THE CLIC RF POWER SOURCE

A NOVEL SCHEME OF TWO-BEAM ACCELERATION FOR ELECTRON–POSITRON LINEAR COLLIDERS


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* On leave of absence from SLAC
ABSTRACT

In this paper we discuss a new approach to two-beam acceleration. The energy for RF production is initially stored in a long-pulse electron beam which is efficiently accelerated to about 1.2 GeV by a fully loaded conventional, low-frequency (~1 GHz) linac. The beam pulse length is twice the length of the high-gradient linac. Segments of this long pulse beam are compressed using combiner rings to create a sequence of higher peak power drive-beams with gaps in between. This train of drive beams is distributed from the end of the linac in the opposite direction to the main beam down a common transport line so that each drive beam can power a section of the main linac. After a 180-degree turn, each high-current, low-energy drive beam is decelerated in low-impedance decelerator structures, and the resulting power is used to accelerate the low-current, high-energy beam in the main linac. The method discussed here seems relatively inexpensive, is very flexible, and can be used to accelerate beams for linear colliders over the entire frequency and energy range.
1 INTRODUCTION

1.1 Background information

The study of a two-beam accelerator for the Compact Linear Collider (CLIC) began in 1986. The original idea for a two-beam accelerator came from A. Sessler [Sessler, 1982] and was based on the use of induction linac technology for drive beam acceleration. The original CLIC scheme as proposed by W. Schnell [Schnell, 1986] was for single-bunch operation and was based on the use of superconducting cavities for drive beam acceleration. In more recent years, CLIC has changed to a multibunch mode of operation to satisfy the increased luminosity requirement and a multi-drive-beam scheme has been proposed as an alternative to the original single drive beam. The most significant recent change has been to replace the superconducting accelerator by a normal-conducting one, thus avoiding the problem of a long storage time of the drive beam in a large ring. The recent changes have increased the energy reach of the system up to 5 TeV and have resulted in a new RF power source for high-gradient acceleration. This continuous evolution of the CLIC study, which has taken advantage of a whole series of new ideas over the last few years, has finally produced a very attractive scheme which we believe to be both technically feasible and, in addition, cost-effective.

The purpose of this report is to document in some detail the new RF power system, and to present the work that has been completed to date towards the design and feasibility of the new system. The design is, of course, not yet complete; however, the first level of detailed study has been completed and is presented in this report.

1.2 A brief description of the basic idea

The energy for RF production is initially stored in a long-pulse electron beam, the ‘drive beam’, which is efficiently accelerated to about 1.2 GeV by a fully-loaded, conventional, low-frequency (~ 1 GHz) linac. The linac is powered by conventional long-pulse klystrons. The beam pulse length that is created is chosen to be twice the length of the high-gradient linac. As the long-pulse beam leaves the ‘drive beam accelerator’, it passes through combiner rings where groups of leading bunches are delayed to fill in the gaps between trailing bunches. The net effect is to convert the long-pulse beam to a periodic sequence of higher peak power drive beams with gaps in between. This sequence of drive beams is distributed from the end of the linac in the opposite direction to the main beam down a common transport line one after the other. Pulsed deflector magnets deflect each beam at the appropriate time into a turn-around. After a turnaround each high-current, relativistic drive beam is decelerated in a 700 m long sequence of low-impedance decelerating structures, and the resulting output power is transferred to accelerate the low-current, high-energy beam in the main linac. As the main beam travels along, a new drive beam joins it periodically to run in parallel but ahead of it to produce the necessary power for a 700 m long linac section. At the end of a section, the remaining energy in the drive beam is dumped while a new one takes over the job of accelerating the main beam. The primary effect of this system is to use the energy stored in different time bins of a long-pulse electron beam to create the RF power necessary for different sections of a long linac. Thus, the same accelerator and beam manipulation system is used to create all the beams necessary for powering the main linac.

1.3 Overview of the report

The Table of Contents shows the topics covered in this report. Chapter 2 introduces the reader to the topic with a discussion of the history and evolution of the concepts of two-beam acceleration. A general description of the parameters envisaged for the CLIC linear collider designs for various final energies is given in Chapter 3. The parameters for the 3 TeV design are highlighted and have been used as the nominal parameters for the remainder of the report. Chapter 4 contains a complete overview and summary of the system. Some of the basic principles used are also discussed and compared with more conventional approaches.

A detailed presentation of the entire RF power source complex is given in Chapters 5–8. Chapter 5 describes the drive beam accelerator. Chapter 6 treats the system that accomplishes energy
compression and frequency multiplication. The beam transport, turn-arounds and bunch compressors are discussed in Chapter 7. Finally, the drive beam decelerator is discussed in Chapter 8.

This type of approach for RF power production has system issues that are quite different from conventional approaches. Although a thorough study has not yet been carried out, our initial thoughts on this subject are presented in Chapter 9.

In order to study the technological and physics uncertainties associated with this scheme, new test facilities have been proposed; they are presented in Chapter 10.

Finally, the report is concluded by a short summary (Chapter 11). A general parameter table, an overall layout of the CLIC complex, and a power flow diagram can be found in the Appendices.
References


2  HISTORY AND EVOLUTION

2.1  Early designs and concepts

The initial Compact Linear Collider (CLIC) design was for a colliding beam energy of 2 TeV in the centre of mass and aimed since the beginning at the use of high accelerating gradients (80–160 MV/m) [Schnell, 1986].

This is the reason for the selection of a linac operating at a very high frequency of 30 GHz, which is considered to be close to the limit beyond which standard technology for the fabrication of normal-conducting, travelling-wave, accelerating structures can no longer be used. Because conventional RF power sources based on modulators and klystrons are not available at this specially high frequency, CLIC was based on the novel and promising concept of Two-Beam Acceleration (TBA) whose principle had recently been proposed [Sessler, 1982].

As stated in the very complete review [Hübner, 1992] of the impressive R&D work associated with this new scheme of RF power generation, “the principle of TBA is based on a high intensity, but low to medium energy relativistic electron drive beam running along the whole linac or at least a large fraction of it. It is periodically interacting with either wiggler magnets, RF cavities or travelling wave RF structures. It excites electromagnetic fields in these RF devices or amplifies the e.m. field in the wiggler via single-pass free-electron laser (FEL) action. Hence, the drive beam is decelerated and beam energy converted into electromagnetic energy; the latter is coupled out and led by waveguides to the main linac accelerating a beam of lower intensity to the highest energies.” Various combinations of these different deceleration and acceleration or re-acceleration methods have been studied and are reported in [Hübner, 1992]. These are mainly:

– RF generation by FEL and acceleration of the drive beam by induction linac [Sessler, 1982; Sessler, 1991; Whittum, 1992; Kaminsky, 1992],

– RF generation by power extraction structures and acceleration of the drive beam by induction linac [Sessler, 1989],

– RF generation by power extraction structures and acceleration of the drive beam by superconducting cavities [Schnell, 1986].

The latter was proposed for the CLIC scheme for maximum power efficiency and to make the best use of the superconducting cavities built at CERN for LEP2 [Schnell, 1986]: “The RF power is generated by one medium energy (6 GeV) electron drive beam running along the whole linac and traversing RF transfer structures, with a few short sections providing re-acceleration. This beam runs parallel to the main beam at about one metre distance and periodically deposits energy in the 30 GHz travelling wave transfer structures where from a 40 MW, 11 ns RF pulse is fed into each of the four accelerating (80 MV/m) travelling wave accelerating structures coupled to it. In order to keep the drive beam highly relativistic and preclude excessive transverse blow-up, the drive beam is re-accelerated in 350 MHz superconducting cavities. The initial acceleration of the drive beam is also performed by this type of cavity.”

2.2  The single drive beam or reference scheme of the drive beam generation

The so-called reference scheme [Thorndahl, 1998] is an evolution of the original single-bunch scheme described above [Schnell, 1986] that has been adapted to the production of long RF pulses needed for the acceleration of multibunches. Furthermore, the drive beam is not periodically re-accelerated after a first stage of RF power generation as in the original scheme since this does not significantly improve the overall efficiency but does require the installation of large quantities of superconducting structures in the main tunnel. As a consequence, the single drive beam of the reference scheme contains the whole energy of the RF needed for beam acceleration up to top energy.

In the case of a colliding beam energy of 1 TeV in the centre of mass, initially low-momentum 50 nC bunch trains are obtained by combining 25 nC bunches from a battery of 10 minilinac pairs (of different momenta) via a spectrometer type magnet system (referred to as the switchyard).
Alternatively, one could use an induction linac and a Free Electron Laser (FEL) to obtain the same bunch structure.

The main acceleration occurs in 200 MHz superconducting structures at 4.2 K containing, in order to make beam-loading compensation feasible, twice the required energy (180 kJ) for the acceleration of one complete drive pulse (28 µC). A two-frequency beam-loading compensation arrangement is based on superconducting cavities at 195.4 and 204.6 MHz. For the sake of energy efficiency, passive beam excited third and sixth harmonic normal-conducting correction structures shape the train momentum profile to permit the beam survival through the 30 GHz power-producing drive beam decelerator with a minimum initial beam energy. A schematic layout is shown in Fig. 2.1.

**Fig. 2.1 Layout of the drive beam generation by the reference scheme (CLIC Note 352)**

One advantage of the scheme is the simplicity of the beam line: the drive beam goes from the switchyard to the final dump along a straight line. Furthermore, the inherently excellent transverse stability during the decelerating phase (thanks to the large beam aperture of 40 mm) alleviates fears that the high energy stored in the drive beam pulse will cause hardware damage.

The reference scheme using a single drive beam without re-acceleration to power each linac as described above has been shown to be very efficient with a wall-plug to RF power generation of about 36%. Nevertheless, because of the heavy beam loading (especially in the multibunch operation), it requires a large number of superconducting cavities and cryogenic hardware (about 10 times the LEP2 upgrade or 14.6 GV of installed cavities) to pre-store a total RF energy of 360 kJ at a frequency as low as 200 MHz and with fields of 6 MV/m.

Another challenge is the generation of the 30 GHz bunch structure with a high charge per bunch from the battery of S band linacs (switchyard) or by FEL bunching.

Finally, the whole drive beam 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 decelerating structures. These problems get worse as the linear collider is upgraded to higher energies and higher accelerating
gradients. Practically, the reference scheme is limited to the RF power generation for a linear collider with a maximum centre-of-mass energy of 1 TeV.

2.3 The multi-drive-beam scheme

In order to overcome the problems and limitations of the reference scheme, an alternative scheme for the drive beam generation which is better adapted to multi-bunch operation at high energy and accelerating gradient has been proposed [Autin, 1994; Corsini, 1998]. A general layout of the scheme is shown on Fig. 2.2.

![Schematic layout of the multi-drive-beam scheme (CLIC Note 331)](image)

**Fig. 2.2** Schematic layout of the multi-drive-beam scheme (CLIC Note 331)

In this scheme, the drive beam is split into a number $N_D$ of drive beams (multi-drive-beam scheme) each one powering a short length of the main linac, in order to distribute the beam energy and make it easier to handle. The energy per drive beam is therefore reduced by the factor $N_D$ with respect to the reference scheme, thus relaxing the tolerances for beam losses during deceleration. Moreover, the drive beams are generated close to the Interaction Point and transported to the beginning of the main linac section to be powered with a time separation of the drive beams equal to twice the travel time in the section. This makes the drive beam generation and transport much easier as the bunch trains extend over a few tens of microseconds rather than a few tens of nanoseconds.

Batches of drive bunches with the same duration as the RF power pulse and with a large interval between bunches (64 cm) are first accelerated on the crest of the RF wave of a low-frequency (937.5 MHz) superconducting injector linac. This results in a very efficient acceleration of the bunches and simplifies the bunch train generation by a standard photoinjector.

The batches of bunches are then 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. This allows a simple beam loading compensation by RF power refilling, in between the acceleration of each batch of bunches, of the superconducting structures of the injector linac running in a continuous-wave (CW) mode of operation. The overall energy is therefore stored in the beam instead of in the
superconducting structures as in the reference scheme and thus minimizes the number of superconducting structures required.

The final bunch structure for RF power generation is then obtained by beam pulse compression and RF multiplication using a funnelling method [Delahaye, 1993; Delahaye, 1994] with transverse deflectors in compressor rings (Fig. 2.3 and Fig. 2.4). Two compressor rings are used in sequence to compress the beam pulse and multiply the bunch repetition frequency by a factor four, thus reducing the bunch interval from 64 cm to 2 cm.

After extraction from the compressor rings, the drive beams are sent towards the beginning of the main linac with adequate interval and injected one after the other into the corresponding decelerating sections for RF power generation.

This method is particularly attractive as it acts as a transformer starting from the RF power produced by low-frequency CW standard klystrons and producing, after efficient beam manipulations, RF power at the desired frequency with the required pulse shape at a very short distance from the accelerating sections of the main linac. No further manipulation of the RF power is then necessary.

The main problem of this method consists in the possible deterioration of the bunch quality during the storage time in the collector ring (typically a few milliseconds) by various effects (collective instabilities, synchrotron radiation losses, debunching by non-isochronicity, etc.). In order to minimize this deterioration, the collector ring is made as isochronous as possible and the bunch charge is reduced by using high-impedance decelerating structures at the limit of beam stability in the decelerating linac.

Moreover, the overall beam energy is stored during a limited but significant amount of time in the collector ring (5 km long), which is potentially critical.

The scheme described in this report is an evolution of the multi-drive-beam scheme where the intermediate beam storage in the collector ring is avoided by accelerating the drive beam in a conventional linac powered by high-power pulsed klystrons.

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**Fig. 2.3** Principle of beam pulse compression and RF multiplication in a compressor ring
**Fig. 2.4** Principle of injection by funnelling with transverse deflector in a compressor ring
References


3 CLIC PARAMETERS FROM 0.5 TO 5 TeV

3.1 Considerations which influenced the parameters

The Compact Linear Collider (CLIC) covers a centre-of-mass energy range for e collisions of 0.5 to 5 TeV [Delahaye, 1998] with a maximum energy well above those currently proposed by any other linear collider study [Loew, 1998]. The main parameters at various colliding beam energies are given in Table 3.1. CLIC has been optimized for 3 TeV in order to meet post-LHC physics requirements [Ellis, 1998] and will be built in stages without major modifications.

The main beam and drive beam generation complexes are located in the centre of the facility close to the detectors, thus making the upgrading to higher colliding beam energies easier by a simple extension of the main linacs and addition of drive beam decelerator sections.

The main beam parameters have been chosen to obtain a reasonable beam emittance preservation in a strong wake-field environment during acceleration in the main linac at an especially high frequency, and to obtain a good RF to beam power transfer efficiency. The main beam consists of a train of 150 bunches $4 \times 10^9$ e per bunch with an interval between bunches of 20 RF wavelength or 20 cm. The duration of the RF pulse is therefore 120 ns when taking into account the 20 ns filling time of the 50 cm long accelerating structures.

The repetition frequency of the linac has been adjusted to reach the required luminosity at the various colliding beam energies but has been chosen to be a multiple of the wall-plug frequency for easy synchronization. It varies from 50 to 200 Hz.

The corresponding beam power is rather high ranging from 5 to 12 MW. With a RF to beam power transfer efficiency typically of 20–35%, the necessary RF power to accelerate such beams ranges from 27 MW to 124 MW respectively at 0.5 TeV and 5 TeV. As a consequence and in order to limit the wall-plug power consumption, the RF power generation efficiency has to be rather good, the target figure being 40%.

3.2 Parameter flexibility

The most probable scenario is that a linear collider of the second generation (the SLC corresponding to the first generation) with a colliding beam energy of 500 GeV upgradable to 1 or 1.5 TeV will be built within the next few years somewhere in the world. The third generation of linear collider would then be based on CLIC technology, the only technology able to reach higher energies, and would take advantage of the knowledge and the experience accumulated by operation of the previous generation. It would then be built with colliding beam energy similar to or slightly above the highest energy reached at this time including from the start the capability for an easy upgrading of the energy. In the case where a second generation of linear collider based on more conventional technology is not built before the CLIC technology becomes mature, then the first CLIC stage would certainly be with a 0.5 TeV e colliding beam energy but with relaxed parameters in order to give time for learning before more challenging parameters are adopted in later CLIC stages at higher energies (see Table 3.1).

In particular and in order to limit the whole facility to reasonable dimensions, the accelerating gradient is made as high as possible at high colliding beam energy (200 MV/m at 5 TeV) but is relaxed for lower energies (150 MV/m at 3 TeV, 100 MV/m at 0.5 and 1 TeV). For such high accelerating gradients, a large amount of RF power is necessary during the passage of the train of bunches (230 MW, 460 MW and 770 MW every metre of the main linac respectively at 1, 3 and 5 TeV). A shaping of the RF power during the filling time of the accelerating structure (see Chapter 8) is required to establish in the structure, prior to the passage of the train of bunches, the equilibrium accelerating field pattern for a constant energy gain along the train of bunches.

An easy adjustment of the RF power provided to each accelerating structure and thus of the accelerating gradient is therefore essential.
### 3.3 The parameter list

<table>
<thead>
<tr>
<th>Centre-of-mass energy [TeV]</th>
<th>2 $U_b$</th>
<th>0.5</th>
<th>1</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam parameters at IP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective luminosity [10$^{33}$ cm$^{-2}$ s$^{-1}$]</td>
<td>$l$</td>
<td>5.0</td>
<td>11</td>
<td>106</td>
<td>149</td>
</tr>
<tr>
<td>Average energy loss [%]</td>
<td>$\delta_b$</td>
<td>3.6</td>
<td>9.2</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>Beamstrahlung parameter [-]</td>
<td>$Y$</td>
<td>0.18</td>
<td>0.57</td>
<td>8.79</td>
<td>26.73</td>
</tr>
<tr>
<td>Number of photons/electron [-]</td>
<td>$n_\gamma$</td>
<td>0.8</td>
<td>1.1</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Linac repetition rate [Hz]</td>
<td>$f_R$</td>
<td>200</td>
<td>150</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>Number of particles/bunch [10$^9$ e]</td>
<td>$N_b$</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Number of bunches/pulse [-]</td>
<td>$k_b$</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>$\Delta_b$</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>Transverse emittances [10$^{-8}$ m rad]</td>
<td>$\gamma\varepsilon_{x/y}$</td>
<td>188/10</td>
<td>148/7</td>
<td>60/1</td>
<td>58/1</td>
</tr>
<tr>
<td>Beta functions [mm]</td>
<td>$\beta_{x/y}$</td>
<td>10/0.1</td>
<td>10/0.10</td>
<td>8/0.10</td>
<td>6/0.10</td>
</tr>
<tr>
<td>RMS beam width [nm]</td>
<td>$\sigma_{x/y}$</td>
<td>196/4.5</td>
<td>123/2.7</td>
<td>40/0.6</td>
<td>27/0.45</td>
</tr>
<tr>
<td>Transverse emittances [nm]</td>
<td>$\sigma_{x/y}$</td>
<td>196/4.5</td>
<td>123/2.7</td>
<td>40/0.6</td>
<td>27/0.45</td>
</tr>
<tr>
<td>Bunch length [µm]</td>
<td>$\sigma_{x}$</td>
<td>50</td>
<td>50</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Enhancement factor [-]</td>
<td>$H_D$</td>
<td>1.48</td>
<td>1.54</td>
<td>1.92</td>
<td>1.99</td>
</tr>
<tr>
<td>Beam power per beam [MW]</td>
<td>$P_b$</td>
<td>4.81</td>
<td>7.21</td>
<td>10.81</td>
<td>12.02</td>
</tr>
</tbody>
</table>

| **Main Linac**               |        |     |   |   |   |
| RF frequency [GHz]           | $\Omega/2\pi$ | 30 | 30 | 30 | 30 |
| Accelerating field [MV/m]    | $G$    | 100 | 100 | 150 | 200 |
| Total two linacs length [km] | $l_T$  | 6.6 | 13.5 | 27.5 | 35 |
| Length of sections [m]       | $l_s$  | 0.50 | 0.50 | 0.50 | 0.50 |
| Beam loading parameter [%]   | $\delta$ | 17.4 | 17.4 | 12.3 | 9.5 |
| RF power/section [MW]        | $P_s$  | 116 | 116 | 231 | 386 |
| RF pulse length [µs]         | $\Delta_K$ | 0.121 | 0.121 | 0.121 | 0.121 |
| Number of drive beams [-]    | $N_D$  | 10 | 20 | 40 | 50 |
| Number of modulators/klystrons [-] | $N_K$ | 200 | 200 | 400 | 400 |
| Klystron power [MW]          | $P_K$  | 50 | 50 | 50 | 90 |
| AC-to-RF efficiency [%]      | $\eta_{RF^{AC}}$ | 40 | 40 | 40* | 40 |
| RF-to-beam efficiency [%]    | $\eta_{BEAM^{RF}}$ | 35.45 | 35.45 | 26.64* | 19.38 |
| AC-to-beam efficiency [%]    | $\eta_{BEAM^{AC}}$ | 14.18 | 14.18 | 10.65* | 7.75 |
| AC power for RF [MW]         | $P_{AC}$ | 67.8 | 101.7 | 206* | 310 |

* Note: In the above table, the values given for efficiencies and global AC power consumption are consistent with [Delahaye, 1998]. They are different from the more conservative values considered elsewhere in this report, while being pessimistic with respect to the target values cited in Table 4.3.
References


OVERALL DESCRIPTION, PRINCIPLES AND SUMMARY

In this chapter we discuss in more detail the latest developments of the CLIC two-beam acceleration scheme, which corresponds to an evolution/simplification of the multi-drive-beam scheme [Corsini, 1998] as described in Section 2.3.

The energy for RF production is initially stored in a long-pulse electron beam which is efficiently accelerated to about 1.25 GeV by a fully-loaded, conventional, low-frequency (~1 GHz) linac. The beam pulse length is twice the length of the high-gradient linac, and is compressed using combiner rings to create a sequence of higher peak power drive beams with gaps in between. These drive beams are distributed from the end of the linac in the opposite direction to the main beam down a common transport line where each drive beam powers a ~700 m long section of the main linac. After a turn-around each high-current, relativistic drive beam is decelerated in low-impedance power extraction and transfer structures (PETS), and the resulting power is used to accelerate the low-current, high-energy beam in the main linac.

The method discussed here seems relatively inexpensive, is very flexible, and can be used to accelerate beams for linear colliders over the entire frequency and energy range.

4.1 Introduction

The CLIC study focuses on high-gradient, high-frequency (30 GHz) acceleration for multi-TeV linear colliders. There are no conventional high peak power RF sources at 30 GHz. This leads naturally to the exploration of the two-beam acceleration technique [Sessler, 1982], but many features of conventional RF systems can be used in two-beam accelerators.

In conventional methods of RF power production, the klystron is the most common power source. The SLAC klystrons operate at 2.856 GHz and produce about 65 MW with 3.5 μs pulses. The NLC klystrons operate at 11.424 GHz and produce about 75 MW with about 1.5 μs pulses. In both cases, RF pulse compression is used to achieve the higher power necessary for high gradients. It is no surprise that more energy compression is needed; the first step in the energy compression process is the klystron modulator, which gives an energy compression of about a factor of 1000–10 000.

Once the klystron has produced a high-power RF pulse, it is possible to compress it by delaying the front part of the pulse so that it is coincident with the trailing part. This can be done with a SLAC Energy Doubler (SLED) system [LEP Injector Power Saver (LIPS) at CERN], a SLED II system with delay lines, or a binary compression system.

Another method of compression (developed at KEK), the Delay Line Distribution System, uses a different approach [Mizuno, 1994a; Mizuno, 1994b]. After 3-dB combination, the power of several klystrons can be switched, by using the relative phases of the klystrons, to different waveguides for distribution to the accelerator. If the power is distributed in low-loss waveguides opposite to the direction of the electron beam, a single RF pulse can power several widely spaced sections of the linac. It is necessary to overlap several of these systems to completely fill the linac. Both of the methods discussed above can also be used with two-beam accelerators: in this case, however, the compression and distribution are done with electron beams that later generate RF locally in a decelerator structure just before the high-energy electron beam arrives.

4.2 CLIC parameters

Four sets of RF parameters for the CLIC design are shown in Table 4.1. To illustrate the drive beam issues consider only the 3 TeV set. The total stored energy in each high-energy beam is 145 kJ per pulse. With a ~25% RF-to-beam transfer overall efficiency, the necessary RF energy per pulse is 590 kJ. With about 63% transfer efficiency from the drive beam to RF, we need 930 kJ in the drive beam for each linac, in each pulse.
### Table 4.1
RF parameters for CLIC designs

<table>
<thead>
<tr>
<th>Beam param. at L.P.</th>
<th>0.5 TeV</th>
<th>1 TeV</th>
<th>3 TeV</th>
<th>5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep. rate (Hz)</td>
<td>200</td>
<td>150</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>$10^9$ e$^\pm$/bunch</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Bunches / pulse</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Bunch spacing (cm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Accel. gradient (MV/m)</td>
<td>100</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Two-linac length (km)</td>
<td>6.6</td>
<td>13.5</td>
<td>27.5</td>
<td>35</td>
</tr>
<tr>
<td>Accelerating sections</td>
<td>10 802</td>
<td>21 604</td>
<td>43 760</td>
<td>54 802</td>
</tr>
<tr>
<td>Power / section (MW)</td>
<td>116</td>
<td>116</td>
<td>231</td>
<td>386</td>
</tr>
<tr>
<td>AC-to-beam efficiency (%)</td>
<td>14.2</td>
<td>14.2</td>
<td>8.5</td>
<td>7.8</td>
</tr>
<tr>
<td>AC power (MW)</td>
<td>68</td>
<td>102</td>
<td>250</td>
<td>310</td>
</tr>
</tbody>
</table>

### 4.3 Two-beam configurations

#### 4.3.1 A single drive beam

The simplest drive beam configuration for a 3 TeV two-beam accelerator consists of a single low-energy, high-current drive beam travelling parallel to, and transferring energy to, a high-energy, low-current beam [Carron, 1998]. The length of the drive beam is equal to the length of the desired RF pulse. To have the required stored energy, a 10 GeV beam with a pulse length of 120 ns would need a current of 770 A. If the beam were comprised of 1800 bunches spaced by 2 cm, each would have 50 nC of charge. It is quite difficult to create and accelerate such a beam because all of the energy is stored in a 120 ns time interval.

#### 4.3.2 The multibeam approach

The alternative approach is to use multiple beams rather than one beam to store the energy [Delahaye, 1995; Corsini, 1997; Corsini, 1998]. Twenty beams are proposed for the 3 TeV design. In this case, if each beam has an energy of about 1.25 GeV and a bunch spacing of 2 cm, the bunch charge is quite reasonable at 18 nC. We do not want of course, for reasons of cost, to create 20 separate drive beam accelerators, but rather we want to create 20 drive beam bunch trains using the same accelerator.

The drive beam generation complex is located at the centre of the linear collider near the final-focus system. The drive beams are distributed to the main linac in a direction opposite to the direction of the main beam. In order for the drive beams to arrive at the appropriate time to accelerate a high-energy beam travelling in the opposite direction, they are spaced in time by twice the length of the linac section that they will power. We produce one drive beam with an energy of 1.25 GeV that powers a length $L_{sec}$ of the main linac, and produce the next drive beam at a time $2L_{sec}/c$ later with the same hardware. The length of the train of 120 ns pulses is twice the length of the high-gradient linac. Creating and accelerating very high current closely spaced bunches is, however, very difficult and therefore we create and accelerate much lower current and more widely spaced bunches, and then use pulse compression as is done with conventional RF systems.
4.4 Electron beam combination

Typically, RF pulse compression requires the capability to combine or split power. This can be accomplished with a 3-dB hybrid provided that the phases of the inputs are correct. The case of a high power electron beam is analogous. The technique is generally referred to as stacking. Typically, one injects into a storage ring so that the injected bunch has either a different amplitude than an existing bunch (stacking in transverse phase space), or a different phase or energy (stacking in longitudinal phase space). After many damping times the bunch emittances are recovered through radiation damping. For storage times much less than a damping time, the emittance is increased by the stacking process. In our case we cannot dilute the emittance, and radiation damping is not a possibility; however, if the bunches are to be used to generate RF, there is another possibility that is very useful [Delahaye, 1993]. We use an RF deflector to inject into a ring, we stack four trains of bunches and then immediately extract them. The process is shown in Fig. 4.1. The pulse consists of trains of bunches separated by a space approximately equal to the pulse width. We inject into a ring with a circumference equal to the periodicity of the bunch train and then, as one train of bunches comes around, it falls on top of the next train. By increasing the circumference by \(\lambda/4\), where \(\lambda\) is the bunch spacing, it is possible to intertwine four bunch trains at the quarter points of the bunch cycle to achieve a factor of four pulse compression.

![Initial pulse train](image1)

**Fig. 4.1 Times-four combination in a ring**

The injector region is shown in more detail in Fig. 4.2. In this case two RF deflectors are used to create an RF bump in the combiner ring. The sequence of trajectories in the bump allows the bunches to miss the septum during the stacking process.

After injection, the high-current bunch train is extracted on the opposite side of the ring, and the process begins again with the next set of four bunches. This process is a kind of frequency multiplication that is not possible with RF compression.
4.5 The drive beam accelerator

The process of bunch train combination described above allows one the possibility of creating the high bunch train current and the gap in time between the different drive beam pulses with a combination system consisting of rings or delay lines. Thus, one can create a continuous train of bunches, then use the bunch combination described above to create higher current, higher power pulses with larger gaps between them.

This long-pulse beam can be accelerated using a conventional travelling-wave linac at low frequency very efficiently. The parameters for such an accelerator are shown in Table 4.2. All of the energy to power one linac is stored in a continuous electron beam with a pulse time of twice the linac length, 91 μs in the 3 TeV case.

The accelerator operates at a relatively low frequency that is related to the amount of bunch combination and frequency multiplication given by the combiner ring complex, in this case a factor of 32. The bunches each have 17.6 nC of charge and are nominally on every other cycle of the RF. Each structure is fed by two 50 MW klystrons that can be phased to provide RF amplitude tuning. Because the filling time of the structure is short (265 ns), the accelerator operates in the steady state for essentially the entire pulse.

The drive beam accelerator is run ‘fully loaded’. It is designed to run at a particular current and gradient so that essentially all of the power is transferred to the accelerated beam and almost none flows out to the load. This condition is a broad optimum and the efficiency changes little when the accelerator is slightly under- or overloaded. It is straightforward to keep the beam stable in this accelerator by detuning and damping the higher-order modes of the accelerator structure. To describe the manipulation of this beam to create the drive beam, it is useful to look at the entire system.
Table 4.2
Parameters for the drive beam accelerator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>937 MHz</td>
</tr>
<tr>
<td>Acceleration gradient</td>
<td>3.85 MV/m</td>
</tr>
<tr>
<td>Structure length</td>
<td>3.1 m</td>
</tr>
<tr>
<td>Number of structures</td>
<td>104</td>
</tr>
<tr>
<td>Power per structure</td>
<td>100 MW</td>
</tr>
<tr>
<td>Klystron power</td>
<td>50 MW</td>
</tr>
<tr>
<td>Number of klystrons</td>
<td>208</td>
</tr>
<tr>
<td>Beam current</td>
<td>8.2 A</td>
</tr>
<tr>
<td>Final energy</td>
<td>1.23 GeV</td>
</tr>
<tr>
<td>Pulse length</td>
<td>91 µs</td>
</tr>
<tr>
<td>RF-to-beam efficiency</td>
<td>93%</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>925 kJ</td>
</tr>
<tr>
<td>Copper losses/metre</td>
<td>6.5 kW</td>
</tr>
</tbody>
</table>

4.6 Overview of the RF power system

An overview of one of the two RF power systems required for a 3 TeV collider is shown in Fig. 4.3. It consists of an injector, the long pulse, normal-conducting, fully loaded linac described above, a times-two delay/combiner, two combiner rings in series for pulse compression, a distribution beam line with deflector magnets, and finally a set of 20 decelerator linacs. The first element to discuss is the times-two combiner. As noted earlier, it is very useful to have a continuous train of bunches so the drive beam accelerator can run in the steady state, fully loaded. On the other hand, we need to have a gap to allow for a kicker rise-time during the extraction process in the first combiner ring. But, with a gap in the beam, there would be small transients in the beam energy that would have to be corrected. The gap could be created using a pulsed magnet, but that would result in some lost efficiency, since we would have to throw away all the charge in the gap.

The times-two combiner gives us an alternative. Imagine that we place bunches on every other RF cycle in the drive beam accelerator, and that we switch from even to odd buckets at the desired RF pulse width. In this case an RF deflector at one-half the drive beam frequency can be used to separate the bunch trains on the even cycles from those on the odd cycles as shown in Fig. 4.4.

This allows us to delay one of the trains and to combine it with a following train using an RF combiner so that a times-two compression is obtained with a bunch now occupying every cycle of the drive beam frequency. The net effect is to produce a train of pulses with gaps appropriate for the next step of the combination process.

To create the odd/even coding we can use two conventional thermionic guns as shown in Fig. 4.5. One gun produces pulses of bunches on the even cycles while the other gun produces pulses of bunches on the odd cycles. The two trains are combined with an RF combiner, with the pulses from one side filling in the gaps from the other side to create a continuous bunch train with a constant current. A short overlap of the odd and even trains is allowed to maintain a constant current.
Fig. 4.3 Overview of the CLIC RF power source

Fig. 4.4 The first times-two combiner
The drive beam accelerator described earlier accelerates the long drive beam pulse. After about 50 MeV of acceleration, the beam is collimated to clean up transverse and longitudinal phase space. The bunches in the train are compressed once at low energy (~ 100 MeV) to a bunch length of about 2 mm. After acceleration, the train is ready to enter the times-two combiner described earlier.

The combiner rings reduce the bunch spacing and at the same time increase the intensity, each by a factor of four, but they must be isochronous and have circumference tuning. This tuning can be accomplished with two small magnetic chicanes integrated into the ring lattice as shown above in Fig. 4.3.

After compression, the sequence of drive beam trains is transported down a common transport line. The first train is delivered to the first 700 m long section with an isochronous turnaround which has path length tuning to provide relative control of the phase in the 20 sections of the linac. The drive beam bunches are compressed to less than 500 μm just before entering the drive beam decelerator.

The decelerator extracts RF power for main beam acceleration for the 700 m long section. At the end of the decelerator, the beam is dumped while the next drive beam is deflected into a turnaround to continue the acceleration process. This process continues until the main beam reaches the end at full energy, and is repeated each cycle of the collider.

4.7 Drive beam decelerator

The drive beam decelerator is the most critical part of the two-beam concept. The configuration of a deceleration/acceleration module is shown in Fig. 4.6.
Each decelerator structure feeds two accelerator structures with RF power. As the beam is being decelerated, it develops an energy spread due to the finite bunch length and due to the transient effects as the structures are filled. Since the beam is decelerated to about 10–15% of its initial energy, the total energy spread at the end of the process is around 90%. To focus such a beam, it is necessary to scale the lattice carefully to keep the lowest energy particles from being overfocused. If this is done, the high-energy part of the beam is stable. In the decelerator we must use an RF structure design that has the correct impedance and group velocity to provide the necessary deceleration and power output. This results in relatively low shunt impedance and a rather large group velocity. There are several possible choices of structure; but the transverse stability of the decelerating beam also requires that the structure be damped and favours lower impedance structures. A good choice is a four-channel structure which has relatively low transverse wakefields [Millich, 1998]. A similar design, shown in Fig. 4.7, is currently installed in CTF2 and has supplied up to 30 MW to a 30 GHz accelerating structure.

Transverse stability is especially critical because of the large stored energy in a drive beam. Losses in the decelerator could result in damage to decelerator structures. To avoid losses and provide stable running, the transverse wakefields must be damped with a $Q$ value of about 50.

Extensive simulations have been done to check the stability in the decelerator [Riche, 1998]. Provided the magnets are aligned with beam-based alignment, and the beam is steered with the average offset of the entire train, it seems possible to decelerate the drive beam to 85–90% of its initial energy. Since the beam is most sensitive at the lowest energy, it can be made more stable, if necessary, by sacrificing some efficiency.

![Fig. 4.7 A four-channel decelerator structure](image)

### 4.8 Test facilities

In order to have confidence in any power source, the method must be tested at some reasonable scale that will address key issues, for example, the use of bunch combiner rings, fully loaded acceleration, and substantial drive beam deceleration. The layout of a modest test facility that would have the key features of the design just described is shown in Fig. 4.8. The facility uses existing klystrons and modulators at 3 GHz to accelerate a drive beam. The system then has a times-ten pulse compression system, using one times-two combiner delay and one times-five ring. The drive beam can then be decelerated to low energy to provide up to 1 GeV of energy to a test beam accelerated at 30 GHz with the nominal CLIC gradient and pulse length.
4.9 Summary

The system described here acts like a transformer of the acceleration gradient and frequency in the drive beam accelerator to the main beam accelerator. The transformer ratio is about 40 for the gradient and 32 for the frequency.

In order to increase the gradient in the main linac, first we increase the gradient in the drive beam accelerator, and then increase the current so that it is once again fully loaded. This higher energy beam can be transported and compressed with scaled magnetic settings. In the drive beam decelerator, the higher energy beam provides more power due to the higher current so that the main linac gradient just increases proportionally to that in the drive beam accelerator. The amount of deceleration of the drive beam also scales so that the higher energy drive beam still powers the same length of linac.

One of the most important features of the RF system is the efficiency. A list of efficiencies for the design discussed here is shown in Table 4.3. It is too early to know the precise efficiencies of all of the subsystems; however, this drive beam system should have an efficiency comparable to the RF systems contemplated for other designs.

<table>
<thead>
<tr>
<th>Item</th>
<th>Assumed</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator</td>
<td>90</td>
<td>92</td>
</tr>
<tr>
<td>Klystron</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>Drive beam accel.</td>
<td>93</td>
<td>94</td>
</tr>
<tr>
<td>Decelerator</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Power extraction</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Power transfer</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Overall</td>
<td>35</td>
<td>46</td>
</tr>
</tbody>
</table>
To conclude this chapter it is important to note that this type of two-beam design is applicable to linear colliders using any frequency of acceleration. In particular, the drive beam complex is rather insensitive to this choice and depends more on the necessary energy stored per pulse and the repetition rate. It is even possible to use essentially the same drive beam for different but harmonically related frequencies.
References


5 THE DRIVE BEAM ACCELERATOR

In this chapter we discuss in some detail the drive beam accelerator described before. It is useful to first give a more detailed overview and discuss parameters and beam structure. Then we give a detailed discussion of the injector system. The RF power system for the drive beam accelerator is discussed next. Finally, we conclude this chapter with a detailed discussion of the drive beam linac and associated beam dynamics issues.

5.1 Overview of the drive beam accelerator

As discussed in the previous chapter, the purpose of the drive beam accelerator is to accelerate a long-pulse electron beam, which stores all the energy necessary for RF production for one entire pulse. The total length of the pulse is simply given by twice the geometric length of a single main beam linac in time units. A schematic layout of the drive beam accelerator is shown in Fig. 5.1.

![Drive Beam Injector to Drive Beam Linac Diagram]

**DRIVE BEAM ACCELERATOR**

104 Accelerating Structures (937 MHz - 3.85 MV/m - 3.1 m)
208 Modulators/Klystrons 50 MW - 100 μs

Fig. 5.1 Overview of the drive beam accelerator

The complex begins with two front-ends, composed of thermionic guns and RF bunchers, which accomplish the phase coding of each pulse.

One front-end produces pulses on the odd cycles of 937 MHz while the other produces a sequence of pulses on the even cycles. After the beam is accelerated to a few megaelectronvolts, these pulses are combined, using an RF combiner, with the pulses of one gun filling in the gaps left by the other. The net effect is an essentially constant beam current, with a phase transition from even to odd every 140 ns. The nominal bunch spacing is every other cycle, except for a small overlap region for transition from even to odd. After the combination the beam is accelerated up to 50 MeV in a solenoid-focused injector linac, whose accelerating structures are identical to the ones in the quadrupole-focused drive beam linac that follows it. This is the logical end of the drive beam injector. After the injector, the beam is collimated to clean up the transverse and longitudinal phase space and then accelerated to 100 MeV, where the bunches are compressed from about 4 mm to about 2 mm for the remainder of the acceleration. The constant current beam is then accelerated up to 1.23 GeV. A list of parameters for the drive beam accelerator is given in Table 5.1.
Table 5.1
Parameters for the drive beam accelerator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>937 MHz</td>
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</tr>
<tr>
<td>Power per structure</td>
<td>100 MW</td>
</tr>
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<td>Klystron power</td>
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</tr>
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</tr>
<tr>
<td>Beam current</td>
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</tr>
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</tr>
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<td>Pulse length</td>
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</tr>
<tr>
<td>RF-to-beam efficiency</td>
<td>93%</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>925 kJ</td>
</tr>
<tr>
<td>Copper losses/metre</td>
<td>6.5 kW</td>
</tr>
</tbody>
</table>

Each 3.1 m structure is powered by two 50 MW klystrons combined in a 3 dB hybrid. This allows tuning of the RF phase and amplitude with low-level phase adjustments of the klystron. The structures are operated in the fully loaded condition.

In the injector sections they are slightly overloaded while in the drive beam linac they can be slightly underloaded with little effect on the efficiency. Thus, the 10% current collimation after the injector has little effect on the overall efficiency.

5.1.1 Drive beam time structure and beam loading

The process of bunch train combination described in Chapter 4 allows one the possibility to create several short high-current pulses starting from a long, lower current pulse, by using combiner rings. In order to do that, we need to have gaps in the long pulse to allow for a kicker rise-time during the extraction process in the ring. The typical rise time of the extraction kicker is of the order of 25 ns, setting a minimal distance of 7.5 m between trains.

On the other hand, as discussed earlier, it is very useful to have a continuous train of bunches in the drive beam accelerator such that it can run in the steady state, fully loaded. In the drive beam accelerator the gaps would cause a significant variation in the beam energy (a few per cent in our case) due to beam loading, as indicated in the upper case of Fig. 5.2. The bunch-to-bunch energy variation should be kept as constant as possible to ease the task of achieving a constant centroid energy for all bunches. This is necessary since the bunch compression after the linac would otherwise shift the bunches in longitudinal position as will be explained later in this chapter.

The problem of the gaps between trains can be solved by filling only every second bucket in the drive beam (see Fig. 5.2). The cavity properties have to be adjusted to fully load the accelerator again. Now the bunches of the first train are filling odd buckets while the ones of the second are filling even buckets and so on. An RF kicker at the linac exit running at half the acceleration frequency is thus able to deflect ‘odd’ and ‘even’ trains into different directions. As explained in Chapter 4, the ‘odd’ trains are delayed with respect to the ‘even’ trains. The two trains reach the point where the two lines meet again separated by one RF period only. The ‘odd’ and ‘even’ trains can then be combined using a second RF kicker, forming one train with twice as many bunches and half the initial bunch separation.
Fig. 5.2 Two different time structures for the drive beam in the accelerator, together with the corresponding beam loading. In the upper case every bucket is filled and the gaps necessary for the kicker in the ring are introduced before the accelerator. In the lower case only every second bucket is filled — the odd trains occupying odd buckets the even trains even buckets — such that a RF kicker at the end of the linac can separate them, thus creating the necessary gap. Except for the additional empty bucket at the intersections between trains the beam loading is constant.

Repeating the operation, we can obtain a sequence of trains with twice the initial current, separated by gaps equal to the train duration.

When the trains are folded in the rings they must consist of a number of bunches with a constant charge — the flat top — preceded by a number of bunches with charges increasing from about 70% of the charge on the flat top to the full charge. These are used to provide the RF power to pre-fill the main linac structure. The charge ramp creates the steady-state beam loaded condition in the main linac (see Section 8.2).

Since the trains contain less charge in the ramp than on the flat top, the beam loading in the drive beam linac is not constant (see Fig. 5.3). This can, however, be achieved easily by adding bunches at the end of the leading train so that the two trains overlap. The charges in these trailing bunches can be adjusted to obtain the required slope of the bunch charge in the ramp.

Since it may be difficult in practice to achieve the sudden changes in charge at the start of the ramp and the end of the flat top, a trapezoidal shape as in Fig. 5.4 is assumed for the drive beam linac simulations. Depending on the performance of the gun the real distribution will be in between this case and the previous one. As explained before, the bunches can be conveniently created with two guns, one producing the odd and the other the even trains.
Fig. 5.3 The time structure and beam loading of the drive beam including the ramp. In the upper case, the beam loading is significantly higher than without the ramp owing to the missing charge. In the lower case the charge missing in the ramp of the second train was appended to the first. The bunch centroid energies can be thus made exactly equal except for those in the tails (that are not used to accelerate the main beam), which may be slightly off.

Fig. 5.4 The time structure assuming that only smooth changes of the bunch charge are possible. In this case the overhead in accelerated charge is larger than in the previous case. One would thus like to choose the ramps as close as possible to that case.

5.2 The drive beam injector

5.2.1 Overview of the system
The drive beam injector is composed of three major sub-systems:
1) Two front-ends providing a bunched beam at 4 MeV.
2) A RF combiner.
3) An injector linac accelerating the beam up to 50 MeV.
Figure 5.5 gives a schematic layout.
The front-end

Each front-end before the RF combiner consists of one thermionic gun, two sub-harmonic bunchers SHB1 and SHB2 working at 937/2 MHz, one buncher B1 (standing wave) working at 937 MHz, and one buncher B2 composed of travelling-waves sections and also working at 937 MHz.

Each gun is powered from a power supply in order to get beam at 200 keV. Two linear ramps, before and after the flat top, are being considered for the gun pulse. The system (function generator and linear power amplifier) should be able to do amplitude variations of the mid point between 60 and 100% of the flat-top current. With a proper charge distribution in the tail (see Fig. 5.6), one can assure a constant current when both trains are recombined at 4 MeV. A triode type thermionic gun with a modulation of the grid would reach such a goal. Under these conditions, the beam current will be constant in the fully loaded linac during the pulse. The pulse shape with the bunch trains generated by each gun and the duty cycle are given in Fig. 5.6.
Fig. 5.6 Current pulses from each gun

After a drift of 50 cm, the first sub-harmonic buncher SHB1 works at 468.5 MHz (half the fundamental frequency). A modulation of ±10 kV is applied to SHB1. Two metres downstream, the second sub-harmonic buncher SHB2 also works at 468.5 MHz but with a modulation of ±50 kV. After another drift of 1.25 m, the buncher B1 works at 937 MHz and the applied voltage is ±100 kV. The buncher B2 has 12 cells (4 × 3 cells) with a phase advance of 2π/3 and operates at an accelerating gradient of 3.5 MV/m, continuing the bunching process while accelerating the beam up to 4 MeV.

The magnetic field along the front-end keeps the beam sizes to a reasonable value of 10 mm (90% of the particles). The length of each front-end is roughly 5 m. This value is convenient in order to minimize the angle between the two front-ends upstream of the RF combiner.

The RF combiner

The RF combiner adds the two trains coming out from each front-end. It works at 468.5 MHz. The bunch spacing is 2 RF periods of 937 MHz for both front-end 1 and front-end 2, but because the bunchers are run π out of phase, the bunches from the front-end 1 are in the odd-numbered buckets while those from front-end 2 are in the even-numbered buckets. During the ramp, there is an overlap so the bunch charge in the odd buckets is decreasing while the bunch charge in the even buckets is increasing. Therefore, the charge can be kept constant all the time over 92 μs. Figure 5.7 shows the RF combination principle. The energy is around 4 MeV and the beam current is around 9.1 A taking into account the beam collimation at 50 MeV.

The deflecting angle is about 300 mrad. Preliminary scaling from an existing transverse RF structure shows that such an angle could be reached with 30 MW power in one structure composed of five cells and being 1 m long. However, the beam loading effects induce an energy spread of several per cent along the train. Further studies are under way.
**The injector linac**

With a short filling time of the sections, the linac works in the steady-state mode. It accelerates the beam up to 50 MeV with 937 MHz travelling wave sections. A long sequence of solenoids is installed along the linac for focusing. The loaded gradient is 3.8 MV/m. The linac is operated in the fully-loaded condition and uses damped and detuned structures for acceleration. Figure 5.8 shows the combined pulses at the entrance to the injector linac. A constant current is obtained over the entire 91 μs pulse. The accelerating structures are 3.1 m long with a loaded accelerating field of 3.8 MV/m. They are similar to those of the accelerating linac. With four structures, an energy gain of 45.6 MeV is obtained. Adding the beam energy from each front-end, the total energy at the injector linac exit is around 50 MeV. At this stage a beam collimation (±3σₚ) is implemented in order to achieve the required beam characteristics. Losses up to 10% are assumed before injecting the 50 MeV beam into the drive beam accelerator.

---

**Fig. 5.7** Principle of the RF combiner

**Fig. 5.8** Combined pulses at the injector linac entrance
5.2.2 Beam characteristics required at the injector exit

**Number of bunches, pulse length, charge, and current**

Two main conditions have to be fulfilled:

1) The total number of bunches should be a multiple of 32.
2) The useful pulse length in the Power Extraction and Transfer Structure (PETS) is achieved with:
   
   \[32 \times 10 \text{ (successive group of bunches)} = 320 \text{ bunches for the pre-fill;}
   
   1504 \text{ bunches (constant charge) for the power generation.}
   
   The first condition is imposed by the beam recombination. The correct bunch spacing (frequency multiplication) and correct beam current (pulse compression) needed in the drive beam decelerator are obtained in the compression system (see Chapter 6) at an energy of 1.23 GeV. A factor 2 is provided by the delay line and two combiner rings provide 2 times a factor 4.

   The second condition is imposed in order to minimize the multibunch energy spread contribution in the CLIC Accelerating Structures (CAS) (see Section 8.2). The bunch charge has to be ramped in order to compensate for beam loading effects in the main linac. If the PETS pre-fill starts with a charge of 67% of the maximum charge (flat-top), the resulting multibunch energy spread is 0.03% (r.m.s.). Figure 5.9 shows the ideal case as required by PETS performance.

![Graph](image)

*Fig. 5.9* Optimized bunch group intensities and accelerating field generated in the PETS versus time

In order to fulfill the two conditions, a particular bunch distribution at the exit of the front-end (4 MeV) before recombination is shown on Fig. 5.10. The two linear ramps for the rise time are very close to the optimized rise time shown on Fig. 5.9. The first 10 bunches are used for the first pre-fill of PETS. The slope is not critical and will be as fast as possible according to the bandwidth of the grid pulsing system. The next 10 bunches are used for the pre-fill of CAS. The slope is optimized according to the second condition mentioned above. A function generator and a linear power amplifier should be able to produce such a pulse shape where the upper part (between 0.7 and 1 on Fig. 5.6) is close to a parabola curve.
In order to get the constant beam current of 8.2 A, the 20 bunches in the tail (gun 1) are added to the 20 bunches in the head (gun 2) by the RF combiner (Fig. 5.7).

Table 5.2 gives the parameters required for the CLIC scheme working at 3 TeV. The time of the first pre-fill is rather arbitrary while the optimized second pre-fill time is obtained from simulations. The number of bunches in the tail ($n_4$) is created to maintain a constant current.

Table 5.3 shows the derived charge and current to get the necessary RF power at 3 TeV. The 55,680 bunches are accelerated from 4 MeV up to 50 MeV in the injector linac, then from 50 MeV up to 1.23 GeV in the accelerating drive linac.

**Table 5.2**
Parameters derived from the geometry for 3 TeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Decel. linac entr.</th>
<th>Injector exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>First + second pre-fill of PETS</td>
<td>ns</td>
<td>21.5 + 21.5</td>
<td></td>
</tr>
<tr>
<td>Flat-top</td>
<td>ns</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>No. bunches / pre-fill (1st ramp)</td>
<td>$n_1$</td>
<td>320</td>
<td>10</td>
</tr>
<tr>
<td>No. bunches / pre-fill (2nd ramp)</td>
<td>$n_2$</td>
<td>320</td>
<td>10</td>
</tr>
<tr>
<td>No. bunches / flat top</td>
<td>$n_3$</td>
<td>1504</td>
<td>47</td>
</tr>
<tr>
<td>Total bunches (useful for CLIC)</td>
<td>$n_1 + n_2 + n_3$</td>
<td>2144</td>
<td>67</td>
</tr>
<tr>
<td>No. bunches / tail (symmetry reason)</td>
<td>$n_4$</td>
<td>640</td>
<td>20</td>
</tr>
<tr>
<td>No. total bunches / pulse</td>
<td>$n_5$</td>
<td>2784</td>
<td>87</td>
</tr>
<tr>
<td>Bunch spacing (2 RF periods)</td>
<td>ns</td>
<td>0.0666</td>
<td>2.13</td>
</tr>
<tr>
<td>Useful pulse length</td>
<td>ns</td>
<td>142.9</td>
<td>91.477</td>
</tr>
<tr>
<td>Number of drive trains</td>
<td>$n_6$</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Total bunches (in accel. linac)</td>
<td>$n_5 \times n_6$</td>
<td>55,680</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.3
Parameters for RF power source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Injector exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge per bunch / flat top</td>
<td>17.6 nC</td>
</tr>
<tr>
<td>Charge / ramp (with overlap)</td>
<td>11.2 μC</td>
</tr>
<tr>
<td>Charge / flat top</td>
<td>26.3 μC</td>
</tr>
<tr>
<td>Charge / drive beam</td>
<td>37.5 μC</td>
</tr>
<tr>
<td>Total charge for 20 drive beams</td>
<td>754 μC</td>
</tr>
<tr>
<td>Average current over 92 μs</td>
<td>8.2 A</td>
</tr>
<tr>
<td>Total energy</td>
<td>46 kJ</td>
</tr>
</tbody>
</table>

**Constant current during the pulse**

As mentioned before, two different slopes are required during the rise time. The control program which drives the grid of the guns will be designed in such a way that the sum of the head ramp with the tail ramp provides a constant current when the ramps overlap. A linear variation of the charge during the ramp can be expressed by the following sum:

\[ Q = \sum_{n=1}^{n=N} q_n \]

where \( q_n \) is the charge in one slice corresponding to the bunch number \( n \) in the linear ramp. Since \( Q_0 \) is the charge per bunch during the flat-top and \( \alpha \) the mid-point (0.7 < \( \alpha < 1 \)), the first sum (10 bunches) is done with \( q_1 = 0.05 \times Q_0 \) and \( q_{10} = \alpha \times Q_0 \). The second sum (10 bunches) is done with \( q_{10} \) as above and \( q_{20} = 0.95 \times Q_0 \). The charge in the first linear ramp (pre-prefill) is 1.9 μC while the charge in the second linear ramp (pre-fill) is 4.7 μC. The first ramp has 3.7 μC in the tail while the second ramp has 0.88 μC. The resulting charge and current are reported in Table 5.3. Figure 5.11 shows the combination of the head and tail ramps. The tail shape for the odd buckets (front-end 1) is such that the sum with the even buckets (front-end 2) provides a constant current.

![Fig. 5.11 Sum of two pulses](image)

**Energy spread, bunch length and emittance**

The energy spread at the exit of the injector linac is partly correlated due to the beam loading. The uncorrelated energy spread is assumed to be 0.75% and the total energy spread is assumed to be less than 1%. These values are expected after a beam collimation of about ±3σE before injection into the accelerating linac. A r.m.s. value of 4 mm for the single bunch length seems reasonable at the injector exit.

In the decelerating structures, a large beam size or emittance could cause losses. It is therefore crucial to obtain a beam at 1.23 GeV with as small an emittance as possible. Assuming an emittance
blow-up of 50% between the injector and the decelerator, an upper limit of 100 mm mrad is required at 50 MeV. Table 5.4 summarizes the beam characteristics required at the injector exit.

**Table 5.4**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Injector exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Pulse length (total train)</td>
<td>91.477 μs</td>
</tr>
<tr>
<td>Beam current per pulse</td>
<td>8.2 A</td>
</tr>
<tr>
<td>Charge per pulse</td>
<td>750 μC</td>
</tr>
<tr>
<td>Number of bunches per pulse</td>
<td>55 680</td>
</tr>
<tr>
<td>Bunch length (FWHH)</td>
<td>32 ps</td>
</tr>
<tr>
<td>Bunch length (r.m.s.)</td>
<td>4 mm</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>≤ 100 mm.mrad</td>
</tr>
<tr>
<td>Energy spread</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>75 Hz</td>
</tr>
</tbody>
</table>

5.2.3 *Thermionic guns and power supplies*

**The gun**

The power calculated for the gun and for the grid is based on the total charge of 750 μC derived above. The bunching efficiency is estimated to be 66% (based on the LEP Injector Linac), the RF combiner efficiency (at 4 MeV) is estimated to be 100% while the collimation efficiency (at 50 MeV) is estimated to be 90%. Therefore the total charge, from both guns, is 1263 μC. Each gun should provide half of this charge, since they are π out of phase, in order to get a constant charge during the 92 μs pulse. At 200 kV, each gun provides an energy of 126 J. With a repetition rate of 75 Hz, the beam power from one gun is 9.45 kW. The average current delivered by each gun is 0.047 A. The duty cycle, with a 92 μs pulse, is 0.0069. It implies an average current of 6.9 A during the pulse or a peak beam current of 13.8 A. The gun is a triode type. With the cathode at ~200 kV, a pulsed grid allows this peak current.

**The grid**

The grid limits the electron current \(I_b\) by space charge effect according to:

\[
I_b = \frac{2.335 \times 10^{-6}}{d^2} V_g^{1.5} \times S \quad \text{MKSA units}
\]

where:
- \(d\) = distance grid–cathode,
- \(S\) = cathode surface,
- \(V_g\) = potential at the grid.
For the LEP Injector Linac (LIL) gun, $d = 1.5$ mm and $S = 10$ cm$^2$, the grid voltage is plotted versus the beam current in Fig. 5.12.

![Graph showing grid voltage versus beam current for the LIL gun](image)

**Fig. 5.12** Grid voltage versus beam current for the LIL gun

One could expect that the CLIC gun would have values close to the LIL ones. Then the grid voltage is estimated around 600 V. The duty cycle for the grid is derived from both duty cycles 0.0069 and 0.5. It gives 0.0035. If the grid current is between 1 and 10 A, the power dissipation on the grid will be between 2 and 20 W.

**The power supply**

Figure 5.13 shows a sketch of a possible thermionic gun with its associated power supply [I. Kamber, CERN, private communication].

A pass tube is fed from a power supply and provides the ~200 kV. The current-voltage characteristic curve is such that the high voltage (200 kV) drops to zero if the current exceeds a limit (15 A). The function generator drives the grid through optical fibres.

The linear power amplifier must have the bandwidth to reach the required grid modulation. While it seems possible to obtain a voltage ripple of one per mil or lower over 100 ns, it remains to be evaluated if the same value can be obtained for the current.

The beam emittance was measured out of the LIL gun [Rinolfi, 1992]. The measured geometrical emittance containing 85% of the beam is $120 \, \pi \, \text{mm} \cdot \text{mrad}$ for a beam current of 1 A. The normalized emittances, in both planes, is $70 \, \text{mm} \cdot \text{mrad}$.

It is obvious that such a gun was not developed for small emittances and one could expect that an optimized thermionic gun would provide a normalized emittance around 10 mm mrad for a beam current of 14 A. Nevertheless this remains to be evaluated.

35
5.2.4 Beam dynamics simulations

Beam dynamics with the PARMELA code

The PARMELA code is the version updated by Orsay [Mouton, 1993].

The initial beam conditions are the following. A given number of particles (between 100 and 500) are generated randomly in a four-dimensional transverse hyperspace with uniform phase and random energy spread at the gun exit. The normalized r.m.s. emittance is 10 mm · mrad at the gun exit. We assume that 100% of particles are within six times this emittance. At 200 keV (βγ = 0.96745) a total emittance of 62 mm · mrad is used for the simulations.

With a radius of 10 mm for the hole in the anode, the horizontal (and vertical) β value of the ellipse is 1.61 m/rad. The r.m.s. beam radius is σ = 7 mm. A straight ellipse (α = 0) is assumed for both planes at the gun exit. The longitudinal coordinate z = 0 is taken at the anode exit where the magnetic field is still zero. The total charge of 29.2 nC (1.8 × 10¹¹ e⁻) is distributed over two RF periods of 937 MHz.

The transverse focusing is provided by a longitudinal magnetic field satisfying the Brillouin-flow condition:

\[ B_z = \frac{1}{R} \sqrt{\frac{2 I(z)}{\pi \eta \epsilon_0 v_z(z)}} \]

where \( B_z(z) \) is the axial flux density, \( R \) is the desired equilibrium radius, \( I(z) \) is the beam current, \( v_z(z) \) is the axial beam velocity, \( \eta \) is the electron charge to mass ratio, and \( \epsilon_0 \) is the dielectric constant of free space.

Taking into account that both axial bunch velocity and bunch current are a function of \( z \), the resulting profile of the magnetic field is as shown in Fig. 5.14.
For preliminary simulations, the magnetic field is taken with a fast rise at the beginning, starting from zero and then being constant along the front-end (= 5 m). Figure 5.15 shows the energy gain from the gun exit (200 keV) up to 3 MeV. The three travelling-wave structures were set at 3.5 MV/m for the accelerating field.
Figure 5.16 shows the horizontal beam envelopes along the front-end. The continuous curve is the r.m.s. envelope and the dotted curves are the 90% and 100% beam envelopes. The entire beam remains inside the 40 mm aperture (radius) of the travelling-wave structures. The buncher's aperture (radius) is 53 mm.

Figure 5.17 shows the bunch length obtained at 3 MeV. The core of the bunch has an extension of 22 degrees while the total bunch has twice this extension (a few particles are located in the tail). The full energy spread is roughly ±10% which corresponds to a r.m.s. value of a few per cent. Simulations
have been done with the GPT code [De Loos, 1996]. Figure 5.18 shows the bunch length obtained at 3.7 MeV. The FWFM is 20 mm.

![Bunch length](image)

**Fig. 5.18** Bunch length at the front-end exit

Figure 5.19 shows the initial phase versus the current phase. It gives a figure of merit concerning the bunching efficiency. For this run with 500 particles and an initial phase of ±500°, one obtained ±300°, in the correct bucket. The bunching efficiency here is 60%.

![Bunching efficiency](image)

**Fig. 5.19** Bunching efficiency of the injector
Figure 5.20 Transverse phase space at the front-end exit

Figure 5.20 shows the horizontal transverse phase space at the exit of the front-end. Before the RF combiner, the geometrical emittance (r.m.s.) is 35 π mm mrad. With a $\beta\gamma = 7$, the normalized emittance is 245 π mm mrad. Obviously this value is higher than the required value. More simulations and optimizations are required.

**Summary**

The results presented above are preliminary. As already mentioned, the target values for the injector have not yet been achieved and more optimization is necessary. One of the issues is the simulation of the continuous charge over the two RF periods (937 MHz). In order to cancel the end-effects due to the space charge, the simulated bunch phase extension should be longer than ±360°. The generation of such a long bunch with very high charge is not easily done by the PARMELA code.

The input and resulting parameters are compared for the two codes PARMELA and GPT in Table 5.5. Although all parameters were not exactly the same (voltage modulation for the SHB, and magnetic field), both codes provide consistent results. Nevertheless the GPT code seems a little bit more optimistic.

<table>
<thead>
<tr>
<th>Beam characteristics at the front-end exit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Table 5.5</strong></td>
</tr>
<tr>
<td>Beam energy (MeV)</td>
</tr>
<tr>
<td>Beam charge / 2 RF periods (nC)</td>
</tr>
<tr>
<td>Bunch population / 2 RF periods ($10^{10}$)</td>
</tr>
<tr>
<td>Bunching efficiency (%)</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
</tr>
<tr>
<td>Phase extension (937 MHz) (degrees)</td>
</tr>
<tr>
<td>Energy spread (single bunch) (%)</td>
</tr>
<tr>
<td>Normalized emittances (mm mm mrad)</td>
</tr>
</tbody>
</table>
5.2.5 Beam performance

Comparison with existing injectors

The CLIC Drive Beam Injector characteristics are compared with two existing injectors, ATF at KEK and SLC at SLAC.

The comparison is made at the thermionic gun exit (200 keV) and at the injector linac exit (50 MeV). Beam characteristics have been either measured or estimated at the ATF [Naito, 1996] and at SLC [Yeremian, 1992].

Table 5.6 gives the beam characteristics at the gun exit for the ATF and SLC. They are compared with those required for CLIC. The design of the ATF thermionic gun is done for 240 keV while the SLC one is for 150 kV. Although the peak-to-peak charge variation in the train could be of the order of 1%, the integral of the current over the time should be much less (= 0.2%). A feedback system would solve this problem.

Table 5.7 gives the measured ATF and SLC beam characteristics at the exit of the injector linac when the beam is relativistic and the bunches are short.

<table>
<thead>
<tr>
<th>Beam characteristics at the thermionic gun exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (keV)</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>Peak current (A)</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
</tr>
<tr>
<td>Train length (ns)</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
</tr>
<tr>
<td>Bunch population ($10^{10}$)</td>
</tr>
<tr>
<td>Peak-to-peak charge variation in the train (%)</td>
</tr>
<tr>
<td>Normalized emittances (r.m.s.) (mrad)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam characteristics at the injector exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (MeV)</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>Number of bunches</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
</tr>
<tr>
<td>Bunch length (ps)</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
</tr>
<tr>
<td>Bunch population ($10^{10}$)</td>
</tr>
<tr>
<td>Energy spread (single bunch) (% [r.m.s.])</td>
</tr>
<tr>
<td>Energy spread (train) (% [r.m.s.])</td>
</tr>
<tr>
<td>Normalized emittances (r.m.s.) (mrad)</td>
</tr>
</tbody>
</table>


**Crucial issues for the injector system**

The following are crucial issues for the injector and need to be carefully addressed:
- Space charge effects
- Beam loading in the structures
- Phase shift from RF combiner
- Beam emittance
- High-frequency modulation
- Beam intensity variation from:
  i) bunch to bunch
  ii) pulse to pulse.

**What could be tested in a test facility**

The present test facility (CTF2) is based on a photo-injector. The next test facility (CTF3) will be based on a thermionic gun. The test facility will probably evolve in several phases starting with the use of the present components from the LIL at 3 GHz and later using the final components for CLIC at 937 MHz.

1) **Thermionic gun** Using the existing LIL thermionic gun, several tests can be done: a) Generation of the required charge (i.e. 30 nC over 2 RF periods). b) Increase of the pulse length from 50 ns to 100 µs. c) Development of a linear power amplifier for the grid modulation with the correct bandwidth. d) Development of a final thermionic gun with the CLIC characteristics.

2) **Bunching system** The LIL buncher (3 GHz) with the present klystrons can be tested with a higher charge and a longer pulse; however, it is not adapted to strong beam loading, and cannot be used in CTF3. Therefore new cavities have to be built at 1.5 GHz and 3 GHz for the sub-harmonic bunchers and bunchers respectively. In order to provide the required beam characteristics, the bunchers will have to have optimized shunt impedance and length. Also new klystrons working at 1.5 GHz are necessary. The bunching system at 937 MHz can be tested when new cavities are built and could be tested with RF sources of a few kilowatts before the final klystrons at 937 MHz become available.

3) **The RF combiner** A RF combiner working at 1.5 GHz could demonstrate the validity of the principle even if the bunch length and the beam loading effects will be different at 937 MHz. The next step is to build the real RF combiner at 937 MHz with the corresponding 30 MW source.

4) **The injector linac** One damped and detuned accelerating structure working at 3 GHz would provide valuable experience and would be a good starting point to scale the ones at 937 MHz. Although this new test facility is based on a thermionic gun source, studies are being carried out in parallel on the possible use of a photo-injector.

5.2.6 **A photo-injector option**

The possibility of using a RF photo-injector as the drive beam source is being investigated.

Figure 5.21 gives a sketch of a possible layout. A CW laser working at 468.5 MHz provides a continuous train. During 92 µs the necessary power is generated in order to create the charge of 750 µC on the photocathode. The laser beam is passing through a polarizer making a polarization profile identical to the one shown on Fig. 5.10. A first Pockels cell deflects the laser beam according to the level of polarization into a delay line. The delay is equal to half a wavelength (i.e. 1.066 ns). A second Pockels cell recombines the laser beams.

The resulting laser beam illuminates the photocathode of a RF gun powered by a klystron at 937 MHz. It generates an electron beam with a momentum of several mega-electronvolts at the exit of the photo-injector with the required sequence of pulses which can then be directly injected into the injector linac.
If such an option could be implemented in the future, it would represent several advantages. It replaces the two front-ends and the RF combiner by a single RF gun. The pulse shaping is done with classical optical devices and since the splitting (based on the polarization level) is made from a unique source (CW laser), the recombination after the second Pockels cell assures a constant current during the 92 μs pulse, provided of course that the laser source is also constant.

Since the beam is accelerated quickly to energies above the space charge regime, small emittances will be achieved. In an analogous way to the function generator which drives the pulsed grid, the pulse shape of the polarizer can be adjusted in order to optimize the RF power generation.

However, several issues remain to be addressed. The first one is the overall CW laser energy [Hutchins, 1998]. The second one is the laser stability. At the moment a 1% long-term stability seems possible for CW laser.

The remaining thermal and mechanical instabilities and acoustic vibrations could be treated with feedback systems and could possibly improve the stability by an order of magnitude. This remains to be evaluated.

The third issue concerns the photocathode. Irrespective of the quantum efficiency, the photocathode should provide a charge of 750 μC. The maximum charge produced from a photocathode up to now is well below 1 μC. The new required charge brings photocathode physics into a new regime not yet explored.

A first step is being developed by the TESLA Collaboration [Schreiber, 1998]. A comparison between CLIC requirements and TTFL (under construction) parameters is given in Table 5.8.
Table 5.8
RF gun comparison between TTFL and CLIC

<table>
<thead>
<tr>
<th></th>
<th>TTFL</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>1300</td>
<td>937</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>10</td>
<td>75</td>
</tr>
<tr>
<td>RF pulse length (µs)</td>
<td>800</td>
<td>92</td>
</tr>
<tr>
<td>Number bunches / pulse</td>
<td>800</td>
<td>42 880</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>1000</td>
<td>2.13</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>8</td>
<td>17.5</td>
</tr>
<tr>
<td>Total charge (µC)</td>
<td>6.4</td>
<td>750</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Norm. emittances (r.m.s.) (m rad)</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>

5.3 The drive beam power system

5.3.1 CLIC RF power sources

There are several types of RF power sources in the CLIC drive beam scheme and these are shown for reference in Table 5.9.

Table 5.9
CLIC RF power sources

<table>
<thead>
<tr>
<th>Power sources</th>
<th>Number of RF sources</th>
<th>Frequency (MHz)</th>
<th>Peak RF power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF deflector for delay + 1st ring</td>
<td>4</td>
<td>937</td>
<td>50</td>
</tr>
<tr>
<td>RF deflector for 2nd ring</td>
<td>2</td>
<td>3750</td>
<td>15</td>
</tr>
<tr>
<td>Sub-harmonic RF Buncher (SHB1)</td>
<td>2</td>
<td>468.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Sub-harmonic RF Buncher (SHB2)</td>
<td>2</td>
<td>468.5</td>
<td>1.2</td>
</tr>
<tr>
<td>RF buncher (B1)</td>
<td>2</td>
<td>937</td>
<td>3</td>
</tr>
<tr>
<td>RF buncher (B2)</td>
<td>2</td>
<td>937</td>
<td>10</td>
</tr>
<tr>
<td>RF combiner</td>
<td>1</td>
<td>468.5</td>
<td>30</td>
</tr>
<tr>
<td>Injector linac</td>
<td>8</td>
<td>937</td>
<td>$2 \times 50$</td>
</tr>
<tr>
<td>Drive beam klystron-modulator</td>
<td>200</td>
<td>937</td>
<td>$2 \times 50$</td>
</tr>
</tbody>
</table>

5.3.2 Drive beam klystron-modulator RF sources

Multibeam klystrons

In a CLIC drive beam accelerator there are 104 RF structures, each 3.1 m long with a field gradient of 3.85 MV/m, and operating at a frequency of 937 MHz. The peak RF power required for filling one structure is 100 MW with a pulse length of about 100 µs operating at a repetition frequency of 75 Hz for the 3 TeV collider design. In order to minimize the number of klystron modulators in the installation, the highest power tube that can be designed with sufficient reliability and lifetime would be chosen. At the moment it seems to be feasible to construct two 50 MW klystrons connected to one accelerator structure, with each klystron being powered by a long pulse modulator. With respect to the total AC power consumption for producing the drive beam RF power, and to its subsequent operating
costs, all areas have to be investigated for efficiency improvements, and in particular the klystron modulators.

The maximum klystron efficiency is obtained when the beam voltage is at a maximum and the beam current at a minimum for a given output power, since the space-charge forces of the beam counteract the beam bunching efficiency. In general, for a lower gun perveance less debunching will take place, and a higher tube efficiency is obtained. A low perveance usually means using a higher beam voltage to obtain a given output power. Under these conditions the single-beam L-band klystron efficiency, with a gun perveance of about $2 \times 10^{-6} \text{A}/\text{V}^{3/2}$, is around 45%.

However, multibeam klystrons (MBK) with individual beam perveances of around $0.5 \times 10^{-6} \text{A}/\text{V}^{3/2}$ can have an electronic efficiency of 70% or more. Since the multiple beams are in parallel, a substantially lower beam voltage for the same output power is required. This may result in a shorter gun structure, thus reducing the overall length of the device. Owing to the low beam impedance the prospective bandwidth is much wider than with single-beam tubes, and, in the case of a single operating frequency, could be partially traded off for a higher tube gain, requiring less drive power. Given these advantages the multibeam klystron becomes an attractive alternative power source.

Electrical breakdowns within the tube are one of the main limitations for obtaining high (50 MW) peak power, together with a long pulse duration. These breakdowns can occur along the insulators and between the electrodes of the klystron gun, as well as in the RF structures of the device. Measurements and calculations show that the design of klystron guns for pulse lengths of 100 µs with beam voltage levels of around 230 kV would become critical and require long-term development. Reliable operation of the klystron in this regime at a peak output power of 50 MW and with six low perveance beams would be close to the empirical [Latham, 1995] high-voltage breakdown limit. This is shown in the plot below, where points below the function line are much less critical than those above it.

The points (A) on Fig. 5.22 of the function $E_{max} \times V = 100 \times \tau^{-0.34}$ (kV)$^2$/mm, are experimental breakdown results made with short pulses on high-voltage electron guns at SLAC [Koontz, 1990] during the development of X-band klystrons for the NLC.

The RF power source foreseen for the CLIC drive beam linac is a 50 MW multibeam klystron, although currently the design of a six-beam, 25 MW MBK with two RF windows is being looked at as the first step. The parameters for this tube have evolved from the Thomson TH1801, 10 MW device operating at 1.3 GHz with a RF pulse width of 1.33 ms and a 10 Hz repetition frequency. The TH1801 was originally designed for the TESLA collider machine at DESY in Hamburg.

The parameters for the 25 MW, 937 MHz multibeam klystron for CLIC are summarized in Table 5.10.

![Fig. 5.22 $E_{max} \times V$ versus pulse length](image)
Table 5.10
25 MW multibeam klystron parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>937 MHz</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>100 µs</td>
</tr>
<tr>
<td>Repetition frequency (max.)</td>
<td>100 Hz</td>
</tr>
<tr>
<td>RF peak output power</td>
<td>25 MW</td>
</tr>
<tr>
<td>RF average power</td>
<td>250 kW</td>
</tr>
<tr>
<td>Peak RF drive power (max.)</td>
<td>1500 W</td>
</tr>
<tr>
<td>Saturated gain (min.)</td>
<td>43 dB</td>
</tr>
<tr>
<td>Minimum instantaneous bandwidth (–1dB)</td>
<td>4 MHz</td>
</tr>
<tr>
<td>Efficiency minimum (objective)</td>
<td>65(70)%</td>
</tr>
<tr>
<td>Number of beams</td>
<td>6</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>6</td>
</tr>
<tr>
<td>Single beam perveance</td>
<td>$0.5 \times 10^{-6}$ A/V$^{3/2}$</td>
</tr>
<tr>
<td>Peak beam voltage</td>
<td>175 kV</td>
</tr>
<tr>
<td>Peak beam current</td>
<td>220 A</td>
</tr>
<tr>
<td>Focusing power (built-in electromagnet)</td>
<td>18 kW</td>
</tr>
<tr>
<td>Ion pump voltage (3 pumps)</td>
<td>5 kV</td>
</tr>
<tr>
<td>Collector power dissipation (max.)</td>
<td>420 kW</td>
</tr>
<tr>
<td>Body power dissipation (max.)</td>
<td>20 kW</td>
</tr>
<tr>
<td>RF output windows (Al 995)</td>
<td>2</td>
</tr>
</tbody>
</table>

The overall mechanical dimensions of this klystron would be around 3.5 m in length with a weight of about 2800 kg. The probable operating position would be vertical with the collector up. In order for the tube to have a reasonably long lifetime (> 30 000 hours) the current density at the cathode is kept to < 7 A/cm$^2$ with a cathode temperature of 1020°C. To achieve this the constant focusing field must be set to 4 times the Brillouin condition and a beam convergence ratio of 3 must be used. A tentative design for the structure of the 25 MW, 937 MHz multibeam klystron is shown in Fig. 5.23.

Using the above results, some of the basic parameters of two higher peak power multibeam tubes at this frequency have been extrapolated and are given in Table 5.11.

![Fig. 5.23 Tentative structure for a 25 MW, 937 MHz MBK](image-url)
Table 5.11
Tentative parameters for 40 and 50 MW MBKs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak klystron RF output power (MW)</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Average klystron RF output power (kW)</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Operating frequency (MHz)</td>
<td>937</td>
<td>937</td>
</tr>
<tr>
<td>Repetition frequency (max.) (Hz)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>RF pulse width (μs)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Number of beams</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Single beam perveance (A/V^{3/2})</td>
<td>0.5 \times 10^{-6}</td>
<td>0.5 \times 10^{-6}</td>
</tr>
<tr>
<td>Cathode current density (A/cm^2)</td>
<td>7</td>
<td>8.5</td>
</tr>
<tr>
<td>RF structure interaction length (approx.) (cm)</td>
<td>240</td>
<td>250</td>
</tr>
<tr>
<td>Peak beam voltage (kV)</td>
<td>211</td>
<td>231</td>
</tr>
<tr>
<td>Peak beam current (A)</td>
<td>291</td>
<td>333</td>
</tr>
</tbody>
</table>

All of these multibeam klystrons require development to ensure the operational parameters can be obtained. In particular the higher power device for 40 or 50 MW peak RF output will require much longer term development and we should consider an MBK with many more parallel beams.

Although at the present the multibeam klystron looks a very strong candidate for achieving the target parameters at the 25 MW power level, an extension of the design to 50 MW may lead to design complexities with a larger number of parallel beams. A general overview of Thomson [Faillon, 1996] microwave tube trends is shown in Fig. 5.24 for output power versus frequency of commercially available klystrons.

A multibeam klystron tube with 12 beams [Caryotakis, SLAC, private communication] has been suggested to increase the output power and maintain the beam voltage at a reasonable operating point as seen on Fig. 5.24.

Therefore, it is considered that the 25 MW multibeam klystron would be achievable in the short term, with a 40 or 50 MW tube becoming available in the more distant future.

**Klystrons for CLIC Test Facility**

The 3 GHz klystrons currently used in LIL will be used as the RF power sources for the first phase of the new CTF3 test facility (see Chapter 10). These tubes are to be connected through a RF pulse compressor, providing up to 80 MW, 1.4 μs wide RF power pulses to the accelerating cavities. For the second phase of CTF3 some additional new 1.5 GHz klystron-modulator sources are required for generating the 4.5 μs wide RF power pulses to be fed to the subharmonic bunchers in the drive beam front-end system.
At a later stage of the test facility development (CLIC 0), a high-power klystron operating at 937 MHz, and directly providing up to 100 MW power, with a RF pulse width of 1.4 μs is needed for the drive beam cavities’ RF accelerating power. This direct power pulse would avoid any phase variation problems caused by a pulse compressor system.

This klystron could be included with the development of the 50 MW, 937 MHz multibeam long pulse (100 ms) klystron, as part of an overall klystron programme for CLIC. As well as the 10 MW and 25 MW Thomson MBK designs, there is a single-beam pulsed klystron at this frequency, with a lower (~2 MW) peak output power, and for 10 μs wide pulses (EISCAT radar system) which is commercially available and gives another reference point for the development.

The RF power required at 486.5 MHz for the subharmonic bunchers and RF combiner in the future CLIC 0 test facility (and also in the final CLIC scheme), could be provided by P-band klystrons or inductive output tubes (IOTs) as used in television transmitters. Both of these RF tube applications are considered as being long-term development items.

5.3.3 Modulator design

The baseline modulator design considered for powering the CLIC drive beam linac’s 937 MHz multibeam klystron RF sources is conventional [Thomas, 1993] but using recent technology [Pearce, 1998] to improve efficiency and reliability as shown in Fig. 5.25. The high-voltage charging system uses several switched-mode power units in parallel enabling a compact modulator layout with efficient conversion of the ac wall-plug power into dc charging energy. The high-power output stage consists of a simple Rayleigh, multicell pulse-forming network (PFN) that is discharged by a thyratron switch, as a high-power 100 μs long pulse into the klystron load via a step-up pulse transformer. A detailed design and simulation of a modulator suitable for powering the 25 MW multibeam klystron has been made and is described in detail below along with changes that can be used to accommodate a 50 MW klystron when it becomes available. The overall emphasis is to build reliability into the system at the design stage by choosing reasonable operating parameters and efficient technology, and also by keeping the design as simple as possible. Additionally, the klystron-modulator system must be easily and quickly maintainable as an important part of a very much larger accelerator complex.
5.3.4 Modulator operating parameters

The operating parameters for the pulse modulator powering a 25 MW multibeam klystron with an efficiency of about 65% are listed in Table 5.12.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse output voltage to klystron</td>
<td>175 kV</td>
</tr>
<tr>
<td>Pulse output current to klystron</td>
<td>220 A</td>
</tr>
<tr>
<td>Voltage pulse width at FWHM</td>
<td>107 µs</td>
</tr>
<tr>
<td>Flat-top pulse width</td>
<td>100 µs</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>75 Hz</td>
</tr>
<tr>
<td>Maximum PFN voltage</td>
<td>45 kV</td>
</tr>
<tr>
<td>Pulse flatness</td>
<td>&lt; ±0.15%</td>
</tr>
<tr>
<td>Pulse-to-pulse amplitude variations</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td>Peak input HV power to klystron</td>
<td>38 MW</td>
</tr>
</tbody>
</table>

5.3.5 Modulator subsystems

High-voltage charging

In order to improve the overall modulator conversion efficiency and reduce the physical size, a switched-mode, high-voltage charging power supply system has been considered for the baseline design as one alternative solution to using a standard resonant charging system with de-qing.

A modular, parallel arrangement, with several switched-mode units each providing 50 to 100 kJ/s charging rates, would enable the required 400 kJ/s charging capacity at 45 kV for the PFN of the 25 MW modulator to be obtained. The high-voltage outputs from each unit are connected in parallel to charge the PFN via a power diode OR gate and a voltage reversal protection circuit. In this way, an internal failure of one power supply unit would not affect the operation of the remaining units, although the PFN charging rate would be reduced.
The switched-mode power supplies charge the PFN during the interpulse period with a constant current and will typically provide voltage regulation of ±0.2%. A dead time between two charging cycles allows the thyatron switch to fully recover before the re-application of the high voltage on the PFN. This built-in dead time will reduce (or eliminate) the need for any positive mismatch between the PFN and the klystron load, and therefore improve the energy transfer efficiency of the system.

The switched-mode power units’ internally stored energy and losses are much lower than a resonant charging system with de-qing. This performance is achieved by the use of high-frequency power switching (up to 50 kHz at the end of charge) which greatly improves the precision of regulation. This also reduces the core size of the internal high-voltage power transformer, so reducing the size and weight of the power unit.

Operating efficiencies of around 90% are being obtained [Oh, 1997] from high-voltage switched-mode power units used in klystron-modulator systems. The parameters for a 25 MW system are given in Table 5.13.

<table>
<thead>
<tr>
<th>Table 5.13 High-voltage charging parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum charging voltage</td>
</tr>
<tr>
<td>PFN charging time</td>
</tr>
<tr>
<td>Minimum charging rate</td>
</tr>
<tr>
<td>Voltage regulation precision</td>
</tr>
<tr>
<td>Average PFN charging current</td>
</tr>
</tbody>
</table>

**Pulse-Forming Network (PFN)**

The PFN uses a Rayleigh type LC lumped parameter network with 40 cells having an electrical pulse length \( T = 2n(LC)^{1/2} \) equal to 100 ms. The capacitance in each cell has a value of 111 nF and has a low internal self-inductance. Each cell-tuning inductor is mounted directly in line with the capacitor and positioned to minimize excessive mutual inductance effects.

The PFN inductors are made from copper tubing over an insulated former, with a copper tuning slug that is adjustable to enable tuning over a range of about 14–16 μH for impedance matching. This individual inductance adjustment together with the number of cells also enables tapering of the PFN impedance to compensate for the 1% pulse transformer droop, and to minimize the voltage ripple amplitude on the pulse flat-top to around ±0.1%.

The minimum rise time from this network is given approximately by \( T_r \sim \frac{\pi}{2} (LC)^{1/2} \) and in this case is about 2 μs. A small amount of positive mismatch is provisionally included in the PFN design to help recovery of the thyatron switch, although this should not be strictly necessary with the type of high-voltage power supply proposed.

The PFN has a characteristic impedance of about 12 Ω, with each of the 40 cells producing a one-way delay time of ~1.3 μs. The impedance matching of the klystron load to the PFN is done through the 1:8 step-up pulse transformer. The thyatron switch average current is made to be < 15 A by the use of the higher circuit impedance, and should increase the operating lifetime of the thyatron. The pulse-forming network parameters are shown in Table 5.14.
### Table 5.14
PFN parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Rayleigh LC network</td>
<td>40 cells</td>
</tr>
<tr>
<td>Cell capacitance</td>
<td>111 nF</td>
</tr>
<tr>
<td>Cell inductance (tunable)</td>
<td>14–16 μH</td>
</tr>
<tr>
<td>PFN impedance</td>
<td>11.86 Ω</td>
</tr>
<tr>
<td>Cell one-way delay time</td>
<td>1.32 μs</td>
</tr>
<tr>
<td>Klystron load to PFN positive mismatch</td>
<td>&lt; 6%</td>
</tr>
<tr>
<td>Energy stored in PFN</td>
<td>4500 J</td>
</tr>
</tbody>
</table>

**Thyratron switch**

The switching of high average currents, with long pulses at high repetition rates and reasonably long lifetimes with high reliability, is a difficult operating condition for most thyratrons. In order to reduce the thyratrons' cathode working temperature and increase lifetime, the active cathode surface area would need to be extended since the heat at the cathode limits the average current.

The development of a long-pulse, high (~ 50 A) average current thyratron in industry for this type of duty would be very desirable. Present short-pulse modulator designs [Pirrie, 1998] tend to keep the average current level below 15 A in order to obtain this reasonable operating lifetime (up to 25 000 hours), even though some thyratrons with average current capacities of around 25 A do exist.

The operation of thyratrons in parallel does enable a higher average power to be handled, provided reliable current-sharing circuits are used. However, this method increases the complexity and cost of the system, and it can have an impact on operating reliability.

The present design of the 25 MW klystron modulator requires an average switch current of about 15 A, so a single two-gap metal/ceramic thyratron, such as the CX1720 or CX2412 from EEV, would be suitable. These tubes must be cooled by total immersion in force-circulated transformer oil to maintain optimum performance. In order to maximize the cathode utilisation and therefore its operating lifetime, a double trigger system together with a negative grid bias is recommended.

The operating position is vertical with the anode up. The thyratron operating parameters are given in Table 5.15.

### Table 5.15
Thyratron operating values for the 25 MW klystron modulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operating value</th>
<th>CX1720/2412</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak forward anode voltage (kV)</td>
<td>45</td>
<td>50/60</td>
</tr>
<tr>
<td>Peak forward anode current (kA)</td>
<td>2</td>
<td>50/15</td>
</tr>
<tr>
<td>Average anode current (A)</td>
<td>14.5</td>
<td>25/15</td>
</tr>
<tr>
<td>Repetition frequency (max.) (Hz)</td>
<td>75</td>
<td>1000/5000</td>
</tr>
</tbody>
</table>

51
**Pulse transformer assembly**

The high-power, step-up pulse transformer provides the correct polarity high voltage to the klystron load, as well as matching its impedance to that of the PFN for optimum energy transfer. It plays an important part in the overall efficiency of the modulator and must be optimized.

The energy transfer efficiency, from the PFN to the klystron load, is mainly determined by the pulse transformer design, and in particular the effect of leakage inductance $L_L$ and stray capacitance $C_D$ on the pulse rise and fall times. The klystron capacitance $C_K$ seen at the cathode is also in parallel with the transformer stray capacitance $C_D$ at the secondary winding and has an added effect. The pulse rise time at the transformer is limited by the resonant period [Glassoe, 1965] and is determined by $L_L$ and $C_D$, (where $C_T = C_D + C_K$) such that $T_R \approx \pi (L_L C_D)^{1/2}$.

The core cross section $(a \times a)$, the separation gap $\Delta$ between primary and secondary windings, the winding former shape, the winding length and the turns ratio $n$, are factors that mainly determine the values of $L_L$ and $C_D$.

For a particular transformer design the values of leakage inductance and stray capacitance are approximately given by $L_L \sim a.\Delta. n^2$ and $C_D \sim a.\varepsilon_r.\Delta^{-1}$. Then substituting above, the rise time [Wilson, 1994] is approximately given by $T_R \sim n.a.\varepsilon_r T_p^{1/2}$, where $\varepsilon_r$ is the dielectric constant of the oil normally used for total immersion of the high-voltage pulse transformer.

At the end of the voltage pulse the core flux density has reached a maximum value and the flux $\phi_{max} = (a)^2. B_{max} = \text{volts-seconds of the transformer core} (V T_p)$. From this we can see that the pulse width ($T_p$) and the core area $(a)^2$ are related by $a \sim T_p^{1/2}$ and then $T_R \sim nT_p^{1/2}. \varepsilon_r^{1/2}$ so that for fast rise times, with respect to the total pulse width, a low transformer ratio $n$ is required. Therefore for a given transformer design, the percentage energy losses due to the rise and fall times will reduce, when using larger ($T_p$) pulse widths. The pulse energy transformer energy efficiency is usually written as:

$$\eta_E = \frac{T_p}{T_p + A \cdot T_R + B \cdot T_F},$$

where $T_p$ is the modulator high-voltage flat-top pulse width, and should equal the RF pulse width to achieve maximum efficiency from the system. The rise and fall times are given by $T_R$ and $T_F$ with the constants $A$ and $B$ being both equal to 0.5 for rectangular rise and fall pulse shapes. If the fall time is assumed to be twice the rise time, then $T_F = 2T_R$ and the energy transfer efficiency equation becomes:

$$\eta_E = \frac{T_p}{T_p + A \cdot T_R + B \cdot T_F},$$

where $\alpha$ is equal to 1.5 for the above case but can vary approximately between 1.1 and 1.7 for different transformer designs. There are also some copper and iron losses $\eta_L$ associated with the pulse transformer and bias isolation choke giving a typical value for $\eta_L$ between 95 and 98%. The overall efficiency of the transformer would be expressed as $\eta_T = \eta_E \times \eta_L$.

The parameters for a pulse transformer with a step-up ratio $= 1:10$ to be used in the 50 MW klystron modulator with a 100 $\mu$s pulse width are given above in Table 5.16.

The rise time (10–90%) is estimated from the above data as $\leq 4$ $\mu$s when internal transformer connections are taken into account. With a 100 $\mu$s flat-top modulator pulse width the calculated energy transfer efficiency $\eta_E \approx 98\%$, again using the above transformer data and pulse shape assumptions.
Table 5.16
Pulse transformer parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer step-up ratio</td>
<td>1:10</td>
</tr>
<tr>
<td>Peak secondary winding voltage</td>
<td>250 kV</td>
</tr>
<tr>
<td>Leakage inductance (at secondary)</td>
<td>~ 6.3 mH</td>
</tr>
<tr>
<td>Distributed stray capacitance (secondary)</td>
<td>~ 300 pF</td>
</tr>
<tr>
<td>Magnetizing inductance (primary)</td>
<td>~ 40 mH</td>
</tr>
<tr>
<td>Flat-top droop</td>
<td>~ 1%</td>
</tr>
<tr>
<td>Primary winding resistance</td>
<td>~ 7 mΩ</td>
</tr>
<tr>
<td>Secondary winding resistance (bifilar)</td>
<td>~ 2.6 Ω each</td>
</tr>
<tr>
<td>Core loss power</td>
<td>~ 4400 W</td>
</tr>
<tr>
<td>DC bias core reset current</td>
<td>~ 12 A</td>
</tr>
<tr>
<td>Bias isolation choke</td>
<td>~ 250 mH</td>
</tr>
<tr>
<td>Estimated klystron capacitance</td>
<td>~ 120 pF</td>
</tr>
</tbody>
</table>

Fig. 5.26 Transformer energy efficiency ($T \times$ ratio $n = 1:10$ and $\alpha = 1.5$)

This transfer efficiency is shown in Fig. 5.26 where the transformer copper and iron losses are calculated as $\eta_L = 98\%$, which gives a total transformer circuit efficiency $\eta_T$ of around 96% when including the bias choke losses.

Traditionally, modulator pulse transformers have their cores reset by using a DC current source connected to the system via an insulating inductor. The power required for this method depends on circuit resistance, repetition rate, and transformer flux swing. Using a pulsed-core reset, however, leads to a reduction of magnetizing current [Adler, 1997] and an improvement in performance and efficiency. A pulsed reset will demagnetize the transformer core to the initial starting point on the BH loop, provided that the applied reset pulse volt-seconds equals the main pulse flux swing. The reset pulse can be applied to the transformer via a small tertiary winding, or to the primary winding. This can make a
reproducible core reset that is independent of the repetition rate and effectively maximizes the useful transformer volt-seconds available.

**Modulator design for a 50 MW klystron**

The changes required in the 25 MW klystron modulator to convert it to a single 800 kW system for an optimized 50 MW design are given in Table 5.17.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>25 MW modulator</th>
<th>50 MW modulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak klystron beam voltage (kV)</td>
<td>175</td>
<td>231</td>
</tr>
<tr>
<td>Peak klystron beam current (A)</td>
<td>220</td>
<td>333</td>
</tr>
<tr>
<td>PFN voltage (max.) (kV)</td>
<td>45</td>
<td>47</td>
</tr>
<tr>
<td>PFN impedance (Ω)</td>
<td>11.86</td>
<td>6.47</td>
</tr>
<tr>
<td>Klystron-to-PFN mismatch (%)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Stored energy in PFN (kJ)</td>
<td>4.5</td>
<td>9.0</td>
</tr>
<tr>
<td>PFN charging time (ms)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>PFN cell capacitance (nF)</td>
<td>111</td>
<td>205</td>
</tr>
<tr>
<td>Number of cells in the PFN</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Thyatron peak current (A)</td>
<td>1850</td>
<td>3520</td>
</tr>
<tr>
<td>Thyatron average current (A)</td>
<td>14.5</td>
<td>28</td>
</tr>
<tr>
<td>PFN charging power (min.) (kJ/s)</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>Pulse transformer ratio</td>
<td>1:8</td>
<td>1:10</td>
</tr>
<tr>
<td>Pulse transformer volt-sec (Vs)</td>
<td>18.5</td>
<td>25</td>
</tr>
</tbody>
</table>

Alternatively, this 50 MW modulator could also be used for driving two of the 25 MW multibeam klystrons in parallel. Since the final peak output power required would be within the 40–50 MW range, the CLIC baseline modulator design is centred on the higher power rating.

**Alternative modulator designs**

Solid-state switching systems using the recent developments in Insulated-Gate Bipolar Transistors (IGBTs) and also Gate Turn-Off devices (GTOs) [Wakeman, 1998], are now starting to be used in various accelerator applications. This is particularly evident for IGBT devices [Zolfaghari, 1998] in klystron modulators. Historically, vacuum switch tubes with storage capacitor energy sources, or thyatrons used with pulse forming networks and pulse transformers have provided a nearly exclusive solution to providing pulsed high-voltage power for klystrons. In order to use IGBTs for high-voltage switching, many devices must be cascaded in series. Additionally, to increase the power handling capability of such an assembly, several of these series chains must operate in parallel. This design requirement also provides a degree of flexibility and modularity over a very large power range. It also requires a very good means of protection to ensure that the load power is shared equally between devices, and that no single device sees harmful or destructive voltages. Up until recently, few commercial or laboratory-built systems using these device-arrays as the principle method of pulsing klystrons have existed.
Today, very compact, efficient, and commercially made 125 kV, 400 A solid-state modulators are being installed for certain applications, and their use will expand as the operational reliability is seen to be adequate. The use of this technology, but operating at a lower voltage of around 25 kV, together with a pulse transformer, is being investigated as an alternative solution to the CLIC baseline modulator design presented above.

In this case the PFN and thyatron switch are removed from the system and replaced by a stable, high-voltage switched-mode power source with storage capacitor and the IGBT series switch array. The width of the pulse generated is determined by the ON-time of the series switch. A block diagram of this possible alternative scheme is given in Fig. 5.27.

![Solid-state modulator with pulse transformer](image)

**Fig. 5.27 Solid-state modulator with pulse transformer**

A second, although less likely alternative, is the use of direct-coupled power switching using IGBT switch arrays. The issue here is the availability of AC line power at high voltage (approximately 170 kV for a system requiring peak pulse power at 235 kV) being rectified into DC and switched directly onto the klystron cathode using the IGBT array. A second high-voltage switch is also needed to work in a back regulator configuration to stabilize the DC input voltage of the system. The second IGBT switch array, and operating at very high DC voltages, complicates the system and increases the component count and cost.

The reliability could also be affected by the requirement to have very effective protection schemes. However, this method has the potential of greatly improving the power conversion efficiency but does require operating a large system, with a very high voltage DC power distribution network, that may also bring many operational safety implications.

An unknown factor for both of the above is the long-term reliability of such systems using large arrays of IGBT solid-state switches. Until this reliability can be proven they have to be treated as possible alternative devices for use in a future long-pulse, high-power modulator. However, with their apparently rapid development, and utilization in many diverse pulsed-power applications, that information should soon become available to confirm the long-term reliability performance.

### 5.3.6 RF drive power system

A drive beam linac RF power system will have 198 pulsed klystron-modulator assemblies connected to 99 accelerating structures, with each assembly as shown in Fig. 5.28.

This arrangement enables the peak power to be obtained by summing at the 100 MW hybrid power combiner, and also has the added advantage of providing differential phase adjustment between the two klystrons, at the low-level inputs.
This permits fine adjustment of the 100 MW peak RF power amplitude via the phase, and because of the length of pulse (100 μs) would allow fast electronic correction of the flatness of the RF pulse during this time.

The microwave frequency of 937 MHz is very close to one of the frequencies that has been reserved by the Federal Communications Commission (FCC) for industrial, scientific, medical and other applications such as microwave heating.

The two frequencies most used for this purpose are 915 MHz and 2450 MHz, and are known as the Industrial, Scientific and Medical (ISM) frequency bands. Because of this, there are quite a large number of specialist manufacturers that produce all types of waveguide components that would be needed, and should be available at competitive prices.

There are two Electronic Industry Association (EIA) equivalent waveguide types available at the 937 MHz frequency; the WR-1150 and WR-975. The basic specifications for these are given in Table 5.18.

**Table 5.18**

937 MHz waveguide basic specifications

<table>
<thead>
<tr>
<th>Waveguide type</th>
<th>Material</th>
<th>Frequency range (GHz)</th>
<th>Attenuation dB/20 m length</th>
<th>Inside dimensions (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR-1150</td>
<td>6061 Al</td>
<td>0.64–0.96</td>
<td>0.0773</td>
<td>29.21 × 14.6</td>
</tr>
<tr>
<td>WR-975</td>
<td>6061 Al</td>
<td>0.75–1.12</td>
<td>0.109</td>
<td>24.765 × 12.383</td>
</tr>
</tbody>
</table>

The attenuation given above is for 125% above the theoretical attenuation and is a practical design figure, although measured values are generally significantly less than this.

Figure 5.29 shows the power handling capacity of these waveguide types in the TE10 mode. The curves are based on a maximum voltage gradient of 30 kV/cm in dry air at standard temperature and pressure.

Other factors that will lower this capacity are the Voltage Standing-Wave Ratio (VSWR) and the waveguide internal pressure. The WR-1150 waveguide has larger dimensions compared to the WR-975 but it also has a higher power handling capacity at 937 MHz, and a lower attenuation by a factor of 1.4 and so is more power efficient for this application.
5.3.7 RF system performance

The overall RF system efficiency is an important parameter for a linear collider and to a large extent is determined by the performance and efficiency of the klystron modulators. Small improvements of the 1% level to reduce the AC power consumption would have a big impact on the exploitation costs of a collider installation.

Additionally, simplicity and modularity of the design will improve the reliability, availability, and maintainability [Pearce, 1995] of the overall system. For these reasons a simple and efficient klystron modulator design is necessary. A block diagram of the major functional parts of a baseline klystron-modulator design that will have an influence on its performance and overall efficiency is shown in Fig. 5.30.

The efficiencies of the above individual subsystems are shown in Table 5.19. The data have been taken from specifications of similar equipment that is operating in klystron-modulator systems, or are projected efficiencies extrapolated from equipment specifications.
An estimation was made for the auxiliary power consumption based on a total of less than 20 kW. This amount takes care of the klystron and thyatron heating power, the focal coil power, and the controls-protection system power needed for each modulator. The duty factor with a 100 µs wide pulse and operating at 75 Hz is 0.0075, so that with a 50 MW klystron being driven by the modulator the average RF power is 375 kW. The average klystron modulator power, with the auxiliary power included, is 600 kW for the target design, and 690 kW for the average performance design. The system has 198 modulators operating within a drive beam linac, so that the line power required would be about 137 MW and 120 MW, respectively, for the assumed and target situations.

Table 5.19
Klystron modulator efficiency

<table>
<thead>
<tr>
<th>System</th>
<th>Parameter</th>
<th>Efficiency symbol</th>
<th>Assumed eff. (%)</th>
<th>Target eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging system</td>
<td>ACl ine powerto DC high voltage</td>
<td>$\eta_c = P_{dc}/P_{ac}$</td>
<td>92</td>
<td>96</td>
</tr>
<tr>
<td>Pulsing system</td>
<td>PFN and thyatron switch efficiency</td>
<td>$\eta_p = P_{rf}/P_{dc}$</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Pulse transformer</td>
<td>Tx losses &amp; energy transfer efficiency</td>
<td>$\eta_t = P_t/P_p$</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Klystron</td>
<td>Electronic efficiency</td>
<td>$\eta_k = P_{rf}/P_t$</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>Klystron modulator</td>
<td>AC-to-RF efficiency</td>
<td>$\eta_{rf} = P_{rf}/P_{ac}$</td>
<td>56</td>
<td>65</td>
</tr>
<tr>
<td>Klystron modulator</td>
<td>Total single system efficiency</td>
<td>$\eta_{km} = P_{rf}(P_{ac}+P_{aux})$</td>
<td>55</td>
<td>64</td>
</tr>
</tbody>
</table>

5.3.8 Summary

The CLIC drive beam RF power system will use 100 µs long pulse klystron modulators to provide the energy for a 1.2 GeV, fully-loaded and conventional 937 MHz linac. Multibeam klystrons are proposed for this task since they require a lower peak beam voltage, thus reducing the problems of internal breakdowns with long pulses at the klystron gun, and have the possibility of high (≥ 70%) electron efficiency.

The parameters for a 25 MW tube have been studied and look very promising, although development and testing must be carried out to confirm these expectations.
The design has been tentatively extrapolated to higher peak powers of 40 and 50 MW, where it is seen that with a six-beam device, the high voltage level becomes critical, and may require extensive development.

A multibeam klystron with up to 12 beams has been proposed to alleviate this problem, and although it would increase the complexity of the internal tube structure, such a device could provide an alternative solution.

Therefore a detailed design study and development programme is needed in order to realize the full potential of multibeam klystrons for this application. This study should look at possible trade-offs between operating parameters and the number of klystron beams as well as reviewing other types of microwave tubes.

A possible application of 937 MHz klystrons for generating 100 MW, 1.4 µs wide pulses that could be used in a later phase of the test facility could also be integrated into this programme. Additionally, some single-beam klystron development will be required for the high-power RF sources to be used with the subharmonic bunchers and RF combiner.

A long-pulse modulator test equipment will also need to be built to evaluate the multibeam klystron and develop the concept of a smart, reliable, and efficient high-power system. This is particularly important for the switched-mode power supply and thyatron switch evaluation, where the appropriate component manufacturers must participate fully.

In general the modulator baseline design is conventional, but the level of average power being considered requires careful system development to ensure that the performance is optimized with respect to efficiency and reliability. The results of this development can be applied to the other modulators required in the system. In parallel with this work, the development status of IGBT solid-state switch arrays and modulators must be constantly reviewed, and experience acquired, to ensure that the most efficient system is being adopted for the final project.

At the present time, a study of the parameters for a 25 MW multibeam klystron has been undertaken. The design of a modulator with a pulse transformer for long-pulse operation has also been designed and simulations with these elements started. The next stage will be to optimize the klystron design, where 25 MW appears to be achievable in the short term [Beunas, Thomson (TTE) - Paris, private communication], whilst the 50 MW klystron will require much more design and development, and will certainly be more difficult. A prototype tube will eventually have to be built and tested at a selected power level. In parallel with this activity the modulator design must be optimized for 50 MW operation and a prototype constructed and tested.

5.4 The drive beam linac

5.4.1 Drive beam accelerating structures

For the sake of simplicity and to avoid excessive surface gradients, a classical geometry was chosen, offering the required group velocities (between 0.053 c and 0.025 c) and $R/\beta$ values, to enable the beam to use up completely the electromagnetic energy before it reaches the end of the structure.

First beam tracking computations with 937 MHz structures of 29 cells having an average iris radius $a = 48.5$ mm, an average outer radius $b = 144$ mm, and disc thickness $d = 19$ mm demonstrated that both detuning and damping were necessary to preserve a sufficiently low transverse-beam emittance. The design is based on the same principles proposed for the CLIC main accelerating structure [Dehler, 1998]. Good beam transmission was obtained with a dipole frequency spread of about 10% and a $Q$-value of 100 for the first mode and 400 for the second one (see Section 5.5.5 on beam stability). Since some scale model work at 3 GHz was planned, the following investigations with the ABCI code [Chin, 1992] were all done for structures with 3 GHz fundamental frequency (average-average iris radius $a$ scales to 15 mm at 3 GHz). A 29-cell structure having for the first cell $a = 17$ mm and for the last one $a = 13.3$ mm was used.

Table 5.20 lists the relevant parameters of the two extreme cells for zero bunch length and a scaled operating frequency of 3 GHz.
Table 5.20
Parameters of the first and last cells of the 3 GHz structure

<table>
<thead>
<tr>
<th>Quantity</th>
<th>First cell</th>
<th>Last cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iris radius $a$ (mm)</td>
<td>13.3</td>
<td>17</td>
</tr>
<tr>
<td>Relative group velocity $\beta_g$</td>
<td>0.025</td>
<td>0.053</td>
</tr>
<tr>
<td>Outer radius $b$ (mm)</td>
<td>43.7</td>
<td>46</td>
</tr>
<tr>
<td>$R/Q$ for fundamental mode [$\Omega$/m (linac)]</td>
<td>4286</td>
<td>3480</td>
</tr>
<tr>
<td>Frequency of first transverse mode (GHz)</td>
<td>4.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Transverse loss factor $k$ of first mode ($V/pC/m^2$)</td>
<td>2080</td>
<td>1060</td>
</tr>
<tr>
<td>Frequency of second transverse mode (GHz)</td>
<td>7</td>
<td>6.85</td>
</tr>
<tr>
<td>Transverse loss factor $k$ of second mode ($V/pC/m^2$)</td>
<td>450</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5.21 lists the relevant parameters of the two extreme cells for zero bunch length and operating frequency 937 MHz as for the CLIC drive beam.

Table 5.21
Parameters of the first and last cells of the 937 MHz structure

<table>
<thead>
<tr>
<th>Quantity</th>
<th>First cell</th>
<th>Last cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iris radius $a$ (mm)</td>
<td>42.6</td>
<td>54.4</td>
</tr>
<tr>
<td>Relative group velocity $\beta_g$</td>
<td>0.025</td>
<td>0.053</td>
</tr>
<tr>
<td>Outer radius $b$ (mm)</td>
<td>140</td>
<td>147.2</td>
</tr>
<tr>
<td>$R/Q$ for fundamental mode [$\Omega$/m (linac)]</td>
<td>1340</td>
<td>1088</td>
</tr>
<tr>
<td>Frequency of first transverse mode (GHz)</td>
<td>1.34</td>
<td>1.22</td>
</tr>
<tr>
<td>Transverse loss factor $k$ of first mode ($V/pC/m^2$)</td>
<td>63.5</td>
<td>32.34</td>
</tr>
<tr>
<td>Frequency of second transverse mode (GHz)</td>
<td>2.18</td>
<td>2.14</td>
</tr>
<tr>
<td>Transverse loss factor $k$ of second mode ($V/pC/m^2$)</td>
<td>13.7</td>
<td>3.1</td>
</tr>
</tbody>
</table>

**Measurements on a 3 GHz model**

A seven-cell constant-impedance clamped aluminium model with $a = 13.3$ mm (corresponding to the structure end-cell with the heaviest coupling) was coarsely checked as regards the damping prospects. Four damping waveguides per cell with dimensions 37 mm $\times$ 6 mm were milled between the cell wall and the structure outside, see Fig. 5.31. Damping was simulated by open-circuiting the waveguides towards the outside and non-damping by short-circuiting.

Measurements with a network analyser showed undamped $Q$-values of the first mode of about 1800 (the cells were lossy mainly due to the clamping contacts) and $Q$-values too low to be measured with damping (open waveguides). For the second mode the undamped $Q$ was 2300 and the damped one 560.

Damping was confirmed by computations on a single cell using the HFSS code yielding $Q$-values of 11 and 100 for the first and second modes, respectively [M. Luong, CERN, private communication]; this time the waveguides were assumed to be perfectly terminated. The model work and the HFSS calculations have demonstrated that sufficient damping for beam survival is obtainable.
5.4.2 *Wakefields and the structure model*

The short-range wakefields of the structures are derived by scaling from those for the S-Band Linear Collider (SBLC). For the SBLC frequency of 2.998 GHz, the longitudinal delta-wakefield can be expressed as [Bane, 1997]:

$$W_L = 250 \text{ V/(pC m)} \exp\left(-0.85\sqrt{z/\text{mm}}\right).$$

The scaling of the wakefield amplitudes with frequency is for fixed $a/\lambda$:

$$\hat{W}_L(f) = \left(\frac{f}{f_0}\right)^2 \hat{W}_L(f_0).$$

If $a/\lambda$ is changed, the scaling is not straightforward but should roughly follow:

$$\hat{W}_L(a) = \left(\frac{a_0}{a_0}\right)^2 \hat{W}_L(a_0).$$

The long-range longitudinal wakefields are neglected in the following simulations. Their effect on the mean bunch energy should be taken out by the beam loading compensation scheme described in Section 5.1.1 — so only the distribution might change slightly. The transverse wakefield for 2.998 GHz can be approximated as [Bane, 1997]:

$$W_L = 5.45 \text{ kV/(pC m)}^2 \left[1 - \exp\left(-1.13\sqrt{z/\text{mm}}\right) \left(1 + 1.13\sqrt{z/\text{mm}}\right)\right].$$

Provided that $a/\lambda$ remains constant, the scaling with frequency is given by [Siemann, 1994]:
\[ \hat{W}_1(f) = \left( \frac{f}{f_0} \right)^3 \hat{W}_1(f_0). \]

For varying \( a/\lambda \) the scaling of the amplitudes follows approximately:

\[ \hat{W}_1(a) = \left( \frac{a_0}{a} \right)^{2.2} \hat{W}_1(a_0). \]

The \( a/\lambda \) chosen for the accelerator is larger than that for SBLC by a factor 1.25. The long-range transverse wakefield is calculated by assigning modes to the individual cells. It is assumed that the modes are trapped and do not propagate longitudinally. For each cell the two modes with the highest loss factors are used. The transverse field of the cell is given by:

\[ \hat{W}_1(z) = \sum_i W_{i,0} \sin \left( \frac{2\pi z}{\lambda_i} \right) \exp \left( \frac{\pi z}{Q\lambda_i} \right). \]

For the realistic simulation the loss factors and frequencies for all 29 cells are estimated by interpolating between the four cells simulated with ABCI at 3 GHz [L. Thorndahl, CERN, private communication]. The radii are equally spaced in the range 42.6–54.4 mm, corresponding to 13 mm and 17 mm at 3 GHz. The frequencies and amplitudes of the two most important modes in the four simulated cells are shown in Figs. 5.32 and 5.33 together with the fit used for the interpolation. For the main transverse mode the fits yield an amplitude:

![Graph showing frequencies and amplitudes for different modes](image)

**Fig. 5.32** The frequencies of the simulated cells and the fit used to interpolate between them
Fig. 5.33 The amplitudes of the simulated cell and the fit used for the interpolation

\[ \hat{W}_1(r) = 1.545 \frac{\text{kV}}{\text{pC m}^2} \left( \frac{a}{\text{cm}} \right)^{-2.24623} \]

and a frequency:

\[ f_1 = \left( 1.7098 - 0.02796 \frac{a}{\text{mm}} \right) \text{GHz}. \]

For the second mode the amplitude is given by:

\[ \hat{W}_2(r) = 18.739 \frac{\text{kV}}{\text{pC m}^2} \left( \frac{a}{\text{cm}} \right)^{-5.07316} \]

and the frequency by:

\[ f_1 = \left( 2.3566 - 0.12336 \frac{a}{\text{mm}} \right) \text{GHz}. \]

The damping was measured on a model indicating an upper limit for the damping of the first transverse mode of \( Q < 100 \) and a value of \( Q = 400 \) for the second mode. In the following for the main mode, \( Q = 100 \) is used but more precise measurements are expected to show significantly smaller values. Calculations predict \( Q = 11 \) for perfect loads [M. Luong, CERN, private communication].
5.4.3 Description of the lattice

The drive beam accelerator accelerates the drive beam from 50 MeV to 1.23 GeV. It consists of a simple FODO lattice with a BPM and a quadrupole between consecutive cavities. The length of the cavities is given by the requirement that the beam loading should be almost 100%. In the present design, for a current of 8.2 A, each cavity consists of 29 cells to get the required length of about 3.1 m with an average gradient of 3.85 MV/m. The BPM, quadrupole, and drifts add another 0.8 m per cavity. The phase advance per FODO cell is 116°. This strong focusing keeps the wakefield effects very low. It is, however, possible to substantially reduce this without changing the stability significantly. One might also think of increasing the cell length towards the end of the linac.

To reach the final energy, 100 cavities are needed. This results in a total linac length of about 390 m. Since each accelerating structure needs to be fed by two klystrons it may be necessary to increase the linac length to have the necessary space for the RF. A simple way of doing this is to double the number of FODO cells and replace every second cavity by a drift. This would also gain space for the beam instrumentation and collimation.

5.4.4 Transverse stability

Each drive beam linac has to accelerate about 40 000 bunches from 50 MeV to 1.23 GeV in the 3 TeV design. The stability of this beam with respect to jitter effects is important since small effects may get amplified. To investigate this a number of simulations were performed with the code PLACET [Schulte, 1998] using a beam that is offset at the linac entrance. Since tracking all trains of bunches is very time- (and memory-) consuming only the first 2000 bunches are used for the calculation. Also, the final energy in the simulation is somewhat lower (1.16 GeV) than the nominal one, being based on a previous parameter set.

For the simulation each bunch is cut longitudinally into 21 slices. Figure 5.34 shows the transverse position of each slice at the linac exit for a beam with an initial offset of one sigma. The horizontal lines visible in the figure are formed by slices in consecutive bunches with the same longitudinal position within their bunch. The variations from train to train are very small within this range. Periodically the slices reach higher amplitudes — this occurs in the transient regime where two trains overlap.

The bunch length will vary along the beamline on account of the one or more compression stations. Since there is no design for them, they will be ignored in the simulation. However, the bunch length was varied to make sure it has only a small impact on the results. All the results shown refer to $\sigma_z = 2000 \mu m$.

To investigate the necessity of damping and detuning of the cavities, calculations were performed using constant impedance structures with a cell radius of $a = 48$ mm and a damping of $Q = 100$.

As can be seen in Fig. 5.35 the amplification of initial jitter is in this case substantial. A factor of about 15 as reached here is not acceptable. Reducing the $Q$-value to $Q = 20$ improves the situation significantly. The amplification stays well below 2 in the transient regime and is close to 1 on the flat top (see Fig. 5.36). This is acceptable.
Fig. 5.34 Position of the slice centre of bunches as a function of slice number. Only the first 500 bunches (with 21 slices each) are shown. The structures used in the simulation have a damping with $Q = 100$ and are detuned.

Fig. 5.35 Amplification of an initial jitter for a case where the cavities are not detuned. Slices within the same bunch are connected with lines. The initial offset was one sigma. A damping with $Q = 100$ was assumed.
In order not to have to rely only on damping, the cavity cells are detuned. Detuning alone does not work since the fields recohere after some time. Using the parameters of the acceleration structures foreseen in the reference design, each structure consisting of 29 cells with varying radii in the range of $a = 41.6 \text{ mm}$ to $a = 54.4 \text{ mm}$, one finds a rather modest increase of the amplitudes, see Fig. 5.37.

**Fig. 5.36** Amplification of an initial jitter for a case where the cavities are not detuned. A damping with $Q = 20$ but no damping was assumed

**Fig. 5.37** Amplification factor for an initial offset of the beam for structures with a damping factor $Q = 100$ and detuning
The long-range wakefield in this case is shown in Fig. 5.38. Taking also the second modes into account does not change the result significantly. The beam is also stable if the focusing is reduced. A phase advance per cell of $\Delta \Phi = 83^\circ$ does not change the results very much, while going down to $\Delta \Phi = 60^\circ$ results in a somewhat larger effect. Because of the detuning, the requirement on the damping could be relaxed, with $Q = 500$ and the nominal lattice one finds an amplification.

It is interesting to note that the offsets of most of the bunches are not amplified in the linac. Only in the transient regions is there a significant effect. A jitter of the quadrupoles of 1 $\mu$m leads to an amplitude of the slice positions at the linac end of about $0.05 \times \sigma_x$, see Fig. 5.39.

In order to provide more space for the installation of modulator-klystrons, it would be preferable to increase the linac length by replacing every second structure by a drift and to double the number of cells. In this case the stability is improved in one plane but reduced in the other, as can be seen in Fig. 5.40. This can be resolved by having pairs of cavities followed by pairs of drifts, rather than single cavities followed by single drifts.

While the simulations are not complete and a number of jitter tolerances remain to be investigated, the present results are very promising. The beam is very stable even relaxing the value for the cavity damping to $Q = 500$. Since $Q = 100$ was already measured and $Q \approx 11$ was calculated so far for a perfect load [M. Luong, CERN, private communication], transverse instability in the drive beam linac does not seem to be an issue.
Fig. 5.39 Amplification factor for a quadrupole jitter of 1 μm

Fig. 5.40 Amplification factor for a linac using the nominal structures if every second cavity is replaced by drift. The graph on the left is for the x-plane, the one on the right for the y-plane
5.4.5 Bunch compression

The bunch length of the drive beam at injection is relatively short compared to the wavelength of the accelerating RF. It is therefore an interesting option to use the energy spread induced by single-bunch beamloading to perform the compression. The most important lower limit for the allowed bunch length at the end of the accelerating linac arises from the coherent synchrotron radiation in the first of the two combiner rings and the final arcs where the beams are bent back in order to run parallel to the main beam. A r.m.s. bunch length $\sigma_z = 2 \text{ mm}$ seems to be sufficient to suppress this effect to an acceptable level (see Chapter 6). In principle one can compress the bunches as much as possible in the accelerator then decompress them before the rings and recompress them after the final arcs again. Another solution would be to compress the bunches only to $\sigma_z = 2 \text{ mm}$ in the accelerator and perform the final compression just after the arcs.

Up to now longitudinal single-bunch wakefields are not available, so it is only possible to use the scaled parametrization given above. To calculate the achievable bunch length a number of simple simulations have been performed using single-bunch wakefields.

The initial bunch length is assumed to be $\sigma_z = 4 \text{ mm}$, the initial energy $50 \text{ MeV}$, and the uncorrelated energy spread $\sigma_E / E = 3/4\%$. The beam is collimated in energy at $\pm 3\sigma_E$ before it is accelerated. The compression is not simulated in detail but only a value $R_{56}$ is chosen, nonlinearities are therefore not taken into account. We expect that the energy spread at the linac entry will be partly correlated since it is mainly due to beam loading. This would allow a first compression at $50 \text{ MeV}$ yielding a shorter bunch. However, the pessimistic assumption of complete uncorrelation is used to evaluate the achievable compression.

**Case 1**

The beam is accelerated at a RF phase $\Phi = -12^\circ$ throughout the linac. At an energy of about $E = 100 \text{ MeV}$ it is compressed a first time to a bunch length of $\sigma_z = 200 \mu\text{m}$.

A second and final compression step after the linac yields $\sigma_{zf} = 290 \mu\text{m}$. The final average energy is $1.16 \text{ GeV}$ with an r.m.s. spread of $18 \text{ MeV}$.

Figure 5.41 shows the phase space after the second step. Introducing some nonlinearity into the compression should allow one to reduce the bunch length even further by decreasing the importance of the high- and low-energy tails. The slight energy–position correlation in the central part of the bunch could then be reduced. In turn it is also possible to reduce the energy spread somewhat by running closer to the crest of the RF.

**Case 2**

To demonstrate the independence of the results on the longitudinal wakefields, they are neglected in this case by setting the bunch charge to zero. Otherwise it is the same as before. The final compression at $E = 1.16 \text{ GeV}$ yields a minimal bunch length of $\sigma_z = 340 \mu\text{m}$, the energy spread is $\sigma_E = 8.5 \text{ MeV}$. So the result is indeed very close to the one above.

**Case 3**

In order to evaluate the headroom available for reducing the bunch length even further, the beam is in the present case compressed three times in the linac, uncompressed at the end to $\sigma_z = 2 \text{ mm}$ and finally compressed again as much as possible.

The final $18 \text{ MeV}$ bunch length is about $167 \mu\text{m}$ with an energy spread of $\sigma_E = 13.4 \text{ MeV}$.

The $R_{56}$ and other values for the compression stages can be found in Table 5.22. The uncompression step is left out.

69
Table 5.22
Parameters of the compression in case 3

<table>
<thead>
<tr>
<th>Step</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{56}$ [mm]</td>
<td>306</td>
<td>104</td>
<td>41</td>
<td>–</td>
</tr>
<tr>
<td>$\langle E \rangle$ [MeV]</td>
<td>98</td>
<td>241.4</td>
<td>527</td>
<td>1163</td>
</tr>
<tr>
<td>$\sigma_E$ [MeV]</td>
<td>1.2</td>
<td>2.7</td>
<td>5.3</td>
<td>13.4</td>
</tr>
<tr>
<td>$\sigma_z$ [$\mu$m]</td>
<td>1310</td>
<td>623</td>
<td>344</td>
<td>167</td>
</tr>
</tbody>
</table>

Fig. 5.41 Phase-space distribution after the second and final compression step of case 1. It should be noted that the macroparticles have different weights.

**Case 4**

This is the same as case 3 except that the RF phases are set to zero after the second compression step to increase the efficiency of the acceleration.

The two per cent loss in gradient due to the $12^\circ$ acceleration phase is thus avoided for most of the linac length. While the bunch length increases slightly to $\sigma_z = 200 \, \mu$m, the energy spread is reduced to $\sigma_E = 11.4$ MeV, see Table 5.23.
The phase space distribution is shown in Fig. 5.42. The final longitudinal end energy distribution is shown in Figs. 5.43 and 5.44.

### Table 5.23
The parameters of the compression in case 4

<table>
<thead>
<tr>
<th>Step</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{56}$ [mm]</td>
<td>306</td>
<td>104</td>
<td>46</td>
<td>--</td>
</tr>
<tr>
<td>$\langle E \rangle$ [MeV]</td>
<td>98</td>
<td>241.4</td>
<td>534</td>
<td>1166</td>
</tr>
<tr>
<td>$\sigma_E$ [MeV]</td>
<td>1.2</td>
<td>2.7</td>
<td>4.6</td>
<td>11.4</td>
</tr>
<tr>
<td>$\sigma_z$ [$\mu$m]</td>
<td>1310</td>
<td>623</td>
<td>380</td>
<td>200</td>
</tr>
</tbody>
</table>

**Fig. 5.42** The final compression using three compression steps in the accelerator for case 4, one decompression step at its end, and a final compression step at the entry of the drive beam decelerator. The upper tail contains about 4 per mil of the beam charge.
Fig. 5.43 Longitudinal bunch distribution after the final compression step

Fig. 5.44 Energy distribution of the bunch after the final compression step

Tolerances
Variations in the acceleration gradient and phase in the linac, the initial beam energy, and the bunch charge lead to a longitudinal shift of the bunches in the compressors.

Table 5.24 summarizes the variations of these parameters leading to a longitudinal shift of 10 \mu m.

The tolerance on the longitudinal position of the bunch centre is given by the phase difference of the drive beam in the decelerator to the main beam. The energy difference $\delta E$ of the main beam resulting from phase shifts $\delta \phi_1$ is given by
\[ \delta E = \sum G_i L_i \sin (\Phi_i) \delta \Phi_i \]

where \( G_i \) and \( L_i \) are the gradient and length of the different drive beam decelerators.

The average phase and the phase shift is denoted by \( \Phi_i \) and \( \delta \Phi_i \). The main beam energy can change significantly if the phase shift is coherent over a significant length of the pulse. Assuming that all phases change coherently, a longitudinal position error of about \( \Delta_x = 8 \, \mu m \) leads to an energy change of 0.1% in the main beam. Such a shift would, however, be straightforward to correct with a feedback system.

The coherent longitudinal offset of a train for one drive beam decelerator after the combiner rings can be corrected using a feedback on the next train. Since the last section is running at a RF phase of \( \Phi = 30^\circ \), a systematic shift of the whole train by \( \Delta_x = 60 \, \mu m \) leads to an energy variation of the main beam of \( \delta E/E = 10^{-3} \). However, it should again be straightforward to correct this offset mostly within the train.

Bunch-to-bunch jitter is less important. The distance between bunches can be controlled using resonant cavities. This should allow us to space the bunches very accurately avoiding systematic differences between the trains.

### Table 5.24
Tolerances required for a longitudinal shift of the bunches of less than about 10 \( \mu m \)

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{(G-G_0)G_0}{G_0} ) ( [10^{-4}] )</td>
<td>0.45</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>( \frac{(E_i-E_{i,0})}{E_{i,0}} ) ( [10^{-4}] )</td>
<td>0.8</td>
<td>16</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>( \delta \Phi_{RF} ) ( [0.1^\circ] )</td>
<td>0.12</td>
<td>0.1</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>( \frac{(q_q-q_0)/q_0} ) ( [10^{-2}] )</td>
<td>0.2</td>
<td>-</td>
<td>0.25</td>
<td>0.2</td>
</tr>
</tbody>
</table>

A completely uncorrelated jitter from bunch to bunch can not be taken out with a feedback, but any bunch of the main beam will see the average effect of a large number of drive beam bunches. The fill time of a main linac cavity corresponds to the passage of about 400 bunches through the transfer structure. In addition, the effects are averaged over about 20 decelerators, where the ones running at a RF phase significantly different from \( \Phi_{RF} = 0^\circ \) contribute most.

Before the trains are folded in the rings, a feedback that corrects a later part of the pulse according to a measurement on the earlier part acts as a feedforward since the part of the pulse going into the same drive beam decelerator will be folded. This allows us to correct errors of the first part with the second. At several places we can also implement direct feedforward as for example in and after the compressor rings and at the arcs which bend the drive beam into the decelerator.

The required short bunch lengths seem to be achievable. It is necessary to take the nonlinearities of the compression into account as well as the effect of the transport from the accelerator to the decelerator which may change the energy spread and longitudinal distribution of particles. It is important to understand the longitudinal beam jitter and it offers an interesting field for applying feedbacks and feedforwards. The large number of options makes us optimistic that we can find solutions to these problems.

#### 5.4.6 Alignment and steering

After installation, all elements of the accelerator will be misaligned with respect to their nominal positions. The distributions of these position errors are taken to be Gaussians centred at the nominal position. For the structures a r.m.s.-width \( \sigma_{\text{struct}} = 100 \, \mu m \) is used while for the BPMs and quadrupoles
\( \sigma_{\text{BPM}} = 100 \ \mu\text{m} \) and \( \sigma_{\text{quad}} = 500 \ \mu\text{m} \), respectively. The misalignment from structure cell to structure cell is also assumed to be \( \sigma_{\text{cell}} = 100 \ \mu\text{m} \) while for the BPM resolution \( \sigma_{\text{res}} = 10 \ \mu\text{m} \) is taken. For the structures a damping of the transverse modes with \( Q = 100 \) was assumed as well as detuning by varying the radius from 42.6 to 54.4 mm. The beam needs to be steered using the BPMs to reduce the effect of misaligned elements. The simplest technique is the so-called one-to-one steering in which each quadrupole starting at the beam entry is moved such that the beam is centred in a following BPM.

![Graph showing emittance growth](image1)

**Fig. 5.45** Emittance growth in the accelerator using a simple one-to-one correction with the first bunch only.

![Graph showing positions of slices](image2)

**Fig. 5.46** Positions of the slices at the end of the accelerator using a simple one-to-one correction with the first bunch only. The beam size at this point is \( \sigma_x = 200 \ \mu\text{m} \) and \( \sigma_y = 200 \ \mu\text{rad} \).

That can be done either mechanically or with the help of correction coils. In principle one can use either a single bunch for this correction or a number of them up to the full train.

If only the first bunch is used for the correction, the emittance growth along the linac is about 3\%, see Fig. 5.45. The transverse positions of all slices normalized to the beam sizes without any effects is shown in Fig. 5.46.
It is obvious that even this simple method is sufficient to achieve a very good alignment. In practice, however, it will be necessary to control the position variation along a train that may arise from slower variations of the bunch properties along the beam. For different alignment tolerances the final position of the slices would scale linearly. It is also possible to use more advanced correction schemes. Most of them take advantage of the possibility to align the BPM to either a quadrupole or a line formed by other BPMs with a higher precision than to the beamline axis by varying the quadrupole strengths.
References


[Faillon, 1996] G. Faillon, Short presentation of high peak power TH2153 klystrons, Workshop for Pulsed RF Sources for Linear Colliders, 1996 (RF96), Kanagawa, Japan.


6 FREQUENCY MULTIPLICATION AND PULSE COMPRESSION

A general layout of the bunch train compression system is shown in Fig. 6.1. Its purpose, as discussed in Chapter 4, is to compress segments of the electron pulse delivered by the drive beam accelerator. Each long pulse is split at first into 640 trains of electron bunches, the trains are then combined in several stages in order to obtain the final 20 drive beam pulses, each one with 32 times the initial current.

![Diagram of the compression system]

Fig. 6.1 General layout of the CLIC RF power source. The compression system is composed of the times-two combiner delay and the two combiner rings. It transforms the initial 91 µs long pulse into the 20 high-current pulses needed to power the 20 drive beam decelerator sections.

6.1 Overview of the compression system

The drive beam accelerator accelerates a 91 µs long electron pulse with a mean current of 8.2 A up to 1.23 GeV.

This pulse is obtained by the combination at low energy of 640 bunch trains, 143 ns long, each one composed in turn of 87 bunches, whose flat-top charge is 17.6 nC. The bunches in each train occupy alternatively even and odd buckets of the drive beam accelerator fundamental frequency (937 MHz). The flat-top bunches are therefore spaced by 64 cm, i.e., twice the RF wavelength.

The overall pulse time structure is depicted in Fig. 6.2, where the way the individual trains overlap to constitute the pulse is also shown. In the bunch train compression system, the individual trains are first 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.
Fig. 6.2 Pulse structure. The bunches switch from odd to even buckets of the accelerating RF every 143 ns (with some overlapping). This allows the separation of 143 ns long slices (bunch trains) for further manipulation, while minimizing the transient beam loading effect in the drive beam accelerator.

The whole device is called the times-two combiner delay (see Fig. 6.3). The entire pulse is now composed of 320 trains, of 174 bunches each. The train spacing (head-to-head) is equal to twice the train length (286 ns, or 86 m), while the bunch spacing is 32 cm.

The same principle of electron bunch train combination is now used to combine the trains four-by-four a first time in the first combiner ring (see Fig. 6.4). This time two RF deflectors at 937 MHz create a time-dependent local deformation of the equilibrium orbit in an 86 m long 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 $\lambda$ is the spacing between bunches (and the wavelength of the RF deflectors). Therefore, at each revolution the RF phase seen by the bunches circulating in the ring increases by 90°, and when the second train arrives and 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 two more times, then the four interleaved trains are extracted from the ring by an ejection kicker half a turn later, and the same cycle starts again. The injection method is shown in detail in Fig. 6.5.

Fig. 6.3 Schematic layout of the times-two combiner. The first RF transverse deflector separates the 143 ns long slices of the incoming pulse. The even bunch trains are delayed by 143 ns with respect to the odd ones, and the second RF deflector recombines the trains two-by-two, doubling the current and halving the distance between bunches.
Fig. 6.4  The times-four pulse train combination in a ring

Fig. 6.5  Schematic description of the four turns injection into the combiner rings. 1) When the first train arrives all of its bunches are deflected by the second transverse kicker on the equilibrium orbit. 2) When the first train comes back, its bunches arrive at the kickers at the zero crossing of the RF field, hence they miss the septum and stay on the equilibrium orbit. The second train arrives 90° later, and its bunches are deflected by the second kicker to the equilibrium orbit. 3) Now the first train bunches are kicked inside the ring, the second train bunches arrive at the zero crossing, and the third train bunches are injected. 4) The first train bunches arrive again at the zero crossing, the second train bunches are in the inner orbit, the third train bunches are also at the zero crossing and the fourth train bunches are injected; after the second kicker the four trains are combined in a continuous train with one-quarter of the initial bunch spacing.
After the first combiner ring the whole pulse is composed of 80 trains, each of 696 bunches. The train spacing is equal to eight times the train length (1144 ns or 344 m), while the bunch spacing is 8 cm.

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 of 2784 bunches, with a bunch spacing of 2 cm. The distance between trains is now 4.576 µs 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, as discussed in Chapter 4.

The evolution of the beam parameters along the compression system is summarized in Table 6.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Initial</th>
<th>After TTCD</th>
<th>After 1st ring</th>
<th>After 2nd ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length (µs)</td>
<td>τ_p</td>
<td>91</td>
<td>91</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>Trains/pulse</td>
<td>N_T</td>
<td>1</td>
<td>320</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Bunch/train</td>
<td>N_B</td>
<td>55 680</td>
<td>174</td>
<td>696</td>
<td>2784</td>
</tr>
<tr>
<td>Train length (µs)</td>
<td>τ_T</td>
<td>91</td>
<td>0.143</td>
<td>0.143</td>
<td>0.143</td>
</tr>
<tr>
<td>Bunch separation (cm)</td>
<td>Δ_B</td>
<td>64</td>
<td>32</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Train separation (µs)</td>
<td>Δ_T</td>
<td>–</td>
<td>0.286</td>
<td>1.144</td>
<td>4.576</td>
</tr>
<tr>
<td>Pulse current (A)</td>
<td>I_p</td>
<td>8.2</td>
<td>16.4</td>
<td>65.6</td>
<td>262.4</td>
</tr>
</tbody>
</table>

### 6.2 Overview of the fundamental issues

The main problem to be solved in the bunch train compression system is to preserve the bunch quality during the compression process and obtain in a stable way the proper timing both between trains and between individual bunches. 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 minimized.

Possible deleterious effects include coherent and incoherent synchrotron radiation emission, non-isochronicity, beam loading and wakefields in the RF deflectors, and collective instabilities.

In the drive beam decelerator, the electron bunch length must be short compared to the 30 GHz wavelength in order to maximize the RF power production efficiency. At present the aim is to have an r.m.s. bunch length of $\sigma = 0.4$ mm, corresponding to 94% efficiency for 30 GHz power production (see Section 4.1).

These bunches are considerably shorter than the ones usually stored in rings, while their charge (17.5 nC) is rather high. Such high-charge, short bunches can radiate coherently a considerable amount of synchrotron radiation in a region of the electromagnetic spectrum below cut-off in the beam pipe, leading to both an average energy loss of the whole bunch and an energy spread within the bunch itself [Murphy, 1997; Kheifets, 1995; Warnock, 1990].

The power emission is concentrated at low frequencies [$\nu \leq 1/(2\sigma)$], and can be partly suppressed if $\nu \leq \nu_{\text{CUTOFF}}$ (shielding effect). The electric field acting on the bunch is independent of its energy.
Fig. 6.6 Longitudinal wakefield by coherent synchrotron radiation emission for a 17.5 nC, 0.4 mm r.m.s. long bunch, making one turn in a 86 m long ring with a bending radius $\rho = 3.6$ m. The different curves correspond to the unshielded case (solid line) and to different values of the beam chamber half-height $h$ (dashed-dotted line $h = 6.5$ mm, dashed line $h = 5$ mm), modelled by two parallel infinitely conducting plates.

An example of the longitudinal wakefield due to coherent synchrotron radiation (CSR) emission of a short high-current bunch is shown in Fig. 6.6.

Since bunches belonging to different trains make a different number of turns in the rings (from 1/2 to 7/2), they will undergo different energy losses, and develop different energy distributions. Bunch energy losses will give rise to relative phase errors between bunches through non-perfect isochronicity of the delay lines and combiner rings while the energy spread within each bunch will lead to bunch lengthening and phase-space distortion.

The CSR emission can be decreased by reducing the height of the beam pipe, which increases the shielding effect, but a limit is imposed by the necessary beam stay-clear unless one relies on having very small $\beta$-functions.

Furthermore, as can be seen in Fig. 6.7, the shielding can be very effective for minimization of the average energy loss, but less so for the induced energy spread. This behaviour is explained by an acceleration of the bunch tail by CSR with shielding, which increases the energy spread of the bunch but reduces the average energy loss by compensating for the energy loss of the bunch core (see Fig. 6.6).

For all of these reasons, and because the simplification of the model considered does not allow one to make a very reliable numerical evaluation of the shielding effect, only a moderate amount of it has been considered in the ring design, and this has been treated more as a safety margin than an operating necessity.

Short, high-charge bunches will also interact with any small discontinuity of the beam chamber (e.g. bellows, septa etc.), possibly being subject to further energy loss and spread and transverse instabilities as well.
Fig. 6.7 Ratio of the energy loss by coherent synchrotron radiation emission with parallel plate shielding to the one in free space, versus the scaling parameter $\Sigma = \sigma \rho^{1/2} \sqrt{2} h^{3/2}$, where $\sigma$ is the r.m.s. bunch length, $\rho$ the bending radius, and $h$ the half-distance between plates.

It is therefore highly desirable to manipulate relatively long bunches in the bunch train compression system, and compress the bunches just before injection into the drive beam decelerator sections. This is the primary reason that the bunches are compressed after acceleration in the drive beam injector only by a factor 2, from 4 mm r.m.s. to 2 mm r.m.s., while introducing a correlated energy spread (~ 1% r.m.s.), suitable for the final bunch compression, by a combination of RF curvature and longitudinal wakefields in the drive beam accelerator (see Section 5.4.4).

The bunch length of 2 mm r.m.s. has been chosen as a compromise; the use of shorter bunches would be preferable in order to improve the transverse stability in the drive beam accelerator, and to minimize the bunch phase extension in the transverse RF deflectors, while longer bunches would be even better, as discussed, from the point of view of CSR emission and isochronicity in the compression system.

The phase extension for a bunch of 2 mm r.m.s. length in the times-two delay and the first combiner ring deflectors (937 MHz) is small; a tail particle located at $3\sigma$ from the bunch centre will have a deflection angle that is only 0.7% smaller than the nominal one, so the effective emittance growth is negligible.

On the other hand, a $3\sigma$ particle of the same bunch will experience a deflecting kick which is 11% smaller than the nominal one in the second combiner ring deflectors (3.75 GHz). The effective emittance growth in this case is anyway limited to ~ 2% for an initial r.m.s. normalized emittance of $2 \times 10^{-4}$ m rad.

The relative emittance growth in the second ring deflectors as a function of the r.m.s. bunch length is given in Fig. 6.8. Such an effect will take place only at injection; tail particles belonging to bunches circulating in the rings will experience reduced kicks in both deflectors, so that they will stay on the equilibrium orbit.
Fig. 6.8 Relative emittance growth in a 3.75 GHz deflector as a function of the r.m.s. bunch length, for an initial r.m.s. normalized emittance of $1.5 \times 10^{-4}$ m rad

In the present design, the bunches have the same length in the drive beam accelerator and in the whole compression system for the sake of simplicity, and are compressed to the final length only at injection in the drive beam decelerator, but it would be possible, at least in principle, to manipulate the bunch length along the RF power generation complex, optimizing it in the different sections.

The need to preserve the correlation all along the compression system means that all the distortions caused in the longitudinal phase space by coherent synchrotron radiation, wakefields in deflecting cavities, and by longitudinal non-linearities must be kept small. In particular, attention must be given to the higher orders of the path length dependence on energy spread. To first order, the isochronicity of a lattice element A (cell or ring) is described by the $R_{56}$ coefficient of the linear transfer matrix $R$ for that element. The $R_{56}$ links the path length difference to the energy spread in the following way:

$$c \Delta t = R_{56} \frac{\Delta p}{p}$$

and is defined as:

$$R_{56} = \int_A \frac{D_s}{p} \, ds,$$
where $D_x$ is the dispersion and $\rho$ is the bending radius. A first-order isochronous element has an $R_{56} = 0$. A second-order transfer matrix $T$ can also be defined. The element $T_{566}$ will then describe the second-order dependence of the path length difference on the energy spread, so that:

$$c\Delta t = R_{56} \frac{\Delta p}{\rho} + T_{566} \left( \frac{\Delta p}{\rho} \right)^2 + \cdots \tag{6.3}$$

In the delay line and the rings, the $R_{56}$ coefficient must be kept close to zero in order to avoid direct bunch lengthening in the compression system; anyway a small error can easily be compensated for during the final compression if the correlated energy spread is unchanged. On the other hand, the higher-order effects will also cause a distortion of the phase space and this will hamper the final compression.

A numerical analysis has shown that second-order effects will cause a relevant bunch lengthening and must be corrected by using sextupoles. A more detailed evaluation will be given for each of the subsystems.

Another main concern is the beam loading in the RF deflectors in the second combiner ring, where the average current along the train is very high, especially just before extraction. In addition, the frequency of the second ring RF deflectors (3.75 GHz) is the highest in the compression system. Hence, the stored energy in these deflectors is the lowest and the beam loading in consequence is the highest. Beam loading could cause a decrease of the transverse kick along the bunch trains, which could give rise to variations in transverse position.

In order to overcome this problem, we have chosen to use short, travelling-wave, iris-loaded deflecting structures with a filling time which is short with respect to the train duration, so that a steady-state condition is reached as soon as possible, with minimum transient effects, although at the expense of a loss in deflection efficiency. A more detailed description is given in the subsections on the different components.

The extraction system for both rings is also a critical item, the issues being the high repetition rate (particularly in the first ring) and the interaction with the high-current beam (particularly in the second ring).

A possibility would be to use RF deflectors for extraction as well as for injection. This is indeed possible in the first ring, but not in the second one, where 15 GHz deflectors would be needed. Such frequency seems to be uncomfortably high, both in terms of beam loading and wakefields and of beam aperture.

The solution presented in the following for both rings is based on the use of a fast kicker constituted by travelling TEM wave transmission line pairs.

### 6.3 Component specifications and parameters

The parameters of the compressor system subsystems are presented in Table 6.2 and Table 6.3.

The lengths of the combiner rings are fixed by the overall timing of the RF power source (see Section 4.1), while only the path length difference is fixed in the times-two combiner delay. Its geometry has therefore been chosen to minimize coherent synchrotron radiation emission, and to keep within acceptable dimensions. Both the delay line and the ring arcs are based on isochronous lattice cells which are described in detail later.

Each subsystem has an independent path length tuning device (magnetic chicane), with a ±0.5 mm tuning range, in order to tune the bunch relative phase and to compensate for orbit variations (due for instance to thermal effects).
The RF deflector frequencies are also determined by the timing. 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 [Bernard, 1968; Bernard, 1970; Loew, 1965].

The design is basically the same for all deflectors, with the dimensions of the cells scaled linearly with frequency.

**Table 6.2**

Times-two combiner delay parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$4L_1/4L_2$</th>
<th>$25/68$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (line 1/line 2) (m)</td>
<td>$L_1/4L_2$</td>
<td>$25/68$</td>
</tr>
<tr>
<td>Bending radius (line 2)(m)</td>
<td>$\rho$</td>
<td>3</td>
</tr>
<tr>
<td>No. dipoles (line 2)</td>
<td>$N_D$</td>
<td>16</td>
</tr>
<tr>
<td>Dipole length (m)</td>
<td>$L_D$</td>
<td>2</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>$B$</td>
<td>1.25</td>
</tr>
<tr>
<td>RF deflector frequency (MHz)</td>
<td>$v$</td>
<td>937</td>
</tr>
</tbody>
</table>

**Table 6.3**

Combiner rings parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ring 1</th>
<th>Ring 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>$C$</td>
<td>86</td>
</tr>
<tr>
<td>Bending radius (m)</td>
<td>$\rho$</td>
<td>3.6</td>
</tr>
<tr>
<td>No. cells</td>
<td>$N_C$</td>
<td>4</td>
</tr>
<tr>
<td>Cell length (m)</td>
<td>$L_C$</td>
<td>13.6</td>
</tr>
<tr>
<td>No. dipoles / arc</td>
<td>$N_B$</td>
<td>16</td>
</tr>
<tr>
<td>Dipole length (m)</td>
<td>$L_B$</td>
<td>1.4</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>$B$</td>
<td>1.1</td>
</tr>
<tr>
<td>No. quadrupoles (arcs / S.S.)</td>
<td>$N_Q$</td>
<td>32 / 20</td>
</tr>
<tr>
<td>Quadrupole length (m)</td>
<td>$L_Q$</td>
<td>0.3</td>
</tr>
<tr>
<td>Max. quadrupole gradient (T/m)</td>
<td>$G_Q$</td>
<td>14</td>
</tr>
<tr>
<td>No. sextupoles</td>
<td>$N_S$</td>
<td>20</td>
</tr>
<tr>
<td>Sextupole length (m)</td>
<td>$L_S$</td>
<td>0.3</td>
</tr>
<tr>
<td>Max. sextupole gradient (T/m²)</td>
<td>$G_S$</td>
<td>26</td>
</tr>
<tr>
<td>Max. Twiss $\beta$-function (m)</td>
<td>$\beta_X, \beta_Y$</td>
<td>10.3, 10.9</td>
</tr>
<tr>
<td>RF deflector frequency (MHz)</td>
<td>$v$</td>
<td>937</td>
</tr>
</tbody>
</table>

6.3.1 *The isochronous cell*

All the arcs of the times-two combiner and of the combiner rings are based on a modified four-cell FODO structure with missing magnets, a solution already adopted in the recirculation arcs at CEBAF [York, 1987], and depicted in Fig. 6.9.

By taking out some of the bending magnets, drift spaces are introduced which generate a negative dispersion region in the two central dipoles. The cell lattice can thus be made isochronous to first order by tuning the strength of the quadrupoles in such a way that the integral of $D_X/\rho$ over the
two central dipoles exactly cancels the same integral over the two lateral ones; $D_X$ is high and positive in the missing magnets region but its contribution to the matrix element $R_{56}$ is zero since there $\rho$ is infinite.

"Missing magnets"

Fig. 6.9 Schematic layout of the basic isochronous cell used in the compressor system arcs

If other elements in the lattice (i.e., in our case, the path length tuning chicanes) have a small non-zero $R_{56}$, 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 corresponding to the missing magnets. By using different families of sextupoles it is possible to correct the third order as well. In principle it should 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.

6.3.2 The path length tuning chicane

The times-two delay combiner and the rings must have a path length tuning device, to tune exactly the relative phase of injected and circulating bunches, and to compensate for orbit variations due for instance to thermal effects. A tuning range of ±0.5 mm is required. Actually in the rings two such devices (one for each arc) are needed, since each train makes an odd number of half-turns in each ring.

A path length variation can be obtained using a magnetic chicane. The space available is rather limited, so the use of an isochronous chicane has been ruled out in the present design, to limit the chicane length. A simple chicane comprised of three bending magnets separated by drifts has been used instead.

Fig. 6.10 Schematic representation of the path length tuning chicane

A schematic representation of the chicane is shown in Fig. 6.10. The chicane must be compact, have a small $R_{56}$, and must perturb the optics only slightly when tuned around the average operating bending angle. The path length variation caused by a three-bending-magnet chicane can be described by the equation:
\[ c \Delta t = 2 \theta_0 \Delta \theta \left( \frac{2}{3} L_B + L_D \right) \] (6.4)

where \( \theta_0 \) is the average bending angle, \( \Delta \theta \) is the variation around \( \theta_0 \), \( L_B \) and \( 2L_B \) are the length of the magnets, and \( L_D \) is the length of each drift.

A high value of the average bending angle \( \theta_0 \) is desirable in order to have a good sensitivity and to span the tuning range with relatively small values of \( \Delta \theta / \theta_0 \) that do not perturb the optics. Also, long magnets and drifts increase the sensitivity.

On the other hand, a high value of \( \theta_0 \) and long magnets and drifts increase the value of the \( R_{56} \) and make the chicane less compact. A long chicane without quadrupoles between bends also means quite big \( \beta \)-functions which complicate the matching with the ring cells.

The parameters, presented in Table 6.4, have been chosen as a compromise between these somewhat conflicting requirements. The chicane is 3.5 m long and works around an average bending angle \( \theta_0 \approx 150 \) mrad. Each chicane has a linear transfer matrix element \( R_{56} = 0.065 \).

<table>
<thead>
<tr>
<th>Table 6.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicane parameters</td>
</tr>
<tr>
<td>Length (m)</td>
</tr>
<tr>
<td>Bending radius (m)</td>
</tr>
<tr>
<td>No. dipoles</td>
</tr>
<tr>
<td>Drift length (m)</td>
</tr>
<tr>
<td>Dipole length (1 &amp; 3) (m)</td>
</tr>
<tr>
<td>Central dipole length (m)</td>
</tr>
<tr>
<td>Dipole field (T)</td>
</tr>
<tr>
<td>Average bending angle (mrad)</td>
</tr>
<tr>
<td>Bending angle variation (mrad)</td>
</tr>
<tr>
<td>Sensitivity (m/rad)</td>
</tr>
<tr>
<td>Linear non-isochronicity (m)</td>
</tr>
<tr>
<td>Path tuning range (mm)</td>
</tr>
</tbody>
</table>

6.3.3 The injection and extraction regions for the rings

The RF injection system used in the rings has been qualitatively described in Section 6.1. Two RF transverse deflectors placed at a \( \pi \) phase advance produce a time-dependent oscillating bump in the ring.

The bunches belonging to the injected train will all 'see' the same deformation of the equilibrium orbit. When considering these bunches, therefore, we can neglect the time dependence.

The injection scheme then looks exactly like a conventional fast injection scheme based on a septum and a kicker [Bryant, 1992], as shown in Fig. 6.11, where the fast kicker role is taken by the second RF deflector.

In our case the first deflector is placed upstream of the septum, and provides the pre-compensation of the kick given by the second deflector to the circulating bunches (see Fig. 6.12).
The use of a $\pi/2$ phase advance FODO lattice, with the septum and kicker close to the focusing quadrupole is optimum since the phase advance between the septum and the kicker is such that the angular kick from the kicker corresponds to a maximum displacement in the septum.

Furthermore, the defocusing quadrupole between them sees a large amplitude and increases the beam deflection, while the focusing quadrupole close to the kicker sees a small amplitude and has a small influence.

As mentioned in Section 6.2, the extraction from the ring can be based on RF deflectors or on travelling TEM wave transmission line pairs. In the first case the extraction region will look very much like the injection region. In the second case, the length of the kicker forces us to find a somewhat less conventional solution, especially in the first ring where the space is limited.

One solution is shown in Fig. 6.13. The phase advance between the kicker and the septum is still $\pi/2$, and the use of a central triplet yields a rather constant $\beta$-function in the region of the kicker.
The amount of deflection needed for both injection and extraction can be calculated as follows: the horizontal r.m.s. beam dimension at the septum is given by:

$$x_b = \sqrt{\beta_{x,s} \varepsilon_{x,r}}$$  \hspace{1cm} (6.5)

where $\beta_{x,s}$ is the horizontal $\beta$-function at the septum and $\varepsilon_{x,r}$ is the horizontal real r.m.s. emittance. The minimum angular kick needed from the deflector can then be evaluated using the formula:

$$\phi = \frac{n x_b + x_s + x_i}{\sqrt{\beta_{x,s} \beta_{x,d}}} = \frac{n \sqrt{\beta_{x,s} \varepsilon_{x,r}} + x_s + x_i}{\sqrt{\beta_{x,s} \beta_{x,d}}}$$ \hspace{1cm} (6.6)

where $\beta_{x,d}$ is the horizontal $\beta$-function at the deflector, $x_s$ is the effective septum thickness, $x_i$ is a margin for injection errors, and $n$ is a margin on the beam clearance.

In our case we will consider $n = 6$, i.e., we allow only particles farther than six times the r.m.s. beam size from the beam centre to intercept the septum; any injection error, represented by $x_i$, must in our case be at a maximum of the order of 10% of the r.m.s. beam size, so we can neglect it altogether.

The minimum value of the deflection angle depends on the exact values of the $\beta$-function in the septum, kickers, and RF deflectors, and is higher in the first ring, where the $\beta$-function values are generally smaller.

More details will be given in the relevant subsections, but, in general, considering a normalized r.m.s. emittance of 150 $\pi$ mm mrad, a beam energy of 1.23 GeV, a value for $\beta_{x,d} = \beta_{x,s}$ of the order of 2 m, and a septum thickness of 1–3 mm, the minimum deflection angle required will be of the order of 2–3 mrad.

6.3.4 The RF transverse deflectors

The 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, negative group velocity, and a phase velocity equal to $c$. 

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We have taken as a reference the CERN design for a beam separator, originally at 2.85 GHz, scaled to 937 MHz and 3.75 GHz [Bernard, 1968; Bernard, 1970; Loew, 1965]. The cell geometry is shown in Fig. 6.14.

![RF deflector cell geometry](image)

*Fig. 6.14 RF deflector cell geometry*

For \( r < a \), where \( a \) is the iris radius, the deflecting mode field distribution has the form [Garault, 1964], (cylindrical co-ordinates):

\[
\begin{align*}
E_z &= E_0 \, kr \cos \theta \cos(kz - \omega t) \\
E_r &= E_0 \left[ \left( \frac{kr}{2} \right)^2 + \left( \frac{ka}{2} \right)^2 \right] \cos \theta \sin(kz - \omega t) \\
E_\theta &= E_0 \left[ \left( \frac{kr}{2} \right)^2 - \left( \frac{ka}{2} \right)^2 \right] \sin \theta \sin(kz - \omega t) \\
Z_0 \, H_z &= -E_0 \, kr \sin \theta \cos(kz - \omega t) \\
Z_0 \, H_r &= -E_0 \left[ \left( \frac{kr}{2} \right)^2 - \left( \frac{ka}{2} \right)^2 \right] \sin \theta \sin(kz - \omega t) \\
Z_0 \, H_\theta &= E_0 \left[ \left( \frac{kr}{2} \right)^2 + \left( \frac{ka}{2} \right)^2 \right] - 1 \cos \theta \sin(kz - \omega t)
\end{align*}
\]  \hspace{1cm} (6.7)

where \( k = 2/\lambda \) is the free-space wave number, and \( E_0 \) is the so-called equivalent deflecting field.

Calculating the Lorentz force on an electron from such a field distribution, it is straightforward to show that the maximum deflecting force is given by (rectangular co-ordinates):

\[
\begin{align*}
F_y &= 0 \\
F_x &= e \, E_0
\end{align*}
\]  \hspace{1cm} (6.8)
so that it is uniform in strength and direction over the aperture. Taking into account the voltage attenuation along the structure, described by the attenuation constant \( \alpha \), the following expression for the final deflection angle can be written:

\[
\phi = \frac{\sqrt{Z P \left( 1 - e^{-\alpha L} \right)}}{U}
\]  

(6.9)

where \( P \) is the input power, \( L \) the deflector length, \( U \) the electron beam energy, and \( Z \) the series impedance, defined as:

\[
Z = r' k \frac{c}{v_g}
\]  

(6.10)

The main parameters of the deflectors are listed in Table 6.5.

Beam loading arises in the RF deflectors of the type considered because the bunch develops in the deflector a transverse velocity component that couples with the transverse electric field.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>( v )</th>
<th>937</th>
<th>3750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td>( N_c )</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>De-phasing / cell</td>
<td>( 2 \pi / 3 )</td>
<td>( 2 \pi / 3 )</td>
<td></td>
</tr>
<tr>
<td>Opening (cm)</td>
<td>( 2 a )</td>
<td>13.7</td>
<td>3.4</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>( 2 b )</td>
<td>71.5</td>
<td>17.9</td>
</tr>
<tr>
<td>Cell length (cm)</td>
<td>( d )</td>
<td>10.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Total length (cm)</td>
<td>( L )</td>
<td>46.2</td>
<td>26.6</td>
</tr>
<tr>
<td>Group velocity</td>
<td>( v_G / c )</td>
<td>-0.0244</td>
<td>-0.0244</td>
</tr>
<tr>
<td>Filling time (ns)</td>
<td>( \tau_F )</td>
<td>58.3</td>
<td>36.4</td>
</tr>
<tr>
<td>Shunt impedance (k( \Omega ) / m)</td>
<td>( r' )</td>
<td>0.79</td>
<td>1.58</td>
</tr>
<tr>
<td>Voltage attenuation (Np / m)</td>
<td>( \alpha )</td>
<td>0.053</td>
<td>0.107</td>
</tr>
<tr>
<td>Deflection (mrad)</td>
<td>( \phi )</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Input power (MW)</td>
<td>( P )</td>
<td>50</td>
<td>15</td>
</tr>
</tbody>
</table>

The transverse velocity is given by:
\[ v_\perp(z) = \frac{e}{\gamma m_e c} \int_0^z E_0(s) \, ds \]  

(6.11)

The energy taken by the bunch from the field in one passage through the structure is given by:

\[ \Delta W = \frac{q_B}{c} \int_0^L v_\perp(s) \cdot E_\perp(s) \, ds \]  

(6.12)

where \( q_B \) is the bunch charge and the integral is evaluated along the bunch trajectory.

Energy exchange between the electrons and the field can also arise through the coupling between the longitudinal velocity and the longitudinal electric field component \( E_z \); this component is equal to zero on-axis, so this is possible only when the bunch starts to be deflected. Since the longitudinal component of the electric field \( E_z \) is 90° out of phase with respect to the transverse deflecting component, there is no direct coupling (beam-loading) for the deflected bunches. However, these bunches will leave behind a transverse wakefield that will deflect following bunches that are 90° out of phase with respect to the main deflecting field. This is in fact the case when the bunch trains are being interleaved during injection in the rings.

If a bunch does not enter the RF deflector on-axis, the beam loading effect stays nearly the same, since its trajectory is parallel to the nominal one, its transverse velocity is unchanged, and the transverse field component seen by the bunch changes only slightly. On the other hand, the transverse wakefield excitation is now enhanced, and can become the dominant one.

In summary:

1. Bunches injected on-axis, in phase with the deflecting field, couple to it through \( v_\perp \), taking energy from it (beam loading); they also can excite a 90° out-of-phase deflecting mode when they are deflected, but this last effect is in general smaller and is neglected.
2. Bunches injected off-axis, in phase with the field, will behave in the same way but, while the beam loading is exactly the same as in the previous case, the wakefield can be big, depending on the initial transverse position. In this case the change in transverse position along the trajectory is neglected in the calculation of the wakefield.
3. Bunches injected on-axis, 90° out of phase with respect to the deflecting field will not be deflected, hence the beam loading is zero. The transverse wakefield is also zero. They can be affected by wakefields left from leading bunches.
4. Bunches injected off-axis, 90° out of phase with respect to the deflecting field will not develop a transverse velocity component, so the beam loading is zero. They will however excite a transverse wakefield that now is in phase with the deflecting field.

The single-bunch beam loading and transverse wakefields are in general very small. The single-bunch beam loading can be evaluated easily using Eq. (6.12). A 17.5 nC bunch crossing the 3.75 GHz deflectors will absorb roughly \( 3 \times 10^{-5} \) of the stored energy. The transverse wakefield has been evaluated for the given deflector cell geometry using the code ABCI [Chin, 1992]. The transverse wake value is \( \pm 1.8 \times 10^2 \) V/pC/m. A complete multibunch analysis, including the field propagation and power refill in the structure, is difficult, and is presently in progress. From the single-bunch results, it appears that the wakefield effect should be smaller than the beam loading if the fluctuation in transverse position of the bunches is kept within \( \sim 10\% \) of the bunch r.m.s. dimension.

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6.3.5 The extraction kickers

Ejection of a drive beam train from the combiner rings with a kicker flat-top of $\leq 143$ ns has to be done after having accumulated bunches during four turns. In order to disturb neither the freshly accumulated drive train nor the next one, the rise and fall times must also be $\leq 143$ ns in the first combiner ring and $\leq 1$ $\mu$s in the second ring.

As discussed in Section 6.2, an extraction system based on a 937 MHz pulsed RF deflector could be used for the first ring, but the 2 cm bunch spacing in the second ring would require an RF deflector frequency of 15 GHz. The feasibility of such a deflector seems doubtful, not only because of the high frequency causing high transverse and longitudinal beam loading, but also because of the high pulsing rate (250 kHz).

It therefore appears interesting to study for both rings solutions based on travelling TEM wave transmission line pairs, powered in antiphase, with the wave moving against the beam. The kick angle $\phi_k$ during the flat-top of the pulse is equal to

$$\phi_k = \frac{2 \ell U}{a \gamma mc^2}$$  \hspace{1cm} (6.13)

where $U$ is the applied voltage; the kicker length is chosen to be $\ell = 2$ m with a half-aperture $a = 1.5$ cm. A deflection of 3 mrad requires a voltage $U = 11.3$ kV, corresponding to 2.6 MW into each 50 $\Omega$ line. The kicker filling time of 6 ns remains small compared with the 143 ns rise time.

Direct kicker pulser

A simple approach to overcome the large energy requirement of TEM waves for the above pulse duration consists in charging up the electrodes with twice the above voltage (22.6 kV) during a short fraction, say, 10–15 ns, of the 143 ns allowed time interval. During the flat-top (with the switch position as shown in Fig. 6.15), only the electric field provides the deflection since no current is flowing during the flat-top. After the flat-top the position of the switch is changed and the electrode is discharged into the terminations [M. Barnes and G. Wait, Triumf, private communication].

In this solution, with electrode capacitances of say 200–300 pF and a characteristic impedance of 50 $\Omega$, time constants of 10–15 ns can be expected. The best parameter set is to be found with a computer optimization.

Direct pulser for the kicker electrodes  \hspace{1cm} (M. Barnes and G. Wait, Triumf)

(only one kicker electrode with its pulser is shown)

---

Fig. 6.15 Sketch of the direct pulser solution for the kicker electrodes

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Note that at all times the beam-perturbing waves (whether beam-induced or from the pulser transients that move against the beam) are terminated for microwave frequencies passing the capacitor, but not for low-frequency ones.

However, the forward reflections from the capacitor do not interact with the beam and are eventually absorbed by the termination at the downstream end. Therefore the above solution seems excellent both from the beam-interaction and the transient point of view.

The large voltage of 22.6 kV to be handled by cascaded MOSFETs could be a problem and in the following a different solution based on TEM waves is discussed.

**Electric ring kicker**

Owing to the large power level needed (2.6 MW/electrode) it would be interesting to reuse a pulse that has traversed the kicker for the next ejection ~ 1000 ns later.

The idea of introducing two circulating electric rings (one for each electrode, see Fig. 6.16) is further supported by the fact that the losses in the ring are low since the majority of the power spectrum is below, say, 15 MHz; the main reason for the low spectrum being the long rise and fall times of 140 ns.

Two electric delay rings, 333 m circumference

TEM kicker electrodes

Beam

Common mode damper

directional coupler only 1 out of 2 shown
termination

50 KW, 1-30 MHz linear amplifier, solid state

Adding network for signals from 30 synthesizers between 1 and 30 MHz with computer controlled phases and amplitudes

**Fig. 6.16** Sketch of the electric ring kicker solution

Assuming a 1000 ns, air-filled, Cu coax. 50 Ω delay line with outer diameter 10 cm, having an attenuation of 0.0075 Np/turn at the fundamental frequency 1 MHz (harmonics have losses proportional to the square root of the harmonic number), we calculate first the signal spectrum of the circulating pulse and then the spectrum of the signal that has to be added per turn to maintain the pulse in steady state (see Figs. 6.17 and 6.18). The addition of loss compensation signals in the forward direction in the electric ring could be done with a wideband directional coupler (as shown in Fig. 6.16).
Fig. 6.17 The spectrum of the circulating pulse (full line) and the spectrum of the loss-compensation pulse times one hundred (dotted line) that has to be fed onto a ring to maintain the pulse in steady state

Fig. 6.18 The main circulating pulse (full line) and the compensation-pulse times one hundred (dotted line) that has to be fed onto a ring to maintain the pulse in steady state, shown in the time domain for a half-period

A high-precision circulating pulse (±1% on the flat-top and also along the zero line) can be maintained by the use of something like, say, 30 harmonic frequency synthesizers (harmonics of 1 MHz) [F. Caspers, CERN, private communication], driving a large-band (1–30 MHz, 50 kW) power amplifier connected to the directional coupler.

With a directional coupler, only AC signals can be maintained in the electric rings; to ensure zero deflection (or to add the DC complement) during the long time intervals (720 ns), when a kicker should be totally off, a wrap-around DC magnet is necessary for each kicker (or compensatory adjustments through adjacent bending magnets).
The synthesizers’ phases and amplitudes would be individually feedback-controlled via a computer algorithm from a pulse-observing monitor (or from an ejected beam-position monitor) in order to create and maintain the best pulse shape. Therefore both the wideband power amplifier and the directional coupler can have poor amplitude and phase characteristics.

The maximum compensation voltage to be added to the circulating wave during one turn is 0.75% of the flat-top voltage or 1.5% of the flat-top power, corresponding to the wideband directional power coupler transferring an instantaneous power of 39 kW.

The precise peak-power requirement for the wideband amplifier depends on the amplitude and phase characteristics of the coupler and the time allowed to establish the circulating wave prior to the arrival of the trains. A first optimistic guess could be 50 kW/electric ring.

Alternatively the directional coupler could be fed from a very fast pulsing network (short power pulses, say, < 2 ns), fired in a variable succession via a feedback system to produce the required pulse shape [H. Braun, CERN, private communication].

A complication could arise from reflected backward signals due to electrical imperfections in the ring; the worst-case situation would require a second feedback system injecting pulses in the backward direction of the electric rings for cancellation.

**Beam-induced common-mode signals in the combiner ring**

When the beginning of a train passes the kicker output ports the beam will induce its image current in the two electrodes. We therefore calculate that the beginning of the train experiences a deceleration of $i_b Z_0$ at the kicker entrance (the fine bunch structure assumed smeared out).

As soon as the beginning of the train passes the output ports of the kicker, the travelling signal on the electrode will empty by propagation towards the electrode input. Thus, after $2 t/c = 12$ ns there will be no more voltage at the electrode entrance (except the one created by the bunch structure) and the remaining part of the train will no longer be influenced. Similar considerations lead to the conclusion that the train tail will pass the kicker entrance before any voltage is created.

In the case of the first combiner ring, the average train current during the storage process being 16.3 A, we can expect a maximum deceleration of 4 turns $\times 16.3 \text{ A} \times 25 \text{ } \Omega = 1632 \text{ V}$ for the first train. Since the electric rings will accumulate the common-mode signals during the production of 80 such drive trains, the last drive beam will have a deceleration 80 times higher: 131 kV.

Such a voltage being unacceptable for the hardware, a common-mode (unwanted-mode) absorber for the electric ring pairs becomes necessary. The absorber should cause low losses to the difference mode (wanted mode, since it is used for the ejection). One concept, as outlined in the left side of Fig. 6.19, is based on a lossy foil in a median plane between the transmission lines of the two electric rings. Waves in antiphase, with no image currents in the lossy foil, should suffer no attenuation. The image current from the right conductor cancels the image current from the left one.

For common-mode waves, however, there are image currents in the foil, causing energy absorption.

The measured attenuation of common-mode waves is in first order proportional to frequency (and particularly strong in the gigahertz range), but so are also the beam-induced signals. One can expect that a large fraction of the electric loop line length would be populated by such damping sections.
Common mode damper concepts

a) with lossy foil

For the difference mode the image currents on the foil add and cancel for the common mode

b) with central coupler electrode

For the difference mode there is cancellation between signals coupled from the right and left electrodes, for the common mode the signals add

Fig. 6.19 Common-mode damper concepts

A different type of damping section could consist of directional couplers in the same symmetry plane and also coupling selectively to the common mode (following the previous considerations), see the right-hand side of Fig. 6.19. Several loops with different lengths would be needed to cover the band (up to several gigahertz) and to provide sufficient coupling.

Unwanted transverse kicks, due to beam-induced difference signals on the plates at low frequencies (1–30 MHz), should in principle be removed by the already described feedback system based on the ejection errors of previous trains, provided the power amplifiers (1–30 MHz, Fig. 6.16) have a generous dynamic range.

Conclusions
If the high voltage of 22.6 kV can be handled with cascaded MOSFETs the direct pulser solution seems to be the preferable technical choice, because it is simple and offers a remarkably low beam-interaction profile.

The more complicated wideband ring solution leaves the possibility of feedback correction of beam-induced transverse kicks via observation of ejection errors of earlier trains.

6.4 The times-two delay combiner

The times-two delay combiner is composed of a couple of RF deflectors, operating at a frequency of 937 MHz, connected by two beam lines with different lengths. Individual bunches will follow one of the two alternative paths depending on the RF phase at their arrival time in the first deflector.

The simplest possible layout, shown in Fig. 6.20, is comprised of a straight line, and a succession of four arcs with the same bending angle $\phi$ and the same average bending radius $\rho_{\text{AVE}}$. The two beam lines will have a length approximately equal to $4 L_1 = 4 \rho_{\text{AVE}} \sin \phi$ and $4 L_2 = 4 \rho_{\text{AVE}} \phi$.

The total length of the two lines can be treated as a free parameter, while the path length difference $\Delta L = 4 \rho_{\text{AVE}} (\phi - \sin \phi)$ must be equal to 43 m. Therefore it is possible to express $\rho_{\text{AVE}}$, $L_1$, and $L_2$ in terms of $\phi$. 

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The total length of the two lines as a function of $\phi$ is shown in Fig. 6.21. In order to limit the total length, a high value of $\phi$ must be chosen, but this can lead in turn to stronger synchrotron-radiation emission.

The arcs must be isochronous, and can be based on the general cell design described in Section 6.3.1. For such a cell the bending radius in the magnets is typically $\rho = \rho_{\text{AVE}} / 0.4$. By knowing that, the relative energy loss from incoherent and coherent synchrotron-radiation (CSR) emission can be calculated, as well as the shielding scaling parameter $\Sigma$.

These quantities are shown in Fig. 6.22 and Fig. 6.23.

While the incoherent synchrotron radiation emission depends quite strongly on $\phi$, (but is anyway small) the power emitted by CSR shows only a weak dependence on this parameter. Furthermore, even for high values of $\phi$, the shielding parameter $\Sigma$ is high enough to guarantee a sufficient suppression of the effect (see Fig. 6.7).

A reasonable choice would be therefore $\phi = 0.7\pi$. In this case the total length will be limited to less than 100 m, with $L_1 = 6.25$ m and $L_2 = 17$ m. Also in this case the unshielded CSR emission effect is more than a factor 3 lower than in each of the two combiner rings. The shielding parameter $\Sigma$ is close to 1.
Fig. 6.22 Relative energy loss for a bunch transported along the curved transfer line of the delay combiner, from incoherent (dotted line) and coherent (solid line) synchrotron-radiation emission. The shielding effect for coherent synchrotron radiation is not considered.

Fig. 6.23 The shielding scaling factor $\Sigma$ for CSR emission as a function of the arc bending angle $\phi$, for a beam pipe radius of 1.5 cm.

The total length of the straight transfer line is 25 m, while the total length of the curved one is 68 m. The latter consists of four 17 m long cells of the type described. The layout of the curved transfer line is shown in Fig. 6.24.

A path length tuning device must be included in one of the two lines. Two choices are possible. The first is to use a first-order isochronous chicane in the straight transfer line, tuning the curved transfer line cells to be isochronous. The alternative choice is to incorporate the short chicane described in Section 6.3.2 in the curved transfer line (between the second and third cells) and to tune the cells to be quasi-isochronous, compensating the $R_{56}$ contribution of the chicane.
Weak bending magnets must be added to both ends of the straight transfer line to cancel the initial RF kick, or, alternatively, a backing magnetic field added to the RF deflectors.

**Horizontal plan view [X-Y plane]**

![Diagram of the curved transfer line]

Drawn on a 3.0000m square grid

**Fig. 6.24** Plan view of the curved transfer line of the delay combiner, drawn on a 3 m square grid

### 6.5 The first combiner ring

As discussed before, the ring must be 86 m long and isochronous. A plan view of the ring is shown schematically in Fig. 6.25. Each arc is composed of two 13.6 m long quasi-isochronous cells, and a 5.6 m long chicane (including the matching sections) for path length tuning.

Two 10.2 m long straight sections are used for injection and extraction. Injection is based on two 937 MHz transverse RF deflectors, and extraction is obtained by the previously described TEM kicker electrodes. Alternatively, an extraction system based on 3.75 GHz RF deflectors could be used.
6.5.1 Lattice and tuning

The arc cells are based on the modified four-cell FODO structure with missing magnets concept described in Section 6.3.1. The cell lattice can be made isochronous to first order by tuning the strength of the quadrupoles. The basic isochronous cell lattice is shown in Fig. 6.26.

There are two cells per arc, and each chicane is located between these cells in the centre of the arcs to improve the lattice symmetry and to keep the ring locally isochronous as much as possible. Since each path length tuning chicane has a $R_{56} = 0.065$ the cell has been tuned to be quasi-isochronous ($R_{56} = -0.0325$) and to obtain first-order isochronicity in the arcs.

A defocusing quadrupole has been added to each side of the chicane for the matching of the $\beta$-functions. The total length of the chicane including the matching regions is 5.6 m. The arc lattice, including the chicane at the centre, is shown in Fig. 6.27.
Fig. 6.26 Lattice of the basic isochronous cell, showing the $\beta$-functions and the dispersion curve

Fig. 6.27 Lattice of the arc region (2 cells + 1 chicane), tuned to first-order global isochronicity. The $\beta$-functions and the dispersion curve are shown
Fig. 6.28 Isochronicity curve (delay as a function of energy spread) for one pass in the arc (no sextupole correction).

Fig. 6.29 Isochronicity curve for one pass in the arc (sextupole correction up to second order)

The isochronicity curve, i.e. the path length difference $c\Delta t$ versus the energy spread $\Delta p/p$, for one arc is shown in Fig. 6.28.

The first order has been completely compensated, but the second order is still too strong to be accepted (~ 6.5 cm delay per pass in the arcs, for a particle having ±2.5% energy spread). Sextupoles have therefore been added in the high dispersion regions of the cells (two sextupoles on each side of the focusing quadrupoles not surrounded by dipoles) to compensate for that.
In Fig. 6.29 is shown the isochronicity curve for the arc, after optimum tuning of the sextupoles for second-order cancellation. The delay per pass in the arc is now only ~ 0.4 mm for a ±2.5% particle, which is acceptable.

By dividing the sextupoles into two families it is possible to further improve the situation by correcting the third order as well and possibly by tuning the isochronicity curve to compensate for other non-linearities.

Two 10 m long straight sections, described below, are also provided to accommodate injection and extraction systems.

6.5.2 RF combination system and injection

The lattice of the injection region is rather conventional, being based on a two-cell FODO lattice and short matching sections to the arcs. Each FODO cell is 2.2 m long and has a π/2 phase advance.

The RF deflectors and the injection septum are placed close to the focusing quadrupoles of the FODO cell, as in a typical injection or insertion lattice (see Figs. 6.11 and 6.12).

The injection region lattice is shown in Fig. 6.30.

![Figure 6.30 Lattice of the injection region](image)

The value of the horizontal β-function at the position of the RF deflectors and of the septum is ≥ 2 m. Considering a septum thickness of 1.5 mm, a normalized r.m.s. emittance of 150π mm mrad and using Eq. (6.6), the required deflection is ≤ 2 mrad. The horizontal beam envelopes (for the deflected and non-deflected beams) are shown in Fig. 6.31.

As discussed in Section 6.2, the bunch phase extension in the first ring deflectors is small; a tail particle located at 3 σ from the bunch centre will have a deflection angle that is only 0.7% smaller than the nominal one, so the effective emittance growth is negligible.
6.5.3 Extraction

The extraction region is composed of a central triplet and two side doublets for matching. In this way it is possible to have a 2 m long drift with almost constant horizontal $\beta$-functions on each side of the triplet to accommodate the extraction kicker and the septum, also with a phase advance between them that is close to $\pi/2$. The extraction region lattice is shown in Fig. 6.32. The value of the horizontal $\beta$-function at the position of the kicker and of the septum is of the order of 2 m, as in the injection region.

In this case some additional margin is required on the angular kick, taking into account the non-exact phase advance relation and a greater apparent septum thickness (a longer septum can be used in this case), so the nominal deflection angle that has been chosen is 3 mrad.

The horizontal beam envelopes (for the deflected and non-deflected beams) are shown in Fig. 6.33.
6.6 The second combiner ring

The second ring is 344 m long and isochronous. Each of the two arcs is composed of ten quasi-isochronous cells with the same length (13.6 m) as the ones of the first combiner ring, and a 5.6 m long chicane for path length tuning, identical to that used in the first ring.

Two long straight sections (30.4 m) are used for injection and extraction. Injection is based on two transverse RF deflectors at 3.75 MHz, and extraction is obtained by TEM kicker electrodes.

6.6.1 Lattice and tuning

The layout of the arc cells is identical to that of the first combiner ring ones. Only the dipole field and bending angle is different, as well as the quadrupole tuning. There are 10 cells per arc. The path length tuning chicanes are also identical to the ones used in the first ring, with the same average bending angle $\theta_0$ and are located in the centre of the arcs. The chicane matrix element $R_{56} = 0.065$.

The arc cells are tuned to $R_{56} = -0.0065$, so their overall contribution exactly cancels the one from the chicanes. In Fig. 6.34 the basic isochronous cell lattice is shown, while Fig. 6.35 depicts the lattice for one cell and the adjacent chicane when the arc is tuned to be globally isochronous.

![Figure 6.34 Lattice of the basic isochronous cell in the second ring](image)
Fig. 6.35 Lattice of one cell plus the path length tuning chicane, matched to first-order isochronicity for the whole arc.

Fig. 6.36 Isochronicity curve, no sextupole correction.
Owing to the smaller bending field, the maximum dispersion in the cell is smaller than in the first ring. This causes a reduced higher-order non-isochronicity, but still a sextupole correction is needed to reduce the second-order contribution (which amounts to about 1 cm delay per pass in the arc for a ±2.5% particle). The isochronicity curves for the arcs before and after the sextupole correction is applied are shown in Figs. 6.36 and 6.37.

The sextupoles have the same location as in the first ring cells, i.e. in the high-dispersion regions on each side of the focusing quadrupoles not surrounded by dipoles. In this case as well, by dividing the arc sextupoles into two families, it is possible to correct the third order or tune it to an optimum value. The injection and ejection systems are located in the two long straight sections (30.4 m) at opposite sides of the ring.

6.6.2 RF combination system and injection

The injection region consists of three π/2 phase advance FODO cells with two matching sections to the arcs on either side. The length of each FODO cell is 6.6 m. Two cells would have been sufficient, as in the first ring, but three have been chosen to limit the value of the β-functions. The lattice is shown in Fig. 6.38. The RF deflectors and the injection septum are placed close to the focusing quadrupoles, at the optimum π/2 phase advance. The value of the horizontal β-function at the position of the RF deflectors and of the septum is ~ 9 m. The minimum deflection angle calculated using Eq. (6.6) is, even allowing 3 mm for the septum thickness, < 1 mrad (for a normalized beam emittance of 150π mm mrad), but a higher nominal value of 2 mrad has been chosen to minimize beam loading in the RF deflectors.

6.6.3 Extraction

The extraction region is similar to that of the first combiner ring, with a central triplet and two matching regions on either side. The lattice is shown in Fig. 6.39. The value of the angular kick is in this case reduced from 3 mrad in the first ring to 2 mrad, because of the higher value of the horizontal β-functions at the kicker and septum locations.
6.7 Radiation effects and longitudinal dynamics

As mentioned before, the preservation of the longitudinal phase-space of the individual bunches is important in order to be able to compress them to the desired length 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. Figures 6.40 and 6.41 show the longitudinal wakes, caused by CSR for one turn in the first and the second combiner rings. Both the unshielded case and the shielded one (2 cm beam pipe radius) are shown.
Fig. 6.40 Longitudinal wakefield due to CSR emission, experienced by a 2 mm r.m.s. long bunch during one turn in the first combiner ring. The full line and the dashed one correspond to the unshielded and the shielded case (2 cm beam pipe radius), respectively.

Fig. 6.41 Longitudinal wakefield due to CSR emission, experienced by a 2 mm r.m.s. long bunch during one turn in the second combiner ring. The full line and the dashed one correspond to the unshielded and the shielded case (2 cm beam pipe radius), respectively.

The evolution of the longitudinal phase-space in the first and second 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 (presented in Figs. 6.29 and 6.37) and considering the initial conditions after acceleration presented in Section 5.4.5 – Case 1.

The results are summarized in Figs. 6.42 and 6.43.
Fig. 6.42 Longitudinal phase space at extraction from the compressor system, and at injection in the drive beam decelerator, after the final compression, for a bunch that has made 7/2 turns in both combiner rings.

Fig. 6.43 Longitudinal phase space at extraction from the compressor system, and at injection in the drive beam decelerator, after the final compression, for a bunch that has made only half a turn in both combiner rings.

The results are promising, since the final bunch length after compression is close to the target one (in the idealized case of Section 5.4.5 it was 290 \( \mu \)m), and the maximum bunch-to-bunch variation in final length, (from 340 to 360 mm r.m.s.) is rather small, especially in terms of the form factor for 30 GHz RF power production (from 0.976 to 0.973 for the amplitude form factor, i.e. a 0.6\% variation in power production capability). Such a small bunch-to-bunch variation can be averaged out along the RF pulse, on a scale of the transfer structure drain time, by the power build-up mechanism in the transfer structures.

The contribution from the times-two delay combiner which can be made rather small, as well as the non-linear contributions from the return arcs and the final compressor system, have been neglected for the moment. Also, as mentioned in Section 6.2, there are some uncertainties about the shielded calculation. On the other hand, the situation can be further improved by optimizing the isochronicity curves with a sextupole tuning, and possibly by adding pulse stretchers and compressors in front of each ring and optimizing the bunch length in each component.
References


7 BEAM TRANSPORT, OPTICS MODULES AND THE TURNAROUND

7.1 Description of the main functions

The different parts of the beam transport system between the drive beam accelerator and the drive beam decelerator must in general terms cover four types of function:

1) bending the beams whenever required in order to follow the geometrical layout of the drive beam generation complex, in such a way that the bunch length is preserved and the bending arc is as compact as possible in compatibility with tolerable synchrotron radiation effects;
2) adjusting the path length of each individual drive beam in order to have a possible regulation of the synchronism of these beams with the main linac beam, when they are injected into the different 700 m long decelerator sections;
3) compressing and also stretching the bunch length according to the needs at the different stages of the beam acceleration and multiplication process;
4) vertical or horizontal beam translation, isochronous or combined in specific cases with a bunch compression.

The four functions have been studied independently and occur in different places of the drive beam generation complex.

Function 1 appears each time the beam has to be bent, for instance after the pre-acceleration, between the combiner rings and mainly in the turnaround loop preceding the injection into the decelerator. Function 2 is only required before injection into the decelerator while function 3 is essential in the accelerating linac (Chapter 4) and immediately after the turnaround in order to obtain the desired bunch length in the decelerator (Chapter 8).

Function 4 serves mainly for the vertical translation that is needed after the turnaround because of the geometry adopted in the tunnel. It is used also for the incoming drive beam which has to be lifted up to the level of the turnaround loop and for the bunch compressors foreseen along the drive beam accelerator, based on two horizontal translations that maintain the beam on the axis of the linac.

Obviously, all four functions are necessary in the turnaround complex. Therefore, it will be described first; its main component can serve as a basis for the other transport system design.

7.2 Overview of the turnaround

The drive beam accelerator and the combiner rings are planned to be in a central position with respect to the two main linacs of the collider (Appendix C). This means that all the drive beams have first to be transported in a direction opposite to the main beams, before being turned around over 360° and injected into the different decelerating sections where they travel parallel to the main beams.

The transport line for the beam going upstream is of course located in the same tunnel as the decelerators, near the tunnel roof in order to minimize the loss of space. In this way we obtain an easily accessible area for the main linac and the drive beam decelerator which are placed on top of the same concrete support, at about 1 m above the level of the tunnel floor (Fig. 7.1). This position also has the advantage of preventing interference with the main linac and the decelerator by keeping the turnaround loops at a different level both in the tunnel and in the individual alcoves which will house these loops.

The difference in elevation of the beams going upstream and downstream (1.5 m approximately) imposes the need for vertical bends to bring the drive beam pulses down before injection into the decelerator sections. In addition, the up-going drive beam line is not exactly above the decelerator beam line, because the two have to run anti-parallel over a short distance near the roof (where the path-length chicane is foreseen); they are separated horizontally by 0.75 m.
Another element to consider is the fact that the transport line carrying the up-going drive beam pulses must run without interruption all the way to the starting point of the main linac (also the injection point of the first drive beam pulse). This transport line must therefore be placed slightly below the level of the turnaround loop (0.25 m) to avoid a crossing at the same level. Each drive beam pulse has therefore to be deflected vertically before entering its own turnaround loop. The relative vertical positions of these different beam lines are shown in Fig. 7.1 (tunnel cross-section) as well as in the elevation drawing of Fig. 7.2. The latter shows the location of the vertical bends bringing the drive beam from roof-level to decelerator-level, just above the transport magnets that guide the preceding drive beam pulse toward the dump. This compact design minimizes the space lost (not useful for power transfer) between two consecutive decelerator sections.

The different beam-transport elements of the turnaround area are schematically shown in the plan view of Fig. 7.2. The up-going drive beam arrives from the left through a simple FODO transfer line. After a vertical deflection the selected drive beam pulse enters the 360° loop, consisting of a 90° right-turn followed by three 90° left-turns. Drifts between these 90° turns are added to adjust the geometry and separate the axis of the down-going beam from the up-going one.
After the loop, the beam traverses a sort of bending chicane that serves to adjust the path length and compress the bunch length. It then goes through a dipole magnet that can be turned on in case of emergency to deviate the beam onto a dump, which is placed on the side of the tunnel. The drive beam pulse is then bent down to reach the decelerator injection-point. A further stage of bunch compression is done in this downward bend. Figure 7.2 also shows the end of the previous decelerator section (coming from the right in the picture) which has a dipole magnet and half-quadrupoles to bend the spent beam (with a large energy spread) into the dump already mentioned. The different elements or optics modules of this area are described in the subsequent sections.

The size of the alcove containing the turnaround as well as its relative position in the tunnel are shown in Fig. 7.2. There are as many alcoves as there are drive beam pulses; they can also be used to house electronic racks.

7.3 Turnaround lattice

As seen in the previous section the turnaround consists of four modules, each bending the beam by 90°. These modules are designed to be isochronous ($R_{56} = 0$) in order to preserve the bunch length and are based on the design concept elaborated for such applications with compact lattice and acceptable synchrotron radiation effects [D’Amico, 1995].

A module includes three bending magnets of equal length, two quadrupole doublets between these bends to control the dispersion as well as beam focusing in both planes, and one quadrupole triplet to join the modules.
The dispersion $D$ is adjusted such that the integral of $D(s) / \rho(s)$ is zero in the bending magnets (of bending radius $\rho$) and $D$ vanishes in the triplet. An optimization of the magnet length and of the drifts makes it possible to obtain compact modules with reasonable $\beta$-amplitudes and magnetic fields. Figure 7.3 gives a sketch of the elements of a module as well as the $\beta$-functions and the dispersion achieved. Table 7.1 summarizes the main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Bending magnet length</td>
<td>1.6 m</td>
</tr>
<tr>
<td>Bending magnet fields</td>
<td>1.0 / 1.8 T</td>
</tr>
<tr>
<td>Bending angle per dipole</td>
<td>23.5 / 43 degrees</td>
</tr>
<tr>
<td>Bending radius</td>
<td>3.9 / 2.15 m</td>
</tr>
<tr>
<td>Quadrupole length</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Quadrupole gradient</td>
<td>26.0 T/m</td>
</tr>
<tr>
<td>Module length</td>
<td>11.0 m</td>
</tr>
<tr>
<td>Transfer matrix coefficient $R_{56}$</td>
<td>0.00 m</td>
</tr>
</tbody>
</table>

Fig. 7.3 Optical functions of an isochronous module
**Fig. 7.4** Path length variation vs. $\Delta p/p$ within the bunch without sextupoles

**Fig. 7.5** Path length variation vs. $\Delta p/p$ within the bunch with one sextupole family
It can be seen from Table 7.1 that the total circumference of the turnaround is 44 m (plus two small drifts for the geometry adjustments).

The drifts are easily obtained by splitting the mid-quadrupole of the matching triplet into two quadrupoles and leaving 0.5 or 0.75 m between the two. We have checked that the coherent synchrotron radiation effect at the energy of 1.24 GeV is tolerable in this loop even in the absence of vacuum chamber boundaries.

The path length variation within the bunch, for a momentum spread $\Delta p/p$ of 0.025, has been calculated using the code MAD, first without sextupoles (Fig. 7.4) and then after compensating for the observed quadratic variation with one single family of sextupoles (Fig. 7.5). The sextupoles are placed near the doublets, where the dispersion is relatively large.

From Fig. 7.5 (note that the scale of the abscissa has been reduced by a factor 1000, i.e., mm instead of m) it can be seen that the remaining (mainly cubic) path length variation is strongly reduced. This effect nevertheless adds to the non-linear phase-space distortion expected after bunch compression in the accelerator (see Chapters 4 and 6). Higher-order compensation with more than one sextupole family remains to be studied.

### 7.4 Path length module

In order to adjust the phasing of each drive beam, a fine tuning of the path length is required before injection into the decelerating drive linac. For this tuning, it is necessary to include a kind of generalized chicane (it is more like a ‘dipole snake’, as we shall see below) immediately after the turnaround described above (Fig. 7.2). This path length module has to provide a non-zero $R_{56}$ coefficient in order to introduce a correlation between the path-length variation $\Delta l$ and a change $\Delta \theta$ of the deviation angle in the snake, around the finite average value $\theta_0$ selected for the dipoles. For this purpose, the sign of $R_{56}$ is not important since we can use both positive and negative values of $\Delta \theta$, but its amplitude must, however, be sufficiently large for an adjustment $\Delta l$ between 2mm and 5mm at most (i.e. half the RF period at 30 GHz). Since we are free to choose the sign of $R_{56}$, it has been chosen such as to achieve in the module a large fraction of the bunch compression needed at this location. According to Section 5.4.5 (case 1 or case 3), the total compression corresponds to a reduction of the bunch length from 2 mm to 290–170 $\mu$m (ideally, see also Section 6.7) with a correlated r.m.s. momentum spread of approximately 1.5–1.2%. This gives a total $R_{56}$ of ~ 0.15 m. The path length module has a $R_{56}$ equal to 0.13 m, the remaining compression being provided by the vertical-bend or translation described in the next section. Bunch compression requires an energy spread correlated with the position $z$ within the bunch. Running off-crest during acceleration with a positive phase and beam loading naturally generates this correlation (Section 5.4.5) which is then maintained in all the subsequent transport systems and rings. In the case of the drive beam accelerator, the head of the bunch has an energy above average and the tail has an energy below average.

Such a correlation (opposite to the one usually applied to the main beam) requires a positive $R_{56}$ for bunch compression (negative, for bunch stretching). A standard chicane made of three dipole magnets and without intermediate quadrupoles can only provide a negative $R_{56}$ because the path of the low-energy particles is longer than the average path. For a positive value, it is necessary to use a double bend with two dipoles deflecting the beam in the same direction, i.e. with a bending radius $\rho$ and a bending angle $\theta$ of the same sign [D’Amico, 1998a]. In this case, the integral of $D/\rho$ over the two dipoles is positive by definition.

The dispersion $D$, assumed to be zero, together with $D'$, at both the entrance and the exit of the double bend, is simply controlled by putting a focusing quadrupole at the mid-point between the two dipoles. The quadrupole inverts the sign of $D'$ and the function $D$ is mirror-symmetric with respect to this point. The path-length variation and the compression coefficient in such a double bend are given by:
It is important to underline that any path-length adjustment via $\Delta \theta$ induces only a small change of the absolute value of the compression coefficient given by

\[ R_{56} = l_B \frac{\theta^2}{3}. \]  

Equation (7.2) gives the contribution of one single double-bend. In order to reach a high value of $R_{56}$ without increasing too much the angle or the dipole length, it is necessary to have a succession of four double bends arranged in a geometry that looks like a chicane (Fig. 7.6); the total contribution to $R_{56}$ is simply equal to the sum of the individual contributions which do not depend on the sign of the deflection, since the double bends are separated by dispersion-free drifts. It is important to note that in the middle of these drifts we must introduce a triplet of quadrupoles, which has no influence on $R_{56}$ but is necessary to focus the beam and match the optics of the two adjacent double bends. Hence, the whole system (Fig. 7.6) looks like a dipole snake [D’Amico, 1998a] with the shape of a chicane. This transport channel, using alternately a single horizontally focusing quadrupole and a quadrupole triplet (as shown in Fig. 7.6), focuses the beam in the two transverse planes and controls the dispersion. Using then the relations (7.1) and (7.2), the following parameters were selected to give $R_{56} = 0.13 \text{ m}$ and $\Delta l = 0.5 \text{ mm/mrad}$:

\[ \theta_B = 16^\circ \quad l_B = 1.23 \text{ m} \quad B = 0.88 \text{ T} \quad l_{\text{drift}} = 0.5 \text{ m} \quad l_Q = 0.2 \text{ m} \quad G_Q = 20 \text{ T/m}. \]  

A path length adjustment of 2 mm implies a change in the bending angle by 4 mrad, which induces in the mid-point of the snake a still tolerable lateral shift by approximately 4.8 cm. With 5 mm, this shift reaches 12 cm.

Fig. 7.6 Layout of the path length module
7.5 **Vertical translation module**

As explained in Section 7.2, there is a difference in elevation of 1.5 m between the drive beams going upstream and downstream. This implies a vertical translation that we can conveniently combine with some bunch compression, using the double-bend concept described in the preceding section [D’Amico, 1998a].

This function is clearly achieved by half the dipole snake of Fig. 7.6, i.e. by using only two doublet-bends separated by an arbitrarily long drift and bending the beam into opposite directions. The main difference comes from the fact that the amplitude of the translation is fixed by the geometry in the tunnel (Fig. 7.1), i.e. 1.5 m.

In addition, the coefficient $R_{56}$ should be equal to 0.03 m in order to give a total of 0.16 m together with the path length module, a value that corresponds to a desirable over-compression with respect to the minimum required. Using the exact geometry and Eq. (7.2), we obtained the following parameters for the elements of the two double-bends:

\[
I_B = 1.23 \text{ m} \quad \theta_B = 11 \quad B = 0.60 \text{ T} \quad l_{\text{drift}} = 0.5 \text{ m} \quad l_Q = 0.2 \text{ m} \quad G_Q = 38 \text{ T/m} \quad (7.5)
\]

Note that the drift in the middle of the module, containing a matching quadrupole triplet, has a total length equal to 1.0 m, adjusted to satisfy the translation amplitude required.

The full vertical translation module is shown in Fig. 7.7 (with an arbitrary triplet in the middle, further studies being needed in order to better define the exact quadrupole requirements). It is also reported in the general layout of the turnaround area in Fig. 7.2.

We can note here that another small vertical translation of 0.25 m is needed, as mentioned in the introduction. Nevertheless, the corresponding module cannot be of the same type since it has to be isochronous — its design remains to be studied.

![Fig. 7.7 Layout of the vertical translation module](Image)

7.6 **Bunch compressors in the linac**

Considering again case 3 described in Section 5.4.5, there are three stages of compression in the accelerating linac (and a stretcher at the end of the acceleration). These compressions take place at different energies between 98 and 527 MeV and the required $R_{56}$ are listed in Table 5.22 of Section 5.4.5. Let us consider the first stage which requires the highest $R_{56}$ value of 0.306. Since we
again need a positive value in direct relation with the energy correlation in the linac, we have to make use of a series of double bends separated by triplets as in the path length module (Section 7.4). We again want to keep the beam along the same axis, i.e. the axis of the linac, but, since the $R_{56}$ value is about twice that of the path length module, it is judicious to have the geometry of a zigzag rather than that of a chicane. To achieve this we want the two inner double-bends (with opposite bends) to have twice the bending angle of the two outer double-bends (with opposite bends also), and to obtain a higher $R_{56}$ for the same compressor length. In this way, the beam remains on the same axis but its left and right excursions are equal and smaller than in a snake geometry for the same $R_{56}$.

At 98 MeV, the synchrotron radiation effects are small enough for a magnetic field of the order of 1 T to be acceptable. Hence, the magnetic length of each dipole magnet can be chosen as small as 0.5 m in order to limit the total length of the compressor module. The bending angle per magnet has to be selected in such a way that $R_{56}$ reaches the required value of 0.306 (Table 5.22 of Section 5.4.5).

We thus found an angle of $22^\circ$ per dipole of the outer double-bends and of course $44^\circ$ per dipole of the inner double-bends. The parameters obtained can be summarized as follows:

$$l_B = 0.5 \text{ m} \quad \theta_B = 22 / 44 \text{ } \beta = 1.1 \text{ T} \quad l_{\text{drift}} = 0.5 \text{ m} \quad l_Q = 0.2 \text{ m} \quad (7.6)$$

With these preliminary parameters, the total compressor length is approximately 11 m. Further studies are required to confirm these first results.

The other two bunch compressors planned in the drive beam accelerator should then be designed on the same basis of a zigzag module. If a bunch stretcher is actually necessary (Section 5.4.5), then a standard magnetic chicane made of three dipoles (without quadrupoles in between) can do the job given the non-standard correlation between energy and position within the bunch that prevails in the drive beam (Section 7.4).

### 7.7 Other beam transport components

In many places of the drive-beam generation complex, large bends are necessary. For a bending angle of $90^\circ$ the isochronous module of Section 7.2 can immediately be used. When the angle differs from $90^\circ$ a similar module based on the same design principles can be optimized to the new conditions without difficulty.

At various particular transitions of the drive-beam transport system, a specific component that matches the Twiss functions at zero dispersion is required. This is for instance the case (Fig. 7.2) at the junction between the transport line of the incoming beam and the $90^\circ$ isochronous module, between the turnaround and the path-length module, the path-length module and the vertical translation, and this latter module and the drive-beam decelerator. In most cases, it is an adjustment to a FODO type lattice or between two FODO type lattices. This is probably best achieved by using quadrupole triplets of the type FODO transformer (that transforms a $\beta$-crossing with equal and opposite derivatives into a different $\beta$-crossing with opposite slopes also), the properties of which have been studied in detail [D’Amico, 1998b] elsewhere.

Finally, the transport line of the upcoming drive beam (Fig. 7.2) is planned to be a simple FODO lattice, where the distance between quadrupoles should be of the order of 15 m or more in order to limit their number since this line is as long as the total main linac (2 × 13.5 km at 3 TeV c.m.). This would give a $\beta_{\text{max}}$ of the order of 30 m, but the final desired adjustment can be done via a FODO transformer as already mentioned.

### 7.8 Conclusions

In this section, the design principles of the different modules or components of the drive-beam transport system are described on the basis of studies done separately and quoted in the references. They provide plausible general parameters and a possible layout of the turnaround area. Nevertheless, detailed studies of the optical function matching and lattice optics (including higher order) remain to be done.
References


8 DRIVE BEAM DECELERATOR

Whilst passing through the compression system (see Chapter 6), the drive beam pulse is divided into 20 high-current pulses. The pulses are transported towards the beginning of the drive beam decelerator, which runs in parallel with the main linac and which is divided into 20 sections. Each pulse is transported and injected by one of the beam turnarounds, described in the previous chapter, into a drive beam decelerator section.

The RF power for main beam acceleration is extracted from a drive beam pulse along the entire section. At the end of the section, the spent drive beam pulse is dumped while the next pulse is deflected into the following turnaround and then the corresponding decelerator section to continue the acceleration process. This process continues until the main beam reaches the end at full energy, and it is repeated during each cycle of the collider.

8.1 General description and principles

![Diagram of Drive Beam Decelerator]

**Fig. 8.1** A deceleration-acceleration module

The drive beam decelerator structure is periodic, being composed of identical modules. The configuration of a deceleration-acceleration module is shown in Fig. 8.1. Each decelerating structure, or Power Extraction and Transfer Structure (PETS), feeds RF power to two main linac accelerating structures.

As the beam is being decelerated, it develops an energy spread due to the finite bunch length and to the transient effects as the structures are filled. Since the beam is decelerated to about 10–15% of its initial energy, the total energy spread at the end of the process is around 90%. To focus such a beam, it is necessary to scale the lattice carefully to keep the lowest energy particles from being overfocused. If this is done, the high-energy part of the beam is stable. In the decelerator we must use a PETS design that has the correct impedance and group velocity to provide the necessary deceleration and power output. This results in relatively low shunt impedance and a rather large group velocity.

There are several possible choices of structure; but the transverse stability of the decelerating beam also requires that the structure be damped and favours lower impedance structures. A good choice is a four-channel structure which has relatively low transverse wakefields [Millich, 1998]. A similar design, shown in Figure 8.22, is currently installed in CTF2 and has supplied up to 30 MW of power to a 30 GHz accelerating structure. Transverse stability is especially critical because of the large stored energy in a drive beam. Losses in the decelerator could result in damage to the decelerating structures. To avoid losses and provide stable running, the transverse wakefields must be damped with a $Q$ of about 50. Extensive simulations have been done to check the stability in the decelerator [Riche, 1998]. Provided the magnets are aligned with beam-based alignment, and the beam is steered with the average offset of the entire train, it seems possible to decelerate the drive beam to 85–90% of its initial energy. Since the beam is most sensitive at the lowest energy, it can be made more stable, if necessary, by sacrificing some efficiency.
8.2 Drive beam bunches for small multibunch energy dispersion

An important specification for the main beams is that the multibunch acceleration spread be less than ±0.2% in order to remain inside the final focus acceptance.

Almost constant multibunch energies are obtained by a specially shaped PETS output power pulse. The pulse time shape is such that, prior to the passage of the multibunches through the main beam CLIC Accelerating Structures (CAS), the steady state of the CAS (with beam-loading) is first established [Thompson, 1993]. This fill requires 11 successive groups of drive bunches through the PETSs. Each group contains 32 constant-intensity bunches as it exits from the second combiner ring. The 11 groups make up a staircase-like rising intensity ramp to produce the steady state in the CASs. During the subsequent passage of the multibunches this steady state is maintained with a constant input power to the CASs (231 MW/CAS). This constant CAS input power is obtained by 1504 full-intensity drive bunches passing through the PETSs. The intensities of the various drive beam groups (for minimum multibunch energy dispersion) are found with a computer program [L. Thordahl, CERN, private communication; Thordahl, 1995]. The accelerating wave inside the detuned CAS is calculated by integration of a differential equation [W. Wunsch, CERN, private communication] which accounts for varying beam-loading, resistive losses, varying $R' Q$ as well as group velocity with longitudinal position. The CASs have linearly varying $R' Q$ values (±26%, 26 kΩ/m average, linac convention) and group velocity (±15%, 0.0795 c average) [I. Wilson, CERN, private communication]. Figure 8.2 (upper curve) gives the optimized relative intensities (with respect to maximum values) of the 11 bunch groups necessary for the fill of the CASs.

![Figure 8.2](image)

**Fig. 8.2** Bunch group intensities (upper curve) and lagging transfer structure output amplitude (lower curve). The first 11 groups are shown. The maximum intensity is 17.54 nC/bunch, there are 32 bunches/group spaced by 2 cm

The optimum bunch intensity for the first group is about 67% of the flat-top value. The last fill group has full-intensity bunches. Figure 8.2 also indicates the accelerating field at the CAS upstream end (lower curve) versus time, resulting via the PETS from the bunch groups. Note that the approximately 10 CAS fill groups are preceded by approximately one pre-fill group for the PETS. The PETS pre-fill corresponds to the initial steep rise of the PETS output curve. The resulting optimized multibunch energy spread is 0.03% r.m.s. Unfortunately, for reasons of limited bandwidth at the HV gun grid level (drive beam), it may be necessary to start the drive bunch groups earlier at a lower intensity than 67%. The energy of such an additional drive bunch would be wasted. See details in Section 5.2 on the injector system.
8.3 Definition and function of the power extraction and transfer structure

The Power Extraction and Transfer Structure (PETS) [Schnell, 1988] is a passive RF device in which the bunched electron beam interacts with the impedance of a periodically loaded waveguide and excites preferentially one synchronous hybrid TM mode. In the process the beam kinetic energy is converted into electromagnetic energy at the mode frequency which travels along the structure with the mode group velocity. The RF power produced is collected at the downstream end of the structure by means of couplers and conveyed to the main linac accelerating structures by means of waveguides.

In its classic configuration the PETS consists of a cylindrical beam chamber which is coupled by longitudinal slits to four teeth-loaded waveguides as shown in Fig. 8.3, which shows a PETS model with waveguide dimensions 3.7 mm × 8.6 mm. The teeth-like corrugations on the waveguide walls are about 2 mm deep and spaced by 3.332 mm so that three teeth make up one wavelength of the 30 GHz \(2\pi/3 \) mode.

![Fig. 8.3 Three-cell section of a PETS](image)

8.3.1 Principle of operation

The steady state voltage drop of a bunched electron beam traversing a traveling wave structure of length \( l \) is given by:

\[
U_d = \frac{\omega}{4c} \left( \frac{R'}{Q} \right) \frac{l^2 I_l}{\beta_x} F(\sigma)
\]  

(8.1)

where \( w = 2 \pi \phi \) is the excited mode frequency, \( R'/Q \) is the longitudinal impedance per unit length (expressed in linac W/m) of the structure at frequency \( f \), \( F(\sigma) \) is the voltage form factor of the bunches and \( \beta_x = v_g/c \) is the normalised group velocity. The average current \( I \) is the bunch charge, \( q_b \), divided by the bunch spacing, \( T_b \).
The steady state output power from the structure is:

\[
P = \frac{\omega}{4c} \left( \frac{R'}{Q} \right) \frac{l_g^2 l_s^2}{\beta_g^2} F^2(\sigma)
\]  \hspace{1cm} (8.2)

A proof that the above 'standard' expressions apply rigorously also to very high group velocity structures such as the PETS contains a number of subtle physical arguments [Braun, 1999; Millich, 1999; Wunsch, 1999]. A partial understanding of these arguments has, for a period of time, lead to errors in the calculation of deceleration in and output power from the PETS. These errors were unfortunately only uncovered after the work that lead to this report was completed. As a result, the PETS output power, \( P \), and the deceleration, \( U_d \), are underestimated throughout the rest of this report by a factor \((1/1-\beta_g)\). In the future PETS design this will be taken into account, enabling us to use a larger PETS aperture, for the same power output and beam parameters. We will therefore profit from the consequent reduction in transverse wake-fields and from the larger acceptance.

In order for the mode excitation to be coherent and therefore constructive, the bunch spacing \( T_{b/c} \) must be a multiple of the mode wavelength which is 10 mm and the mode phase velocity must be equal to the speed of the relativistic bunches. The bunch time separation \( T_d \) however, must be much shorter than one drain time

\[
T_d = \left( \frac{1}{\beta_g} - 1 \right) \frac{l_g}{c}
\]  \hspace{1cm} (8.3)

in order for several bunches to contribute to the build up of the voltage \( U_d \). The drain time is simply the time it takes for the energy deposited by one bunch in the fundamental mode to travel out of the structure starting from the moment the bunch has left the structure itself. For a train of bunches lasting much longer than the structure drain time the peak power level in equation 8.2 cannot be exceeded but stays constant after one drain time has elapsed provided that the charge per drain time remains constant. Expression 8.2 therefore gives the steady state power level at the structure output when neglecting the internal wall losses; it shows the importance of the bunch charge and the bunch spacing which intervene at the second power.

The mode \( R'/Q \) contributes linearly to the output power level, which however is strongly influenced by the filling time factor \((1/\beta_g)\) in equation 8.2. The function \((1/\beta_g)\) versus \( \beta_g \) is plotted in Figure 8.4 where one remarks that low group velocities or high values of drain time are favourable to the output power level. The structure length \( l_g \) fixes the duration of the drain time and therefore the output power.
8.4 Power extraction and transfer structure designs

8.4.1 The four-waveguide structure parameters

The four-waveguide PETS shape is the result of a development started six years ago [Carron, 1992; Millich, 1993] aiming at the production of the most suitable device in terms of conceptual simplicity and functionality that satisfies the requirements imposed by the evolving drive beam and main linac parameters.

The 3D simulations were performed using the MAFIA set of codes [Weiland, 1994]. The frequency domain solver was used to determine the dimensions of the waveguides and of the teeth-like corrugations. The solution found for the resonant hybrid mode appears in Fig. 8.5. Because of symmetry, the electric field line pattern is shown in only one-quarter of the transverse PETS section. The arrow length being proportional to field intensity, we see that most of the mode energy is located in the vicinity of the waveguides, a feature which favours power extraction.

Figure 8.6 shows one PETS section in the longitudinal plane composed of three teeth where the mode phase advance of $2\pi$ per three cells is well illustrated. The mode frequency of the MAFIA solution differs by only 2 MHz from the nominal value of 29.985 GHz. The dispersion curve of the structure was established using a six-cell model, the $R/\mathcal{Q}$ and group velocity of the $2\pi/3$ mode were then easily derived.

Versions of the four-waveguide structure with different apertures and impedances have been examined.

Table 8.1 shows the main geometrical and RF parameters of the reference four-waveguide PETS. Such structure gives the desired power output (512 MW, i.e. 462 MW at the CAS input, including losses) for the nominal drive beam parameters (train of bunches with $q_b = 17.57$ nC, $\sigma = 0.4$ mm, corresponding to a form factor $F^2(\sigma) = 0.94$, spaced by 20 mm).
Fig. 8.5 Electric field of the main decelerating mode in the four-waveguide PETS

Fig. 8.6 Electric field pattern in the longitudinal plane
Table 8.1
Parameters of the four-waveguide PETS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam chamber diameter</td>
<td>24.000 mm</td>
</tr>
<tr>
<td>Waveguide width</td>
<td>8.600 mm</td>
</tr>
<tr>
<td>Waveguide height</td>
<td>3.700 mm</td>
</tr>
<tr>
<td>Slit aperture</td>
<td>7.000 mm</td>
</tr>
<tr>
<td>Teeth spacing</td>
<td>3.332 mm</td>
</tr>
<tr>
<td>Teeth height</td>
<td>2.053 mm</td>
</tr>
<tr>
<td>Teeth rounding radius</td>
<td>0.833 mm</td>
</tr>
<tr>
<td>Synchrotron mode frequency/c</td>
<td>29.985 GHz</td>
</tr>
<tr>
<td>Synchrotron mode group velocity/c</td>
<td>0.440</td>
</tr>
<tr>
<td>Synchrotron mode impedance (R'/Q)</td>
<td>62.200 (\Omega/m) (linac)</td>
</tr>
<tr>
<td>Peak transverse wakefield</td>
<td>0.420 V/pC/mm/m</td>
</tr>
</tbody>
</table>

8.4.2 Wakefields in PETS

The computation of longitudinal and transverse wakefields in PETS was done using the time domain solver T3320 in MAFIA. The transverse wake induced in a 24-cell section of PETS by a Gaussian bunch with \(\sigma = 0.6\) mm and a charge of 1 pC displaced 1 mm off-centre is shown in Fig. 8.7 and its spectrum in Fig. 8.8.

Fig. 8.7 Transverse wakefield in 24 PETS cells
One can see the purity of the spectrum which shows almost no higher order modes. It is therefore justified to assume that practically all the transverse deflection of an off-centre beam is caused by the main deflecting mode, the frequency of which is only a few tens of megahertz away from the main longitudinal mode. The value of the peak transverse wakefield is listed in Table 8.1 and is used in the computation of the transverse stability of the drive beam.

8.4.3 Transverse-mode damping

Overmodeled structures like the PETS have little frequency difference between longitudinal and transverse modes. Consequently, the damping method that is normally used for classical accelerating structures, based on frequency selective interception of the longitudinal wall current, does not work. We have therefore adopted longitudinal damping slits that intercept the transverse image current of the TE type hybrid mode. The PETS has been equipped with transverse-mode dampers which consist of four waveguides oriented at 45 degrees in the transverse plane. Each damping waveguide is formed by a slit 5.0 mm deep and 0.8 mm wide running along the whole structure. The slit is periodically widened by holes 2 mm in diameter with the same periodicity of 3.332 mm as the teeth. The slit is closed at its outer end with respect to the beam chamber by a rod of silicon carbide, a lossy material forming an RF lead. The position of the dampers is chosen to be in symmetry planes such that the main mode is not affected by their presence (no image current across the slits). The deflecting mode, on the contrary, couples to the corrugated slits that reduce its local phase velocity below c with the consequence of turning the Poynting vector towards the dissipating load.
Fig. 8.9 Longitudinal decelerating mode electric field pattern

Fig. 8.10 Transverse deflecting mode electric field pattern
The difference in mode coupling is well illustrated in Fig. 8.9 and in Fig. 8.10 relative to the study performed for the high-impedance version of PETS [Millich, 1995], which was built and successfully tested with the low-energy beam of the CLIC Test Facility [Carron, 1998]. In this particular structure the beam aperture is reduced to 15.0 mm to obtain the value $R'/Q = 1080 \, \Omega/m$ (linac), which is necessary to produce the nominal output power with reduced beam intensity and longer bunch spacing.

For the reference structure, model measurements indicate that the $Q$ value of the transverse mode could be lowered to about 60 by the dampers. This value is sufficiently low to ensure the transverse stability of the drive beam.

8.4.4 PETS parameter variation with beam chamber aperture

The tight alignment tolerances of the drive beam decelerator make it very desirable to have the largest possible PETS beam chamber aperture that is compatible with the output power level requirements.

We have studied three versions of the four-waveguide structure keeping the dimensions of the waveguides constant but varying the beam chamber radius. Fine adjustments of the teeth height were necessary in order to keep the right phase velocity. The results are given in Table 8.2 where we remark that the structure impedance decreases while the mode group velocity increases with larger chamber radius and both these effects reduce the output power level for given beam parameters.

The design with 24 mm diameter was chosen for the drive beam decelerator mainly because of the relatively low transverse wakefield in spite of the lower power output value. The longitudinal mode pattern for this geometry is shown in Fig. 8.11.

<table>
<thead>
<tr>
<th>Radius (mm)</th>
<th>$R'/Q$ (linac $\Omega/m$)</th>
<th>$\beta_g$</th>
<th>Output power (MW)</th>
<th>Peak wake Wy (V/pC/mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>104.2</td>
<td>0.40</td>
<td>1025</td>
<td>0.95</td>
</tr>
<tr>
<td>11.0</td>
<td>83.4</td>
<td>0.42</td>
<td>745</td>
<td>0.65</td>
</tr>
<tr>
<td>12.0</td>
<td>62.2</td>
<td>0.44</td>
<td>512</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 8.2

PETS parameter variation with beam chamber aperture. The output power has been calculated for the nominal drive beam parameters (2 cm spacing, $q_b = 17.57$ nC, $F^2(\sigma) = 0.94$)
8.4.5 PETS integrated longitudinal electric field uniformity

We pointed out earlier that, because of the particular geometry of the PETS, the electric field distribution of the main decelerating mode is not uniform. This fact causes the integrated decelerating field to vary as a function of angular position as well as of radial position within the beam chamber. This is well illustrated by the plots given in Fig. 8.12 and in Fig. 8.13, which show the variation of the normalized longitudinal integrated field over a three-cell section of the PETS as a function of radial position for $\varphi = 0^\circ$ (towards the middle of the waveguide) and $\varphi = 45^\circ$ (towards the chamber wall), respectively. The non-uniform beam deceleration causes the particles to receive transverse kicks which are a function of the particle position within the PETS chamber and which can be computed using the Panofsky–Wenzel formula [Panofsky, 1956]. The overall result found in tracking programs is that the drive beam transverse blow-up would be unacceptable if no cure were found for the problem (see Section 8.7). One possible simple solution consists in rotating by $45^\circ$ every other PETS in the drive linac so that a particle off-centre at $\varphi = 0^\circ$ in the first structure would be at $\varphi = 45^\circ$ in the second one, thus averaging the harmful effect of field non-uniformity. Figure 8.14 shows the normalized integrated field when averaged over two rotated structures as described above.
**Fig. 8.12** Normalized integrated field at $\varphi = 0^\circ$

**Fig. 8.13** Normalized integrated field at $\varphi = 45^\circ$
The useful effect of the alternate PETS rotation is reduced by the betatron motion of the particles in the drive linac lattice; however, tracking programs have shown that the overall result is beneficial to the transverse beam stability and worth the implementation effort (Section 8.7).

For the purpose of this study, the preferred PETS design is the reference four-waveguide structure with 24 mm aperture. However, we have different structure geometries, described below, for the purpose of increasing the aperture (for the same $R/Q$) and improving the field uniformity.

### 8.4.6 The six-waveguide structure

An alternative approach to the problem of field non-uniformity in the PETS consists of increasing the number of waveguides in the structure. Figure 8.15 shows a one-quarter transverse section of a six-waveguide structure with the electric field lines of the main decelerating mode. For the study of this geometry we used the MAFIA E400 module with $r \varphi z$ geometry. The beam aperture diameter is 24 mm, the sectors appearing as full metal are sufficiently large to house the transverse mode dampers not shown in this model. The other sectors form the teeth-loaded waveguides where the lips have been suppressed. The geometric and RF parameters are given in Table 8.3. The integrated longitudinal field as a function of radial position at $\varphi = 90^\circ$ and at $\varphi = 0^\circ$ is shown in Fig. 8.16 and in Fig. 8.17.
### Table 8.3
Parameters of the six-waveguide PETS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam chamber diameter</td>
<td>24.00 mm</td>
</tr>
<tr>
<td>Total structure diameter</td>
<td>33.40 mm</td>
</tr>
<tr>
<td>Teeth height</td>
<td>2.45 mm</td>
</tr>
<tr>
<td>Synchrotron mode $\beta_g$</td>
<td>0.41</td>
</tr>
<tr>
<td>Synchrotron mode $R/Q$</td>
<td>92.80 $\Omega$/m (linac)</td>
</tr>
<tr>
<td>Peak transverse wakefield</td>
<td>0.82 V/pC/mm/m</td>
</tr>
<tr>
<td>Effective structure length</td>
<td>0.80 m</td>
</tr>
<tr>
<td>Nominal output power</td>
<td>875 MW</td>
</tr>
</tbody>
</table>

---

**Fig. 8.15** A one-quarter transverse cross-section of a six-waveguide PETS
Fig. 8.16 Normalized integrated field at $\varphi = 90^\circ$ of the six-waveguide PETS

Fig. 8.17 Normalized integrated field at $\varphi = 0^\circ$ of the six-waveguide PETS
Fig. 8.18 Average normalized integrated field of the six-waveguide PETS

The radial integrated field distribution appears to be more favourable than in the four-waveguide structure with the same chamber aperture. We can again take advantage of the alternate rotation (by 90° in this case) of successive structures, and we see in Fig. 8.18 that the averaged integrated field is very uniform up to a radius of 8 mm. The six-waveguide structure is relatively new and has not yet been studied in detail. It represents, however, a very promising alternative to the four-waveguide structure with the one drawback that it is mechanically more complex. The output RF couplers for this type of structure have not yet been designed but ideas exist on possible solutions.

8.4.7 The eight-waveguide PETS

For the purpose of minimizing the adverse effects of non-uniform deceleration within the beam chamber of the PETS, we have investigated more exotic geometric configurations such as the eight-waveguide structure and the cylindrically symmetric structure.

The eight-waveguide PETS is simply an extension of the six-waveguide concept although we examined it first. Indeed the field uniformity in this PETS is remarkable, which would be ideal in this respect. However, the main drawback of the eight-waveguide structure comes from the fact that in order to house the transverse mode dampers and the eight waveguides we need to increase the chamber diameter to 28 mm as shown in Fig. 8.19. This large aperture causes the main longitudinal mode to have a relatively high group velocity, which lowers the output power level. Also this structure is more complex and the output power recombination causes additional concern. The main parameters of the eight-waveguide PETS are summarized in Table 8.4.
Fig. 8.19 Electric field lines in the eight-waveguide PETS

Table 8.4

Parameters of the eight-waveguide PETS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam chamber diameter</td>
<td>28.00 mm</td>
</tr>
<tr>
<td>Total structure diameter</td>
<td>34.40 mm</td>
</tr>
<tr>
<td>Teeth height</td>
<td>1.95 mm</td>
</tr>
<tr>
<td>Synchrotron mode $\beta_g$</td>
<td>0.74</td>
</tr>
<tr>
<td>Synchrotron mode $R/Q$</td>
<td>117.00 $\Omega$/m (linac)</td>
</tr>
<tr>
<td>Peak transverse wake-field</td>
<td>1.05 V/pc/m/m/m</td>
</tr>
<tr>
<td>Effective structure length</td>
<td>0.80 m</td>
</tr>
<tr>
<td>Nominal</td>
<td>270 MW</td>
</tr>
</tbody>
</table>

8.4.8 The cylindrically symmetric PETS

The cylindrically symmetric PETS constitutes the extreme case in the process of optimization of the field uniformity. Indeed this particular PETS is just a cylindrical waveguide with corrugated walls very similar to a bellows. In order to keep the right phase velocity, the teeth-like corrugations must be very shallow as shown in Fig. 8.20 which shows a section in the transverse plane. The normalized impedance of this structure is, however, rather high as is the peak value of the transverse wake. The main parameters of this cylindrical structure are given in Table 8.5. The two main drawbacks of the cylindrical PETS are the relatively high value of the group velocity and the high transverse wakefields, which cannot be strongly attenuated by the slit dampers. Indeed the transverse hybrid mode in this type of structure is essentially TM so that it presents little image current across the slit. This is not the case for the four-waveguide structure in which the mode pattern is essentially TE and presents a strong image current component across the damping slits.
In the cylindrical structure the transverse mode dampers are cut directly through the corrugated wall and lower the $Q$ value of the transverse mode to about 150. This structure would be the simplest to manufacture but probably the least suitable from the point of view of drive beam stability.

![Electric field lines in cylindrical PETS](image)

**Fig. 8.20** Electric field lines in cylindrical PETS

| Table 8.5  
Parameters of the cylindrical PETS |
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam chamber diameter</td>
</tr>
<tr>
<td>Total structure diameter</td>
</tr>
<tr>
<td>Teeth height</td>
</tr>
<tr>
<td>Synchrotron mode $\beta_g$</td>
</tr>
<tr>
<td>Synchrotron mode $R'/Q$</td>
</tr>
<tr>
<td>Peak transverse wakefield</td>
</tr>
<tr>
<td>Effective structure length</td>
</tr>
<tr>
<td>Nominal output power</td>
</tr>
</tbody>
</table>

8.5 PETS construction method, model work and beam tests

8.5.1 Construction method

Figure 8.21 gives a cross-section of the damped PETS installed and tested with beam in the CLIC Test Facility (CTF2). It consists of four copper racks with the periodic teeth to lower the phase velocity to $c$. In the present version the racks are held by four square-profile Cu-plated stainless steel bars that also hold the SiC absorbing material in slots along an inside bore of 15 mm. Steel is used for mechanical rigidity.
Fig. 8.21 Cross-section of the damped PETS used in the CLIC Test Facility

Fig. 8.22 Extremity of open PETS with output couplers and channels. Also visible to the right is a piece of SiC damping material engaged in its groove and held by a helicoidal spring

The corrugated damping slits with the SiC slabs are visible. The SiC slabs are pressed into the slots by helical springs running over the whole length.
All eight metal pieces are vacuum-brazed in a single operation. Furthermore, as can be seen from Fig. 8.22, 'adiabatic output couplers' constitute the extremities of the structure. The output power is channelled into the output slits by increasing the tooth height at the beginning of the outward ramp, thus slowing down the phase velocity locally. This causes the wavefronts to bend outwards (and also the Poynting vector). Towards the end of the ramp, inside the waveguides but before the last bends, the tooth height is slowly reduced to zero.

Alternatively, but not attempted yet, one may use as output couplers two distributed waveguides running behind two of the four rows of teeth and communicating with the structure inside via many holes (situated between teeth). By proper hole spacing and dimensioning it should be possible to couple out the energy totally (the output guides would also need corrugations to ensure that $v_{ph} = c$).

The expected advantages could be:
1) two output ports instead of four (this is the number needed, since two accelerating structures will be powered by one PETS),
2) more flexibility in coupling,
3) simpler construction and a smaller total structure length.

8.5.2 Model work

Major difficulties were encountered in calculating $Q$ values of damped transverse modes in the PETSs with badly known SiC properties. Since this $Q$ value is important for the transverse stability we attempted to measure it with short (to select the relevant mode) resonating models having $\lambda/2$ length and the real SiC damping material. Such a model is shown in Fig. 8.23. The model was totally encapsulated in metal and equipped with RF probes. In the case of the CTF2 structure the absorbers lowered the $Q$ to values not measurable. In the case of the PETS with 20 mm aperture ($R'/Q = 104 \, \Omega/m$, linac) $Q$ values of 60 were obtained.

Fig. 8.23 RF model for measurements of $Q$ values of transverse modes. Only a half-structure with a metal centre plane has been used. The SiC absorbers behind the corrugated slits are visible.

8.5.3 Beam tests in the CLIC Test Facility (CTF2)

Comparisons between signals on the four output channels of a CTF2 PETS when the beam is displaced laterally show a large beam-position dependence when the PETS is not equipped with damping material and rather position-independent signals when the material is installed (Fig. 8.24).
8.6 Layout and lattice

In principle, the drive beam decelerator is a succession of 30 GHz power extraction and transfer structures (PETSs), loaded by a stream of high-charge bunches (Fig. 8.25). Bunches are short and the fundamental frequency of the cavities is twice the bunch frequency. Energy is extracted from the bunches, piles up in each structure, and is simultaneously evacuated and transferred to the main linac. The expected efficiency is obtained if most of the initial energy of the injected bunches is deposited in the successive cavities, provided that the beam remains confined in the structure aperture to the lowest required energy. At least two effects can interfere with the working of such a device.
1) the increase of the energy spread along the machine, due to the initial transient, and attaining at the end of each decelerator section (~ 700 m) the unusual value of nearly 100%;
2) the increase of the beam emittance and transverse size, which is due mainly to misalignments of focusing quadrupoles, to incoming beam mis-steering, (as in accelerators [Helm, 1963]), and to transverse wakefields.

In the absence of wakes, when following the charge centre of each slice, we can superimpose the kicks generated by all local errors, or apply matrix operators modified by these errors. Strong focusing, which diminishes the amplitude of these oscillations, helps also to reduce the effect of dipole wakes on the following bunches, an effect proportional to the amplitudes in the structures. This is important also for the dynamics in cavities without rotational symmetry, since longitudinal and transverse wakes are very non-linear with transverse displacement.

In the following, these effects are analysed for some of the proposed PETS versions [Thorndahl, 1991; Thorndahl, 1995; Millich, 1997]. The main parameters of these structures have been investigated, and some of them lead to the necessary transverse beam stability.

A beam-based ballistic alignment method has been proposed [Riche, 1998], which when simulated gives results that are extremely encouraging for the control of the beam size growth and the losses. The layout and the lattice of the drive decelerator result from choices for all the parameters of the machine. Some of them, which concern the decelerator structures and the focusing will be discussed below.

![Diagram of an accelerator/decelerator module](image)

**Fig. 8.25** Layout of an accelerator / decelerator module

### 8.6.1 Focusing

At least three effects determine the design of the focusing lattice:
1) the very large energy spread, which increases along the decelerator, with, at the end, particles still having their initial energy and particles whose energy is close to zero;
2) the transverse kicks due to the transverse wake induced by misalignments;
3) the transverse kicks due to the non-uniform longitudinal decelerating mode.

Transverse kicks can be partly controlled through a careful design of the PETS, including damping, while the large energy spread is inherent with the process of power extraction, so the primary requirement on the focusing system is that it must be able to cope with it.

We will prove in the following, first in an intuitive way, then by rigorous reasoning, that if the focusing is designed to transport the particles with the lowest energy along the whole decelerator, then the envelopes for these particles contain the ones for the other higher energy particles.
**Intuitive reasons [Riche, 1994]**

For a FODO mesh with a quadrupole distance \( L \), beam energy \( P \), integrated gradient \( GI \), focal length \( F \) [m] = \( P \) [GeV] / (0.3 GI [T m]), we can draw a map of the Twiss function \( \beta_F (F, L) \) at the focusing quadrupole and of the phase advance \( \mu \) per period with the relations:

\[
\beta_F (F, L) = 2 \frac{F}{\sqrt{F + L/2}}
\]

(8.4)

\[
\beta_F (F, L) = 2 \frac{1 + \sin(\mu/2)}{\sqrt{1 - \sin(\mu/2)}}
\]

(8.5)

This representation is valid for acceleration or deceleration of particles with different energies at any place in the machine.

![Diagram](image)

**Fig. 8.26** \( \beta_F \) and phase advance \( \mu \) as functions of the quadrupole focus length \( F \)

Any particle going along an accelerator may be described by a line in Fig. 8.26. One has to choose the details of the lattice. A simple example is to keep the distances between the quadrupoles constant by selecting one of the curved lines. Another simple example is to keep an equal phase advance, by moving on one of the straight lines passing through the origin.

Whatever the choice, only slow variations of parameters along the decelerator are allowed. For any choice of lattice, at a given point of the accelerator, \( L \) and the integrated gradient \( GI \) are fixed. The particles with different energies at that point are represented by a segment of the \( L \) line, with the higher energy particles on the right.

The equation of the \( L \) line is the first of the above equations. The square of transverse position \( x^2 \) is:
\[ x^2 = \frac{\varepsilon}{\gamma} \beta_F \]

where \( \varepsilon \) is the normalized emittance which is supposed to be constant. According to the previous expression, for a given \( L \), a given integrated gradient \( Gl \), \( \beta_F / P \) is a decreasing function of \( P \):

\[
\frac{\beta_F(P)}{P/(0.3Gl)} = 2 \sqrt{\frac{P/(0.3Gl) + L/2}{P/(0.3Gl) - L/2}}.
\] (8.6)

In other words, the maximum envelope \( x \) is obtained for \( P \) minimum, and all the other particles at that point will have smaller transverse positions, even if their \( \beta_F \) values are higher (Fig. 8.27). As the particle with the minimum energy (the one on the left of the segment on \( L = \text{constant} \)) has the maximum transverse position, all we have to do is to choose along the line representing the behaviour of the particles with the lower energy such that they stay away from the instability occurring at \( F = L/2 \) (\( \mu = 180^\circ \)). One choice could be to stay at constant \( L \), constant \( F \), for example at the minimum for \( \beta_F \) on one of the lines \( L = \text{constant} \).

**Fig. 8.27** At a given position, the envelope is a maximum for the particles with minimum \( P \)
**Rigorous proof [Riche, 1997]**

With the canonical variable $q$, $p_x = P \, dx/ds$, the transformation matrix for a FODO mesh is:

$$
\begin{bmatrix}
1 - \lambda \frac{Q}{2} - \left( \lambda \frac{Q}{2} \right)^2 & \lambda + \left( \lambda^2 \frac{Q}{4} \right) \\
-\lambda \frac{Q^2}{2} & 1 + \lambda \frac{Q}{2}
\end{bmatrix}
$$

(8.7)

Here, $\lambda$ is the mesh length (2 L), $Q = 0.3 \, G_l$.

In the case of a constant quadrupole spacing, as the energy drops, the coefficients of the matrix are changing, and they are not periodic. But, as this change is slow, reference can be made to an adiabatic invariant [Sturrock, 1953].

The expression for the ellipse, with transformation matrix elements $a_{ij}$:

$$
-a_{21} \, q^2 + (a_{11} - a_{22}) \, q \, p + a_{12} \, p^2 = U
$$

(8.8)

is not constant, but varies in the successive quadrupole planes. However, the ellipse area is conserved at these reference planes:

$$
\frac{\pi \, U_{n+1}}{\sin \alpha_{n+1}} = \frac{\pi \, U_n}{\sin \alpha_n}
$$

(8.9)

where

$$
\cos \alpha = \frac{a_{11} + a_{22}}{2}
$$

(8.10)

This area is invariant for all $z$ of the reference planes along the linac, for the all the particles having different momenta at a given $z$ because of their different position along the train: all of the particles have the same value $P_0$ at the origin (see Fig. 8.28).

![Diagram](image)

**Fig. 8.28** Momenta along the decelerator

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So the invariant concerns all the particles along the whole linac for this very chromatic beam. The maximum amplitude $x$ at the $n^{th}$ reference plane (quadrupole) can be expressed as:

$$
(x_n)^2_{\text{max}} = \frac{(a_{12})_n}{\sin \alpha_n} \frac{U_n}{\sin \alpha_n}.
$$

(8.11)

The second term is invariant, so $(x_n)^2_{\text{max}}$ varies as $(a_{12})_n / \sin \alpha_n$. In terms of mesh parameters, this is:

$$
\frac{a_{12}}{\sin \alpha} = \frac{2}{Q} \sqrt{\frac{1 + \lambda Q/(4P)}{1 - \lambda Q/(4P)}}.
$$

(8.12)

At a given $z$, $P$ is the only varying parameter. It is easy to verify that $a_{12}/\sin (\alpha)$ is increasing when $P$ decreases, so the maximum excursion is obtained for minimum $P$. We have found the same equation and reached the same conclusion as with the intuitive reasoning.

### 8.7 Transverse instabilities

A pure numerical solution of transverse dynamics in the drive beam is the only practical one, because analytical models are still under development [Guignard, 1998; R. Ruth, SLAC, private communication], and not yet ready for description of many different effects.

Several codes have been developed at CERN to analyse the wakefield effects in the special context of drive beam decelerators [Guignard, 1992]. A code including also space-charge effects (therefore adapted to low-energy beams) discovered serious beam blow-up problems in the CLIC Test Facility (CTF2), resulting in the development of damped transfer structures for CTF2 [Riche, 1995]. Another code [C.D. Johnson, CERN, private communication] showed that the non-symmetric decelerating mode of the planned two-channel PETS caused excessive transverse drive beam blow-up and that a four-channel version provided better field homogeneity. A further version [Fartoukh, 1996] calculates functions for the statistical occurrence of a given emittance increase.

Codes are the only tools we have for feasibility studies and for choosing the best structure and beam and lattice parameters. For these reasons, and also to follow the fast evolution of the CLIC decelerator design, two independent fast codes were developed: ‘PLACET’ (D. Schulte) and ‘WAKE’ (A. Riche), with new procedures and approximations. Briefly, both are based on an update, with each particle entering a cavity, with the phase and intensity of a phasor representing the action of such a cavity on the following particles. The methods are sufficiently different that one can have confidence in the results by comparing them.

#### 8.7.1 Representation of the wakes in the tracking programs

The longitudinal and transverse wakefields are each represented by a single mode. Each mode is decomposed in two waves that are sine-like and cosine-like at some arbitrary reference point in the beam. Since the phase velocity of the mode is the speed of light, the phase of each particle with respect to the waves is fixed throughout the decelerator, only the amplitude varying with position. Each particle experiences at any point a field that is a simple function of the two amplitudes $C$ and $S$ at this point, as excited by the leading particles, like $\Delta G_i = C \cos \phi_i + S \sin \phi_i$. Each particle in turn changes the amplitudes for the following ones.

The matter is complicated by the drain-out of the wakefields at the end of the structure, due to the non-zero group velocity. The field created by a particle at a given point is experienced by a following particle at a point further downstream. The field levels are therefore higher at the structure end than at
its entrance. In the steady state the longitudinal wakefield will rise in very small steps almost linearly from the entrance to the exit of the structure. The bunches are assumed to be short compared to the structure. This allows us to neglect the wave displacement between the passage of the first and last particle of the bunch. The effect of each leading bunch can thus be represented by a single particle.

Pertinence of the use of MAFIA results
Most codes dealing with RF calculations with an equations solver, using the meshes of a net as in MAFIA, give the frequencies and associated amplitudes for the transverse wake in frequency or in time domain, under conditions limiting their direct application for solving problems with dynamics such as
a) small number of cells, chiefly if the structure is 3D;
b) given charge distribution, such as a truncated Gaussian one;
c) transverse displacement fixed for all particles of the driving bunch.

In a tracking program, Maxwell's equations are not solved, but the above limitations are suppressed by using summations on single-particle potentials ($\delta$ wake) for each mode, or an approximation of their sum for the short-range description. These $\delta$ wake potentials are derived from MAFIA results.

In order to see if the results of MAFIA were well interpreted with the simplifications of a tracking program, we search for frequencies and amplitudes by a least squares comparison of the results of MAFIA in the time domain, and the reconstruction of the fields from three frequencies only, keeping the same basic data (structure length, bunch length) as those for MAFIA. The reconstruction is found to be equal to the MAFIA results.

Expressions used in the calculations
We use expressions derived from the vector wake potential definition

$$\widetilde{W}(\mathbf{r}, s) = \frac{1}{q} \int_{0}^{s} dz \left( \mathbf{E}(\mathbf{r}, z, t) + c \mathbf{v} \times \mathbf{B}(\mathbf{r}, z, t) \right)_{t \to \infty}$$

(8.13)

on a test particle following a particle ahead at distance $s$, see Fig. 8.29.

---

![Fig. 8.29 Distance to cavity entry versus time](image)

**Fig. 8.29** Distance to cavity entry versus time

a) Symmetric structures
Because the amplitudes of the HOM were so low, we used the δ wake description with one frequency only:

$$W_{\delta t} = 2 k_L \cos \left[ \frac{\omega_T s}{c} \right]$$  \hspace{1cm} (8.14)

with $R/Q$, linac longitudinal impedance of the structure such that

$$2 k_L = \frac{\omega_L}{2} \frac{R}{Q}$$  \hspace{1cm} (8.15)

$$W_{\delta t} = 2 \frac{c}{a^2} \frac{k_T}{\omega_T} \sin \left( \frac{\omega_T}{c} \right) \exp \left( -\frac{\omega_T}{2Q} \frac{s}{c-v} \right)$$  \hspace{1cm} (8.16)

where the exponential term is for the necessary strong attenuation of the dipole transverse wake by absorption.

b) Structures with $m$-fold symmetry due to waveguides

For structures with several waveguides collecting the longitudinal field all along their cores, symmetry of an order corresponding to the number of waveguides gives rise to 3D modes with longitudinal wakes varying with radius and azimuth.

Using Maxwell's relation between $\vec{E}$ and $\delta B/\delta t$, replacing $\vec{B}$, as in [Weiland, 1991], leads to a relation between the gradient of the longitudinal wake potential and the derivative with $s$ of the transverse one.

$$\frac{\partial \vec{W}_L}{\partial s} = \frac{1}{q} \left[ \vec{E}_T \left( \frac{z+s}{c} \right) \right]_0^L - \frac{1}{q} \int_0^L ds \nabla_T E_z (\bar{r}, z, t)$$  \hspace{1cm} (8.17)

or, if $\vec{E}_T$ vanishes at boundaries,

$$\frac{\partial \vec{W}_L}{\partial s} = -\nabla_T W_s$$  \hspace{1cm} (8.18)

known as the Panofsky–Wenzel theorem [Panofsky, 1956]. The longitudinal potential is a harmonic function of the transverse coordinates. For a structure with four waveguides ($m = 4$), we get:

$$W_s = 2 K q \left( \frac{r}{a} \right)^4 \cos(4\phi) \cos \left( \frac{\omega_T s}{c} \right)$$  \hspace{1cm} (8.19)
where \( r \) and \( \phi \) are the coordinates of the test particle, with \( \phi \) measured from a fixed origin. Note that this wake differs from that of the octupole in a symmetric structure: it does not depend on the leading particle’s transverse coordinates and \( \phi \) is measured from a fixed position in the structure. With

\[
r^4 \cos(4\phi) = \left( x^2 - y^2 \right)^2 - 4x^2 y^2
\]

(8.20)

(example for \( m = 4 \)), one gets:

\[
W_c = 8 K \frac{c}{\omega_L a} q \frac{x(x^2 - 3y^2)}{a^3} \sin \left( \omega_L \frac{s}{c} \right).
\]

(8.21)

\[
W_L = -8 K \frac{c}{\omega_L a} q \frac{y(3x^2 - y^2)}{a^3} \sin \left( \omega_L \frac{s}{c} \right).
\]

(8.22)

The results shown in Fig. 8.30 have been obtained by A. Millich with MAFIA. The longitudinal potential \( W_c \) of Fig. 8.30 is the sum of the fundamental monopole and of the octupole potential coming from the four-fold symmetry, its ratio to the fundamental is 1 at \( r = 0 \). It has the same sign as the monopole potential (i.e. decelerating) for \( \phi = 0^\circ \), and an opposite sign for \( \phi = 45^\circ \). The variation in \( r^4 \) can be easily fitted, and \( K/k \) derived from it.

![Graph](image.png)

**Fig. 8.30** \( W_c(r)/W_c(0) \) as a function of \( r \) for \( \phi = 0^\circ \) and \( \phi = 45^\circ \) (A. Millich)

**Methods**

When a particle crosses a structure, its change in momentum and transverse position depends on propagating fields created by the nearest particles in front. The changes in longitudinal and transverse momenta are obtained by integrating the forces, the displacements by integrating the momenta. The computations are simplified by the assumption that the longitudinal and the transverse wake each contain only one mode (single amplitude, single group velocity). For structures with \( m \)-fold symmetry, the transverse forces of the 2 m pole wakes \( a \) have to be added to that of the dipole.
Role of group velocity

The field \( E(z, t = (z + s)c) \) on particle \( j \) at distance \( z \) from cavity entry, due to the particle \( k \) at distance \( s \) in front of \( j \), results from the interaction with the cavity of particle \( k \) when at position \( k' \), which propagates with group velocity \( v (v > 0) \), Fig. 8.29. In this two-particle interaction, the group velocity determines the integration length which is different from structure length. It also limits the number of particles in front whose fields affect the test particle.

Figure 8.31 shows that when at distance \( z_j \) from entry, particle \( j \) sees the wake from particles in front up to position \( i \). If the cavity frequency is a multiple of the bunch separation frequency, effects on \( j \) add up and tend to be proportional with distance \( ij \):

\[
ij = z_j \frac{1-v/c}{v/c} \tag{8.23}
\]

and then, to \( z_j \). Maximum field value is obtained for \( j \) at exit, i.e., \( z_j = L \).

Figure 8.31 shows also that particle \( j \) experiences the effect of the particle at \( i \) only from its position \( z_j \) and up to the structure exit, that is along segment \( L - (z_i - z_j) v/(c-v) \).

Fig. 8.31 Charges between \( i \) and \( j \) contribute to the field on \( j \)

Longitudinal wake, its approximation, exact algorithm
The budget of the numerical calculation is similar for any wake, thus described in the simple case of the monopole longitudinal wake. Consider a test particle \( j \) following the driving particle \( i \) at a constant distance \( s_{ij} \) (Fig. 8.32).

Particle \( j \) is in the wakefield

\[
2 k q_i \cos \left( \omega_L \frac{s_{ij}}{c} \right) \quad (8.24)
\]

of particle \( i \) as soon as \( j \) reaches its position \( j^1 \) at \( y_{ij} \) from the entry

\[
y_{ij} = s_{ij} \frac{v}{c-v} \quad (8.25)
\]

and up to the end of the structure, that is along

\[
L - y_{ij} = L - \frac{v}{c-v} s_{ij} \quad (8.26)
\]

The integrated field (potential) experienced by \( j \) is therefore

\[
W_{a,ij} = 2 k q_i \left( L - \frac{v}{c-v} s_{ij} \right) \cos \left( \omega_L \frac{s_{ij}}{c} \right) \quad (8.27)
\]

In the case \( j = i \) (self-field), there is the factor \( 1/2 \) from the fundamental beam loading theorem. Consider now the superposition of the actions of particles in front of test particle \( j \). When particle \( j \) crosses the structure, its distance \( z_j \) from the entry increases as does the number of influencing particles, because they are on segment \( ij \) the length of which increases in the same proportion as \( z_j \) (Fig. 8.33).
On the other hand, the farther the particles $i$ are from $j$, the smaller the path length of $j$ on which their fields apply. With the grouping of particles in regular slices of bunch with equal populations and separation, the total fields seen by particle $j$ according to its position $z_j$ along the structure are as shown in Fig. 8.34.

The wake potential $W$ is obtained from summing the fields along $z$:

$$W_{i,j} = \sum_{m=j}^{i} 2k_L \cos(\omega_L \frac{s_{lm}}{c}) q_0 \left( L - s_{lm} \frac{v}{c - v} \right)$$

the maximum value for $i$ being given by:

$$L - s_{i,j} \frac{v}{c - v} \geq 0.$$  

**Approximation**

At steady state, the number of bunches is proportional to $z_i - z_j$ (Fig. 8.33), i.e. with $z_j$. It varies when position $z_i$ is within a bunch.
But as the bunch length is small, compared to the cavity free wavelength, and as $L$ is much greater than the bunch separation $\Delta b$, the force could be considered as proportional to $z_j$, for a uniform charge $\rho = q_b / \Delta b$, where $q_b$ is the charge per bunch. This approximation leads to

$$\frac{dW_{\delta, \omega_0}}{dz} = 2k_L z_j \frac{c - v}{v} \frac{q_b}{\Delta b}$$

(8.30)

and the integration to a voltage of

$$W_{\delta, \omega_0} = k_L L^2 \frac{c - v}{v} \frac{q_b}{\Delta b}$$

(8.31)

which is the usual formula for the voltage loading in a cavity.

The average current being $I = c q_b / \Delta b$, the power $V \cdot I$ can be written as:

$$P = k_L L^2 \frac{c - v}{v} c \left( \frac{q_b}{\Delta b} \right)^2$$

(8.32)

**Exact algorithm**

The superposition of the wakes due to the leading slices should not be repeated for all of the test slices. One way to avoid this repetition is sketched here. The total force (25) on slice $j$ is saved in memory, and used for slice $j + 1$ with the following minimum changes:

1) self-field for the new slice $j + 1$,
2) multiply by 2 the effect of slice $j$, which was counted as self-field before,
3) abandon the effect on slice $j$ of particles whose fields have propagated out of the structure,
4) change the integration lengths for all particles between, counted for $j$ from

$$L - s_{j,m} \frac{v}{c - v}$$

(8.33)

to the integration length for leading particle $j + 1$:

$$L - s_{j+1,n} \frac{v}{c - v} = L - s_{j,m} \frac{v}{c - v} - \Delta s \frac{v}{c - v}$$

(8.34)

where $\Delta s = s_{j+1}$. All quantities are constant, apart from $s_j$. Therefore

$$C_{j+1} = \cos \left( \omega_L \frac{s_{j+1,n}}{c} \right) = \cos \left( \omega_L \frac{s_{j,m}}{c} \right) \cos \left( \omega_L \frac{\Delta s}{c} \right) - \sin \left( \omega_L \frac{s_{j,m}}{c} \right) \sin \left( \omega_L \frac{\Delta s}{c} \right)$$
There is a similar expression for $S_{j+1} = \sin \left( \omega_t \frac{s_{j+1,m}}{c} \right)$.
Thus, four quantities must be kept. These are

$$C_j = \sum_{m=j}^{i} 2k_l \cos \left( \omega_t \frac{s_{j,m}}{c} \right) q_m$$

$$C^*_j = \sum_{m=j}^{i} 2k_l \cos \left( \omega_t \frac{s_{j,m}}{c} \right) q_m \left( L - s_{j,m} \frac{v}{c-v} \right)$$

and equivalent expressions with sines, $S_{j}$, $S^*_j$. They should be updated considering point 2 and point 3 above, when passing from $j$ to $j + 1$. Then they should also be updated because of the change of $s/c$ (point 4), as, for example:

$$C^*_{j+1} = \cos \left( \omega_t \frac{\Delta s}{c} \right) \left( C^*_j - \Delta s \frac{v}{c-v} C_j \right) - \sin \left( \omega_t \frac{\Delta s}{c} \right) \left( S^*_j + \Delta s \frac{v}{c-v} S_j \right).$$

Then, the self-field of new slice $j + 1$ should be added on. This allows one to calculate directly the $C$ and $S$ quantities for the first particle only, then to pass from the $C^w$ momentum change of $j$ to the one of $j + 1$ by just a linear combination of $C_j$, $C^*_j$, $S_j$, $S^*_j$, with constant coefficients.

**Transverse dipole wake**

The main differences with the longitudinal wake effect are as follows:

a) The frequency is different from that of the longitudinal wake (generally by more than $10^{-3}$), the phase between slice $j$ of bunch $n$ and slice $i$ of bunch $m$ depends now on $m - n$. The group velocity is different, but by only 5% for the structures considered so far.

b) An attenuation term exists, depending on the distance.

c) The force is proportional to the average transverse position of the leading slice.

d) The calculations must be made for each successive cavity.

The change in momenta in a structure for slice $j + 1$ can be deduced from the one for slice $j$ by a procedure nearly as simple as the procedure for longitudinal fields, also based on replacing $z_i - z_{i+1}$ by $z_i - z_{j+1} + \Delta s$. The transverse position of the leading slice may be taken as the value at the cavity entry, exit, or centre, or as a cubic defined with its input, exit positions, and angles. Experience has shown that results are very similar for the three assumptions. If the transverse position of the leading slice is considered as constant, the displacement of a test particle is parabolic, and the total transverse momentum change due to this leading slice can be applied at the middle of the integration length $L - s_{j,m} \frac{v}{c-v}$ to obtain the displacement.

**End effects**

Applying $\text{div } E = 0$ at the end of the structure shows that there is a radial field proportional to the longitudinal field loaded by the leading slice. The radial fields at entry and exit of the integration length $L - s_{j,m} \frac{v}{c-v}$ are opposite only if the trajectory in between is parallel to the axis. Taking the influences of these radial fields on the trajectory according to the angle at entry gives a visible, but small difference for the envelopes at the decelerator end. This effect is not accounted for in MAFIA, because the bunch transverse displacement is assumed rigid.

**Transverse wake due to n-fold symmetric cavities**

The consequences of the transverse fields induced by this effect alone (no transverse dipole wakes) have been tested for structures with $m = 4$. It is important that the algorithm accounts for the non-linearities and the coupling given by Eqs. (8.19)–(8.22), and calculates altogether momenta and displacements. As an example, a Runge–Kutta integration gives a stable result with two steps per structure. Turning every even cavity by 45° cancels locally and partially (because of the variation of the
the longitudinal wake inhomogeneity and the transverse wake resulting from it. Results can also be obtained in a shorter time by developing the trajectory in power of $r$ and using one dimension, as shown later.

### 8.8 Simulation results

A first requirement for the drive beam decelerator is that the beam must be stable in spite of an initial jitter. In these simulations the beam line is perfectly aligned and a beam with an initial offset is simulated without applying any correction. For the decelerator using the four-waveguide structure the effect of the non-uniformity of the longitudinal field is ignored in the first part of this section. It is considered separately at the end.

#### 8.8.1 Longitudinal effects

Each drive beam pulse consists of 2144 bunches. The part of the pulse actually used for RF power production consists of a ramp in which the charge per bunch increases with the bunch number and a flat top where the charge stays constant. The ramp is necessary to achieve a field profile in the main linac structures that corresponds to the one in the steady state for the first bunch. The flat top consists of 1504 bunches; these are preceded by 160 bunches needed for the pre-fill of the main linac structure, and followed by another 160 bunches that are necessary to achieve a constant beam loading in the drive beam accelerator. In addition we consider a maximum of another 320 bunches added at the front and tail because of the limited bandwidth of the gun (see Chapter 5).

![Energy spread within a bunch on the flat top at the decelerator end](image)

**Fig. 8.35** Energy spread within a bunch on the flat top at the decelerator end

In the following a simplified situation is assumed; the ramp starts with half the charge of the flat top and the charge increases over 320 bunches linearly. The tails are usually not simulated. During the deceleration the bunch train develops an energy spread. Within each bunch this spread is mainly determined by the overlap of the charge distribution with the RF and with the adiabatic undamping of an initial energy spread, see Fig. 8.35.

Along the train the energy also varies: very strongly over the first fifty bunches, which corresponds to a PETS drain time; the variation is slower along the next bunches and is due to the charge increase within the ramp. At the flat top the energy remains constant, see Fig. 8.36.
8.8.2 Lattice layout

For the lattice a phase advance of $\Delta \Phi = 88^\circ$ per FODO cell is chosen. Smaller phase advances would reduce the maximum beam size due to the optics while larger phase advances would reduce the wakefield effect due to beam jitter.

The reference four-waveguide structure with 12 mm iris radius is used in the following (see Table 8.1). It has an impedance $R/O = 62.2 \, \Omega/m$ in linac convention, a group velocity $\beta_g = 0.443$ and a transverse wakefield of 425 V/pC/m².

Figure 8.37 shows the envelope of a beam that is initially collimated at three sigma transversely and longitudinally. The largest offset of a particle is shown. The larger and smaller sizes correspond to the beam in the focusing and defocusing quadrupoles. The size of the individual slices is shown in Fig. 8.38. As expected they do not vary strongly over the length of the train.

8.8.3 Initial offset

To investigate the beam stability the beam is offset at the decelerator entry by $\delta_x = \sigma_x$. Even with this very large offset the beam is stable. Figure 8.39 shows the three-sigma envelope with and without wakefields. The beam at the exit of the decelerator is shown in Fig. 8.40 where the positions of all slices of the first 420 bunches are displayed.

Each bunch consists of 21 slices. It is clear from this picture that on the flat top the steady state is reached well within the first 100 bunches, while each bunch sees the wakefields of about 50 preceding ones. The largest deviation from the axis occurs in the ramp were the slices are smaller than on the flat top. For small offsets the envelope will thus be determined by the beam size on the flat top while for offsets of more than about $\sigma_x/2$ the ramp will give the limit.
Fig. 8.37 Envelope of a three-sigma beam in the drive beam decelerator due to the optics. The four-waveguide cavity is used.

Fig. 8.38 Size of the slices of a three-sigma beam at the end of the drive beam decelerator. The first 420 bunches are displayed, each containing 21 slices.
Fig. 8.39 Envelope of a three-sigma beam with an initial offset of $\delta_x = \sigma_x$.

Fig. 8.40 Position of the individual slices at the end of the drive beam decelerator. The initial beam offset was $\delta_x = \sigma_x$. Each bunch contains 21 slices and the first 420 bunches are displayed. On the right side one can see the bunches reach the steady state.

8.8.4 Influence of the ramp

To understand the importance of the ramp, two different models of the charge increase are compared in Fig. 8.41. In the first the charge is increased from every bunch in the ramp to the next in 320 small steps. In the second only 10 steps are used, increasing the charge every 32 bunches. The difference is visible but relatively small.

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Fig. 8.41 Beam envelope for an initial offset of $\delta_x = \sigma_x$, for increases in the charge in the ramp either in 320 or in 10 steps.

Also the initial charge can vary depending on the requirement for beam loading compensation in the main linac. Figure 8.42 shows the envelope for three different starting charges 0.25, 0.5, and 0.75 times the one on the flat top. The differences are small. The number of bunches in the ramp can also slightly modify the envelope, as can be seen in Fig. 8.43. All these variations are of course smaller or vanish completely as the initial offset is decreased. The details of the ramp have little effect on the envelope of a three-sigma beam that starts with an initial offset of one sigma. The envelope remains significantly smaller than the aperture.

Fig. 8.42 Beam envelope for an initial offset of $\delta_x = \sigma_x$ when increasing the charge in the ramp in 10 steps. The initial charge is 0.25, 0.5, and 0.75 times the one on the flat top.
Fig. 8.43 Beam envelope for an initial offset of $\delta_x = \sigma_x$, increasing the charge in the ramp in steps of 32 bunches each. The initial charge is 0.5 times the one on the flat top. The length of the ramp was varied

8.8.5 Energy spread

The beam in the decelerator will have an initial energy spread. For a three-sigma beam the full width of this spread is expected to be about 50–80 MeV depending on the compression scheme. The focusing is adjusted to the lowest energy, as before. While the difference at the entrance of the linac is relatively small, it is significant at the linac exit. If we had started with the same mean energy but an energy spread of $\pm 3\%$, the lowest final energy would be 7% instead of 10%. Thus the envelope would be larger already on account of the optics. The weaker focusing would also increase the amplification of initial offsets. On the other hand the beam would be stabilized by the energy spread.

Here we will not change the lattice but rather increase the initial mean energy by 3%. The beam size due to the optics therefore does not change.

The envelope of a three-sigma beam is shown in Fig. 8.44. The energy spread is $\pm 3\%$ but the charge is concentrated around the mean energy. If the charge is spread out more equally the stability improves. In a simple model 25% of the charge has the minimum and maximum energy and 50% the mean one. As can be seen in Fig. 8.45, the envelope is indeed smaller than in the first case. Since the initial charge distribution has not yet been determined we consider in the following the worst case, with almost all charge at the mean energy.

This case is, however, very close to the one where the initial beam has no energy spread, as can be seen in Fig. 8.46.

The energy spread may slightly affect the efficiency of the drive beam decelerator if the final energy has to be increased. The stability is not affected very much even in the most pessimistic model. It actually seems conceivable that the energy spread will increase the beam stability. This would enable us to reduce the final energy. As more realistic energy distributions become available it will be possible to switch from the pessimistic model to a more realistic one.
Fig. 8.44 Envelope of a three-sigma beam assuming a perfect linac and an initial offset of \( \delta_x = \sigma_x \). The energy spread is ±3% and the focusing is adjusted for the lowest energy.

Fig. 8.45 Comparison of the envelopes for two different charge distributions.
8.8.6 Non-uniformity of the longitudinal field

For the four-waveguide structure the transverse non-uniformity of the longitudinal field is important (see Section 8.4.5). As a particle reaches a large amplitude it will be quickly lost because of the transverse force arising from this non-uniformity. This effect thus reduces the available aperture.

In the simulation the non-uniformity is approximated by a development into powers of \( r \) as described above. At first only the lowest order term is taken into account. The amplitude of such a term is chosen to fit the deviation from the linear field at the aperture limit, in the plane where the variation is larger. Even if higher order terms are neglected this should be pessimistic, considering also that the total amplitude is attributed to the lowest term which is bigger at low radii.

In the simulation it is very important to do the full integration along the trajectory to obtain the kick. If it is evaluated only at a single point the beam appears to be significantly less stable. Taking the field value at the structure's centre does not give a good representation of the average since the field is not linear with the radius.

The envelopes of a beam with no offset and for a perfectly aligned lattice are shown in Fig. 8.47. While a three-sigma beam passes without any significant increase in the envelope a four-sigma beam does not. A possible cure is of course to shorten the lattice, hence reducing the efficiency slightly.
Fig. 8.47 Envelopes for an on-axis beam in a perfectly aligned decelerator including the non-uniformity of the longitudinal field.

Another option is to turn every second cavity by 45° around its longitudinal axis. For a particle travelling parallel to the axis the transverse deflections by the lowest order of the non-uniformity mode cancel in two consecutive structures, see Fig. 8.14. However, since the structure length is not small compared to the betatron wavelength, the particle transverse position will vary within a structure and in between successive structures leading to an imperfect cancellation.

In addition, the field rises towards the end of the cavity weighting the different phases of the betatron oscillation differently. In spite of this, the results shown in Fig. 8.48 are promising — even a five-sigma beam does not exhibit any significant effect. While the lowest term is nicely cancelled in this configuration, the next order becomes important since the cancellation does not apply here. So additional tracking was performed, taking into account the two lowest order terms. As can be seen in Fig. 8.49 the result is not significantly modified.

To estimate the combined effect of wakefields and the non-uniformity, the simulation of a beam with an initial offset is repeated. It should be noted that the non-uniformity not only changes the position of particles in the beam envelope but also the position of the centre of charge.

To fully simulate this each slice of the beam should be represented by a large number of macro particles. This would exceed our currently available computing power. The problem is avoided by simulating only one single particle in the centre of each slice and a few on the envelope in phase space. The central slice thereby contains the charge of the beam.
Fig. 8.48 Envelopes of an on-axis beam in a perfectly aligned decelerator with every second cavity rotated by 45°

The result of the tracking, in the case in which every second cavity is rotated, is shown in Fig. 8.50. The envelope is very close to that obtained without taking into account the non-uniformity (see Fig. 8.44). To verify that the variation of the centre of charge is a minor effect, the same simulation was repeated attributing the charge to the particles on the envelope thus exaggerating the shift of the centre. As shown in Fig. 8.51 the results are very close. One can conclude that the effect of the non-uniformity of the longitudinal field is important but can be controlled by rotating every second cavity by 45°. In addition, structures with a larger number of waveguides could be used. For the same amplitude of the field variation these would be more stable since significant transverse kicks occur only at larger radii.
Fig. 8.49 Envelopes of an on-axis beam in a perfectly aligned decelerator with every second cavity rotated by 45°. Also the second lowest term of the non-uniformity is taken into account.

Fig. 8.50 Envelope of a three-sigma beam with an initial offset of $\sigma_z$ in a perfectly aligned decelerator for rotated and non-rotated cavities.
8.9 Stability for different structures

In the following section the dependence of the beam stability on different structure properties is investigated. As a basis, the four-waveguide structure is mainly used neglecting the non-uniformity of the longitudinal field and the initial energy spread. The lattices used in the simulations are somewhat different from the nominal one — the number of structures in each decelerator section is here 340 and 450 rather than 550 — but the scaling properties hold true in both cases.

8.9.1 Frequency shift

The shift of the transverse frequency $f_\perp$ to the longitudinal one $f_L$ is important for the beam stability. The transverse wakefield is a sine-function so if the two frequencies were exactly equal all bunches would be at a zero crossing of the wakefield of the centroid of leading bunches. The multibunch wakefield effects then essentially depend on the bunch lengths.

Figure 8.52 shows the beam envelope for different values of $\Delta f / f = (f_\perp - f_L) / f_L$. Small frequency shifts do not affect the result very much until they exceed about one per cent, where the differences become important. In practice these shifts are of the order of $10^{-3}$, so they should not play an important role.

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Fig. 8.51 Envelope of a three-sigma beam with an initial offset for different charge distributions
8.9.2 Group velocity

The transverse stability also depends on the group velocity. To illustrate this the same structure was simulated assuming different group velocities. All other parameters of the structure were kept constant. To obtain the same output power the bunch charge was adjusted in each case. It scales as

\[ q(\beta_z) = q(\beta_{z,0}) \left( \frac{1}{\beta_z} \right)^\frac{1}{\beta_{z,0}^2 - 1} \]  \hspace{1cm} (8.35)

Accordingly the initial energy has to be changed as

\[ E(\beta_z) = E(\beta_{z,0}) \left( \frac{1}{\beta_z} \right)^\frac{1}{\beta_{z,0}^2 - 1} \]  \hspace{1cm} (8.36)

These laws are approximations in the case where the number of bunches is small. The lattice is scaled to achieve the same phase advance of the low-energy particles in all cases.
As can be seen in Fig. 8.53 the group velocity significantly affects the stability. A low group velocity is more stable than a high one. This can be understood by comparing the distance over which the longitudinal and transverse wakefields of a leading particle can be seen by a following one. The longitudinal distance scales as

\[ L_x \propto \frac{1-\beta}{\beta} \]  

(8.37)

since it is given by the drain time of the power from the structure. The effective distance of the transverse wakefield scales as

\[ L_\perp \propto 1-\beta \]  

(8.38)

since it is determined by the damping. The charge in the longitudinal window has to be kept constant for constant \( R/Q \) to keep the output power constant. The charge in the window of the transverse wakefield is thus increasing for high group velocities.

**Fig. 8.53** Maximum amplitude of particles for different group velocities. The bunch charge and initial energy were adjusted to get the same power and relative deceleration in all cases, but the other parameters were fixed.
8.9.3 Varying R/Q

When comparing different structure designs, it seems that the longitudinal and transverse wakefields often are proportional for a fixed radius but different geometries. For a fixed group velocity the power can be adjusted by varying the charge $q$ to keep $q^2 R/Q$ constant. To pass the same number of cavities this requires the initial energy to scale as $E \propto 1/q$. The transverse kick experienced in a structure normalized to the beam energy thus remains constant. Except for effects of the beam size and the variation of the bunch charge, the situation remains unchanged for varying $R/Q$.

8.9.4 Radius

In order to understand the effect of different parameters on the transverse stability of the drive beam during deceleration, a simple scaling of the longitudinal and transverse wakefields with the radius was derived for the four-waveguide structure.

This model was based on three cavities with radii of $a = 10$, 12, and 20 mm with a comparable geometry and group velocity. In the model the longitudinal wakefield scales as

$$W_L \propto a^{-2} \tag{8.39}$$

and the transverse as

$$W_T \propto a^{-3}. \tag{8.40}$$

It is assumed that the group velocity remains constant, and the variations are actually very small. To keep the drive beam decelerator layout invariant, the charge $q$ and initial energy $E_i$ of the bunches are adjusted following

$$q \propto \sqrt{W_L} \tag{8.41}$$

and

$$E_i \propto \sqrt{W_L}. \tag{8.42}$$

The results of several runs using this scaling are shown in Figs. 8.54 and 8.55. The lattice contained 340 cavities and the envelope shown is that for particles that are at two sigma in a beam that is offset by one sigma initially.
As a reference the structure with $a = 10$ mm is used. As expected, stronger damping helps to reduce the aperture requirement. Increasing the radius also is found to be useful to reduce the wakefield effect. The higher charge and lower initial energy necessary in this case are more than compensated by the reduction in the transverse wakefield. The small increase in the beam size towards small $R/Q$ is due to the smaller initial energy leading to a larger emittance. It is, however, smaller than the increase in available aperture since the beam size scales with

$$
\sigma = \sqrt{\frac{e \beta \frac{m c^2}{E}}{\epsilon}} \approx a^\frac{3}{2}.
$$

(8.43)

The relative gain in aperture for low $R/Q$ structures is thus very small. The radius chosen will be limited by the final energy, providing the particles are still ultrarelativistic at the end of the decelerator. This could be modified by increasing the linac length and initial energy accordingly. This would in turn increase the pulse length in the main linac. A more severe limitation arises from the charge per bunch that the drive beam injector can deliver, which is around 20 nC in the current design. The bunch spacing achieved with the two combiner rings is two RF periods. This distance depends mainly on the achievable frequency of the last RF deflector.

![Graph showing maximum envelope in the drive beam decelerator as a function of R/Q (units are in 100 Ω/m, linac convention) for different damping conditions Q. The four-waveguide structure is used and the R/Q is varied by varying the iris radius $a$, and the charge and initial energy of the beam are adjusted accordingly.](image)

**Fig. 8.54** Maximum envelope in the drive beam decelerator as a function of R/Q (units are in 100 Ω/m, linac convention) for different damping conditions Q. The four-waveguide structure is used and the R/Q is varied by varying the iris radius $a$, and the charge and initial energy of the beam are adjusted accordingly.
Fig. 8.55 Maximum envelope in the drive beam decelator as a function of the $R/Q$ (units are in 100 $\Omega/m$, linac convention) for different damping conditions $Q$

The bunch length is 400 $\mu$m, the active structure length about 80 cm and the required power extracted from the beam is 512 MW (corresponding to the nominal 231 MW power fed to each CAS). A four-waveguide structure with a radius of $a = 12$ mm has an impedance $R/Q = 62$ $\Omega/m$ (linac convention) and a group velocity $\beta_g = 0.443$. The bunch charge therefore has to be $q = 17.6$ nC which is slightly below the limit. This design is therefore the most stable four-waveguide structure and is taken as a reference.

8.9.5 Alternative structures

Another structure to investigate is the circular symmetric one. Contrary to the four-waveguide structure this one does not have any longitudinal field non-linearity. In principle one can therefore use the full aperture (except for the safety margin). However, with the high group velocity the structure is not expected to be as stable as the four-waveguide one with respect to the transverse wakefields.

To achieve the required output power with the nominal bunch spacing the bunch charge has to be $N = 8.5 \cdot 10^{10}$ particles and the initial beam energy $E = 1.7$ GeV. The bunch length is assumed to be $\sigma_x = 400$ $\mu$m as for the four-waveguide structure. The final beam energy is also ten per cent of the initial.

In Fig. 8.56 the envelopes of a three-sigma beam with an initial offset of $0.3 \cdot \sigma_x$ are shown for a damping with $Q = 50$ and different focal strengths of the lattice. For this calculation the cavities were cut into ten slices each. It is clear that a relatively large phase advance is necessary in order to keep the wakefield effect small. The structure is more difficult to damp than the four-waveguide one. Measurements have shown $Q$ values well in excess of 100 [L. Thorndahl, CERN, private communication]. It seems doubtful therefore that this structure can be used.
Fig. 8.56 Envelope of a three-sigma beam with an initial offset of $0.3 \cdot \sigma_y$ for damping with $Q = 50$ and different phase advances per cell

8.10 Alignment and steering

When the decelerator is put in place the individual elements will deviate from their nominal positions. This pre-alignment error is expected to be less than 10 $\mu$m for the main beam line of CLIC — using a very sophisticated stretched-wire alignment system.

With the help of a beam-based alignment technique the element positions must be corrected to allow the beam to pass despite the large energy spread. The highest particle energy at the end is a factor ten larger than the smallest.

A possible way to correct the drive beam decelerator is to use the ballistic method [Riche, 1998]. In this method the beam line is divided into bins containing a small number of quadrupoles and BPMs. In the first step all quadrupoles in the bin but the first are switched off and the beam is steered into the last BPM moving the first quadrupole — either electrically or mechanically. The beam position in each BPM is now accepted as its nominal centre. In the next step the quadrupoles are switched on again and the beam is steered into the BPM centres by a simple few-to-few correction.

This procedure can be iterated to yield convergence. Once this is reached the next bin is corrected and so forth. Since this alignment method requires quadrupoles in a bin to be switched off to align the BPMs, the beam has to have an emittance small enough that it is able to pass through the aperture. The size of the drive beam is too large and it cannot be used. A possible option is to use the main beam after the first damping ring. Its emittance is $\varepsilon_x = 0.6$–1.9 $\mu$m (depending on the centre-of-mass energy of the main linacs) and its energy and bunch length are $E = 1.98$ GeV and $\sigma_z = 300$ $\mu$m. Its charge of $N = 4 \times 10^9$ particles per bunch is significantly lower than that of the drive beam which will reduce the wakefield effect during correction.
In the following it is assumed that one will use only a single bunch out of the main beam. If one uses a large emittance of $\epsilon_x = 2 \, \mu m$, the beam size of the correction beam along the decelator is less than $\sigma = 260 \, \mu m$ for bin lengths of 12 quadrupoles and $\sigma = 500 \, \mu m$ for bin lengths of 24.

In Fig. 8.57 the position of the beam position monitors can be seen before and after the correction. The method aligns the BPMs within a sector to a straight line and the quadrupoles are moved to the same line with the one-to-one correction.

![Fig. 8.57 Positions of the beam position monitors before and after correction](image)

The first one in each bin, however, shows a larger deviation since it is used to steer the beam from one straight line onto another one.

A full correction can be performed using a main beam bunch. Then the drive beam is switched on and a further one-to-one steering can be performed. In principle it would be advantageous if this correction step could be avoided. This would especially reduce the requirements on the BPMs which then would need to be able to measure the single-bunch small charge beam only.

The initial position errors of the beam line elements are assumed to be $\sigma_{\text{struct}} = 100 \, \mu m$ for transfer structures, $\sigma_{\text{BPM}} = 100 \, \mu m$ for BPMs, and $\sigma_{\text{quad}} = 500 \, \mu m$ for quadrupoles. It should be noted that the initial displacement of the quadrupoles is quite unimportant since they will affect only the speed of the convergence rather than the final result. The resolution of the BPMs is taken to be $\sigma_{\text{res}} = 5 \, \mu m$.

In the following, three different structure options are studied separately. For the circularly symmetric structure the effect of the correction is shown in Fig. 8.58. The deviation from the nominal envelope—for a beam without offset and a perfectly aligned lattice—is small. The method is thus able to steer the beam properly despite its large energy spread. For the four-waveguide structures the result is shown in Fig. 8.59.
**Fig. 8.58** Envelope of the drive beam for a perfectly aligned machine and a corrected one. The circularly symmetric structure is used

**Fig. 8.59** Envelope of the beam for a machine corrected with the ballistic method. The four-waveguide structure is used
8.11 Power transfer efficiency between the drive and main linacs

An estimate of the efficiency with which power can be transferred from the drive linac to the main linac in the present design of CLIC is presented.

In the design a single transfer structure feeds two 500 mm long symmetrically-coupled accelerating structures with successive input couplers 540 mm apart. The two linacs are separated by 500 mm to allow independent alignment and mechanical isolation. Waveguide runs are made from the largest possible rectangular waveguide that is not overmoded at 30 GHz.

A large single-mode waveguide gives low attenuation and also allows bends and flexible sections. Such a waveguide is 10 mm wide by 5 mm high and has a group velocity $v_g/c = 0.866$. The waveguide has an attenuation of 0.317 dB/m assuming a conductivity of copper equal to $5.22 \times 10^7 \, \Omega^{-1} \, \text{m}^{-1}$, which is 90% of the theoretical value. In order to provide the correct RF timing, the waveguide run to the downstream accelerating section must be longer by $v_g/c \times 540 \, \text{mm} = 468 \, \text{mm}$ than the waveguide run to the upstream section. The waveguide run dimensions are shown in Fig. 8.60.

![Fig. 8.60 Geometry of the waveguide run](image)

Power coming out of opposite arms of a transfer structure must be combined and power entering an accelerating section must be split; it is assumed that splitting and combining can be made with a power efficiency of 0.99. A pair of short flexible sections of waveguide at either end of each long waveguide run are included to allow independent movement of the two linacs. It is assumed that the power efficiency of the flexible sections is 0.99, losses coming mainly from mismatch.

The power attenuations are shown in Fig. 8.61. The total attenuations are:

$$
\begin{array}{ll}
\text{Waveguide run 1} & \text{Waveguide run 2} \\
\text{Power attenuation} & 0.92 & 0.89
\end{array}
$$

Increasing the waveguide dimensions to 20 mm $\times$ 10 mm reduces attenuation to 0.12 dB/m. If 80% of the length of the long waveguide runs could be converted to such an overmoded guide (assuming loss-free transitions) the attenuations become:

$$
\begin{array}{ll}
\text{Waveguide run 1} & \text{Waveguide run 2} \\
\text{Power attenuation} & 0.94 & 0.92
\end{array}
$$

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Although this estimate is based on the present CLIC design, some improvement in these attenuation values may be possible through major changes to the linac and structure configurations. Such new configurations might include a small linac separation and a single accelerating section per PETS, field-compensated single-feed accelerating structure inputs, and a modified transfer structure output.

The implications of such changes are numerous and are not limited to RF issues; the feasibility and actual benefits must be studied in detail. Effects not included in the previous analysis, PETS output mismatch and accelerating structure input mismatch, for example, must also be studied.

![Diagram](image)

Fig. 8.61 Cross-sectional view of the waveguide layout showing the power attenuation of the different components

### 8.12 Beam dumps

At the end of each drive linac section the unused portion of the drive beam will be dumped. This represents 1–2 MW of beam power with energies spanning a ten-fold range from that of first bunch with the highest energy to the core of the bunches in the main part of the beam which will have the lowest energy. An example of the distribution of beam power versus beam energy is shown in Fig. 8.62.

The peak at low energy represents the unused core power, but an approximately equal amount of unused power is in the pre-fill portion of the drive beam pulse.

This beam must be diverted into a water-cooled dump placed in an excavated niche (see Fig. 8.63). The beam is first deflected using a dipole over a range of angles from say 25 mrad to 250 mrad. The resulting spatial dispersion is used to advantage since it will reduce the power density at the exit window from the beam vacuum chamber. This can be placed just before the next elements, a string of half-quadrupoles, which is used to give more beam deflection without too much increase in dispersion as shown in Fig. 8.63. This allows the beam to continue to the dump without excessive transverse growth. This part of the beam path must be in a vacuum of about 1 torr or in an inert gas atmosphere to avoid the production of $O_3$.

The dump itself could be of the SLAC Sphere Dump design [Walz, 1969] in which the beam power is absorbed in a water-cooled bed of aluminium spheres. Catalytic hydrogen–oxygen recombiners are used to remove the hydrogen resulting from radiolysis.

Overall, each dump would be very similar to the 1 MW beam dump used at TJNAF [CEBAF, 1988; Stapleton, 1988].
Fig. 8.62 Distribution of power in the dumped beam versus energy

Fig. 8.63 Plan view and elevation of the beam dumps at the end of each drive linac
References


9 SYSTEM ISSUES

The overall simplicity of the two-beam concept adopted for the CLIC study has much appeal over more conventional linac designs, particularly in the high-frequency range where klystrons or other discrete power sources do not yet exist. This appeal of the two-beam layout has inspired several elegant solutions to the detailed design features of the collider, but less effort has been invested in studies of the control of the drive beam and the operability of the entire complex.

These issues place constraints on the details of the two-beam layout, particularly concerning the avoidance of particle loss from the multi-megawatt drive beam and the accommodation of the inevitable low-level losses that would accompany setting up and, in all probability, routine operation. The relatively high emittance of the drive beam, the uncomfortably low acceptance of the beam line, and the extremely large beam energy spread, even within individual bunches, accentuate the beam control problems.

In the following we consider the 3 TeV machine parameters. Two separate drive beam generation complexes (one per main linac) are assumed. Each complex comprises an injector, a high-power linac, and a set of bunch train combiner rings (see Fig. 4.3 or Appendix A). Each complex generates 20 drive beam pulses, which are transported and injected into the 20 drive beam decelerator sections (each ~ 700 m long). An option aimed at reducing the overall cost in which all 40 drive beam pulses would be generated in a single complex could be envisaged.

9.1 Beam damage potential

The potential for damage by a particle beam, in terms of the heat deposition leading to strain, shock-wave damage, or melting, depends upon the beam current, energy, and type of particle. Some typical high-power electron beam applications are listed in Table 9.1. The ‘damage potential’ (i.e. an approximate measure of the extent to which a copper absorber would be damaged when struck by the beam) for continuous beam loss, is estimated by dividing the power deposited by the total length of absorber over which the loss would be distributed. Thus a low-energy, high-current beam is considered to be more damaging than a high-energy, low-current beam of the same power. For pulsed beams the ‘damage potential per pulse’ is the beam energy in a single pulse divided by the absorber length. Table 9.2 lists some high-power facilities that are currently in various stages of design. The CLIC drive beam is included in each table for comparison.

The total power in the CLIC drive beams is almost two orders of magnitude greater than existing electron linacs, and its relatively low energy accentuates the damage potential. These drive beams are comparable to beams in high-power proton linacs intended for tritium production and/or transmutation. Driver linacs designed for neutron spallation sources and muon colliders have considerably lower power at about the same energy. For hadron accelerators the concept of damage potential is less useful on account of the larger extent of the hadron cascade compared to the $e^-$-$e^+$ shower. In general, for a given beam power the risk of localized damage to machine components is an order of magnitude lower for the hadron machines.

CLIC drivers will require the same care and attention to beam loss management as the transmutation drivers [Wangler, 1998]. Induced activity is less of a concern for the electron machines, and the particularly troublesome low-energy space-charge-induced losses of proton linacs are absent. Nevertheless, the low margin between beam emittance and machine acceptance is a constraint that requires particular attention in the CLIC design.

The damage potential of the CLIC drive beam accelerator is similar to that of the high-power pulsed klystrons (in CW mode) developed for linear colliders. This is somewhat less of a concern since accidental damage to klystrons would be limited to individual units that could be replaced.

9.2 Machine protection overview

Minor drive beam loss (in terms of fraction of beam current) will represent a fairly sizeable power loss. One part in a thousand at top energy in the accelerating linac is 70 kW. Destructive beam loss could occur more or less anywhere along the drive beam accelerator or combiner rings, unless
special provisions are made to localize losses. In the drive beam decelerator sections these power levels are reduced by a factor 20, corresponding to the number of sections, but within a lower beam aperture.

The design must provide and maintain precise alignment of the drive beam decelerator despite heat load from minor beam loss. Mechanical interference between the drive beam decelerator with its high-capacity cooling system and the extreme mechanical stability requirement of the nearby main linac are also of some concern. One must also bear in mind that the refined main linac alignment procedure cannot be started until the drive beam has been correctly tuned and all of its feedback systems stabilized. A robust solution to the drive beam design problem is essential.

The consequence of high- and low-level beam loss has been studied in collaboration with P. Kloeppel (TJNAF), [Johnson, 1995; Johnson, 1997]. The method that has been used for this analysis is a combination of EGS4, which can predict the distribution of the power that is deposited in the structure by a mis-steered beam, and ANSYS, which is used to find the resulting temperature distribution and thermal distortions.

Although the programs are not readily combined, meaningful results were obtained after some effort. The thermal and mechanical effects of beam loss have been reported for a nominal beam loss rate such that the effects can be scaled to other values.

9.3 Drive beam accelerator and ring protection

The energy of one drive beam pulse in the accelerator (distributed later in 20 decelerator sections) is 1 MJ, which is sufficient to melt 1.5 kg of copper, or to pierce a hole 10 mm diameter and 2 m long. As the range of 1.23 GeV electrons in copper is in the region of 150 mm, the beam would have to be blown up to a diameter of greater that 35 mm to avoid melting any copper structure that it might strike.

The overall pulse length is 91 µs and the length of the drive beam accelerator is about 400 m. Allowing 600 m (2 µs) for the signal path from the position of a 1.23 GeV loss (e.g. from one of the combiner rings), a fast shutdown signal would limit the amount of energy in the pulse to ~ 2% of the total. This energy, 20 kJ, if deposited locally could melt 30 g of copper and so, in addition to the fast shutdown action, a beam blow-up device would be needed to dilute transverse energy density of the already accelerated beam.

9.4 Drive beam decelerator protection

We assume that at the extremes of the two main linacs (i.e. the injection points at opposite ends of the collider) we shall have 70 MW beam dumps for full-power tune-up of the drive beams. These will also be available to dump already accelerated drive beam power should an injection fault occur in any of the 20 decelerator sections. However, should a beam steering fault develop some little way down a decelerator section, all of the 143 ns train (50 kJ) could be lost with some damage to the power extraction and transfer structures (PETS). We are studying the use of aperture restrictions to localize such losses, but in general only 50% of a loss can be localized, the remainder propagates by way of the electron/positron shower and spreads its energy over a short region mainly downstream of the primary loss point. This secondary loss causes no melting.

Low-level continuous beam loss in the region of a few to a few hundred kilowatts has been studied and discussed [C.D. Johnson, 1997]. The localization of these losses and the accompanying shower, mentioned above, is of particular relevance in this case since a low level of continuous loss must be accommodated during beam tuning. The downstream shower could perturb position monitors and lead to mis-steering and a runaway loss situation.

9.5 Safe start-up scenarios

The start-up scenario of the RF power source, and the subsequent (or concurrent) collider start-up have not been fully evaluated. Nevertheless, some obvious provisions must be made to handle the high-energy bunch trains and to run up gradually to high power operation.
The drive beam accelerator will be aligned and run up at low power—single bunches and then short bunch trains at low charge. Under these conditions the linac will not be fully beam-loaded and RF loads will be needed to absorb the unused RF power. A low repetition rate will be used to avoid the need to have high (average) power loads. As the number of bunches and their intensity is increased, high-power dumps will be needed. It is proposed to use the two 70 MW dumps situated at the upstream end of the main linacs. These dumps and the linac tunnels will have to be completed before full-power testing of the drive beam accelerator is undertaken. An option might be initially to site these dumps close to the linac and to relocate them later, but this might be impractical on account of the induced activity.

The combiner rings will also be set up in stages: low intensity, short trains, and low repetition rate, increasing each in the order given until the full power can be handled.

The 700 m long drive beam decelerator sections will be set up individually. Initially a single 143 ns train can be switched into one section after another. The decelerator section will have been previously mechanically aligned and then beam-aligned using a single bunch from the main linac injector at 1.23 GeV. Then the bunch train at 30 GHz, but low intensity and very low repetition rate will be injected and steered to the beam dump at the end of each decelerator section. The bunch intensity will be gradually increased with re-steering and loss management until the full power level is reached. At this stage all feedback and feed-forward systems will have been implemented based on experience gained in previous test facilities. Also the allowed level of continuous beam loss will have been set according to the installed cooling capacity and the redundancy of beam position monitors (assuming that in the region of beam losses, some will have been disconnected). The last stage will be to increase the repetition rate to match the needs of the collider performance.

RF phasing to the main linac beam will be done in a bootstrap mode whereby a high-emittance main linac bunch is phased to the first decelerator section (assuming that all of the individual phases between PETS and accelerating structures have been preset to within the necessary tolerances). This main linac bunch will be lost at the start of the second decelerator section (hence the need for a high emittance to avoid damage), but the phase information will be used to adjust a path length, and thus the drive beam phase, in the injector loop of the second section. This setting will compensate for such changes as those due to the solar and lunar tides and possibly temperature and atmospheric pressure variations. The tidal phase settings will be pre-programmed as far as possible. After setting the phase of the second decelerator section to the main linac bunch, acceleration will continue to the third section, and so on until the end. The complexity of this setting-up operation should not be underestimated.

It remains to examine in full these operational requirements for beam start-up. Many details will only become clear as the study programme continues through the next stages of testing. Nevertheless, some attempts will be made to test some procedures on existing machines and to use computer simulation results where possible. In this respect simulation programs of the drive beam decelerator are now being implemented for this purpose.

9.6 Activation

There is ample information available from existing machines and their respective beam dumps (e.g. TJNAF, SLC) to provide engineered solutions for the handling of beam power and induced activity of beam dumps. Elsewhere the activation will be necessarily limited by the heat limit imposed on uncontrolled beam loss and this should be no worse than in other accelerators. The important point to note for the CLIC power source is that over 99% of the beam power must be converted to RF power or must arrive at the beam dumps for unused beam. The latter will handle an integrated power in the region of 38 MW spread over 40 dumps each one receiving beam power equal to that of the TJNAF beam for example.
Table 9.1
Damage potential to copper structures of various electron beams

<table>
<thead>
<tr>
<th>Project</th>
<th>CLIC</th>
<th>CLIC</th>
<th>TESLA</th>
<th>NLC</th>
<th>NLC/TBA</th>
<th>NLC</th>
<th>TESLA</th>
<th>TJNAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>Drive beam accelerator</td>
<td>Drive beam decelerator</td>
<td>Main linac</td>
<td>Main linac</td>
<td>Relativistic klystron</td>
<td>Klystron</td>
<td>Klystron</td>
<td>Recirculating linac</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>1.24</td>
<td>1.24</td>
<td>250</td>
<td>250</td>
<td>0.01</td>
<td>4.4 × 10⁻⁴</td>
<td>1.16 × 10⁻⁴</td>
<td>4</td>
</tr>
<tr>
<td>Particles</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
</tr>
<tr>
<td>Current/pulse (A)</td>
<td>8.2</td>
<td>262</td>
<td>0.0165</td>
<td>0.543</td>
<td>600</td>
<td>350</td>
<td>7 × 133</td>
<td>2 × 10⁻⁴</td>
</tr>
<tr>
<td>Pulse duration (µs)</td>
<td>92</td>
<td>0.143</td>
<td>800</td>
<td>0.27</td>
<td>0.3</td>
<td>2</td>
<td>1300</td>
<td>CW</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>75</td>
<td>75</td>
<td>5</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>10</td>
<td>CW</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>56.5</td>
<td>2.825</td>
<td>0.066</td>
<td>0.0175</td>
<td>22</td>
<td>125</td>
<td>1.2 × 10⁴</td>
<td>0.2</td>
</tr>
<tr>
<td>Energy/pulse (kJ)</td>
<td>935</td>
<td>46.7</td>
<td>3300</td>
<td>36.5</td>
<td>1.8</td>
<td>0.463</td>
<td>140</td>
<td>NA</td>
</tr>
<tr>
<td>Meanpower (MW)</td>
<td>70</td>
<td>3.5</td>
<td>16.5</td>
<td>4.38</td>
<td>0.216</td>
<td>5.5 × 10⁻²</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Range of particle in Cu (m)</td>
<td>0.07</td>
<td>0.07</td>
<td>14.3</td>
<td>14.3</td>
<td>7 × 10⁻³</td>
<td>2 × 10⁻⁴</td>
<td>5.3 × 10⁻⁵</td>
<td>0.28</td>
</tr>
<tr>
<td>Damage potential (per pulse) (kJ/m)</td>
<td>1.34 × 10⁴</td>
<td>668</td>
<td>231</td>
<td>2.55</td>
<td>257</td>
<td>2312</td>
<td>2640</td>
<td>NA</td>
</tr>
<tr>
<td>Damage potential (average) (MW/m)</td>
<td>10³</td>
<td>50</td>
<td>1.15</td>
<td>0.30</td>
<td>30.9</td>
<td>277</td>
<td>2.64 × 10⁴</td>
<td>2.86</td>
</tr>
</tbody>
</table>
Table 9.2
The CLIC drive beam compared to beams proposed for other high-power linacs

<table>
<thead>
<tr>
<th>Project</th>
<th>CLIC</th>
<th>CLIC</th>
<th>APT</th>
<th>SNS Oak Ridge</th>
<th>ESS Europe</th>
<th>Muon collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>Drive beam accelerator</td>
<td>Drive beam decelerator</td>
<td>Linac</td>
<td>Spallation source linac</td>
<td>Spallation source linac</td>
<td>Pion production driver (linac/synchrotron)</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>1.24</td>
<td>1.24</td>
<td>1.7</td>
<td>1.33</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Particles</td>
<td>e⁻</td>
<td>e⁻</td>
<td>p</td>
<td>H⁻</td>
<td>H⁻</td>
<td>p</td>
</tr>
<tr>
<td>Current/pulse (A)</td>
<td>8.2</td>
<td>262</td>
<td>CW</td>
<td>0.17</td>
<td>0.6</td>
<td>66.7</td>
</tr>
<tr>
<td>Pulse duration (µs)</td>
<td>92</td>
<td>0.143</td>
<td>CW</td>
<td>10³</td>
<td>1.2 × 10³</td>
<td>0.2</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>75</td>
<td>75</td>
<td>CW</td>
<td>60</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>56.5</td>
<td>2.825</td>
<td>100</td>
<td>1.0</td>
<td>3.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Energy/pulse (kJ)</td>
<td>935</td>
<td>46.7</td>
<td>NA</td>
<td>17</td>
<td>100</td>
<td>267</td>
</tr>
<tr>
<td>Mean power (MW)</td>
<td>70</td>
<td>3.5</td>
<td>170</td>
<td>1.0</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>
References


10  THE CTF3 TEST FACILITY

10.1  Description

The CLIC drive beam generator as proposed in this report will produce 20 drive beams per linac (see Fig. 10.1). All major problems associated with this scheme can, however, be studied by generating only one drive beam. A possible future installation (CLIC 1) to test one complete CLIC drive beam is shown in Fig. 10.2.

Since this is a very large installation, a much smaller facility is proposed as an intermediate first step to demonstrate the technical feasibility of the key concepts of this new RF power source. Two designs for this new CLIC Test Facility (CTF3) are being considered. The first is shown in Fig. 10.3 and is called CTF3a. The second is shown in Fig. 10.4 and is called CTF3b.

The main difference between the two is the choice of the frequency of the drive beam accelerator. In CTF3a it is 3 GHz and in CTF3b it is 937 MHz.

Technically the preference is for CTF3b, which is much closer to the final CLIC scheme. It would, however, require the development and construction of eight 100 MW or sixteen 50 MW 937 MHz klystrons with a 1 µs RF pulse. The LPI modulators could be used with relatively minor modifications. The cost of this klystron development work and the time required to complete it will ultimately decide which design to start with.

Fig. 10.1  Schematic layout of the CLIC RF power source
Fig. 10.2 Schematic layout of CLIC 1

Fig. 10.3 Schematic layout of CTF3a
The advantage of CTF3b is that the injector and initial acceleration up to 100 MeV are identical to the planned CLIC power source, but at a shorter pulse length. The RF combination for the times-two combiner and the first ring combiner is also identical.

It would also enable the klystron manufacturers to start the development of the 937 MHz klystrons with a relatively easier pulse length specification of 1 µs (100 µs is finally required for CLIC).

Since CTF3a is initially expected to be less expensive than CTF3b, most of the design effort has gone into this design which is referred to in the rest of this report simply as CTF3.

To reduce costs CTF3 differs from the RF power source proposed for CLIC in the following ways (Table 10.1). The frequency of the drive beam accelerator is chosen to be 3 GHz instead of 937 MHz. This enables the 3 GHz klystrons, modulators, and RF power compression units from the LEP Injector Linac Complex to be used for power production, which is always a very costly item.

Since there are only eight of these units the maximum energy of the drive beam is 80 MeV (compared to 1.23 GeV for CLIC). The modulators produce a maximum pulse length of 4.5 µs which after compression becomes 1.4 s. This pulse is just long enough after the ×10 frequency multiplication to produce the nominal CLIC RF pulse of 140 ns. The average current of 8.2 A in the drive beam accelerator is the same as in CLIC to create realistic beam loading test conditions.

The Delay Combiner and the first Combiner Ring are very similar to those required for CLIC but the second more expensive (×4) Combiner Ring is not included (the scheme of combination is the same and there is little to be learnt by including it).

This results in a 30 GHz acceleration system. The drive beam decelerator is limited to a total length of about 15 m (seven transfer structures) compared to 625 m for CLIC.
Table 10.1
Comparison of CTF3 and CLIC 1 parameters for one drive beam

<table>
<thead>
<tr>
<th></th>
<th>CTF3</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of drive beam accelerator</td>
<td>3 GHz</td>
<td>937 MHz</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>10 Hz</td>
<td>75 Hz</td>
</tr>
<tr>
<td>Average drive beam current</td>
<td>8.2 A</td>
<td>8.2 A</td>
</tr>
<tr>
<td>Drive beam pulse length</td>
<td>1.4 s</td>
<td>92 s</td>
</tr>
<tr>
<td>Drive beam energy</td>
<td>80 MeV</td>
<td>1160 MeV</td>
</tr>
<tr>
<td>43 m delay combiner (× 2)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>86 m combiner ring (× 4)</td>
<td>× 5</td>
<td>Yes</td>
</tr>
<tr>
<td>344 m combiner ring (× 4)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>140 ns</td>
<td>140 ns</td>
</tr>
<tr>
<td>Frequency of RF power generated</td>
<td>30 GHz</td>
<td>30 GHz</td>
</tr>
<tr>
<td>Number of transfer structures</td>
<td>7</td>
<td>550</td>
</tr>
<tr>
<td>Number of accelerating structures</td>
<td>14</td>
<td>1100</td>
</tr>
<tr>
<td>Main linac accelerating gradient</td>
<td>150 MV/m</td>
<td>150 MV/m</td>
</tr>
<tr>
<td>Drive beam energy on beam dump</td>
<td>36 MeV</td>
<td>150 MeV</td>
</tr>
</tbody>
</table>

Since the designs of the two thermionic guns, the 43 m delay line, and the 86 m combiner ring are very close to those required for CLIC, most of the components can be used in future installations. To limit the radiation produced by CTF3 it is proposed to run at 10 Hz instead of 75 Hz.

10.2 Design of test facility

The even and odd bunches of the drive beam are generated by separate injectors and then combined by an RF deflector to form one continuous train. The bunch spacing is 20 cm (two 3 GHz buckets).

Each injector consists of a pulsed thermionic gun, two 1.5 GHz sub-harmonic bunchers, a 3 GHz standing-wave buncher, and a 3 GHz travelling-wave buncher.

The 1.4 μs long beam (average current 8.2 A) is accelerated to 50 MeV in a solenoid-focused 3 GHz travelling-wave linac operating at 12 MV/m (a spare LIL section can be used for this). After collimation the normalized emittance of the bunched beam at this stage is expected to be < 100 mm mrad.

The main beam parameters are given in Table 10.2.

The 3 GHz drive beam accelerator increases the beam energy from 50 MeV to 80 MeV using eight 0.9 m long normal-conducting travelling-wave structures (see Table 10.3). This linac has a conventional quadrupole FODO focusing.

To maintain beam stability in both this linac and the 4–50 MeV injector linac the wakefield levels of the first and second transverse dipole modes will be damped to $Q$ values of 25 and 100 respectively. This will be done by introducing waveguide damping and detuning in the accelerating structures. The same structure design will be used for both linacs.
The RF power is supplied by 30 MW klystrons which after compression by a factor 3 by the LIPS system (with added pulse-flattening correction cavities) provide 90 MW at the input to each structure. Operating these linacs in the fully-loaded condition results in an RF-to-beam efficiency of 96%.

A correlated single-bunch energy spread is introduced in the drive beam accelerator by a combination of off-crest running and beam loading so that the bunches can be compressed at a later stage.

<table>
<thead>
<tr>
<th>Table 10.2</th>
<th>Main parameters of the injectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>1.4 µs</td>
</tr>
<tr>
<td>Beam current per pulse</td>
<td>8.2 A</td>
</tr>
<tr>
<td>Charge per pulse</td>
<td>8.2 µC</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>4.8 nC</td>
</tr>
<tr>
<td>Bunch length (r.m.s.)</td>
<td>&lt; 2 mm</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1712</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>&lt; 100 mm mrad</td>
</tr>
<tr>
<td>Energy</td>
<td>4 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

The continuous train of bunches is split into a series of 43 m long bunch trains with 43 m gaps by the combiner delay line. It also produces a frequency multiplication (×2) by interleaving the bunches in the even buckets with the bunches in the odd buckets to produce a bunch spacing of 10 cm. The two RF defectors in this line operate at 1.5 GHz.

A further frequency multiplication (×5) is obtained in the 86 m circumference combiner ring to obtain a final bunch spacing of 2 cm. The injection section of this ring consists of two 3 GHz RF defectors and a septum magnet.

<table>
<thead>
<tr>
<th>Table 10.3</th>
<th>Drive beam accelerator structure parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shunt impedance $R'$</td>
<td>54 MΩ/m</td>
</tr>
<tr>
<td>$Q$</td>
<td>14 904</td>
</tr>
<tr>
<td>Group velocity $v_g/c$</td>
<td>3.5%</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>11 MV/m</td>
</tr>
<tr>
<td>Detuning (1st dipole mode)</td>
<td>10%</td>
</tr>
<tr>
<td>Damping (1st dipole mode)</td>
<td>25</td>
</tr>
</tbody>
</table>
To prevent bunch lengthening, the lattices of both the delay line, and the combiner ring with its two path-length-adjusting sections, have to be isochronous. The 140 ns bunch train is extracted from this ring using a septum magnet and a single-pulse electrostatic kicker with a 100 ns rise time and a 150 ns flat top.

The bunches with their correlated energy spread still intact are then compressed using a magnetic chicane.

This bunch train with a maximum charge of 5.5 nC per bunch is then decelerated in the 30 GHz drive beam decelerator from an initial energy of 80 MeV to a final energy of 36 MeV by seven transfer structures before being sent to a dump. The main beam is accelerated to 1.0 GeV by fourteen 30 GHz accelerating structures operating at a gradient of 150 MV/m. For reasons of beam stability the accelerating structures have to be both damped and detuned.

10.3 Important issues

In spite of all these differences CTF3 would incorporate all the basic features of the final scheme. The components or systems that CTF3 would or would not test are listed and commented on below.

10.3.1 Thermionic electron guns

These guns would be designed to give CLIC nominal parameters (17.5 nC/bunch) which means 30 nC from the gun over two RF periods. They could therefore be used later for CLIC. They would test the grid pulsing system and demonstrate the ability to produce a current per pulse of 14 A at a repetition frequency of 75 Hz even though CTF2 would operate at 10 Hz.

10.3.2 Sub-harmonic (SH) bunchers

These two SH bunchers would operate at 3/2 GHz rather than 937/2 MHz and could not therefore be used later for CLIC. Since the frequency and therefore the longitudinal impedance are higher, beam loading effects and induced phase shifts will also be higher. This is, however, not a problem for the first SH buncher which essentially sees a DC beam.

10.3.3 Bunchers

These two bunchers would operate at 3 GHz rather than 937 MHz and could not therefore be used later for CLIC. Because of the higher frequency the r.m.s. bunch length will be shorter (for CLIC at this stage it is about 2 mm) but will be chosen to have the same space-charge forces so that the design emittance of < 100 mm mrad can be convincingly demonstrated.

10.3.4 RF combiner

This combiner would operate at 1.5 GHz rather than 937/2 MHz and could not therefore be used later for CLIC. This requires the same technology as an RF separator. We need to verify that beam loading is not a problem.

10.3.5 Injector linac and drive beam accelerator

These linacs would operate at 3 GHz rather than 937 MHz and could not therefore be used later for CLIC. The effects of the increased beam loading due to the higher longitudinal impedance have to be studied. Experience would be obtained in building damped and detuned accelerating structures which would be scaled versions of the 937 MHz design, and in operating fully-loaded linacs. The combination of a reduced charge (5.5 nC instead of 17.5 nC), a higher frequency, and a lower final energy results in the required single-bunch correlated energy spread for later bunch compression.
10.3.6 The delay and ring combiners

Since the relative energy spread of the injected bunches has been adjusted to be the same as CLIC, the specification on isochronicity is also the same. The final CLIC lattice and magnet design can therefore be used for these two combiners and the fields scaled down to the lower energy (80 MeV instead of 1.23 GeV). The RF deflectors in the injection section of the delay combiner will operate at a higher frequency than that required for CLIC (1.5 GHz instead of 937/2 MHz). The increased beam loading effects associated with this higher frequency will have to be studied. The RF deflector in the 86 m combiner ring, however, has approximately the same frequency (3 GHz) as that required for the second CLIC 344 m combiner ring (3.7 GHz). This will enable an accurate evaluation of beam loading effects of the transverse mode to be obtained. This loading may produce varying kicks along the train resulting in a scatter of transverse position just before injection into the drive beam decelerator. Although the bunch train length is much shorter in CTF3, it is possible that, owing to the very small fill time of the deflector (< 20 ns), long time transverse wakefields will only be slightly different. It is important that the correlated energy spread that is put in by the drive beam accelerator is not spoilt by coherent radiation effects in the combiner rings. The injection and extraction septum magnets, and a lot of other equipment for this ring such as quadrupoles, beam instrumentation, and vacuum can be obtained from the LEP Injector Complex LPI after LEP is closed down.

10.3.7 The bunch compressor

No particular difficulty is expected here, a similar bunch compressor has operated successfully in CTF2.

10.3.8 Injection into the drive beam decelerator

The drive beam can be used to develop and try out the precise control of the injection conditions (steering and jitter), including the use of feed-back and feed-forward systems.

10.3.9 The drive beam decelerator

Seven special 30 GHz transfer structures are required here. They will be of a similar design to that required for CLIC but will have a higher coupling to the beam to compensate for the reduced beam current. Valuable experience will be obtained in the fabrication and alignment of these types of structures; they will, however, have no use in later schemes. The primary concern in the decelerator is the stability of the beam as more and more energy is extracted from the beam. CTF3 will help determine the minimum beam energy that is compatible with a low-loss mode of operation. It will also provide a test bed for bench-marking beam dynamics simulations which have to predict the behaviour of full-scale CLIC drive beams where the energy spread within the beam approaches a factor of 10. This line will require multibunch beam-position monitors to gain experience with steering multibunch beams. These monitors should be designed to have the same 5 \( \mu \text{m} \) resolution required for CLIC. Given the very short length of this linac, it is unlikely that any tests of the all important beam trajectory correction and control schemes can be carried out.

10.3.10 The main beam accelerator

Fourteen 30 GHz accelerating structures, of the same design foreseen for CLIC, are required here. Again, valuable experience would be obtained in the fabrication of these types of structures and they could be used in later schemes. This linac would test the ability of the structures to suppress transversely deflecting higher modes albeit over a very limited length, and possibly the scheme for controlling the main beam energy to within the specified limits. A separate injector linac would be required to provide the probe bunches for this linac. The injector currently being used in CTF2 could perhaps be used.
10.4 Construction of CTF3 in stages

CTF3 could if necessary be built in two stages. The first stage is shown in Fig. 10.5. The existing LIL gun, pre-buncher, and buncher are used to produce one continuous 850 ns long pulse with one bunch every RF bucket (10 cm) to give the same mean current of 8.2 A. The eight LIL klystrons, modulators, and pulse compression units are used to supply the RF power. The delay line combiner which would normally split this pulse into several bunch trains is suppressed and the 850 ns pulse is fed directly into the times-five combiner ring to produce a 170 ns final pulse with a bunch spacing of 2 cm.

Since there is no delay line combiner and therefore no gaps, extraction of this pulse is messy. During the rise time of the extraction kicker (approx. 30 ns) electrons are swept across the extraction septum and lost. After 30 ns, however, a clean 140 ns drive beam is obtained with a mean current of 41 A. This beam is used to drive the 6 m long two-beam test accelerator built for CTF2 but requires four new power extraction structures to generate enough power to obtain accelerating gradients of 150 MV/m.

This first-stage CTF3 could also be operated at reduced currents in order to obtain higher beam energies. If the same drive beam accelerating structures are used, reducing the current to 4.1 A increases the energy to 125 MeV. The linac would not in this case be fully loaded and would run at a reduced RF-to-beam efficiency. Energies as high as 160 MeV could be obtained with 4.1 A by replacing the eight 0.9 m long structures by eight 1.8 m long structures.

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**Fig. 10.5** Schematic layout of the first stage of CTF3
10.5 Special tests

10.5.1 High gradient tests

The most important single issue for CLIC is to demonstrate that accelerating gradients of 150 MV/m and more can be obtained at 30 GHz for RF pulses of 140 ns. A high priority should be given to this. The test facility described above would in principle provide the necessary power, pulse length, and gradient for these tests.

10.5.2 RF deflector tests

A 3 GHz RF deflector already exists and should be tested in CTF2.
11 SUMMARY AND CONCLUSION

In this report we have presented a new kind of two-beam accelerator and applied it to the 3 TeV design for CLIC. The basic idea of two-beam acceleration was proposed by A. Sessler [Sessler, 1982]. This was later adapted to a single-bunch linear collider by W. Schnell using highly relativistic drive beams [Schnell, 1986]. The new scheme is the result of 12 years of study and developments by the CLIC study team and the more recent changes have significantly increased the maximum energies that can realistically be proposed [Braun, 1998].

The beauty of the method is that the energy for the RF production is initially stored in a long-pulse electron beam (drive beam) which is efficiently accelerated by a fully loaded linac working at low frequency where powerful and efficient modulators and klystrons are available. The energy is then multiplied in frequency and compressed in time using beam combination techniques, after which it is transported very efficiently close to the accelerating structure of the main beam where it is transformed into RF power with the required amplitude and pulse length. The overall power efficiency from wall plug to RF should be about 40%.

The entire RF system acts like a transformer of the frequency and accelerating gradient of the drive beam accelerator to the main beam accelerator. The transformer ratio for frequency is 32 and for accelerating gradients is about 40 in the example described in this report, but it is very flexible and can be changed according to available technologies.

The method is quite general and is applicable to linear colliders using any frequency of acceleration. In particular, the drive beam complex is rather insensitive to this choice depending more on the required stored energy per pulse and the repetition rate. It is even possible to use the same drive beam for a different but harmonically related frequency. The complex can easily be upgraded for a longer collider with a higher colliding beam energy by simply extending the duration of the RF pulse from the modulator and klystrons of the drive beam accelerator without changing the rest of the drive beam complex. Alternatively, higher energies can be obtained without changing the length of the main linac by increasing the main linac gradient, this is achieved by increasing the gradient and current in the drive beam accelerator.

In order to test the feasibility of the method, a new phase of a CLIC Test Facility (CTF3) is proposed to be built in the next few years. CTF3 will address the key issues of the scheme, particularly the drive beam generation, its acceleration in a fully-loaded linac, and energy compression and frequency multiplication in combiner rings. A high-energy stage could then be envisaged to test the ability to handle high-power beams and the corresponding reliability.

Finally, this method, which is based on conventional technology and a rather reasonable number of modulators and klystrons, is particularly appropriate for high-energy linear colliders and is potentially cost-effective since the same complex is re-used many times to generate the various beams necessary for RF power production one after the other.
References


# APPENDIX A

## CLIC PARAMETERS AT TeV CENTRE-OF-MASS ENERGY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main linac</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.M. energy</td>
<td>$E_{CM}$</td>
<td>3 TeV</td>
</tr>
<tr>
<td>Gradient</td>
<td>$G_{main}$</td>
<td>150 MV/m</td>
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<tr>
<td>Total length/linac</td>
<td>$L_{tot}$</td>
<td>13.75 km</td>
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<tr>
<td>Frequency</td>
<td>$f_{RF}$</td>
<td>30 GHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_{rep}$</td>
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</tr>
<tr>
<td>Bunch charge</td>
<td>$Q_{main}$</td>
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<tr>
<td>Number of bunches/pulse</td>
<td>$N_{main}$</td>
<td>150</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>$\Delta_{main}$</td>
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<tr>
<td>RF pulse duration</td>
<td>$\tau_{RF}$</td>
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<tr>
<td>RF peak power/structure</td>
<td>$P_{RF}$</td>
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</tr>
<tr>
<td>Number of structures/linac</td>
<td>$N_{struct,main}$</td>
<td>21 880</td>
</tr>
<tr>
<td>Total RF peak power/linac</td>
<td>$P_{RF,\text{tot}}$</td>
<td>5.05 TW</td>
</tr>
<tr>
<td>Total RF energy/pulse</td>
<td>$W_{RF,\text{tot}}$</td>
<td>580 kJ</td>
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<td><strong>Drive beam (in the accelerator)</strong></td>
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<td></td>
</tr>
<tr>
<td>Energy</td>
<td>$E_{in}$</td>
<td>1.23 GeV</td>
</tr>
<tr>
<td>Current</td>
<td>$I_{acc}$</td>
<td>8.2 A</td>
</tr>
<tr>
<td>Bunch charge (max)</td>
<td>$Q_{b}$</td>
<td>17.6 nC</td>
</tr>
<tr>
<td>Number of bunches/pulse</td>
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<td>55 680</td>
</tr>
<tr>
<td>Bunch separation</td>
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</tr>
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<td>Pulse duration</td>
<td>$\tau_{pulse}$</td>
<td>91 µs</td>
</tr>
<tr>
<td>Total charge</td>
<td>$Q_{\text{total}}$</td>
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<tr>
<td>Total energy</td>
<td>$W_{\text{tot}}$</td>
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<tr>
<td>Average beam power</td>
<td>$P_{\text{acc,ave}}$</td>
<td>70 MW</td>
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<tr>
<td><strong>Drive beam (in the decelerator)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (initial)</td>
<td>$E_{in}$</td>
<td>1.23 GeV</td>
</tr>
<tr>
<td>Energy (final)</td>
<td>$E_{fin}$</td>
<td>123 MeV</td>
</tr>
<tr>
<td>Current</td>
<td>$I_{\text{dec}}$</td>
<td>264 A</td>
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<tr>
<td>Bunch charge (max)</td>
<td>$Q_{b}$</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Bunch separation</td>
<td>$\Delta_{b,\text{dec}}$</td>
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<td>Value</td>
</tr>
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<td>-----------</td>
<td>--------------------</td>
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<tr>
<td>Average beam power</td>
<td>$P_{\text{dec,ave}}$</td>
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</tr>
<tr>
<td><strong>Drive beam accelerator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (active)</td>
<td>$L_{\text{acc}}$</td>
<td>320 m</td>
</tr>
<tr>
<td>Frequency</td>
<td>$v_{\text{acc}}$</td>
<td>937 MHz</td>
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<tr>
<td>Loaded gradient</td>
<td>$G_{\text{acc}}$</td>
<td>3.85 MV/m</td>
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<tr>
<td>Structure length</td>
<td>$L_{\text{struct,acc}}$</td>
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<tr>
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<td>$N_{\text{struct,acc}}$</td>
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<tr>
<td>Shunt impedance</td>
<td>$r_{\text{acc}}$</td>
<td>1214 $\Omega$/m (linac)</td>
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<tr>
<td>Quality factor</td>
<td>$Q_{\text{acc}}$</td>
<td>26 660</td>
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<tr>
<td>Group velocity</td>
<td>$\beta_{g,\text{acc}}$</td>
<td>0.039 c</td>
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<td>Filling time</td>
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<td>Power/structure</td>
<td>$P_{\text{acc}}$</td>
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<td><strong>Drive beam decelerator</strong></td>
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</tr>
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<td>Section length (total)</td>
<td>$L_{\text{sec,tot}}$</td>
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</tr>
<tr>
<td>Section length (active)</td>
<td>$L_{\text{sec,act}}$</td>
<td>440 m</td>
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<tr>
<td>Number of PETS/section</td>
<td>$N_{\text{PETS,sec}}$</td>
<td>547</td>
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<td>Decelerating gradient</td>
<td>$G_{\text{dec}}$</td>
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<td>$L_{\text{PETS}}$</td>
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<td>PETS shunt impedance</td>
<td>$r_{\text{PETS}}$</td>
<td>62 $\Omega$/m (linac)</td>
</tr>
<tr>
<td>Group velocity</td>
<td>$\beta_{g,\text{dec}}$</td>
<td>0.443 c</td>
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<tr>
<td>Drain time</td>
<td>$\tau_{\text{drain}}$</td>
<td>3.6 ns</td>
</tr>
<tr>
<td><strong>Efficiencies</strong></td>
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<tr>
<td>Modulators</td>
<td>$\eta_{\text{mod}}$</td>
<td>90%</td>
</tr>
<tr>
<td>Klystrons</td>
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<td>65%</td>
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<td>DB acceleration</td>
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<td>DB power extraction</td>
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<td>PETS extraction</td>
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<tr>
<td>PETS to CAS transfer</td>
<td>$\eta_{\text{transf}}$</td>
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</tr>
<tr>
<td>Wall plug to RF</td>
<td>$\eta_{\text{plug,RF}}$</td>
<td>34.5%</td>
</tr>
<tr>
<td>RF to main beam</td>
<td>$\eta_{\text{RF,main}}$</td>
<td>24%</td>
</tr>
<tr>
<td>Overhead for BNS</td>
<td>$1/\eta_{\text{BNS}}$</td>
<td>10%</td>
</tr>
<tr>
<td>Wall plug to main</td>
<td>$\eta_{\text{hot}}$</td>
<td>8.4%</td>
</tr>
</tbody>
</table>
APPENDIX B
POWER FLOW DIAGRAM

253 MW Wall Plug

- 251 MW
- \( \eta_M = 0.90 \)
- \( \eta_K = 0.65 \)
- Power Supplies Klystrons
- Compressor Rings
- Beam Transport
- Linac Optics

- 147 MW
- \( \eta_d = 0.95 \)
- \( \eta_\lambda = 0.981 \)
- Drive Beam Acceleration
- Drive Beam Power Extr.
- Dumps

- 137 MW
- \( \eta_{TRS} = 0.95 \)
- \( \eta_f = 0.95 \)
- Transfer Structures

- 96 MW
- \( F(\sigma) = 0.97 \)
- \( \eta_d = 0.724 \)

- 87 MW
- \( (2 \times 580 \text{ kJ} \times 75 \text{ Hz}) \)
- Main Linac

- 21.5 MW Main Beam
- \( \eta_{RF} = 0.247 \)

\[ \eta_{\text{plug/RF}} = 34.6\% \]
\[ \eta_{\text{RF/main}} = 24.7\% \]
\[ \eta_{\text{tot}} = 8.5\% \]

Fig. B.1 Power flow diagram for a 3 TeV c.m. CLIC complex
Fig. C.1 Only one RF Power Source (for the position main linac) is shown in the picture. The main beam generation complex is not explicitly shown.
Acknowledgements

The CLIC study team would like to express their special thanks to two co-authors of this report. First of all to Ron Ruth from SLAC for accepting to chair and animate the activities of the CLIC RF power source working group during his one-year sabbatical stay at CERN from August 1997 to July 1998, and for carrying out this task with such dynamism and motivation. His expertise proved to be extremely beneficial in reviewing the multi-drive beam scheme with its counter-flow distribution of the drive beams and its beam combination schemes for frequency and power multiplication on which the CLIC team had been working for several years. Looking at the scheme with a new and expert eye, he made essential contributions to the scheme, the most important being the replacement of the 937 MHz superconducting drive beam accelerator by a normal-conducting one working at the same frequency but in the fully-loaded mode to be even more efficient (no cryogenic power). This modification resulted in an important simplification of the scheme because the drive beam could then be accelerated at the same speed as it is used (no limitation of the peak RF power by the superconducting technology) and therefore did not require intermediate storage (during 2 ms) in a large-circumference isochronous ring. This made the whole scheme not only simpler but also safer, cheaper, and even more importantly testable in a reasonably sized test facility (CTF3 is currently in the design phase and will be proposed to the CERN management in early 1999). He worked very closely with all members of the study on the various parts of the scheme and initiated its description in this report. The CLIC study team has particularly appreciated the public expression of his enthusiasm and conviction for the two-beam approach presented here.

Special thanks also go to Roberto Corsini for his important contributions to the CLIC scheme and who, acting as scientific secretary, had the very difficult task of collecting and documenting a huge amount of scientific information and putting it together and editing it to produce this report.