CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC – Note – 1058

BEAM DYNAMICS STUDIES OF THE CLIC DRIVE BEAM INJECTOR

Sh. Sanaye Hajari, S. H. Shaker, IPM, Tehran, Iran & CERN, Geneva, Switzerland
S. Doebert, CERN, Geneva, Switzerland

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 with the main linac. The beam in the Drive Beam Accelerator is phase coded. This means only every second accelerator bucket is occupied. However, a few percent of particles are captured in wrong buckets, called satellite bunches. The phase coding is done via a sub-harmonic bunching system operating at a half the acceleration frequency. The beam dynamics of the Drive Beam injector complex has been studied in detail and optimised. The model consists of a thermionic gun, the bunching system followed by some accelerating structures and a magnetic chicane. The bunching system contains three sub-harmonic bunchers, a prebuncher and a tapered travelling wave buncher all embedded in a solenoidal magnetic field. The simulation of the beam dynamics has been carried out with PARMELA with the goal of optimising the overall bunching process and in particular decreasing the satellite population and the beam loss in magnetic chicane and in transverse plane limiting the beam emittance growth.

Presented at: LINAC2014, Geneva, 31 August-5 September 2014

Geneva, Switzerland
17/06/2015

BEAM DYNAMICS STUDIES OF THE CLIC DRIVE BEAM INJECTOR

Sh. Sanaye Hajari, S. H. Shaker, IPM, Tehran, Iran; CERN, Geneva, Switzerland
S. Doebert, CERN, Geneva, Switzerland

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 with the main linac. The beam in the Drive Beam Accelerator is phase coded. This means only every second accelerator bucket is occupied. However, a few percent of particles are captured in wrong buckets, called satellite bunches. The phase coding is done via a sub-harmonic bunching system operating at a half the acceleration frequency. The beam dynamics of the Drive Beam injector complex has been studied in detail and optimised. The model consists of a thermionic gun, the bunching system followed by some accelerating structures and a magnetic chicane. The bunching system contains three sub-harmonic bunchers, a prebuncher and a tapered travelling wave buncher all embedded in a solenoidal magnetic field. The simulation of the beam dynamics has been carried out with PARMELA with the goal of optimising the overall bunching process and in particular decreasing the satellite population and the beam loss in magnetic chicane and in transverse plane limiting the beam emittance growth.

INTRODUCTION

The Compact Linear Collider (CLIC) is a future Multi-TeV electron-positron collider under study at CERN. In the acceleration scheme of CLIC, the RF power for the acceleration of the Main Beam is extracted from a high-current Drive Beam that runs parallel with the main linac. The Drive Beam loses its energy in special RF structures called Power Extraction and Transfer Structure (PETS) [1].

DRIVE BEAM TIME PROFILE

At the end of the Drive Beam complex the main pulse of the beam consists of 24 bunch trains of 244ns length with a bunch repetition frequency of 12 GHz.

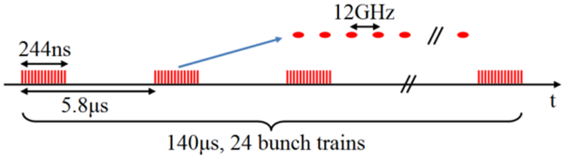

Figure 1: Drive Beam final time structure.

To achieve such a time structure the continuous beam of 5 A current from the electron gun passes through the 0.5 GHz sub-harmonic bunching system with a phase switching of 180° every 244 ns [2]. Afterwards, a 1 GHz prebuncher and buncher are used to reduce the bunch length then the beam is accelerated with 1 GHz frequency. Therefore, only every second accelerator bucket is occupied. Due to the phase switching of the sub-harmonic bunching system the main pulse is made up of even and odd bunch trains. This procedure is called phase coding. However, a few percent of particles captured in wrong buckets, called satellite bunches. These bunches have to be eliminated from the beam for reasons of efficiency and machine protection at the end of injector [1].

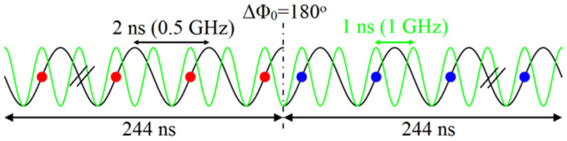

Figure 2: The phase switching and the satellite concept.

At the end of Drive Beam Accelerator a delay loop is used to combine even and odd trains to double the bunch repetition frequency and the peak current. The trains then are recombined three and four times in the following two combiner rings. Therefore, the overall multiplication of the frequency and the peak current is 24 and the final time structure (cf. Fig. 1) will be achieved.

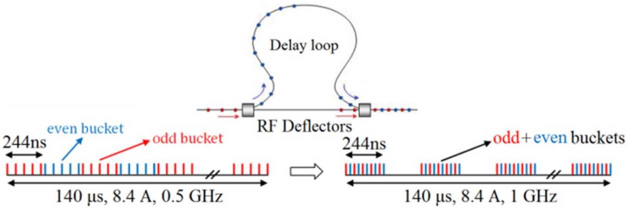

Figure 3: The bunch combination in the delay loop [1].

SUB-HARMONIC BUNCHING SYSTEM AND PREBUNCHER

The general layout of the bunching system is shown in Fig. 4. The sub-harmonic bunching system consists of three travelling wave sub-harmonic bunchers (SHB). The optimisation criteria for this system are to minimise the satellite population and together with the prebuncher to accumulate the particles as many as possible in the acceptance of the buncher.

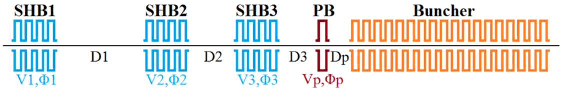

Figure 4: General layout of the bunching system.

For optimisation, we need to decide on the values of 12 parameters. For each cavity the phase, voltage and the drift space afterwards should be determined. However, beforehand we need a deep understanding of the dynamics of such a system to clarify the road map.

The principle of bunching with the sub-harmonic bunching system and the prebuncher is based on velocity modulation bunching [3]. As illustrated in Fig. 5 just after the first SHB the longitudinal phase space is convergent for the main bunch and divergent for the satellite bunch (diagram (a)). This results in bunching and debunching of

Copyright © 2014 CC-BY-3.0 and by the respective authors

the main and satellite bunch respectively in the following drift space (diagram (b)). After some distance, the phase space of the main bunch becomes divergent and particles start to leave this bunch (diagram (c)). This would be the time to use another SHB to convert the phase space of the main bunch to a convergent state (diagram (d)). Therefore, the phase space of the main bunch become convergent after each SHB and changes to a divergent state passing through the drift spaces while the satellite bunch is always longitudinally divergent. In this way, we make particles oscillate in the main bunch and continuously evacuate the satellite bunch. To minimise the satellite population we need to provide the maximum time for these particles to leave satellite bunch and the maximum time means maximum length for the drift spaces. This is the key point of the optimisation.

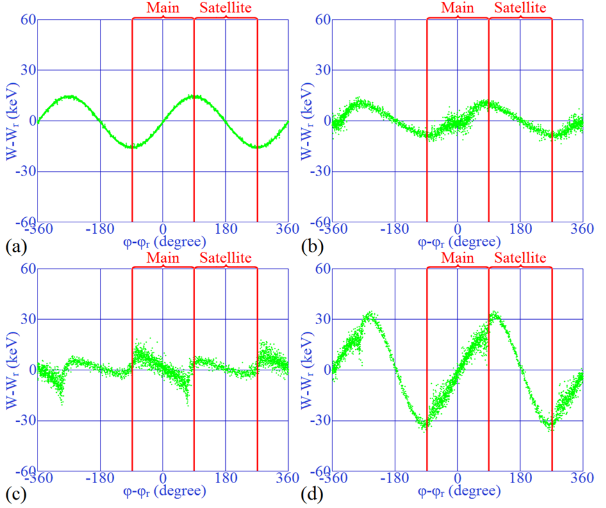

Figure 5: Longitudinal phase space just after SHB1 (diagram (a)), 90 and 175 cm away from it (diagram (b) and (c) respectively) and just after SHB2 (diagram (d)).

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 a shorter bunch length. However, at early stages we don't prefer short bunch lengths in which particles are longitudinally close together and experience a stronger space charge forces. For this reason we start with a relatively low value of the voltage for the first SHB and increase it for the downstream cavities.

We try to determine the parameter of each cavity one by one. For the first and second SHB we just try to have the minimum satellite population after each cavity. However, for the third SHB and the prebuncher we need to consider the both criteria. As we increase the length of the drift spaces to reduce the satellite population the bunch length also increases. The effect of the prebuncher is to compensate for this bunch length increase allowing a lower satellite population. The optimum values of the parameters are listed in Table 1 and the longitudinal phase spaces are shown in Fig. 6. With this optimisation the satellite population will be 2.4% which is smaller by a factor 2 Compared to the previous model (the CDR version [1]).

Table 1: Parameters of the sub-harmonic bunching system and the prebuncher

Cavity	Voltage (kV)	Drift space (cm)
SHB1	15	175
SHB2	30	50
SHB3	45	45
Prebuncher	60	25

The phase of each cavity is chosen such that we don't have a power transfer between the beam and the cavities. The length of each SHB is 50 cm by the RF design [2] and the prebuncher is assumed to be a thin lens cavity.

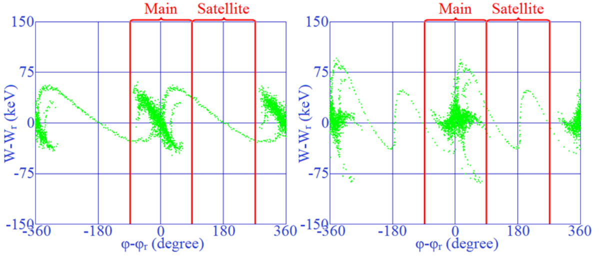

Figure 6: The longitudinal phase space after third SHB (left diagram) and the prebuncher (right diagram).

TRAVELLING WAVE BUNCHER

When a beam is accelerated inside a travelling wave structure, the particles execute damped oscillations around the synchronous particle. The amplitude of these oscillations is proportional to $[(\gamma^2\text{-}1)^{3/2}\ E_z]^{-1/4}$ [3], where E_z is the electric field amplitude on axis. Therefore, for an effective bunching, the beam energy and longitudinal electric field should be increased. However, how we should accelerate the beam and increase the electric field remains as the optimisation problem.

After the buncher, 13 accelerating structure are used to accelerate the beam up to the 50 MeV. A magnetic chicane is also used for beam chopping to reduce the energy spread and to trim the longitudinal phase space.

The buncher is optimised to provide the minimum rms bunch length end energy spread. The important point is that the beam acceleration and filed increase should be done adiabatically to capture as many as particles in the damped oscillatory orbits especially at the beginning of the structure. Therefore, the beam is launched at the zero crossing and we demand a linear increase in synchronous phase as $\theta_s=\theta_1 z$. We also choose a parabolic function for the electric field amplitude as $E_z=E_0+E_1z+E_2z^2$. A computer program is written with Mathematica that tracks particles and changes the optimisation parameters (θ_1, E_0, E_1 and E_2) to find the optimum structure.

With this optimisation the rms bunch length and the energy spread at the end of buncher are 7.2 mm and 0.32 MeV. The electric field amplitude at the beginning and the end of the structure are 1.2 MV/m and 5.7 MV/m respectively. The most important feature of the current buncher design is the resulting extremely low energy spread which is smaller by a factor 3 compared to the

Copyright © 2014 CC-BY-3.0 and by the respective authors

CDR version. The main responsible for this effect is the low value of the electric field employed at the beginning of the buncher. For a beam of smaller energy spread we will have a lower beam loss at the chicane which for the current model is less than 4% while for the CDR version is 24%. At the end of injector the beam rms bunch length and energy spread are 2.6 mm and 0.48 MeV which fulfil the requirements of the Drive Beam injector [1].

TRANSVERSE DYNAMICS

Solenoidal Focusing Channel

The bunching system with the following two linacs is embedded in the solenoidal magnetic field. For the rest of the beam line the focusing is provided by quadrupoles.

For transverse design the main issue is to limit the beam emittance growth due to the nonlinear space charge forces. The main source of the emittance growth is the beam mismatching. When the external focusing field does not have the correct magnitude the beam envelope oscillates around its matched value. The extra energy associated with these oscillations will be available for the beam emittance growth. Therefore, we will look for a matched beam of constant envelope. The matching condition for a monoenergetic continuous beam is provided theoretically by the envelope equation [4]. This equation gives the external magnetic field as a function of beam parameters. However, because of the bunched nature of the beam and the beam energy spread perfect matching is not possible because different values of current and energy are associated with different parts of the beam and in the best condition we can match the larger fraction of the beam to the focusing filed.

The beam dynamics of the system is investigated for three different target beam sizes of 1, 2 and 3 mm. As indicated in Fig. 7 there is a jump in the beam emittance at the entrance of the buncher. The main responsible for this jump is the beam energy spread which has a large pic at this point. However, size of this jump decreases as we reduce the beam size. This is exactly in agreement with Wangler's formula which states the emittance growth is larger for beam of larger envelope [5]. However, for a smaller envelop we need to apply a larger focusing field.

Back to the emittance evaluation diagram we recognise that the rate of the emittance growth in the sub-harmonic bunching system and through the accelerating structures is small. Therefore, to limit the beam emittance growth we only need a large magnetic field over first half of the buncher. This suggest a variable beam envelope scheme in which for example we start with a rms beam size of 3 mm through the sub-harmonic bunching system then decrease it adiabatically to 1 mm over the first half of the buncher and again increase it to 2 mm inside the linacs (dashed lines in Fig. 7). Such a scheme can reduce the average magnetic field significantly with a small degradation in beam emittance due to the beam size changes. For the variable beam size scheme the total emittance growth through the solenoidal channel is 22.6 μm and the average magnetic field is only 534 G.

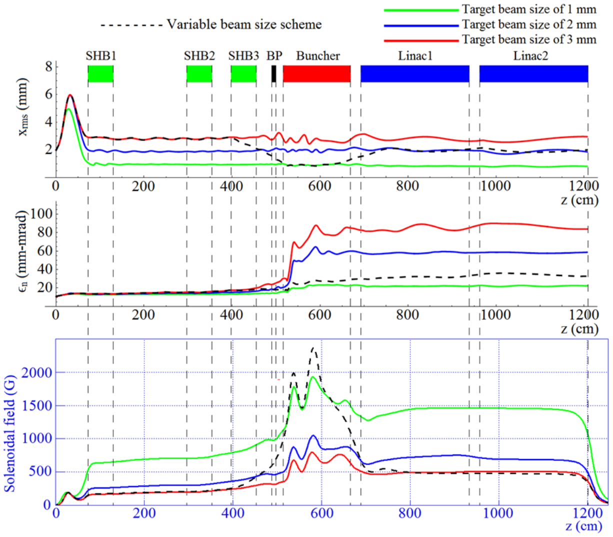

Figure 7: Evaluation of the rms beam size and normalised emittance and the ideal filed map for different beam sizes.

Quadrupole Focusing Chanel

Four quadrupoles are used as a matching cell to match the optical functions from the end of solenoid channel to a FODO lattice. The main question is where to cut the solenoids and start the quadrupole channel. As we move the matching cell downstream the beam energy becomes higher so the space charge forces and hence the emittance growth will be smaller. However, we will need a longer solenoid which increases the cost. Different positions for the matching cell have been investigated and it is turned out that we can start the quadrupole channel after the end of second linac where the bam energy is 9.1 MeV with an acceptable emittance growth of 9.1 μm. At the end of injector the final emittance will be 41.7 μm which is well below the target value of 100 μm.

CONCLUSION

The beam dynamics of the CLIC Drive Beam injector has been optimised. Several important parameters are improved compared to the CDR version. In longitudinal direction the satellite population and the beam loss is reduced significantly. In transverse plane, keeping the emittance well below the target value we reduced the need for solenoidal field which affect the machine cost.

REFERENCES

[1] A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report, edited by M. Aicheler et al., CERN-2012-007.

[2] H. Shaker et al., "Sub-harmonic Buncher Design for the CLIC Drive Beam Injector", TUPME052, IPAC'13, Shanghai, China (2013).

[3] P.M. Lapostolle, A.L. Septier, *Linear Accelerators*, (North-Holland Publishing Company, 1970).

[4] M. Reiser, *Theory and Design of Charged Particle Beams*, (2nd edition, John Wile & Sons, 2008).

[5] T.P. Wangler et al., *RF Linear Accelerator,* (2nd edition, John Wile & Sons, 2008).

Copyright © 2014 CC-BY-3.0 and by the respective authors