THE STUDY OF A CERN LINEAR COLLIDER, CLIC

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1. Introduction

At CERN work on linear colliders for electrons and positrons in the TeV energy range began with an advisory panel set up by a Long-Range Planning Committee which had been initiated by the CERN Council and was chaired by C. Rubbia. The panel (under the chairmanship of K. Johnsen) adopted the name of CERN Linear Collider (CLIC) for the subject of its work, made the tentative choice of 2 TeV for the centre-of-mass energy and initiated a study at CERN, in collaboration with other laboratories. The panel issued its final report [1] in May 1987 and its conclusions are now being followed by the ongoing study. Although the pace of our work is limited by available funds and manpower an attempt is being made to cover all fundamental aspects of a TeV linear collider - from beam formation to the final focus system - so as to arrive at a realistic assessment of the possibility of initiating a project within the next decade.

For the main linear accelerators we envisage radio-frequency structures whose frequency is chosen as high as is permitted by beam-induced wake fields and by manufacturing problems. A tentative value of 30 GHz has been adopted. Accordingly, theoretical and computational studies of wake stabilization and development work on centimetre-wave accelerating structures form central parts of our work. The reason for this emphasis on the highest practicable frequency is the observation that the average RF power input is proportional to $f_r E_0/\omega^2$, with little else to choose, where f_r is the repetition frequency, E_0 the peak accelerating gradient and ω^2 the RF frequency. And running at the highest practicable repetition frequency seems important because of the limitation of luminosity per beam pulse by beam-beam radiation (beamstrahlung) and other effects.

Another distinctive feature of our work is the proposal of RF power generation by a two-beam scheme in which the drive beam is in the GeV energy range and receives its energy from a drive linac formed by superconducting cavities [2]. A serious problem here is the generation and preacceleration of a tightly bunched drive beam of sufficient intensity. Consequently, preparations for a test facility for drive-beam generation form another important part of our study.

Table 1 below shows a set of tentative CLIC parameters. They are for a single bunch per RF pulse.

Much could be gained by "multibunching", i.e. by using a number n of bunches - of the order of ten - following each other in rapid succession during the same RF pulse. Clearly this would multiply the effective repetition rate and, hence, the luminosity by n without a large increase of input power, since the n bunches share most of the same batch of electromagnetic energy from which they can extract a much larger fraction than a single bunch. In a travelling-wave linac a simple and flexible way of giving all n bunches the same energy gain is to pass the first one before the end of the fill time and adjust the bunch interval so as to make the continuing influx of electromagnetic energy compensate for the beam loading. The details of this remain to be studied, however, and tolerances may present problems.

Table 1. Tentative parameters for a CERN Linear Collider

Parameters for one linac, single bunch

Energy	eU	1.0	TeV
Luminosity	L	1.1×10^{33}	$cm^2 s^{-1}$
Accelerating Gradient	E_0	80	MV/m
Final Focus Aspect Ratio	R	5	
Final Focus Beam Height	σ_y	12	nm
Fractional Energy Loss by Beam Radiation	δ	0.27	
Fractional Average Critical Energy	Υ	0.71	
Pinch Enhancement	$H_x H_y \approx H_y$	2.37	
Repetition Rate	f	1.69	kHz
Number of Bunches per Pulse		1	
Bunch Population	N	0.50	$\times10^{10}$
Beam Power	P_b	1.35	MW
Energy extraction	η	5.0	%
Iris Aperture over Wavelength	a/λ	0.2	
Shunt Impedance over Q per Unit Length	r'	28	kΩ/m
Fill Efficiency	η_τ	0.78	
RF Frequency	$\omega/2\pi$	29	GHz
RF Power (average)	P_{RF}	35	MW
Bunch Length	σ_z	200	μm
Disruption	D	3.3	
Vertical Emittance (normalized)	ε_{ny}	10^{-6}	rad m
Emittance Ratio	$\varepsilon_{nx}/\varepsilon_{ny}$	3 (say)	
Vertical Amplitude Function	β_y^*	282	μm

Following a proposal by R. Palmer [3] multi-bunch beam breakup by long-range wake fields might be avoided by means of damping slots worked into the accelerating structure. In order to be effective such damping slots must reduce the Q-factor of transverse deflecting modes to values of the order of ten without affecting the E_{01} accelerating mode. First experiments have indicated that this is in fact possible and the incorporation of transverse damping has now become one of the main features of our structure development. Nevertheless, considering the engineering problems presented by this and the problems of multiple-bunch crossings near the final focus [4], we prefer to regard multibunching as a potential improvement for which we should create the necessary conditions whenever possible but on which we cannot rely yet.

2. The Injector Complex

A conceptual design for a megawatt electron-positron conversion target is available [5] and indicates that there should be no fundamental problem in generating the positron flux required for the parameters of Table 1. In fact the design, which incorporates a multitude of Cu or W target rods embedded in graphite and mounted on a water-cooled rotating wheel, has been made for the more stringent requirements (12 kHz repetition rate) of a superconducting low-energy high-intensity collider, the ARES project [6].

The damping rings which are probably required for both positrons and electrons have to combine short damping times with very low values of equilibrium emittance (cf. Table 1) in the face of quantum excitation and intra-beam scattering. One way to achieve this is to make extensive use of wiggler magnets. A compact design of such a ring is under study at CERN [7]; the first column of Table 2 gives a few typical parameters. If a suitable ring tunnel is already available at the prospective site, damping rings of large circumference may be employed in order to store a larger number of bunches at the minimum distance dictated by the ejection system, thus permitting a correspondingly reduced damping rate. Using the LEP tunnel for this purpose was proposed some time ago [8]. More recently a proposal has been made [9] to place a pair of low-field rings into the SPS tunnel. Parameters of this are shown in column B of Table 2. The ex-ISR tunnel available on the CERN site might offer a good compromise between these extreme solutions and this will be studied.

Table 2. Typical parameters for damping rings; proposal B is in the SPS tunnel

Proposal		A	B
Energy	GeV	1.8	3.5
Circumference	m	348	6911
Number of bunches		46	500
Particles per bunch	10^9	5	5
Energy loss per turn	keV	860	2820
RF voltage	MV	25	50
RF frequency	MHz	40	800
Transverse damping times	ms	4.85	57.3
Horizontal equilibrium emittance	$10^{-10}\pi$rad m	3.9	1.5
Vertical equilibrium emittance	$10^{-10}\pi$rad m	1.3	0.5
Equilibrium bunch length	mm	3.7	2.9
Equilibrium momentum spread	10^{-4}	8.4	8.5

In any case it seems advantageous to place the damping-ring complex near the centre of the collider and transport the damped beams - at a few GeV energy - back to the inputs of the main linac. The necessary 180° bends can be combined with first stages of bunch compression. Pre-acceleration by 3 GHz linac sections and further longitudinal compression are likely to be necessary in order to achieve the required bunch length of a few hundred micrometres at most.

3. High gradient accelerating structures

The basic cell of the accelerating structure will be a variant of the familiar disc-loaded configuration. Damping slits suppressing higher modes of resonance will be incorporated. A fraction of the total number of structures will be given asymmetric apertures for transverse RF focusing, as explained in section 4 below. Choosing an RF frequency near the maximum possible implies a compromise between the highest impedance of the fundamental mode of resonance and the magnitude of beam-induced wake fields at higher modes. Thus, the aperture to wavelength ratio will be larger than that used in present-day linacs.

The main work at CERN is concerned with travelling-wave sections which offer the great advantage of a common, matched, feedpoint for many cells and, thus, of complete separation of high-gradient structure and power source (or transfer structure in a two-beam scheme). At the high frequency chosen here, the length between feedpoints (section length) has to be short - about 25 cm containing 70 cells - if a high value of η_τ is to be obtained, in spite of the high group velocity concomitant with a large aperture. The short section length may be considered inconvenient but it helps to reduce tolerance requirements and peak power through feeder waveguides. Standing-wave arrangements, whereby power is fed into individual cells, continue to be proposed [10] and will be studied in parallel.

A comprehensive development effort [11] for 30 GHz structures has started at CERN. Dimensional tolerances are in the 2 to 3 µm range; the surface finish on copper required to avoid more than 5% increase of the wall losses is in the N2 class (0.05 µm). Both appear to be obtainable with diamond tools on appropriate machines. Water cooling does not seem to present great difficulties. However, induced thermal stress due to the pulsed operation is a potential problem deserving further investigation, in spite of the modest gradient chosen so far, because of the long life required at kHz operation. Precise mechanical referencing from the beam aperture (4 mm diameter) to the outer wall of the support structure is required for alignment.

Out of a number of imaginable ways of manufacturing individual sections two methods which have already been applied to one-centimetre structures elsewhere [12] have been singled out for further development. The first of these methods is brazing from machined cups. At this time, cups for a number of short test sections have been ordered from a specialized firm and brazing tests are in progress. A full-length section will follow in a few months' time. The second method is complete electroforming (including the irises) on an aluminium mandrel. After completion of the electroforming the outer diameter of a section is machined with reference to the mandrel, which is then etched out chemically. Figure 1 shows the mandrel for a full-length section including cut-off pipes and beam-position monitor cells. Clearly, mass fabrication will have to be studied, as the order of 10^5 sections will be required.

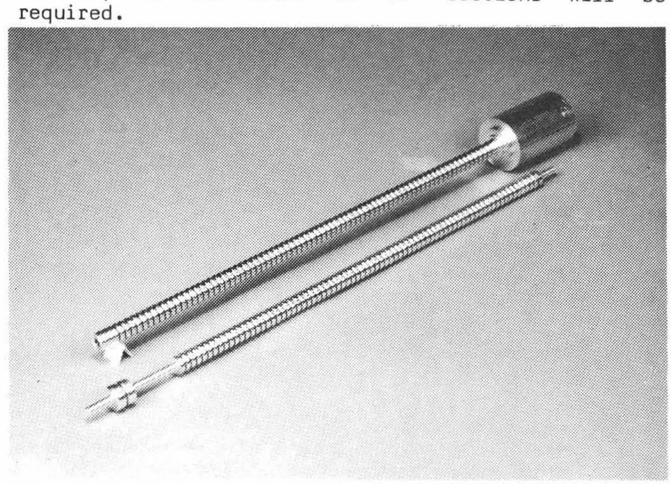

Fig. 1 Aluminium mandrels for electroforming of a complete 25 cm accelerating section. The piece in front includes cut-off pipes and a beam position monitor cell.

Several high-precision sections, made in one of the ways indicated above, may be inserted into the central bore of a larger and longer copper cylinder which affords mechanical support, water cooling and vacuum pumping. A conceptual design is shown in Fig. 2. It is intended that one self-contained unit of this kind will be about one metre long and contain four sections with individual power inputs.

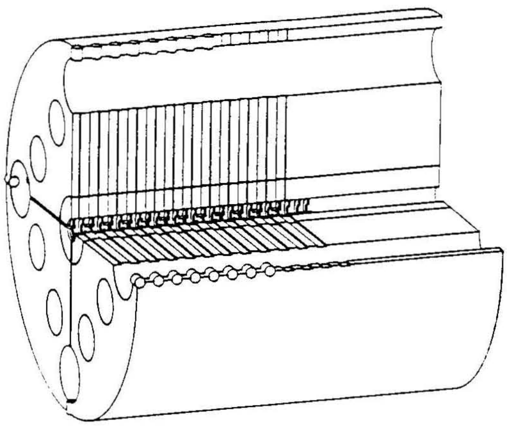

Fig. 2 Conceptual design of an accelerator unit containing the high-gradient structure (at the centre), damping and pumping slots, pump manifolds and cooling channels.

Damping slots for higher modes ought to be part of the basic design so as to create the potential for multibunching. These slots may take the form of rectangular waveguides (four for every second cell at most) leading radially away from the centre and discharging higher mode energy into a suitably damped "sump". The irises themselves have to be slotted in order to create sufficient damping. While a detailed model study of slot-damped structures has been started our tentative design already includes 1 × 3.5 mm^2 damping slots as shown. A possible way of machining these slots into the otherwise finished sections and support tubes is by wire machining (electro-erosion with a running wire). This has been successfully tried and the present design is based on this method. The same slots are being used for pumping the structure. Figure 3 shows a sample with slots cut by electro-erosion.

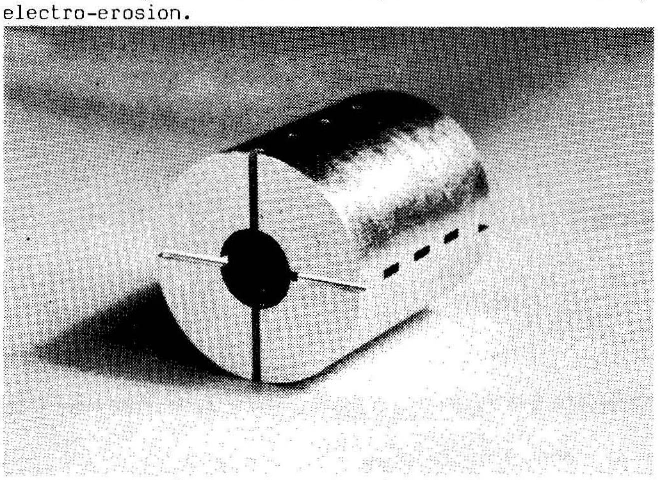

Fig. 3 Sample (one to one scale) of rectangular waveguide channels for damping and power feeders cut into copper by precision wire erosion.

4. Wake fields

This section deals with the action of beam-induced wakes within one and the same bunch where damping of resonances, obviously, has no effect. Longitudinal wake fields scale with ω^2 for given cell geometry. They produce an energy spread within the bunch. This spread can be made to cancel, partially, with the opposite spread caused by the cosine time dependence of the RF wave.

The action of transverse deflecting wakes, which scale with ω^3 for given geometry, is potentially more dangerous still since the resulting self deflection, propagating from head to tail of a bunch, can lead to enormous amplification of any accidental transverse displacement and subsequent emittance increase or even beam loss. This can be remedied by introducing a spread in transverse oscillation wave numbers within the bunch [13]. The method is commonly called "Landau damping" although it is predominantly a coherent effect; by giving stronger focusing to trailing particles than to leading ones the phase of the wake fields is made to produce damping instead of excitation.

Employing a large energy spread for Landau damping is likely to be inadequate for our parameters. Instead a spread of the transverse focusing force may be created by RF focusing [14]. To this end a fraction (roughly 10%) of the accelerating sections are given asymmetric apertures (slits instead of circular holes) and placed alternately vertically and horizontally at suitable period lengths. The slit apertures produce RF quadrupoles of considerable strength. Computations have shown that slits wide enough not to create excessive wake fields themselves yield strong RF driven quadrupole moments without appreciable loss of shunt impedance for acceleration. The main feature of RF focusing is an essentially linear spread in phase advance per period which could be as large as three to one (say) over $\pm 2\sigma_z$, if so desired. Although this turns out to be very effective in stabilizing the wake fields the objection has been raised that the short coherence length associated with such large spreads would lead to unacceptably small tolerances for transverse alignment. Computer simulations [15] indicate, however, that the combined action of the wake fields and the imposed spread can, indeed, create coherence. For a suitable choice of parameters this will make the tolerances with respect to transverse displacement of the order of 10 μm which seems to be achievable with the help of active, pulse-to-pulse, feedback for steering the beam. The fast repetition rate of several kilohertz will be helpful in this respect. It is intended that each one-metre unit (some of them being in fact RF quadrupoles) will be equipped with its own microwave beam-position monitor [16] and alignment facility, both at micrometre resolution. A test set-up of a micrometre alignment facility is in preparation.

5. Radio-frequency Power Generation

Several terawatts of total peak power will be required for a TeV linear collider. The total amount increases with E_0, the peak power per unit length with E_0^2. Our effort to solve this basic problem has concentrated on a two-beam scheme where a high-intensity drive beam runs parallel to the main linac. The bunched drive beam is being decelerated in "transfer structures" where RF power at the desired frequency is generated and fed into the high-gradient accelerating structures. The drive beam energy is replenished periodically in "drive linac" re-acceleration units. The basic idea is that of the original TBA proposed by A. Sessler [17] and studied at LBL/LLL but the scheme considered here differs from the TBA in several important aspects.

The CLIC proposal [1,2] features a drive beam of GeV energy, travelling wave transfer structures and CW superconducting cavities at UHF frequency (350 MHz) as the drive linac. The drive beam is well separated from the main beam. The transfer structures feed the main linac via matched waveguides, as in the TBA.

Some of the ingredients of the CLIC proposal are already available. This is certainly true for the high efficiency continuous wave klystrons required to power the drive linac. It is also becoming true for the superconducting cavities which have been developed for circular collider applications (LEP, HERA) and whose present performance is already sufficient for this new application. Even a moderate increase of operational accelerating gradient (e.g. to 15 MV/m) would be very profitable, however, and the same is true for all cost-saving measures, the crucial parameter being cost per unit stored energy.

A travelling-wave transfer structure for CLIC is being developed. Proper energy balance requires the transfer impedance to be extremely low. This is obtained by placing structures of relatively high impedance at suitable distance from the drive beam in a smooth pipe which is narrow enough not to propagate in E_{01} mode at the RF frequency. Scaled model measurements and computations alike indicate excellent transfer efficiency [18]. The wake fields (longitudinal and transverse) induced by the intense multibunch drive beam will be dominated by the wall resistance and unavoidable cross section variations of the vacuum envelope rather than the active part of the transfer structure. This requires careful study although the problems revealed so far do not look insurmountable. A few per cent suitably shaped energy spread will be required for Landau damping. A scaled 3 GHz model of the transfer structure is undergoing first beam tests at the LEP injector linac at present.

A major problem is the generation and preacceleration of a fully relativistic drive beam. For the CLIC parameters this beam will have to consist of many (40) bunchlets of about 1 mm rms length - each containing close to 10^{12} electrons - arranged in bunch trains so as to contain both the 30 GHz frequency of the high-gradient linac and the 350 MHz of the superconducting drive linac. In order to match the gradual build-up of field in the transfer structure the bunches have to coincide with the rising slope of the drive wave. The drive bunches may be generated by a battery of laser-driven photocathode guns. Each gun produces only one bunch per drive cycle which means four bunches at 2.9 ns interval for present CLIC parameters. The bunches from each gun undergo separate pre-acceleration to about 100 MeV (say) and longitudinal compression before they are combined into 30 GHz combs and accelerated to several GeV by an extension of the superconducting drive linac. The details of this scheme remain to be studied. A reduced performance version, using but a single gun, is in preparation as a joint effort of CERN and LAL, Orsay. The aim is to permit the powering of short sections of accelerating structures to full gradient at 30 GHz [19].

6. The Final Focus System

Fundamental parameter constraints imply apparently inescapably that the beams' cross section at collision ($4\pi\sigma_x\sigma_y$) must be compressed to less than 10^{-14} m^2 if a luminosity of at least 10^{33} cm^{-2}s^{-1} at 2×1 TeV is to be achieved with reasonable input power. The beam height at the final focus is further reduced by the necessity of using flat beams as the only way to make the beam-beam radiation loss acceptable. The final focus system, therefore, presents what is probably the most difficult problem associated with TeV linear colliders.

Once again it appears that the only solution which begins to look feasible at this time is an extension of known methods, namely quadrupoles for focusing and dipoles and sextupoles for chromaticity correction. The quadrupoles may be permanent magnets [20] but pulsed (or superconducting) ones will also be studied. Chromatic aberration - the tendency of a particle of other than central momentum to find its focus outside the collision area - is the most serious problem.

In the first place the energy spread within the bunch must be reduced as much as possible by balancing the longitudinal wake against the RF cosine. Energy spreads of a few parts per thousand in the face of 5% energy extraction seem possible in principle (albeit at the price of tight tolerances in bunch charge and RF phase and of sacrificing particles in the tails of the gaussian distribution).

Secondly, following the design of the SLC final focus, bending magnets and sextupoles in a telescopic system can be used for chromaticity correction. The bending fields have to be weak, however, to reduce quantum fluctuations of the radiation loss and concomitant emittance increase [21]. A theoretical design approaching the CLIC parameters has been made [21, 22, 23] and further progress by optimisation can be expected.

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