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THE CLIC PROJECT AND THE DESIGN FOR AN e^+e^- COLLIDER

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THE CLIC PROJECT AND THE DESIGN FOR AN e^+e^- COLLIDER

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1. INTRODUCTION

The name CLIC (CERN Linear Collider) originally referred to an advisory subpanel of CERN's long range planning committee in the years 1985-87. CLIC (presided by K. Johnsen) dealt with linear electron-positron colliders in the TeV range, trying to survey the field and arrive at some understanding of future possibilities. The results of this work were published in a formal report¹.

Although this panel was dissolved, the studies (which had mobilised many individuals at CERN on a part-time basis) were continued under the leadership of W. Schnell, a small budget was obtained and the name CLIC now covers these activities, carried out by a varying number of people, not all from CERN, and most of whom also have other responsibilities.

Whereas the original CLIC panel considered many different ways that might lead to a practical collider, most of the work by far is nowadays concentrated on a two-beam scheme proposed in 1986 by W. Schnell².

Other directions are also pursued to a certain extent (e.g. the switched power linac) but I will only discuss the two-beam approach here. Before doing this, I must first explain the most important problems for collider designers.

2. LUMINOSITY, DISRUPTION AND BEAM RADIATION

The only existing example of a linear collider is the SLC at Stanford, now in the commissioning stage. Compared to this machine, we have set ourselves the goal of a 20 times higher energy (1 TeV + 1 TeV). Since the interaction cross-sections scale roughly as $1/E^2$, this means that we need a luminosity of the order of 400 times higher. It is this that causes the main problems, rather than the high energy by itself.

The luminosity of a linear collider is equal to

$$L = \frac{fN^2}{4\pi\sigma^2}$$

where f is the repetition frequency, N the number of particles per bunch and σ the r.m.s. size of the beam spot (assumed to be round and gaussian) at the interaction point. Since increasing f or N will increase the average beam power, and this will be uncomfortably high in any case, the required L can only be made with a very small beam size at the collision point.

This is limited by two effects: disruption and beam radiation, sometimes called "beamstrahlung". The two colliding bunches will be pinched by each other's focusing fields (space charge). This effect, called disruption, will be beneficial up to a point, increasing the luminosity. However, the beams may destroy each other before they have had a good chance to interact, especially if they are not perfectly aligned³. Also, the strong divergence of the disrupted beams after the collision will make it very difficult to avoid hitting the last focusing elements of each beam and causing excessive heating⁴.

The pinching will also result in radiation of photons, which may cause a considerable energy loss and energy spread before the electrons and positrons interact. This beam radiation and the disruption depend on the various beam parameters in different ways and both effects together will constrain the design in important ways.

Two extreme regimes of beam radiation exist: the classical and the quantum regime. In the first, the beam parameters are such that the typical photon energy, derived in a classical way, is less than the electron energy. If this is not the case, a quantum-mechanical approach is needed. The radiated power then depends on the beam parameters in a different way; and the more we get into this regime, the smaller the effect will be. Unfortunately it turns out that extremely short bunches, beyond present possibilities, are then needed. Most present-day designs and especially the CLIC one are working in the wide transition region between the classical and quantum regimes.

The beam radiation may be reduced by using flat beams at the interaction point. With equal area, the luminosity is the same, but space-charge fields are smaller.

3. MAIN CLIC PARAMETERS

It would be beyond the scope of this talk to discuss the detailed relationships between the various parameters following from the desired

luminosity and the limited allowable beam power, disruption, beam radiation and many other effects^{5,6,7}. The main CLIC parameters (very tentative) are at present as follows⁸:

Table I

Main Linac Parameters

Energy	1.0 TeV
Luminosity	$1.1 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
Accelerating gradient	80 MV/m
Final focus aspect ratio	5
Final focus beam height	12 nm
Fractional energy loss	
by beam radiation	0.27
Fractional average	
critical energy	0.71
Pinch enhancement	2.37
Repetition rate	1.69 kHz
Number of bunches	
per pulse	1
Bunch population	$0.50 \cdot 10^{10}$
Beam power (per beam)	1.35 MW
Energy extraction	5.0%
Iris aperture over	
wavelength	0.2
Shunt impedance over Q	
per unit length	28 k Ω /m
Fill efficiency	0.78
RF frequency	29 GHz
RF power (average	
per beam)	35 MW
Bunch length	200 μm
Disruption	3.3
Vertical Emittance	
(normalised)	10^{-6} rad m
Emittance ratio	3 (say)
Vertical amplitude function	282 μm
Ratio of amplitude functions	8.3
Length, per Linac	12.5 km

Many of these parameters are close to practical limits. The luminosity should not be much lower (in fact, we would prefer $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The focus aspect ratio cannot be much increased without reducing even further the extremely small beam height required. The fractional energy loss by beam radiation should certainly not be any higher and increasing the pinch-enhancement might be very difficult. The RF frequency is uncomfortably high. However, relaxing any of these parameters would lead to even higher beam power and RF power.

It would be very attractive to accelerate several bunches per pulse. This could be done by injecting the first bunch when the accelerating structure is not yet entirely filled. Successive bunches would see a more completely filled structure; this would balance the gradient decrease caused by beam loading from the preceeding bunches. A power extraction efficiency of 30% might be reached² but multi-bunch wakefield effects might not allow the scheme to work.

4. SUPPLYING THE RF POWER - THE CLIC TWO-BEAM APPROACH

The peak power required during each pulse is about 3.6 TW per beam. To provide this with klystrons as in conventional linacs would be out of the question financially, even if high-power 29 GHz klystrons would exist.

The solution proposed is to combine all klystrons into a single high-intensity electron beam (drive linac) running in parallel with the main linac (Figure 1).

FIGURE 1
Two-beam accelerator

This beam is accelerated by superconducting cavities filling only a fraction of its length and the beam energy is transmitted to so-called transfer structures that feed the main linac at 29 GHz. The superconducting cavities

work at a much lower frequency (350 MHz) and with a much lower average field strength (6 MeV/m over the cavity length) than the main linac (80 MeV/m)

To make the various transfers of energy possible, each pulse of the drive beam must contain a number of bunches at 350 MHz and each of these must be subdivided into bunchlets at 29 GHz. The drive beam must have an energy of a few GeV to avoid phase slippage with respect to the main linac. Of course, the total charge per pulse must be much higher in the drive linac than in the main one, since the gradient is lower and energy is conserved.

The transfer structures have a filling (or rather emptying) time of one 350 MHz period, so that the first bunchlet of each 350 MHz bunch will see an empty structure. Each successive bunchlet will see a higher decelerating gradient as the transfer structures charge up. However, the acceleration by the superconducting cavities will also increase, since the bunches will pass these on the rising slope of the sine wave (Figure 2). These two slopes can be made to balance.

FIGURE 2

Voltage on transfer structure and accelerating voltage in drive linac.
Only 10 of the 40 bunches are shown.

The main linac's structures will have a longer filling time, corresponding to the total duration of the drive linac's bunch train.

It turns out that the ratio of the accelerating gradients of main linac and drive linac scales with the frequency ratio. (Some other factors, such as the fraction of the drive linac occupied by superconducting cavities, also play a role). This makes the 350 MHz drive frequency near-optimum. As it happens, CERN has developed such cavities for LEP. Their cost will have to be reduced for use in CLIC, but otherwise they are just right.

To obtain the relatively low deceleration of the drive beam together with a large energy transfer, the transfer structures must have a low impedance (a few hundred times less than the main linac's structures). They will thus have a large aperture which helps to avoid problems with the intense drive beam such as transverse wakefield effects. The losses in these structures also turn out to be low (90% efficiency).

It would, in principle, be possible not to dissipate the power at the end of the main linac's sections in terminating resistors, but to feed it back to the next transfer structure of the driving linac, which could then accelerate additional bunchlets injected at the correct phase. These might in turn give back their gained energy to the superconducting cavities. In this way, the efficiency might be increased by a factor 2.

Typical parameters for the drive linac are given below.

Table II

Drive Linac Parameters

Fraction of main linac active length occupied by drive linac	0.2
Drive linac active length	2.5 km
Drive linac frequency	350 MHz
Number of bunches per pulse	4
Number of bunchlets per bunch	10
Bunchlet population	4×10^{11}
Bunch length	1 mm
Transfer efficiency assumed	0.9
Drive linac energy extraction	0.1
Drive linac R over Q parameter	270 Ω/m
Drive linac accelerating field	6.0 MV/m
Drive linac total voltage gain	15.0 GV
Drive linac quality factor	5×10^9
Cryogenic efficiency assumed	2×10^{-3}
Total cryogenic input power	33.5 MW

The main problem with the drive linac will be to generate the short, intense bunchlets. The emittance need not be small, and in principle we could imagine to combine a number of SLC-like beams in transverse phase space. However, a more elegant solution may well be found. Some preliminary work on a possible test facility has been done by Y. Baconnier and colleagues⁹, but this is still at a very early stage.

In the following sections, I shall describe some of the detailed work that

has been done lately on various aspects of this scheme.

5. WAKEFIELD EFFECTS AND RF FOCUSING

A serious problem in high-energy linacs is the so-called beam break-up caused by the transverse wakefield generated by a bunch displaced from the central axis. Such a bunch will execute transverse oscillations because of the focusing (quadrupoles) around the beam and the wakefield will oscillate in the same way. The wake caused by the front of the bunch may now excite the transverse movements of the tail in resonance if front and tail have the same oscillation frequency. The effect scales inversely with the 3rd power of the structure's aperture and is therefore especially dangerous at high accelerating frequency.

This effect would be catastrophic in the main linac if nothing were done to suppress it. One way to do this is to use very strong transverse focusing. This, however, is expensive and makes the beam very sensitive to small misalignments and jitter (the tolerance could be a fraction of a μm), which is dangerous because it might prevent the two opposing beams to meet precisely in the very small focal spot.

Another way to reduce the effect is to make the focusing field for the trailing particles stronger than for the leading ones. The phase of the wakefield excitations will then be such as to damp the effect rather than to excite it. This is very important because without this damping any misalignments would be rapidly transformed into emittance increases because of the filamentation caused by the spread in transverse wavelength.

One way to achieve this is to allow a strong beam loading so that the trailing particles will have less energy than the leading ones and will thus be more strongly focused. The amount of energy spread needed to suppress the effect turns out to be uncomfortably large for the CLIC parameters^{10,11}. It would make the final focus design extremely difficult (chromatic aberrations).

A better solution appears to be the use of radio-frequency focusing obtained by using slits instead of round apertures in the irises. This method, first proposed by R. Palmer and analysed in detail by Schnell¹² and Henke¹³ is interesting because the focusing effect scales both with frequency and with accelerating gradient and thus becomes appreciable in the present application.

The particles have to pass on the rising slope of the waveform to compensate the energy spread arising from the longitudinal wakefield. Trailing particles then are also focused stronger (the focusing is zero at the crest of the wave and increases away from it), which is just what is wanted. The calculations suggest that the problem is solved: the centre of the bunch is strongly damped

and alignment tolerances are relaxed to 10-20 μm . Also the energy spread of the beam may now be reduced as much as is possible, without causing problems from beam break-up. Finally, RF focusing will reduce the cost (fewer or no quadrupoles).

Numerical studies of slotted-iris structures¹⁴ have shown that earlier rough estimates of their performance were correct within 15%.

6. WAKEFIELDS IN THE DRIVE LINAC

Study of the wakefield effects has just started¹⁵. It has appeared that the longitudinal effects of cross-section changes along the line may be important and that such changes will have to be minimized. In the super-conducting cavities the longitudinal wakefield may also be harmful, as it will change the linear voltage increase for successive bunchlets.

In the transfer structures the resistive wall impedance of the smooth sidewalls may cause beam break-up; to suppress this, either an energy spread of 5% over the entire bunch train will be needed, or the aperture of the structure will have to be increased.

7. TRANSFER STRUCTURES

Model tests have been made on scaled-up (2 GHz) models of the low-impedance transfer structure. Properties of a 4-cell and later a 12-cell model (Figure 3) were measured¹⁶, such as dispersion curves and coupling impedance.

FIGURE 3

Test model (2 GHz) for a transfer structure with its cover taken off

The structure is a rectangular waveguide with teeth far away from the beam to obtain the required low impedance. The teeth do not extend across the full width of the guide so that adjacent cells couple both electrically and magnetically.

The model measurements are encouraging: the impedance, the group velocity and the efficiency of energy transfer to the fundamental mode ($\pi/2$) seem about right. Further optimisation is now being done by computer modelling¹⁷, using the MAFIA codes developed by Weiland at DESY.

8. MAIN LINAC STRUCTURES¹⁸

Tests on different geometries for the main linac structures¹⁹ and calculation²⁰ have shown that it is difficult to find a better structure than the classical disc-loaded waveguide. This has therefore been adopted for further study. The centre hole has to be relatively large compared to existing linacs to minimize wakefield effects and to obtain a high group velocity; this is necessary to keep the section length reasonable. Despite the short wavelength, the tolerances (mainly because of the high group velocity) turn out to be reasonable ($\pm 3\mu\text{m}$).

A complication is the provision of longitudinal slots in the structure's sidewalls, foreseen (following a suggestion by R. Palmer) to increase the dissipation of undesired transverse modes. This might make the use of multiple bunches possible. The slots would be somewhat longer than the inter-iris distance and would therefore have to cut through the irises.

Many different fabrication methods for the 25 cm long, 9 mm outer diameter sections have been considered, but it is far too early to make a choice among them. The large number ($\sim 100'000$) of structures to be manufactured means that a very careful consideration of all details is essential.

The structures proper will have to be embedded into a larger diameter cylinder provided with longitudinal and transverse holes for vacuum and water cooling, and for feeding in and out the power. Beam position monitors will have to be included in the structures. The study of all this has only just started.

Calculations of the dissipation show that the maximum average temperature increase on the copper surface will be only 1.9 °C. Slightly more worrying is the instantaneous increase of 5 °C during each 11 ns pulse and it still has to be shown that this is acceptable from the fatigue point of view.

9. DAMPING RINGS

Three groups have worked on damping rings in connection with the CLIC studies. All groups propose rings with wigglers in zero-dispersion straight

sections.

Bassetti, Guiducci and Palumbo²¹ studied various types of lattices for a proposed beauty factory. These would require a higher repetition rate (12 kHz) and a larger bunch population ($2 \cdot 10^{10}$) than CLIC and are therefore not directly applicable, but many results of this study seem useful for CLIC also. Transverse normalised emittances of $2 \cdot 10^{-6}$ m and a transverse damping time of 1.5 ms are obtained with a ring of 646 m circumference.

A similar approach by Delahaye, Krejcik and Potier²² at CERN has so far resulted in a ring of half the size, damping times of 4.5 ms and similar final emittances, now adapted to the CLIC parameters.

Both approaches would need further study on collective effects, dynamic aperture, etc.

Evans and Schmidt²³ have investigated the possibility of using the CERN SPS tunnel for a damping ring. Because of the large circumference a longer damping time (30-60 ms) is now acceptable. A lattice similar to the SPS one (although far from optimum) is assumed for a start.

However, to obtain a sufficiently low longitudinal emittance, the RF frequencies and voltage would have to be increased, and this would indirectly lead to higher transverse tunes. With the parameters adopted, the longitudinal impedance would have to be less than 0.2 ohm, which might be difficult. In any case, if a CLIC machine would eventually be built, it is not sure that it would be at CERN or that the SPS tunnel would be available.

10. FINAL FOCUS

The very small beam height at the focus given in Table I was postulated in order to have an acceptable beam power, at a stage where no corresponding design for the final focus existed.

This still does not quite exist, and it may therefore be said that we have no consistent set of parameters. Nevertheless much work is being done in this area and it is hoped that a satisfactory solution may be found.

The most important problem is chromatic aberration. Using telescope optics (phase shift π) for demagnification, designs may be found that minimise the chromatic effects^{24,25} but the remaining aberration is still too high; it would require a reduction of the normalised emittances to less than 10^{-7} m, which might be very difficult.

Better results have been found by using bending magnets and sextupoles, as was done at SLC. This allows correction of the first-order chromatic terms; but - at least for present designs - the higher-order aberrations (both chromatic and geometric) remain somewhat too high (about a factor 2 in each plane). In

addition, the quantum fluctuations in radiation loss, caused by the bending magnets will increase the emittance and cause an increase of final beam height that is still unacceptable in present designs. It may well be that this may be improved by reducing the bending field and perhaps using combined function magnets having both dipole and sextupole components.

A final energy spread of $\pm 0.25\%$ was assumed for these studies. To obtain this with an energy extraction of 5% from the main linac will require a reduction of the "natural" energy spread caused by beam loading by an order of magnitude. This may be possible, but it has not been proven conclusively.

11. CONCLUSION

In spite of the low level of funding (1 MSF for 1988) and the fact that nearly all work is done on a part-time basis, some interesting progress has been made during the past two years. The main point has been the better understanding of the beam break-up effect and its suppression by RF focusing. Some hardware tests and calculations on models of the transfer structure have increased our confidence in this unusual component. Studies on the main structures and their fabrication are just starting. Some damping ring designs now exist that nearly promise the required performance and it is thought that some further improvement may be possible. Lastly, the final focus design is improving, although the nominal performance specification has not yet been met. It may be possible that multi-bunch operation will be one way of solving some of the outstanding problems. It is hoped that during the coming years a better-understood, consistent design for a 1 TeV + 1 TeV collider will emerge.

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