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THE SLAC-LINAC-COLLIDER (SLC) PROJECT*

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Abstract

The proposed SLAC Linear Collider Project (SLC) and its features are described in this paper. In times of ever increasing costs for energy the electron storage ring principle is about to reach its practical limit. A new class of colliding beam beam facilities, the "Linear Colliders", are getting more and more attractive and affordable at very high center-of-mass energies. The SLC is designed to be a pioneer of this new class of colliding beam facilities and at the same time will serve as a valuable tool to explore the high energy physics at the level of 100 GeV in the center-of-mass system.

I. Introduction

The center-of-mass energy of fixed target accelerators as well as electron positron storage rings has gone up by a factor of about 10 for every 10 years. In the case of the fixed target accelerators we know that this progress was possible only because new techniques have been developed in time before the old technique reached its limitation.

It seems that the design of the storage ring LEP in Geneva will stretch the principle very close to its fiscal limit. The design of an electron positron storage ring with a center-of-mass energy of say more than 200 GeV leads to unrealistically high investment and operating costs.

We at SLAC have committed ourselves to the development of a new technique for a colliding electron positron beam facility which seems feasible, both economically and technically, for center-of-mass energies far into the hundreds of GeV. The idea is about as old[1] as it is simple. Take two linear accelerators aiming at each other, one producing a beam of electrons, the other a beam of positrons and collide these two beams. Obviously there is no synchrotron radiation involved, which causes the cost for storage rings to scale much faster than the energy. On the other hand, the cost for linear accelerators scales just like the energy. Not all the necessary technology for a colliding linac beam facility has been developed yet and therefore it is difficult to make accurate cost comparisons. However, it is believed that a center-of-mass energy of some 200 GeV marks the transition point above which linear colliders become less expensive than storage rings.

The Stanford Linear Collider (SLC) project[2,3] is designed to be a pioneer facility to demonstrate the feasibility of larger colliding linac beam facilities. Apart of being the first of its kind, the energy of the SLC of 100 GeV in the center-of-mass system is high enough to allow us to investigate the unification of the weak and electromagnetic interactions which is expected to manifest itself just below this energy.

II. The SLC Project

1) General Description

The SLC project is a variant of a linear collider in as far as it uses only one linear accelerator. Both the electron and the positron bunch are accelerated in the same linac rf-pulse. At the end of the linac both beams are separated and travel through long arcs till they aim at each other. There a final focus system will compress the transverse size of the beams at the collision point to a radius of about 2 micrometer.

The luminosity of a linear collider is given by

$$\mathscr{L} = \frac{N^+ N^- \nu_{rep}}{4\pi\sigma^2} \tag{1}$$

where N^+, N^- are the number of particles in the respective bunches, ν_{rep} the linac pulse repetition rate and σ the radius of the beam at the collision point. With the present performance parameters of the Stanford Linear Accelerator we could expect a luminosity of no more than about $10^{24}\text{cm}^{-2}\text{sec}^{-1}$ apart from the fact that the beam energy would be only 30 GeV. The SLC project, to be a feasible facility for high energy physics, requires therefore a significant upgrading of the linac beam parameters in energy, intensity and beam emittance (Table 1). The higher energy requires some modification of the klystron modulator while the intensity of the beams can be drastically increased only by completely new designs of the electron gun as well as the positron source. The required small beam emittance is achieved by two small storage rings (damping rings) where the beams are stored for a few milliseconds to reduce the beam emittance through synchrotron radiation. A more detailed description of the new components will follow later in this report.

Table 1

	SLAC now		For SLC
energy (GeV)	32		50
intensity/S-band bunch	e^+	e^-	e^+/e^-
	10^8	10^9	$5\cdot10^{10}$
beam emittance $\sigma\,\sigma'\gamma$(m)	$6\cdot10^{-3}$	$6\cdot10^{-4}$	$3\cdot10^{-5}$

A schematic layout of the SLC facility is shown in Fig. 1 and the operation cycle goes as follows. This cycle begins just before the pulsing of the linac. The electron and positron damping rings each contain two bunches of 5×10^{10} particles at an energy of about 1.2 GeV. One of the positron bunches is extracted from the damping ring, passes through a pulse compressor which reduces the bunch length from the centimeter typical of the storage ring to the millimeter required for the linac, and is then injected into the linac. Both electron bunches are extracted from the electron damping ring, pass through an independent pulse compressor, and are injected into the linac behind the positron bunch. The spacing between bunches is 17.8 meters in the linac.

The three bunches are then accelerated down the linac. At the two-thirds point, the trailing electron bunch is extracted from the linac with a pulsed magnet and directed onto a positron-production target. The positron bunch and the leading electron bunch continue to the end of the linac, where they reach an energy of 50 GeV. At the end of the linac the two opposite charge bunches are separated into the two arcs after which they pass through an achromatic matching and focusing section to collide head on with the opposite beam.

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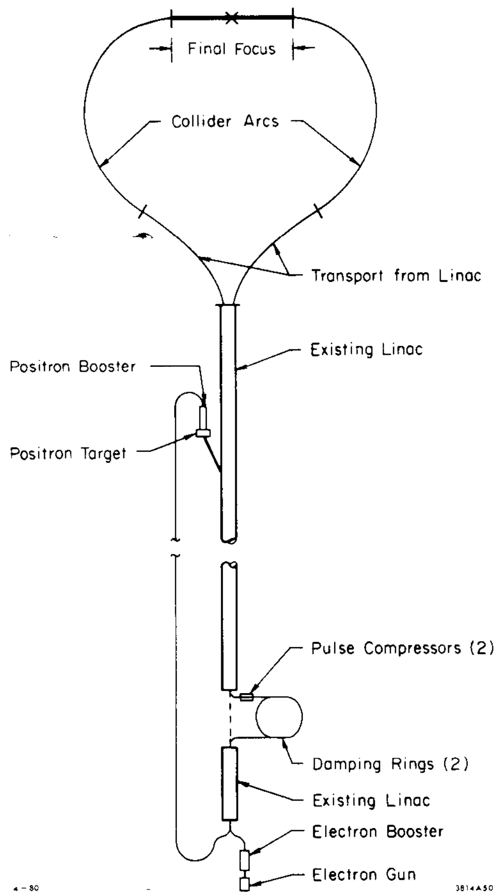

Fig. 1. General layout of the SLAC Collider.

The positrons produced by the "scavenger" electron bunch that was extracted at the two-thirds point of the linac pass through a focusing system at the positron source, a 200 MeV linear accelerator booster, a 180° bend, and an evacuated transport pipe located in the existing linac tunnel. This brings the positron bunch back to the beginning of the linac. At this point, the positrons pass through another 180° bend and are boosted to an energy of 1.2 GeV in the first sector of the existing linac and then injected into the damping ring.

2) New Components for the SLC Project

Modification of the klystron modulator. In order to get a higher energy in the linear accelerator the second stage of the SLED rf-pulse compression system (SLED II)[4] will be installed. In the SLED principle the amplitude of the rf-pulse is increased at the expense of the pulse length. The maximum energy we expect to reach in this way is 51.6 GeV.

Electron source.[5] $5 \cdot 10^{10}$ or more electrons must be produced into a small emittance and captured into a single S-band bucket. Thermionic guns fall far short of meeting these characteristics. We will therefore utilize a powerful frequency doubled, actively mode locked, Q-switched Nd: YAG laser to produce the electrons by photoemission from a semiconductor cathode. Such a gun has been used successfully at SLAC to provide polarized beams for the recent parity violation experiment.

Positron source. Since we need as many positrons as we have electrons per bunch we are faced with the problem of producing one useful positron for every electron that strikes the convertion target. Fortunately the positron production is proportional to the energy of the electron. We accelerate therefore an electron bunch up to 33 GeV. At this point the electron bunch gets directed to a tungsten-rhenium target to produce positrons. A series of pulsed and dc-solenoids between 100 kG and 5 kG capture positrons between 2 and 20 MeV at an emittance of 5 MeV mm. The effective yield is calculated at 4.8 positrons for each electron. This is far more than we need but it seems prudent to allow for considerable losses between the target and the damping ring.

Damping rings and bunch compressor.[6] Two damping rings are required since both electrons and positrons cannot be produced with the required small emittance and high intensity. Some of the parameters of the damping rings are compiled in Table 2.

Table 2

energy	$E = 1.21$ GeV
intensity	$N = 5 \cdot 10^{10}$ particles/bunch or
	$I = 68$ ma/bunch
no. of bunches	$n = 2$
circumference	$C = 35.27$ m
tunes	$\nu_x/\nu_y = 7.23/2.78$
damping time	$\tau_{x,y} = 3.06$ msec
equilibrium beam emittance	$\varepsilon_x = \varepsilon_y = 9 \cdot 10^{-9}$ rad m

In order to achieve fast damping we have to utilize high bending fields (2 Tesla) and to obtain small emittance the focusing has to be very strong (63 T/m).[7] We need for the electrons a damping time of one inter linac pulse interval of 5.6 msec and twice that much for positrons. Therefore, every 5.6 msec there are 2 electron bunches and one positron bunch ready to be accelerated in the linac. One of the electron bunches will be used for positron production and the other electron bunch and the positron bunch are accelerated to 50 GeV for collision.

The damping of the bunches introduces a slight complication. Particle bunches in storage rings are of the order of 2 cm long. This is too long a bunch for an S-band linear accelerator. Between the damping ring and the linear accelerator, we therefore have a bunch compressor system. This system compresses the bunch length to 1 mm at the expense of the energy spread.

Linac control system. The acceleration of $5 \cdot 10^{10}$ particles in one S-band bucket in SLAC is at this time not feasible. The interaction of a bunch of this intensity ($I_{peak} = 2400$ amps) with the accelerator structure generated wake fields which act back on the bunch in a destructive way. There are two components of the wake field. The longitudinal component generated by the head of the bunch decelerates the tail of the bunch causing a large energy spread. This effect we can counteract by accelerating the bunch ahead of the crest of the rf-wave. In this way the tail gets accelerated more than the head and if we now add the deceleration of the tail due to the wake field we can minimize the energy spread at the end of the linac. An energy spread of less than 1% seems to be possible.

If the head of a bunch travels off center through an accelerating structure a transverse wake field is generated. This field acts back on the tail of the bunch in such a way as to increase the deviation from the center. Therefore, a straight bunch changes more and more to a "banana" shape during acceleration till the tail gets scraped off. This is called the beam break-up phenomenon. Clearly the effect is enhanced proportional to the charge in the bunch. For a given charge in the bunch this beam break-up can be minimized by improving the focusing, the control of the trajectory in the accelerator and the alignment of the accelerator. A major upgrading of the linear accelerator control system is required to make the SLC project a viable project. With the new control system calculations show that for a bunch population of $5\cdot10^{10}$ the emittance growth due to the "banana" effect is not more than 15% assuming an alignment tolerance of 0.1 mm for the focusing elements and the accelerating structures. With some optimism and operating experience it might be possible later to increase the intensity to about $7\cdot10^{10}$ particles per bunch.

Arc beam transport and final focus. After acceleration to 50 GeV the two bunches are split and travel through two half circles toward the collision point. Special precaution has to be taken to minimize the increase of the beam emittance due to synchrotron radiation. The growth in the beam emittance is given by

$$\Delta\varepsilon \text{ (rad m)} = 2.1\cdot10^{-11}\rho\phi\langle\mathscr{H}/\rho^3\rangle\, E^5 \qquad (2)$$

where ρ(m) is the bending radius, ϕ(rad) the total bending angle of the arc, $\rho\cdot\phi$ the length of the arc, E(GeV) the energy and $\langle\mathscr{H}/\rho^3\rangle$ a quantity which depends on the focusing and the bending radius. Since $\langle\mathscr{H}/\rho^3\rangle \sim \rho^{-5}$ it is clear that the arcs should be as large as the available site allows them to be. The focusing is chosen to be very strong to get a betatron phase advance of 120° which gives a minimum emittance growth.[8,9] With these parameters in mind it turns out impossible to design a separated function lattice which would not destroy the small beam emittance coming from the linac. We chose therefore a combined function magnet with a cross section as shown in Fig. 2. Each arc has some 400 magnets

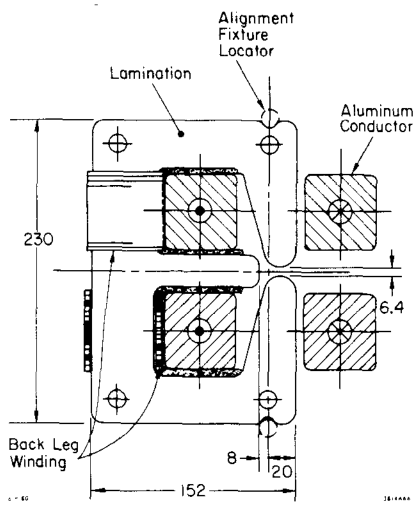

Fig. 2. Cross section of the SLC arc magnets. Dimensions are in millimeters.

each 2.6 m long with every second magnet rotated by 180° about the beam axis with respect to the orientation of the magnet in Fig. 2. This way one cross section serves for both the focusing and the defocusing magnet. All magnets are strung like beads on four aluminum conductors which serve as the excitation coils.

At the ends of the arc the beam enters a 100 m long final focusing system which compresses the typical beam size of 100 μm in the arc down to 4 μm at the interaction point. Since the energy spread in the beam is about ±0.5% we face severe chromatic image errors in the final focus system. A sophisticated final focus system was worked out to both minimize the chromatic and geometric (astigmatism etc.) errors in the beam spot size at the collision point. A ray tracing study confirmed the feasibility of the design of the final focus system.[10]

In Fig. 3 the result of the ray tracing calculations shows 50% of the beam within a radius of 2μ and 90% within 4μm which is what we assumed as a design goal.

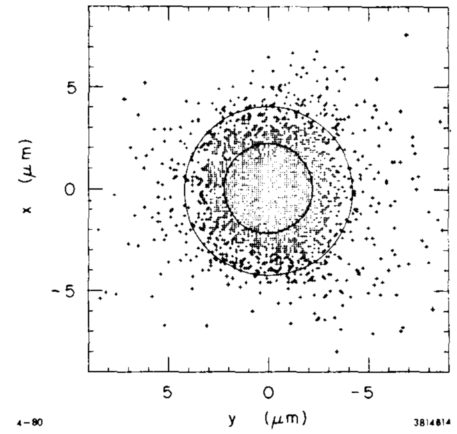

Fig. 3. A scatter plot of 3000 rays traced through the final focus system.

III. Luminosity and Improvements

At the collision point we expect the $5\cdot10^{10}$ particles per bunch to have a gaussian distribution with a standard value for the beam radius of σ = 2 μm at 50 GeV. Since the pulse repetition rate is ν_{rep} = 180 sec^{-1} we calculate from Eq. (1) a luminosity of

$$\mathscr{L} = 1 \times 10^{30} cm^{-2} sec^{-1} \text{ at 50 GeV} . \qquad (3)$$

For other energies the luminosity is shown in Fig. 4.

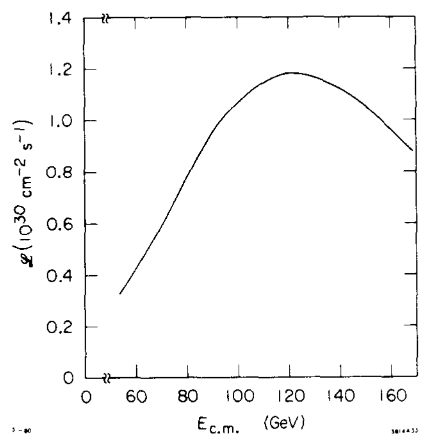

Fig. 4. Luminosity vs center-of-mass energy in the SLC.

Here at lower energies the luminosity increases with energy since adiabatic damping during acceleration in the linac reduces the beam emittance. At energies above 60 GeV per beam, however, the emittance blow-up in the arcs becomes dominant and reduces the luminosity.

A good prediction of the luminosity in storage rings always has been very difficult because it is still not known which parameters cause the beam-beam effect to limit the luminosity at a certain level. We think that a much safer prediction of the luminosity can be made for a colliding linac beam facility. Unlike in a storage ring here the beams meet only once and are disposed of after the collision. We, therefore, believe we can calculate what actually happens when both beams collide.

When an electron and positron beam collide each beam is focussed by the other beam, a phenomenon well known in plasma physics as the pinch effect. In Fig. 5 the ef-

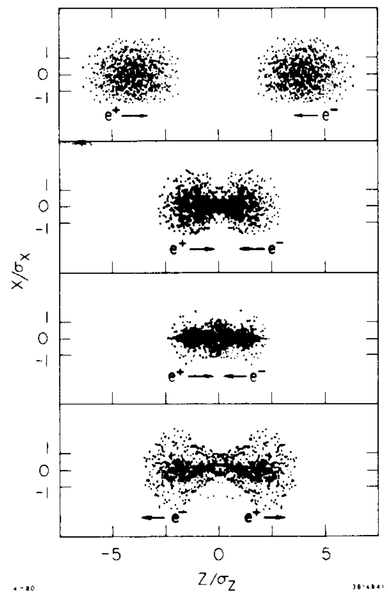

Fig. 5. Side view of the collision of oppositely charged beams, showing the pinch effect for Gaussian profiles and a disruption factor D = 14.4.

fect of the pinch effect on the beam cross section is shown.[11] Obviously there is an effective reduction in the cross section which should lead to an increase in luminosity. We parametrize the pinch effect with the so-called disruption parameter D, which is defined as the ratio of the bunch length σ_z to the focal length f due to the space charge focusing of the other beam. We have

$$D = \frac{\sigma_z}{f} = \frac{r_e N \sigma_z}{\gamma \sigma^2} \qquad (4)$$

where r_e is the classical electron radius, N the number of particles per bunch, γ the energy and σ the beam radius at the collision point. Numerically it has been found that with increasing disruption parameter the luminosity can be increased up to a factor of six.[11]

In the first stage of the SLC project we expect a disruption parameter of only $D \approx 0.4$ and the luminosity is expected to increase only by about 30% above the value quoted in Eq. (3) for 50 GeV. There are, however, possibilities for improvement.

One possibility, which is evolutionary, is to attain more precise control of the trajectory in the linac. This would allow an increase in the number of particles to maybe $7 \cdot 10^{10}$ per bunch before exciting serious emittance growth from transverse wakefields.

Another possibility is being actively pursued at SLAC right now. This is to reduce the beam spot size at the collision point further to about 1.3 μm. In order still to control the chromatic and geometric errors we plan to use for the last quadrupoles on either side of the collision point permanent magnets made from a cobalt samarium alloy ($SmCo_5$).[12] Such magnets have a permeability of $\mu = 1$ and can therefore be moved into the detectors without perturbing the detector fields. A small sample quadrupole has been found suitable and a full size prototype is being built soon. If both improvement possibilities should be realized we could expect a luminosity of $4.7 \cdot 10^{30} cm^{-2} sec^{-1}$ without enhancement due to the pinch effect and $\mathscr{L} = 2.3 \cdot 10^{31} cm^{-2} sec^{-1}$ if we include the pinch effect.

Longitudinal Polarization

From a theoretical point of view it is very important to do the high energy physics experiments with polarized beams. We do not see any practical way to produce polarized positron beams but the type of electron source used in the SLC project has already produced an intense beam of longitudinally polarized electrons.[13] The polarization then was 50% and with the new electron gun a polarization of 90% seems possible.

The longitudinally polarized electron beam is accelerated to 1.21 GeV. In the transport system from the linac to the damping ring a proper combination of vertical magnetic fields and a 6Tm superconducting solenoid will cause a g-2 precession such as to erect the electron spin into the vertical direction.[14] This direction of the spin will be preserved during the storage time in the damping ring. In the transport line from the damping ring to the linac we have two 6Tm superconducting solenoids together with the necessary vertical magnetic fields. Depending on the setting of the strength of these two solenoids we can produce any spin direction we want at the reentry point to the linac. In practice this spin direction will be chosen such that together with the g-2 precession in the collider arcs we obtain the desired polarization (longitudinal or transverse) at the collision point.

Conclusion

The SLC is designed to be a pioneer project for a new kind of colliding electron positron beam facility. It serves two purposes, first to provide a center-of-mass energy at the collision point of 100 GeV to allow the exploration of an extremely interesting area in high energy physics, second to test the feasibility and special features of still larger linear colliding beam facilities.

Critical questions for such a facility can be answered from the operation of the SLC, like what are the maximum charges per bunch that can be generated and accelerated in a linear accelerator, what is the minimum beam emittance achievable, is our present knowledge on the final focus system sufficient, can we use permanent magnet quadrupoles and does the pinch effect work in our favor.

Since the electron storage ring technique is reaching its limits, new avenues in accelerator physics have to be pursued and we at SLAC are ready to do just that.

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