A Drive Beam Injector for CLIC

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Abstract

One of the difficulties to be solved in the design of two beams linear colliders is the generation of the extremely intense, very short bunches of the drive beam. Several schemes can be considered to try to construct this beam. Here we analyse in a simplified way a damping scheme in which most of the compression is achieved by damping rings.

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1 Introduction

One of the difficulties to be solved in the design of two beams linear colliders is the generation of the extremely intense, very short bunches of the drive beam. In particular in the CERN Linear Collider (CLIC) the drive beam of about five GeV required is made of a succession of trains of four bunches each constituted of eleven bunchlets, each bunchlet carries $1 \times 10^{12}$ electrons and has a length of 1mm (one $\sigma$). The repetition frequency of these trains is at 1.7 kHz [1]. A schematic diagram of this succession of bunches is represented fig (1).

Several schemes can be considered to try to construct this beam. Here we analyse in a simplified way a damping scheme in which most of the compression is achieved by damping rings.

Figure 1: CLIC Drive beam bunch timing

![Diagram of CLIC Drive beam bunch timing]
2 The damping scheme

The scheme is based on a powerful linac feeding a set of 11 damping rings. Each of these damping rings is arranged to create four bunchlets of $N$ electrons with a longitudinal bunch length $\sigma_z$. The compression to 1 mm is finally made at high energy by magnetic compression. The trains of four bunchlets created by each of the rings are added to provide the required train of four bunches of eleven bunchlets. The process is repeated each 1.2 ms. The .6 ms nominal repetition rate seems difficult to achieve with this scheme.

Figure 2: Linac pulse with damping rings

3 Linac

A linac fills successively four consecutive 350 MHz buckets of each of the eleven damping rings at the repetition frequency. A time of about 200 ns is left between each batch for the distribution kickers’ rise time. The linac pulse timing is given fig.(2). The linac average current is given eq. (1), the peak current eq. (2). The energy results from the optimization made below of the damping ring energy.

\[ I_{av} = F_{rep} k_b k_{bl} N e \]  
\[ I_{peak} = \frac{I_{av} F_{rf}}{k_b k_{bl} F_{rep}} \]  

Where $F_{rep}$ and $F_{rf}$ are the repetition frequency (1.7 kHz) and the RF frequency of the damping rings (350 MHz), $k_b$ and $k_{bl}$ are the bunch and bunchlets number (4 and 11), $N$ is the number of electrons per bunchlets ($1 \times 10^{12}$), and $e$ is the electron charge.
These numbers could be revised as a result of an overall optimization of CLIC. In particular we have divided by two the nominal repetition frequency in order to arrive at requirements compatible with conventional technology. With these parameter values the peak current in the linac pulse is 56 A when the average current is 6 mA.

4 Feasibility of the linac

A superconducting linac is probably better adapted than a normal conducting one to the pulse rate and power considered. The beam power at the end of this first linac is simply the product $I_{av} \times E$. That is 10 MW with the parameters selected here. The frequency could be either 350 MHz or a higher harmonic. A 350 MHz prebuncher could be used, to avoid losses at injection in the damping rings. A recirculating linac of the type considered for nuclear physics machines should also be considered. The average current of 6 mA is close to the limit of what can be reasonably expected in such machines due to BBU instabilities. The effect of a duty cycle of about $10^{-4}$ should be studied. The electron gun will have to provide a current of 60 A during 11.4 ns.

5 Bunch rotator

The linac beam will come as a train of eleven batch of four long bunches at 1.6 GeV, a third harmonic accelerating system would allow to reduce its energy spread to less than a %. A single ring used as a bunch rotator could then be used as a first stage of bunch compression. In such a ring a beam is injected in a mismatched RF bucket, after a quarter of a synchrotron oscillation, the beam is extracted. The compression is adjusted by adjusting the mismatch. This would have to be investigated at a later stage. The point is that the use of 11 damping rings allows to spread the required current at low energy on a much longer time so that a single linac and a single bunch rotator ring can be used for all 44 bunchlets. Magnetic compression is not feasible with the very long bunches considered.

6 Damping ring

Each pulse (11.4 ns long) of the linac is injected into a damping ring of energy E, radius $R$, and bending radius $\rho$, where the amplitudes of the longitudinal oscillations are damped with an e-folding time $\tau$. $J_c$ is the longitudinal damping partition number. A length $l_w$ of wigglers with the same field as the main bending magnets is installed in the ring. The aim is to generate the four bunches and to damp them in the 1.2 ms between two successive batches.

Fast damping induces a high synchrotron radiation power $P_s$ which in turns prevents the use of superconducting magnets, the field B in the bending magnets is therefore limited to normal conducting values, namely 2 Tesla. The linear density of power $P_m$ deposited by the synchrotron radiation must also be limited to values acceptable by the vacuum chamber.

The total bending length is limited by the space available in the machine:

$$k_w = \frac{2\pi R}{2\pi \rho + l_w}$$

(3)
has to be larger than 1, to leave space for other equipment. In the absence of wigglers it reduces to \( k_w = R/\rho \). This factor (the acceptable fraction of the circumference to be occupied by bending magnets) is independent of the presence or not of wigglers and has been taken equal to 1.5 in all cases.

In order to characterize the effect of wigglers we have introduced the quantity:

\[
k = \frac{2\pi \rho + l_w}{2\pi \rho}
\]  

(4)

This factor is minimum and equal to 1 in the absence of wigglers. The above quantities are then linked by the following equations

\[
E = \left( \frac{4\pi}{eC_\gamma} \right) \frac{k_w}{\tau_e J_c} \frac{1}{(eB)^2}
\]  

(5)

\[
\rho = \frac{E}{eB}
\]  

(6)

\[
R = \left( \frac{4\pi}{eC_\gamma} \right) \frac{(k_w)^2}{\tau_e J_c} \frac{1}{(eB)^3}
\]  

(7)

\[
I = \frac{(k_h N e)c}{2\pi R}
\]  

(8)

\[
P_s = 2 \left( \frac{4\pi}{eC_\gamma} \right) \frac{k_w}{(\tau_e J_c)^2} \frac{1}{(eE)^2} (k_h N e)
\]  

(9)

\[
P_m = \frac{1}{\pi} \frac{1}{\tau_e J_c} (eB)(k_h N e) \frac{1}{k}
\]  

(10)

Where \( E \) is expressed in (eV), \( C_\gamma = 8.85 \times 10^{-32} \) is the parameter of Sands [4] (eq 4.2) expressed in m.(eV)\(^{-3}\), \( c \) is the velocity of light, \( I \) the total circulating current.

The damping partition number \( J_c \) can be as large as 3.5 the horizontal stability being insured by coupling with the vertical plane. The machine circumference must be large enough to let time for the injection/extraction kicker to pulse (50ns) before the train of four bunches comes back (11.4ns), which imposes a minimum radius of three meters.

From the above equations we see that the introduction of wigglers will change neither the energy \( E \) nor the total synchrotron radiation power \( P_s \). It will increase the radius \( R \) by the factor \( k \). As a consequence the intensity \( I \) will be decreased by the same factor, with the effect of reducing the power loss per meter \( P_m \) by the same factor \( k \).

### 6.1 Without wigglers

In the absence of wiggler \( k=1 \), a typical list of parameters as a function of the damping time \( \tau_i \) is given table (1). No acceptable solution can be found at this level of charge per bunch. Even for very long damping times the current is too high and the power dissipated per meter (70 kW/m for \( \tau_i=500 \mu s \)) seems beyond acceptable values. For even longer damping times the radius becomes too small to be compatible with the extraction kickers rise time.
Table 1: Damping ring parameters for $J_c=3.5$, $B=2$ T, $k=1$, $k_w=R/\rho=1.5$, $N=1 \times 10^{12}$

<table>
<thead>
<tr>
<th>Damping time ($\mu$s)</th>
<th>Radius (m)</th>
<th>Energy (GeV)</th>
<th>Bending radius (m)</th>
<th>Current (A)</th>
<th>Synchrotron radiation per meter (kW/m)</th>
<th>Power total (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>7.07</td>
<td>2.82</td>
<td>4.71</td>
<td>4.3</td>
<td>175</td>
<td>5.17</td>
</tr>
<tr>
<td>300</td>
<td>4.71</td>
<td>1.88</td>
<td>3.14</td>
<td>6.5</td>
<td>116</td>
<td>2.30</td>
</tr>
<tr>
<td>400</td>
<td>3.53</td>
<td>1.41</td>
<td>2.36</td>
<td>8.7</td>
<td>87</td>
<td>1.29</td>
</tr>
<tr>
<td>500</td>
<td>2.83</td>
<td>1.13</td>
<td>1.88</td>
<td>10.8</td>
<td>70</td>
<td>.83</td>
</tr>
</tbody>
</table>

6.2 With wigglers

In order to reduce an initial bunch length of about 60 cm at injection to a bunch length of 2 cm at extraction ($\sigma=8/10$ mm) a reduction factor of 30 is required corresponding to about 3.4 damping times. To accommodate that damping in 1.2 ms requires a damping time of 350 $\mu$s. In the examples given table 2 the length of bending magnet has been varied (factor $k$) and the main machine parameters calculated each time to achieve a damping time of 350 $\mu$s.

Table 2: Damping ring parameters for variable $k$, $\tau_n=350$ $\mu$s $J_c=3.5$, $B=2$ T, $k_w=1.5$, $N=1 \times 10^{12}$

<table>
<thead>
<tr>
<th>$k$ factor</th>
<th>Radius (m)</th>
<th>Energy (GeV)</th>
<th>Bending radius (m)</th>
<th>Current (A)</th>
<th>Synchrotron radiation per meter (kW/m)</th>
<th>Power total (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.04</td>
<td>1.61</td>
<td>2.69</td>
<td>7.6</td>
<td>100</td>
<td>1.69</td>
</tr>
<tr>
<td>2</td>
<td>8.08</td>
<td>1.61</td>
<td>2.69</td>
<td>3.8</td>
<td>50</td>
<td>1.69</td>
</tr>
<tr>
<td>3</td>
<td>12.1</td>
<td>1.61</td>
<td>2.69</td>
<td>2.5</td>
<td>33</td>
<td>1.69</td>
</tr>
<tr>
<td>4</td>
<td>16.2</td>
<td>1.61</td>
<td>2.69</td>
<td>1.9</td>
<td>25</td>
<td>1.69</td>
</tr>
<tr>
<td>5</td>
<td>20.2</td>
<td>1.61</td>
<td>2.69</td>
<td>1.5</td>
<td>20</td>
<td>1.69</td>
</tr>
<tr>
<td>6</td>
<td>24.2</td>
<td>1.61</td>
<td>2.69</td>
<td>1.3</td>
<td>17</td>
<td>1.69</td>
</tr>
</tbody>
</table>

For $k=4$ the power dissipated per meter (25 kW) seems at the limit of what can be accepted [5]. The circumference of 100 meter per damping ring (1.1 km for 11 rings) is still acceptable. The synchrotron power (1.7 MW per ring, close to 20 MW for 11 ring) and the circulating current 1.9 ampere are high for a small ring.

7 Feasibility of the damping ring

We examine here the feasibility of the damping ring with $k=4$ in table (2).
The technology of the magnet working at 2 tesla requires a detailed analysis. Reducing the field would have severe consequences on the machine parameters as is obvious from eq.(5.9). On the contrary if it was possible to increase this field the damping ring energy could be reduced as well as the beam power.

The wigglers are best constituted of a set of reverse bends and compensating normal bends in order to spray rather than concentrate the radiation. The required gradient in order to adjust the value of \( J_z \) is best achieved in dedicated Robinson wigglers.

Normal conducting cavities are imposed due to the heavy radiation loss and the small diameter of the ring. Ten RF cavities are needed in order to provide the focusing required by the final bunch length, each will provide about 600 kV with a 300 kW power coupler corresponding to a total RF power per ring of 3.0 MW (33 MW for the 11 rings). In these 1.7 MW are due to synchrotron radiation losses, 400 kW to dissipation in the cavities (40 kW per cavity) and the remaining 900 kW to Higher Order Mode losses.

The problem will be to limit these HOM losses in the ring. With a final bunch length \( \sigma = 10 \) mm one can expect that suitably shaped cavities will present a loss factor not less than .2 V/pC. To this corresponds an energy deposition of 60 kW per cavity. 10 cavities are required, which will consume 600 kW. The loss factor of the vacuum chamber is more difficult to estimate. The scaling laws with radius differ from one author to the next. It can be expected to contribute at least 1 V/pC, to which corresponds an other 300 kW. All these contribution are however calculated for the bunch length before extraction. In the course of the damping process the bunch length will be long enough to reduce these effects by a considerable factor. The effect of this "transient HOM" has not been investigated, it should reduce the power load due to the HOM by at least a factor two and impose a modulation of the power during the pulse. The "total average power" consumed by the system should then be of the order of 30 MW.

The longitudinal impedance \( |Z/n| \) can be deduced from the loss factor, given a number of approximations, and compared to the acceptable impedance deduced from the Keil-Schnell formula. The results in our case are comparable \( (|Z/n|_0 \approx 1 \Omega) \) so that the beam should be stable up to the end of the damping process. This stability however is only obtained (as in the case of the HOM losses) with a serious effort at reducing the vacuum chamber discontinuities. The transverse impedance should not introduce a limitation. The situation of multibunch instabilities has not been considered, dampers will be required even after the damping of HOM in the cavities. The transient beam loading in this ring where 96% of the circumference is empty will not be simple. The proper recombination of the 11 rings with a timing accuracy of a pS is an other challenge.

Finally it is always possible to reduce the current, at the expense of the radius by going to higher values of \( k \) in table 2, or by doubling the number of rings and installing only two bunches per ring.

8 Magnetic compression and acceleration

The energy dispersion is an essential ingredient of the magnetic compressor. At the entrance of the compressor system the energy dispersion is small \( (\sim 510^{-4}) \) due to the powerful damping in the damping ring. In a certain measure this quantity can be adjusted by modifying the momentum compaction. However it is already adjusted for the ring requirements. It has

7
to be small to reduce the RF voltage and large to avoid the longitudinal instability.

With this reduced energy spread a compression by a factor 10 in a single stage of compression is possible. This allows the recombination of all bunchlets in a single train immediately after the compressors and the reacceleration of the train in a single 350 MHz, 3.4 GeV linac up to the final energy of 5 GeV.

The phase extension of the train of 11 bunchlets in this 350 MHz, 3.4 GeV linac is 42 deg, corresponding to an energy spread between the 11 bunchlets of 7% (10 intervals). This could be reduced to less than 2 per mil with a third harmonic linac of less than 500 MeV. The same is true all along the drive beam linac, since the damping rings will produce a beam of small transverse dimensions, compatible with third harmonic cavities.

Figure 3: Schematic layout of the test lab proposed

9 A test set-up proposal

It is possible to build a scaled down model of the drive beam injector capable to produce one bunchlets of $10^{12}$ electrons and of $\sigma$, 1 mm with a low repetition frequency. The model is represented fig.(3).

The linac should use 350 MHz superconducting cavities of the type foreseen for the drive beam. A total of 10 to 20 such cavities would be required depending on their performance. The phase extension of the bunch riding on the top of the wave could be extended by the use of a third harmonic cavity. A bunch rotator could be inserted between the linac and the damping ring.

The energy of the damping ring must be such that the final bunch delivered is well away from the space charge regime. We use for this a formula deduced from the paraxial equation [2, 3] and therefore only valid for bunches with a diameter much smaller than their length. This formula states that the maximum current that can be pushed through a beam pipe of diameter $\phi$ and length $l$ is

$$I_{\text{max}} = 1.1696 \pi \epsilon_0 \left( \frac{E_0}{\epsilon} \right) c \beta^3 \gamma^3 \left( \frac{\phi}{l} \right)^2$$
Recent computations on short bunches have shown that the space charge limit for short bunches is higher than for long bunches so that we can safely apply this to our final bunch. The current corresponding to the above charge and bunch length is approximately 20 kA. If we want to be able to push it through a beam pipe of 5 meter length and 4 cm diameter the required energy is 20 MeV, so that our 60 MeV system is well above the space charge regime.

A tentative list of parameters of a damping ring is given table (3). We assumed that a momentum compaction factor of 4 was possible in such a small machine and that the impedance of the vacuum chamber could be limited to 1.2 ohm for a 2 cm bunch, which corresponds to a loss factor $k = 0.3 \text{ V/pC}$, very small indeed. The cavities have been assumed normal conducting with a loss factor of .1 V/pC (which may be feasible with a special design), corresponding to an impedance of .5 ohm per cavity. This allows to keep stable a beam with a peak current of 1 kA, and an rms energy spread of $10^{-3}$ for an rms bunch length of 2 cm. The very high value of $Q_s$ imposes to have 4 cavities distributed around the ring.

The test lab would also be used in order to test the feasibility of magnetic compressors, the final energy spread of the 1 mm, 20 kA bunch would be 2%.

This parameter list has only been worked out in order to estimate the feasibility of the project. It is always possible to release the requirements by increasing the ring energy or reducing the bunch charge.

**Table 3: Damping ring parameters for the test proposal**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>60 MeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>23 m</td>
</tr>
<tr>
<td>Damping time</td>
<td>150 ms</td>
</tr>
<tr>
<td>Bending field</td>
<td>.5 T</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>4</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1</td>
</tr>
<tr>
<td>Nb of particle per bunch</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Average current</td>
<td>2.1 A</td>
</tr>
<tr>
<td>Wiggler length</td>
<td>13 m</td>
</tr>
<tr>
<td>$\sigma_r/E$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$\sigma_s$</td>
<td>20 mm</td>
</tr>
<tr>
<td>Predicted impedance $</td>
<td>Z/n</td>
</tr>
<tr>
<td>Acceptable impedance</td>
<td>3.1 Ohm</td>
</tr>
<tr>
<td>Nb of cavities</td>
<td>4</td>
</tr>
<tr>
<td>RF Power</td>
<td>260 kW</td>
</tr>
<tr>
<td>Cavity gap voltage</td>
<td>470 kV</td>
</tr>
<tr>
<td>$P_{HOM}$ per cavity</td>
<td>30 kW</td>
</tr>
<tr>
<td>$P_{HOM}$ vacuum chamber</td>
<td>85 kW</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>.7</td>
</tr>
</tbody>
</table>
10 Conclusion

The generation of the drive beam of CLIC is one of the major challenges of the scheme, various solutions have been proposed or are being considered.

The use of damping rings is at the limit of predictable technology but does not seem excluded, it provides a means to accelerate relatively long bunches at low energy, therefore reducing the formidable space charge effects in short bunches of 160 nC. Only one linear accelerator is needed before as well as after the damping rings. however the compression by eleven damping rings requires a large amount of RF power. It seems difficult to achieve the required repetition rate of 1.7 KHz. More detailed studies are obviously required. A test bench could be prepared with the aim of producing the CLIC drive beam bunchlets.

Acknowledgements

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References

W. Schnell CERN-LEP-RF/86-14,1986 (CLIC note 21)
W. Schnell CERN-LEP-RF/88-59,1988 (CLIC note 85)


Appendix

Derivation of damping ring equations

We first introduce the factors:

\[ k = \frac{2\pi \rho + l_w}{2\pi \rho} \]  \hspace{1cm} (1)

\[ k_w = \frac{2\pi R}{2\pi \rho + l_w} \]  \hspace{1cm} (2)

so that:

\[ R/\rho = kk_w \]  \hspace{1cm} (3)

The bending radius and the energy are linked by the equation:

\[ eB = \frac{(E/e)}{\rho} \]  \hspace{1cm} (4)

In the following we have replaced the quantity \((E/e)\) by \(E\) since all energies are expressed in eV.

The average power irradiated per electron is \(<P_\gamma> = U_0/T_0\) in a machine with revolution time \(T_0 = (2\pi R)/e\) and energy loss per turn \(U_0\), so that one has successively:

\[ U_0 = \frac{C_\gamma E^4}{2\pi} \int \frac{1}{\rho(s)^2} ds \]  \hspace{1cm} (5)

\[ \int \frac{1}{\rho(s)^2} ds = \frac{2\pi \rho + l_w}{\rho^2} \]  \hspace{1cm} (6)

\[ U_0 = C_\gamma \frac{E^4}{\rho} k \]  \hspace{1cm} (7)

\[ <P_\gamma> = U_0/T_0 = \frac{eC_\gamma E^4}{2\pi R\rho} k \]  \hspace{1cm} (8)

The coefficient of Sands [4] \(C_\gamma\) is here expressed in eV in order to be consistent with the notation of eq.(4), \(C_\gamma = 8.85 \times 10^{-32}\) m eV^{-3}. The quantity \(R\rho\) can be eliminated using eq.(3, 4) to give:

\[ <P_\gamma> = \frac{eC_\gamma E^2(cB)^2}{k_w} \]  \hspace{1cm} (9)

The damping time \(\tau_e\) is given by eq.(4.53) of Sands [4].

\[ \tau_e = \frac{2E}{J_e <P_\gamma>} \]  \hspace{1cm} (10)

The energy \(E\) is obtained by eliminating \(P_\gamma\) using eq.(9)

\[ E = \left( \frac{4\pi}{eC_\gamma} \right) \frac{1}{\tau_e J_e (cB)^2 k_w} \]  \hspace{1cm} (11)
The radius $R$ is obtained by eliminating $\rho$ from eq.(3,4) and $E$ using eq.(11)

$$R = \left( \frac{4\pi}{cC_\gamma} \right) \frac{k_w^2}{\tau_e J_e} \frac{1}{(cB)^2} k$$

(12)

The synchrotron power is $P_s = U_0 I$:

$$I = \frac{c}{2\pi R} (k_b N_e)$$

(13)

$$P_s = 2 \left( \frac{4\pi}{cC_\gamma} \right) \frac{k_w}{(\tau_e J_e)^2} \frac{1}{(cB)^2} (k_b N_e)$$

(14)

The power emitted per meter of magnet is $P_m = P_s/(2\pi \rho + l_w)$ where $(2\pi \rho + l_w)$ is eliminated using eq.(2,4) and $E$ using eq.(11)

$$P_m = \frac{1}{\pi} \frac{1}{\tau_e J_e} (cB) (k_b N_e) \frac{1}{k}$$

(15)