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INTENSE BEAMS AT THE MICRON LEVEL FOR THE NEXT LINEAR COLLIDER*

John T. Seeman
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

ABSTRACT

High brightness beams with sub-micron dimensions are needed to produce a high luminosity for electron-positron collisions in the Next Linear Collider (NLC) [1]. To generate these small beam sizes, a large number of issues dealing with intense beams have to be resolved. Over the past few years many have been successfully addressed but most need experimental verification. Some of these issues are beam dynamics, emittance control, instrumentation, collimation, and beam-beam interactions. Recently, the Stanford Linear Collider (SLC) [2] has proven the viability of linear collider technology and is an excellent test facility for future linear collider studies.

PARAMETERS OF THE NEXT LINEAR COLLIDER

The luminosity of a future linear collider [3] must increase approximately as the square of the beam energy. Then, the projected event rate is constant at all energies given an expected cross section that falls with the square of the energy. The desired increase in luminosity with energy is shown in Figure 1. The methods to increase the luminosity can be seen from the equation for the luminosity L.

$$L = k\, N^- N^+ f / 4\pi\ \sigma_x\ \sigma_y\ , \qquad (1)$$

where N^- is the average number of electrons in a bunch, N^+ is the corresponding number of positrons, k is the number of bunches in each beam, f is the repetition rate, and σ_x and σ_y are the horizontal and vertical beam sizes at the interaction point (IP), respectively. Multiple bunches, large bunch charges, high repetition rates, and small spot sizes are all desirable. All of these goals push technological limits. Multiple bunches make the task of having equal bunch energies at the end of the linac difficult as well as requiring more difficult injectors and damping rings. Large bunch charges require strong dispersion and wakefield controls indicating tight alignment and control tolerances. High repetition rates introduce considerations of reasonable AC power usages and average power issues of RF systems (modulators, loads, klystrons, ...). Small spot sizes require very small emittance sources, careful bunch length shortening after the damping rings, control of acceleration, and highly corrected final focus systems. Finally, the overall efficiency of operation must be as close to unity as possible so that the time integrated luminosity is maximized.

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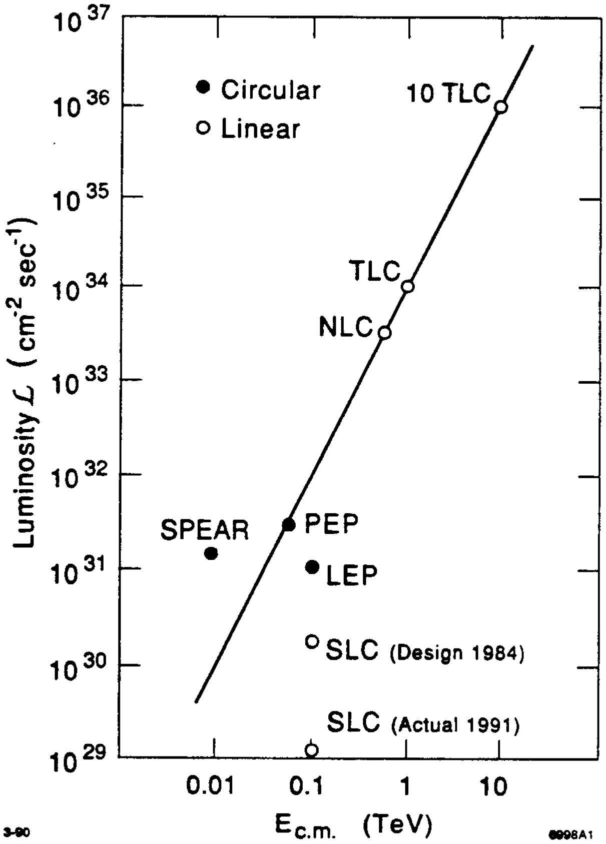

Figure 1 Desired increase in luminosity with center of mass energy for future linear colliders.

NLC REQUIRED LUMINOSITY

The required luminosity of the NLC at 250 GeV per beam is about 3 X 10^{33} $cm^{-2}\ s^{-1}$, which is a factor of about 33,000 over the present routine value of the SLC. The parameter changes that lead to this necessary increase are shown in Table 1. The parameters for a potential 10 TeV collider are also shown for comparison [3]. The expected increase in luminosity for the NLC comes primarily from the reduced spot sizes (X 3900) but partially from accelerating more bunches (X 10) and a higher repetition rate (X 3) but with a lower charge per bunch (X 0.28). Thus, the main task, in addition to providing the appropriate acceleration, is to increase the density of the bunches ($N / \sigma_x \sigma_y$) at the IP by a factor of 1100 from the SLC to the NLC. There are several contributing factors. The number of particles per bunch is reduced for reasons of the energy spectrum and multibunch energies. The betatron functions at the interaction point are reduced approximately by factors of 2 horizontally and 50 vertically. The increased acceleration by a factor of five reduces the emittances by that factor. At the final focus vertically flat beams are desired to reduce beam-beam effects. Thus, the injected invariant emittances provided by the sources (damping rings) must be reduced by a factor of 10 horizontally and 1000 vertically over the SLC. Consequently, considerations to preserve the vertical emittance dominate nearly all tolerance issues.

Table 1 Parameter comparison for SLC, NLC, and 10TLC

Parameter	SLC (actual)	NLC	Ratio NLC / SLC	10TLC
Luminosity (10^{31} /cm/s)	0.01	300.	X 3 X 10^4	1 X 10^5
Energy (GeV) / beam	50	250.	X 5	5000
Bunch length (mm)	1.1	0.075	X 0.07	0.015
Repetition rate (Hz)	120	360	X 3	150
Bunches / beam	1	10	X 10	120
σ_y (nanometers)	2500	4	X 625	0.1
σ_x (nanometers)	2500	400	X 6.3	27
(Charge / bunch)^2	$(3 \text{ X } 10^{10})^2$	$(1.6 \text{ X } 10^{10})^2$	X 0.28	$(0.4\text{X}10^{10})^2$

BRIGHTNESS OF BEAMS

The emittance of a particle bunch cannot be reduced to below that given by the uncertainty principle.

$$\Delta x \, \Delta p_x = \gamma \, mc \, \sigma_x \, \sigma_{x'} = \gamma \, \varepsilon_x \, mc \geq h / 2\pi \qquad (2)$$

where p is the momentum, c is the speed of light, mc^2 is the mass of the electron, γ is the relativistic energy E/mc^2, ε is the emittance, and $h/2\pi = 6.58 \times 10^{-22}$ MeV sec. A similar equation holds for the vertical emittance. It is not surprising that the invariant emittance is the natural measure of this uncertainty limit. Given the necessity of flat beams, the vertical limit is reached first. A plot of the required vertical emittance projected as a function of the beam energy is shown in Figure 2. The SLC beams are a factor of 10^8 from the uncertainty limit. However, the NLC is only a factor of 10^5 from the limit. With the present scaling laws, the uncertainty limit is reached at center of mass energies in the range 100 to 500 TeV. At those energies the flat beam requirement must be relaxed.

The beam brightness B for future linear colliders can be calculated for a single bunch given the emittances and the number of particles.

$$B = N / \pi^2 \gamma \varepsilon_x \gamma \varepsilon_y \qquad (3)$$

Examples of several accelerators with single bunch pulses (no multiple pulse stacking) are shown in Table 2 along with projections of the NLC. The achieved SLC brightness is significantly above (X 10^4) that produced by either older conventional linacs or injected and damped single bunches in a second generation storage ring (PEP). The NLC bunches must be brighter than those of the SLC by a similar factor (3 X 10^3).

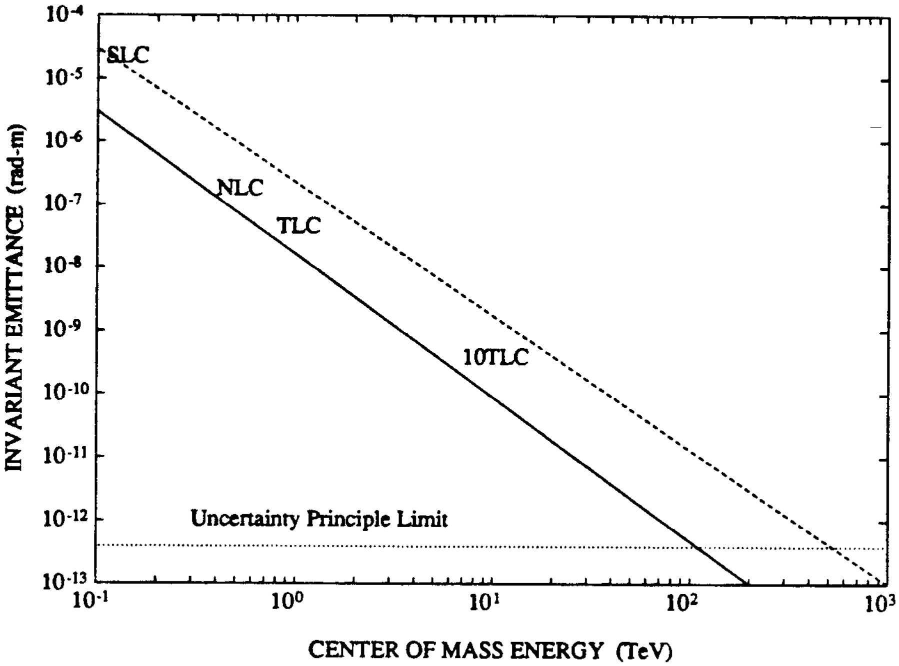

Figure 2 The uncertainty principle limit for the emittance is reached in the vertical dimension for colliders with center of mass energies of 100 to 500 TeV.

Table 2 Beam brightness for existing and future single pulse accelerators.

Accelerator	E (GeV)	N (10^{10})	$\gamma \varepsilon_x$ (10^{-5} r-m)	$\gamma \varepsilon_y$ (10^{-5} r-m)	$B=N/(\pi^2 \gamma \varepsilon_x \gamma \varepsilon_y)$ (m^{-2})
SLAC Linac*	30.	0.1	300.	300.	1.1×10^{13}
SLAC PEP**	14.5	0.2	340.	10.	6.0×10^{14}
SLC(Actual)	50.	3.0	3.0	2.7	3.8×10^{18}
NLC (Design)	250.	1.6	0.38	0.0038	1.1×10^{22}

* Before SLC upgrades.
** Single linac pulse, then damped in PEP.

ACCELERATOR PHYSICS NEEDED FOR THE NLC

There are many beam dynamics issues of concern for the next linear collider. The various subsystems of the NLC have different requirements for beam brightness and, thus, have different needs (1) for instrumentation due to phase space density, (2) for emittance control from chromatic and wakefield effects, (3) for halo collimation from backgrounds, and (4) for the beam-beam effects during collisions. Many of these issues have been resolved [4]. However, most solutions call for experimental verification.

Damping Rings

Damping rings for the NLC must operate at a high repetition rate (60 to 360 Hz) producing a horizontal equilibrium emittance an order of magnitude smaller than the SLC and with flat beams where the vertical emittance is about one percent of the horizontal. Wiggler magnets in low dispersion insertions are required to increase the radiation and thus reduce the damping time to 1 to 3 milliseconds with minimal increase in the equilibrium emittance. The choice of the optimum energy is important because of the strong effect of intrabeam coulomb scattering at low energies and strong quantum fluctuations at high energies which lead to emittance growth. Transverse and longitudinal instabilities, for example mode coupling and longitudinal multibunch effects, also influence the ring design as the bunch intensities and the number of bunches strongly effect the instability thresholds. Ring energies of 1.5 to 3 GeV are optimum in the present designs.

In addition to providing a rapid damping time, these rings must accept and damp several batches of bunches. In SLAC's NLC design ten batches of ten bunches are required. The vacuum chamber design must have a reduced impedance to avoid transverse and longitudinal instabilities. The radiation loading is not severe but requires care. To provide the required beam spacing and stability, the RF frequencies for the various designs tend to be higher than that of present rings reaching values of 1 to 3 GHz. The resulting bunch lengths are 1.3 to 8 mm, depending on the design. The use of many bunches requires feedback systems similar to the B Factory designs and common investigations can be made.

To test these systems several experimental studies are underway. There is a proposal to build a version of the damping ring for the Japan Linear Collider (JLC) [5] at KEK, which could start construction in 1992. At SLAC studies are under investigation to operate the SLC damping ring in an uncoupled regime to study the production of very flat beams and provide a decoupled beam to the Final Focus Test Beam [7].

Bunch Length Compression

In order for the main NLC linac, operating at x-band frequencies, to accelerate the bunches efficiently, the bunch length must be quite short. Lengths (σ_z) on the order of 0.03 to 0.08 mm are needed. The bunch lengths in the damping rings are, on the other hand, about a factor of 100 larger. Bunch length shortening is done with magnetics compressors. The new designs have two compression sections separated by a preaccelerator of 5 to 15 GeV to avoid the strong chromatic emittance enlargement expected in a single compressor. Each compression section contains an accelerator phased at 90 degrees to produce an RF induced head-tail energy spread of order 1 percent followed by a non-isochronous bend. The tolerances on the chromatic and geometric effects in these transport lines have a similar flavor to those calculated for the SLC Arc system. Anomalous dispersion, magnet rolls, RF phase errors, second order chromatic terms, ring coupling, magnet stability, and feedback systems are all important.

Linear Accelerator

The main NLC linear accelerator provides about 250 GeV of energy gain. The accelerator between the two bunch length compression sections contributes about 5 to 15 GeV. These accelerators must not increase significantly the invariant emittances of each bunch. (The absolute emittances, however, are reduced directly though acceleration, inversely with energy.) Furthermore, to keep within economically and environmentally acceptable limits, the total accelerator power should be limited to below 100 to 300 MW, including any future upgrade to increase the beam energy. An x-band frequency is the likely choice as it provides more gradient per stored joule of energy than present s-band structures and has parameters not too far from conventional working klystrons.

The RF power source must provide approximately 100 MW over a 100 to 800 nsec pulse. Several designs are under intense investigation. Several possible devices are nearing the power levels needed when combined with RF pulse length compression schemes. Several examples have been discussed at this symposium.

There are many effects in the linac that can increase the emittance. In the SLC the spot sizes are such that wakefield effects dominate the chromatic effects in most regions of the accelerator. In the NLC the reverse is true. However, the NLC beam intensities are at a level where transverse wakefield effects enter whenever significant accelerator parameters are adjusted.

The acceleration of multiple bunches requires that the RF structures have sufficiently small long range transverse wakefields so that trailing bunches do not experience an increase in their emittances. Therefore, the structures will include a combination of transverse waveguides to damped higher order modes and cell-to-cell detuning to dephase the higher order fields. Furthermore, the captured modes in the structure that are driven by long trains of bunches must be detuned to avoid unwanted multiple beam breakup.

The injection conditions of the beam from the bunch compressors into the linacs are important. Betatron mismatches filament along the linac increasing the emittance. The betatron functions must be matched to about 30 percent. The residual dispersion must be matched to below a millimeter compared with the 1 cm value at the SLC. Static injection errors if uncorrected cause the beam to smear producing a larger beam size and emittance. Second order contributions to the spot size, for example T_{166}, T_{266}, and T_{116} matrix elements, also lead to filamentation. Any quadrupole rolls will skew the beams and cause mixing between the planes. This mixing will produce either real or projected increases of the emittance. The rolls must be controlled to a few milliradians.

The corrected trajectory produced by steering the beam to position monitors with offset errors introduces chromatic and wakefields effects. Also contributing to these effects are the alignment errors of the quadrupoles and accelerator structures. All are further complicated by the effects of energy and energy spectrum changes during acceleration. Careful control of the lattice design and steering algorithms can reduce the effects of chromatic steering on the trajectory and the emittance [8].

The effects of dispersion, betatron mismatches, and wakefields can produce beam dimensions at the end of the accelerator with non-gaussian distributions. Special methods and controls are available to model and control these changes [9].

Feedback systems that work pulse-by-pulse are essential for keeping the beam parameters within acceptable limits for collisions. Beam positions, angles, and energy are controlled routinely in the SLC. Energy spectrum feedback is also important but has proven not to need pulse-by-pulse control. Modern control theory is used to provide cascaded control loops from the beginning to the end of the accelerator that minimally interfere with each other and thus provide maximum control. Reduction of oscillations with frequencies up to one sixth of the accelerator pulse rate can be expected.

Injection jitter that is too fast for the feedback system must be controlled by the elimination of the source or by reducing the beam's sensitivity. Controlling current fluctuations in power supplies, quadrupole transverse vibrations, RF phase and amplitude changes, noise introduced by the feedback system, and man-made seismic activity are of active concern. High repetition rates are best for feedback. The weakening of the effects of jitter on wakefields is also important for emittance control. The use of BNS damping [10] and potentially autophasing [11] are important for operation. The SLC uses BNS damping continuously with great advantage [12]. Examples of observed induced oscillations in the SLC linac with BNS damping in use are shown in Figure 3 and illustrate the complex influence of transverse wakefields on beam trajectories [2].

The halo of a beam is an enlarged population of particles at displacements of 4 to 10 sigma. The population is greater than that expected from gaussian profiles even though only a small fraction of the beam is involved. If these particles enter the final focus, they cause undesirable backgrounds in the physics detector. Removal upstream is important. The present SLC collimation design is not adequate for the next collider as the presence of any asymmetrically placed metal surfaces close to the beam, when combined with the expected small emittances, makes strong wakefields effects. The beam emittance with incorrectly designed collimators can increase significantly [13]. Additional work is needed on collimation for a fully integrated design.

The long term position stability of the accelerator and quadrupole supports and the alignment techniques of the accelerator components depend strongly on the temperature stability in the tunnel and any associated active controls. Temperature control and monitoring at the 0.5 F^{o} level, stable support designs with reduced temperature sensitivities, and new automated alignment procedures are needed [14].

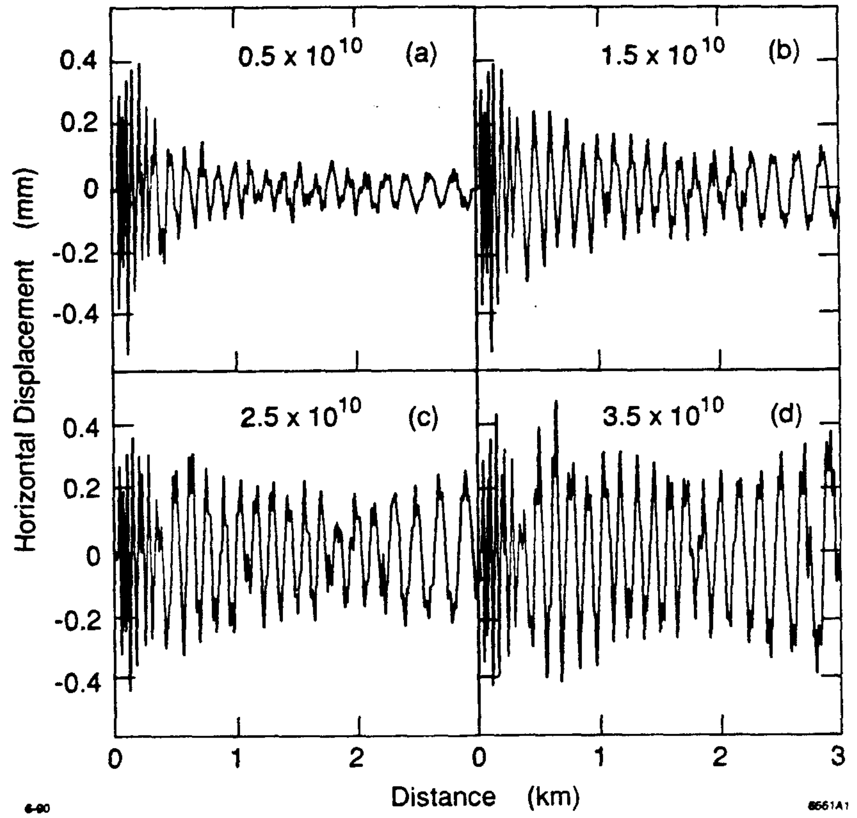

Figure 3 Observed driven single bunch oscillations along the SLC linac for various bunch charges.

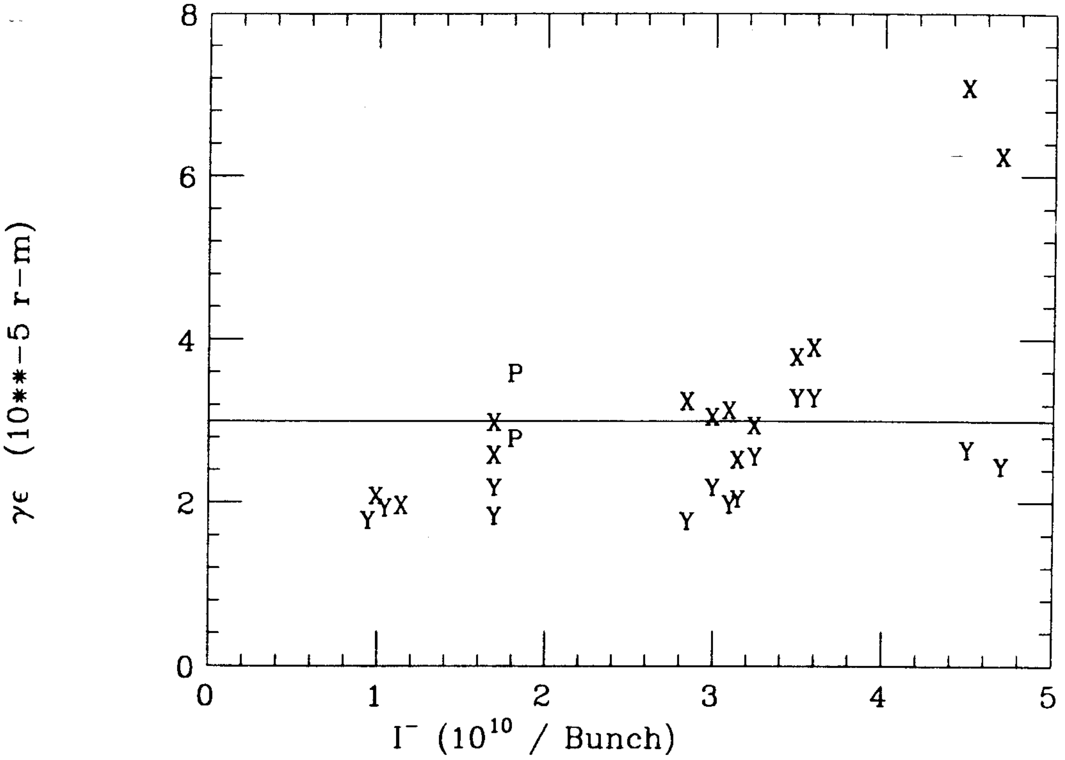

Figure 4 Measured beam emittances at 47 GeV in the SLC as a function of single beam intensity. The design emittances were reached with beam currents up to 3 X 10^{10} during colliding beam conditions. With the use of proven emittances controls, the emittances above 3 X 10^{10} are expected to be reduced in the near future.

Operation and studies of the SLC have shown that these emittance enlargement effects including chromatic and wakefields effects can be controlled during colliding beam operations to provide significant luminosity [6]. The best measured single bunch emittance conditions of the SLC to date are shown in Figure 4. These results were also obtained during collisions with three bunch colliding operation (e+,e-, e- scavenger) up to 3 X 10^{10} particles per bunch. The extension of these techniques to higher currents is now under active study as intensities of near 4.5 X 10^{10} are needed for the next run.

Finally, experimental verification of the accelerator physics effects and cures involved with the NLC are needed before a sound proposal can be made. Many experiments using the SLC to test beams with more realistic NLC parameters including flat beams and low emittances are being considered to be performed over the next several years. In addition, several other laboratories around the world are actively performing tests. Hopefully, the time and the staff needed for these vital linear collider studies will continue to be fully supported.

Final Focus

The very high density beams in the final focus of the next linear collider present many challenges. These new challenges have been dealt with, by in large, using special techniques [3], several to be tested in the Final Focus Test Beam [7] at SLAC.

The required spot sizes are small and flat. The vertical to horizontal size ratio is about 1 to 100. The chromatic correction problem in the final focus is easier with flat beams, and this advantage is fully used in the design. The small vertical size of 3 to 10 nanometers is a difficult size to measure with normal profile devices and many new devices are under consideration.

The two opposing beams are strongly disrupted because they focus each other during collision. The incoming and outgoing beams must use separate vacuum chambers. The incoming chambers have small apertures and use small bore, high gradient quadrupoles. The out going beam has a very large angular spread and needs adequate clearance for reducing backgrounds. Thus, a crossing angle is desired which requires the use of a longitudinal-transverse tilt to the beam at the interaction point to keep the beam aligned during collisions. This tilt is introduced with a transverse RF cavity near the final focussing quadrupoles, in a scheme called crab crossing [3]. On the other hand, disruption is very helpful by producing beam-beam deflections that provide a relatively non-interfering method to align the beams in collision and to determine their spot sizes. Also, the mutual focusing provides some centroid realignment if the two beams are slightly misaligned. The disruption is also expected to increase the luminosity by shrinking the beam sizes. However, to satisfy other constraints, the disruption has been reduced to a point where only minimal luminosity gain can be realized. Also, photons generated by the beam-beam forces interact with the opposing beam causing a low energy background from pair production [15]. This background can be controlled with the choice of beam parameters and the careful design of the masking of the physics detector.

Optimization techniques for reducing the spot sizes, setting the skew parameters, and correcting the timing for these small spots have been devised but need testing [16]. The Final Focus Test Beam at SLAC has been designed to test these ideas with the goal of focusing a specially prepared SLC electron beam to a 60 nm by 500 nm spot. This beam line is scheduled to be operational in late 1992 with initial tests of understanding tuning optimization, focusing schemes, small size monitoring, and stability tests for NLC style beams. The spot size as a function of the angular divergence and β^* will be studied, as well as the improved instrumentation. New alignment techniques and vibration damping useful for NLC final focus designs are also a necessary component of these tests.

A LOOK TO THE FUTURE

The NLC must be based on a design that is technically sound, operationally stable and reliable, and is economical. The technology will most likely be as conventional as possible to take advantage of proven techniques. Every new technological extension must be experimentally tested. The overall flexibility of the NLC accelerator is very important because a broad range of parameters makes the design more robust and more likely to commission rapidly. Having many options for give-and-take parameters for increasing the luminosity was very important for the SLC and will also be important for the next collider. For example, planning for up to 2 to 3 times the charge per bunch and having options to collide up to two to three times the number of bunches are reasonable. Having the potential to reduce beta functions at the IP to significantly below the design and planning for enlarged spot sizes throughout the final focus system are prudent. Background insensitive detectors are also important. Feedforward systems that fix beam errors on the same beam pulse are desirable if not necessary. Adequate commissioning time and beam monitoring are needed to provide for rapid initial progress. Issues concerning the brightness of the beams need continual attention. Finally, the accelerator should be extendable to the next level of energy operation and luminosity level without major rebuilding.

What will the global design look like? Here are my guesses. The beam energies will be about 300 GeV, extendable to 750 GeV. The length of each linac will be about 10 km. The RF frequency will be 9 to 14 GHz. The alignment tolerances will be 25 to 50 microns upstream of the IP. The transverse support movements from vibration must be kept to below 10 nm. Beam position monitors will have a resolution of about 5 microns. Pulse-by-pulse feedback systems will be globally spread over the project with many feedforward systems incorporated. Overall, the likelihood that NLC technology will experimentally converge to an acceptable level in the next 5 years is very good.

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