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THE TECHNICAL CHALLENGE OF FUTURE LINEAR COLLIDERS*

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ABSTRACT

The next generation of high energy e^+e^- colliders is likely to be built with colliding linear accelerators. A lot of research and development is needed before such a machine can be practically built. Some of the problems and recent progress made toward their solution are described here. Quantum corrections to beamstrahlung, the production of low emittance beams and strong focusing techniques are covered.

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1. Introduction

The advantages of a high energy e^+e^- collider over a proton collider are well known. There is a simple initial state of known energy and quantum numbers. This makes it easier to untangle the physics involved in the final state. Also, the production of particles is democratic. As long as there is enough energy available, all charged particles, independent of mass are produced at similar rates. As a result the fraction of events involving new physics would be much higher than in a proton machine.

The only disadvantage is that a high energy, $E_{beam} = 1 - 50\,\text{TeV}$ e^+e^- collider, can't be built with today's technology. It is much more difficult to have colliding electron beams than proton beams as the small electron mass results in much more synchrotron radiation. As a result, electron storage rings must have much larger radii than the same energy proton storage ring. In fact, it is clear that at sufficiently high energy the most practical electron collider will be two linear accelerators pointing at each other.[1]

Developing the technology needed to build such a high energy linear collider presents a great challenge. The emphasis here will be on technology that will work for more than just the next accelerator, but for a whole generation of them. The next linear collider, with an energy of several hundred GeV, could be built with fairly conventional linac technology. At TeV energies, this technology will clearly be too expensive. A 5 on 5 TeV machine will be used here as an example. This is a high enough energy that new techniques are needed to allow an economically feasible machine to be built. The idea is that the technology to be developed should be capable of attaining such a high energy (or even 50 TeV) but the first machine built would presumably have a lower energy.

Some very good work has been done in the last 1 or 2 years. The basic concept of how a high energy collider would work has changed radically. Many novel ideas have been put forward. Some of these ideas will be reviewed here while making it clear that there is still a lot of work to do before a practical linear collider can be designed. This talk emphasizes developments needed for small ϵ and β^* as the next speaker will address the accelerator and power supply.

It wouldn't be fitting to talk about future high energy linear colliders without first mentioning the linear collider being built at SLAC, the SLC. The detailed status report given at the conference isn't appropriate for these proceedings as it will (hopefully) be out of date by the time of publication. Commissioning of the full SLC system is scheduled to start in December 1986 and beams should be delivered to the Mark II experiment in February 1987. The success of this prototype machine is a prerequisite for the building of future machines. We will assume that it does work and use the SLC as a "working example" from which we will extrapolate to higher energies and luminosities.

2. Scaling Laws of Colliding Beams and Beamstrahlung

The first step in designing a linear collider is to determine the parameters of the colliding beams. These parameters in turn determine most of the characteristics of the accelerator. For example, if the bunch length, σ_z, is long, the wavelength of the accelerator must be long. Eleven parameters of colliding beams are described in Table 1 where their values at the SLC are also given. By studying how the parameters' values scale with energy one can gain an understanding of what research and development must be done to realize a high energy linear collider. A few of these parameters will now be described in a bit more detail. The luminosity, $\mathcal{L}$, along with the cross section determines the event rate. As the e^+e^- cross section falls as $1/\gamma^2$ the luminosity must increase as γ^2 to keep a constant event rate as the energy is increased. This is necessary as physicists are an impatient breed and don't want to wait decades to accumulate sufficient statistics. This high luminosity requirement causes as much difficulty in accelerator design as the high energy does. The disruption parameter, D, provides a measure of how much the beams are focused in each others magnetic fields as they collide. For $D < 0.1$ there is very little focusing. For $0.1 < D < 20$ they are focused which results in an enhancement of the luminosity by up to a factor of 6. For $D \gtrsim 20$ the focusing is so strong that a plasma instability develops, blowing up the beam and reducing the luminosity. A long, narrow, intense beam results in a large D which must be avoided. The beamstrahlung parameter, δ, is a measure of what fraction of the incident electron's energy is lost to synchrotron radiation during the collision of the two beams. The same deflection of the particles in the other beams electromagnetic fields that causes disruption also causes them to radiate photons. It's pointless to accelerate the beams only to have them radiate away all their energy before interacting. A large δ also causes a large spread in the center of mass collision energy. Usually one requires $\delta < 0.3$ for a practical collider. The normalized emittance, ϵ_n, provides a measure of the size of the beam; $\epsilon_n = \gamma\{\text{spot size}\}\{\text{angular divergence}\}$. A small ϵ_n allows a small spot size which gives a high luminosity.

There are 5 equations relating the 11 parameters in Table 1. Just two of them will be highlighted here.

$$\sigma_r^2 = \frac{\epsilon_n \beta^*}{\gamma} = \frac{k}{\Gamma} \frac{\delta P^2 \sigma_z}{\gamma^2 \mathcal{L}^2} \tag{1}$$

Note that everything we want forces the right hand side of this equation to be small. In the numerator is δ which should be small to keep a small energy spread, P which should be small because power is expensive as are the power supplies and accelerator needed to supply the power, and σ_z which should be small to keep the disruption parameter from getting too large. In the denominator are γ and $\mathcal{L}$ both of which obviously need be large for a high energy collider. It is then clear, independent of acceleration technique, that the beam radius at the interaction point, σ_r, must be very small and that ϵ_n and β^* must be small. If we can't make them small enough as the beam energy is increased (note that the denominator scales as γ^6) then the beam power must be increased. This means it will be important to make an efficient accelerator since the beam power is large. Equation (1) shows that it is difficult to make a high energy, high luminosity collider. One must either increase the power or decrease ϵ_n and β^* or both by many orders of magnitude. Here, we'll concentrate on the latter. Bob Palmer in the next talk will address the former.

Table 1. The parameters of colliding beams.

Variables	Value at SLC
γ = E/mc^2	1×10^5
$\mathcal{L}$ = Luminosity	6×10^{30}cm^{-2}sec^{-1}
f = repetition rate	180 Hz
D = Disruption Parameter	0.6
P = Total beam power	74 kW
N = number of $e^{\pm}$ per bunch	5×10^{10}
σ_z = bunch length	1 mm
σ_r = radius of beam at I.P.	1.8 μm
δ = $\frac{\Delta E}{E}$ = beamstrahlung param.	8×10^{-4}
ϵ_n = normalized emittance	3×10^{-5}m-Rad
β^* = focusing strength at IP	0.75 cm

The fraction of an electron's power radiated as it passes through the fields of the opposing bunch can be calculated using the classical synchrotron radiation formula. Expressing this in terms of γ, $\mathcal{L}$, f, P, and D gives

$$\delta_{classical} = \frac{(4\pi)^2 r_e \gamma \mathcal{L}^2 mc^2}{6\sqrt{3} f D P}. \tag{2}$$

The $\gamma\mathcal{L}^2$ in the numerator scales as γ^5 so it will be 10 orders of magnitude larger for a 5 TeV machine than for the SLC. The SLC has a very small δ; an increase of 10^3 is the maximum that could be allowed. This still leaves a factor of 10^7 to be made up. The disruption, D, in the denominator could be increased by a factor of 100 and the beam power, P could be increased by 1000 to 100 MW. This is a very large beam power as the accelerator's efficiency will most likely be about 10% resulting in a wall plug power of 1 gigawatt. Even with these rather extreme values of the beam parameters, δ is still a factor of 10^2 larger than desired. The frequency of collisions, f, could be increased by this factor to 20 kHz to give the desired δ. It is clear that to keep δ small enough all the other beam parameters must be strained to or past reasonable limits. There is clearly a problem here, especially if still higher energies are ultimately desired; for a 50 TeV machine another 5 orders of magnitude would have to be gained.

Fortunately the problem isn't as bad as it appears because $\delta_{classical}$ is wrong in this regime. The classical calculation does not take into account the fact that photons are quantized. The frequency spectrum of classical synchrotron radiation is characterized by the parameter ω_c, the critical frequency. As shown in Fig. 1 the radiated power increases slowly with frequency until ω_c where it rapidly falls off. Just using $E = \hbar\omega$ from Q.M. and classical

E. and M. from Jackson[2] gives

$$E_c = \hbar\omega_c = \frac{3}{2}\hbar c\frac{\gamma^3}{\rho} = \frac{\sqrt{3}\hbar c\gamma^2 N r_e}{2\sigma_r}. \tag{3}$$

For γ large and σ_r small this can give $E_c > E$. As an electron can not radiate a photon with more energy than it has, there is clearly a regime where the classical calculation isn't appropriate. Quantum effects must be accounted for. A proper quantum mechanical calculation of synchrotron radiation in a uniform magnetic field was first done in 1952[3] but it has only recently been applied to colliding beams.[4] A more recent calculation using a different method has confirmed the previous results.[5] The conclusion is that as long as the beam energy, E, is much greater than the critical energy, E_c, the classical calculation is accurate. However for $E \ll E_c$ much less energy is radiated than the classical calculation indicates. As shown in Fig. 1, the power spectrum follows the classical curve and then drops sharply at the electron's energy. The quantity, E/E_c can be expressed in terms of the beam parameters.

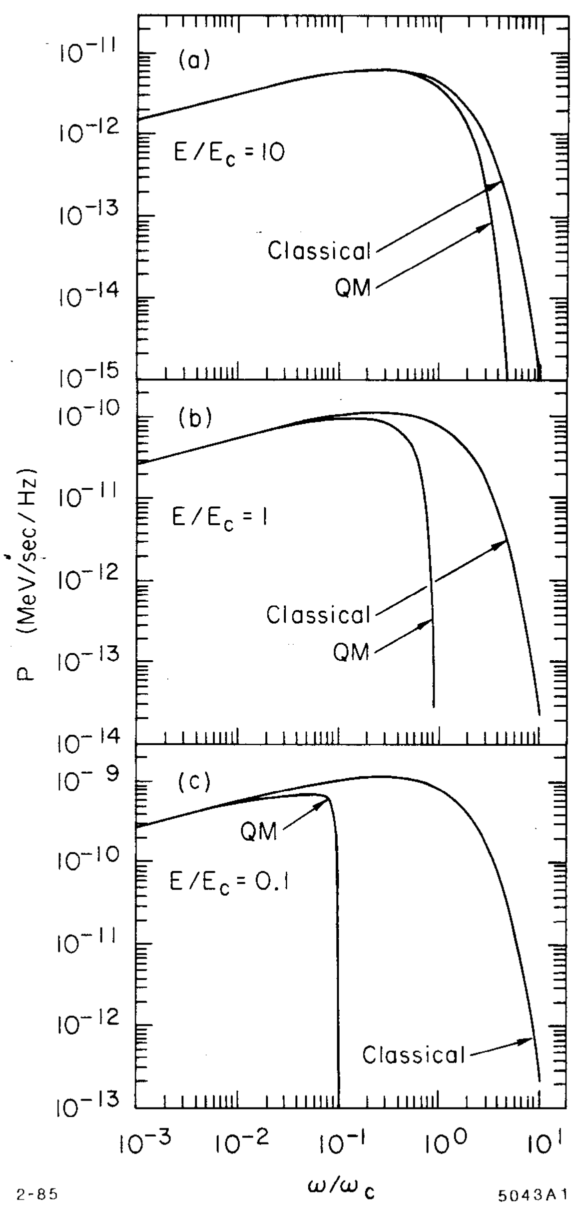

Fig. 1. Differential power spectra of the radiation emitted by 5 TeV electrons for several values of E/E_c. Parts (a)-(c) are in the classical, intermediate and quantum regimes respectively. Shown are the classical calculation and the exact quantum calculation.

$$\frac{E}{E_c} = \frac{P f^{\frac{1}{2}} D}{2\sqrt{3}\pi^{\frac{3}{2}}\mathcal{L}^{\frac{3}{2}} r_e^2 \hbar c\gamma} \tag{4}$$

With $\mathcal{L} \propto \gamma^2$ the denominator of this formula scales as γ^4. Unless one increases the beam power enormously (to increase the numerator), one is forced into the quantum regime in designing a high energy high luminosity machine.

Changing to the quantum regime has a profound effect on the scaling laws of the colliding beams. At fixed energy, $\delta_{classical} \propto B^2$ while $\delta_{QM} \propto B^{\frac{2}{3}}$. Hence in the classical regime long beams (with small magnetic fields) are needed to avoid having too much radiation, while in the quantum regime short bunches result in less radiation. Much shorter bunches are thus allowed (even encouraged) due to the quantum beamstahlung formula. These short bunches then reduce the problem of emittance growth in the accelerator due to transverse wake fields and avoid any problem of D getting too large.

Having considered the scaling of the beam parameters with energy, one can now write down a consistent set of high energy beam parameters. As there are 11 parameters and only 5 equations, there is some flexibility in the parameter choice. Table 2 presents two such choices, one which achieves the high luminosity with a relatively low power but very small ϵ_n and β^* while the second has a much more conservative ϵ_n and β^* but a very high beam power of 63 MW. Both of these parameter sets are self–consistent, but neither is optimized. Optimization requires more information about the acceleration mechanism and the difficulty of producing low emittance beams.

Table 2. Beam parameter examples. The two numbers given for δ are the quantum and classical δ's.

	SLC	5 TeV Low Power	5 TeV High Power	Energy Scaling $*$ = input
γ	$1 \times 10^5 = 50$ GeV	$1 \times 10^7 = 5$ TeV	1×10^7	$\gamma*$
$\mathcal{L}$	$6 \times 10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$	10^{34}	10^{34}	γ^2*
f	180	5000	5000	1$*$
D	0.6	0.1	8×10^{-4}	1$*$
P	74 kW	500	63,000	1$*$
N	5×10^{10}	1.2×10^8	1.5×10^{10}	γ^{-1}
σ_z	1000 μm	0.4	0.4	γ^{-2}
σ_r	18000Å	2.5	315	γ^{-2}
δ	8×10^{-4}	0.29/30,000	0.29/30,000	$\gamma^{-1/3}$
ϵ_n	3×10^{-5}m-Rad	2.5×10^{-8}	1×10^{-5}	γ^{-2}
β^*	7500 μm	25	0.1	γ^{-2}

3. A Sampler of Recent Work

There have been many novel ideas for new acceleration techniques. An excellent reference is the Proceedings of the Workshop on Laser Acceleration of Particles.[6] Here I only have time to give the basic idea behind a few of the techniques. A plasma beat wave accelerator uses two laser frequencies to generate a beat wave. These lasers shine through a plasma where the beat wave excites a plasma oscillation. The electric fields of this plasma oscillation are then used to accelerate electrons. A plasma wakefield accelerator functions like a plasma beat wave accelerator except the plasma oscillation is excited with a beam instead of a laser. These plasma accelerators could potentially achieve very high gradients (several GeV/m) as there are no walls to melt. A wakefield accelerator uses the wakefield set up in a structure by an intense low energy beam to accelerate a high energy beam. A grating accelerator uses lasers shining on a grating to create fields capable of accelerating a particle.

A Two Beam Accelerator (TBA) uses a low energy beam to excite a free electron laser. The resulting radiation (of about 1 cm wavelength in the present experiment) is then used to drive a conventional linac waveguide. These different acceleration techniques are at various stages of development. Some are just calculations. Others have been prototyped and had their accelerating fields measured. It is not yet clear which acceleration technique will work the best. All of the methods still need more work. Even if a technique works to accelerate beam, it may still not make a viable accelerator for reasons of high cost or low efficiency. However, the intense fields of many of the above ideas can be used for focusing the beams even if they are too expensive to use for a whole accelerator.

To allow some of these concepts to be tested, there are plans to build an accelerator test facility at SLAC. This facility will provide a 50 MeV electron beam synchronized with a 10 μm laser pulse which can be used to power a laser accelerator. The electron beam has an extremely small emittance of 1.5×10^{-8}. This is 3 orders of magnitude smaller than that of the SLC. There will be optics to focus the beam down to a 0.5 μm waist with a 3.2 mm depth of field. This small emittance and spot size are achieved by restricting the number of accelerated particles to 10^5. This allows the source to be a 20 μm photo cathode. With such a small source size, no damping ring is necessary to achieve the small emittance.

SLC has an accelerating gradient of 20 MeV/m. With this gradient a 5+5 TeV collider would be 2×250 km long. Clearly higher gradients will be needed to make such a machine practical. Gradients are limited by problems of electrical breakdown or surface melting in the acceleration cavity. Recent experiments using a standing wave in a SLAC disk loaded waveguide showed that an accelerating gradient of 150 MeV/m could be achieved at 10 cm wavelength without breakdown. Using the scaling rule that the breakdown voltage is proportional to $\omega^{\frac{7}{8}}$ it appears that 1 GeV/m should be feasible at $\lambda = 1$ cm. This would result in a 2×5 km long accelerator. This is a much more reasonable length.

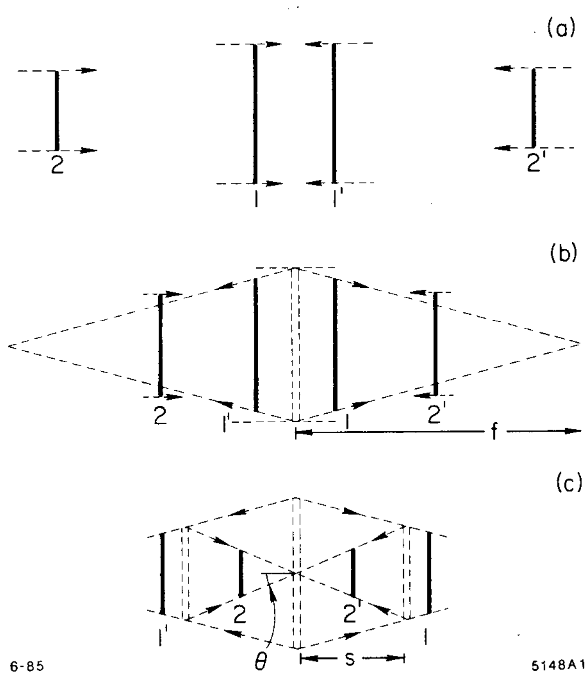

Fig. 2. Super disruption. The beams focus each other as described in the text.

Making a very strong final focus (small β^*) is an important part of the attainment of high luminosity. As many of the proposed acceleration methods have transverse fields as large as their longitudinal accelerating fields, several schemes have been developed to use short accelerator sections as focusing devices. Another scheme, called super disruption,[7] has been suggested. In it, the beams focus themselves. This idea is illustrated in Fig. 2. Each beam consists of 2 bunches separated by about 1 mm. They are focused by conventional means to a β of, for example, 1 cm. As the first bunches of each beam pass through each other, they focus one another. Note that if the bunches have a uniform charge distribution, the magnetic field is proportional to the radius and the bunch makes a perfect spherical lens. Only chromatic aberrations will be present. After the first two bunches have passed through each other, they are converging to a point at a distance f from the center (Fig. 2(b)). After a further distance, they meet the second bunches and focus them. With careful arrangement of the bunch spacing and charges the second bunches will be focused to a small spot size at the collision point. Using beam parameters similar to the low power example in Table 2 a β^* of 24 μm could be achieved. This remarkably strong focusing can be achieved because of the enormous fields and gradients inside one of these bunches. For this example, the field at the edge of the bunch is 10^{10} Gauss and the gradient is 4×10^{16} Gauss/cm. Compare this to the 7×10^4 G/cm that the superconducting quadrupoles for the SLC are expected to achieve. Super disruption is not without its problems however. Realistic beams do not have uniform charge distributions; they are usually Gaussian. Hence the lens quality will not be perfect and the gain will not be as great as calculated. It is also nontrivial to maintain the bunch separation and intensities with the required accuracies.

3.1 DAMPING RINGS

To obtain the high luminosity needed by a 5 TeV collider without using an enormous power requires a small emittance. The SLC has an emittance of 3×10^{-5}. Can the emittance of 2.5×10^{-8} of Table 2 be achieved? This is 3 orders of magnitude smaller than that of the SLC. The creation of low emittance beams is a place where synchrotron radiation is useful for a change. In a damping ring, electrons emit radiation in their direction of motion. If an electron has some transverse momentum, the radiated photon carries some of this away. The electron is then accelerated in an RF cavity where only the longitudinal momentum is replaced. Hence as a result of emitting a synchrotron radiation photon and being reaccelerated, the electron ends up with less transverse momentum and thus the emittance (product of beam size and angular spread) is reduced.

Unfortunately, the emittance can't be reduced indefinitely this way. There are heating mechanisms which tend to make the beam larger. The final emittance is determined by the equilibrium between the heating and cooling mechanisms. The two heating mechanisms are coulomb scattering and synchrotron radiation. Both change the energy of an electron: in the latter by the emission of a photon and in the former by the elastic scattering of the electrons off another one in the same bunch. In both cases this change in energy results in an increased transverse oscillation because particles of different energies follow different orbits in a storage ring and after losing energy the electron oscillates about the new orbit. To minimize these heating effects a damping ring needs to have very strong focusing (high tune, Q_x) so the orbits for electrons of different energy are not very different.

It is difficult to obtain a high tune in a conventional storage ring because there is not enough room to put all the quadrupoles to do the focusing. Following the suggestion of Steffen,[8] Palmer[9] has added a new wrinkle to an old idea. Namely, he has described a damping ring where each bending magnet wiggles the beam in addition to bending it. The ratio of the average field to the local absolute field is called the wiggler fraction, α. For a given bending field and beam energy these wiggler-bend magnets allow a larger radius and thus there is more room for quadrupoles. Optimizing the rings parameters to give an equilibrium emittance of 1×10^{-8} results in the parameters shown in Table 3. Note that the tune is very large (390) and the beam pipe is very small (2.5 mm). The latter allows small quadrupoles which can then provide stronger focusing. The cooling time is still reasonably short so one such ring would suffice to provide the 5000 Hz repetition rate needed for the 5 TeV collider. The described ring would not be easy to build as it has very tight alignment tolerances, but it should be feasible. The parameters have only been derived using scaling laws. A detailed design is needed to be sure it is feasible.

Table 3. Wiggler damping ring parameters.

		SLC	Wiggler D.R.	
ϵ_n	Equilibrium emittance	3×10^{-5}	1×10^{-8}	m-Rad
N	Particles/bunch	5×10^{10}	4×10^{8}	
E	Energy of Damping Ring	1.2	2.4	GeV
R	Radius of ring	5.6	130	m
α	Wiggler fraction	1	0.06	
Q_x	Tune	7.25	390	
τ	cooling time constant	3	0.9	msec
d	Beampipe diameter	25	2.5	mm

4. Conclusions

The development of high energy linear collider technology is still in its infancy but is advancing rapidly. No detailed design exists but scaling laws have been used to narrow down the possible range of beam parameters. Many technologies are being investigated and many new ideas have been put forward in the past couple of years. It still is not clear what accelerator technology should be used. All of them should be pursued for a few years. More work is needed on scaling laws and cost estimates to aid in the determination of the best technology. It is already clear that low ϵ and β^* are necessary. Hence work done towards achieving this will be profitable independent of the acceleration method. There are also more down-to-earth problems which need consideration such as: ground motion, alignment, getting angstrom size beams to collide, and making micron long bunches. It is a real challenge to create the next linear collider. A lot of creative effort is still needed. It may be as much fun as the unravelling of the mysteries of the fundamental particles and forces that its completion will allow.

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