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CLIC – Note – 1060

CTF3 DRIVE BEAM INJECTOR OPTIMISATION

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Abstract

In the Compact Linear Collider (CLIC) the RF power for the acceleration of the Main Beam is extracted from a high-current Drive Beam that runs parallel to the main linac. The main feasibility issues of the two-beam acceleration scheme are being demonstrated at CLIC Test Facility 3 (CTF3). The CTF3 Drive Beam injector consists of a thermionic gun followed by the bunching system and two accelerating structures all embedded in solenoidal magnetic field and a magnetic chicane. Three sub-harmonic bunchers (SHB), a prebuncher and a travelling wave buncher constitute the bunching system. The phase coding process done by the sub-harmonic bunching system produces unwanted satellite bunches between the successive main bunches. The beam dynamics of the CTF3 Drive Beam injector is reoptimised with the goal of improving the injector performance and in particular decreasing the satellite population, the beam loss in the magnetic chicane and the beam emittance in transverse plane compare to the original model based on P. Urschuetz works.

Geneva, Switzerland
30/06/2015

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Abstract

In the Compact Linear Collider (CLIC) the RF power for the acceleration of the Main Beam is extracted from a high-current Drive Beam that runs parallel to the main linac. The main feasibility issues of the two-beam acceleration scheme are being demonstrated at CLIC Test Facility 3 (CTF3). The CTF3 Drive Beam injector consists of a thermionic gun followed by the bunching system and two accelerating structures all embedded in solenoidal magnetic field and a magnetic chicane. Three sub-harmonic bunchers (SHB), a prebuncher and a travelling wave buncher constitute the bunching system. The phase coding process done by the sub-harmonic bunching system produces unwanted satellite bunches between the successive main bunches. The beam dynamics of the CTF3 Drive Beam injector is reoptimised with the goal of improving the injector performance and in particular decreasing the satellite population, the beam loss in the magnetic chicane and the beam emittance in transverse plane compare to the original model based on P. Urschuetz works.

1. Introduction

The Compact Linear Collider (CLIC) is a future multi-TeV electron-positron collider under study at CERN [1]. In CLIC acceleration scheme the RF power for the acceleration of the main beam is provided by a high current Drive Beam that runs parallel to the main linac. The Drive Beam loses its energy in special RF structures (decelerators) called Power Extraction and Transfer Structures (PETS).

The Drive Beam is generated and accelerated in lower frequency structures then it goes through a frequency multiplication process because klystrons at lower frequencies are more efficient. The main characteristics of the Drive Beam injector is the phase coding process done by the sub-harmonic bunching system operating at half the acceleration frequency. The phase coding process (described below) is essential for the Drive Beam frequency multiplication. During this process the so called satellite bunches are produced which adversely affects the machine power efficiency.

The main feasibility issues of the two-beam acceleration scheme have being demonstrated at the CLIC Test Facility 3 (CTF3) which is a small-scale version of CLIC [2]. The main points which have been demonstrated at CTF3 are the efficient generation of the Drive Beam and the RF power production as well the phase coding process [1].

The CTF3 Drive Beam injector consists of a thermionic gun providing a beam with a current of 6 A, a bunching system and two accelerating structures to accelerate the beam up to about 19 MeV and a magnetic chicane with a horizontal slit to reduce the beam energy spread and trim the longitudinal phase space of the beam. The bunching system consists of three 1.5 GHz sub-harmonic bunchers, a standing wave prebuncher and a travelling wave buncher both operating at 3 GHz as the accelerating structures. In the transverse plane, the focusing is provided by solenoid magnets up to the end of second accelerating structure and for the rest of the beam line quadrupole magnets are used. The general layout of the injector is shown in fig.1.

The sub-harmonics bunching system operates at half the acceleration frequency, therefore only every second RF bucket is occupied. However, a few percent of particles are captured in wrong buckets called satellite bunches. The sub-harmonic bunching system changes its phase at the end of each bunch train by 180°. This process is called the phase coding [1]. Therefore, as illustrated in fig. 2 the main pulse is made up of even and odd bunch trains. Such a phase coded beam then passes through a delay loop and a combiner ring for the frequency multiplication process.

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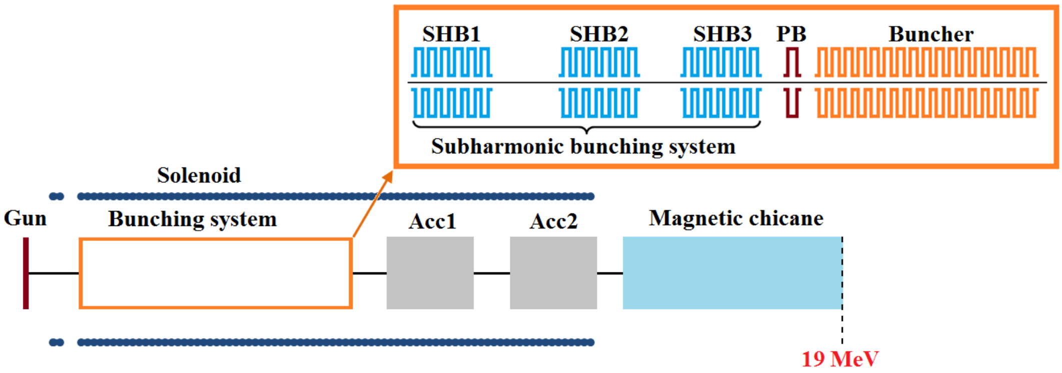

Fig. 1. CTF3 Drive Beam injector layout.

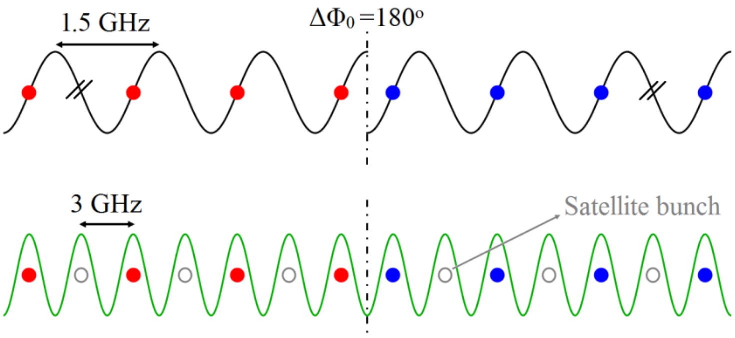

Fig. 2. Phase switching of the sub-harmonic bunching system and the satellite concept.

The CTF3 Drive beam injector is reoptimised with the goal of reducing the satellite population, the beam loss at the chicane and the beam emittance. In this optimisation only minor changes are applied rather than changing all the parameters of the system and the effort has taken to improve the injector performance using the small number of the available knobs. In the next sections, we first describe the original model which is based on P. Urschuetz works [3] and then the effect of minor changes on the injector performance. The optimisation methods used here are already applied on CLIC Drive Beam injector. The physics behind the optimisation procedures and the design of CLIC Drive Beam injector are described extensively in [4, 5].

2. Description of the original model

In the original model, the voltages of the three sub-harmonic bunchers are the same and equal to 20 kV and for the prebuncher it is 50 kV. The length of each SHB and the prebuncher is 15 cm and 2 cm respectively. The length of the drift spaces of the sub-harmonic bunching system is listed in Table I and the beam parameters after the magnetic chicane can be found in Table II.

TABLE I. Drift spaces of the SHB system

Drift space	Length (cm)
D1	43
D2	7.8
D3	10.2
Dp	9.5

The satellite to main bunch population after the buncher is 10.2%. The satellite population reduces about 3% in the chicane because of particle losses. In fact the energy spread of the satellite bunches is larger than the main bunch therefore we lose a larger fraction of the satellite particles compare to the main bunch particles. Figure 3 shows the longitudinal phase space of the both bunches before the chicane.

TABLE II. Beam parameters after the magnetic chicane

Beam parameters	**Value**
RMS bunch length	1.66 mm
RMS energy spread	0.143 MeV
Beam energy	18.6 MeV
Satellite to main bunch population	7.0%
Beam loss at chicane	18.8%
Beam emittance	38.8 mm-mrad

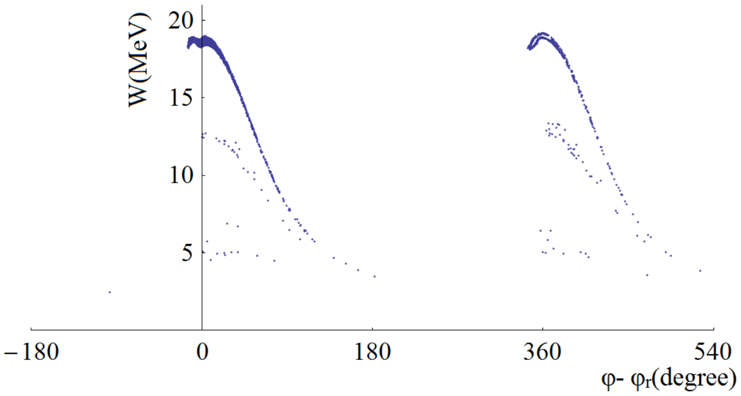

FIG. 3. Longitudinal Phase space of the beam before the magnetic chicane.

The low energy tail of the bunches cause a large beam loss at the chicane. The population of the particles in these low energy tails depends mostly on the buncher design and on the shape of the longitudinal phase space at the buncher entrance as well. The longitudinal phase space of the beam at the buncher entrance is shown in fig. 4. As will be discussed in next section the tail particles shown in red ellipses are mostly added to the low energy tail of the bunches and especially to the satellite bunches after the buncher. If we can reduce the tails shown in fig. 4 somehow then we probably will be able to reduce the satellite population and the beam loss at chicane as discussed in next sections.

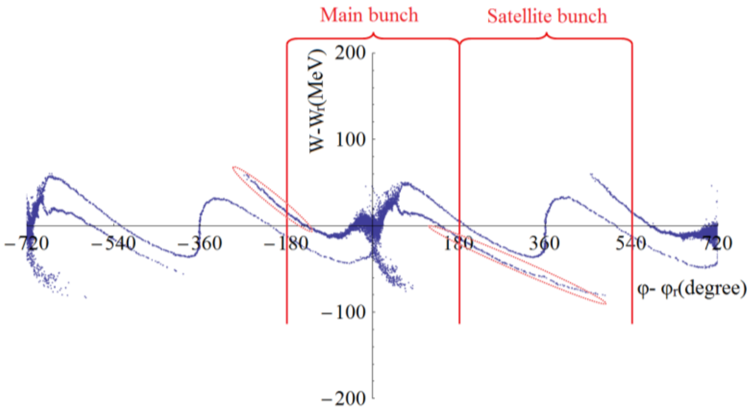

FIG. 4.Longitudinal Phase space of the beam at the buncher entrance.

For the transverse plane, the evaluation of the beam size and the beam emittance is illustrated in fig. 5.

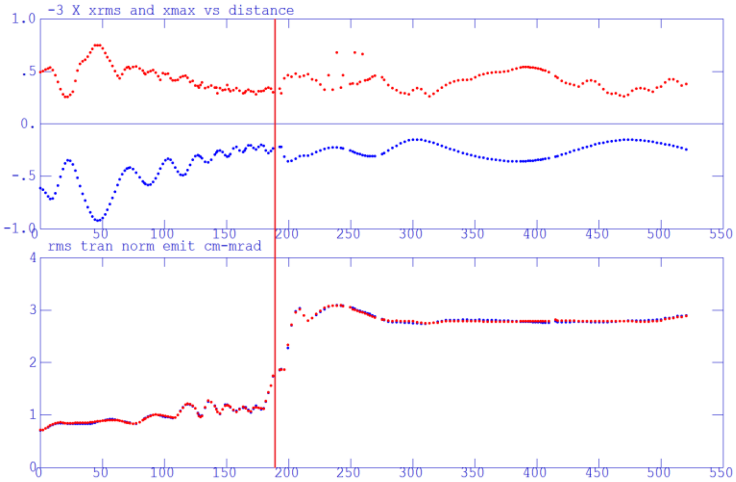

FIG. 5. Evaluation of the beam size and the beam emittance. In the first diagram the red curve is the x coordinate of the outermost particle with respect to the beam axis and the blue cure shows the rms beam size multiplied by minus 3 ($-3x_{rms}$). The second diagram illustrates the beam emittance coordinate in x and y direction in cm-mrad. The red line displays the longitudinal position of the buncher entrance.

The beam emittance has a large jump at the prebuncher and the buncher entrance. As will be discussed in section 5, if we increase the focusing field in this region we will expect a smaller jump. In the next sections we first focus on the satellite reduction issue then discus shortly the emittance growth problem.

3. Satellite population reduction

The satellite population is mostly determined by the sub-harmonic bunching system. In the sub-harmonic bunching system, the phase of each cavity is adjusted so that the main bunch is always launched at zero crossing (approximately) and after each cavity the phase space of the main bunch is longitudinally convergent. On the other hand the longitudinal phase space of the satellite bunch is always divergent. In this way particles continuously evacuate the satellite bunches and are added to the main bunches. To reduce the satellite population we need to provide the maximum time for the satellite particle to leave this bunch. Therefore, as the first general approach for optimisation of the sub-harmonic bunching system we need to choose the maximum length for the drift sections.

For the cavity voltages we note that a larger voltage (larger velocity modulation) helps particles penetrate more into the main bunch against the space-charge forces resulting in a shorter bunch length. However, we don't prefer a short bunch length especially at early stages. In a shorter bunch, particles are longitudinally close together experiencing strong space-charge forces. When such a bunch is passed through a long drift space some particles at the border of the bunch might get a large energy deviation due to the large repulsive forces as illustrated in fig. 6. Therefore, as the second general approach we start with a relatively low value of the voltage for the first SHB and increase it for the downstream cavities. More details on the optimisation procedure can be found in [4].

We first optimise the sub-harmonic bunching system without any restrictions to see to what extend the satellite population can be reduced. In this optimisation we will try to reduce the satellite population while keeping the other beam parameters unchanged. The parameters of the sub-harmonic bunching system for this case are listed in Table III and the beam parameters can be found in Table IV.

According to this optimisation the satellite population can be reduced significantly. The satellite population after the buncher is 3.5% and reduces to 2.5% after the chicane.

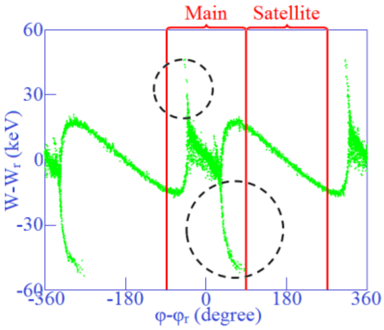

FIG. 6. Longitudinal phase space of the beam 45 cm away from a 30kV cavity. Using a large voltage, results in accumulation of particles in a short bunch of high particle density. Due to the large repulsive forces, some particles at the border of the bunch are pushed out getting a large energy deviation. In this situation it would be difficult (or impossible) to keep these particles in the main bunch downstream.

TABLE III. Parameters of the sub-harmonic bunching system optimised without any restriction.

Parameters	Value
D1	60 cm
D2	20 cm
D3	15 cm
Dp	6 cm
V1	12 kV
V2	30 kV
V3	45 kV
Vp	70 kV

TABLE IV. Longitudinal beam parameters after the magnetic chicane for a system optimised without any restriction.

Beam parameters	**Value**
RMS bunch length	1.60 mm
RMS energy spread	0.108 MeV
Beam energy	18.7 MeV
Satellite to main bunch population	2.5%
Beam loss at chicane	19.1%

The next step is to keep the drift spaces fixed and optimise the sub-harmonic bunching system only by changing the voltages. The optimum value of the voltages and also the beam parameters are given in Tables V and VI.

TABLE V. Parameters of the sub-harmonic bunching system optimised by keeping the drift sections unchanged.

Parameters	Value
V1	13 kV
V2	25 kV
V3	40 kV
Vp	70 kV

TABLE VI. Longitudinal beam parameters after the magnetic chicane for a system optimised by keeping the drift sections unchanged.

Beam parameters	**Value**
RMS bunch length	1.92 mm
RMS energy spread	0.139 MeV
Beam energy	18.7 MeV
Satellite to main bunch population	4.5%
Beam loss at chicane	19.3%

In this case the satellite population after the buncher is 7.5% and reduces to 4.5%. Although the satellite population is reduced significantly, we will need larger power for the second and third cavities which is not currently available. Therefore, in the last case, we will try to reduce the satellite population by keeping the voltages below 20 kV.

If we reduce the voltage of the first SHB from 20 kV to 15kV the tails shown in fig. 4. will be shortened. This is illustrated in fig. 7.

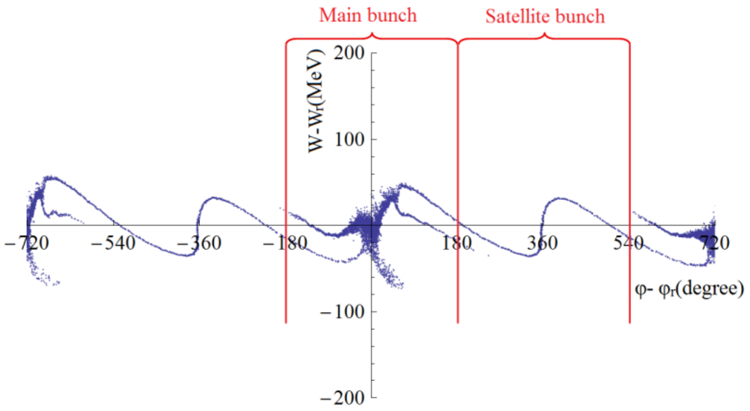

FIG. 7. Longitudinal Phase space of the beam at the buncher entrance for the case in which the voltage of the first SHB is reduced to 15 kV.

By reducing the voltage of the first SHB to 15 kV the satellite population after the buncher reduces from 10.2% to 8.5% however, after the chicane it becomes 7.0% as in the original model. This means that the tails shown in fig. 4 are added to the low energy tail of the satellite bunch which is going to be lost in the chicane. Therefore, by reducing the voltage of the first SHB, the satellite population after the magnetic chicane cannot be reduced. However, the population of the low energy tail of the bunches after the buncher is reduced which results in a reduction in beam loss at the magnetic chicane of about 4%. The beam parameters for the case of V1=15 kV can be found in Table VII.

TABLE VII. Longitudinal beam parameters after the magnetic chicane for the case of V1=15 kV.

Beam parameters	**Value**
RMS bunch length	1.69 mm
RMS energy spread	0.157 MeV
Beam energy	18.6 MeV
Satellite to main bunch population	7.0%
Beam loss at chicane	14.6%

Therefore, with such a small change the beam current after the magnetic chicane will be about 5% larger.

4. Beam emittance growth reduction

In transverse plane, the main issue is the beam emittance growth. The main reason for the emittance growth in a solenoid channel is the beam mismatching. When the focusing field does not have the correct magnitude the beam envelope oscillates around its matched value. The extra energy associated with these oscillations is then available for the beam emittance growth [6, 7]. The envelope equation provides mathematically the matching condition for a continuous monoenergetic beam. However, because of the bunched nature of the beam and the beam energy spread perfect matching is not possible and in the best condition we can match the larger fraction of the beam to the focusing field and the mismatched part of the beam will contribute the beam emittance growth.

As illustrated in fig. 5. The largest emittance growth occurs through the prebuncher and at the buncher entrance. This is because the beam relative energy spread has its largest value through the channel at the prebuncher and at the entrance of the buncher. According to Wangler's formula [8], the rate of the beam emittance growth is smaller for a beam of smaller size. However, to reduce the beam size we will need a larger focusing field.

The beam emittance growth can be reduced easily by increasing the soleniodal field in small region around the buncher entrance. For example if we increase the coil's current from z = 160 cm to z = 208 cm by about 50% the beam emittance at the end of injector will reduce from 38.8 mm-mrad to 29.5 mm-mrad. The beam size and emittance evaluation trough the soleniodal channel is illustrated in fig. 8 which can be compared with fig. 5.

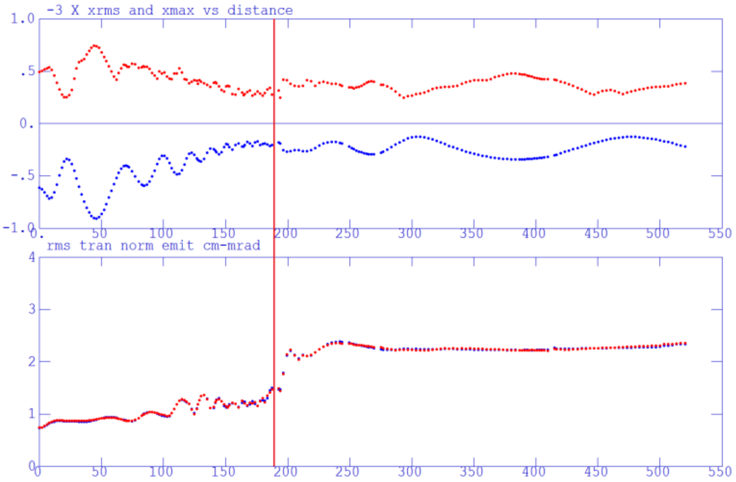

FIG. 8. Evaluation of the beam size and the beam emittance for a focusing channel in which the soleniodal field at the entrance of buncher has been increased.

The solenoidal field of this case can be compared with the original model in fig. 6.

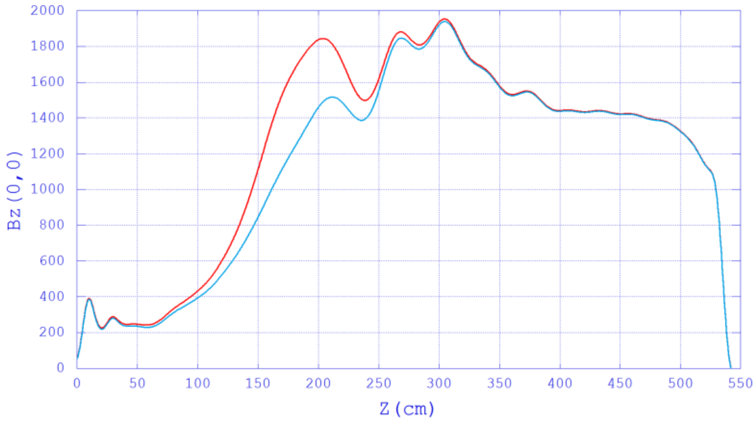

FIG. 6.Solenoidal focusing field for the original model (blue line) and the increased one (red line).

5. Conclusion

The performance of the CTF3 injector can be improved slightly by applying minor changes to the operational parameters. For instance by reducing the voltage of the first SHB the beam loss at chicane can be reduced and by increasing the focusing field at the buncher entrance the beam emittance growth can be limited. However if it would be possible to choose the distance of the drift space and the power to the sub-harmonic bunchers freely a substantial reduction of the satellite population could be obtained.

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