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

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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:

$$L = kN^+ N^- / (4\pi \sigma_x \sigma_y) \quad (1)$$

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 points 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 injection 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 outputs and average power issues of RF systems (modulators, loads, klystrons, etc.). 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 $3 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, 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 [7]. 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.

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

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

BRIGHTNESS OF BEAMS

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

$$\Delta x \Delta p_x = \gamma mc \sigma_x \sigma_x' = \gamma \epsilon_x mc \geq h / 2\pi \quad (2)$$

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 10^3 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

$$B = N / (\pi^2 \gamma \epsilon_x \gamma \epsilon_y) \quad (3)$$

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 ($\times 10^4$) that produced by either older conventional linacs or injected and damped single bunches in a second generation storage ring (10^{13}). The NLC beams must be brighter than those of the SLC by a similar factor ($\times 10^3$).

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})	$\gamma \epsilon_x$ (10^{-5} m-m)	$\gamma \epsilon_y$ (10^{-5} m-m)	$B = N / (\pi^2 \gamma \epsilon_x \gamma \epsilon_y)$ (m ⁻²)
SLAC Linac*	30.	0.1	300.	300.	1.1×10^{13}
SLAC PEP**	14.5	0.2	110	10	6.0×10^{14}
SLC (Actual)	50.	3.0	3.0	2.7	3.8×10^{18}
NLC (Design)	250.	1.6	0.88	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 reviewed [4]. However, most solutions call for experimental verification.

amplitude changes must be 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 antiphasing [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 10^{-3} level, stable support designs with reduced temperature sensitivities and new automated alignment procedures are needed [14].

Figure 3 Induced oscillations in the SLC linac for colliding beam conditions.

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 3×10^{10} during colliding beam conditions. With the use of proven emittance controls, the emittances above 3×10^{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 luminosities [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- scavenger) up to 3×10^{12} particles per bunch. The extension of these techniques to higher currents is now under active study as intensities of near 3.5×10^{10} are needed for the next run.

Finally, experimental verification of the accelerator physics effects and errors involved with the SLC are needed before a solid proposal can be made. Many experiments using the SLC to test beams with more realistic SLC 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 in large, using special techniques [3], were demonstrated in the Final Focus Test Beam [7] at SLAC.

The required spot sizes are very different. The vertical to horizontal size ratio is about 1 to 100. The chromatic aberration problems 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 produce 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 outgoing beam has a very large angular spread and needs adequate clearance for reducing backgrounds. If a crossing angle is desired which requires the use of a longitudinal transverse tilt in the beam at the interaction point to keep the beams aligned during collision. This tilt is introduced with a transverse RF cavity near the final focusing quadrupoles in a scheme called crab crossing [2]. On the other hand, disruption is very helpful by providing 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 readjustment 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 marginal 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 ringing for these small spots have been devised but need testing [16]. The final focus for the SLAC final focus 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 timing 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 500 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.

REFERENCES

1. B. Richter, *Part. Accel.* 1990 26: 53-59.
2. J. Seeman, *Annu. Rev. Nucl. Part. Sci.* 1991 41: 389-428.
3. R. Palmer, *Annu. Rev. Nucl. Part. Sci.* 1990 40: 529-592.
4. D. Burke, et al., *Linear Collider*, 1990 DPF Summer Study on High Energy Physics, Snowmass, CO, July 1990, and SLAC-PUB 5597 (1991).
5. K. Takata and Y. Kimura, *Part. Accel.* 1990 26: 87-96.
6. J. Seeman, et al., US PAC San Francisco 1991, and SLAC-PUB 5517 (1991).
7. D. Burke, et al., US PAC San Francisco 1991, and SLAC-PUB 5517.
8. T. Raubenheimer, SLAC-PUB 5355 (1990).
9. J. Seeman, et al., US PAC San Francisco 1991, and SLAC-PUB 5440.
10. A. Bafakir, et al., *Proc. 12th Int. Conf. High Energy Accel.* CNAI p. 119 (1983).
11. V. Balakin, *Proc. of 1st Intl. Workshop on The Next Generation Linear Collider*, Stanford SLAC Report-335, p. 56 (1988).
12. J. Seeman, et al., SLAC-PUB 4968 (1991).
13. L. Merminga, et al., US PAC San Francisco 1991, and SLAC-PUB 5507.
14. G. Fischer, *Part. Accel.* 31: 47-55 (1990).
15. P. Chen, US PAC San Francisco 1991, and SLAC-PUB-5557.
16. J. Irwin, US PAC San Francisco 1991, and SLAC-PUB 5539.

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