

THE DRIVE BEAM PULSE COMPRESSION SYSTEM FOR THE CLIC RF POWER SOURCE

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Abstract

The Compact LInear Collider (CLIC) [1] is a high energy (0.5 to 5 TeV) e^\pm linear collider that uses a high-current electron beam (the drive beam) for 30 GHz RF power production by the Two-Beam Acceleration (TBA) method. Recently, a new cost-effective and efficient generation scheme for the drive beam has been developed [2,3]. A fully-loaded normal-conducting linac operating at lower frequency (937 MHz) generates and accelerates the drive beam bunches, and a compression system composed of a delay-line and two combiner rings produces the proper drive beam time structure for RF power generation in the drive beam decelerator. In this paper, a preliminary design of the whole compression system is presented. In particular, the fundamental issue of preserving the bunch quality along the complex is studied and its impact on the beam parameters and on the various system components is assessed. A first design of the rings and delay-line lattice, including path length tuning chicanes, injection and extraction regions is also presented together with the simulation results of the beam longitudinal dynamics.

1 DESCRIPTION OF THE SYSTEM

A general layout of the bunch train compression system is shown in Figure 1. Its purpose is to split segments of the electron pulse delivered by the drive beam accelerator and later combine them in several stages in order to obtain 20 high-current pulses, each with 32 times the initial bunch repetition frequency and current. The system acts therefore both as a splitter and compressor as well as a frequency multiplier.

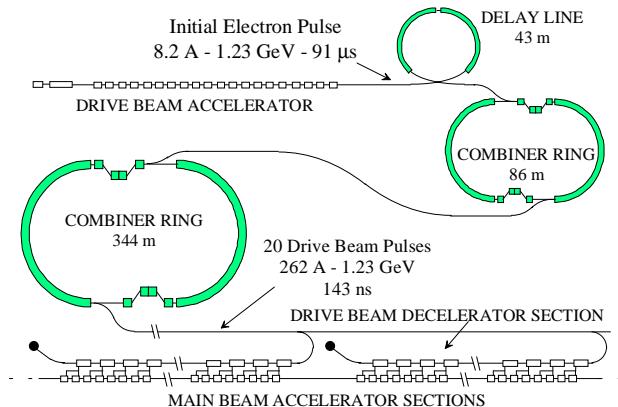


Figure 1: Layout of the drive beam compression system

The drive beam accelerator delivers 91 μ s long electron pulses with a mean current of 8.2 A at 1.23 GeV. Each pulse is obtained by the combination at low energy of 640 bunch trains, 143 ns long, whose flat-top bunch charge is 17.6 nC. In each train the bunches occupy alternatively even and odd buckets of the drive beam accelerator fundamental frequency (937 MHz). At first, the individual trains are separated by a transverse RF deflector at the frequency of 468.5 MHz, and each “even” bunch train is delayed with respect to the following “odd” one by 143 ns, in order to recombine them using a second RF deflector at the same frequency. The whole device is called the “times-two delay combiner” (see Figure 1). After recombination, the pulse is composed of 320 trains whose spacing is equal to twice the train length (286 ns, or 86 m). The bunches fill all the buckets of the fundamental frequency (320 mm spacing). The same principle of electron bunch train combination is then used to combine the trains four by four in the first combiner ring, 86 m long. Two 937 MHz RF deflectors create a time-dependent local deformation of the equilibrium orbit in the ring. This bump is used for injection of a first train in the ring (all its bunches being deflected by the second RF deflector onto the equilibrium orbit). The ring length is equal to the spacing between trains plus $\lambda/4$, where λ is the spacing between bunches, equal to the wavelength of the RF deflectors. Thus for each revolution period the RF phase seen by the bunches circulating in the ring increases by 90°, and when the second train is injected, the first train does not see any deflection and its bunches are interleaved with the ones being injected (at a $\lambda/4$ distance). This is repeated twice, then the four interleaved trains are extracted from the ring by an ejection kicker half a turn later, and the same cycle starts again. After the first combiner ring the whole pulse is composed of 80 trains. The train spacing is equal to eight times the train length (1144 ns or 344 m), while the bunch spacing is 80 mm.

The trains are combined again, using the same mechanism, in the second combiner ring, 344 m long, yielding another factor four in frequency multiplication, and obtaining the final 20 trains, with a bunch spacing of 20 mm. The distance between trains is now 4.576 μ s or 1375 m, corresponding to twice the length of a drive beam decelerator section. This spacing is now correct to obtain proper phasing with the main beam pulse, distributing the drive beam trains along the decelerator in the opposite direction to the main beam.

2 DESIGN ISSUES

The main problem to be solved in the system is to preserve the bunch quality during the compression. In particular, bunch length and longitudinal phase-space distribution must be preserved and train to train, bunch to bunch fluctuations in phase and transverse position minimised. The rings and the delay line must then be isochronous.

The final bunch length must be short in order to maximise the 30 GHz RF power production efficiency in the drive beam decelerator. At present the aim is a rms bunch length of $\sigma = 0.4$ mm (94% efficiency). Such high-charge (17.6 nC), short bunches can radiate coherently a considerable amount of synchrotron radiation, leading both to an average energy loss of the whole bunch and to an energy spread within the bunch itself [4]. The emission is concentrated at low frequencies ($\nu \leq 1/(2\sigma)$), and can be partly suppressed if at least part of the emitted spectrum is below cutoff in the beam pipe (shielding effect), but a limit is imposed by the necessary beam clearance. Since bunches belonging to different trains make a different number of turns in the rings (from 1/2 to 7/2), they will develop different energy distributions. This will cause relative phase errors between bunches, bunch lengthening and phase-space distortion through non-perfect isochronicity of the delay line and the combiner rings. Short, high-charge bunches will also interact with any small discontinuity of the beam chamber (e.g., bellows and septa), possibly being subject to longitudinal and transverse wake-fields. It is therefore highly desirable to manipulate relatively long bunches in the compression system and compress them just before injection into the drive beam decelerator sections. However, too long bunches experience a non-uniform kick in the RF deflectors, due to their phase extension, and the single-bunch emittance can grow. Therefore the bunch length at the exit of the accelerator is limited to 2 mm rms. The maximum emittance growth in this case is $\sim 2\%$ (for an initial rms normalized emittance of $2 \times 10^{-4} \pi \text{ m rad}$), in the second combiner ring deflectors (3.75 GHz). A correlated energy spread ($\sim 1\%$ rms), suitable for the final bunch compression, is obtained in the accelerator by the combined effect of RF curvature and longitudinal wake-fields. The need to preserve the correlation all along the compression system means that all the distortions of the longitudinal phase space must be kept small. In particular, attention must be given to the higher orders of the path length dependence on energy spread. A numerical analysis has shown that second order effects will hamper the final bunch compression and must be corrected by using sextupoles [3].

Another concern is the beam loading in the RF deflectors, especially just before extraction in the second combiner ring, where the average current along the train is very high and the frequency of the deflectors

(3.75 GHz) is the highest in the compression system. In order to overcome this problem, a travelling-wave iris-loaded structures with a short filling time with respect to the train duration has been chosen. A steady state condition is then reached with minimum transient effects, although at the expenses of a loss in deflection efficiency. The extraction system for both rings is also a critical item, the issues being the high repetition rate (particularly in the first ring - 250 kHz) and the interaction with the high-current beam (particularly in the second ring - 262 A). The solution adopted for both rings is based on the use of travelling TEM wave transmission line pairs [5].

3 SUB-SYSTEMS AND COMPONENTS

In Table 1 and Table 2 the parameters of the sub-systems are presented. The lengths of the rings are fixed by the overall timing; the delay combiner geometry has been chosen to minimise both coherent synchrotron radiation emission and overall dimensions. One 3-bend magnetic chicane is located in the delay line and one in each ring arc. They are used for path length tuning (± 0.5 mm tuning range), in order to adjust the bunch relative phase and to compensate for orbit variations. Each chicane is 3.5 m long and works around an average bending angle $\theta_0 \sim 150$ mrad. The tuning range is obtained with a bending angle variation $\Delta\theta = 1.5$ mrad; such a small value of $\Delta\theta/\theta_0$ does not perturb the optics. Each chicane has a linear transfer matrix element $R_{56} = 0.065$.

Table 1: Delay combiner parameters

Length (line 1 / 2)	25/68	m
Bending radius (line 2)	3	m
# Dipoles (line 2)	16	
Dipole length	2	m
Dipole Field	1.25	T

Table 2: Rings parameters

	Ring 1	Ring 2	
Circumference	86	344	m
Bending radius	3.6	17.8	m
# Cells	4	20	
Cell length	13.6	13.6	m
# Dipoles	16	80	
Dipole length	1.4	1.4	m
Dipole field	1.1	0.22	T
# Quadrupoles	52	184	
Quadrupole length	0.3	0.3	m
Max quad gradient	14	14	T/m
# Sextupoles	20	84	
Sextupole length	0.3	0.3	m
Max sext gradient	26	120	T/m ²
Max β -function (h,v)	10.3 , 10.9	32.6 , 16.8	m

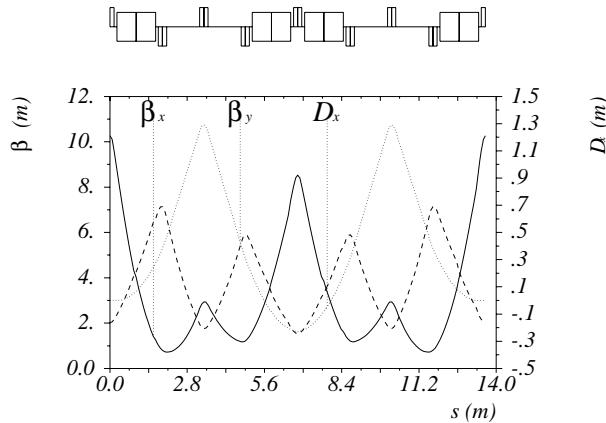


Figure 2: Basic isochronous cell lattice

Both the delay line and the ring arcs are based on the same type of isochronous lattice cell (see Figure 2), a modified four-cell FODO structure with “missing magnets” [6]. If other elements in the lattice (i.e., the chicanes) have a small nonzero R_{56} , the cell can be tuned to be quasi-isochronous, its residual R_{56} being such that the sum of the individual contributions is zero.

In order to avoid distortions in the longitudinal phase space, all the arcs are made isochronous up to second order by the use of sextupoles placed in the high-dispersion regions in correspondence with the missing magnets. By using different families of sextupoles it is possible to correct the third order as well. In principle, it should also be possible to tune the path length dependence from the energy spread (the isochronicity curve), in such a way as to compensate distortions in the longitudinal phase space of the electron bunches due to other non-linear effects. The ring injection is similar to a conventional fast injection scheme based on a septum and a fast kicker, where the kicker’s role is taken by a RF deflector. Another deflector is placed upstream of the septum (at $-\pi$ phase advance), and provides the pre-compensation of the kick given by the injection deflector to the circulating bunches. A $\pi/2$ phase advance FODO lattice is used in the injection straight section, with the septum and deflectors close to the focusing quadrupoles, such that the angular kick from the deflector corresponds to a maximum displacement in the septum. All RF deflectors are short travelling wave iris-loaded structures, whose fundamental mode is a deflecting hybrid mode with a $2\pi/3$ phase advance per cell and negative group velocity [7]. The design is basically the same for all deflectors, with the dimensions of the cells scaled linearly with frequency. They are made up of 4 cells at 937 MHz and of 10 cells at 3.75 GHz and provide the needed 2 mrad deflection, equal in both rings, with 50 MW and 15 MW power consumption, respectively. The extraction kickers consist of travelling TEM wave transmission line pairs [5], powered in anti-phase, with the wave moving against the beam; the kicker length is chosen to be 2 m with a half-aperture of

1.5 cm. A deflection of 3 mrad requires a voltage of 11.3 kV, corresponding to 2.6 MW into each 50Ω line. The kicker filling time of 6 ns remains small compared with the 143 ns available rise time. Due to the length of the extraction kicker, a different solution is used for the extraction region lattice, based on matching quadrupole doublets plus a triplet placed between the kicker and the extraction septum. The phase advance between the kicker and the septum is still $\sim \pi/2$, and the use of a central triplet allows a rather constant β -function along the kicker to be obtained.

4 BEAM DYNAMICS

As mentioned earlier, the preservation of the longitudinal phase-space of the bunches is important in order to be able to compress them before injection in the drive beam decelerator. The main sources of phase-space distortion in the compressor system chain are the coherent synchrotron radiation (CSR) emission and the higher-order non-isochronicity in the arcs. The bunch longitudinal dynamics in the both rings has been evaluated taking into account the CSR effect with shielding and the isochronicity curves for the arcs after sextupole correction up to second order [3]. The results are promising; the final bunch length after compression is smaller than the target one, with small bunch to bunch variation in final length (from 340 to 360 μm rms, depending on the number of turns in the rings). The contribution of the delay combiner arcs, as well as the non-linear contributions from the return arcs and the final compressor, have been neglected for the moment. Nevertheless, these contributions are smaller, and further improvement can be obtained, e.g., either by using different sextupole families in order to compensate nonlinearities, or by adding pulse stretchers and compressors in front of each ring and optimizing the bunch length in each component.

5 REFERENCES

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