INEAR e^+e^- COLLIDERS

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ABSTRACT

This seminar is based on the concluding report prepared by the Advisory Panel on the Prospects for e^+e^- Colliders in the TeV Range, a panel set up by the CERN Long-Range Planning Committee chaired by C. Rubbia. It covers some general considerations, before summing up various possible acceleration methods - normal rf linacs, superconducting acceleration structures, structures excited by opto-electrical switches, wake-field acceleration, and plasma beat-wave acceleration. It is concluded that one approach to a TeV collider, based on a normal conducting linear accelerator at a frequency of approximately 30 GHz and with a gradient of about 100 MeV/m, seems to give promise of leading to a real project in three to five years if enough manpower and money were invested in research and development.

1. INTRODUCTION

By around the mid-seventies, when the high-energy physics community in Europe was deeply involved in an evaluation of possible future accelerator facilities at CERN, it had a spectrum of options to choose from, ranging from relatively modest upgradings of existing facilities to new large hadron or electron colliders. This was fortunate as the scientific potentialities as well as considerations of complementarity with projects elsewhere could thus play appropriate roles in the final selection. The choice in the end became a twofold one. On a relatively short-term basis the scientific and technically exciting $p\bar{p}$ collider was chosen involving a relatively modest financial burden, and for the longer term programme of CERN there was general agreement to go for a Large Electron Positron Ring (LEP) of a centre-of-mass (c.m.) energy of 100-200 GeV. At about the same time the complementary ep collider, the Hadron Electron Ring Collider (HERA) was authorized at the Deutsches Elektronen Synchrotron (DESY).

By the early nineties, when the selections for the next generation of accelerator facilities in Europe will have to be made, the spectrum of possibilities may be narrower. The upgrading of LEP to 2 × 100 GeV (LEP II) is expected to be under way at that time. On a much larger scale is the option of a Large Hadron Collider (LHC), with a c.m. energy of ~ 16 TeV and a luminosity of 10^{33} - 10^{34} cm^{-2} s^{-1}, to go into the LEP tunnel. There is general agreement that this is scientifically a very valuable project and technically quite feasible. An important issue is therefore whether this can be fitted naturally into a world-wide programme.

In such a situation it would once more be an advantage to be able to take alternative options into account. There are expectations that one such future option might be a linear collider for electrons and positrons with a c.m. energy of about 2 TeV and a luminosity above 10^{33} cm^{-2} s^{-1}. However, a CERN Linear Collider (CLIC) will not be available unless the present linear-collider studies are put on a substantial and well-supported basis very soon.

Electron-positron colliders have a few clear advantages over hadron colliders; in particular e^+e^- collisions are much cleaner than hadron collisions, and a much higher luminosity can be exploited, if achievable. Furthermore, an order of magnitude less energy is required since the colliding particles are themselves 'constituents', which makes an e^+e^- collider with 2 TeV c.m. roughly equivalent to a hadron collider with 20 TeV c.m. energy.

However, synchrotron radiation imposes a serious limitation on the energy of circular e^+e^- colliders, and therefore LEP, at present under construction at CERN, with a circumference of 27 km, will most likely be the largest circular e^+e^- collider ever to be built. Reducing the radiation by increasing the circumference of the machine leads in the ultimate limit to infinite bending radius, in other words to colliding beams from linear accelerators. The first speculations on this kind of approach, which introduces a host of new problems, started more than ten years ago [1, 2] and have recently gained considerable momentum. (Figure 1 illustrates the general concept of linear colliders.)

The CERN Council established in June, 1985, a Long Range Planning Committee (LRPC), under the chairmanship of C. Rubbia. This committee considered it very desirable that the community have both these options to choose from when, in the future, very important decisions have to be made. Therefore, one of the Advisory Panels to the Committee was charged with analysing the linear collider possibility*). This Panel submitted its report to the

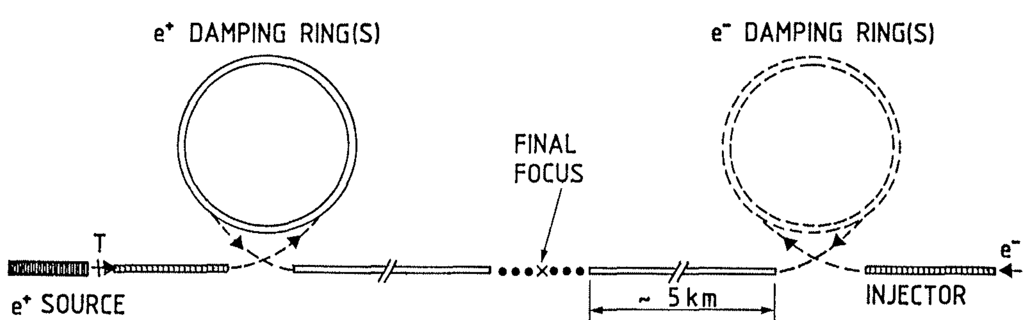

Fig. 1 Schematic representation of a 1 TeV linear collider. The electron damping ring is dashed because recent progress in low-emittance electron sources may make damping rings unnecessary.

*) Membership: U. Amaldi, K. Johnsen (Chairman), J.D. Làwson, B.W. Montague, W. Schnell, S. van der Meer, W. Willis.

LRPC in May, 1987 [3]. By this time the Panel had gained considerable insight into many aspects of a possible future CLIC project. There are, however, still important areas of uncertainties and lack of knowledge that will need much deeper studies.

The main conclusions are recommendations of the Panel and can be summed up as follows. With the present state of knowledge, one approach to a TeV collider seems to hold the promise of leading to a real project. This approach is based on a normal conducting radio-frequency (RF) linear accelerator with a resonant frequency one order of magnitude above that of present-day linacs. The drive power can be derived from an auxiliary beam, which is in turn powered by a superconducting structure. Even with this seeming extrapolation from present-day technology several fundamental problems remain as yet unsolved, while few of the innumerable details have been studied so far. It is recommended, therefore, that problems related to this kind of scheme should be given first priority by the study team, in addition to general problems, such as the injectors, the final-focus system, and tolerances along the main accelerator. A 3-5 year intensive study is needed to prove the feasibility of such a machine and provide rough cost estimates and a technical basis for starting a decision-making process.

On a much longer time scale more exotic schemes of acceleration might lead to solutions offering higher performances, in particular a higher energy for a given total length of collider. Sufficient effort should, therefore, go into a continuation of these approaches, so as to keep the corresponding options open.

2. GENERAL CONSIDERATIONS

At the time the CLIC Advisory Panel was established some work was already in progress in the CERN context on some general considerations related to linear colliders [4, 5]. This, together with similar analyses in other publications and conference contributions from SLAC and other laboratories, formed a good basis for the Panel's activity. The general idea was to single out those collider parameters that do not depend on a particular accelerating structure, to establish their interrelation, and to see how these interrelations constrain the choice of parameters.

The design of linear colliders presents a number of challenges not encountered in fixed-target machines or circular colliders. Since the accelerated bunches collide only once, very high transverse-beam densities must be produced if adequate luminosity is to be obtained without an excessive consumption of power. This requires extremely high quality beams with very low transverse and longitudinal emittances so that one can produce submicron transverse dimensions at the crossing point. Naturally this leads to very demanding tolerances on alignment; it also requires the formation of beams with very low initial emittance (see Section 3 of [3]), and the maintaining of this low emittance during acceleration. Further, a highly sophisticated 'final-focus' system must be designed, able to produce a very small spot from a beam in which there is inevitably some energy spread (see Section 4 of [3]).

These difficulties become rapidly more severe as the energy is increased from say 50 GeV to 1 TeV per beam. Firstly, the effective cross-section for interesting physics events decreases as $1/\gamma^2$ and this must be compensated by a corresponding increase of luminosity. This requires more power, as does the need to accelerate to higher energies. These factors are only partly compensated by the fact that the unnormalized emittance decreases as $1/\gamma$, enabling a smaller spot size to be obtained. The need for high power requires higher efficiency than in traditional linacs, and leads to the need for an efficient and inexpensive power source. Efficient energy extraction from the accelerating structure together with a high gradient requires a reduction in effective wavelength unless 'bunch trains', consisting of several bunches per RF pulse, rather than individual bunches, are used. As we see below, it is difficult to maintain both efficiency and beam quality if bunch trains are used. Secondly, experimentation is likely to be more difficult.

Before commenting specifically on problems of linac design, some very general constraints must be considered. As explained above, very small bunches must be produced. Single small bunches, once they are formed, are stable in the sense that the repulsive self-fields due to the charge are balanced to within $1/\gamma^2$ by the attractive self-fields from the magnetic field associated with the current. When e^+ and e^- bunches collide, however, the electric fields cancel but the magnetic fields add, giving rise to a violent 'pinch' in which the particles are deflected towards the axis.

A moderate pinch of this sort is helpful, since it reduces the beam size and increases the luminosity. If it is too violent, however, the angular spread of the disrupted beams after the interaction can cause damage, further downstream, to the components used to focus the opposing beam. Not only can this disruption be troublesome, but the radiation associated with the sudden deflection, known as 'beamstrahlung', wastes beam energy and gives rise to a spread of energies. Particles on the axis experience no forces, but those at the beam edge can experience severe deflection and radiation loss.

The disruption and beamstrahlung are functions of the number of particles in the bunch, and of the transverse and longitudinal dimensions. Originally the constraints implied by keeping these quantities within bounds, at the same time as attaining adequate luminosity and energy, seemed to dictate all the main operational parameters of the machine, namely number of particles per bunch, transverse and longitudinal bunch dimensions, and repetition rate. Fortunately, however, it is now realized that at an energy approaching 1 + 1 TeV, where these constraints appear severely restrictive, the beamstrahlung approaches a new and less destructive regime (the 'quantum regime', described, for example, by Wilson [6]), and some freedom of choice returns.

After a period of some confusion, the disruption and beamstrahlung constraints are now well understood. They now seem less threatening, and less likely to determine the parameters than more conventional considerations. One feature that may not be considered 'conventional', however, is beam-quality degradation arising from wake fields. Related to the traditional beam breakup instability, but now generally looked at from a different point of view, this imposes constraints on bunch configurations and alignment accuracy.

High gradient and efficient energy extraction for the RF field require shorter wavelength, for which wake-field effects rapidly become more serious. Efficiency can be restored to some extent by having trains of bunches, but 'bunch-to-bunch' wake fields in the train and 'energy drop' between bunches in the train introduce severe difficulties.

Collisions using polarized electrons appear to be possible within the current range of CLIC parameters [7]. Depolarization in the linac is expected to be very small, and the main contribution will arise from the intense, localized fields in the colliding bunches, which could give rise to a loss of projected polarization typically in the range of 10%. The same would of course apply to polarized positrons if a suitable source were ever to be available.

Despite many constraints, there does seem to be a window of feasible parameters. The detailed nature of the trade-offs, and the overall complexity and cost of a realistic system are still quite unknown. A very considerable amount of detailed theoretical work backed up by experimental studies is required. The general direction in which to go is, however, now clear.

3. ACCELERATION METHODS

The first linear collider, the SLC, is now approaching completion at SLAC [8]. For this purpose their (by now old) electron linear accelerator has been upgraded to a beam energy of 50 GeV and two damping rings, two bending arcs, and a sophisticated final focus (among many other smaller elements) have been added. It is hoped that a luminosity of 6×10^{30} cm^{-2} s^{-1} will be reached. The SLC is being commissioned and will provide valuable information for the development of higher energy linear colliders.

For CLIC energies in the TeV range and luminosities above 10^{33} cm^{-2} s^{-1} have been considered, i.e. more than an order of magnitude higher energy than at SLAC and nearly three orders of magnitude higher luminosity. This requires more than simple extrapolation.

A brief review will now be given of the most important acceleration methods that have been proposed for linear colliders.

3.1 Normal-conducting RF linacs

With normal-conducting RF structures, accelerating gradients of several hundred megavolts per metre are possible, in principle. In practice, maximum attainable gradients are given by considerations of efficiency and limitations of peak power more than by electrical breakdown. Another fundamental problem is presented by self-deflection and self-deceleration due to the electromagnetic wake fields left behind by the particles. A short qualitative review of these problems and possible solutions are given here. A more quantitative analysis and references to consult can be found in the CLIC Panel's report [3].

A layout of a linear collider was presented in Fig. 1. For the two linear accelerators, travelling-wave structures offer the important advantage of presenting a matched load to a short pulse of RF power at a single feed point per section. It is assumed, therefore, that the accelerator be made of travelling-wave sections, each one of length L, group velocity v, and fill-time for electromagnetic energy, $\tau = L/v$.

The enormous dissipation per unit length associated with accelerating gradients E_0, of the order of 100 MV/m or more, requires the RF power to be applied in the form of very short pulses with low duty cycle. The duration of each power pulse is made approximately equal to the fill-time t and a beam pulse (consisting of a bunch of particles or a train of several bunches) is made to pass at the end of the power pulse. As the decay-time of stored energy will be much shorter than the repetition period, any energy not extracted by the beam is lost. Therefore, the efficiency of transferring power from the RF feed point to the beam approaches, at best, the fraction h of energy extracted. On the one hand, this extraction efficiency is limited to about 10% at most by the concomitant energy spread (roughly $\eta/2$) which must remain correctable before the final-focus system is reached. On the other hand, η is proportional to the charge per beam pulse, the square of the resonant frequency, and the inverse of the accelerating gradient. The charge per bunch of particles is limited by the wake fields and by beam-beam radiation in the final focus. Therefore, the price for reaching a high value of accelerating gradient at acceptable efficiency is a very high frequency, much higher than the customary 3 GHz of present-day electron linacs. A value of about 30 GHz, corresponding to 1 cm wavelength, appears to be a limit imposed by transverse wake fields and by constructional problems of travelling-wave accelerating structures. Test structures for about 1 cm wavelength have, indeed, been manufactured and tested. The CLIC panel, therefore, proposed that about this wavelength should be used in spite of the considerable extrapolation from present-day technology implied by this choice.

If the RF-to-beam efficiency is to approach the extracted energy fraction η, dissipation during the fill-time has to be made as small as possible. The only way to do this is to make the fill-time very short in spite of the concomitant increase of peak power. A reasonable compromise may be a choice of fill-time that makes the peak power per metre of section length twice the classical minimum. The corresponding dissipation during the structure fill-time amounts to 28% of the input energy. With the typical Q-factor of a copper structure at 1 cm wavelength this fill-time amounts to only 11 ns.

Case A in Table 1 represents a conservative choice of parameters resulting from the arguments outlined above. There is only one bunch of electrons or positrons per pulse, extracting 8% of the stored energy. The accelerating gradient is 80 MV/m, giving the accelerator a total active length of 2 × 12.5 km for 2 × 1 TeV. The efficiency of energy transfer from the RF input to the beam is a little over 6%, yielding 5 MW beam power (and a luminosity of 10^{33} cm^{-2} s^{-1}) for 80 MW average RF power per linac. Beam power and luminosity may be doubled or the input power halved if the electromagnetic energy reappearing at the output end of each accelerating section after the beam passage can be recovered. The superconducting drive system described below appears to permit just this but the details remain to be studied.

Table 1

Main linac parameters for two accelerating gradients.
Parameters for one linac.

Case	A	B
Final energy eU (TeV)	1	1
Frequency f (GHz)	29	29
Average accelerating gradient E_0 (MV/m)	80	160
Total active length L_{tot} (km)	12.5	6.25
Peak power per unit length $\hat{P}_L/L$ (MW/m)	96	384
Bunch population N	5.35×10^9	5.35×10^9
Number of bunches per pulse n_b	1	2
Repetition rate f_r (kHz)	5.8	5.8
Average RF power $\langle P_{RF} \rangle$ (MW)	80	80
Average beam power $\langle P_b \rangle$ (MW)	5	5
Beam radius at collision σ_r^* (nm)	65	65
Luminosity (cm^{-2} s^{-1})	1.1×10^{33}	1.1×10^{33}

The accelerating gradient could be doubled and the total active length reduced to 2 × 6.5 km if two bunches per beam pulse could be used (case B of Table 1). Moreover, at the price of a 20% reduction in average accelerating gradient, an RF-to-beam efficiency of as much as 30% may be reached by using a larger number of bunches, whose interval is adjusted so as to make the fresh influx of RF power cancel the bunch-to-bunch depletion of energy due to beam loading. This is shown in the two columns of Table 2. The corresponding luminosity of 6×10^{33} cm^{-2} s^{-1} represents an optimistic prediction since a final-focus system accepting multiple bunches at close interval has yet to be designed and the problems of bunch-to-bunch wake fields remain to be solved. Note, however, that the actual hardware is the same for both Tables 1 and 2 (apart from an extra 25% in overall length in the second case). At the present state of knowledge it would, therefore, be a safe plan to design the collider so as to yield the minimum required luminosity with single-bunch operation. It will hold the potential of a five-fold to six-fold increase in luminosity by compensated multibunching at a later stage of development.

The intense deflecting wake fields cause problems for the preservation of the transverse emittance. However, these wake fields can be stabilized by a combination of very strong external focusing and 'Landau damping' [9-12]. In spite of this, very tight alignment tolerances will be needed for focusing quadrupoles and accelerating structures. In fact, the tolerances for quadrupole alignment turn out to be exceedingly tight because of the very strong focusing required to stabilize the wake fields. Two methods which hold the promise of alleviating this problem are being studied at present. In addition, an active feedback system for steering the beam will certainly be required. The fast repetition rate of many kilohertz, required in any case, wil be very helpful in this respect.

Table 2

Table 1 modified for compensated multibunch operation.
Parameters for one linac.

Case	A	B
Final energy eU (TeV)	1	1
Frequency f (GHz)	29	29
Accelerating field E_0 (MV/m)	80	160
Filling factor for first bunch χ	0.8	0.8
Average accelerating gradient χE_0 (MV/m)	64	128
Total active length L_{tot} (km)	15.6	7.8
Bunch population N	5.35×10^9	5.35×10^9
Number of bunches per pulse b	6	11
Repetition rate f_r (kHz)	5.8	3.2
Average RF power $\langle P_{RF} \rangle$ (MW)	100	100
Average beam power $\langle P_b \rangle$ (MW)	30	30
RF cycles between bunches $\tau_b f$	~ 13	~ 7
Beam-pulse duration $(b-1)\tau_b$ (ns)	2.28	2.28
Luminosity (cm^{-2} s^{-1})	0.6×10^{34}	0.6×10^{34}

The main remaining problem is the generation of the enormous peak power required. All known power converters contain space-charge-limited electron guns, limiting the current density of the beam of electrons which is used to transfer energy from d.c. to RF. It follows that the output power decreases as the square of the wavelength if a given design is scaled. The kilohertz repetition rate poses another very serious problem. No suitable power converter at 1 cm wavelength is available at present and, even if it could be developed, the very large number of units required is likely to make this solution economically unattractive.

Instead of the multitude of d.c.-to-RF power converters a continuous drive beam running along the main linac may be employed. The drive beam supplies energy to the main linac at regular intervals via transfer structures. The drive-beam energy is restored by accelerating structures forming a 'drive linac'. Free electron lasers and direct RF deceleration sections have been proposed as transfer structures, induction units and superconducting RF accelerating cavities as drive linacs [13-16].

A drive linac formed by superconducting cavities, combined with decelerating RF transfer stuctures, opens up the possibility of a fully relativistic drive beam, thus eliminating all phasing problems. The principle is illustrated in Fig. 2. The mains input is converted to RF power at ultra-high frequency (UHF) by large continuous wave (c.w.) klystrons. Such klystrons of over 1 MW output and nearly 70% transfer efficiency are available today. The c.w. operation of the drive linac, made possible by the high Q-factor of the superconducting cavities, means that the main linac repetition rate is limited by pre-injector considerations only.

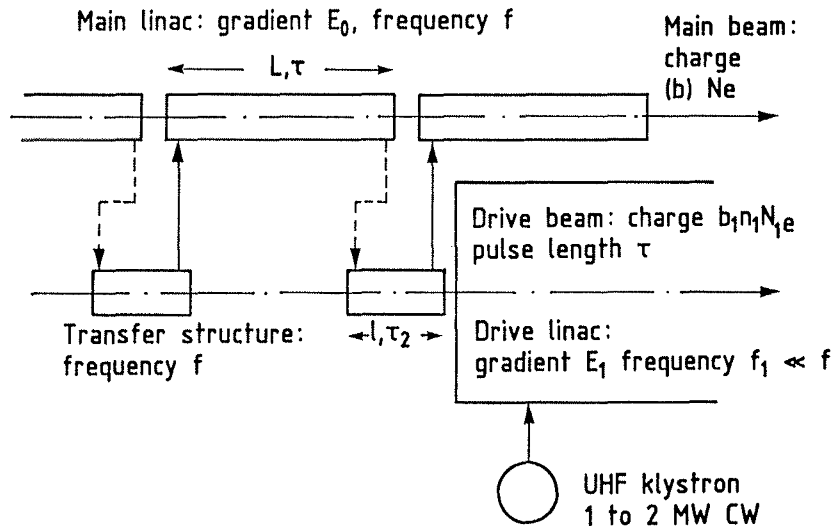

Fig. 2 Two-stage linear accelerator, composed of a superconducting c.w. drive linac at ultra-high frequency and a microwave main linac

Drive-beam pulses of a duration equal to the main linac fill-time τ have their energy periodically restored by being passed through the superconducting cavities. Energy conservation along the drive beam demands that the 'transformer ratio', i.e. the ratio of the accelerating gradient E_0 in the main linac to that, E_1, in the drive linac be proportional to the ratio of frequencies. The resulting choice of drive-linac frequency in the low UHF range is quite suitable for superconducting cavities. In fact, the 350 MHz superconducting cavities developed for the second stage of LEP could be used in their present state without any change.

Table 3 gives parameters of superconducting drive linacs. The first column is for the main linac of column A, Table 1. The corresponding drive-linac parameters (E_1 = 6 MV/m and $Q_1 = 5 \times 10^9$ at 350 MHz) are present-day performances. The second and third columns correspond to E_1 = 15 MV/m, a development that is expected to occur in a few years' time. In case B, 2 × 6.25 km of main linac are powered by only 2 × 800 m of superconducting drive linac. In case C (admittedly an extreme example), the entire installation is compressed to only 2 × 2.24 km active length, the main linac and drive linac having the same length. This would, however, require multiple bunches from the start.

Energy transfer to the main linac may be via free electron laser units or by RF deceleration in short sections of travelling-wave structures, each one coupled to the input of a main section via a short piece of waveguide. The latter scheme requires the drive beam to be tightly bunched at the main linac frequency. However, it has the great advantage of permitting drive beams of several GeV energy. This assures rigid drive bunches and the absence of any phase slip between the beams, thus eliminating all phasing problems for the tens of thousands of main linac sections. The required impedance of the transfer structure is very low. This will permit a design with a large enough aperture to cope with the longitudinal and transverse wake fields due to the intense drive beam. The required drive charge is rather large. For the parameters of the first columns of Tables 1, 2

Table 3

Case	A	B	C
Main linac			
- energy eU (TeV)	1	1	1
- frequency f (GHz)	29	29	29
- accelerating gradient E_0 (MV/m)	80	160	445
- active length L_{tot} (km)	12.5	6.25	2.24
Drive linac			
- voltage gain U_1 (GV)	15	12	33.6
- frequency f_1 (MHz)	350	350	350
- R over Q parameter r_1' (Ω/m)	270	270	270
- accelerating gradient E_1 (MV/m)	6	15	15
- active length mL_{tot} (km)	2.5	0.8	2.24
- quality factor Q_1	5×10^9	5×10^9	5×10^9
Cryogenic input power (η_{cr} = 0.2%)$\langle p_1 \rangle / \eta_{cr}$ (MW)	33	67	186

and 3, each drive bunch has to contain 4×10^{11} electrons and there are 40 such bunches per main linac pulse. Generation and acceleration to relativistic energies of these drive bunches appears to be the main difficulty with this scheme. At least this difficulty is confined to the injector.

If the output of each accelerating section is connected to an input of the following transfer section a suitably timed and phased recovery pulse, following the drive-beam pulse, permits transfer of the energy left after the passage of the beam back into the superconducting cavities. This means a factor of 2 in power economy for single-bunch operation at the expense of extra complication but little additional cost of hardware.

3.2 Superconducting accelerating structures

Linear colliders based on superconducting (SC) cavities were proposed and studied at CERN more than ten years ago [2, 17]. In recent years much progress has been made in the construction and understanding of SC RF cavities [18, 19]. For single-cell cavities, gradients as large as E_0 = 23 MV/m and quality factors up to $Q \simeq 10^{10}$ have been obtained. Multicell cavities in the laboratory have reached $E_0 \simeq$ 15 MV/m for the frequency f = 1.5 GHz, and are routinely constructed by industry with accelerating fields $E_0 >$ 7 MV/m and $Q > 3 \times 10^9$ in the frequency range $0.35 < f < 1.5$ GHz. It is believed that a few years of technological developments on the preparation of clean and defect-free surfaces should allow $E_0 \simeq$ 25 MV/m and $Q = 5 \times 10^{10}$ to be reached. The development of type II superconductors, such as Nb_3Sn and NbN, which may be sputtered on a copper substrate, offers great promises for reaching even higher gradients and quality factors. For linear colliders, economic fabrication and treatment will also become of paramount importance. In the work summarized in CLIC Note 15 [20] the following parameters have been assumed: f = 1 GHz, E_0= 25 MV/m, $Q = 5 \times 10^{10}$, temperature = 1.8 K.

In parallel with the work done at CERN, the Cornell group has also studied fully superconducting linear colliders, devoting particular attention to cost optimization [21]. Their independent assumptions and conclusions are very similar to the ones reached in Ref. [20]. In particular, Sundelin uses E_0 = 28.8 MV/m and Q = 5 × 10^{10} (1.8 K) at a frequency f = 2.86 GHz. At CERN it is believed that, when using SC cavities, lower frequencies have to be preferred because: i) the power dissipation at low temperature is proportional to ω (= $2\pi f$), ii) transverse wake fields vary as ω^3, iii) the ratio between the energy extracted by a bunch and the energy stored is proportional to ω^2/E_0 [19]. Moreover, the cost per metre increases wth the frequency because the number of cells and feed points increases.

Table 4, taken from Ref. [20], lists the main parameters of two designs of a high-luminosity (10^{34} cm^{-2} s^{-1}) (1 + 1) TeV collider, for which some cost optimizations have been performed. The first design uses the principle of energy recovery to save on the total power, and has parameters which are extrapolations by a factor of 10 only with respect to the SLC design. This is particularly true for the invariant emittance, while the β-value is equal to the SLC one. The damping ring system is not based on the FODO structure used at the SLC, but on an optimized lattice and it is a very important and expensive part of the complex. In both designs, in order to damp the emittance of a maximum number of bunches, it is supposed that ten of them are placed at about 30 cm distance from each other. The ten bunches are extracted from their ring and accelerated as a single train. The second set of parameters is for a collider which has no energy recovery and requires an emittance ten times smaller; this is considered possible in other laboratories, but still requires very careful investigation.

The cost-optimization procedure, which takes into account klystron replacement and electricity consumption over ten years, leads to the conclusion that the accelerator has to be run with a macroscopic duty factor C ≃ 10%, and that both designs need a power from the mains of about 350 MW. By making different hypotheses on the cost components and by assuming that only one bunch is damped at any time in each ring, the Cornell studies [21] concluded that the optimum macroscopic duty factor has to be about ten times smaller.

Superconducting accelerating structures, with their capability of running continuously, promise luminosities in the 10^{34} cm^{-2} s^{-1} range with parameters which are not very different from the SLC ones. They would be an ideal solution for CLIC if it were not for the relatively low value of the accelerating field which is technically feasible today. Since in Nb_3Sn cavities the theoretical limit is 100 MV/m [17], there is space for future improvements. The problem is challenging because Q-factors definitely larger than 10^{10} have to be obtained to reduce the losses at cryogenic temperatures. It is comforting that at 1.8 K the theoretical limit is Q ≃ 10^{11} at f = 1 GHz and Q ≃ 10^{12} at f = 0.35 GHz. The 'warm' superconducting substances recently discovered may open up very interesting possibilities for the future. First measurements indicate that their critical magnetic fields are much larger than in Nb_3Sn, so that they could give larger gradients if the deposition of thin stable layers on a copper substrate proved to be feasible.

Table 4

Sets of parameters for fully-superconducting (1 + 1) TeV colliders with $L = 10^{34}$ cm^{-2} s^{-1}

	Energy recovery	No recovery
Accelerator		
Beam power P (MW)	100	10
Recovery efficiency η	0.90	0.00
Fractional energy loss by beamstrahlung $\langle\varepsilon\rangle$	0.03	0.3
Quantum parameter	0.075	0.235
Invariant emittance ε_n (m)	2.5×10^{-6}	3.1×10^{-7}
Bunch length σ_z (mm)	3.6	0.36
β-value at crossing β^* (mm)	10.7	1.07
Bunch radius $\sigma_x = \sigma_y$ (μm)	0.12	0.013
Particles per bunch N	5.4×10^9	6.5×10^8
Macroscopic duty factor C	0.15	0.15
Bunch peak repetition frequency (kHz)	670	820
Train peak frequency (kHz)	67	82
Average bunch repetition frequency f_r (kHz)	48	53
Average train repetition frequency f_t (kHz)	4.8	5.3
Accelerating field E_0 (MV/m)	25	25
Q-value	5×10^{10}	5×10^{10}
Frequency of RF f_{RF} (GHz)	1.0	1.0
Damping rings		
Damping energy E_d (GeV)	2.5	5.0
Damping field B (T)	1.8	0.9
Length of magnet ℓ (m)	0.40	0.40
Damping time τ (ms)	1.3	3.6
Circumference of a ring $2\pi R$ (m)	58	230
Number of rings N_d	220	64
Power radiated in rings (MW)	3	0.6

3.3 Structures excited by optoelectrical switches

The availability of powerful and very accurately timed pulses of light from lasers has excited interest, in a number of laboratories, with regard to their use in generating electromagnetic (e.m.) energy, in the form of pulses or RF power. The aspect of this concept which requires research at the level of basic physics is the performance of the opto-electric switches. They must retain adequately high electrical efficiency for frequencies up to 30 GHz; in addition, the ratio of e.m. power produced to the optical control power must be 10^3 or more to make the overall system viable, and of course the lifetime must be long and the overall cost must be attractive.

The lasertron developments at SLAC, in Japan, and at LAL Orsay [22], are in this category. They have originated in the relatively conservative approach of replacing the electron gun and bunches in a klystron by a photocathode illuminated by a train of laser pulses. The photocathode designs have emphasized the use of low work function photocathodes which require a clean ultra-high vacuum. The dimensions must decrease as the frequency rises, resulting in a relatively low power per device at 30 GHz.

It has also been proposed to use optoelectric switches to drive a 'switched power linac' [23]. By distributing the switches over the surface of a radial line enough power may be delivered to reach very high field gradients at the centre of the line, where the voltage levels are increased by an order of magnitude by transformer action for pulses less than 20 ps in length.

These lines of research have been pursued during the last two years in order to investigate different aspects of the switched power linac.

i) At CERN, a scale model of the radial line transformer has been studied [24]. The predicted transformation ratio has been verified for different pulse lengths. The dependence of the transformation ratio and higher multipole fields on imperfections in the drive pulse have been measured. It was found that the transformation ratio is not sensitive to the drive pulse, and that higher multipoles are suppressed.

ii) The coupling of the vacuum photodiode to the line has been studied using the MASK programme at SLAC [25]. This problem turns out to be complex, and the gradients in the e.m. pulse have been steadily increased as the optimization has continued. This process is still going on.

iii) In collaboration with the Instrumentation Division of Brookhaven National Laboratory an extensive study of the switches is under way. The conditions in which we wish to operate - high photon flux in a very short pulse with very high electric fields - do not correspond to any measurements or theory in the literature. It is necessary, then, to measure the photocurrents under the correct conditions. As a start, a quadrupled Nd:yag laser with a 20 ps pulse length (four times that of the intended design) has been brought into operation. Gold/tungsten wire cathodes of 50 μm diameter have been used, with surface fields of up to 0.06 GV/m. Stable photocurrent densities of $\sim 10^4$ A/cm^2 have been obtained, with quantum yields of the order of 10^{-3}. In the next series of measurement pulsed charging will be used, where surface fields up to ~ 1 GV/m are expected. Cathodes of materials with a lower work function, such as zirconium, will be used, as well as cathodes with micromachined surface structures.

A one stage switched power linac is foreseen on a time scale of about two years, as well as a microlasertron RF generator.

3.4 Wake-field acceleration

High accelerating gradients can be produced by the pasage of bunches of charged particles through structures such as cavities or disk-loaded waveguides. A number of accelerators have been proposed based on this wake-field principle. In fact, the two-beam schemes with a drive beam passing through decelerating RF structures (Subsection 3.1) belong to this class. However, historically the name 'wake-field accelerator' has been reserved for designs where energy is coupled from one beam to the other all along the length of the structure rather than at specific feed points.

The most straightforward method is the collinear wake-field acceleration, where a bunch to be accelerated travels on the same path as the 'driver' bunch. With longitudinally symmetric driving bunches the useful accelerating field is then at most twice the decelerating field in the driver itself; hence it seems that one could at most double the energy. There are several ways to avoid this limitation:

i) unsymmetric bunches, in particular sawtooth-shaped ones, with which high 'transformer ratios' can be obtained;

ii) trains of properly spaced bunches, for which the maximum accelerating field increases as the square root of their number (but all inter-bunch spaces are different);

iii) multistage accelerators, where the driver is renewed each time it has given up most of its energy.

It is hoped that very high transformer ratios, i.e. ratios of the maximum accelerating field behind the driver to the decelerating field inside it, will be obtainable with the 'wake-field transformer', as proposed by Voss and Weiland, in which the driver passes along a different trajectory from the beam to be accelerated [26]. In the coaxial type, the driver passes through an annular slot on the outside of a series of circular cylindrical cavities. The induced fields converge towards the beam to be accelerated on the axis. A model of such an accelerator has undergone its first tests at DESY. Producing and conserving the ring-shaped beam introduces non-negligible complications, and it may turn out to be difficult to obtain the azimuthal symmetry of the ring-shaped driving beam required for reducing transverse deflection sufficiently.

Wake fields may also be produced by a bunch of electrons passing through a plasma. This will excite plasma oscillations travelling with a phase velocity equal to the bunch velocity. Gradients of several GeV/m seem possible. The fields behind the driving beam are similar to the wake fields in a linac structure, with the difference that only a single mode is present and the group velocity is zero so that the field pattern does not spread out laterally. A following bunch can be accelerated by this field. The principle was proposed by Chen, Huff and Dawson [27]. Since the two beams must be collinear with this scheme, one of the three methods mentioned above for increasing the transformer ratio must be adopted.

Some of the properties of the scheme important for accelerator applications were described by Ruth, Chao, Morton and Wilson [28]. It appears that the transverse focusing by the wake field tends to be very strong; with the low-emittance beams needed for a narrow final focus, this results in beam diameters of the order of a micron. The driving beam, however, must have a diameter of the order of a plasma wavelength (0.1-1 mm for typical plasma densities) to prevent excessive radiation loss by particles with large transverse amplitudes [29]. It is not evident that the energy transfer between the beams will be efficient enough with parameters suitable for TeV accelerators. The sawtooth-shaped driving bunches, proposed to obtain a high transformer ratio, will suffer from the unequal focusing force along their length. No satisfactory set of parameters for a practical accelerator has, so far, been found. Plasma instabilities or multiple scattering of the main beam may, with some sets of parameters, also cause problems.

3.5 Plasma beat-wave acceleration

Two collinear laser beams propagating in a plasma with frequencies differing by the plasma frequency can drive a Langmuir wave whose phase velocity is close to the velocity of light. Resonant buildup of plasma-electron oscillations into the non-linear regime generates a ponderomotive force leading to charge separation and a travelling electrostatic wave. With plasma densities in the range of 10^{16}-10^{17} cm^{-3} accelerating fields of several GV/m can be produced.

Initial experiments (UCLA and Quebec, CO_2 lasers), together with computer simulations, have shown that the basic principle is valid. A RAL/Imperial College experiment, in which CERN is participating, is under way; it uses the RAL Nd-glass laser (1.06 μm) and is thus complementary to experiments with CO_2 lasers (10.6 μm).

The plasma beat-wave accelerator (BWA) and the plasma wake-field accelerator are unique in being the only acceleration methods so far proposed that could plausibly offer energy gains of several GeV/m. These high fields result from charge separation in a medium which, being fully ionized, cannot break down, and seems particularly attractive for the very long term. However, plasmas are notoriously difficult to control and are prone to many instabilities. The expectation is that, by building up the beat-wave amplitude very rapidly (a few picoseconds), these instabilities will not have time to develop. It should be emphasized that the relevant plasma regime - cold, relatively high density and very short time scale - is quite different from that of interest for magnetic fusion reactors or extra-terrestrial studies.

In the plasma BWA the beat-wave propagates slightly slower than light velocity, leading to dephasing of the accelerating field with respect to the particles. A high-energy accelerator therefore has to be supplied with laser power in stages, just like an ordinary linac. Unlike in the latter, however, there are difficulties in designing efficient high-power optical feeding systems of a size which is short compared with the Rayleigh length, which would imply a substantial increase in the length of the machine. Attempts to compensate the phasing error by oblique laser beams revealed that the dephasing length is essentially the same as the power-depletion length, so the problem remains. There is nevertheless a possible way of circumventing this constraint by making use of the optical self-focusing properties of the plasma itself; the programme of basic plasma experiments should yield some information on this notion.

The plasma beat-wave principle could be applied to the generation of very strong focusing fields for the interaction region. An accelerating field of 6 GV/m corresponds to a magnetic field of 20 T, and a typical plasma wavelength of around 100 μm is rather well adapted to the required beam diameters in the focusing elements. In this application the problems of tolerances and stability over long distances would be much less severe than for a TeV accelerator, and there is therefore a considerable incentive to pursue plasma studies in this regime for possible use with accelerators of a more conventional type in the fairly near future.

3.6 Comparisons and conclusions

In reviewing the various schemes the CLIC Panel concluded that, although many schemes offered some very attractive features, most of them would require extensive and long studies to establish feasibility, and even longer studies to arrive at practical projects. This puts them into the next-but-one generation of accelerator facilities, if at all feasible. Their apparent advantages are such, however, that they ought to be followed up in future accelerator research programmes. In particular the importance of recent developments in high-temperature superconductors should be emphasized, which could lead to a substantial re-evaluation of possibilities for superconducting RF structures. These developments should be followed closely since, apart from the limitation on accelerating field, a superconducting linear collider in c.w. operation could avoid most of the problems inherent in other solutions.

One approach, that of normal-conducting 30 GHz RF linacs (Subsection 3.1) falls in a class by itself, since it offers the promise of becoming feasible within a relatively short time. This is the basis for the recommendation summed up in the Introduction. Though unconventional in many respects, and presenting many new problems, this concept showed the least departure from existing technology.

Progress beyond this initial study, as outlined in this seminar, will require considerable further effort. For this reason the CLIC Panel recommended in its Report [3] that 'CERN should create very soon a self-contained unit consisting of a few full-time staff, some part-time staff, and visitors'. It is satisfying that CERN has taken a first and important step in this direction by appointing one of the members of the CLIC Panel (Schnell) as coordinator for future CLIC studies, to continue and enlarge the effort the Panel started. Such a study will need to perform experimental tests of concepts and relevant techniques.

With adequate support, a Study Group may be able, within 3-5 years, to establish the feasibility of the scheme based on ideas presented in Subsection 3.1 and also to provide solutions of the outstanding problems related to emittance shaping, final focus, tolerances, etc.

However, as stated already in the Introduction, the other schemes described in Section 3 offer on a longer time scale promises that should not be neglected, and sufficient effort should therefore also be devoted, at CERN or elsewhere, to such more speculative schemes.

Despite the substantial technical challenges to be faced, a strong confidence has emerged that effective practical solutions will be found and that therefore linear e^+e^- colliders may provide one of the ways for Europe to maintain its leading position in elementary particle physics.

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