CLIC Note 331

The CLIC multi-drive beam scheme

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ABSTRACT

The CLIC study of an e^+ / e^- linear collider in the TeV energy range is based on Two-Beam Acceleration (TBA) in which the RF power needed to accelerate the beam is extracted from high intensity relativistic electron beams, the so-called drive beams. The generation, acceleration and transport of the high-intensity drive beams in an efficient and reliable way constitute a challenging task. An overview of a potentially very effective scheme is presented. It is based on the generation of trains of short bunches, accelerated sequentially in low frequency superconducting cavities in a c.w. mode, stored in an isochronous ring and combined at high energy by funnelling before injection by sectors into the drive linac for RF power production. The various systems of the complex are discussed.

INTRODUCTION

The CLIC Study Team examine the possibility to build an electron-positron linear collider in the TeV energy range, whose main characteristic is the high frequency (30 GHz) chosen for the acceleration of the main beam [1]. Such a high frequency opens up the possibility of using a high acceleration gradient (~ 100 MV/m), resulting in a shorter linac; on the other hand at present no high power sources exist in this frequency range. A reliable and efficient RF power source is indeed one of the main issues for the proposed electron-positron linear colliders.

While conventional designs at lower frequencies make use of klystron tubes for this scope, a good alternative is the two-beam accelerator scheme (TBA) [2]. In such a scheme, the RF power is extracted from a high-current relativistic electron beam (the drive beam) by means of low impedance resonant structures (CLIC transfer structures, CTS [3]) and applied to adjacent high-gradient accelerating structures, which accelerate the lower charge main electron beam to high energy. In the following we will consider the 1 TeV upgrade of CLIC [4]. The CLIC main goal parameters in this case are listed in Table 1.

Table 1 - CLIC main parameters for 1 TeV c.m. operation.

RF Frequency	ν_{RF}	30	GHz
Accelerating Field	E	100	MV/m
Number of bunches/RF pulse	n	60	
Distance between bunches	Δ	.67	ns
RF pulse repetition rate	f_{rep}	500	Hz
Beam power/beam	P_b	9.6	MW
Number of particles/bunch	N_b	$4\ 10^9$	
Normalized emittances (h × v)	$\gamma\,\varepsilon_{x,y}$	$147 \times 12.5\ 10^{-8}$	m rad
rms bunch length	σ_z	50	μm
relative energy loss	d_B	10	%
Luminosity with pinch	$\mathcal{L}$	$14.1\ 10^{33}$	$cm^{-2}\ s^{-1}$

A CLIC accelerating structure (CAS) adapted to 60 bunch operation is presently under study [5]. In this paper the following preliminary set of CAS parameters is considered:

R/Q	=	25 kΩ/m	shunt impedance (circuit convention)
l	=	0.49 m	length
Q	=	3500	quality factor
v_G	=	0.065 c	group velocity
E_{ACC}	=	100 MV/m	gradient (loaded)

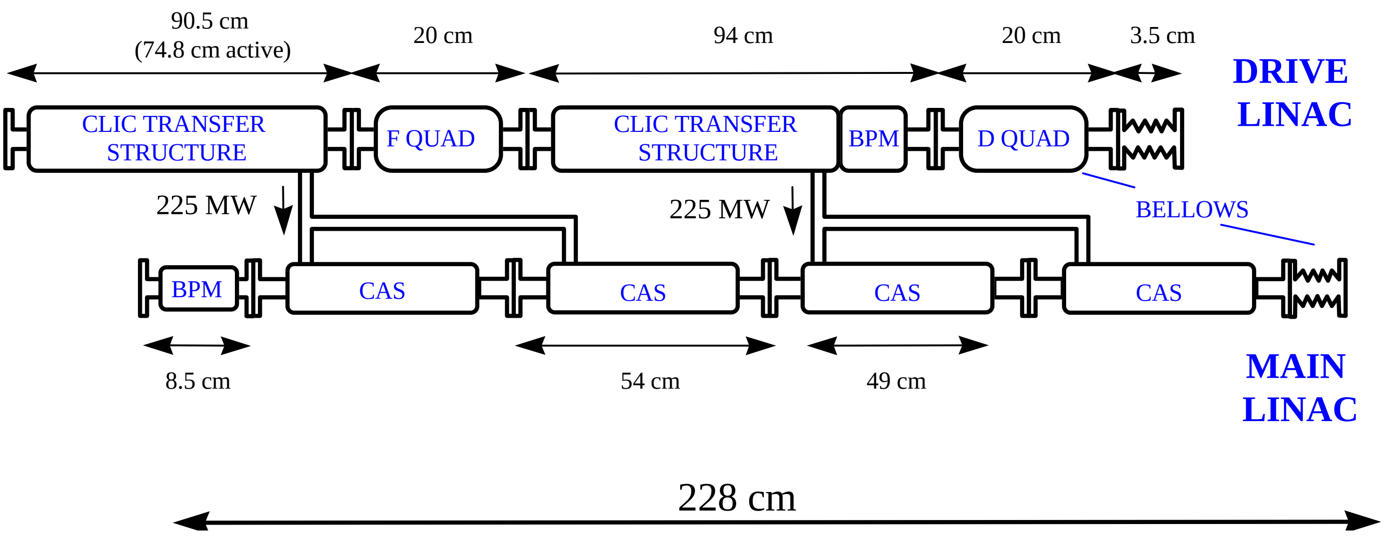

Figure 1. Layout of the main linac and drive linac modules.

With such parameters, the necessary RF power pulse to feed the CAS structures is shown on Fig. 3, where the prefill time of 28.6 ns corresponds to the drain time of the CTS plus the filling time of the CAS and the flat top time of 39 ns corresponds to the duration of the main beam pulse.

The RF power is extracted from the drive beam, by deceleration in the so-called drive linac running in parallel with the main linac. The two linacs are composed of modular units (modules) pre-assembled on a girder whose layout is depicted on Fig.1.

An overall amount of 65 MW of 30 GHz RF power is necessary to accelerate the two main beams with a total beam power of 19.2 MW (see Table 1) and an acceleration efficiency of 30%. Assuming a realistic power extraction efficiency of 70%, the necessary drive beam power becomes 93 MW (186 kJ per pulse at 500 Hz repetition rate). For a drive beam of 2 to 3 GeV, this means a total charge per pulse of 60 to 90 μC which is distributed in short (0.6 mm RMS) bunches spaced by 1 to 2 cm in order to resonantly excite the 30 GHz CTS.

Various options are presently considered to efficiently generate such an intense drive beam.

In the so-called reference scheme [6], low frequency superconducting cavities (pre-filled with power during the interval between pulses) and running in CW mode, are used to accelerate the drive beam at once, delivering the total charge to the drive linac in the time scale of tens of ns. This scheme has been shown to be very efficient but, because of the heavy beam loading, necessitates a large amount of superconducting cavities (18 GV) at a frequency of 200 MHz in order to store the RF energy. Another challenge consists in the generation of the 30 GHz bunches structure with a high charge per bunch of 50 μC by a battery of S band linacs (switchyard) [7] or by FEL bunching [8]. Finally, the whole drive beam power is concentrated in a single pulse, making it particularly difficult to handle as very small fractional losses can heat up, bend or possibly damage the transfer structures [9].

In order to overcome these problems, an alternative scheme where the energy is stored in the drive beam itself instead of the low frequency accelerating structures, is proposed in this note.

DESCRIPTION OF THE SCHEME

The general layout of the scheme is shown on Fig.2. The drive beam bunches are at first accelerated on crest of the RF wave of a low frequency superconducting linac, then stored in the accumulator ring, compressed by standard magnetic compression, and finally combined with the right spacing in the compressor rings.

The drive beam for each linac is split in a number N_D of drive beams (multi-drive beams) each one powering a section of the linac. The energy per drive beam pulse is therefore reduced by a factor N_D with respect to the reference scheme, thus relaxing the tolerances for beam losses along the drive linac.

The drive beams are generated close to the Interaction Point and transported downwards to the beginning of the main linac section to be powered in such a way that the drive beams are separated in time by twice the travel time in the section. That helps the generation and transport of the drive beams which, at the end of the generation process, extend over a few microseconds instead of a few tens of ns.

The 30 GHz bunch train sequencing by 2 cm interval between bunches is made after acceleration at high energy using a funneling method by transverse deflectors in compressor rings [10]. This allows an effective acceleration of individual bunches on crest of the RF wave and simplifies the bunch train generation by a standard RF gun.

After acceleration, the bunch trains are stored one after the other in a collector ring in order to spread the acceleration of the various bunches of a pulse over the whole time interval between RF pulses (2 ms).

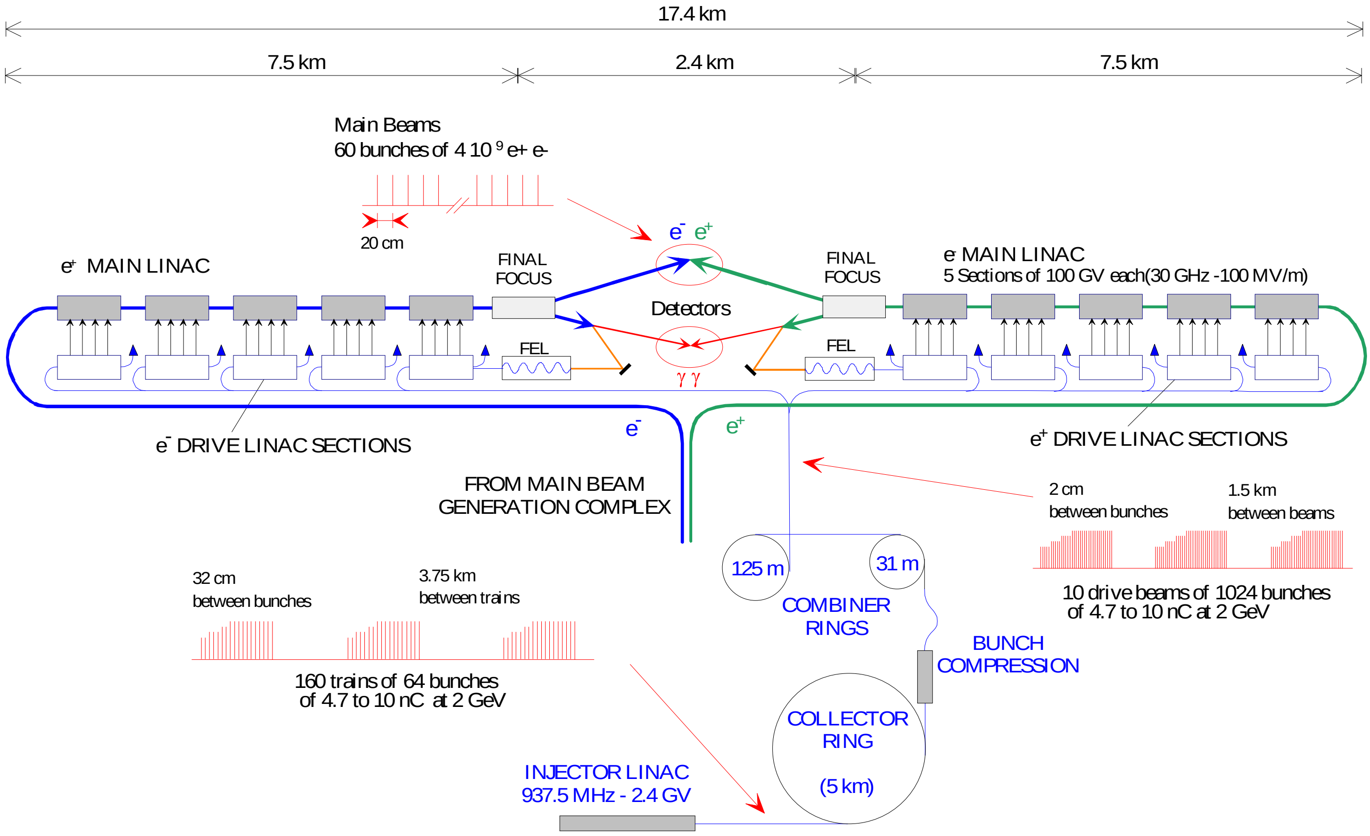

Figure 2. Layout of drive beam generation using a Collector Ring.

This allows a simple beam loading compensation by RF power refilling, in between the acceleration of each bunch train, of the superconducting structures of the injector linac running in a c.w. mode.

The main problem consists in the possible deterioration of the bunch quality during the storage time in the collector ring by various effects (collective instabilities, synchrotron radiation losses, debunching by non-isochronicity….). In order to minimise this deterioration:

a) the collector ring (without any RF system) is made as isochronous as possible;
b) the bunch length is compressed by standard magnetic bunch compressors after extraction from the collector ring. In this way the isochronicity requirements for the combiner ring are relaxed, and the resistive wall effect is minimised;
c) the charge per bunch is reduced by using relatively high impedance transfer structures as shown in the following chapter.

CHOICE OF PARAMETERS

The charge in the drive beam can be deduced from the RF power required to feed the CAS, P_{CAS} = 112.5 MW, taking into account that (since 1 CTS feeds 2 CAS):

$$P_{CAS} = \frac{1}{2}\eta_T \eta_{CTS} P_{CTS} \qquad (1)$$

where P_{CTS} is the power lost in the CTS by the drive beam, and $\eta_{CTS} = \eta_T = 0.95$ are the extraction efficiency from CTS and the transfer efficiency from CTS to CAS, respectively. In a steady state regime, the drive beam power loss is expressed by:

$$P_{CTS} = \frac{W_{CTS}}{\tau_{DRAIN}} \qquad (2)$$

where W_{CTS} is the energy deposited by the drive beam during one drain time of the transfer structure and τ_{DRAIN} is the effective drain time when taking into account the group velocity of the RF wave in the structure with a length l_{CTS} [3]:

$$W_{CTS} = \frac{\omega\, r'_{CTS}}{4}\, l_{CTS}\, F^2(\sigma)\, q^2_{DRAIN} \qquad (3)$$

$$\tau_{CTS} = l_{CTS}\left(\frac{1}{v_g} - \frac{1}{c}\right) \qquad (4)$$

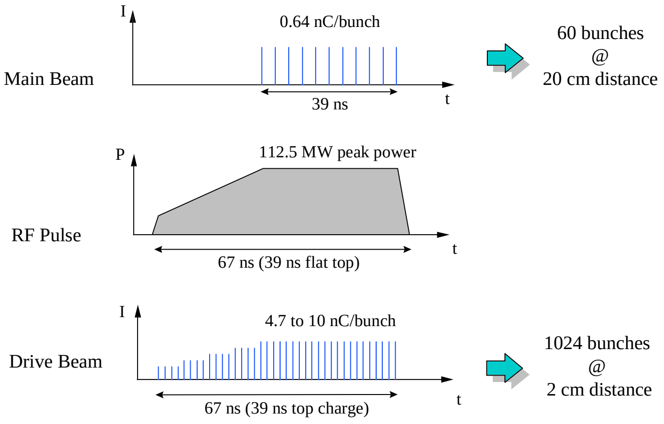

Figure 3. Main Beam pulse, RF pulse and Drive Beam pulse temporal structure, 1 TeV operation.

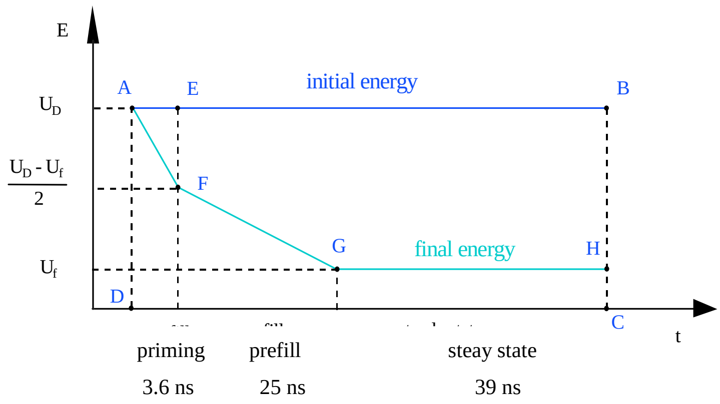

Figure 4. Energy distribution along the drive beam pulse at the beginning and at the end of a drive linac section.

In formulas (3) and (4), q_{DRAIN} is the drive beam charge during a drain time and (assuming a CTS design optimised for the present scheme [11]):

$r`_{CTS}$	=	100 Ω/m	CTS shunt impedance (linac convention)
v_g	=	0.41 c	CTS group velocity
$F(\sigma)$	=	0.93	form factor, i.e. the Fourier component at 30 GHz of the beam current (gaussian bunches with σ = 0.6 mm)

The power lost by the drive beam can finally be expressed as:

$$P_{CTS} = \frac{1}{4}\frac{\omega\, r'_{CTS}\, v_g\, F^2(\sigma)}{1 - v_g / c} \cdot q_{DRAIN}^2 \qquad (5)$$

From (5), one can calculate q_{DRAIN} = 542 nC, from which follows the charge per bunch in the steady state part of the pulse, q_B = 10 nC (there are ~ 54 bunches in a drain time, since τ_{DRAIN} = 3.6 ns, and the time interval between bunches τ_B = 0.067 ns).

The CTS shunt impedance has been chosen as a compromise, in order to keep the charge per bunch low enough to be compatible with the drive beam generation and acceleration, while keeping the transverse wake kicks in the CTS at a reasonable level. For a given impedance, the group velocity can be varied in a limited range. Also in this case the choice is a compromise; a high group velocity means a higher charge, but also a larger beam pipe and weaker transverse wakefields.

The final drive beam temporal structure to be obtained with the present scheme is depicted in Fig. 3, together with the temporal structure of the main beam and of the RF pulse. As in the reference scheme, the RF pulse is composed of a pre-fill that is used to establish steady state conditions in the CAS [12], followed by a constant power part corresponding to the duration of the main beam pulse. The drive beam pulse is composed of 1024 bunches of variable charge in a continuous train, in order to generate the needed RF pulse shape. The optimum interval between bunches (minimum charge per bunch) would have been 1 cm, i.e., the minimum compatible with 30 GHz excitation. The final bunch interval is on the other hand linked to the frequency of the RF deflectors used in the combination process. The choice of 2 cm spacing allows us to operate the deflectors at a relatively low frequency (≤ 3.75 GHz); a higher frequency would imply a significant beam loading in the deflectors, resulting in orbit injection errors in the combiner rings.

Given the above CTS parameters, the efficiency losses and the needed steady state pulse duration, the flat top charge is evaluated as q_{ss} = 5.94 μC and the charge needed during pre-fill is 3.1 μC. Actually the pre-fill is composed by two parts: the real pre-fill (during one filling time of the accelerating structure and with 2.82 μC charge) and an initial part ("priming", during one drain time of the transfer structure and with 0.27 μC) used to optimise the energy extraction efficiency. The "priming" part of the RF pulse is not seen by any of the main beam bunches. The total charge of the drive beam pulse is q_D = 9 μC.

The momentum of each drive beam is deduced from the energy exchange between the drive beam to the RF pulse, as described by the following formula:

$$W_{RF} = \eta_T\, \eta_{CTS}\, \eta_D\, F(\sigma)\, q_D\, U_D\, N_D \qquad (6)$$

Where W_{RF} is the energy in the RF pulse, N_D is the number of drive beam sections, U_D is the drive beam injection energy, and η_D is the extraction efficiency from the drive beam. The drive beam being constituted by a continuous train of bunches, this last is defined as (see Fig. 4):

$$\eta_D = 1 - \frac{q_P\, U_D + q_F \left(\frac{U_D + U_f}{4}\right) + q_{SS}\, U_f}{q_D\, U_D} \qquad (7)$$

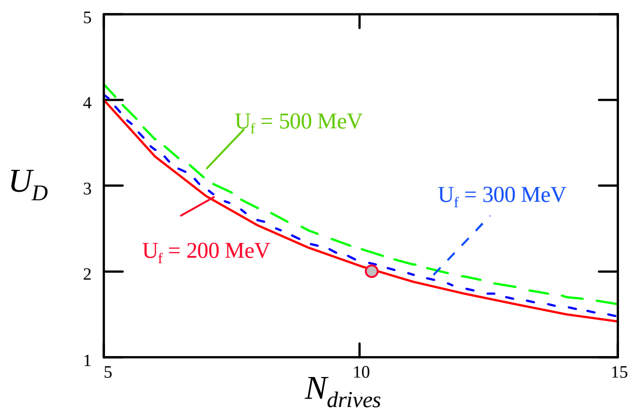

Figure 5. Drive Beam energy (GeV) as a function of the number of drive beam sections for different final energies. The circle indicates the proposed operating point (N_D = 10, U_D = 2.1 GeV).

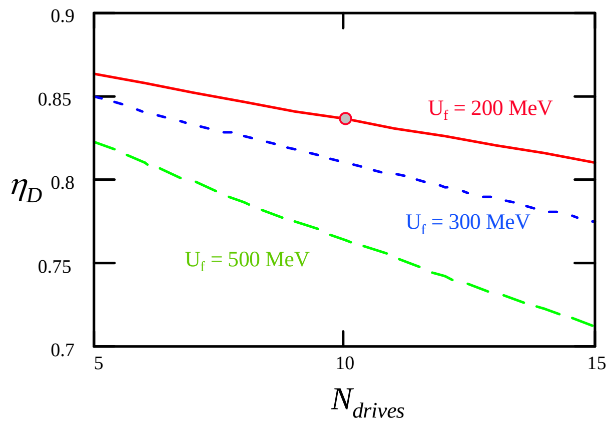

Figure 6. Energy extraction efficiency from Drive Beam to RF (not including TRS and transfer losses) as a function of the number of drive beam sections. The circle indicates the proposed operating point (N_D = 10, η_D = 0.84).

Where q_P is the charge during "priming", q_F is the charge during pre-fill and U_f is the minimum energy of the drive beam bunches when they are dumped at the end of every drive beam line. Using the above equations one can calculate the initial drive beam energy needed and the extraction efficiency as a function of the number of drive beam sections and of the final drive beam energy U_f, as shown in Fig. 5 and 6. The chosen value of U_f = 200 MeV is at present considered the minimum compatible with transverse beam stability in the drive linac.

The choice of the operation point (N_D = 10, U_D = 2.1 GeV) is a trade-off between efficiency, installed voltage and considerations based on longitudinal beam dynamics during the generation process. Namely, the longitudinal wakefields in the injector linac and in the ring determine an energy spread in the bunchlets whose absolute value does not depend from the drive beam energy. This has to be high enough in order that the relative energy spread is kept at a reasonable level.

DRIVE BEAM GENERATION COMPLEX

As shown in Fig. 2, each main beam pulse is accelerated to the 500 GeV final energy by 5 drive linac sections (100 GV each). Every section is powered by an individual drive beam pulse. Therefore 10 drive beam pulses must be generated for each e^+ / e^- pulse in the main linac. Initially, 2 ×80 trains composed of 64 bunches each are generated in a 937.5 MHz photo-injector. The bunches in a train are spaced by 32 cm, corresponding to the above frequency, and have an rms length of 3 mm. This is repeated with the repetition rate of the main linac (500 Hz). The trains are then accelerated up to 2.1 GeV in a 937.5 MHz superconducting linac. A total of 2.2 GV of cavities at fundamental plus ~ 200 MV cavities at 937.5 MHz ± ε to provide beam loading compensation along the train will be installed.

The beam loading from train to train is compensated by RF refilling of the injector linac structures in between the passage of the 160 trains at a repetition frequency of 500 Hz. The necessary RF power is:

$$P = q_D \, N_D \, U_l \, f_{rep} \qquad (8)$$

where U_l is the total installed voltage of the injector linac and f_{rep} the repetition rate. The resulting power is 90 MW. The power per meter of structure will be 450 kW/m. The distance between trains will be at this stage 1.25 μs ~ 3.75 km.

The trains are then injected into the collector ring using magnetic deflectors. After 2 ms the whole ring will be filled. The train distance is now 104 ns. When the last train is injected, the ring is emptied. Ten pulses of 16 trains each are extracted from the ring, leaving gaps between them of 5 μs. The bunches are then individually compressed in length by a factor four (from 3 mm to 0.6 mm rms length). The compression is obtained using a telescopic compression system [13], with two stages of RF superconducting cavities + magnetic chicanes. The total installed RF voltage will be 350 MV at 937.5 MHz.

The trains are then combined four by four in a first combiner ring (31.25 m long, corresponding to the 104 ns gap between trains).The injection into the combiner ring is made using 2 transverse RF deflectors at 937.5 MHz that creates a time dependent local deformation of the equilibrium orbit (see Fig. 7). The revolution time is not exactly a multiple of the kicker frequency (while the distance between incoming trains is) so that each revolution time the RF phase increases by 90°. This will allow to interleave the subsequent bunch trains, obtaining a final distance between bunches of 8 cm.

When all of the four trains are inside the ring, they are extracted by a magnetic kicker, and the whole cycle is repeated for the next four. The trains are combined again, using the same mechanism, in another ring (125 m long), yielding another factor four in frequency multiplication. The ten pulses thus obtained are alternately switched by a magnetic kicker in the two drive linacs.

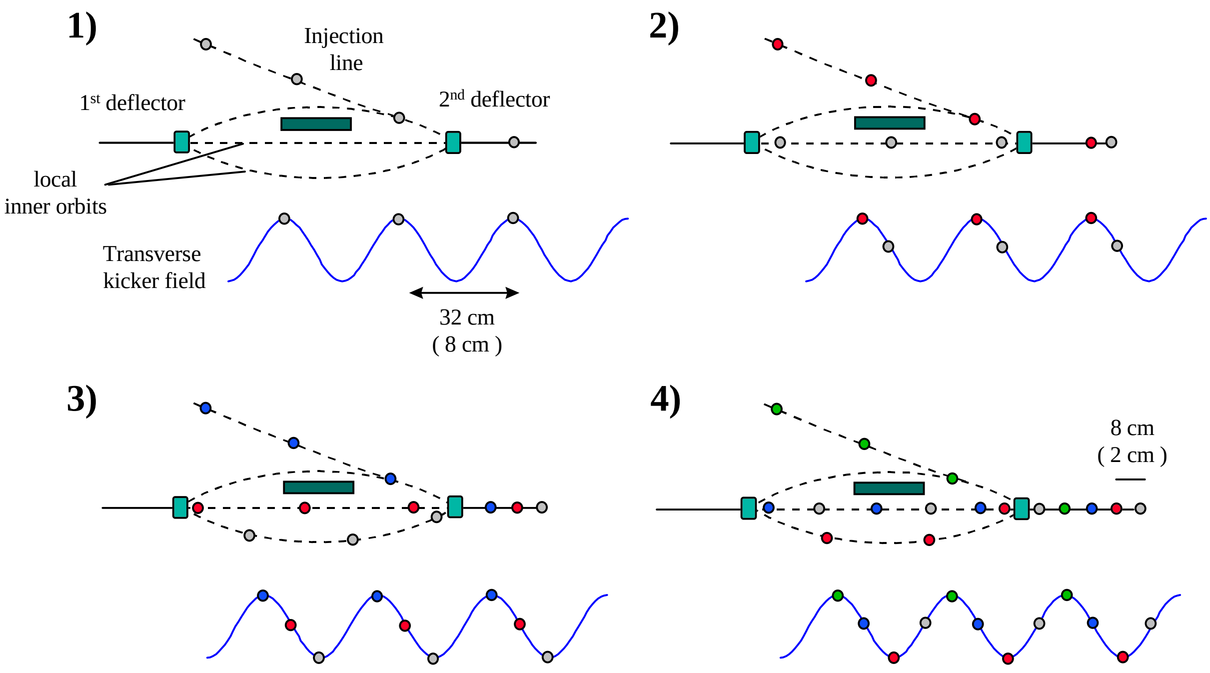

Figure 7. Schematic of the four turns injection into the combiner ring. 1) When the first train arrives all of its bunchlets are displaced by the 2nd transverse kicker on the equilibrium orbit. 2) When the first train comes back, its bunchlets arrive at the kickers at zero crossing of the RF field, hence it stays on an internal orbit. The second train arrives 90° later, and its bunches are displaced by the 2nd kicker on the equilibrium orbit. 3) Now the 1st train bunchlets are kicked inside the orbit, the 2nd train bunchlets arrive at the zero crossing, and the 3rd train bunchlets are injected. 4) The 1st train bunchlets arrive again at the zero crossing, the 2nd train bunchlets are in the inner orbit, the 3rd train bunchlets are also at the zero crossing and the 4th train bunchlets are injected; after the 2nd kicker the four trains are combined in a continuos train with 3 cm spacing between bunches.

LONGITUDINAL BEAM DYNAMICS

The longitudinal beam dynamic has been evaluated all along the drive beam generation complex, in order to ensure that the final parameters (bunch length and energy spread) will allow the beam transport and power production in the drive linac.

The beam loading in the injector linac during the acceleration of each train can be calculated as follows:

$$\frac{dU}{U} = \frac{1}{2}\frac{dW}{W_{stored}} = \frac{r`_I \omega_I q}{2 E_I} \qquad (9)$$

where:

ω_I	=	$2\pi \times 934.5$	MHz	pulsation of injector linac
$r`_I$	=	700	Ω/m	shunt impedance per meter
E_I	=	10	MV/m	accelerating field in injector linac
q	=	560	nC	charge per train

The energy variation along the bunch train at the end of the linac is of the order of 12 %. This will be compensated by two sets of additional cavities, distributed along the linac, with frequencies of 934.5 MHz ± ε. The starting phase in the correction cavities can be chosen such as to minimize the overall energy spread taking into account the charge variation along the train. The results of the optimization are shown in Fig. 8; the rms spread after correction is $2 \cdot 10^{-3}$.

The single bunch energy spread at the exit of the injector linac is determined by the combined effect of the longitudinal wakefields and of the RF curvature and is of the level of $2 \cdot 10^{-3}$. The longitudinal self-wakefields have been calculated in the case of a gaussian bunch using ABCI [14], for a frequency scaled version of the 1.3 GHz TESLA cavities.

In Fig. 9 the calculated longitudinal phase space at injection in the combiner ring is shown for the first bunchlet in the train (low charge = 4.7 nC) and for a bunchlet in the steady state part of the train (high charge = 10 nC).

The last train will be ejected from the combiner ring during its first turn, while the first train will stay in the ring for quite a long time (2 ms). It is therefore important to avoid deterioration of the quality of the first train bunchlets during this time. Potentially deleterious effects in the ring include synchrotron radiation losses, resistive wall effect and space charge.

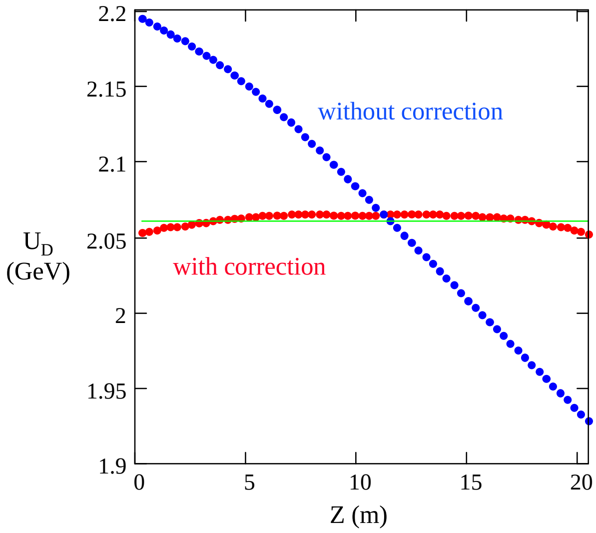

Figure 8. Drive beam energy (GeV) along the train at the end of the injector linac, with and without beam loading compensation.

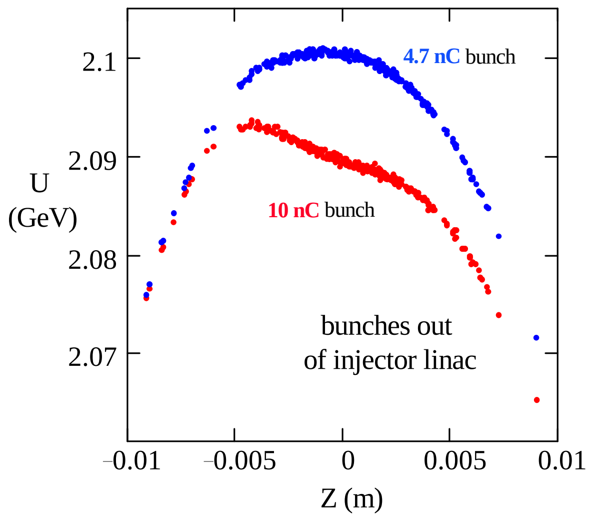

Figure 9. Longitudinal phase space for high and low charge bunches at the end of the injector linac.

These can produce an energy spread within the bunches, different from train to train. In practice the biggest effect is due the resistive wall wake, since both synchrotron radiation and space charge are negligible. For the calculation we assume a round copper chamber of 10 cm diameter, and we used the formula for short gaussian bunches given by O. Henry and O. Napoly [15]. Only the self-wake is relevant in our case. The effect of longitudinal impedance due to bellows and injection/extraction septa are still to be included.

The ring must be isochronous to a very good degree, in order to avoid bunch lengthening, both from the incoming energy spread and on the energy spread developed by the bunch in the ring itself. A preliminary investigation based on a isochronous cell type developed by G. Guignard and E.T. D'Amico [16] has shown that it is possible to obtain the desired degree of isochronicity, using sextupoles located in high dispersion regions of the lattice to correct the second order terms. Bunch lengthening due to different path lengths along the betatron orbits has been found to be negligible.

In Fig. 10 is shown the longitudinal phase space for the high charge bunchlets, at injection and extraction from the collector ring. The incoming spread from longitudinal wakes and RF curvature in the injector linac, the radiation losses, the resistive wall effect, the space charge and the residual non-isochronicity in the collector ring are all included in the calculation. The rms energy spread at extraction from the ring is ~ $4 \cdot 10^{-3}$. A difference in average energy between bunches of the order of 10^{-3} is also present. If the bunches would be compressed in a standard RF + magnetic chicane bunch compressor, such an energy difference would result in a phase difference between bunches after compression. To avoid that it is planned to use a “telescopic” two-stage compression system.

An overall correlated spread of ~ 2 % rms is introduced by two sets of RF cavities at 934.5 MHz. After each set, a magnetic chicane compresses the bunches. The final rms bunch length is 0.6 mm, and the final full energy spread is ~ 8 %, which should be acceptable in the combiner rings and transport lines following the bunch compressor.In Fig. 11 and 12 the longitudinal phase space for different bunches before and after compression is shown.

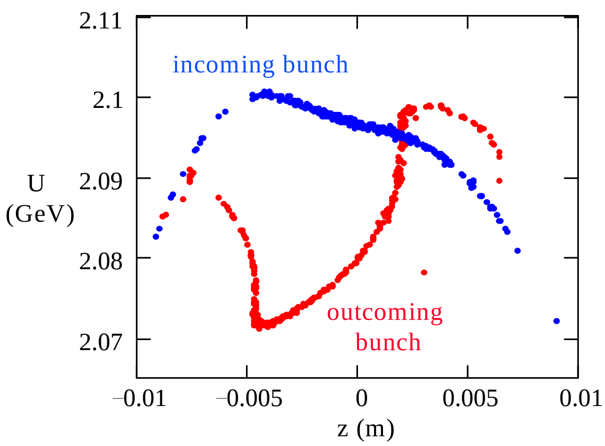

Figure 10. Longitudinal phase space for high charge bunches at injection and extraction from the collector ring.

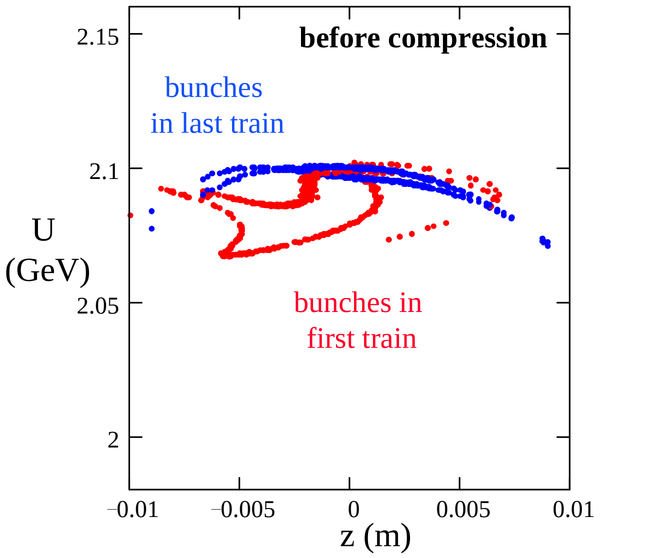

Figure 12. Longitudinal phase space for bunches before bunch compression.

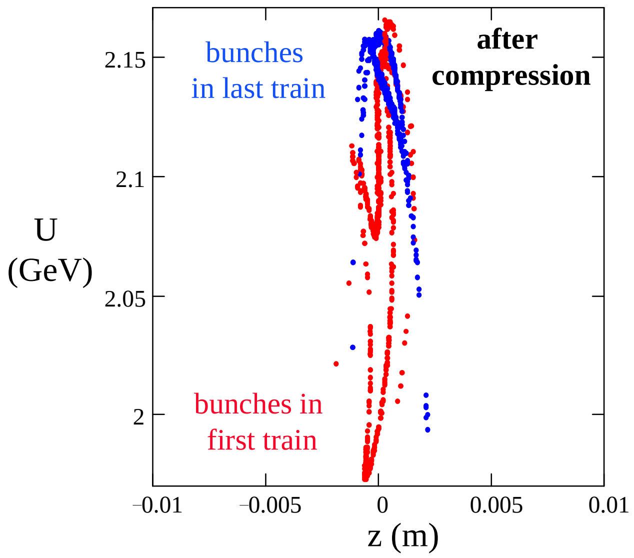

Figure 13. Longitudinal phase space after compression.

EFFICIENCY

In Fig. 14 a power flow chart (wall plug to main beam) is presented that shows the efficiency for the scheme.

We have allowed a total of 4 MW for the power supplies for magnets, pumps and other components in the Collector Ring and the long beam transport lines. The quite high efficiency (70 %) for the klystrons and their power supplies is based on the assumption of the use of depressed collectors, made possible by c.w. operation. We have also allowed for 2 % losses (η_s) in the drive beam during acceleration and transport. The overall efficiency is similar to the one evaluated for the reference scheme for drive beam generation, but the advantage of the alternative scheme developed in this note lays in the lower installed voltage (capital cost). Beside that, it should be able to handle more total charge than at present considered, such that an increase in the number of multibunches in the main beam can be considered, leading to a higher efficiency.

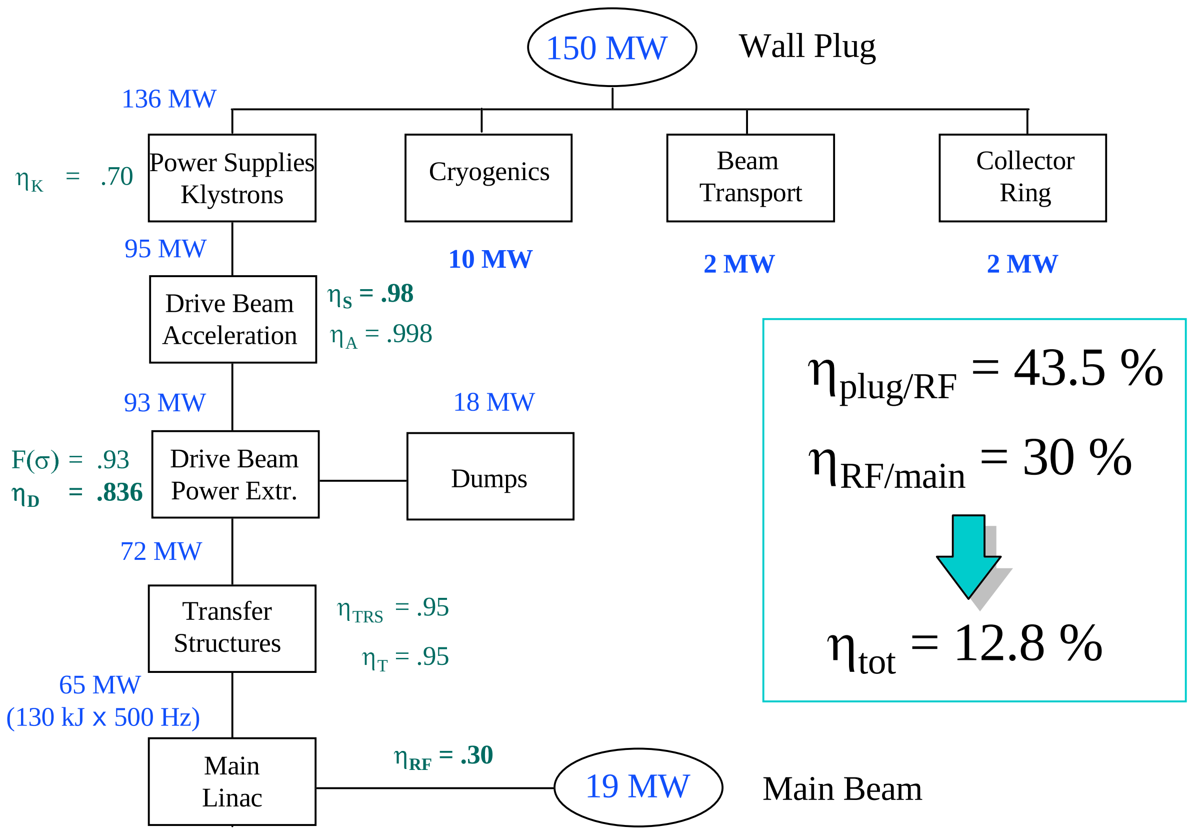

Figure 14. Power flow in the present CLIC scheme, from wall plug to main beam.

CONCLUSIONS

The multi-drive beam scheme presented in this paper, based on recombination of bunch trains at high energy, appears to be a good alternative as a CLIC Drive Beam source.

In particular it can provide a good wall-plug to RF efficiency, while the capital cost is limited, due to the relatively small amount of superconducting cavities. The generation and acceleration of the drive beam are pretty conventional and within the limits of present technology, although the gymnastics in beam storage and combination is surely a drawback.

The splitting in sections of the drive and main linacs makes the scheme easily extensible at higher energies and reduces the power in each drive beam pulse, relaxing the requirements on beam losses

However, the relatively high CTS impedance needed in such a scheme results in increased transverse wakefields. In order to keep the drive beam stable, damping must be introduced in the CTS and quite tight tolerances are required on the drive beam alignment. In particular, the transverse wakefields must be reduced by 30 % over 333 ps, while the maximum rms misalignments allowed are of 50 μm and 5 μm for the structures and the drive beam quadrupoles, respectively. Although a simple steering algorithm can in principle be applied to the drive beam, relaxing these conditions, this is complicated by the huge energy spread developed in the drive beam during interaction, and at present is not yet clear if it is possible in practice.

Furthermore, the scheme is not easily tested at small scale, even if this is not necessarily true for the single critical components.

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