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CLIC: PROBLEMS AND PERSPECTIVES

S. van der Meer

ABSTRACT

A rapid review of work on linear electron-positron colliders. Various ideas and problems associated with them are discussed in a phenomenological way, without any detailed theoretical background, and the latest work at CERN in this field is discussed.

Invited talk given at the Symposium
dedicated to Professor Conversi, Roma, November 1987.

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A rapid review of work on linear electron-positron colliders. Various ideas and problems associated with them are discussed in a phenomenological way, without any detailed theoretical background, and the latest work at CERN in this field is discussed.

1. CLIC - HISTORY

In February 1985, the CERN Council asked Professor C. Rubbia to chair a Long Range Planning Committee (LRPC) to explore various options for the long range future of CERN. One of the advisory panels created by this committee was asked to explore new ideas for e^+e^- colliders in the TeV range. This panel called itself CLIC (CERN Linear Collider). Its members were:

K. Johnsen, Chairman
U. Amaldi
J.D. Lawson (RAL)
B.W. Montague
W. Schnell
S. van der Meer
W. Willis

The panel organised many meetings in which specific ideas and proposals were discussed in detail. A few dozen people contributed to these discussions. In May 1987, the panel published its report to the LRPC[1].

In the meantime, ideas about the possible design of a 1+1 TeV collider had started to crystallise around a proposal made by W. Schnell[2]. It was generally recognised that the studies (both of this design and of other ideas) should be continued beyond the life of the LRPC and that some funds and manpower should be made available. W. Schnell was appointed to lead this programme, which is still called CLIC. No money has yet been earmarked for it, but it is hoped that this may happen in 1988.

In the following, the main problems in designing high-energy e^+e^- colliders will be illustrated and some aspects of the main line of present CLIC activities will be described.

2. HADRON VERSUS LEPTON COLLIDERS

The main advantage for high-energy physics of using leptons (i.e. electrons and positrons) is that the resulting collisions are far easier to interpret. Electrons, as far as we know, are point-like particles, unlike protons, which consist of 3 quarks, bound by gluons. The only interesting collisions at the high-energy frontier are those between point-like constituents such as electrons or quarks. In proton-proton collisions such events with high centre-of-mass energy are only a very small fraction of the total. As Fig. 1 illustrates, the background-producing cross section is typically 10 orders of magnitude above the interesting point-like cross section at 1 TeV. The latter is comparable for electrons and quarks. Also, the individual quarks have typically only 5 to 10% of the total proton energy. Proton colliders therefore must have 10 to 20 times the energy of comparable lepton machines.

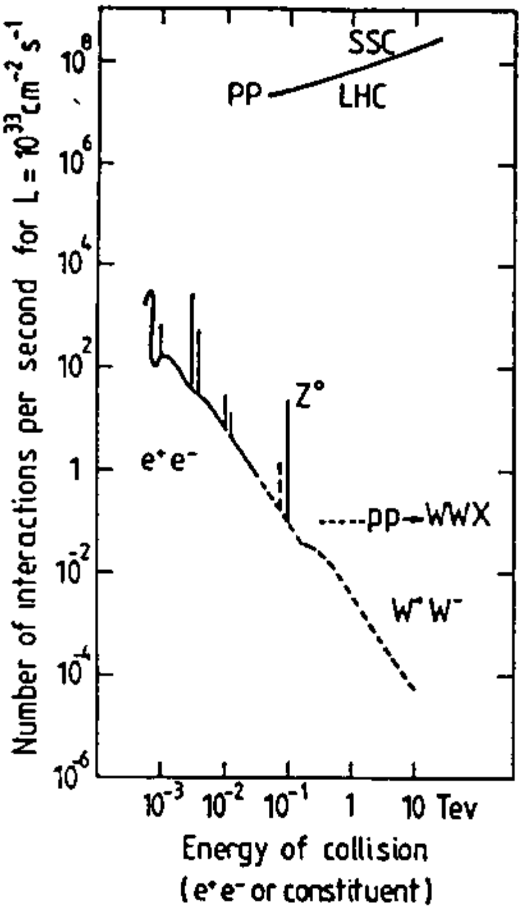


Fig. 1

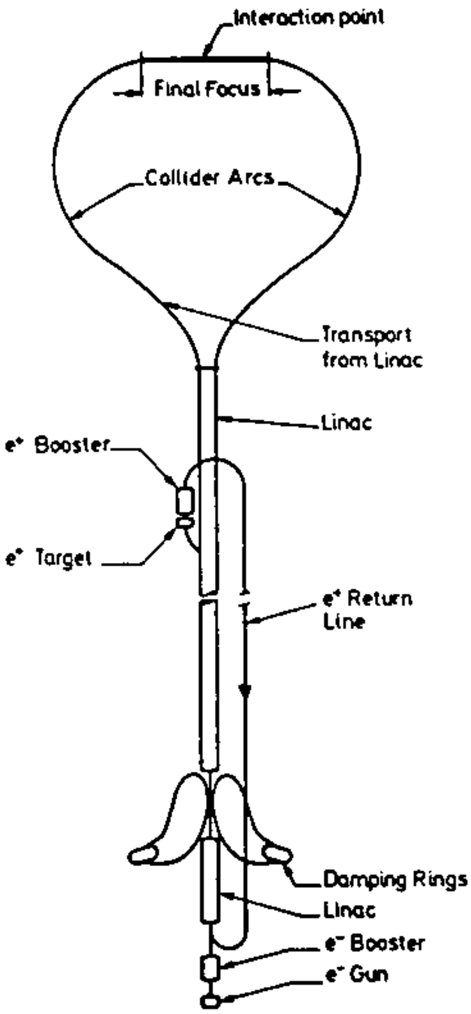
Interaction rate for e^+e^- or quark-quark collision vs collision energy. For pp collisions the energy is the effective energy for the constituent collisions. (After ref. [3]).

The main reason that proton machines are nevertheless so important is that electron machines are far more difficult to build. This is because high-energy electrons turning around in a ring radiate energy far more than protons do. The power radiated varies inversely with the fourth power of power of the rest mass, so that for protons, at present-day energies, the effect is negligible. This radiation loss is the reason why electron rings must work with a low magnetic field, and therefore have a large radius. For example, LEP, at CERN, is designed for 100 GeV electrons and positrons, but uses a ring of 4 km radius. Since the radiation loss increases rapidly with energy, this is probably the largest electron ring that will ever be built. For higher energies, lepton colliders will have to be linear, i.e. consist of two opposed linacs. Such machines nowadays consist mainly on paper, but their popularity is rapidly growing. As shown in Fig. 1, the cross section for interesting phenomena decreases roughly with the square of the energy. A high luminosity is therefore needed for high-energy machines. Since in a linear collider the particles meet only once, this is not easy to obtain.

3. *AN EXAMPLE*

At present, the only linear collider is the SLC machine[4] at SLAC (Stanford, USA), now just starting its first tests. This consists of a single linac (Fig. 2) accelerating both electron and positron bunches, following each other at a short distance and colliding after being deflected in opposite directions. The energy is 50 GeV per beam, the luminosity 6×10^{30} $cm^{-2}s^{-1}$. Note that what we really would like for a future machine would be 1 TeV and 10^{33} $cm^{-2}s^{-1}$ or more, to be competitive with the SSC machine mentioned before. Thus, large improvement factors are needed.

The trick of using a single linac will not work at much higher energies because of the increasing radiation loss. We have to use two opposing linacs.



<u>*Fig. 2*</u>

Schematic representation of the SLC collider at Stanford (USA). (After Ref. [4]).

4. LUMINOSITY AND BEAM POWER

For two round beams meeting each other, the luminosity is

$$L = \frac{N^2 f}{4\pi\ \sigma_r^2} \tag{1}$$

with N the number of particles per bunch, f the repetition frequency and σ_r the rms transverse beam size at the interaction point. We may increase N or f, but this leads to higher power in the beam, and it is in fact the megawatts of power needed that will limit the machine performance. A better solution is to decrease σ_r by using beams of small emittance and focusing them strongly at the interaction point. For instance, at SLC the beam size foreseen in the focus is 1.3 μm. At future machines for higher energy this will have to be reduced by an important factor.

5. LIMITATIONS TO BEAM SIZE

Several limitations exist. In the first place, there are technological problems. The beam emittance must be very low to start with; this requires the use of so-called damping rings to reduce emittances and energy spread before the particles are injected into the accelerator. For future machines these rings will require very careful design.

In addition, it is not easy to provide the strong focusing before the interaction point. The main problem here is that the accelerated particles have an energy spread that will lead to chromatic aberrations in the final focusing system. Sophisticated achromatic systems must be used. The final lens must be very strong.

A more fundamental limitation is the so-called *beam disruption*. Relativistic particles in a bunch will not influence each other much, since their electric repulsion and magnetic attraction cancel. However, these effects will add up for the opposing bunch, so that the beams will focus each other strongly. Some focusing is, of course, helpful, but beyond a certain limit the beams will overfocus and disperse before having had much chance to interact.

The phenomenon is described by a disruption parameter D. For bunches with Gaussian distribution

$$D = \frac{r_0 \sigma_z N}{\gamma \sigma_r^2} \qquad (2)$$

where σ_z is the longitudinal rms dimension of the bunch, r_0 is the classical electron radius and γ the usual relativistic parameter. For not too high values of D, the luminosity increases by a factor H (Fig. 3), but D should not be much larger than 20 and, in fact, tolerances will probably impose a much lower value.

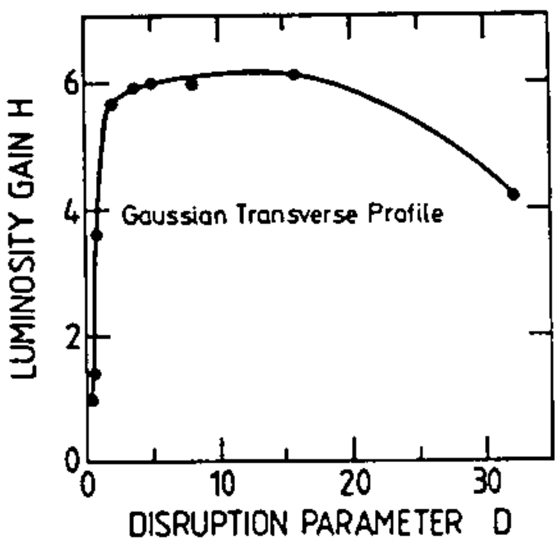


Fig. 3 *Luminosity increase by disruption effect vs disruption parameter. (After Ref.* [5]*).*

Because of the mutual strong focusing the deflected particles will emit photons (the so-called *beam radiation*). This represents a further limit on spot size, since the energy loss should remain acceptable.

In fact, a parameter δ may be defined, corresponding to the mean energy loss from beam radiation. The dependence of δ on the beam parameters is not the same as for the disruption D. In fact, two different regimes may be distinguished. In the first ("classical") regime, the radiated photons have an energy distribution with a peak well below the electron energy, if calculated in a classical, non-quantised way. In the second, so-called "quantum" regime an exact quantum mechanical description is required because the classical one would lead to photon energies higher than the electron energy.

The disruption and beam radiation together with the allowed beam power severely restrict the choice of accelerator parameters[6]. Although a detailed discussion of this would exceed the scope of the present talk, Fig. 4 shows as an example how the power per beam varies with bunch length for given δ, final beam size and luminosity. The left-hand side corresponds to the quantum beam radiation regime, the right-hand side to the classical one. The limit imposed by disruption is also shown.

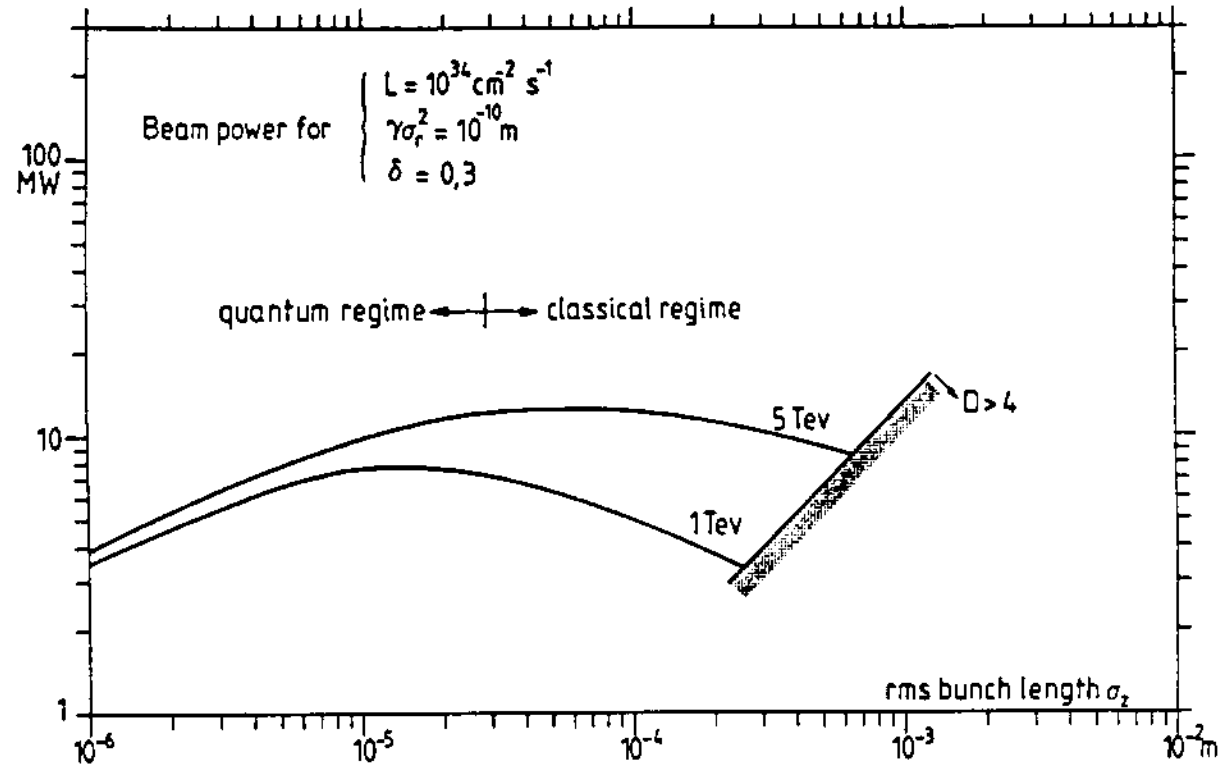


Fig. 4 *Average beam power (one beam) vs bunch length, for the conditions specified. The disruption effect is included, and a reasonable limit (D = 4) is indicated.*

It seems probable that the next generation of e-p colliders will work in the classical region, near the disruption limit. The extremely short bunches required for going into the quantum regime seem to pose important problems at present, although for future very high-energy machines there may be no other choice.

6. *DAMPING RINGS*

The low emittance beams needed for e^+e^- colliders may be produced by first letting the particles circulate in a so-called damping ring. In this ring they lose energy by radiation. The energy is replenished by rf accelerating cavities. If the focusing and bending structure of the ring is properly designed, this process leads to reduction of emittances, in both transverse planes and longitudinally; this technique is well known from electron synchrotrons. Wiggler magnets may be used to enhance the damping rate. For the beams needed for future colliders (say 1 + 1 TeV), the required emittances are so small that the utmost will be required from such rings.

The performance limit is given by the damping time τ and the equilibrium emittance. Both should be as small as possible. The final emittance is the result of an equilibrium between the radiation damping process on the one hand and excitation on the other one. The excitation comes both from the quantised character of the radiation and from intra-beam scattering. The study of means to improve performance is still in process in various places, but it seems that with the most advanced designs emittances at least one order of magnitude smaller than in the Stanford machine may be reached. This might just be good enough for the next generation of colliders.

One problem with damping rings is that they have to store a number of bunches of the order of a few times τf (f is the repetition rate). Since the distance between bunches must be enough to enable a rapid kicker to inject and eject them, this tends to lead to a large circumference. Thus, the damping rings may well represent a significant fraction of the cost of a future collider.

7. *ACCELERATING STRUCTURES; POWER PROBLEMS*

In a typical present-day linac (such as the SLC at Stanford), the particles are accelerated by passing through a sequence of structures that support an electromagnetic wave with a large longitudinal component of electric field. In many cases these take the form of corrugated wave guides that support a travelling wave with phase velocity equal to the beam velocity (i.e. practically equal to light velocity). Typically, each section is powered by a pulsed klystron and at the far end the remaining power is dissipated in a matching load (Fig. 5).

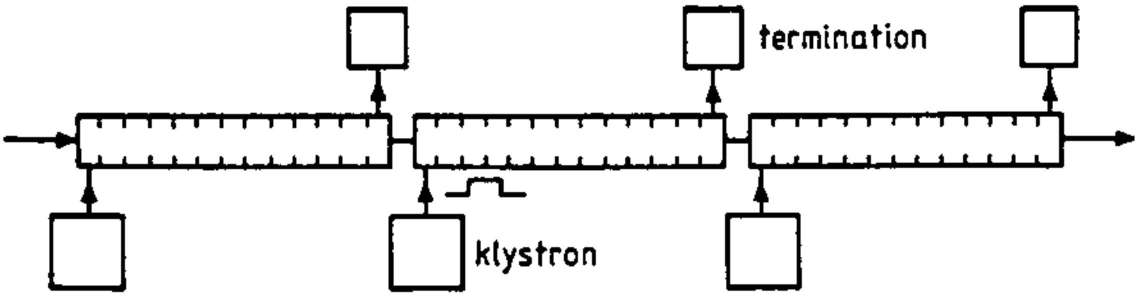


Fig. 5 *Schematic diagram of a typical electron linac using travelling-wave structures. More than one section may be fed by each klystron.*

For the very high field gradients needed, it is not possible to excite the structure continuously; only short pulses (typically a few μs) can be supplied. The peak power is very large (e.g. about 10 GW for SLC).

A balance may be struck between peak power (klystron cost) and mean power by choosing the group velocity of the structure that determines the filling time of a section. A low group velocity or long sections will reduce the peak power, but increase the filling time and therefore the dissipation and the mean power. The section length is also limited because the dissipation causes the gradient to decrease as the wave passes along the structure. Present-day linacs are built for low peak power to reduce capital cost, but for future machines the average power becomes the dominant factor. The peak power will grow because of this and because of the increasing accelerator length. Reducing the latter by increasing the gradient will lead to even higher peak power.

The mean rf power needed is much higher than the beam power because of dissipation during the pulse and because with a pulsed machine only a small fraction of the stored energy can be transferred to the beam and the remaining energy is dissipated.

The passing bunch of particles cannot take more than a fraction of the energy out of the structure because the trailing particles would then see less gradient than the leading ones. The resulting energy spread is bad for the final focus optics (chromatic aberration). It can be compensated in part by letting the bunch pass on the rising part of the waveform, but even so, more than 10% efficiency will certainly not be obtainable.

8. *SUPERCONDUCTING LINACS*

Obviously, most of these problems could be overcome by using a superconducting structure with CW excitation. This would lead to high efficiency. The greatest objection at the present time is that the gradients that may be obtained with present-day superconducting cavities are at least an order of magnitude lower than required for machines of reasonable length. The structures are also far more expensive than normal-conducting ones and require very careful cleaning and conditioning to obtain even the modest present-day gradients. The gradient is limited by field-emission at specific points where impurities or irregularities occur. A further theoretical limit given by the critical magnetic field has so far not been reached.

Whether the new high-temperature superconducting materials will change the picture is not clear. A high current density is needed, and for rf superconductivity, in contrast to d.c., the entire surface must be superconducting to obtain a high Q. We are still far away from this, but in the future this could well be the way to go.

9. *METHODS TO INCREASE EFFICIENCY*

Without superconductivity, we certainly have to find methods to reduce the peak power and improve the efficiency by a large factor. Many different ways have been proposed. Some of these aim at reducing the stored energy by increasing the frequency and therefore reducing the volume of the structure. Lasers as power source are at the extreme end of this line. Other schemes use pulsed excitation rather than an rf wave. Yet other methods combine the many klystrons into a single auxiliary beam parallel to the main linac. Methods using plasma have also been proposed. In the following, some of these schemes will be described. Such descriptions will not be very useful without a comparison of their merits. I will express my personal thoughts about this; note that others may not agree with me.

10. WAKEFIELD ACCELERATION

A bunch of particles moving thorugh a linac structure will leave a wakefield behind. The longitudinal component of this field diminishes the accelerating field behind the bunch and, in fact, the wakefield from the leading particles decelerates the trailing ones and so causes energy spread in the bunch. Further behind the bunch, the wakefield may change sign several times. In a scheme proposed by Voss and Weiland[7], the wakefield is used to accelerate following particles (Fig. 6). An intense, low-energy, ring-shaped beam is used. Its wakefield reflects on the outer wall of the structure, then moves inward along the gaps formed by parallel plates. Because of the decreasing radius, the gradient increases toward the centre; the structure behaves as a set of tapered transmission lines. Through the central aperture the main beam sees a gradient much higher than the one that decelerates the driving beam on the outside. The field only exists for a short period of time and thus the structure losses should be low. However, the driving beam must be periodically refreshed or reaccelerated, and the usual efficiency problem is not solved. Another problem is the good cylindrical symmetry required in the driving beam and in the structure to avoid transverse fields in the centre. A small scale experiment with this system is in progress at DESY, Hamburg.

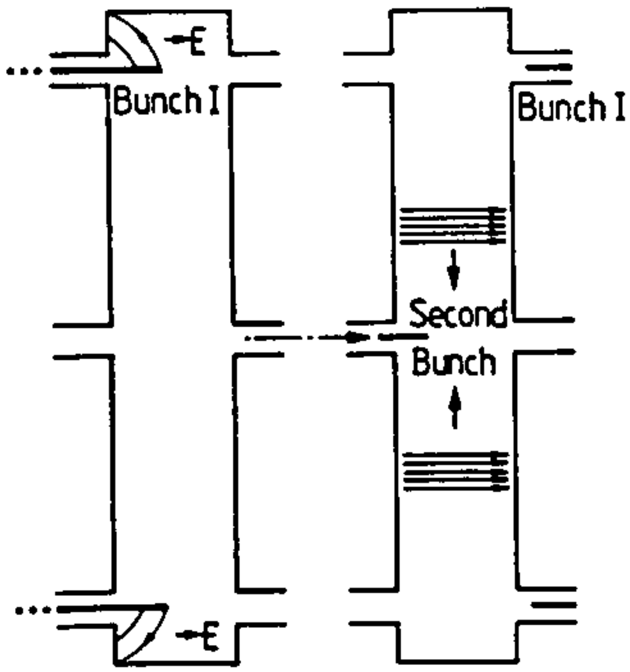


Fig. 6

Wakefield produced by a ring-shaped electron bunch, accelerating a second bunch.

11. SWITCHED POWER LINAC

A somewhat similar structure, but now excited in a completely different way is shown in Fig. 7. Metal rings at the outside of the structure are charged to a potential of a few tens of kV and suddenly discharged by illuminating a photocathode at one side by a very short laser pulse. The resulting e.m. wave again travels to the centre as before, its electric field being amplified in the process[8].

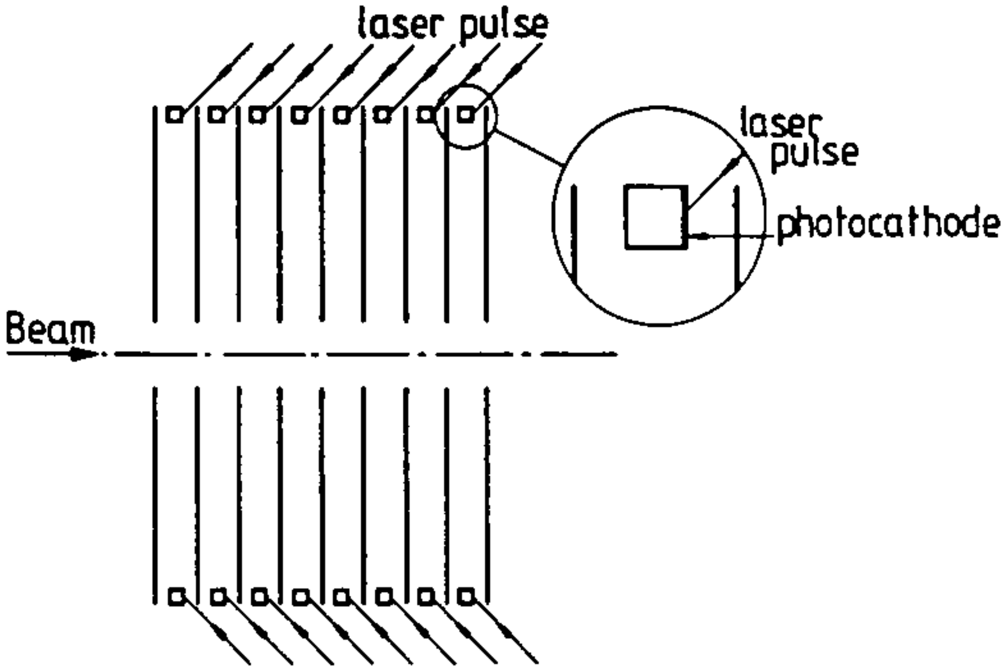


Fig. 7 *Principle of switched power linac.*

There are many problems, one of the most difficult being the production of reliable and efficient photocathodes. Theoretical calculations to establish the efficiency that may be expected have been done. Some measurements have also been made on a scaled-up model. It is far to early to say if this scheme will eventually be successful.

12. PLASMA WAKEFIELD ACCELERATOR

Wakefields may also be produced by a bunch of charged particles traversing a plasma. The plasma electrons will start to oscillate in the wake of the bunch; it is a property of these plasma waves that they have zero group velocity so that the wave does not spread out but remains confined to the volume in the wake of the driving bunch. A following bunch may be accelerated by this wake, but this is only useful if the accelerating field is much larger than the field that decelerates the driving bunch. It now turns out that this may be achieved by giving the longitudinal distribution of the driving bunch a saw-tooth shape long compared to the plasma wavelength (Fig. 8). The latter may be in the range 0.1-1 mm for typical plasma densities and in theory gradients of several GeV/m may be obtained[9,10].

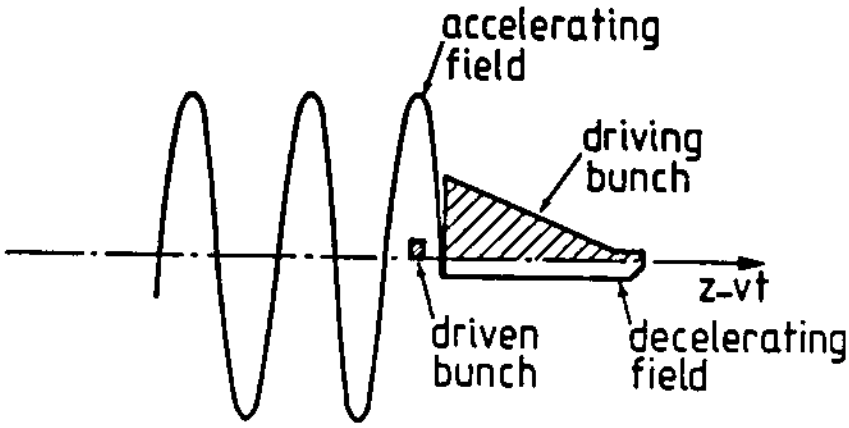


Fig. 8 *Longitudinal profile of electric wakefield in plasma caused by saw-tooth shaped bunch.*

The problem with this scheme is that the following beam tends to be focused very strongly by the transverse components of the wakefield. With the low emittance needed for the final focus this results in beam diameters of the order of microns. The driving beam, however, must be at least a few plasma wavelengths wide to avoid too strong focusing of this low energy beam, which would lead to important radiation losses. As a result, the lateral dimensions of the wakefield are then much larger than the diameter of the driven beam and energy transfer efficiency suffers. Plasma instabilities or multiple scattering may also occur.

The present situation is that the linear theory of plasma wakefields is well understood, but that no parameter combination has been found that is satisfactory from the point of view of accelerator design. Of course, a break-through can never be excluded; the attractive feature of this method is the high gradient that seems to be possible in principle.

13. THE PLASMA BEAT-WAVE ACCELERATOR

The same type of plasma oscillations can also be excited by a pair of collinear laser beams with slightly different frequencies, the difference being equal to the plasma frequency[11]. The excitation is now gradual rather than sudden as in the case of the wakefield scheme, and many oscillations are needed before the wave is strong enough. As a consequence, plasma instabilities are more dangerous with this scheme. Also, the phase velocity of the resulting wave is somewhat lower than the light velocity so that the particles get out of step with the wave. This effect, and the depletion of the laser beams, necessitate an accelerator structure consisting of many stages; this makes the focusing and efficiency problems even more difficult than for the plasma wakefield accelerator. Proof-of-principle experiments have been performed on a very small scale, but it does not seem likely that this principle will lead to a practical accelerator in the near future.

It may, however, be that the high fields generated in this way could be used for constructing a strongly focusing device for the final focus.

14. TWO-BEAM ACCELERATOR SCHEMES

The schemes that show at present most promise of bearing fruit in the near future, are those that use more-or-less standard linac structures, scaled down and excited at higher frequencies than used up to now, e.g. 30 GHz. The problem, of course, is still the gigantic peak power required and the absence of suitable high-power klystrons in this frequency range.

This problem may be overcome by using a low-energy, high intensity driving beam (in parallel to the low intensity main beam) as a power source. The driving beam may be accelerated at a number of points along its length by means of inductive acceleration (pulsed accelerator gaps), or by superconducting cavities, which would be suitable for this low-gradient, but high-efficiency application. The kinetic energy of the beam is transformed to rf power either by means of a free electron laser or by bunching the beam at 30 GHz and letting it pass through linac structures (wakefield principle).

A free-electron laser for this purpose has been studied at Berkeley-Livermore, USA[12,13], and a trial section, producing power of the order of 1 GW, was constructed. One problem with this principle is that the rf frequency is directly related to the wiggler period and to the driving beam energy; with reasonable wiggler wavelengths the drive beam energy must be rather low (a few MeV) so that its velocity is not highly relativistic and it is quite difficult to maintain correct phasing between all sections of the long accelerator. This problem is absent if the alternative method, using the wakefield of the driving beam, is used (also called "relativistic klystron"). The driving beam energy may then be in the GeV range and the velocity is equal to the light velocity for all practical purposes.

Much work on this last method, combined with superconducting cavities for accelerating the drive beam (Fig. 9) has been done at CERN[2,17]. Detailed calculation shows that the transformer ratio between acceleration of the main beam and deceleration of the drive beam is obtained by choosing a large ratio between the final rf (30 GHz) and the frequency used for accelerating the drive beam (say 350 MHz as used for the LEP superconducting cavities), and by giving the structures of the drive linac a much lower impedance than the ones of the main linac. This is done by using large-aperture irises or their equivalent. Although the main beam acceleration may be as much as 100 times stronger than the drive beam deceleration, energy is conserved because the mean intensity is very much higher in the drive linac. The drive beam is bunched at 30 GHz before being injected so that it can give its energy to the 30 GHz

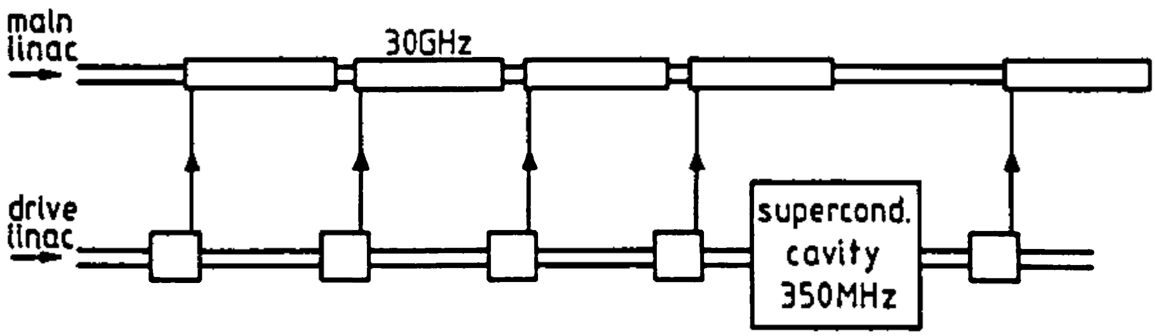


Fig. 9 *Two-beam acceleration using a drive beam accelerated by superconducting cavities and linac-type structures to generate a high peak power pulse feeding the main linac structure.*

structures, and these bunches are in turn grouped into "super-bunches" at 350 MHz repetition frequency so that they can be accelerated in the low-frequency cavities. This scheme has been studied in some detail, and the resulting parameters seem reasonable. Apart from generating the initial high-intensity drive bunches, the main problem (as with all similar high-frequency schemes) is related to transverse wakefield effects. Also, the final focus system remains to be designed.

15. TRANSVERSE WAKEFIELDS

A problem common to high-energy electron linacs is that a slight transverse misalignment between beam and rf structure leads to wakefields with non-zero transverse components at the beam centre. As a consequence, the wake caused by the front of the bunch deflects the tail; if the transverse focusing strength for front and tail is the same, resonant excitation of the tail will lead to rapid beam loss. This effect, first observed at SLAC, depends strongly on the aperture of the structure. High frequency leads to small aperture and to strong transverse wakefields. To cure this effect, short bunches or very strong focusing are needed; alternatively different focusing strength for front and tail of the bunch may be arranged to alleviate this problem. Unfortunately, short bunches are difficult to make and lead to strong longitudinal wakefields. Different focusing for front and tail of the bunch may be obtained by accepting a large energy spread along the bunch length. This is undesirable from the point of view of the final focus (chromatic aberration). Recent study[14] has shown that focusing by means of rf quadrupoles may suppress the transverse wakefield effects without requiring a large energy spread. The rf quadrupoles are simply made by using irises with slots instead of circular apertures. The focusing effect increases with frequency and with gradient; this makes it interesting for future linacs.

16. FINAL FOCUS

Even with the small energy spread allowed by the rf focusing scheme, it is not easy to design a final focus system that satisfies all requirements. The chromatic aberrations can be minimised by placing the final focusing element near the interaction point. This, however, may interfere with the experimental set-up and will require a very high focusing gradient. Ideas for high-gradient devices using plasma have originated in various places, but none of these have materialised yet and it is not sure that the extreme positional stability required may be obtained with plasma.

This last problem, although severe, might be somewhat less difficult to solve if normal quadrupoles were used. Because of their lower gradient, they would have to be further from the collision point, which is good for experiments. However, the compensation of chromatic aberrations is then more difficult. Recent studies have come to within roughly a factor 5 of what is needed[15], and some further improvement may be possible.

One of the problems associated with the final focus appears to be to avoid destruction of the last focusing device by scattered particles from the opposite beam (disruption effect)[16]. It may well be necessary to make the beam collide at a small angle to avoid this.

17. *CONCLUSION*

This rapid survey of e^+e^- collider work may leave an impression of multiple problems, difficult choices, dead alleys and pitfalls. It is true that each parameter seems to influence nearly all others and that it is difficult to arrive at a consistent design. In fact, even if we would have the necessary financial support, we could not really start building at 1+1 TeV collider at this moment. However, given a reasonable support for further study and experimental work, it seems to me that in a few years we might be in a position to make a well-founded proposal for such a machine. In this energy range, probably one of the two-beam schemes would be the most plausible solution; a considerable amount of thinking about the relevant problems is going on at various places in the world.

More speculative methods, such as plasma acceleration, might on a longer time scale become interesting, although it now seems that new ideas are needed before they will be acceptable. Finally, high-temperature superconductivity might eventually find an important application in this field.

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