COLLIDING LINACS

Ugo Amaldi
CERN, Geneva, Switzerland

Summary

The radius and the cost of electron-positron colliding rings increase as the square of the beam energy, so that it is generally felt that new approaches are needed for reaching energies definitely larger than the ones attainable with LEP. This article reviews the schemes that have been proposed. They are all based on the use of linear accelerators so that, before describing them, we write down the general conditions that a few beam parameters have to satisfy in order to reach the wanted luminosity at any given energy. The presentation of the various proposed schemes is as complete as possible; but it is in the nature of a futuristic subject, and we can only list the technological problems that have to be solved in the next decade before electron-positron colliding linacs become the reliable tools that storage rings are nowadays.

1. Introduction

The scaling laws of the parameters and cost of e^+e^- colliding rings were derived some years ago by Richter[1], and the LEP design study proves that machines of this type can extend the presently available energy range up to about 200 GeV in the centre of mass[2,3]. These energies can be obtained with copper cavities by dissipating powers of the order of 200 MW. With superconducting cavities LEP will reach (2 x 130) GeV without increasing the total power[2,4]. Cost optimizations of storage rings with conventional or, alternatively, superconducting cavities have been made by Ritson and Tigner[5] and by Bauer[4]. The conclusion is that, for a machine with superconducting cavities (SC), the optimum cost C scales roughly as the square of the beam energy E,

$$C = C_0 + kE^2 \ , \qquad (1)$$

as for conventional cavities (CC) [1], but the constant k is about two times smaller. [In Eq. (1) C_0 is the cost of the installations that are energy independent, such as the injector and the experimental areas.] Ritson and Tigner gave low and high values for the constant k for a cavity frequency of 1500 MHz [6]:

$$k_{CC} = (0.10\text{-}0.13)\ \text{M\$/GeV}^2 \qquad (2)$$

$$k_{SC} = (0.045\text{-}0.065)\ \text{M\$/GeV}^2 \ . \qquad (3)$$

It is generally believed that in about 10 years time, superconducting cavities of the required characteristics will be mass produced and will work with high reliability. The above arguments show that these technological advances will be useful for obtaining more energy within a fixed budget, but will not influence the cost scaling law of Eq. (1), which is determined by the well-known dependence of the energy loss per turn by synchrotron radiation U on the beam energy E and the radius of curvature ρ: $U \propto E^4/\rho$.

I have been invited to review the status of the various proposals that have been put forward to substitute Eq. (1) by a *linear* dependence of cost upon energy. This invitation has been extended to me, I presume, because of a short article written about four years ago proposing the use of two superconducting linacs to obtain energies larger than 300 GeV in the centre of mass, with a collider having no radiation problem and thus with a cost proportional to the energy[7]. This kind of accelerator, in which the beam energy is recovered by the opposite linac was proposed[8], as a possible basis for a world-wide enterprise, at the International Study Group on Future Accelerators and High-Energy Physics held at Serpukhov in May 1976 [9]. The idea was discussed in various laboratories, and in the following months I was informed that similar schemes had already been proposed in the past. In the rest of this Introduction I shall present a sketch of the developments in this field in chronological order as they are now known to me.

Superconducting colliding linacs firing one into the other were proposed in 1965 by Tigner[10]. At such an early stage of development of the storage ring technique, the energies aimed at were low (0.5 and 3 GeV) and only electron-electron collisions were considered. Synchrotron radiation was not yet a problem for e^+e^- rings and, since the linac scheme offers no other advantage, it was too easily forgotten. In March 1971, at the American Accelerator Conference, ideas on upgrading the SLAC accelerator were presented[11], the main one being the recirculation of the electron beam in the linac to increase the energy for fixed-target physics. Also considered was the possibility of accelerating two intense electron bunches in the same SLAC pulse, so that they could collide at one point after having been deflected in the two branches of one of the two recirculator loops[12]. At Novosibirsk, conventional and superconducting linacs were considered, in the same years, as tools for reaching the hundred GeV region by G.I. Budker, A.N. Skrinsky and collaborators. In 1971, at the Morges seminar, Skrinsky spoke briefly about these ideas and also about the possible use of storage rings for muons[13]. Electron-electron collisions at (2.5+2.5) GeV were also mentioned by Saranzev in a Dubna report which concerns the construction of a collective linear accelerator for protons and deuterons[14]. These various suggestions contained the germs of the present developments but unfortunately did not attract the attention of the high-energy physics community until the publication, in 1976, of my short article[7] and its presentation at the Serpukhov meeting[8]. At CERN, at the beginning of 1976, Lengeler looked into the technical problems connected with the realization of a 2 × × 100 GeV superconducting linac and made a realistic cost estimate[15]. By comparing these costs with the optimized costs of electron-positron storage rings as derived by Richter[1], it was concluded at the Moriond meeting in February 1976 that, costwise, a collider based on superconducting linacs would be advantageous with respect to a storage ring for energies of the order of 2 × 150 GeV, only if accelerating fields of the order of 10 MV/m could be obtained[16].

In recent years conventional linacs have attracted increasing attention. Voss laid down a parameter list for a 2 × 100 GeV collider[17], and the Novosibirsk group considered the main technical problems to be solved if colliders of this type are to be realized, and proposed original solutions for some of them[18]. Almost every one who is interested in colliding linacs was present at the First ICFA Workshop held at Fermilab in October 1978. The working group on electron-positron colliders, chaired by J. Rees, was thus an active forum for comparing ideas developed independently in various laboratories, and many of the points I shall discuss in the following were clarified in the final report issued by this group[19]. They were also summarized and complemented in the concluding talk given by Richter at the

San Francisco Particle Accelerator Conference in March 1979 [20].

In 1979 this field saw two interesting developments. Gerke and Steffen proposed an improved version of the scheme with energy recovery[21], while a new scheme started to be studied at Stanford[22]. This latter idea is to use the SLAC linac to accelerate positron and electron bunches simultaneously; these bunches would eventually collide in a special ring after only half a turn.

The rest of the article is devoted to a derivation of the simple equations that relate the main parameters of a collider based on linacs, and then to a discussion of the possibilities and the limitations of the proposed schemes. For completeness in the presentation I shall also quote the main results obtained by the electron-positron working group of the Second ICFA Workshop, held at Les Diablerets in October 1979 [23].

2. Basic Equations

Let us consider two streams of colliding bunches, each containing N particles, crossing in the interaction point at the frequency f with energy $E = \gamma mc^2$. The luminosity is given by the simple relation

$$L = \frac{fN^2}{4\pi\sigma^2} , \qquad (4)$$

where σ is the r.m.s. radius of each bunch; for the moment these bunches are assumed to have circular cross-section. The bunch radius has the form

$$\sigma = \sqrt{\frac{\varepsilon\beta}{\pi\gamma}} , \qquad (5)$$

where $\varepsilon = \pi\sigma\ \Delta p/mc$ is the normalized emittance at 1 r.m.s., and β is the amplitude function at the interaction point.

The luminosity cannot be arbitrarily increased by decreasing ε and β, because of the consequent strong effects of one bunch on the other. With reference to Fig. 1, we consider a particle incident on an opposite bunch at a typical distance σ from the axis. The bunch acts as a focusing lens so that the particle is deflected towards the axis and emits synchrotron radiation, which at the ICFA Workshop was dubbed "beamstrahlung". Two parameters have been introduced to quantify these effects[19,20]:

$$\text{disruption parameter} \quad : \quad D = \frac{r_e dN}{2\gamma\sigma^2} , \qquad (6)$$

$$\text{beamstrahlung parameter:} \quad \delta = \frac{2}{3}\, r_e^3\, \frac{\gamma N^2}{d\sigma^2} , \qquad (7)$$

where r_e is the electron classical radius. If $D \ll 1$, the disruption parameter equals the relative migration $\Delta r/r$ of the typical particle towards the axis (Fig. 1). For $D \gg 1$ the particles oscillate around the axis during the collision, and the phenomenon becomes very complicated. Pinch effects are expected to play a role and, for large enough value of D, the bunches will blow up. Calculations of the maximum allowed value for D have been made at Novosibirsk[18,24] and are under way at SLAC[25]. According to the Novosibirsk group, D can be as large as 20-30 without any adverse effect, while at the First ICFA Workshop $D \simeq 1$ was taken as a conservative maximum. At the Second Workshop, by applying an approach recently developed in the field of storage rings, Pellegrini and Tigner came to the conclusion that D cannot be larger than a few units[26]. Clearly, both calculations and experimental data are needed in

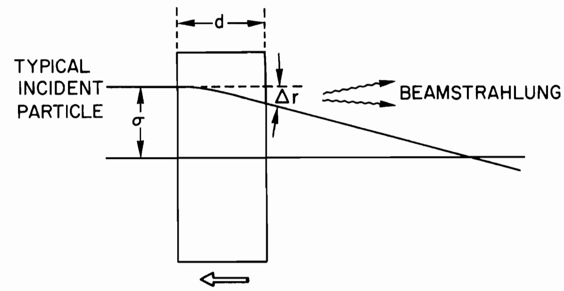


Fig. 1 Schematic representation of the effects of a moving bunch on a typical particle of the opposite bunch.

order to resolve this very important issue. It has also to be noted that the "disruption parameter" is proportional to the familiar quantity ΔQ, the incoherent beam-beam tune shift so widely discussed in connection with electron-positron storage rings:

$$D = 2\pi\, \frac{d}{\beta}\, \Delta Q . \qquad (8)$$

The introduction of a new quantity could thus be avoided. However, I think that since ΔQ has by now a very clear place in the theory of storage rings, it is better to use a different parameter in discussing colliding linacs.

In storage rings the luminosity is limited by the maximum ΔQ value according to the relation[3]

$$L(\text{cm}^{-2}\ \text{s}^{-1}) \simeq 1.23\times 10^{33}\ \frac{P(\text{MW})\,\rho(\text{m})}{E^3(\text{GeV})\,\beta(\text{m})}\ \Delta Q\ (\text{storage rings}) , \qquad (9)$$

where ρ is the bending radius and P is the power of *both* stored beams. For an optimized machine with conventional cavities $\rho(\text{m}) \simeq 0.5\ E^2(\text{GeV}^2)$, so that Eq. (9) becomes

$$L(\text{cm}^{-2}\ \text{s}^{-1}) \simeq 6.2\times 10^{32}\ \frac{P(\text{MW})}{E(\text{GeV})\,\beta(\text{m})}\ \Delta Q\ (\text{storage rings}) . \qquad (10)$$

For a colliding linac scheme, by introducing Eq. (6) into Eq. (4) we obtain

$$L(\text{cm}^{-2}\ \text{s}^{-1}) \simeq 3.5\times 10^{31}\ \frac{P(\text{MW})}{d(\text{mm})}\ D\ (\text{colliding linacs}) , \qquad (11)$$

so that the luminosity depends on the beam power but *not* on the beam energy. In a storage ring the beam power must scale linearly with E to maintain the luminosity constant, while the cavity losses and the power cost increase as E^2. In the linac scheme the beam power can be kept constant, and the cavity losses and the power cost depend only linearly upon the beam energy.

When D is small the beamstrahlung parameter of Eq. (7) equals the fractional energy lost by the particle in radiation. Since the beamstrahlung introduces an energy spread, δ must always be smaller than 1. Formally δ can be expressed as a function of E and L:

$$\delta = \frac{8\pi r_e^3}{3mc^3}\ \frac{EL}{fd} \simeq 0.37\ \frac{E(\text{GeV})\ L(10^{32}\ \text{cm}^{-2}\ \text{s}^{-1})}{f(\text{Hz})\ d(\text{mm})} . \qquad (12)$$

Once E is fixed and d, P, and D have been chosen to give the desired luminosity [Eq. (11)], the beamstrahlung process imposes through δ a lower limit on the bunch frequency f. It is necessary to stress that the number of radiated photons is small[19], so that one must worry not only about the average loss but also about the fluctuations during the radiation process.

If the crossing bunches have elliptical section, the above equations have to be modified. By introducing the ratio between the two transverse dimensions

$$R = \frac{\sigma^{max}}{\sigma^{min}} > 1 , \qquad (13)$$

the modifying factors can be read in Table 1 [19].

Table 1

Modifying factors to take into account the bunch shape ($\sigma^{max} \cdot \sigma^{min} = \sigma^2$)

Quantity	Equation	Multiplicative factor
D	6	$2R/(R+1) \geq 1$
δ	7	$4R/(R+1)^2 \leq 1$
L	4	1

The table shows that, if it would be possible to make $R \gg 1$ while keeping the product $\sigma^{max} \cdot \sigma^{min}$ constant, the luminosity would not be influenced, while the beamstrahlung parameter could be substantially reduced.

3. Superconducting Linacs with Energy Recovery

The collider that uses superconducting linacs and recovers the energy of the used bunches was chronologically the first to be proposed[10] and was named *peloron*[7] which in Greek means "large and prodigeous being" but can also be read as: Positron and Electron Linear Oscillator Radiating Only Negligibly. The working principle of a peloron is best illustrated by first supposing that one can easily produce electron and positron beams of very small emittance [Fig. 2].

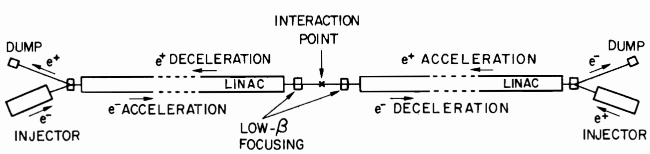


Fig. 2 Working principle of colliding linacs with recovery of the beam energy. For simplicity, in this drawing it is supposed that electron and positron bunches can be directly produced from an injector with small emittances.

The collinear, superconducting linacs accelerate two beams, and magnetic lenses focus then to very small transverse dimensions in one or more low-β interaction regions. After crossing, the bunches give their energy back to the electromagnetic field of the opposite linac, since there they find an electric field having opposite phase to decelerate them. Stationary conditions are achieved, and in each linac the energy given back to the electromagnetic field is used to accelerate the beam, which moves in the opposite direction. The beams are dumped at the end of the "uphill" path when very little energy is left, so that the power consumption will mainly be contributed by the losses of the cryogenic system and by the cavity losses (which include the very important "higher-order mode" losses, to be discussed later).

The very fact that in this scheme energy has to be recovered poses special conditions on the parameters. To avoid too many undue crossings of the bunches along the linac, the bunch frequency f cannot be arbitrarily large:

$$f \leq (2n+1) \frac{ceV}{2E} , \qquad (14)$$

where V is the voltage per unit length and n is the number of points in which the bunches cross in each linac. On the other hand, by requiring that the energy spread at the crossing point is small, through Eq. (12), the beamstrahlung process poses a lower limit on the frequency. The two conditions are very restrictive and in practice fix the frequency. For instance, with E = = 250 GeV, V = 10 MV/m, d = 5 mm, and $L = 10^{33}$ cm^{-2} s^{-1}, the choice $n \leq 2$ and $\delta \leq 1 \times 10^{-2}$ implies $f = 2.5 \times 10^4$ Hz. Then, for a given value of D, Eq. (11) fixes N and Eq. (4) determines σ. In the example, with D = 1 one obtains $N = 7.2 \times 10^{10}$ and $\sigma = 1$ μm. Even by choosing a small value of β at the interaction point ($\beta = 5$ cm), the required normalized emittance turns out to be $\varepsilon = 10^{-5}$ πm, about a factor of 3 smaller than the one measured at SLAC with $N \simeq 10^9$ [22].

Since the energy of the bunches has to be recovered, the beam-beam interaction should not cause a too large increase of the emittance. For $D \lesssim 1$, the emittance due to the collision is

$$\varepsilon^* \simeq 2\pi \frac{\sigma^2 D\gamma}{d} = \pi r_e N \qquad (15)$$

and is simply proportional to the number of particles per bunch. In the example, ε^* comes out to be 20 times larger than ε, but is still small enough to be in the acceptance of the opposite linac. However, the *same* emittance growth would take place at each bunch crossing in the linacs and, since this is unacceptable, the bunches have to be spatially separated in the 2n unwanted crossings by means of suitable combinations of electric and magnetic fields. (For this reason, n cannot be too large.) By the same token, after the collision the bunches cannot be refocused in another interaction region, so that in all schemes in which $N \gtrsim \varepsilon/\pi r_e$ the experiments have to be served by time-sharing.

At SLAC, positron emittances are at present 10 times larger than electron emittances, so that the reduction of electron emittances and the production of positron bunches of much smaller emittances than are now available are the main problems to be solved in order to build electron-positron colliding linacs of reasonably high luminosities. These problems are common to all schemes, both with and without energy recovery. A problem that, instead, is special to the peloron is the need to have very efficient energy recovery in the braking linac. I will now discuss these two subjects in turn.

Steffen designed a wiggler storage ring that would produce small beam emittances in damping times that are of the order of 1 ms [27]. The lattice of this ring consists of strong sector magnets of high field and alternating polarity (Fig. 3) that produce a strong radiation damping. At 1 GeV with a field of 1.67 T and 300 cells, each 1 m in length, the damping time is 1.8 ms and the renormalized emittance is $\varepsilon \simeq 6.4 \times 10^{-5}$ πm. This emittance is of the order of the present electron emittances at SLAC, but still 7 times larger than the one requested by our previous example. For this reason, in the superconducting scheme with energy recovery of Gerke and Steffen[21] the amplitude function at the interaction point was taken to be $\beta = 0.25$ cm. The general layout is shown in Fig. 4. Each of the two superconducting standing-wave linacs is backed up by a low-energy electron-positron double storage ring. The bunches stored in each of these damping rings are called off symmetrically, one at a time, so that they cross only at the interaction point. The debuncher is needed to reduce the energy spread of the decelerated bunches so that they fit into the energy acceptance of the damping rings. The debunchers are traversed in opposite directions by the bunches coming from the storage rings, in such a way as to reduce the length of the bunches before injection into the linac.

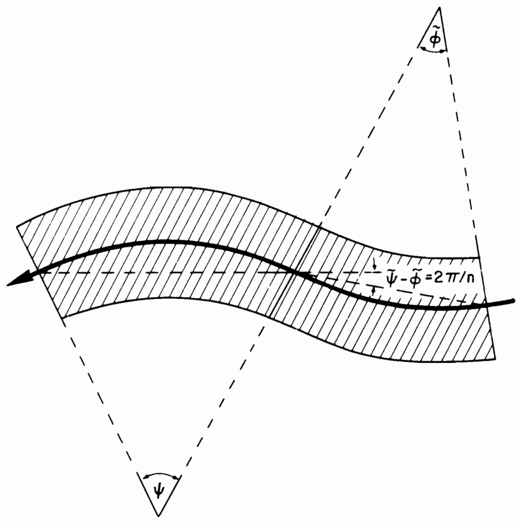


Fig. 3 One cell of the 1 GeV Wiggler storage ring proposed by Steffen to cool electron and positron bunches (Ref. 27). The angles are $\tilde{\phi}$ = 0.25 and $\tilde{\psi}$ = 0.27, and the number of 1 m long cells is 300.

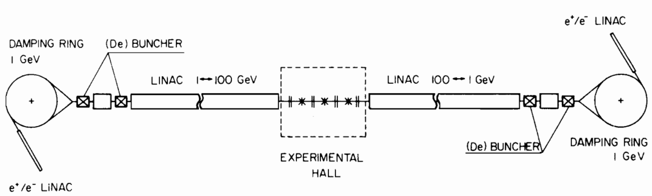


Fig. 4 The superconducting linacs of Gerke and Steffen use two superimposed damping rings at each end to cool the slowed-down electron and the positron bunches before re-use (Ref. 21).

It has to be noted that Gerke and Steffen were the first to propose a recovery scheme with such a low frequency that there are no unwanted crossings. The field gradient was assumed to be 20 MV/m at 3 GHz, so that with a bunch frequency f = 3 × 10^4 Hz and E = 100 GeV there is only one bunch in each linac at any time and no unwanted crossings (n = 0). Since each bunch must spend about 2 ms in the cooling ring, 30 positron and 30 electron bunches are stored in the double rings at the input of the two linacs. The other parameters are N = 6 × × 10^{10} and σ = 0.9 μm, so that the instantaneous luminosity is 10^{33} cm^{-2} s^{-1}. With the assumed Q-value of the cavities (2 × 10^9), owing to the high gradient the radiofrequency losses at helium temperature are so large that the authors propose to run the collider at a duty cycle equal to 1/30, with a corresponding reduction in average luminosity[21].

This last point brings me to the problems of superconducting RF cavities. They have been reviewed by Tigner at the First ICFA Workshop[28] and very recently by Picasso in the framework of the European program for phase two of LEP [29]. At present in Europe a large program is under way to develop the relatively low frequency (350 MHz) superconducting cavities needed to reach (130 + 130) GeV with LEP. This concrete need will certainly speed up progress, but extrapolations are particularly difficult in this field and I shall limit myself to mentioning the main issues relevant to superconducting linacs.

i) Fundamental parameters are the attainable accelerating gradient V and the Q-value of the cavities. The first determines the length of the linac, and the two together determine the power that has to be spent to maintain the field. According to Tigner[28], well-constructed niobium cavities can at present reach accelerating fields and Q-values that, for frequencies larger than 1.5 GHz, are represented by the empirical relations

$$V(MV/m) \approx 2\nu(10^9\ Hz)\ ; \quad Q(10^9) \times \nu(10^9\ Hz) \approx 9\ . \tag{16}$$

Higher fields and higher Q-values, by factors of at least 3, are needed to make superconducting linacs worth considering as electron-positron colliders. No fundamental principle is known today that forbids this development, in particular if Nb_3Sn cavities are used.

ii) When the field surrounding an electron (positron) bunch expands into a cell of the linac, as schematically shown in Fig. 5, part of it is reflected backward and its energy is lost[30]. Most energy goes into higher frequency modes of the electromagnetic field and cannot be dissipated at liquid-helium temperature because it would represent an enormous power load for the cryostatic system. For a fixed cavity length the energy loss per particle scales as $N\nu^2$, if the ratio d/λ of the bunch length to the radiofrequency wavelength λ = c/ν is constant[31], so that[32]

$$U_{hml} = kN\nu^2\ , \quad k \simeq 3 \times 10^{-30}\ e^{-27d/\lambda}\ MeV\ s^2/m\ ; \tag{17}$$

from this point of view low frequencies are favoured.

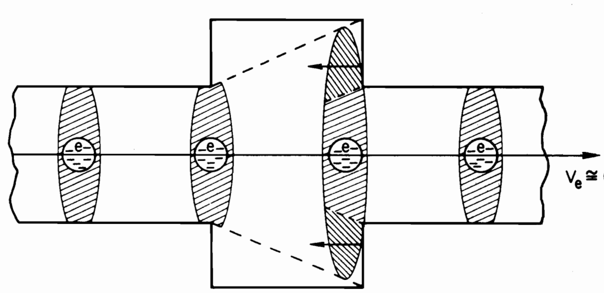


Fig. 5 Schematic representation of the physics behind the phenomenon of the higher-order mode losses.

Higher-order modes of the cavities have to be extracted to room temperature with devices such as the one constructed at Karlsruhe[33] for a cavity to be installed in DESY (Fig. 6). This single-cell cavity should achieve an accelerating field of about 3 MV/m at a frequency of 0.5 GHz. Room temperature tests have shown that the two higher-mode couplers mounted on the cell couple out all modes up to 2 GHz with an efficiency ε > (1 - 10^{-4}).

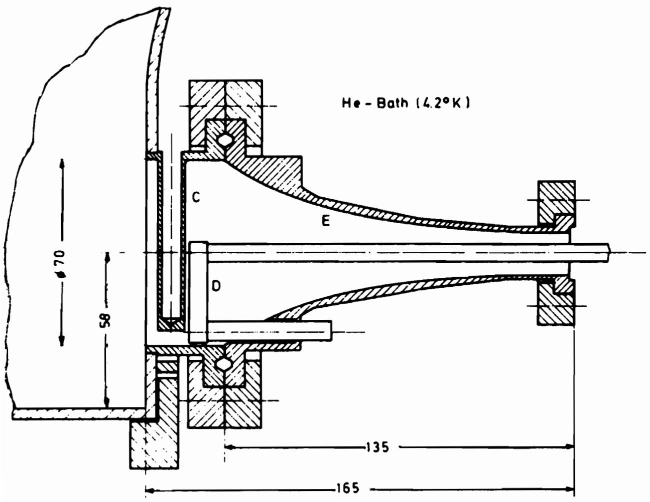


Fig. 6 Higher-mode coupler designed by the Karlsruhe group for the superconducting cavity to be installed in DESY.

iii) Power has to be spent to keep the structure at low temperature. The passive heat load P_{ph1} has to be supplied also when the cavities are not excited, while the power dissipation due to the field is proportional to the square of the gradient V:

$$P(W/m) = P_{ph1}(W/m) + \frac{V^2(V/m)}{\bar{R}(\Omega/m)Q} . \qquad (18)$$

$\bar{R}$ is a characteristic of the structure and is equal to $\sim$ 1000 Ω/m for the Cornell structure at 1.5 GHz [28] and to $\sim$ 3000 Ω/m for the 3 GHz structure considered by Steffen[27]. Since the linac length is $\ell = E/V$, Eqs. (17) and (18) give

$$\text{(Total power of one linac)} = \eta^{-1}\, E\left[\frac{(1-\varepsilon)kN^2f\nu^2 + P_{ph1}}{V} + \frac{V}{\bar{R}Q}\right] , \qquad (19)$$

where η is the cryogenic efficiency of the system ($\sim 2.5 \times 10^{-3}$ at 4°K and $\sim 10^{-3}$ at 1.8°K) and ε is the efficiency for extracting higher-mode losses.

In a peloron the beam energy is recovered by the opposite linac, but during the deceleration the slowed-down beam also excites higher-mode losses. The power dissipated is thus given by Eq. (19) where the constant k is multipled by a factor of 2. As previously done by Hutton and Richter[34], Fig. 7 shows the total power absorbed by a superconducting linac with energy recovery for the optimum parameters of a 2E = 2 × 250 GeV collider: $N = 7.2 \times 10^{10}$, $f = 2.5 \times 10^4$ Hz, and $\nu = 3$ GHz. I have assumed $\bar{R} = 2000$ Ω and $Q = 5 \times 10^9$. Such a Q-value is about four times smaller than the theoretical maximum that can be obtained either in a Nb cavity at 1.8°K or in a Nb_3Sn cavity at 4°K. The passive heat load was taken to be $P_{ph1} \simeq 2$ W/m. At CERN this quantity is at present estimated[35] to be 4 W/m, while Ritson and Tigner assumed a value about 10 times smaller[5]. Figure 7 shows that the power has a minimum for a relatively small value of the gradient and that the efficiency for extracting the higher mode losses has to be larger than 99%. At 99.9% they are already negligible with respect to the assumed passive heat load and there is no point in reducing them even further. In the example I took $\eta = 2.5 \times 10^{-3}$, which requires Nb_3Sn cavities, which will probably be mass produced in a few years from now.

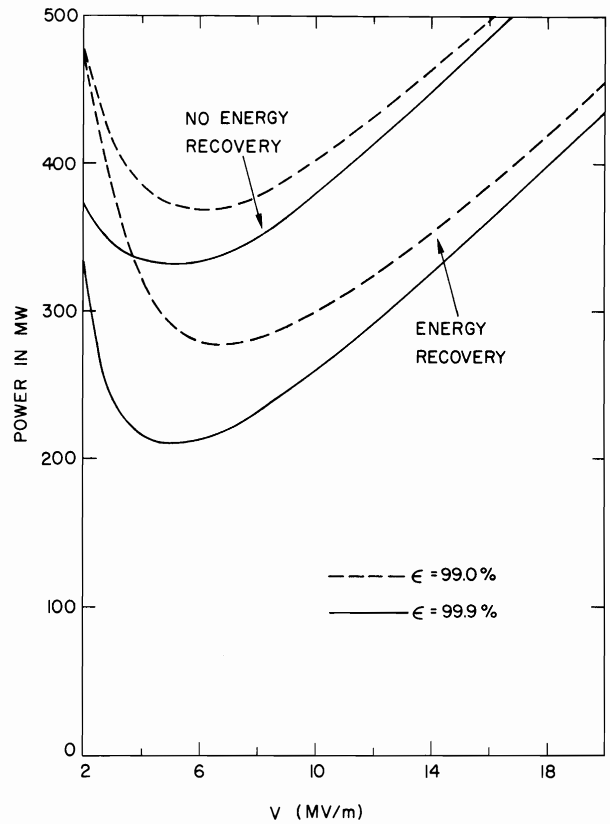


Fig. 7 Power consumption of superconducting colliders for 2 × 250 GeV and 10^{33} cm^{-2} s^{-1}. The passive heat load and the Q-value were assumed to be equal to 2 W/m and 5×10^9 respectively, which implies to work with Nb_3Sn cavities at a temperature of 4°K; ε is the efficiency with which the higher-mode losses are extracted. In the non-recovering schemes it is assumed that 33% of the beam energy ($\sim$ 140/3 MW) is recuperated through heat production.

Before closing this section it is worth describing a recently suggested variant of the energy recovery scheme. In the colliding linacs of Fig. 4 the spent bunches are injected in the damping rings and later used again. This poses a series of problems, because very complicated debunchers are needed to fit the degraded bunches into the acceptance of the rings and, owing to the losses, a system has to be devised to add particles[36]. To avoid these difficulties, Claudio Pellegrini and myself have proposed the scheme shown in Fig. 8, in which the energy is recovered but the particles are *not*[37]. At every cycle new particles are produced by passing the beams through wiggler magnets, in which monochromatic photons of a few MeV are produced. In a 100 m long wiggler with a wavelength of 2.5 cm and a field of 0.37 T about 50 photons are produced. This number is independent of the beam energy, while the photon energy increases with E as shown in Fig. 9. Above about 150 GeV, more than one electron and one positron per incident particle are produced by these photons in a target thickness of less than one tenth of a radiation length within the acceptance of a very conventional collector working at a few MeV [37].

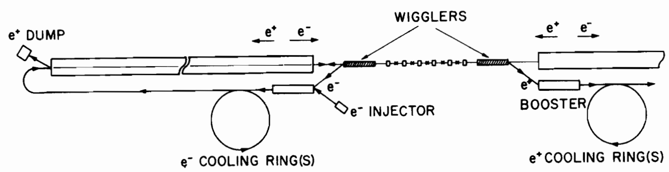


Fig. 8 In this scheme[37] the energy is recovered but the particles are not. The low-energy positrons and electrons are produced by the photons radiated by the beams in wiggler magnets.

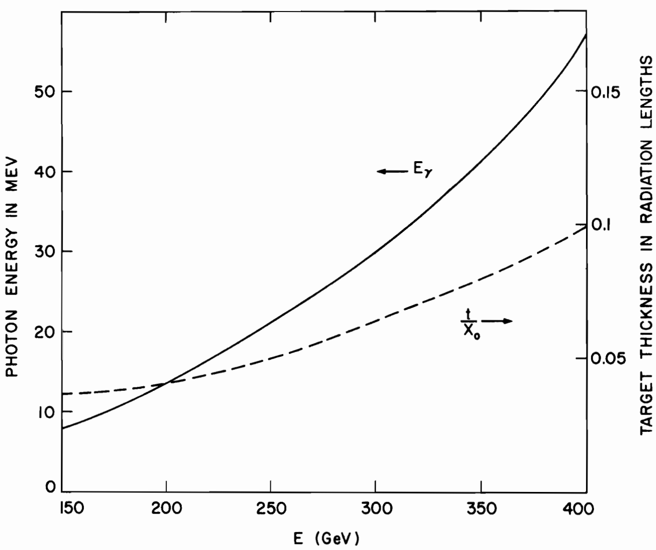


Fig. 9 Energy dependence of the photon energy produced in a wiggler of 2.5 cm wavelength and 0.37 T field. The dashed curve gives the target thickness needed for a 100 m wiggler to produce one low-energy positron per electron.

Each particle loses less than 1% of its energy in traversing the wiggler, so that, by throwing away the particles after a single pass, one does not modify either the economy of the energy recovery scheme or the procedure adopted at the beginning of this section to choose the parameters.

4. Colliding linacs without energy recovery

The beam power of the 2 × 250 GeV peloron is ∿ 150 MW for a luminosity of 10^{33} cm^{-2} s^{-1}. Since this power is smaller than the power going into the linac (Fig. 7), it is worth while asking whether a scheme without energy recovery could not be advantageous. In this case one can use room-temperature linacs, whose technology is well understood. Schemes of this type have recently been considered by Voss[14], by the group at Novosibirsk[15] and at the First ICFA Workshop[19].

Until a few months ago, in all schemes it was assumed that the needed positrons would be produced in a target illuminated by the used electron beam. Figure 10 displays a compilation of data and computations on the

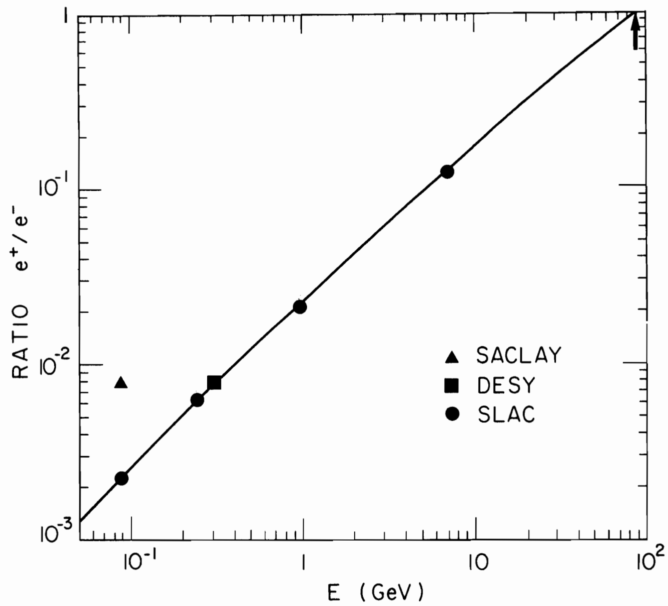


Fig. 10 Yield of positrons as a function of the energy of the electrons impinging on a target of 1-2 radiation lengths (the optimum thickness varies logarithmically with energy). The points from Saclay[38] and DESY[39] are measured with collectors of different acceptances. The points of SLAC have been computed with a very sophisticated program and the line extrapolates them to higher energies.

yields of positrons produced by electrons of energy E impinging on a target of about 1.5 radiation lengths[38-40]. The acceptances of the positron focusing systems are not exactly comparable, but the extrapolation of the existing information allows a safe conclusion: for electron energies E ≳ 90 GeV the (low-energy) positron current is larger than the impinging electron current, and the positron beam can be produced by the used electron beam downstream of the interaction point. However, the realization of a target that can absorb a power of some 10 MW is not a trivial problem. Recently, to overcome this difficulty, use of wiggler magnets has been proposed by Balakin and Mikhailichenko[41] and by Pellegrini and myself[37]. (Some properties of such wigglers were shown in Fig. 9.) The former authors have also computed the polarization that can be obtained by means of an helical wiggler, arriving at the very interesting conclusions that the electrons and the positrons could be longitudinally polarized to ∿ 80%. The production of possibly polarized intense positron bunches is no longer a problem after these recent developments.

If the energy is not recovered in the opposite linac the emittance can grow in the interaction point and thus the number of particles per bunch can be larger. In a peloron the emittance due to the collision [Eq. (15)] has to be such that the beam remains within the acceptance of the linac also when its energy is reduced to ∿ 1 GeV, i.e. when $\gamma_{min} \simeq 2 \times 10^3$. The linac acceptance is $\pi r^2 \gamma_{min}/\bar{\beta}$, where r is the radius of the iris and $\bar{\beta}$ is the amplitude function along the linac, and from Eq. (15) it follows that for recovering the energy

$$N \le \frac{\pi}{F^2}\frac{r^2}{r_e\bar{\beta}}\gamma_{min} . \qquad (20)$$

The minimum number F of r.m.s. beam radii that are needed to keep the beam far from the superconducting structure is not known at present, but $F \simeq 10$ appears as a safe estimate. With $r = 2$ cm and $\bar{\beta} = 50$ m, Eq. (20) gives $N \lesssim 2 \times 10^{11}$, so that it will certainly be difficult to recover energy from bunches 10 times larger than this approximate limit. Schemes that do not recover the energy are free from this limitation and one can choose lower bunch frequencies and a higher number of particles per bunch.

Table 2 summarizes the parameters of the schemes considered. Note that the luminosities are of the order of 10^{32} cm^{-2} s^{-1}, in spite of the necessity of sharing the time between various interaction regions.

The most detailed proposal has been worked out by the group at Novosibirsk for the 2 × 100 GeV collider shown in Fig. 11. The shape of the accelerating cavity was optimized[41] at a frequency of 5.6 GHz to obtain gradients as large as 100 MV/m with a resistance $\bar{R}$ = = 4000 Ω/m and $Q = 8 \times 10^3$. A first prototype cell has been built and has accelerated electrons with the expected gradient. Balakin et al. have also discussed some of the most important problems to be solved if conventional linacs have to work in these extreme conditions[42]. In particular they have considered the monochromaticity of the bunch, the transverse forces that cause instabilities of the "head-tail" type, and various means of reducing the beamstrahlung parameter, which is very large (Table 2).

As shown in Table 2, the disruption parameter of this collider is also large, in agreement with the calculations performed at Novosibirsk. If D cannot be greater than a few units[26] the beam power has to increase to keep the same luminosity [Eq. (11)]. However, the qualifying choice in this scheme is not the value of D but the idea of avoiding beamstrahlung effects altogether either by using flat beams or by superimposing, just before the crossing, an electron and a positron bunch, accelerated at a distance of $\lambda/2 \simeq 2.5$ cm by the same linac. These possibilities have both been suggested by the Novosibirsk group and are essential for reducing beamstrahlung to such a level that the lower limit imposed on the bunch frequency by Eq. (12) can be relaxed. According to Table 1, to reduce the beamstrahlung parameter from 0.72 to 0.05 one needs a ratio $\sigma_{max}/\sigma_{min} \simeq 50$, very large indeed. Charge compensation thus seems an essential ingredient. Since it has to work only for a single crossing, it should not be subject to the instability problems observed at the DCI storage ring. On the other hand, difficulties could come from the wake fields which, produced by the first bunch, act on the bunch that follows it at a distance of only 2.5 cm.

If the energy radiated by beamstrahlung can be diminished the bunch frequency can be correspondingly decreased and the number of particles per bunch increased. However, this implies a very high peak power, because the energy stored in the accelerating structure must be at least three times larger than the bunch energy 2 NE, and this energy has to be supplied in a time which is of the order of the cavity characteristic time $Q/2\pi\nu$. The peak power is thus $\sim 10\pi\, NE\nu/Q \simeq 5 \times 10^{11}$ W, i.e. about half a terawatt. To meet this requirement, special klystrons and gyrocons are under development at Novosibirsk.

The order of magnitude of the average power needed for a collider based on conventional linacs is easily obtained by using the fact that the over-all efficiency of high-energy linacs in transferring energy from the mains to the beam is of the order of 3%. By supposing that it is possible to multiply this efficiency by a factor of 2, Eq. (11) gives

$$P_{mains} \simeq 50\, \frac{L(10^{32}\text{ cm}^{-2}\text{ s}^{-1})\, d(\text{mm})}{D}\ \text{MW} . \qquad (21)$$

This implies that, to give to eight interaction regions an average luminosity of 10^{32} cm^{-2} s^{-1}, with the conservative choice $D = 1$, the power needed is ~ 800 MW ($d = 2$ mm is a minimum value from the beamstrahlung point of view). Indication exists that larger disruption parameters can be accepted. With $D = 5$ the power would reduce to ~ 160 MW.

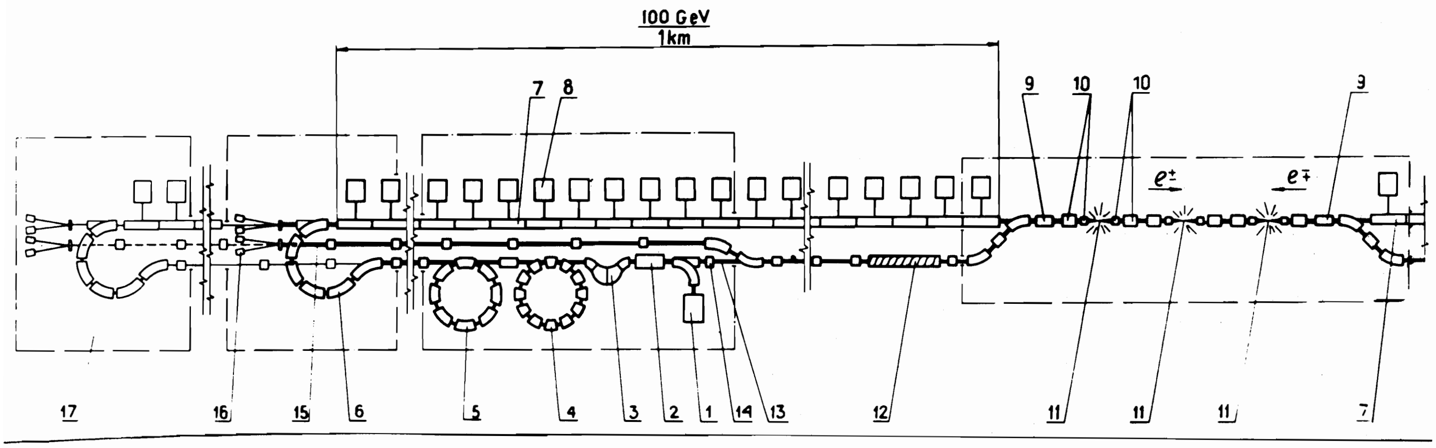
Colliders without energy recovery could also be based on superconducting linacs. In this case there would be neither the upper limit on the frequency, imposed by condition (14) requiring not too many unwanted crossings along the linacs, nor the upper limit (20) on the number of particles per bunch, due to the acceptance of the braking linac. Still, the parameters would not be very different from the ones derived above for a recovering scheme, because in a superconducting continuous-wave linac there is not much reason to reduce the bunch frequency, while increasing N has the negative effect of increasing the higher-mode losses quadratically [Eq. (19)]. Thus the comparison between schemes with and without energy recovery and having the parameters found in the last Section and listed in

Table 2

Parameters of the schemes without energy recovery

Author	Ref.	E (GeV)	N (particles/bunch)	f (Hz)	σ (μm)	L (10^{32} cm^{-2} s^{-1})	d (mm)	P (MW)	D (Eq. 11)	δ (Eq. 12)
Voss	17	100	1.5×10^{11}	400	1.2	0.5	3	1.9	2.2	0.015
Balakin Budker Skrinsky	18	100	10^{12}	10	0.9	1.0	5	0.32	45	0.72 *)
		300	10^{12}	10	0.9	1.0	5	0.96	15	2.5 *)
First ICFA Workshop	19	350	10^{11}	2500	1.4	1.0	5	28	0.5	0.01

*) These values are reduced by using flat beams (Table 1) and/or charge compensation.



1. Injector
2. Booster
3. Debuncher
4. Storage ring
5. Cooling ring
6. Buncher
7. Accelerating sections
8. RF sources
9. Pulsed deflector
10. Focusing lenses
11. Collision point
12. Helical wiggler
13. Photon beam
14. Conversion target
15. Used electron beam
16. Fixed target experiments
17. Second stage

Fig. 11 The Novosibirsk project

Table 3, reduces to the comparison of their power consumption. This is made in Fig. 7.

Table 3

Parameters of a superconducting collider (with or without energy recovery)

Quantity	Symbol	Value
Total energy	2E	2 × 250 GeV
Luminosity	L	10^{33} cm^{-2} s^{-1}
Number of part./bunch	N	7.2×10^{10}
Bunch/s	f	2.5×10^{4} Hz
Bunch length	d	5 mm
Disruption parameter	D	1.0
Beamstrahlung parameter	δ	0.75%
Total beam power	P	144 MW
Normalized emittance × β	εβ	10^{-5}βπm
Bunch transverse radius (β = 5 cm)	σ	1.0 μm
Fraction of energy extracted by a bunch		4%

As already done by Hutton and Richter[34] with somewhat different parameters, the power was computed by adding to Eq. (19) the beam power divided by 0.70 (to take into account the klystron efficiency) and assuming that 33% of it can be recuperated through heat production. Figure 7 shows that energy recovery is worth while. From the point of view of power consumption the optimum voltage per metre is on the low side (4.5 MV/m in our case) and in general is given by the simple equation

$$V_{opt} = \left[\left((1-\varepsilon)kN^2 f\nu^2 + P_{ph1}\right)\bar{R}\,Q\right]^{\frac{1}{2}} . \qquad (22)$$

For ε = 1 it varies as $\nu^{\frac{1}{4}}$, because $\bar{R} \propto \nu$ and $Q \propto \nu^{-\frac{1}{2}}$, while if the heat losses would be negligible with respect to the higher-mode losses it would be proportional to $\nu^{5/4}$.

5. Scaling laws

In this Section I discuss the following points: i) the variation of various quantities as a function of the disruption parameter D at a given energy; ii) the scaling laws of the parameters defining a linear collider as a function of energy; iii) the energy dependence of some rough estimate of the cost and a comparison with the cost of storage rings. These scaling laws are determined by the basic equations (4), (5), (6), and (7). For the case of energy recovery, we must add Eq. (14) and the limit (20). For the present purposes they can be rewritten in the simplified form

$$L \sim fN^2/\sigma^2 \; ; \quad \varepsilon \sim \sigma^2 E/\beta \; ; \quad D \sim N/E\sigma^2$$
$$\delta \sim EN^2/\sigma^2 \; ; \quad n + \tfrac{1}{2} \sim fE \; ; \quad P \sim ENf \, , \qquad (23)$$

since the RF frequency ν and thus the bunch length d are supposed to remain constant.

In most of this presentation, D = 1 was used as a reference value, but it is very probable that the disruption parameter can be made larger than 1 [24,26]. This increases the luminosity, and Table 4 shows three possible ways of scaling the parameters while keeping the energy fixed.

With the scaling laws of column A the luminosity increases as D and the power remains constant. However, the bunch frequency decreases and the beamstrahlung parameter increases as D^2, so that for $D \gtrsim 2$ it would become too big if the starting point is, for instance, the parameter list of Table 3. Columns B and C display other possible ways of scaling, $P \sim 1$, and give either $\delta \sim D$ or $\delta \sim 1$. The price to be paid is a decrease of the beam radius σ and/or an increase of the bunch frequency f. In column B the decrease of the radius is

Table 4

Scaling laws as a function of D for E fixed

Parameter	A	B	C
L	D	D	D
δ	D^2	D	1
f	D^{-1}	1	D
N	D	1	D^{-1}
P	1	1	1
σ^2	1	D^{-1}	D^{-2}
ε	1	1	D^{-1}
β	1	D^{-1}	D^{-1}
$n + \frac{1}{2}$	D^{-1}	1	D

obtained by decreasing the β-value at the crossing point. This implies that $\beta = 1$ cm if $D = 5$ is used in Table 3.

Let us now consider the scaling laws as a function of the beam energy E. These laws are very important because colliding linacs are considered to be advantageous with respect to storage rings because they can be lengthened in stages, with a consequent increase of energy and no waste of previous investments. As we shall see, however, the conditions (23) are quite restrictive, and the "natural" scaling laws pose some problems. They vanish if, by applying for instance the idea of charge compensation, the condition on the beamstrahlung parameter δ becomes inessential. The general expressions and some of the possible scaling laws are collected in Table 5. The hypothesis is made that the frequency ν and the bunch length d are kept constant.

Table 5

Scaling laws as a function of the beam energy E

Quantity	General laws	A	B	C	D	E
D	E^u	1	$E^{-1/2}$	E^{-1}	1	E^{-1}
δ	E^v	1	E	E	1	E
P	E^w	1	$E^{1/2}$	E	E	E^2
L	E^{u+w}	1	1	1	E	E
f	$E^{u-v+w+1}$	E	1	1	E^2	E
ν	E^{v-u-2}	E^{-2}	$E^{-1/2}$	1	E^{-2}	1
σ^2	E^{v-2u-3}	E^{-3}	E^{-1}	1	E^{-3}	1
$\varepsilon\beta$	E^{v-2u-2}	E^{-2}	1	E	E^{-2}	E
$n + \frac{1}{2}$	$E^{u-v+w+2}$	E^2	E	E	E	E^2

Column A shows that the most natural choice ($D \sim 1$, $\delta \sim 1$ and $L \sim 1$) leads to very unattractive consequences: the beam dimension has to decrease as $E^{-3/2}$ and, for a constant normalized emittance, the β-value at the interaction point is proportional to E^{-2}. (This scaling law was the only one considered at the First ICFA Workshop[19].) Columns B and C have still energy-independent luminosities but different laws for the beam power, and beamstrahlung parameters which are proportional to E. This scaling law for δ is acceptable, because one can argue that the widths of the states possibly coupled to the e^+e^- channel increase rapidly with E and that, if a narrow peak is found, the cross-section is large and then the luminosity can be decreased proportionally to the energy spread δ by reducing the number of particles per bunch. In the scaling laws of Column B the power increases slowly (proportionally to $E^{1/2}$) but the β-value is energy independent, and this is not what is required by the optics of the low-β insertions[3]. Indeed to maintain the beam inside the acceptance of the focusing quadrupoles, the length of the interaction region and the β-value have to increase as E. This is obtained by using the scaling laws of Column C, but then the beam power increases as E, while D does not remain at its maximum value, but decreases as E^{-1}. A positive feature of columns B and C is that: (i) $f \sim 1$, so that the number of damping rings is energy independent, and (ii) the number n of unwanted crossings is roughly proportional to E, so that in a scheme with energy recovery the position in space of these crossings remains unchanged while increasing the energy by lengthening the linacs. Columns D and E have a luminosity that increases proportionally to E to partially compensate the decreasing cross-section. As before it is impossible to have at the same time $D \sim 1$ and $\delta \sim 1$, because $\beta \sim E^{-2}$ (column D), while $\beta \sim E$ and $\delta \sim E$ imply the strong energy dependences $P \sim E^2$ and $n \sim E^2$ (column E). In summary, the scaling laws reported in column C appear as the best compromise among the many different requirements.

The last item to be considered in this Section refers to the cost of colliding linacs. While it is obvious that the investment increases roughly proportionally to the energy, it is today very difficult to make safe estimates of the cost per GeV of conventional and, even more so, superconducting linacs. However I believe that at least approximate answers have to be given to the question always posed to those who discuss colliding linacs: at which energy do these schemes become less costly than storage rings? My answers are summarized in Fig. 12, but have to be taken only as rough indications, and the discussion of the many assumptions will justify this cautious remark.

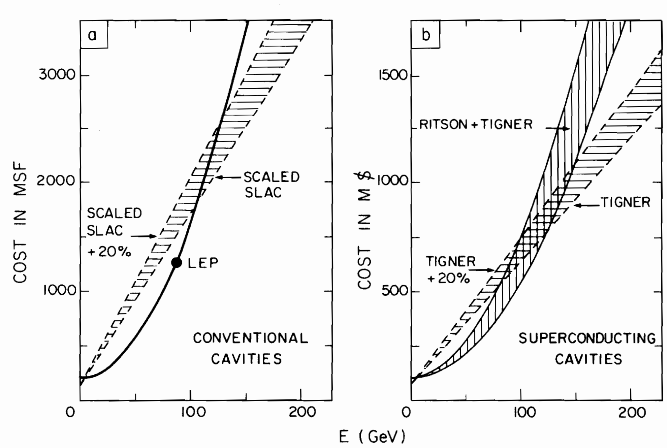


Fig. 12 The costs of conventional and superconducting colliding linacs are compared with the cost of optimized storage rings. The many assumptions that go into this comparison are listed in the text.

For storage rings that use conventional cavities we have a solid number: stage 1 of LEP, which costs 1275 MSF (at 1979 prices) for an energy E = 86 GeV. The continuous line of Fig. 12a is a parabola [see Eq. (1)] that passes through this point and for E = 0 gives 200 MSF, of which ∿ 120 MSF are for the injector and ∿ 80 MSF for eight interaction regions. The dashed line is based on an estimate made by Crowley-Milling[43], who scaled the cost of the SLAC linac (62 M$ in 1964) by multiplying this number by a factor 2.1, to take into account the increase of the American consumer price index from 1964 to 1979, and by a factor 2.7, which is considered to be the "real" conversion factor from dollars to Swiss francs[44]. To these 350 MSF Crowley-Milling added 50 MSF for the improvement program, to be discussed in the next Section, that will allow the 3 km SLAC linac to accelerate electrons to 50 GeV with a gradient of ∿ 17 MV/m. Thus the unit cost of a conventional linac, that has a gradient of ∿ 20 MV/m at 3 GHz, turns out to be ∿ 8 MSF/GeV. Note that this cost depends very much upon the procedure adopted to pass from $ (1964) to SF (1979).

To obtain a 2E = 2 × 100 GeV collider with a luminosity of 4×10^{32} cm^{-2} s^{-1}, half of the total LEP luminosity, the parameters would be $N = 10^{11}$, $f = 5 \times 10^3$ Hz and $\sigma = 1$ μm [43]. By choosing d = 7 mm, the disruption parameter is D = 5 and the beamstrahlung parameter $\delta = 0.4\%$, with a total power consumption of about 200 MW [Eq. (21)]. Clearly LEP is superior to this hypothetical collider. In spite of this, the two are compared in Fig. 12: the lower dashed line represents a linear relationship between cost and energy with a slope of 15 MSF/GeV. The straight line passes through 150 MSF for E = 0 because the interaction regions, being in the same building, will cost less than in a storage ring, and the 1 GeV damping rings will cost less than the 20 GeV LEP injector. The upper dashed line of the figure has a 20% larger slope, a variation certainly smaller than the uncertainty inherent in the above estimate.

Figure 12b compares the costs of the superconducting version of the two machines. This is much more difficult, since the technology is far from being at the stage of mass production. To be at least consistent, I have used for the storage ringe with superconducting cavities the cost estimate of Ritson and Tigner[5], condensed in Eqs. (1) and (3), and for the colliding linac the cost formula given by Tigner at the first ICFA Workshop[28] and represented in Fig. 13. In this figure q and h are the Q-value measured in units of 10^9 and the RF frequency ν measured in units of 10^9 Hz. With present technology one can reach the maximum gradients given in Eq. (16), and represented in the figure by the vertical bars, while for the product Qν, values of the order of 9×10^{18} Hz have been obtained. The higher set of curves correspond to this choice of parameters, and the lower set to what will presumably be obtained in a few years. For the collider of Table 3 I assumed $\nu = 3 \times 10^9$, $Q = 5 \times 10^9$, values intermediate between those of the two sets of curves. According to Tigner's formula[28], the cost of such a linac is 2.6 M$/GeV at a gradient of 10 MV/m, including vacuum, instrumentation, quadrupoles, cryostat and refrigerator. In drawing the lower straight line of Fig. 12b I have added the cost of the LEP tunnel (0.2 M$/GeV). The parabolae are instead obtained by using the lower and upper limits computed by Ritson and Tigner for a storage ring with 1.5 GHz superconducting cavities[5] [Eqs. (1) and (3)].

Figure 12 shows that colliding linacs become economically convenient above ∿ 2 × 150 GeV. If the many problems outlined in the previous sections will be solved, and if physics will require it, they will probably be used as a basis for after-LEP electron-positron research. At the present stage it is impossible to

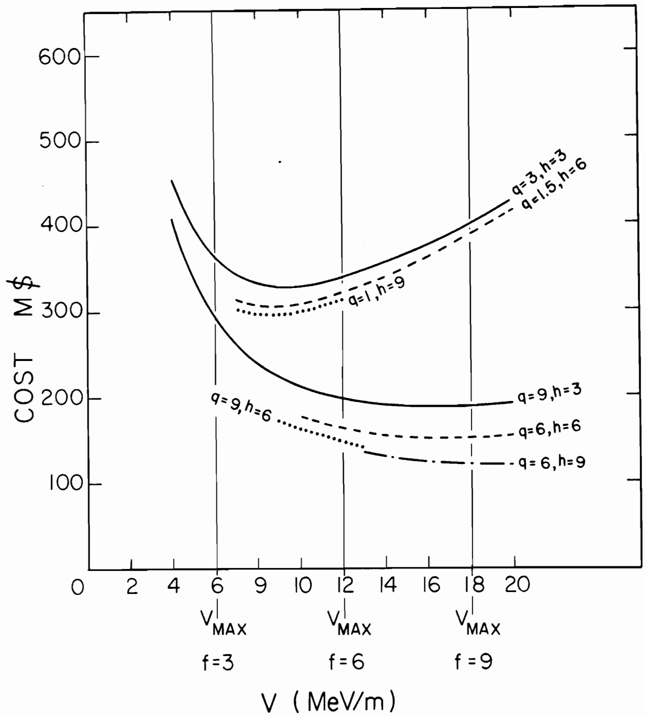


Fig. 13 Cost of superconducting linacs versus the voltage per unit length as estimated by Tigner[28]. In this figure q is the Q-value measured in units of 10^9 and h the RF frequency ν measured in 10^9 Hz. Present technology has qh ≃ 9. The cost is given for a 100 GeV linac.

compare the economics of superconducting and conventional schemes, and this also reflects in the necessity of using different currencies in the two graphs of Fig. 12. What can be said is that present cost estimates do not favour one of the approaches with respect to the other. For schemes without charge compensation and relatively small disruption parameters, superconducting linacs could consume less power than conventional linacs [compare Fig. 7 with Eq. (21)] but the argument is inverted if the disruption parameter can be made larger than ∿ 5.

6. The SLAC Single-Linac Collider

Lively discussions on future linear colliders took place at the First ICFA Workshop in October 1978 [19]. As sometimes happens, an idea for immediate application originated from these apparently academic considerations of a very distant future. At SLAC, within a few weeks, Richter had proposed the Single Pass Collider Project (SPCP) represented in Fig. 14 and feasibility studies

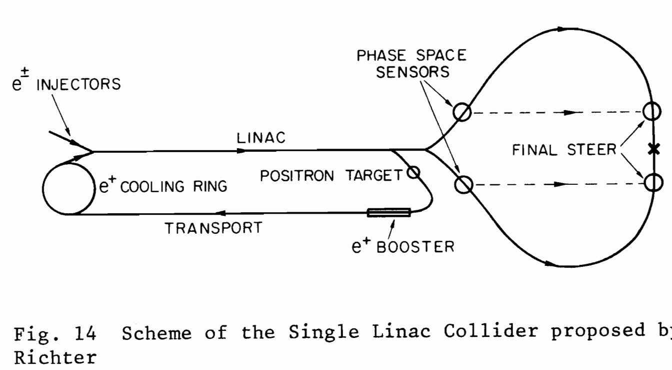


Fig. 14 Scheme of the Single Linac Collider proposed by Richter

were started[22]. At present a budget request has been put to DOE to obtain 800 k$ in the fiscal year 1980 for preliminary engineering and design.

The principle of operation of the SPCP (named also SLIC, Single LInac Collider) can be described as follows. A positron and an electron bunch are accelerated at a distance of about 20 m in the linac and collide after having travelled around half of the ring. The centring of the two bunches is controlled by the measurement of the phase-space sensors. The positrons are produced by a multibunch electron beam ("scavenging beam") which is injected behind the positron and electron bunches and hits the positron target. These positrons are boosted to $\sim$ 1 GeV and their emittance is reduced to $\varepsilon \simeq 3 \times 10^{-5}$ πm in the cooling ring that has a large tune ($Q \simeq 100$). The main parameters of SLIC are collected in Table 6.

Table 6

Main parameters of SLIC

Parameter	Symbol	Value
Beam-energy	E	50 GeV
Luminosity	L	10^{30} cm^{-2} s^{-1}
Particles/bunch	N	5×10^{10}
Bunch frequency	f	180 Hz
Bunch length	d	1-3 mm
Normalized emittance	ε	3×10^{-5} πm
β-value	β	1 cm
Bunch radius	σ	1.8 μm
Disruption parameter	D	$\sim$ 0.5
Beamstrahlung parameter	δ	$\sim 6 \times 10^{-4}$

The energy will be reached when the full SLAC development program SLED II will be completed. The SLED principle is described in Fig. 15: by means of two cavities and a 3 dB coupler inserted on the line which joins a klystron to the accelerator cavity, the pulse is shortened and the accelerating field multiplied by a factor of about 2 [45]. A first phase of the improvement program has already increased the SLAC energy to $\sim$ 35 GeV, and $\sim$ 50 GeV will be reached with the second phase (SLED II). In SLIC, 50 GeV are aimed at to obtain centre-of-mass energies larger than the presumed threshold of Z^0 production.

During 1979 preliminary measurements of the emittance of bunches containing 10^9 electrons were made at SLAC, with the result that, during acceleration, the invariant emittance ε does not deteriorate by more than a factor of 2 with respect to the value measured at low energies (3×10^{-5} πm). Effects of the first bunch on the bunch that follows it have been observed and the conclusion was reached that, to control them, a minimum distance of about 20 m is needed. Calculations have shown that for 5×10^{10} electrons in a bunch an energy spread of ±0.1% is achievable by properly phasing the bunch in the accelerator. The stability of the terrain on a very short time scale ($\simeq 1/f$) was measured and seismic disturbances with a r.m.s. value of 0.5 μm were observed. A preliminary scheme for correction of the chromatic aberrations for a $\Delta p/p \simeq \pm 0.5\%$ was worked out[46]: it turns out that the needed magnetic system is very long, at least ten times the space left free for the interaction region, i.e. about 100 m. The last quadrupoles will have to be stable to within 1 μm [47].

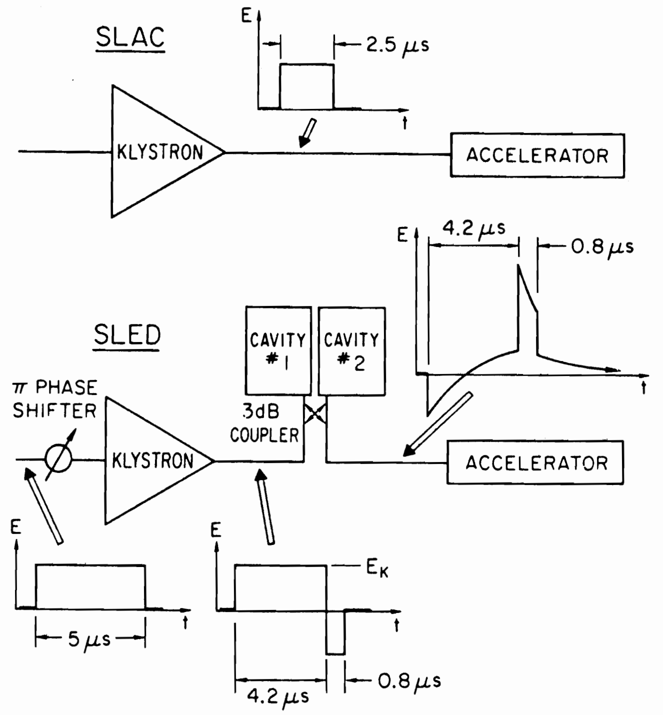


Fig. 15 In the SLED scheme the RF pulse is shortened and the peak field increased by adding a 180° phase shifter and two cavities with a 3 dB coupler.

These and many other problems are now under active investigation with the aim of having a design ready by July 1980. The enthusiasm of the group of people working on the project is the best guarantee that many problems that are common to all linac colliders will be better understood, and hopefully solved, in times which are much shorter than what one could foresee one year ago.

7. Conclusion

For the time being no fundamental limitation has been found to the use of colliding linacs for producing electron-positron collisions at energies much larger than the ones attainable with LEP, if physics will require it. This is very fortunate because, as discussed by Keil[3], storage rings are limited to energies smaller than $\sim 2 \times 200$ GeV. However, the lack of fundamental limitations is not sufficient to guarantee that some paperwork will eventually generate reliable hardware. Here also the situation is favorable, because three independent lines of development will produce essential information in the near future: the CERN programme on superconducting cavities for the second stage of LEP, the Single Pass Collider Project at SLAC and the developments of the Novosibirsk project. There are thus many reasons to believe that, in the next years, we shall still hear a lot about colliding linacs.

I am greatly indebted to the "colliding linac community" for many enlightening discussions and constructive criticism. In particular I would like to thank V. Balakin, M. Crowley-Milling, A. Hutton, E. Keil, B. Richter, A. Skrinsky, K. Steffen and M. Tigner. I am also grateful to P. Bernard, H. Lengeler, E. Picasso and W. Schnell for many discussions on superconducting and conventional cavities.

References and footnotes

1. B. Richter, Nucl. Instrum. Methods 136 (1976) 47.

2. *Design study of a 22 to 130 GeV e^+e^- colliding beam machine (LEP)*, The LEP Study Groups (August 1979), CERN/ISR-LEP/79-33.

3. E. Keil, this Conference.

4. W. Bauer, Proc. LEP Summer Study, Les Houches and CERN, 1978 [CERN 79-01 (1979)], Vol. 2, p. 351.

5. D. Ritson and M. Tigner, *Large electron-positron storage rings using superconducting RF acceleration; a feasibility study*, CLNS-406, Cornell Univ. (1978).

6. Note that in the optimization of Ref. 5 the luminosity is taken to be proportional to the energy, so that the effect on the rates of the decreasing cross-section is partially compensated by the increasing luminosity.

7. U. Amaldi, Phys. Lett. 61B (1976) 313.

8. U. Amaldi and H. Lengeler, *Collinear accelerators for high-energy e^+e^- collisions*, CERN-SD-7 (May 1976) and VBA/CMS/7.

9. As a consequence of this study, the IUPAP Division of Particles and Fields has set up the International Committee for Future Accelerators (ICFA).

10. M. Tigner, Nuovo Cimento 37 (1965) 1228.

11. R.H. Miller et al., IEEE Trans. Nucl. Sci. NS-18 (1971) 604.

12. This scheme was proposed by S.S. Brodsky.

13. Y. Goldschmidt-Clermont summarized the contents of the talk in an unpublished note: A.N. Skrinsky, *Intersecting Storage Rings at Novosibirsk* (September 1971).

14. W.P. Saranzev, *Basic ideas concerning the constrution of a collective accelerator for high energy at JINR* (in Russian), SM11-1003, Dubna (1973).

15. H. Lengeler, *Who is afraid of a superconducting peloron?*, CERN/ISR-LTD/76-30 (July 1976).

16. U. Amaldi, *An unconventional scheme to obtain electron-positron collisions at $E_{cm} \gtrsim 300$ GeV*, Moriond meeting (1976) unpublished.

17. G.A. Voss, *Collision of very high energy e^+e^- beams with the use of linear accelerators* (July 1977) unpublished.

18. V.E. Balakin, G.I. Budker and A.N. Skrinsky, *Feasibility of creating a super high energy colliding electron-positron beam facility*, Novosibirsk Preprint 78-101, presented at the Int. Seminar on Problems of High-Energy and Controlled Nuclear Fusion, Novosibirsk, 1978.

19. J.E. Augustin et al., *Limitations on performance of e^+e^- storage rings and linear colliding-beam systems at high energy*, Proc. ICFA Workshop on Possibilities and Limitations of Accelerators and Detectors, Fermilab, 1978 (Fermilab, Batavia, 1979), pp. 87-105.

20. B. Richter, IEEE Trans. Nucl. Sci. NS-26 (1979) 4261.

21. H. Gerke and K. Steffen, *Note on a 45-100 GeV "electron swing" colliding-beam accelerator*, DESY-PET 79/04 (1979).

22. B. Richter, *Conceptual design of a linear colliding beam system to reach 100 GeV in the center of mass*, AATF/7913 (August 1979) and private information.

23. The working group on electron-positron colliders of the Second ICFA Workshop (4-10 October 1979) was chaired by E. Keil and A.N. Skrinsky, and was formed by: U. Amaldi, V. Balakin, A. Hutton, E. Keil, C. Pellegrini, B. Richter, G. Saxon, K. Steffen, R. Stiening and M. Tigner.

24. A.N. Skrinsky and V.E. Balakin, private communication.

25. The persons involved at SLAC in the calculation of the beam-beam effect are B. Richter, D. Ritson, R. Stiening and H. Wiedemann.

26. C. Pellegrini and M. Tigner, to be published in the proceedings of the Second ICFA Workshop. The paper on which their conclusion is based is by M.S. Uhm and C.S. Liu, *Filamentation instability of electron and positron colliding beams in storage rings*, Phys. Rev. Lett. 43 (1979) 914.

27. K. Steffen *The wiggler storage ring, a device with strong radiation damping and small beam emittance*, DESY PET 79/05 (1979).

28. M. Tigner, *RF superconductivity for accelerators -- is it a hollow promise?*, Proc. ICFA Workshop on Possibilities and Limitations of Accelerators and Detectors, Fermilab, 1978 (Fermilab, Batavia, 1979), pp. 81-86.

29. E. Picasso, *Developments in superconductivity*, CERN/SPC/444, ANNEX III (August 1979).

30. R.F. Koonz, *Single-bunch beam loading on the SLAC two-mile accelerator*, SLAC-195, (May 1976).

31. See, for instance, A. Chao, PEP-118 (1976).

32. The numerical constant k is obtained from the measurement made at SLAC, which gave an HML of 50 MeV for $N = 10^9$ particles with a bunch length of d = 1.5 mm and an accelerator length of 3 km (for SLAC λ = 105 mm). The exponential dependence of k on d/λ is valid for a geometry which scales with λ and reproduces within $\sim$ 20% both the SLAC results quoted above and the measurement at PETRA ($\lambda \simeq$ 600 mm) as reported, for instance, by M. Henke, *Comparison between calculated and measured higher mode losses of the PETRA cavity*, LEP note 171 (June 1979).

33. W. Bauer et al., IEEE Trans. Nucl. Sci. NS-26 (1979) 3252.

34. A. Hutton and B. Richter, contribution to the Second ICFA Workshop (4-10 October 1979).

35. P. Bernard and H. Lengeler, private communication.

36. K. Steffen, contribution to the Second ICFA Workshop (4-10 October 1979).

37. U. Amaldi and C. Pellegrini, contribution to the Second ICFA Workshop (4-10 October 1979).

38. B. Aune et al., IEEE Trans. Nucl. Sci NS-26 (1979) 3773.

39. G. Stange, IEEE Trans. Nucl. Sci. NS-26 (1979) 4146.

40. M.B. James et al., *A calculation of positron source yields,* Proc. 10th Int. Conf. on High-Energy Accelerators, Protvino (IHEP, Serpukhov, 1977).

41. V.E. Balakin et al., *Accelerating structure of colliding linear electron-positron beams (VLEPP),* Novosibirsk preprint 79-83 (1979).

42. V.E. Balakin et al., *Beam dynamics of colliding linear electron-positron beams (VLEPP),* Novosibirsk preprint 79-79 (1979).

43. M. Crowley-Milling, *Clashing conventional linacs* (October 1979) unpublished.

44. C. Roche, *Resources given to high energy physics in 1978 in the CERN Member States,* DI/CPO/239 (July 1978).

45. Z.D. Farkas et al., Proc. of the 11th Int. Conf. on High Energy Accelerators, Stanford, 1974 (SLAC Stanford, 1974), p. 576.

46. D. Ritson, private communication.

47. B. Richter, seminar given at the Second ICFA Workshop (4-10 October 1979).

Discussion

Q. (Perez, Orsay) It is well-known that in colliding rings the beams are more or less obliged to meet because of PCT. In linacs they are not obliged to meet, and you have a very small beam dimension. Can you comment on that?

A. This is a problem of which everyone is aware. Of course one can think of an automatic system to position the beam. There is some discussion in one of the papers of the Novosibirsk group on how to align the beam at such an accuracy and there are ideas at SLAC. But there is no final answer on how to do it.

Q. (Gittelman, Cornell) In the SLAC scheme that you talked about last, do they require some sort of a cooling system to get this luminosity?

A. Yes. They need a cooling ring and they claim they know the scaling law of it. I also think there is no problem from the point of view of cooling the positrons to the right emittance before injecting into SLAC.

Q. (W. Paul, Univ. of Bonn) It is interesting to see from your slide that zero energy already costs 200 MSF!