's theorem) implies the reducing of $\Phi_{int}$ (Fig. 1) which after compression gives a shorter pulse. On the contrary, for lower $\Phi_{booster}$, $\delta p/p$ is smaller for a same initial bunch length which tends to increase $K$ (Fig. 1) and requires larger bending angle in the chicane to reach the optimum compression. Nevertheless, during the experiment, the saturation of the instrumentation for such a beam charge led to an uncertainty in the determination of the $\phi_{booster}$.

## *3.2 Emittances*

Emittance measurements were performed for 1.5 and 5 nC beams. We used a correlated beam for one specific bending angle in the chicane corresponding to the angle needed for an optimum compression (12 $^\circ$ and 23 $^\circ$ respectively). The Table 1 resumes the effects on the horizontal ($\epsilon_H$) and vertical ($\epsilon_V$) emittances when the compressor is turned on. They are compared to the simulation figures.

These emittances are reported in Fig. 6 together with the simulations.

| | Measurement | | Simulations |
|---|---|---|---|
| Emittances [mm.mrad] | without compression | with compression | with compression |
| | **Q = 1.5 nC** | | |
| $\epsilon_H$ | 24±3 | 24±4 | 21.5 |
| $\epsilon_V$ | 27±4 | 30±4 | 29 |
| | **Q = 5 nC** | | |
| $\epsilon_H$ | 65±11 | 124±28 | 150 |
| $\epsilon_V$ | 50±12 | 56±12 | 51 |

Table 1: Normalised emittances measured and simulated for 1.5 and 5 nC beams.

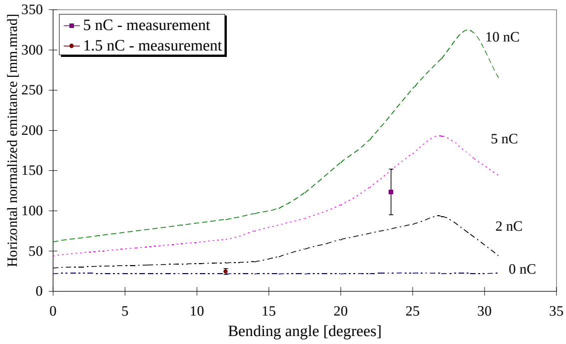
From the simulation point of view, the horizontal emittance blow up appears in the presence of the space charge force (2, 5 and 10 nC). The chicane is by design non–dispersive ($R_{16}$ and $R_{26}$ equal to zero) even if it is dispersive locally in each dipole. Nevertheless, when the space charge is important the reduction of the longitudinal extension of the beam leads to increase the Coulomb forces between particles. The head particles are accelerated by the core of the beam while the particles from the tail are decelerated. In consequence, $\delta p/p$ varies along the system which becomes dispersive. This chromatic coupling increases the horizontal emittance.

In the vertical plane, the beam is not deflected, there is no dispersive term and the emittances remain low.

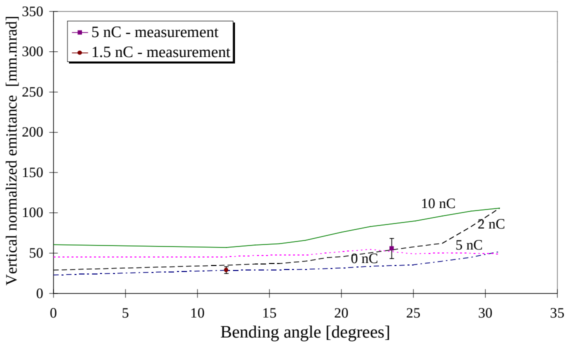
At low charge (1.5 nC), the measurements confirm that the chicane does not affect the transverse emittances. When the charge is increased (5 nC), the measurements show a blow up in the horizontal plane while in the vertical plane the emittances remain small as expected.

# 4 CONCLUSION

This study, done in the frame of a thesis [5], shows a good agreement between the simulation predictions and the ex-




(a) Horizontal emittance




(b) Vertical emittance

Figure 6: Emittance measurements for 2 charges and comparison with the simulation plots

perimental results. It has been possible to compress bunches between 2 and 17 nC to respectively 1.8 and 7.3 ps (FWHH) close to the CLIC specification of 5 ps. The study has also underlined several problems in the use of the chicane. First, at low energy (11 MeV), the space charge force limits the possible compression of a bunch with a charge higher than 17 nC. Secondly, the process affects also the beam horizontal emittance. Finally, the resolution of the streak camera installed in the CTF limits the measurement precision.

In conclusion and taking into account the above remarks, it has been decided to implement the bunch compressor system in the new version of the CTF line in 1996 but at a higher beam energy where the space charge force will be negligible.

# 5 REFERENCES

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