REPORT OF GROUP I

e^+e^- COLLIDERS

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1. INTRODUCTION

The e^+e^- collider working group at the 2nd ICFA Workshop based its work on the results of the corresponding working group at the 1st ICFA Workshop[1]) which may be summarized as follows.

The synchrotron radiation emitted by the particles of one beam in the collective electromagnetic field of the other beam, which has so far been negligible in e^+e^- storage rings including LEP[2]), plays an important rôle in e^+e^- colliders at higher energies. This phenomenon was dubbed beam-strahlung. Its consequences were taken into account in the selection of parameters for colliding linacs and, to a lesser extent, for storage rings.

The important parameters which relate the beam dynamics and performance in a system of colliding linacs were identified. They are:

i) the disruption parameter D which describes the strength of the beam-beam interaction, and hence replaces the beam-beam tune shift ΔQ familiar in storage rings,

ii) the relative energy loss due to beam-strahlung δ.

A parameter list for a system of colliding linacs, based on reasonable choices of these parameters, was compiled.

In order to make further progress in these fields the Organizing Committee of the 2nd ICFA Workshop suggested the following list of topics to be studied:

i) Scaling of e^+e^- storage rings and limitations,

ii) Colliding linacs,

iii) Multiple interaction regions in colliding linacs,

iv) Polarization in electron-positron colliders.

The findings of the working group are summarized below. The main conclusions arrived at are given in the last chapter.

2. STORAGE RINGS

The scaling of e^+e^- storage ring parameters to higher energies than LEP and the difficulties associated with it are presented in a contributed paper to this Workshop[3]). The approach and main conclusions can be summarized as follows.

The size of an e^+e^- storage ring is obtained by observing that the cost of a machine is minimized when its size scales approximately like the square of the energy[4]. This scaling law holds over a range of energies for which the prices per running metre for a tunnel equipped with a magnet lattice and vacuum system, for a tunnel equipped with an RF accelerating system, etc., remain constant. It also implies that the fraction of machine circumference occupied by the RF system is independent of the energy.

This geometrical scaling law provides a firm basis for an analysis of the beam dynamics in such a machine and of its performance, which includes several phenomena:

i) the beam-beam tune shift ΔQ,

ii) beam-strahlung,

iii) design of crossing regions,

iv) single-beam space-charge phenomena such as bunch lengthening and coherent tune shift,

v) synchrotron tune Q_s.

The scaling laws for these phenomena with energy were obtained. They indicate that as the design energy is increased the RF frequency must be reduced and the number of bunches increased.

As an example, the parameters of a machine with a design energy of 260 GeV and four times the size of LEP were computed. A brief summary is shown in Table 1. This machine has several disagreeable features:

i) The RF frequency of 50 MHz is very low. Economic ways of building 7.5 km of such an RF system must be found - if they exist.

ii) The low field in the bending magnets implies that they cannot easily be used to excite sputter-ion pumps. Economic ways of installing lumped pumps for 120 km of vacuum chamber must be found.

iii) Since the number of bunches exceeds half the number of crossing points, the e^+e^- beams must be separated at the unwanted crossings while they are in collision in the interaction regions, or they must be stored in two independent rings. This proposition also needs further study.

3. COLLIDING LINACS

In its simplest form, a linear e^+e^- collider consists of two pulsed linear accelerators which accelerate e^+ and e^- bunches in opposite directions. The two beams are brought to a tight focus at the interaction point. At first sight, there appears to be no limit on the smallness of the beam at the crossing point, in contrast to storage rings where such a limit arises from the beam-beam tune shift ΔQ. However, it was already mentioned that such a limit exists also for linear e^+e^- colliders, because of the beam-strahlung phenomenon. The relevant expressions will be reviewed in Section 3.1.

Table 1

Parameters of 260 GeV e^+e^- storage ring

Energy	E	260		GeV
Number of crossings	n_x	8		
Number of bunches	k	16		
Circumference	C	126		km
Average radius of lattice cells	R	16		km
Bending radius	ρ	14		km
Betatron tune (arcs only)	Q	257		
Phase advance/cell	μ	60^o		
Period length	L_p	65.2		m
Dipole field	H	0.062		T
Max. and min. amplitude functions	β	112.9	37.6	m
Max. and min. dispersion	D	0.33	0.20	m
Max. hor. and vert. rms beam radius in cell		1.06	0.22	mm
Natural rms energy spread	σ_{eo}	$1.88x10^{-3}$		
Natural bunch length	σ_{zo}	19.9		mm
Bunch lengthening factor	B	3.4		
Actual bunch length	σ_z	67.4		mm
Hor. and vert. amplitude functions at crossings	$\beta_{x,y}$	1.6	0.1	m
Luminosity	L	10^{32} cm^{-2} s^{-1}		
Free space around crossings	ℓ_x	5		m
Beam-beam tune shift	ΔQ	0.06		
Hor. and vert. rms beam radius at crossing	σ_x, σ_y	100	6.3	μm
Beam-strahlung parameter		$1.26x10^{65}$		
Circulating current/beam	I	2.78		mA
Synchrotron radiation loss per turn	U_s	28.9		GeV
Synchrotron radiation power (two beams)	P_b	161		MW
Length of RF system	L_c	7.5		km
RF frequency	f_{RF}	50		MHz
Peak RF voltage	V_{RF}	29.1		GV
Stable phase angle	ϕ_s	96.6^o		
Synchrotron tune	Q_s	0.023		

The linacs can have either a pulsed room-temperature RF structure in which the RF power is dissipated between pulses and the average power is determined by the repetition frequency, or may be superconducting linacs in which only the RF power transferred into the beams must be replaced, but the RF structure has to be cooled to cryogenic temperatures. This alternative is discussed in Section 3.2.

After the collision, the bunches are used to produce the particles for the next pulse and discarded. Techniques for particle production are discussed in Section 3.3.

Depending on the choice of parameters, the stored energy and the power in the colliding bunches may be considerable. If they are discarded in a beam dump, the power can at best be recovered in the form of steam or lukewarm water. This waste of power can be avoided in the superconducting linac if the beam power is recovered by decelerating the bunches in the opposite linear accelerator. This alternative is discussed in Section 3.4.

Recovering also the decelerated particles is a natural extension to energy recovery. Its advantages and difficulties are discussed in Section 3.5.

A schematic diagram of the different schemes for colliding linacs is shown in Fig. 1.

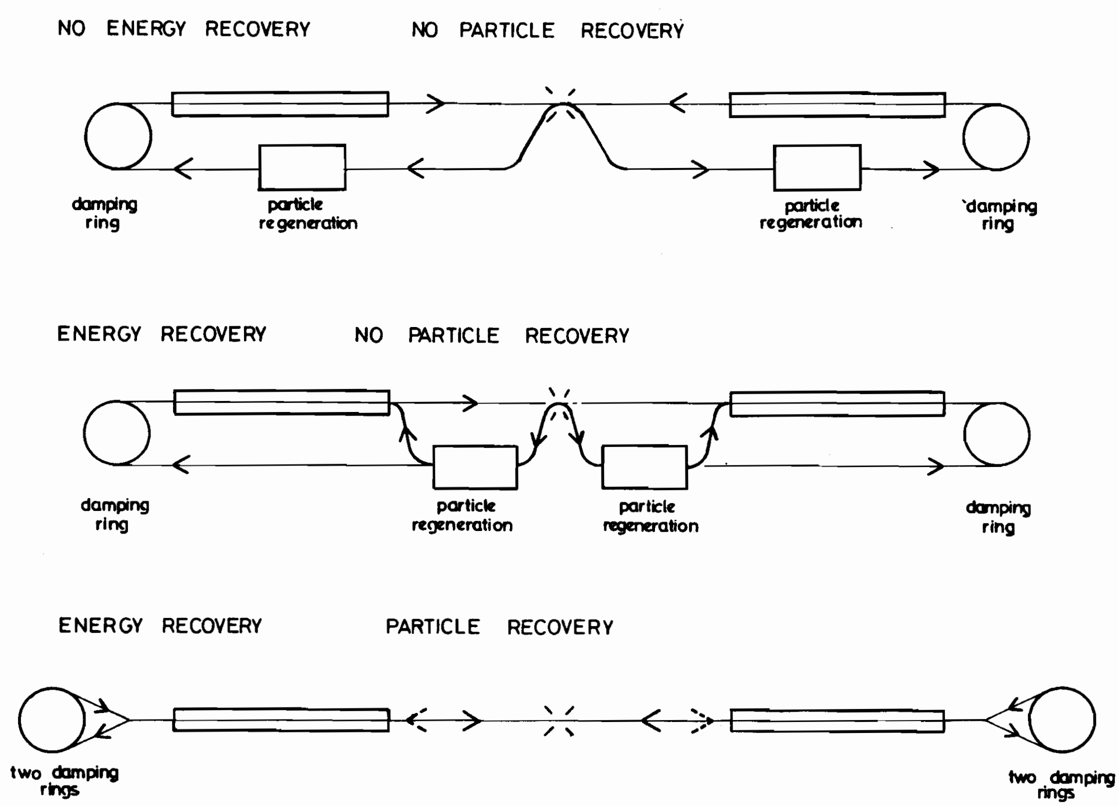

Fig. 1 : Various colliding-linac schemes

All these schemes have already been incorporated in proposals for colliding linacs. A 2 x 100 GeV collider with a pulsed room-temperature linac and neither energy nor particle recovery has been proposed by the Novosibirsk group[5]. It is described in more detail in a contributed paper[6]. Another 2 x 100 GeV machine with energy recovery was considered by Amaldi[7]. A 2 x 100 GeV machine with energy and particle recovery was discussed by Gerke and Steffen[8]. Modifications to this scheme arising from discussions at this Workshop are given in a contributed paper[9]. The concept of charge compensation by simultaneously colliding two e^- and two e^+ bunches and its consequences are discussed in Section 3.6. The working group has not made a choice between the alternatives of pulsed and superconducting linacs. Instead, the parameter list presented in Section 3.7 includes two 2 x 350 GeV machines, an extrapolation of the Novosibirsk design and a superconducting one with energy recovery.

3.1 Basic equations

In order to define the notation for the subsequent discussion, a summary of the basic equations for colliding linacs is given below. The equations are derived with two simplifying assumptions, that the shape of the bunch is not modified by the collision (the weak beam-strong beam approximation), and that the transverse position of the test particle does not change much while colliding with the strong beam.

The formulae obtained are compiled in Table 2. The definition of the luminosity L should be obvious. The definition of the disruption parameter agrees with that in ref. 1

$$D = \sigma_z/F \qquad (1)$$

where F is the focal length of the lens which gives the same kick as the bunch to a test particle with transverse positions x and y small compared to the bunch dimensions σ_x and σ_y, respectively. If $\sigma_x > \sigma_y$ the vertical disruption parameter is larger and is therefore given in Table 2.

Table 2

Basic formulae for colliding linacs (see Fig. 2 for definitions)

Uniform elliptic rod	Tri-Gaussian bunch
length $d = 2\sqrt{3}\,\sigma_z$	rms length σ_z
Half axes $a = 2\sigma_x$, $b = 2\sigma_y$	rms radii σ_x, σ_y

Density distribution

$$\chi(x, y, z) = \frac{N}{\pi abd} \qquad \chi(x, y, z) = \frac{N\exp(-x^2/2\sigma_x{}^2 - y^2/2\sigma_y{}^2 - z^2/2\sigma_z{}^2)}{(2\pi)^{3/2}\,\sigma_x\sigma_y\sigma_z}$$

$$|x| \le a, \ |y| \le b\left[1 - (x/a)^2\right]^{\frac{1}{2}}, \ |z| \le \frac{d}{2}$$

N = number of particles/bunch

Luminosity

$$L = \frac{N^2 f}{4\pi\ \sigma_x \sigma_y}$$

f = collision frequency

Vertical disruption parameter

$$D = \frac{r_o \sigma_Z N}{\gamma \sigma_y^2\ (1 + R)} \qquad\qquad D = \frac{2 r_o \sigma_Z N}{\gamma \sigma_y^2\ (1 + R)}$$

r_o = classical electron radius

$R = a/b = \sigma_x/\sigma_y$ = aspect ratio

Beam-strahlung parameter

$$\delta = \frac{4}{3^{3/2}} \frac{r_o{}^3 N^2 \gamma R}{\sigma_x \sigma_y \sigma_z\ (1 + R)^2} \qquad \delta = \frac{16}{3\pi^{\frac{1}{2}}} \frac{r_o{}^3 N^2 \gamma}{\sigma_x \sigma_y \sigma_z} \frac{\arctan\ [A/(3\ R + 8 + 3/R)]}{A}$$

$$A = (3\ R^2 - 10 + 3/R^2)^{\frac{1}{2}}$$

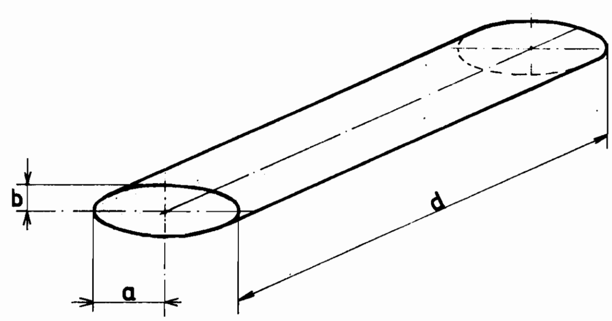

Fig. 2 : Geometrical parameters of a uniform elliptic rod

The disruption parameter is trivially related to the linear vertical beam-beam tune shift ΔQ_y familiar to storage rings

$$\Delta Q_y = \frac{\beta_y D}{4\pi\sigma_z} \tag{2}$$

and also to the circular frequency of plasma oscillations ω_p of the test particles in the field of the opposite bunch:

$$D = \frac{(2\pi)^{\frac{1}{2}}}{1 + \sigma_y/\sigma_x} \left(\frac{\omega_p \sigma_z}{c}\right)^2 \tag{3}$$

Roughly speaking, D is $2\pi^2$ times the square of the number of plasma oscillations during a collision[10].

The maximum value of D which can be achieved in practice is the subject of much debate. Since the bunches collide only once it is hoped that much stronger beam-beam forces could be realized in a colliding linac than in a storage ring. That a high value of D would be an advantage follows from the basic equations if the beam size is properly adjusted:

$$L = \frac{Nf\gamma D}{8\pi r_0 \sigma_z} \left(\frac{R + 1}{R}\right) \quad (4)$$

We note in passing that $Nf\gamma$ is proportional to the power in one beam. An estimate $D \leq 2$ has been obtained from plasma physics in a contribution to this Workshop[10]. Computer simulations have been done at Novosibirsk[5,6].

The beam-strahlung parameter δ is the fraction of the beam power converted into synchrotron radiation by the bunch collisions. The expression for δ for a Gaussian beam was recently obtained by M. Bassetti and M. Gygi-Hanney[11].

Since the beam-beam force is attractive, the motion of the particles is, during the beam-beam collision, oscillatory. This leads to a pinch effect which reduces the beam cross-section and enhances the luminosity. In the pulsed machine of the parameter list the enhancement factor is 1.2. The oscillatory character of the particle motion also has an effect on their spin motion, and care should be taken in the choice of δ if the polarization in the beam is not to be destroyed. The typical spin rotation angle ϕ is given by

$$\phi = \alpha(2d\delta/r_0\gamma)^{\frac{1}{2}} \quad (5)$$

where $\alpha = \frac{1}{2}(g - 2)$ is the gyromagnetic anomaly.

On the one hand, δ should be low in order not to dump too much synchrotron radiation into the detectors and in order to avoid excessive energy spread in the beams, which is, in turn, detrimental to energy and particle recovery as discussed in Sections 3.4 and 3.5, as well as to the physics of narrow resonances. However, experiments with narrow resonances could be performed at reduced luminosity and δ.

On the other hand, the repetition frequency f is inversely proportional to δ. A low repetition frequency is favoured in a room-temperature linac because the mains power, a very relevant parameter economically, is proportional to it. This conflict is difficult to resolve.

The values of D and δ can be reduced by a large factor if the space-charge field of a bunch is compensated by that of a bunch of opposite charge travelling in the same direction (cf. Section 3.6).

Picking a set of parameters satisfying all constraints is not an easy task. Let us assume that the energy γmc^2 and the luminosity L are given from the start. If any importance at all is attached to the space charge parameters D and δ, they must also be considered fixed. The bunch-length σ_z can only vary over a rather narrow range given by the RF frequency.

At this point the aspect ratio $R = \sigma_x/\sigma_y \geq 1$, the repetition frequency f, the bunch population N, and the beam cross-section ab (or $\sigma_x\sigma_y$) still remain to be determined. For the subsequent discussion, we shall use the formulae for the uniform elliptic rod.

Essentially, the product Rf is determined by the beam-strahlung parameter δ:

$$f = \frac{32\pi r_o{}^3 \gamma L R}{3d\delta(1+R)^2} \tag{6}$$

In order to obtain a low repetition frequency, an aspect ratio $R \gg 1$ should be chosen. There is considerable uncertainty as to the values of R which can be realized in practice, in particular because of several phenomena which increase the vertical beam size, e.g. deflecting modes in the linac, vertical dispersion because of alignment errors, etc. Once R is chosen, f is fixed by (6). Note that equ. (6) does not contain D.

The bunch population N then follows from:

$$N = \frac{1}{4\sqrt{3}} \; \frac{d^2\delta(1 + R)}{r_o{}^2\gamma^2 D} \tag{7}$$

Finally, the beam radii are obtained from:

$$b = \frac{d}{D\gamma} \left(\frac{d\delta}{6r_o\gamma}\right)^{\frac{1}{2}} \tag{8}$$

$$a = Rb \tag{9}$$

In this presentation, the vertical beam size b only depends on d, D, δ and γ, but not on L, N or f.

3.2 Normal or superconducting RF structure?

The advantages and disadvantages of RF structures made of copper and superconducting materials are briefly summarized in Table 3 which needs a few words of explanation. Some of the qualitative comments at this point will be substantiated by the figures in the parameter list in Section 3.6.

Table 3

Advantages and disadvantages of normal and superconducting RF structures

	Normal	Superconducting
Power sources	Hard	Easy
Voltage gradient	High	Low
Structure length	Short	Long
Cavity technology	Conventional	Harder
Refrigeration	None	Needed
Energy recovery	None	Possible
Repetition rate	Low	High
Charge per bunch	High	Low
Higher-mode problems	Easier	Harder

The peak RF power in a pulsed machine is of the order of a TW, while the peak power in a single RF generator is about 1 GW according to paper studies. Hence about 1000 generators would be needed. Exciting the linac by a bunched high-energy proton beam is considered in a contributed paper[12]. In a superconducting machine CW power sources can be used to replace the power extracted by the beam. Hence the RF power is of the order of the beam power. It could be supplied by a small number of existing RF generators.

For a given beam energy, the product of voltage gradient and structure length is determined. In a superconducting structure the maximum gradient is smaller than in a copper structure since at best it is limited by the critical magnetic field. The electric breakdown limit in copper structures is much higher. The actual gradient can be chosen as an optimum between the cost of the structure which is proportional to its length, and the cost of the peak RF power which is proportional to the voltage gradient.

The technology of pulsed linacs with copper cavities is entirely conventional. It follows the examples of existing linacs with frequencies of several GHz. The technology of superconducting cavities suitable for mass production needs extensive development. It is obvious that a cryogenic refrigeration system which needs substantial amounts of refrigerator power is only required for superconducting cavities. On the other hand, superconducting cavities open the possibility of recovering the beam power by decelerating the beams in the opposite linacs, and storing it in the cavities from one pulse to the next. This possibility does not exist in copper cavities because of their short filling time.

For a machine with given energy E, luminosity L and disruption parameter D, the product of repetition rate and charge per bunch is determined. In order to obtain a reasonable average power despite the high peak power in a pulsed linac made of copper cavities a low repetition rate must be chosen, and hence a high charge per bunch is inevitable. In a superconducting machine, more freedom exists in the choice of repetition rate and charge per bunch. A further consideration entering into the choice of the repetition rate is beam loading. The energy extracted from the RF structure by the passage of a bunch must be smaller than the energy stored in the structure. It follows that for constant beam loading the repetition rate must be inversely proportional to the voltage gradient.

The passage of intense short bunches through RF cavities excites higher-mode fields[13]. In either structure, the resulting variation of the accelerating field along the bunches causes an energy spread within the bunches which increases in proportion to the bunch charge and the length of the structure. The energy spread can be minimized but not completely removed by the choice of the stable phase angle[14]. In a copper structure, the excitation of higher modes also causes an energy loss of the bunches. However, there is practically no net energy loss in a superconducting structure unless one of the higher modes happens to coincide with a harmonic of the repetition frequency - a situation which ought to be avoidable fairly easily. This is due to the small ratio of the bunch spacing and the decay time of the higher modes in a superconducting structure[15], when the higher modes are not damped by coupling them to room-temperature loads by high-pass filters. This approach implies that also the transverse deflecting modes are not damped between bunches and therefore might become harmful.

Many of the above arguments also have an effect on the choice of the RF frequency. Designing RF power sources with high peak power becomes more complicated with increasing frequency, while the RF accelerating structure becomes smaller in diameter and possibly less costly. The stored energy in the accelerating structure is proportional to the inverse square of the frequency. Constant beam loading therefore requires the number of particles in a bunch to decrease like the square of the frequency. In order to keep the luminosity constant, the repetition frequency must be increased when the frequency is raised as can be seen from (4). Therefore, the ratio between mean and peak RF power is less favourable at higher frequency. All these arguments favour a frequency in the region of several GHz.

3.3 Particle production

Two alternatives exist for using the particles in one pulse to produce the particles, in particular the positrons, required for the subsequent pulse: electromagnetic showers - the conventional method - or pair-production from synchrotron radiation in a conversion target - a new method.

In the first method, the beam strikes a conversion target, several radiation lengths thick, and the emerging positrons are collected at a few MeV. A useful rule of thumb[16] indicates that each electron of energy E in GeV produces 0.01 E positrons in a suitable range of energies and emittances for subsequent acceleration in a conventional linac. Hence, for energies above 100 GeV, an electron bunch can produce all the positrons required for the next pulse.

The second method was invented by the Novosibirsk group[5,6], and independently by Amaldi and Pellegrini during the Workshop[17]. Here the electron beam travels through a periodic wiggler magnet of suitable pitch and total length. The nearly monochromatic synchrotron radiation strikes a thin conversion target in which electron-positron pairs are created. The positrons are again collected and accelerated in a conventional linac. The main parameters of the wiggler are summarized in Table 4. The photon energy and the

Table 4

Wiggler parameters

Pitch	0.02 m
Total length	100 m
Maximum field	0.37 T

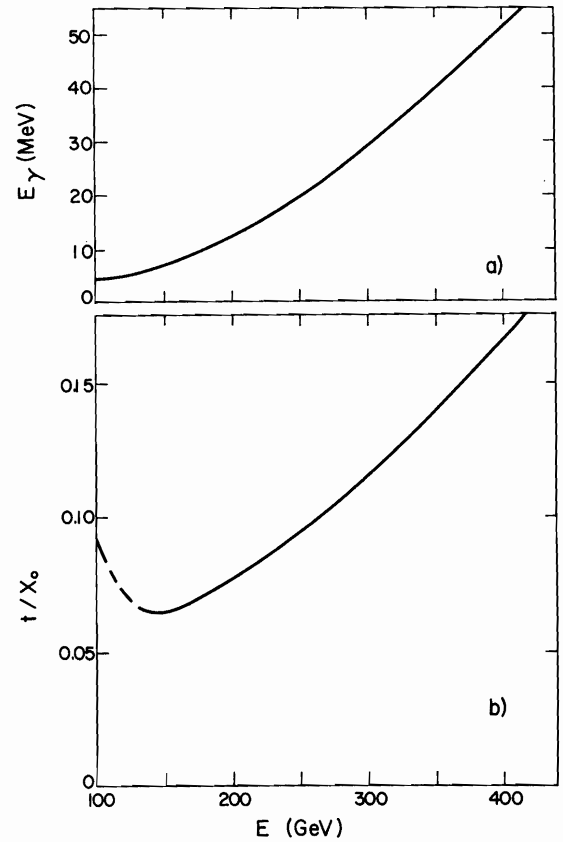

Fig. 3 : a) Photon energy E_γ from periodic wiggler magnet with parameters shown in Table 4.
b) Target thickness t in radiation length X_0 of positron production target.

target thickness required to produce one positron per electron in a useful energy and emittance range are shown in Fig. 3 as a function of the energy.

An additional attraction of this scheme is the possibility of obtaining polarized electrons and positrons. If a helical wiggler is used the synchrotron radiation is circularly polarized and the electrons and positrons are longitudinally polarized to about 80%. If one succeeded in preserving this polarization during all the subsequent beam manipulations, and also the beam-beam collisions proper, collisions between longitudinally polarized electrons and positrons of arbitrary helicity could be obtained.

In either scheme, the emittance of the positron beam by far exceeds that required for the beam-beam collisions. Hence, a damping ring is required between the positron source and the input ends of the colliding linacs. It must simultaneously have a short synchrotron damping time and a small equilibrium beam emittance. This combination of requirements imposes special precautions on its design. An example was given by Steffen[18].

3.4 Energy recovery in superconducting linacs

The total power needed for the operation of a linear collider with a superconducting RF system consists of three parts:

i) the static heat losses from the cryostat which are proportional to its length,

ii) the RF power dissipated in the superconducting RF structure,

iii) the RF power which has to be supplied to the beam.

Quantitatively, this may be put into the following form:

$$P = 2\eta_c^{-1}\left(\frac{E}{e}\right)\left[\frac{W}{G} + \frac{G}{ZQ}\right] + 2\eta_{RF}^{-1}\ (1 - \varepsilon)\ P_b \qquad (10)$$

Here P is the mains power, η_c is the cryogenic efficiency, E the energy of one linac, W is the static heat loss per unit length, G is the voltage gradient, Z is the characteristic impedance per unit length and Q is the quality factor of the structure, η_{RF} is the efficiency of the RF sources from mains to RF power, ε is the fraction of the beam energy recovered and P_b is the power in one beam. Higher-mode losses do not appear in (10) since there is no net energy loss (cf. Section 3.2). Energy recovery enters into (10) only by the coefficient ε. Hence there is always a reduction in total mains power when energy recovery is used. This argument is presented in detail by Amaldi and Pellegrini in a contribution to this Workshop[17]. They argue in favour of energy recovery even without recovering the particles at the same time. The mains power is shown in Fig. 4 as a function of the voltage gradient G, for a typical machine with parameters given in the caption. Most of the mains power is needed for the cryogenic system whose contribution could be reduced by further improvements in the heat insulation and the Q factor of the superconducting structure.

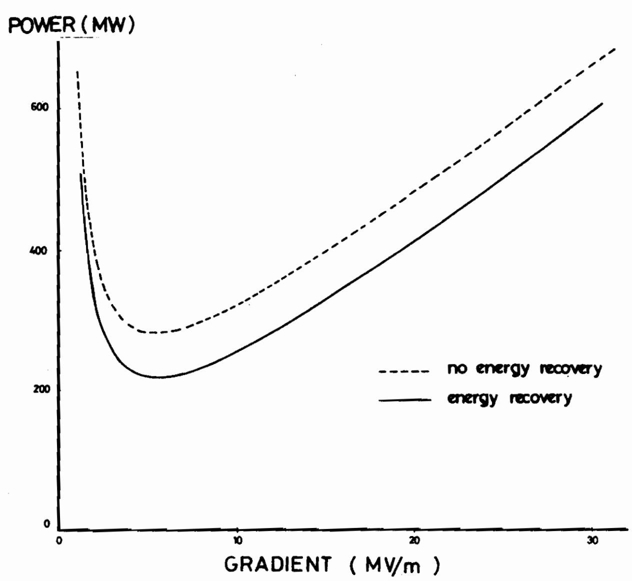

Fig. 4 : Mains power versus voltage gradient. The curves shown assume an energy of 350 GeV and a power of 44 MW in each beam, a cryogenic efficiency of 2.5 x 10^{-3}, heat losses of 2 W/m, a characteristic impedance of 3 kΩ/m, a Q factor of $5 \cdot 10^9$ and an RF efficiency of $^2/_3$. Without energy recovery 40% of the RF power is recovered, and with energy recovery 90%.

A further argument in the choice of energy recovery are bunch crossings outside the interaction region. Without energy recovery, the bunches in one linac move only in one direction, and bunches moving in the opposite direction only meet at the interaction point. With energy recovery, bunches moving in opposite directions may meet in the linacs when the repetition frequency is high. At these points the beams must be separated from each other since extra beam crossings cannot be tolerated. The relation between the number n of extra crossings in one linac and the repetition frequency f is

$$f \leq \frac{(n + 1)\ ce\ G}{2E} \tag{11}$$

Finally, energy recovery requires that the interaction region optics and the beam transport systems along the linacs be capable of handling the emittance of the bunches after the collision.

3.5 Particle recovery

At first sight, particle recovery is a straightforward extension of energy recovery in a superconducting linear collider. The decelerated particles are collected at the input end of the linac, injected into a damping ring and used again in a later pulse. However, at least two difficulties are associated with such a scheme. Firstly, no particle recovery can have an efficiency of 100%, hence some scheme for "topping up" the bunches, i.e. of particle production, is required in any case. Secondly, and this is more important, severe difficulties arise from the energy spread in the beam caused by beam loading and beam-strahlung.

In the discussion of beam loading the field in the cavities due to the higher modes is neglected. This is a fairly good approximation even though these fields do not decay appreciably between pulses[15]. In this approximation the beam loading can be described by a wakefield whose variation along the bunch - together with the variation of the cavity voltage excited by the RF transmitters - causes an energy spread in the bunch. The energy spread is a minimum if the variations of the wakefield and of the RF voltage compensate each other. For a given RF voltage gradient and RF frequency, and a given bunch length, this cancellation is best if the bunches ride ahead of the crest of the accelerating RF waveform and if their charge and length are at the optimum value. A higher bunch charge requires a larger bunch length or a higher voltage gradient for optimum compensation. Fig. 5 shows an example in which the energy spread has been limited to about 1% for a large fraction of the particles in the bunch.

The energy loss due to beam-strahlung is one of the design parameters, δ, of a linear collider as discussed in Section 3.1. In the parameter lists in Section 3.7 its value is δ = 1%. This energy loss is accompanied by an energy spread of the same order of magnitude.

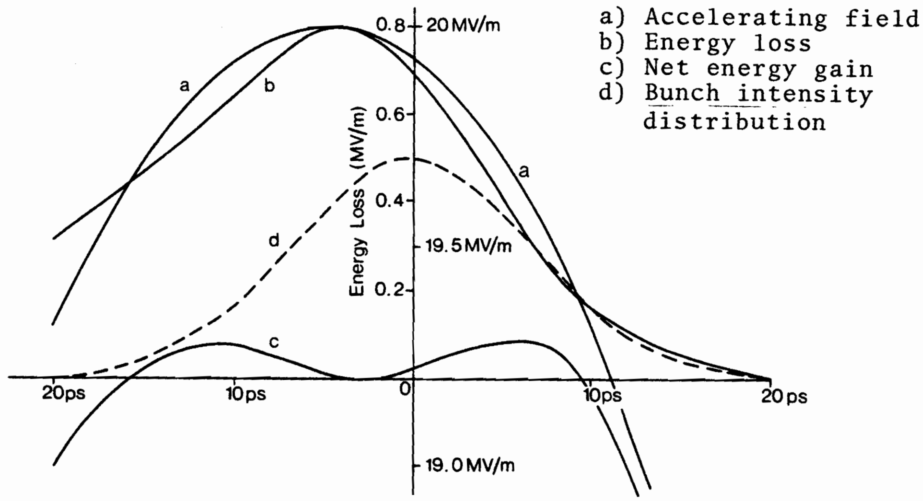

Fig. 5 : Energy loss compensation (σ = 6.8 ps (2 mm), N = 6.6 x 10^{10}, E = 20 MV/m).

Since the curvature of the decelerating RF waveform during energy recovery is the opposite of that in the accelerating linac, the contribution of the decelerating linac to the energy spread is higher than 1%. Therefore, a conservative estimate of the energy spread after energy recovery is 2%, or about 7 GeV in a 350 GeV machine.

Since an energy spread of about 7 GeV cannot be handled in a damping ring at a few GeV, it must be reduced in a relativistic debuncher. The peak RF voltage in this device must be a few times 7 GeV, i.e. the RF system required is equivalent to several superconducting LEP RF systems. At an energy of 350 GeV, the technical difficulties and cost of particle recovery compare unfavourably with positron production as discussed in Section 3.3. Therefore particle recovery is not recommended at this energy. At lower energies, i.e. at about 100 GeV, the absolute energy spread in the beam is smaller and positron production is more difficult. This has led Steffen to retain particle recovery in a 100 GeV machine[9].

3.6 Space-charge compensation

Most of the difficulties connected with the strong beam-beam interaction can be avoided if one arranges two e^- and two e^+ bunches to collide at the same time, with a pair of e^+ and e^- bunches travelling in the same direction[5,6]. If the bunches overlap perfectly and if their intensities differ by 1%, say, the disruption parameter would be reduced by a factor of 100, and the beam-strahlung parameter by 10^4.

At a given energy and luminosity, this reduction in the space-charge forces can be exploited in several ways. One can reduce the number of particles but one must reduce the vertical beam size at the same time. One can also reduce the aspect ratio R and/or the repetition frequency f. Compensation is proposed for one of the machines in the tentative parameter list given in Section 3.7.

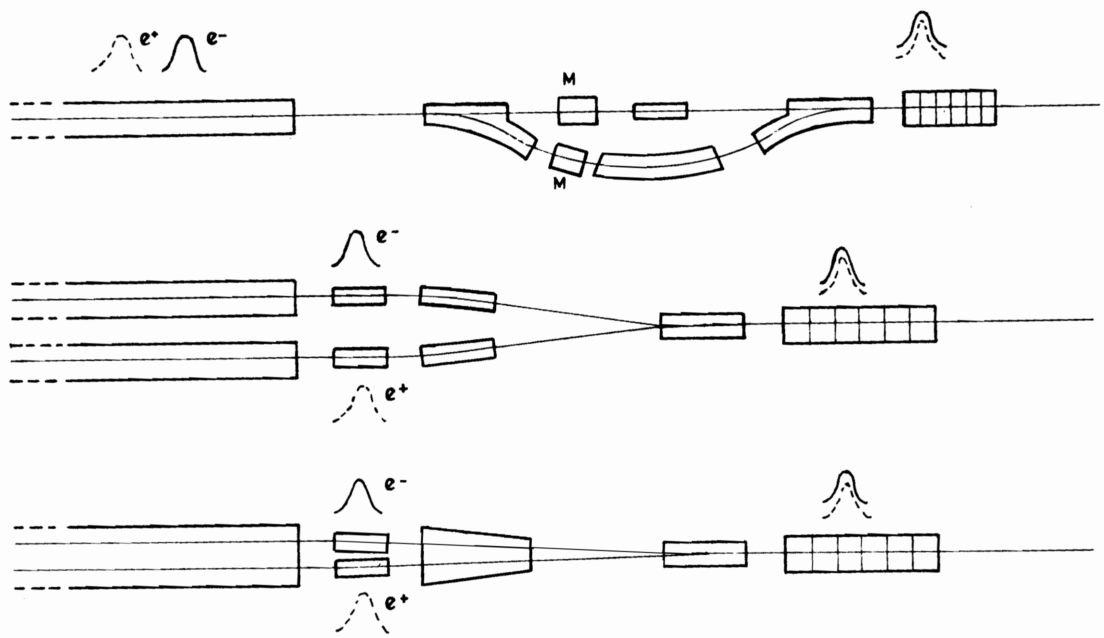

Fig. 6 : Various schemes for compensating the space-charge effects

Several methods of simultaneously accelerating e^+ and e^- bunches are schematically indicated in Fig. 6. In the first method, e^+ and e^- bunches are accelerated one behind the other in one linac, and superimposed by a beam-optical decay line. An example of such a delay line, designed by Steffen[9], is shown in Fig. 7. Since the distance between the e^+ and e^- bunches is of the order of one metre, the trailing bunch may suffer from the wakefields, both longitudinal and transverse, of the leading bunch. Experiments at SLAC[19] have shown that a distance of about 15 m was necessary to avoid this effect. This difficulty is avoided in the second and third schemes. Here, the two bunches are accelerated in two parallel linacs, or off-axis in one linac driven in a mode with the accelerating field pointing in opposite directions above and below the axis.

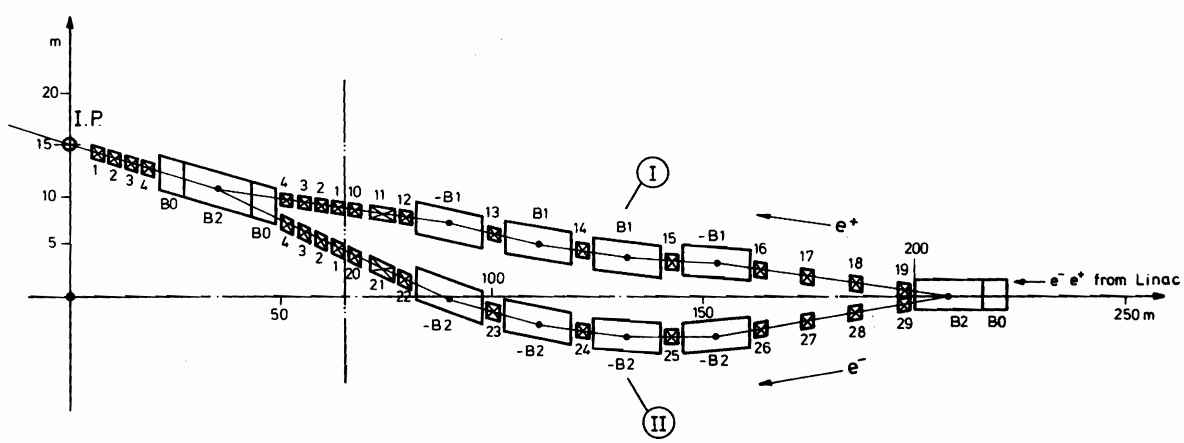

Fig. 7 : Space charge compensated achromatic beam collision system, plan view

3.7 Tentative parameter lists

The art of designing linear colliders is in its infancy and many questions are as yet unanswered, as should have become clear from the above discussion. There is also no agreed "standard method" for designing linear colliders because design choices are largely based on extrapolations of other machines, rough estimates, guesses and prejudices, rather than on results of prototype work and accurate calculations.

This state of the art has led the working group to include two machines in the tentative parameter list of Table 5, one with a room-temperature pulsed RF system and charge compensation, which is an extrapolation of the Novosibirsk design[5,6], and a superconducting one with energy recovery rather similar to that described by Amaldi and Pellegrini[17]. These machines are most likely extreme examples.

Table 5

Tentative parameters of colliding linacs

Energy/beam E(GeV)	350	350
Luminosity $L\,(cm^{-2}\,s^{-1})$	10^{33}	10^{33}
rms bunch length σ_z (mm)	3	3
Repetition frequency f (s^{-1})	1.4×10^4	10
Particles/bunch N	5.6×10^{10}	10^{12}
Beam cross-section $(\sigma_x\sigma_y)^{\frac{1}{2}}$ (μm)	0.6	0.3
Disruption parameter D	2	310 (2.4)*
Axis ratio R	1	5800 (3.3)*
Beam-strahlung parameter δ	0.01	0.01 (0.001)*
RF voltage gradient G (MV/m)	20	100
Length (km)	2 x 17.5	2 x 3.5
Average mains power (MW)	414	40
Peak RF power (MW)	10	10^6

* The figures in brackets apply to space-charge compensation with 1% accuracy

Most of the considerations governing the choice of parameters have already been discussed, mainly in Sections 3.1 and 3.2 but a few further comments may be in order. The values for the disruption parameter D and the beam-strahlung parameter δ for the pulsed machine are calculated without the space-charge compensation. Hence they are expected to be smaller by factors 100 and 10^4, respectively, if compensation to the level of 1% is achieved. They would then fall into the same regions as D and δ for the superconducting machine.

Space-charge compensation and flat beams are fully exploited in the pulsed machine to obtain a low repetition rate and thereby a low mains power, despite the very high peak RF power required. The price to be paid for this is a higher charge per bunch and smaller bunch dimensions. The repetition rate of the superconducting linac is still small enough to avoid extra beam crossings in the linacs. The average mains power and the peak RF power are calculated using the parameters shown in Fig. 4.

4. CONCLUSIONS

The conclusions of the working group may be summarized as follows.

Storage rings for e^+e^- collisions at energies of several hundred GeV per beam must be operated with many bunches. The most elegant way seems to be separate rings for e^+ and e^-. Even with this assumption, storage rings appear to be impossible for energies above 200 GeV per beam.

For colliding linacs, there is a choice between two extreme schemes: pulsed room-temperature linacs with a low repetition rate, or superconducting linacs with a higher repetition rate. Re-using the same particles for subsequent collisions appears unattractive at energies much above 100 GeV per beam since an elegant scheme of particle generation is available which also permits polarized particles to be obtained. Recovering the stored energy in the beams by decelerating them in the opposite linac is always worthwhile in a superconducting linac. Luminosities in the range of 10^{33} cm^{-2} s^{-1} look possible. However, because of the beam blow-up in a single collision, it is excluded to accelerate trains of bunches and to collide them in a string of interaction regions simultaneously. Hence, even if a string of experimental areas is constructed only one of them can be operated at any one time.

A number of open problems with colliding linacs were identified.

i) The low-emittance damping rings required in all schemes in order to obtain the emittances required operate with many bunches which are filled and ejected one by one. The collective phenomena associated with this need further study.

ii) Pulsed room-temperature linacs require economic RF power sources in the GW range in order to become a practical proposition. Such power sources must be developed.

iii) Superconducting linacs require the development of economic RF structures. Because of the long decay time of the RF fields in an unloaded superconducting linac, beam break-up due to transverse deflecting modes may occur, leading to a growth of the beam emittance beyond tolerable limits. This could be avoided by extracting the higher longitudinal modes and the deflecting modes from the structures. Further studies are needed in this direction.

iv) The design of the interaction regions should be improved in several directions. Further investigations into the limitations on the disruption parameter D and the beam-strahlung parameter δ are in order. The latter should also include the effects of beam-strahlung on the detectors. The small beam sizes required impose tight tolerances on the chromatic aberrations of the interaction region optics and also on the stability of the ground. How these tolerances can be met also needs further study.

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