2.2.2 Sub-Harmonic Bunching System of CLIC Drive Beam Injector

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2.2.2.1 *Drive Beam Time Profile*

In the final time structure of the Drive Beam, as shown in Figure 1, the main pulse with the length of 140µs, consists of 24 bunch trains of 244ns length and each bunch trains contains 2922 bunches with a time separation correspond to 12 GHz.

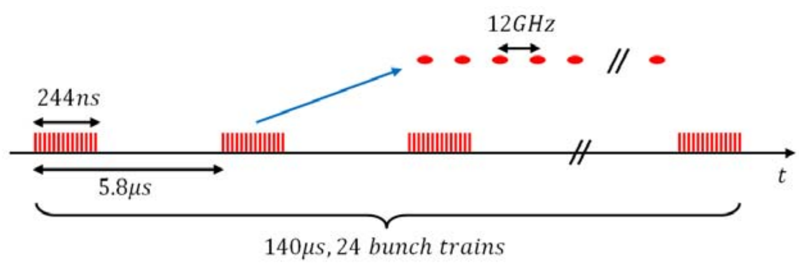


Figure 1: The final time structure of the Drive Beam.

To achieve such a time structure the continuous beam from the electron gun passes through the 0.5 GHz sub-harmonic bunching system. This system switches its phase by 180^{o} every 244ns.

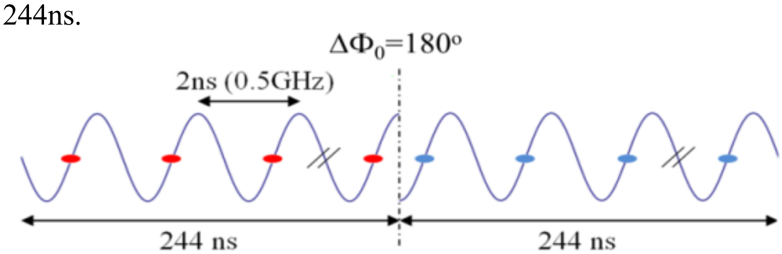


Figure 2: Phase switching

After the sub-harmonic bunching system a 1 GHz travelling wave buncher is used to reduce the bunch length more and then the beam is accelerated with 1 GHz frequency. Therefore, only every second of RF bucket of the accelerator is occupied. Thanks to the phase switching of the sub-harmonic bunching system the main pulse is made up of even and odd bunch trains (Figure 3). This procedure is called phase coding.

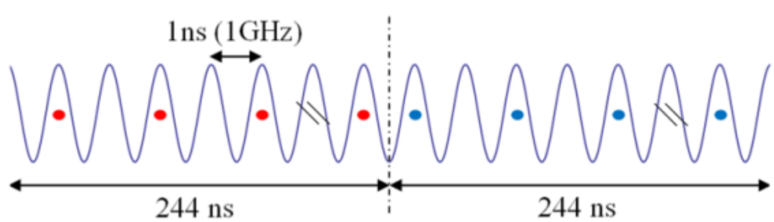


Figure 3: Phase coded Drive Beam

Although in real system about 5% of particles captured in wrong buckets, called satellite bunches. These bunches have to be eliminated for reasons of efficiency and machine protection at the end of injector. Having even and odd bunch trains according to Figure 4 a delay loop is used to combine these trains to get twice bunch repetition frequency and twice peak current.

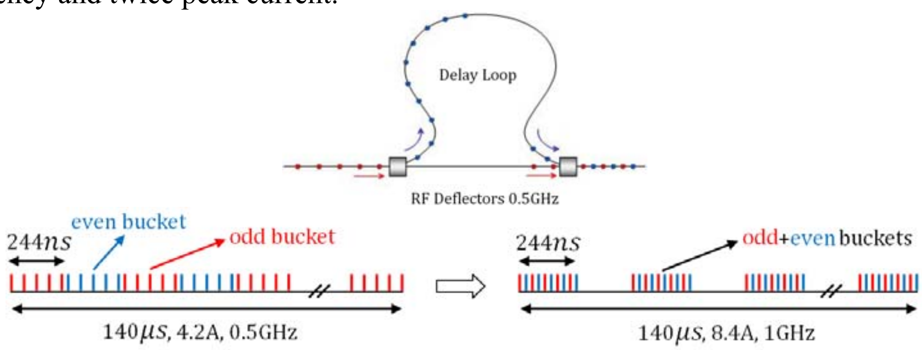


Figure 4: The principle of bunch combination in the delay loop [1].

In a roughly same procedure, the trains are recombined three and four times in the following two combiner rings. Therefore, the overall multiplication of the frequency and the peak current will be 24 and we will achieve the final time structure needed.

2.2.2.2 ***Sub-harmonic bunching system***

The general layout of the CLIC Drive Beam bunching system is shown in Figure 5.

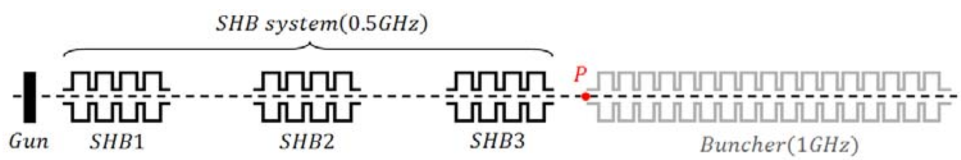


Figure 5: General layout of bunching system.

The sub-harmonic bunching system consists of three travelling wave sub-harmonic bunchers (SHB). This system has two functions. The first is to provide even and odd bunch trains and secondly to act as a prebuncher for the travelling wave buncher. This system should be optimized with the following optimization criteria.

- To maximize the population of the particles in the acceptance of the buncher.
- To minimize the population of satellite bunches.

The principle of bunching with sub-harmonic bunching system is based on velocity modulation bunching [2, 3]. The sub-harmonic bunching system is optimised in three stages. First, we ignore the effect of space charge and consider thin lens approximation for simplicity. Then the effect of space charge is considered and finally the realistic travelling wave structures are studied.

Thin lens approximation

In thin lens approximation the travelling wave structures is replaced with the simple thin lens cavities.

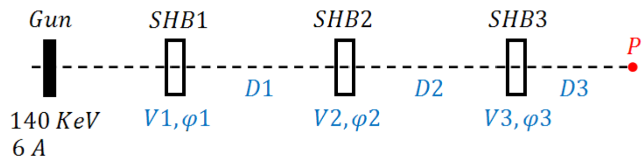


Figure 6: Thin lens approximation

In this approximation one can easily track particles in longitudinal phase space using the following relations.
In a drift space:

$$\begin{aligned} \Delta\varphi &= 360 fD/\beta c \\ \Delta w &= 0 \end{aligned} \tag{1}$$

In a SHB:

$$\begin{aligned} \Delta\varphi &= 0 \\ \Delta w &= eV\sin[\Phi_0 + \varphi - \varphi_r] \end{aligned} \tag{2}$$

Where φ and w are the phase and the kinetic energy of particles. φ_r is the phase of the reference particle and Φ_0 is the phase of the RF field seen by that particle. After tracking we can count the percentage of particle in the buncher acceptance and the satellite population according to relations (3) and (4) respectively.

$$-60 \le \varphi_P \le 60 \tag{3}$$

$$-180 \le \varphi_P \le -90 \vee 90 \le \varphi_P \le 180 \tag{4}$$

The buncher acceptance is found to be [-60, 60] after inserting and optimizing the buncher.

For the optimization of the thin lens system a simple computer code is written with *MATHEMATICA* software which changes the phases and voltages of the cavities and also the drift spaces between them to fine the optimum configuration. Figure 7 shows the final longitudinal phase space and the phase spectrum of the beam at the entrance of the buncher. In this configuration 92.3% of particles are in the acceptance of buncher and the satellite population is 5.0%.

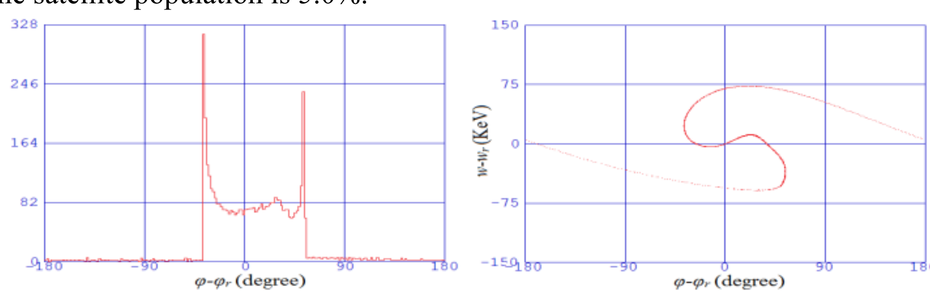


Figure 7: The final phase spectrum (left diagram) and longitudinal phase space (right diagram) of the beam at the entrance of the buncher (ignoring the space charge).

The space charge effect

The effect of the space charge forces is investigated in various configuration of the system. The destroying effects of the space charge on longitudinal beam profile start when the phase spectrum becomes very narrow. In This situation particles are longitudinally close together. This mostly occurs in the first drift section.

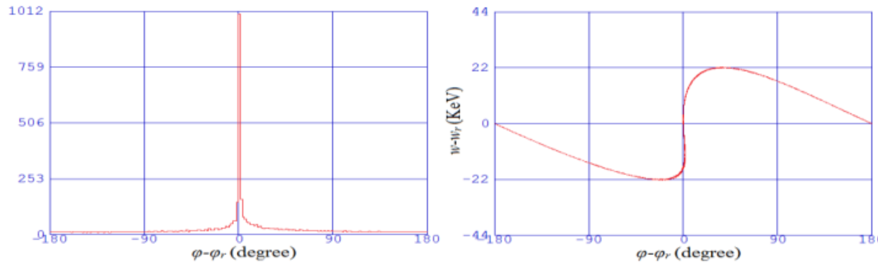
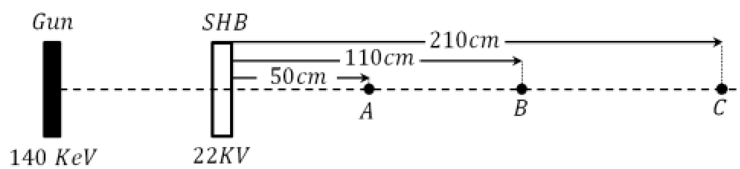
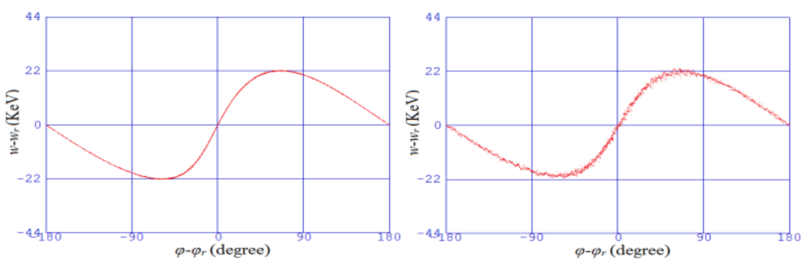


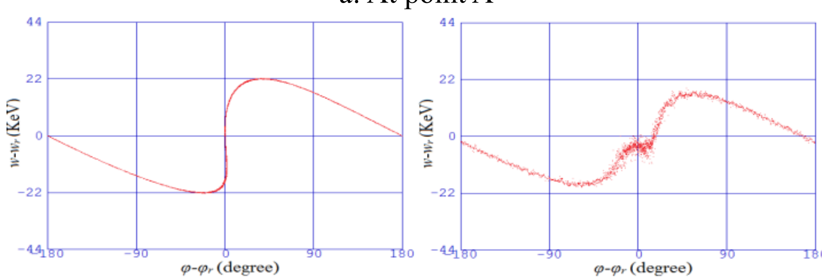
Figure 8: Phase spectrum (left) and phase space (right) of the beam at 110 cm away from a 22 KV SHB.

One can compare the phase space of the beam after passing through the first SHB ignoring the space charge effect and taking it into account in Figure 9.

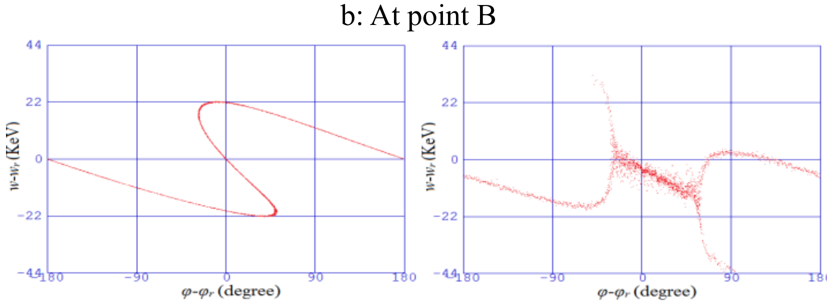




a: At point A



b: At point B



c: At point C

Figure 9: The phase space of the beam at several distances away from SHB ignoring the space charge (left diagram) and taking it into account (right diagram).

As shown in Figure 9 the effect of space charge can hardly be seen at distances less than 110 cm where the phase spectrum becomes narrow. After this point the debunching effect of space charge forces starts. And at point C the phase space is completely different from the case of ignoring the space charge forces and the bunch length is much bigger. To reduce the destroying effect of the space charge one should avoid long drift spaces, specially the first one. When the beam enters the second SHB the strong RF field of SHB reduces the effect of space charge forces. So in the optimization code we should restrict the maximum value of drift spaces. Following this procedure, Figure 10 shows the phase space of the optimum configuration of the Figure 7 with taking the space charge into acount. After turning on the space charge, 91.6 percent of particles lie in the buncher acceptance and the satellite population becomes 5.4%.

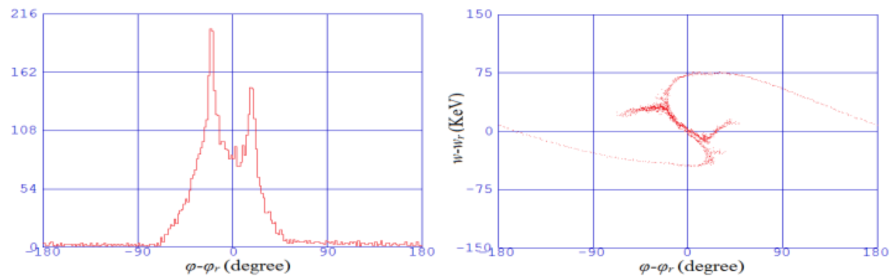


Figure 10: The phase spectrum (left diagram) and the phase space (right diagram) of the beam in thin lens model at the entrance of the buncher.

Travelling wave SHBs

If we look to the phase space of the beam after passing through a 50 cm travelling wave structure SHB we will interestingly find out that it is very similar to the case of simple thin lens cavity.

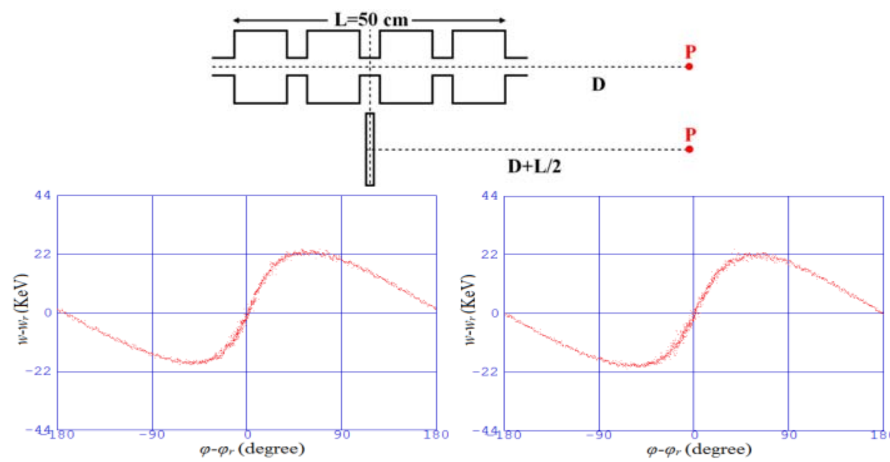
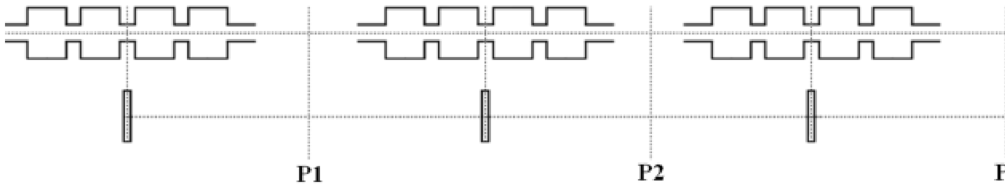
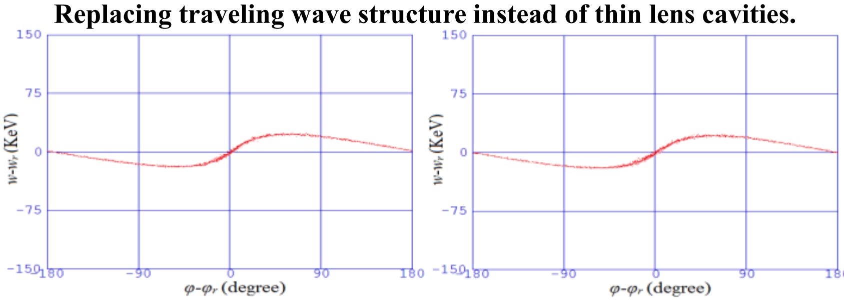


Figure 11: The phase space of the thin lens SHB (left diagram) and travelling wave SHB (right diagram).

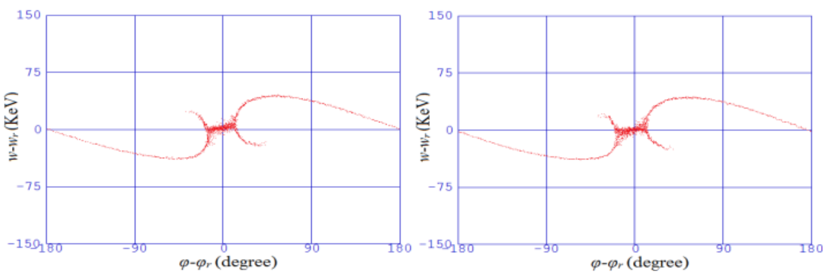
This means that the thin lens approximation is a good approximation and the details of the electric field of the travelling wave structure is not important and the only important thing is the voltage of SHB. To be sure, Figure 12 provides more comparison been travelling wave structure and thin lens system.



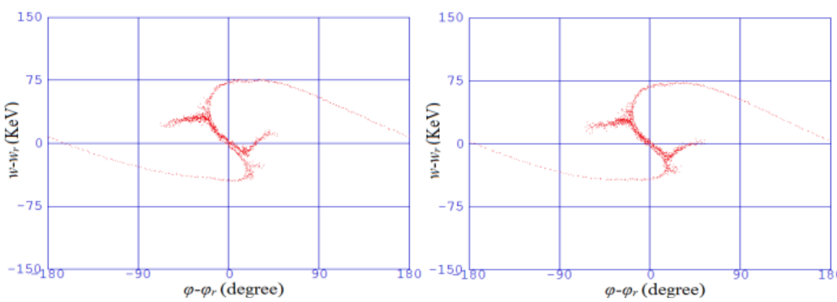
a: Replacing traveling wave structure instead of thin lens cavities.



b: At point P1



c: At point P2



d: At point P3

Figure 12: Comparison between thin lens system (left diagram) and travelling wave structure (right diagram).

For the travelling SHB system 92.0 percent of particles lie in the buncher acceptance and the satellite population is 5.0%.

2.2.2.3 *Conclusions*

The optimization process of the sub-harmonic bunching system can be summarized as follows:

- Optimization of the thin lens system with a code written in *MATHEMATICA*.
- Selection of an optimum configuration in which the effect of space charge is low, this occurs in configurations with the shorter drift spaces.

- Reconstruction of the SHB system with the travelling wave SHBs instead of thin lens cavities.

2.2.3 Sub-Harmonic Buncher Design for the CLIC Drive Beam Injector

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2.2.3.1 *Introduction*

Sub Harmonic Bunchers (SHBs) are the first RF components of the CLIC drive beam after the electron gun. The electron gun produces a continuous beam with about 140 μs pulse length, 50Hz repetition rate, 140 KeV energy and about 5A current. Inside SHBs the continuous beam is bunched and subdivided in 576(24x24) sub-trains with 243.7ns length. At the beginning of each sub-train, RF source phase is flipped by 180° as needed for further combination process in delay loop and combiner rings [1].

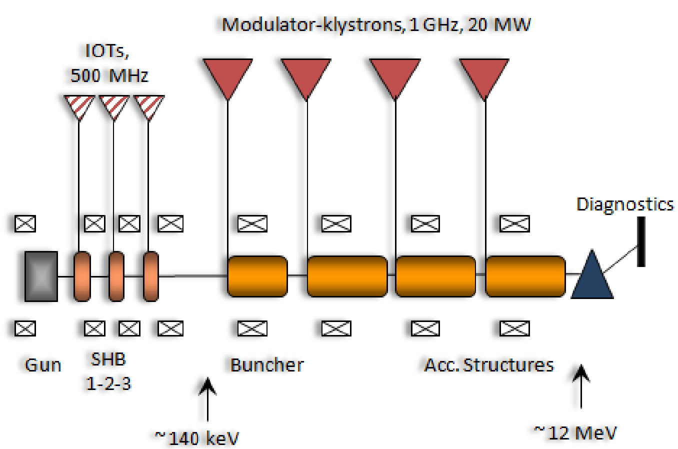

Figure 1: CLIC drive beam front-end layout.

Therefore, wide-band RF sources and SHBs is needed with fast 180° phase switching capability in 10 ns. For the combination process the SHBs resonant frequency (499.75 MHZ) should be half of the following RF accelerating structures resonant frequency (999.5 MHz). Figure 1 shows a layout of drive beam front-end as a first stage of the CLIC drive beam. At the moment, wide-band IOT seems to be the best option for SHBs RF sources.

2.2.3.2 *SHB Design*

Band-width requirement calculation

Equation 1 and Figure 2 show a simple model of smooth 180° phase switching in 10ns from section A to C. It shows two half amplitudes $\omega_0 \pm \Delta\omega = 499.75 \pm 50$ MHz RF wave is needed in transit section (B).