LINEAR COLLIDER STUDIES IN EUROPE

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1. Introduction

In an early phase of work on linear colliders in Europe the main emphasis was put on new methods of acceleration at very high gradient. Substantial research and development work originating in this early period are the wake field acceleration pursued at DESY [1], the plasma beat wave experiments carried out at the Rutherford Laboratory and Imperial College [1] and the switched power linac proposal [1] leading to experimental work at BNL and CERN. Also originating in this period but already concerned with RF acceleration is the development of lasertrons [1] at LAL Orsay.

In a later phase, when it was fully realized that the main problem was the generation of adequate luminosity and the fundamental constraints on the choice of parameters were better understood the emphasis shifted back to radio-frequency acceleration, classical in principle but not at all in the choice of parameters and technologies required here. This is certainly true for the study of a CERN Linear Collider (CLIC) [2]. It is also true for DESY where a Resonant Wake Field Transformer - a string of RF cavities excited by a ring-shaped drive bunch - is being proposed [3] following the successful completion of a first round of experiments with the original Wake Field Transformer set-up.

The work for CLIC - centred at CERN but carried out in collaboration with other European laboratories and ECFA - aims at paving the way for an actual project and attempts, therefore, to cover all fundamental aspects of a linear e^+e^- collider. For this reason the present paper is mainly based on this work.

2. General Parameters

The greatest difficulty is the generation of adequate luminosity which should increase with the square of particle energy and exceed 10^{33} $cm^{-2}s^{-1}$ at 1 TeV per beam, the energy chosen for CLIC. One fundamental limitation is given by the energy loss due to beam-beam radiation (beamstrahlung). The fractional average radiation loss is given by

$$\delta = 1.8 \frac{r_c^2}{\lambda_c} (H_T T) \sqrt{\frac{L}{f}} \frac{2\sqrt{RH_x H_y}}{H_x + RH_y} \qquad (1)$$

where r_c and λ_c are the classical electron radius and the Compton wavelength respectively, L is the luminosity, f the repetition rate, $R = \sigma_x/\sigma_y$ the beam's aspect ratio at the collision point and H_x, H_y the pinch enhancement factors in horizontal and vertical direction. The product of the quantum reduction factor H_T and its argument T is essentially constant [4] in the transition regime from classical to quantum radiation, where all present-day proposals are in fact situated. Thus, the only way [5] to gain a certain freedom for the choice of the repetition rate f is to choose a flat beam, i.e. $R > 1$. In our opinion this remedy should be used with caution, however, in order to avoid excessively small values of the beam height σ_y at the final focus (nanometres in any case!) and of the normalized emittance ε_{ny} to be achieved in the damping rings and maintained throughout the linac.

On the other hand, for a single bunch per beam pulse and without energy recovery from a normal conducting linac, the repetition rate f is inescapably related to the general input power P_i (for both linacs) from the mains by the relation

$$\frac{\omega^2}{E_0} = f \frac{4\pi c U}{\eta_i \eta_\tau P_i Z(1-\xi)} \qquad (2)$$

where $\omega/2\pi$ is the RF frequency, E_0 the zero-beam accelerating gradient and ξ its fractional reduction by beam loading (equal to about half the energy extraction and small in any case). The particle energy is eU and Z (shunt impedance over Q per wavelength) equals the free wave impedance times a geometry factor depending on the aperture to wavelength ratio. The fill efficiency η_τ (accounting for dissipation during the structure fill time) can be made to approach 80% at the price of increased peak power; the efficiency η_i for mains to RF power conversion clearly depends on the technology used but will hardly exceed 20% in practice. Thus, the choice of RF frequency and accelerating gradient again limits the repetition rate via the maximum affordable mains power (a couple of hundred megawatts at most) with little else to choose.

We conclude from equations (1) and (2) that the accelerating gradient should be chosen near the minimum compatible with considerations of economy and of site limitations and that the RF frequency should be pushed to the maximum possible. This maximum is given by manufacturing problems - tolerance problems in particular - and by the deleterious action of the beam-induced wake fields discussed in Section 5. It is generally accepted that 30 GHz is an upper limit from both points of view and we have chosen, tentatively, to work at this limit, devoting much of our effort to structure development and wake-field stabilization at this frequency.

Table 1 below shows the latest set of tentative CLIC parameters. They are still for single-bunch operation and differ from the ones published earlier [2,6] only by a reduction in repetition rate and concomitant introduction of a flat beam with R = 5. These measures which entail a reduced beam height at the collision point, have been dictated by a more realistic estimate of η_i and affordable input power. The CLIC parameters differ from a comparable set published by SLAC [5] in assuming a higher-frequency linac with much faster repetition rate. For this reason the values of σ_y and ε_n in the SLAC design are even smaller, and R is much larger, than those shown here.

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.

Following a proposal by R. Palmer [7] beam break-up 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.

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	T	0.71	
Pinch Enhancement	$H_xH_y \approx H_y$	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

3. Positron production and damping to small emittances, preacceleration

A conceptual design for a megawatt electron-positron conversion target is available [8] 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 [9].

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 [10]; 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 [11]. More recently a proposal has been made [12] 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

A similar study is being carried out [13] at INFN Frascati and Rome University for the 5 to 10 GeV ARES project. A very interesting and different approach is being followed in a study carried out at ESRF Grenoble [14] and this may be applicable to CLIC as well.

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. Since bunch compression is accomplished by rotation in longitudinal phase space small energy spread at the damping ring output is mandatory, thus making the longitudinal parasitic impedance at the damping ring a critical quantity.

4. High gradient accelerating structures

The basic cell of the accelerating structure will be a variant of the familiar disc-loaded configuration. Variants may include asymmetric apertures for transverse focusing and damping slits suppressing higher modes of resonance. 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, however, and will be discussed at the end of this section.

A comprehensive development effort 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 (many years) 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 manufacturing methods for individual sections two have been singled out for first practical tests and samples of short test sections are being made in specialized workshops. The first of these methods is brazing from machined cups as shown in Fig. 1. The chosen shape facilitates the machining without deterioration of RF properties. The second method is complete electroforming (including the irises) on an aluminium mandril as shown in Fig. 2. After completion of the electroforming the outer diameter of a section is machined with reference to the mandril, which is then etched out chemically. Clearly, mass fabrication will have to be studied, as the order of 10^5 sections will be required.

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. 3.

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". It is likely that 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.

Instead of travelling waves, standing wave schemes, where an intense low energy drive beam directly supplies electromagnetic energy to individual cells of the high gradient structure, have been proposed. One such scheme is the resonant version of the Wake Field Transformer, energized by a ring-shaped drive beam surrounding the main linac. This is now the preferred solution at DESY. Other proposals use separate storage cavities side-coupled to the main structure. In one proposal [15] the drive beam follows the same path as the high energy beam. A transformer ratio of the order of ten is created during the drive beam pulse by rapid energy transfer to the

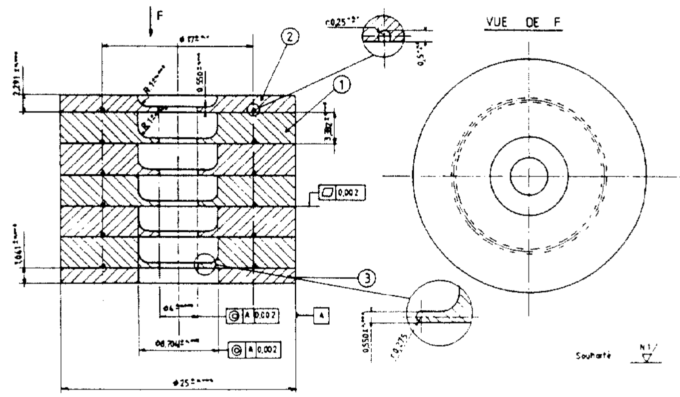

Fig. 1 30 GHz accelerating structure: test section brazed from cups.

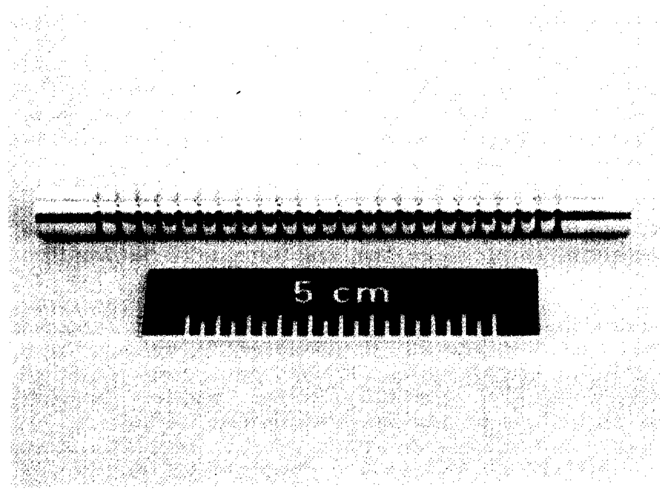

Fig. 2 Aluminium mandril for electroforming of 30 GHz structure

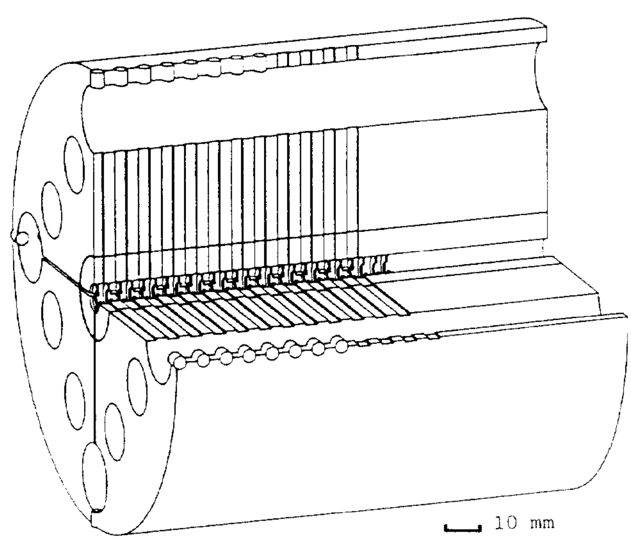

Fig. 3 Conceptual design of the CLIC Main Linac accelerating structure

(ring-shaped) storage cavity. The main beam passes when the energy has fully moved back. It is not easy to see, however, how the wake fields created by the drive beam passing through the high-gradient structure itself could be made acceptable.

In another proposal [16] the drive beam passes through the storage cavities. As in the two-stage scheme discussed in Section 6 below a large transformer ratio can be created by giving the storage cavity a low impedance. The absence of a travelling-wave with its cascade of coupled cells will relieve the constructional tolerances. And the rapid energy transfer might permit recuperation of much of the energy not absorbed by the beam to a second beam pulse in the drive channel and thence to a superconducting drive linac. A disadvantage is the complicated construction of two structures side by side and the closeness of the two beams which have to be threaded through separate focusing channels while the high energy beam unavoidably has to pass the drive linac sections as well.

5. 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 [17] (commonly called "Landau damping" although it is predominantly a coherent effect).

Instead of employing a large energy spread for Landau damping a spread of the transferse focusing force may be created by RF focusing [18]. To this end a fraction 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 [19] 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.

6. Generation of peak power

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. In Europe, most of the efforts to solve this basic problem have concentrated on two-beam schemes where a high-intensity drive beam of relatively low energy 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 [20] and studied at LBL/LLL but the schemes considered here differ from the TBA in several important aspects.

The DESY proposal features ring-shaped drive bunched which enclose the accelerating structure. Energy is fed radially inwards and directly into each resonant cell. In this, DESY profits from all the experience already gained with their Wake Field Transformer set-up.

The CLIC proposal [2,6] 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. The variant [16] mentioned at the end of Section 4 may be considered a partial transition towards the DESY scheme and will also be studied.

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 [21]. 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 will soon undergo first beam tests at the LEP injector linac.

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.

7. Final Focus and Alignment Problems

The fundamental parameter constraints mentioned in Section 2 imply inescapably that the beam has to be focused to a spot size hardly exceeding 10 nm, at least in one direction, in order to reach adequate luminosity. The final focus system, therefore, presents what is probably the most difficult problem associated with TeV linear colliders.

For the moment the only trustworthy method available is the use of "classical" quadrupoles formed by ferromagnetic poles or, possibly, by high-current pulsed conductors. The problem, then, is the enormous ratio of the shortest feasible focal length to the required amplitude function β^*, which is also a measure of the depth of focus. Extremely precise chromaticity correction is required, therefore, even if the energy spread within the bunch has been reduced to a few per mil by balancing longitudinal wakes against the RF cosine.

Adequate chromaticity correction may be just possible, however, employing dipoles and sextupoles to generate energy-dependent focusing. A first final focus design for CLIC will be presented at this conference. This design is based on permanent magnet quadrupoles and comes within a factor five in spot area of what is postulated in Table 1. Clearly, the multibunching would alleviate the situation sufficiently to bridge this gap (but ought preferably to be reserved to reach luminosities above 10^{33} $cm^{-2}s^{-1}$). The design of a pulsed quadrupole giving 10^4 T/m at 1 mm aperture is being attempted at CERN. Further progress may be expected from short focal-length plasma lenses or from beam-beam focusing. In the latter respect the recent finding by Chen and Yokoya [22] of monotonically increasing pinch enhancement for large disruption is very encouraging although the parameters apparently required to produce this mutual "confinement" (large disruption, small ratio of bunch length to amplitude function, round beam) will be hard to reach.

Little development work is known to us, so far, concerning the component alignment, beam steering and diagnostics required to make the beams collide at nanometre tolerance. A few statements, at least, can be made. The final quadrupole lenses must be mounted on a common support to assure mutual stability. Even so, the beams, once put in collision (presumably with enlarged spot sizes to start with) have to be kept in collision by continuous steering using the kilohertz repetition rate and some manifestation of the beam-beam interaction itself as diagnostics. Upstream of the final focus optics the tolerances for beam steering are magnified in proportion to the beam size. Unfortunately this is not true for beam-driven plasma lenses.

Along the linac transverse alignment of the focusing elements will have to be to the order of 10 μm tolerance. For the lower frequency linac of the SLAC design [5] the tolerance will be somewhat larger. For the strong Landau damping associated with the 30 GHz choice of CLIC even tighter tolerances can be avoided only if the wake-induced coherence found in our computer simulations can, in fact, be confirmed and exploited. Alignment to the order of 10 μm seems quite possible, however, using the best techniques now available in combination with fast beam-derived adjustments. Microwave beam position monitors, being integral parts of quadrupoles, RF quadrupoles and non-focusing acceleration sections, will have to be developed. The uncorrectable jitter due to component motion at acoustic frequencies can probably be reduced to acceptable values. A detailed study of this entire complex has just begun and will have to become a major part of the research and development for linear colliders.

8. Conclusions

Looking back only a few years one cannot help being impressed by the progress of linear collider studies - wherever they are conducted - which have begun to touch the reality of details. This statement also means, however, that a substantial increase of effort will soon be required to continue fruitfully along all the many paths which, so far, have only just been opened.

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