

**FROM THE SLAC LINEAR COLLIDER
TO THE NEXT LINEAR COLLIDER:
A STATUS REPORT AND ROAD MAP***

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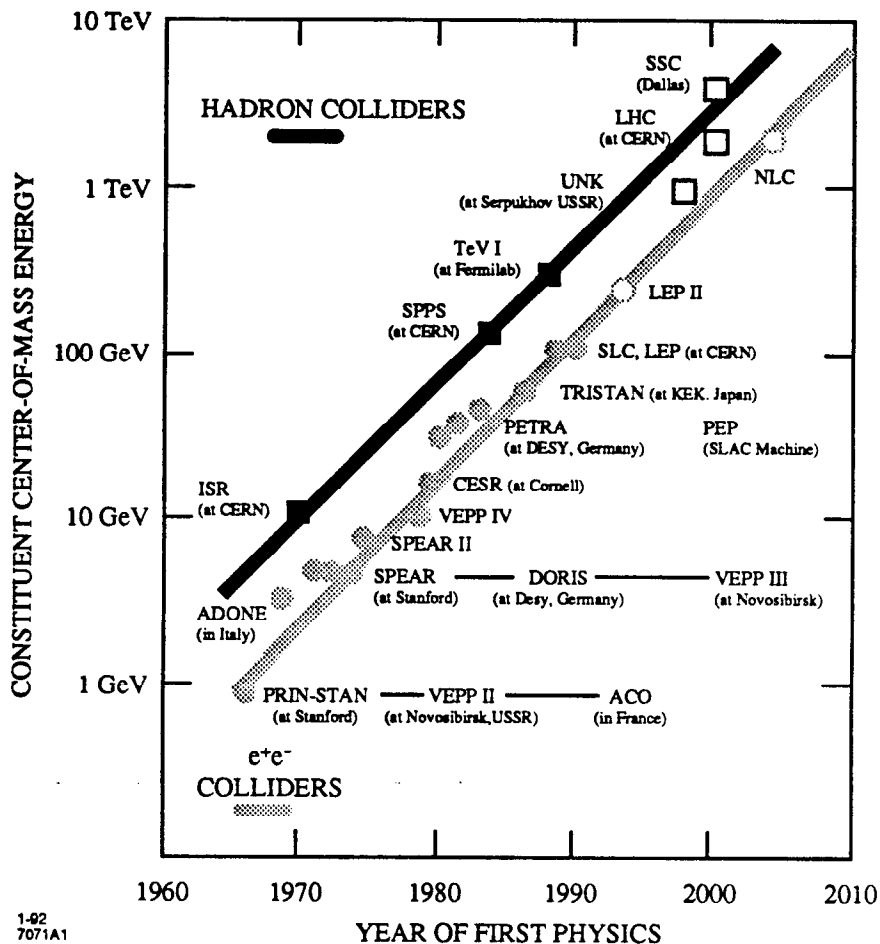
1. Introduction

The development of accelerator technology since the early 1930's, when the first particle accelerator was built, has been driven by the quest for ever higher energy. The higher energies have allowed physicists to probe deeper and deeper into the ultimate structure of matter, along the way uncovering all kinds of new particles, new layers of substructure, and discovering more about the forces that govern the interactions of all of the constituents of matter. This advance of energy is clearly illustrated in Figure 1 which charts the accelerators of the colliding beam era, plotting the energy in the constituent center-of-mass frame versus the time that the machines first started to operate. It is remarkable to note that both for hadron and electron colliders energy has climbed by a factor of ten every twelve years, and this trend shows no sign of ending, although simple extrapolation of size and cost indicate that the machines will soon become unaffordable. Perhaps so, but so far the ingenuity of the physicists and the accelerator builders has saved us from the calamity of simple extrapolations as new technology replaces old.

This meeting has been convened to consider the physics potential of the next generation of electron-positron colliders, and it happens at a time when a new technology, the linear collider, allows us to consider energies than would be financially impractical through an extrapolation of present-day storage-ring technology. That technology has been used to build the largest of the electron-positron colliding-beam storage rings, the 27 km-circumference LEP machine at CERN, which is now successfully operating and churning out huge amounts of data. It is now generally agreed among the community of accelerator builders that LEP is the largest and the last of the storage rings that will be used to push ahead the energy frontier. This conclusion arises from the scaling law for electron storage rings, which shows that the size and cost of such facilities must increase as the square of the center-of-mass energy of the machine. This scaling law is driven by the synchrotron radiation emitted when bending electron or positron beams in a magnetic field, and which requires ever increasing amounts of RF power to keep the beam circulating as the energy increases. A storage-ring facility ten times the energy of LEP would have a circumference of around 2700 km and would have costs measured in the hundreds of billions of dollars.

Storage-ring technology is now being replaced by the new technology of linear colliders for the highest energy machines. Linear colliders are basically two linear accelerators firing beams of electrons and positrons at each other; this technique has a more favorable scaling law, since there is no synchrotron radiation emitted in

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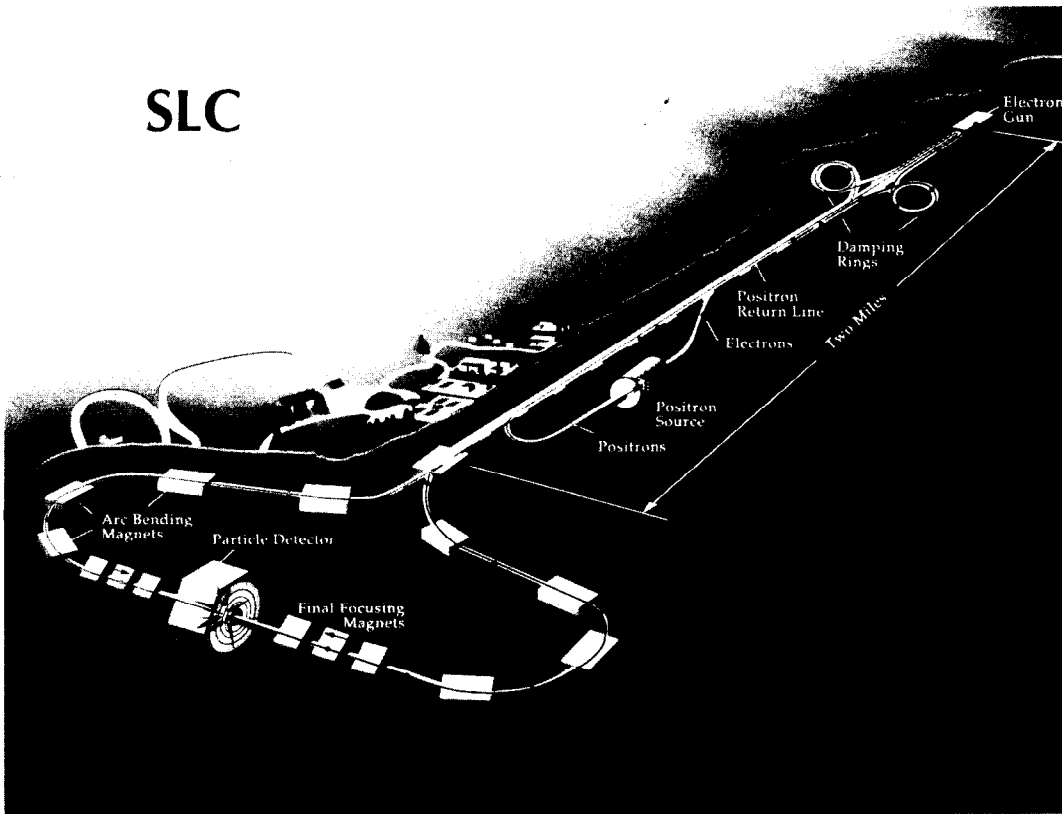


1. Trends in C.M. energy versus time.

the accelerator process. However, nothing comes completely for free, and to attain the high luminosity (reaction rate per unit cross section), beams of very tiny cross-sections must be collided to compensate for the lower repetition rate of linear colliders compared to the circulation frequency of beams in storage rings. This makes new challenges for the accelerator designer, and part of the story of how we will get to the next generation of machines with much higher energy than LEP involves how we will produce and use these tiny beams.

In this presentation, I will review what we have learned about linear colliders, the problems that have been uncovered, and the technology-development program aimed at realizing the next high energy machine. I will then close with a few comments on how to get on with the job of building it.

SLC



2. Schematic of the SLC.

2. The SLC

The first linear collider is now running at the Stanford Linear Accelerator Center (SLAC). The machine is shown schematically in Figure 2. It is a hybrid device in which both electrons and positrons are accelerated in a single pulse of one linear accelerator and then separated at the end of the linac and guided into head-on collisions by an ensemble of high precision, extremely strong focusing magnets. The SLC contains all of the basic elements of the linear collider: damping rings near the beginning of the linac to produce very small emittance electron and positron beams, a high energy accelerator, a system for regenerating positrons, and the focusing system which produces beams of only two micron radius at the collision point. Serious commissioning of the facility started in 1987, and it was not until 1989 that the first Z bosons were produced. As is often the case with new technology, nature had a few surprises that the designers did not anticipate.

At present (Fall 1991) the machine produces about 50 Z 's per day and has exceeded all the goals for luminosity, beam size at the interaction point, and average on time that had been set for it for the year. In the next year we hope to increase the luminosity by an order of magnitude and to begin running the machine with polarized electron beams (about 35% polarization initially). There are new developments

in polarized sources that have been made both by a Wisconsin/SLAC/UC Berkeley collaboration and by a Nagoya/KEK collaboration. While these cathodes are very promising, there is still a lot of work to do to see if they are sufficiently robust to survive in routine operation in the accelerator environment. The experimental program for the next year at SLC aims to begin measurements of the left-right asymmetry in Z^0 production.

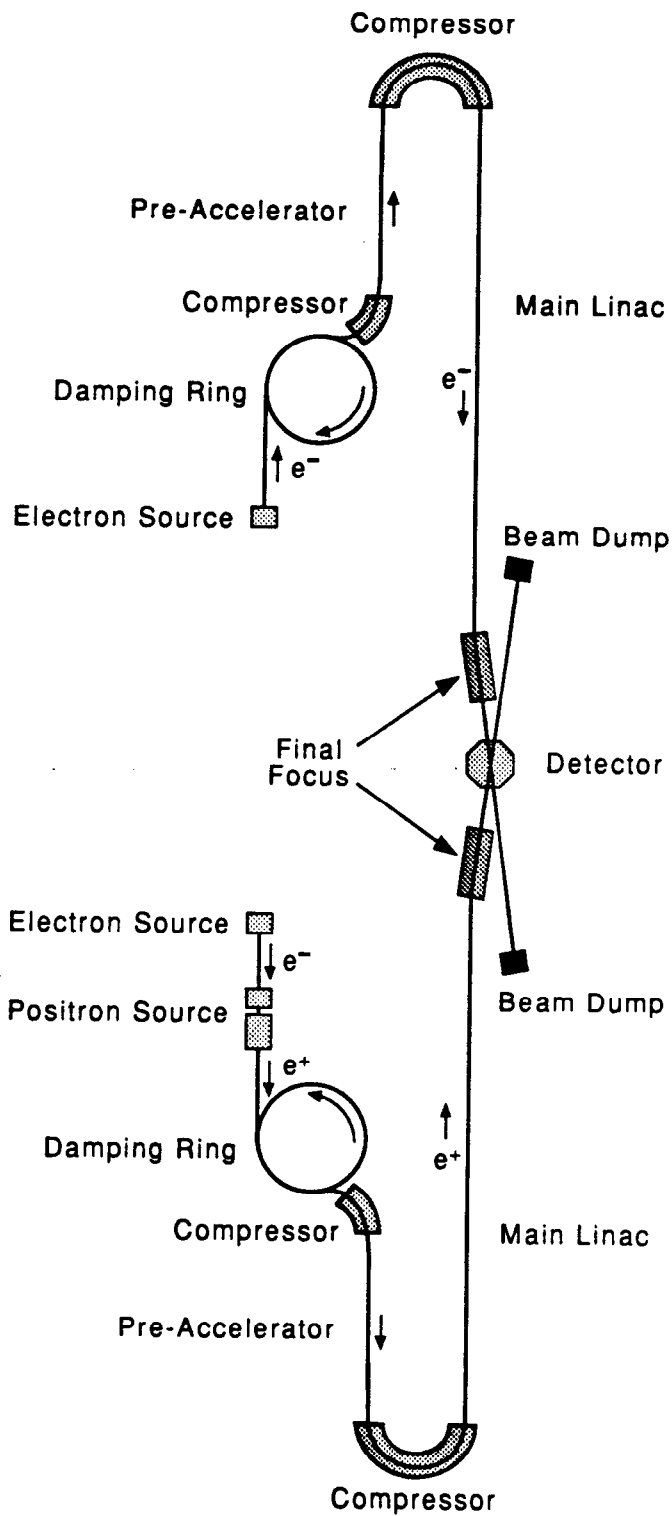
In the very long run, it will probably be true that the SLC will make its greatest contribution to particle physics through the pioneering work being done in accelerator physics. The SLC is the only operating prototype for future linear colliders. We have already learned a great deal from it and will continue to learn more about the real problems of stably achieving very large peak currents in very small bunches and controlling those beams precisely enough that they remain in collision. The requirements of the experimenters at the collision point wonderfully concentrates the minds of the accelerator physicists. The accelerator physics program has a strong involvement by accelerator physicists from Japan, Europe and the USSR. It is a test bed for everyone's bright ideas and will continue to be so for quite a few more years.

3. The Next Linear Collider (NLC)

3.1 General

The schematic of a generic linear collider is shown in Figure 3. Work is continuing on all the critical components, and before going on to describe the main issues, I will give a brief status report on the individual elements.

- **Electron Source** — This technology is in hand, and both the thermionic source and polarized source developed for the SLC are entirely adequate for all the variants of large linear colliders now being considered.
- **Positron Source** — The positron source for the NLC may have to stand considerably higher power densities than the SLC source, although this is not yet clear. Novosibirsk is developing a liquid metal technology that can do the job, and several laboratories are studying conversion of photons produced by synchrotron radiation from the very high energy beam.
- **Damping Ring** — The SLC damping ring can produce a beam of invariant emittance 3×10^{-5} (horizontal) by 1×10^{-6} (vertical). Variants of the NLC design require emittances of as much as a factor of ten smaller than the SLC damping ring. The problem has received considerable theoretical study, and a prototype of the next generation damping ring will be built at the KEK laboratory in Japan.
- **Compressors** — The natural bunch length in a damping ring is on the order of a few millimeters, while the bunch length required for the main linac in the NLC can be as short as a few hundred microns. The SLC technology is completely adequate for this job, although the shortest bunches in some of the NLC designs require two stages of compression, compared to the one stage used in the NLC.



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3. Schematic of a full-scale linear collider.

- Pre-accelerator — This technology is in hand; it is essentially the existing SLAC 10 cm wavelength technology.
- Main Linac — This is where the largest expense of the linear collider is located, and this is where a great deal of technology development is required. There are four main approaches: X-band linac, S-band linac, superconducting linac, two-beam accelerator. I will talk more about these later.
- Final Focus — The beam size at the final focus in the NLC must be much smaller than the SLC. Third-order corrected optics are required as compared to the second-order corrected optics used on the SLC. An international collaboration is building a prototype at SLAC.

Some typical parameters of zeroth-order reference designs made by several different laboratories are given in Table 1. The SLAC and the KEK designs are essentially twins, which should not be a surprise since the two labs have been collaborating closely for several years. The Novosibirsk design uses a single extremely high-intensity bunch per linac pulse and will have more troubles with various beam instabilities in the linac than other designs. The DESY approach essentially uses existing SLAC technology. The CERN approach is for a two-beam accelerator that is quite innovative and requires the most in the way of technology development. The Tesla group is a broad collaboration of many laboratories who are investigating superconducting linac technology. From all this work, a final design for the NLC will evolve.

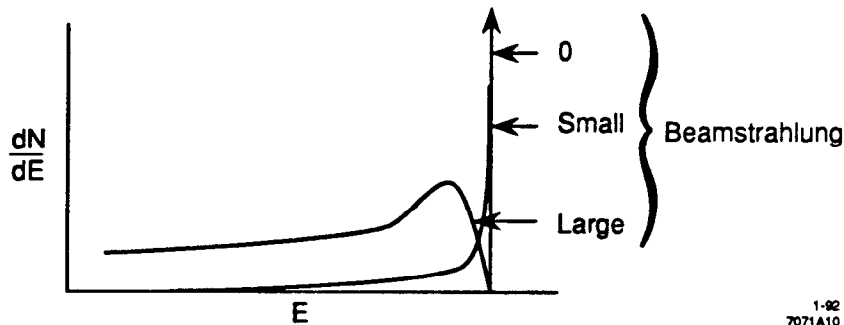
I now want to go on to spend a little more time describing some of the critical issues in two particular areas: one around the interaction point, and the second involving the main accelerator.

3.2 *Interaction Point Issues*

At the collision point of the NLC, bunches will collide that contain around 10^{10} electrons or positrons, that have submicron transverse dimensions, and have bunch lengths on the order of 100 microns. All these parameters taken together imply extremely large magnetic fields in the beam. These fields are on the order of megagauss in the SLC and can be many tens of megagauss in the NLC. Such extremely high fields can generate severe problems unless care is taken.

The first of these problems goes by the name of “beamstrahlung,” which is simply synchrotron radiation emitted by the particles of one beam in the macroscopic magnetic field of the other beam. If beamstrahlung is too great, the energy spread of the beams at the collision point can become very large, thus losing the constraint of a well-determined center-of-mass energy that has proved to be so useful in all earlier electron-positron work. The situation is shown schematically in Figure 4.

In case of zero beamstrahlung, the energy distribution is very narrow, typically being on the order of a few tenths of a percent, which is characteristic of the energy spread in the acceleration process. For small beamstrahlung there is a tail on the distribution, but most of the particles are still contained in a peak at the maximum



4. Electron spectrum for various beamstrahlung parameters.

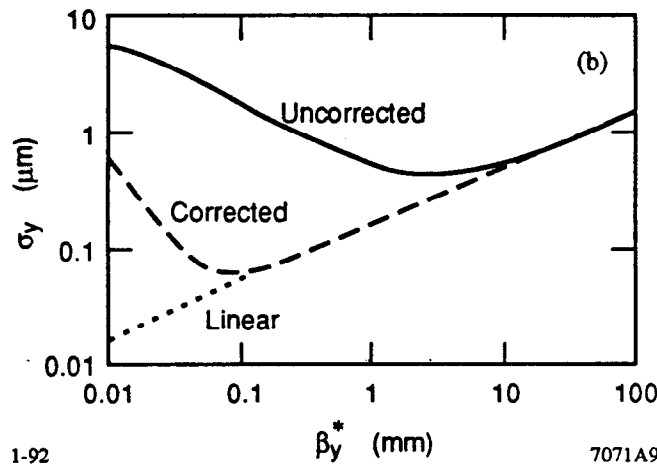
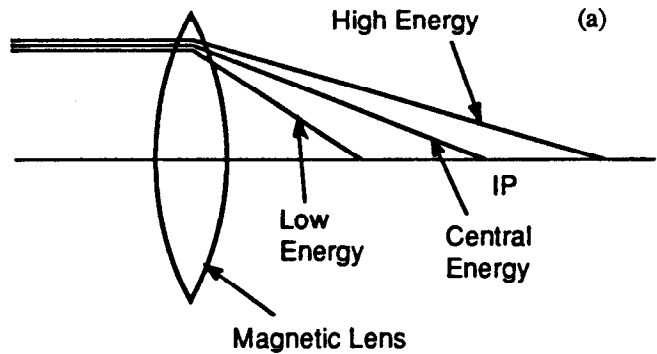
energy. If the beamstrahlung parameter gets very large, the particle energy distributions can spread out and become quite wide. Many physics experiments are best served by energy spreads on the order of a percent or so, and so this constraint must be considered in the basic design of the accelerator.

Another potential problem is various strong-field electrodynamic processes such as coherent pair production. If the energy (in rest-mass units) of a particle in one beam times the magnetic field of the other beam becomes on the order of the critical field of 4×10^{13} Gauss, pair-production and other higher order strong-field processes become completely intolerable. Here is another constraint on the designer.

There are two solutions to this general problem. The first uses so-called flat beams, where the ratio of horizontal to vertical beam size is a large number. For a fixed current, the magnetic field strength in the beam is proportional to the perimeter of the beam cross-section, while the luminosity depends on the area. Thus, with flat beams, it is possible to reduce the magnetic field while maintaining high luminosity.

The second method decreases the number of particles per bunch while increasing the number of bunches per second. Here too, the magnetic field goes down because the peak current decreases while the luminosity remains high because of the increase in the number of bunch collisions per second. Different approaches have been taken by different accelerator designers. Referring back to Table 1, the first three designs all use the flat-beam approach, while the last three all use an approach which uses a large number of bunches per second.

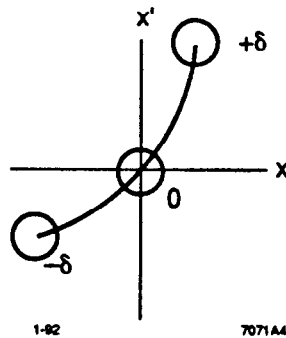
A second very critical problem is the production of a submicron, transverse beam size in the presence of the finite energy spread in the incoming beam and the natural chromatic aberrations of magnetic lenses. The situation is illustrated in Figure 5. Figure 5a shows how different energies are focused at different points by a simple magnetic lens on a quadrupole. Figure 5b shows what happens to the actual beam size as the beta function at the collision point (related to the inverse of the demagnification factor) is decreased with no chromatic correction. A minimum in the beam size is reached when the chromatic aberrations give a contribution to the beam size equal to



5. Chromatic effects at the final focus. (a) Effects of a simple lens. (b) Theoretic and actual beam size for corrected and uncorrected systems.

the monochromatic beam size, while with a properly corrected system one can reduce the beam size much further before chromatic aberrations take over.

The SLC uses a second-order-corrected optical system to produce beams with transverse dimension on the order of a micron. The NLC requires considerably smaller beams, and so the correction system must be much more sophisticated. This is an issue of such importance for all variants of the NLC that an international collaboration has come together to build a prototype at SLAC called the Final Focus Test Beam. This beam line will use the high energy, low emittance beam from the SLAC linac to produce a beam size of 0.06 microns (vertical) by 1.0 microns (horizontal). While this beam size is somewhat larger than many variants of the NLC design, it has the same 300:1 demagnification from the beam size at the end of the linac that is planned for many of the NLC designs. The Russian Institute of Nuclear Physics at Novosibirsk and Protvino is contributing all of the iron magnets except the final doublet. The KEK laboratory in Japan is contributing the high precision final quadrupoles and their support and vibration-isolation systems. The Orsay laboratory in France is



6. Dispersion effects on emittance in a linear accelerator with a simple steering algorithm.

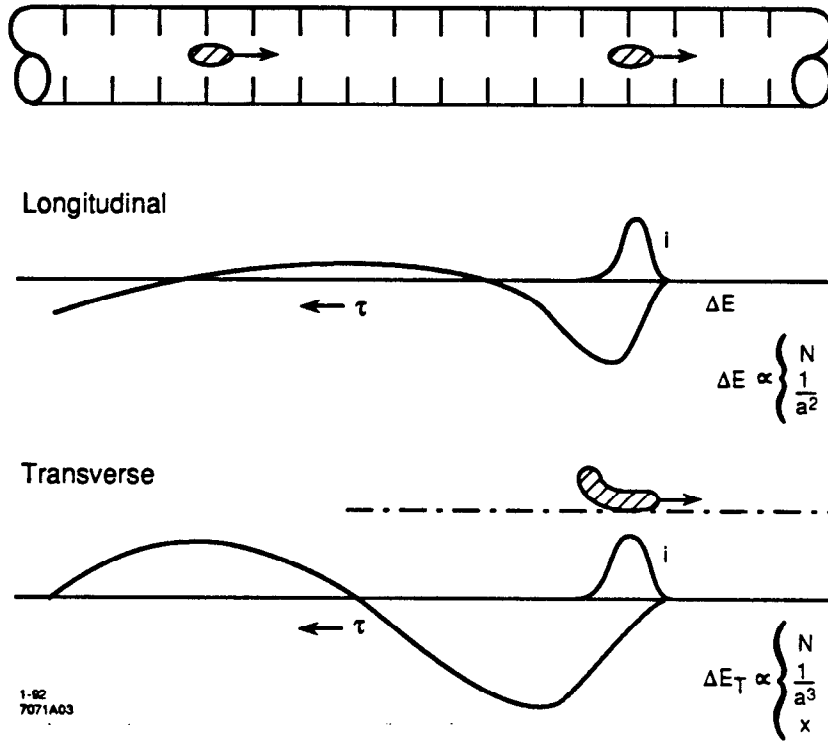
contributing beam instrumentation and final beam spot-size measuring equipment (a very difficult problem). DESY in Germany is building the automatic alignment system. The Max Planck Institute in Munich is building the precision magnet movers. SLAC is supplying all the rest of the facilities. Everyone has participated in the optical design, and this \$16 million project should be ready to begin operation at the end of 1992.

3.3 *The Main Accelerator*

The issues in the main accelerator are preserving the beam emittance during acceleration so as to allow the very small beam spots to be produced while attaining the energy, and keeping costs down. In preserving the emittance there are three main enemies — accelerator misalignments, random ground motions, and longitudinal and transverse wake fields. Misalignments of the accelerator and focusing structure deflect the beam as it travels through the accelerator, and these trajectory offsets are corrected with periodic steering. However, if one is not careful the dispersion [$D = \Delta x / (\Delta p / p)$] builds up, as shown in Figure 6, and chromatic effects mix phase space so that the apparent beam emittance can grow by a large factor. The solution to this problem is to align the magnets well enough (100 microns is good enough, and beam-based alignment systems have been developed on the SLC) and to introduce so-called dispersion-free steering (also developed on the SLC) to keep the dispersion from building up in the first place.

Random ground motions with wavelengths of less than about ten times the quadrupole spacing are very pernicious, since they cannot be corrected with any steering system. Large linear colliders will be sensitive to ground motions of a small fraction of a micron, and isolations will thus have to be built into the accelerator to prevent these effects from destroying the emittance of the beam. Fortunately, there has been an enormous amount of progress in vibration-isolation systems in the past few years, and it now seems possible to isolate the accelerators to the few hundredths of a micron level.

Wake Fields



7. Wake fields in accelerators. See text for explanation.

The most pernicious effect goes by the name of wake fields; it is illustrated schematically in Figure 7. As a train of intense bunches travels down a linear accelerator structure, it excites that structure with fields that can act back on the generating bunch itself and on the bunches trailing behind. The effect on the generating bunch is known as the short-range wake, while the effect on subsequent bunches is known as the long-range wake. The longitudinal wake affects the energy of the particles in the bunch, as shown in the middle section of Figure 7, and its strength is proportional to the number of particles in the bunch and to one over the square of the size of the hole in the accelerator. The transverse wake is proportional to the number of particles in the bunch, to one over the cube of the size of the hole in the accelerator structure, and to the mean distance of the bunch off axis. The short-range wake is always such as to deflect particles in the bunch further away from the axis.

What can one do about it? Clearly one wants to make the number of particles per bunch as small as possible consistent with other required constraints on the accelerator, and make the hole size in the accelerator as large as possible consistent with getting the necessary accelerator gradient. For the short-range longitudinal wake nothing further can be done, and one must live with it. One has to keep the non-linear part of the momentum spread in the beam generated by the short-range

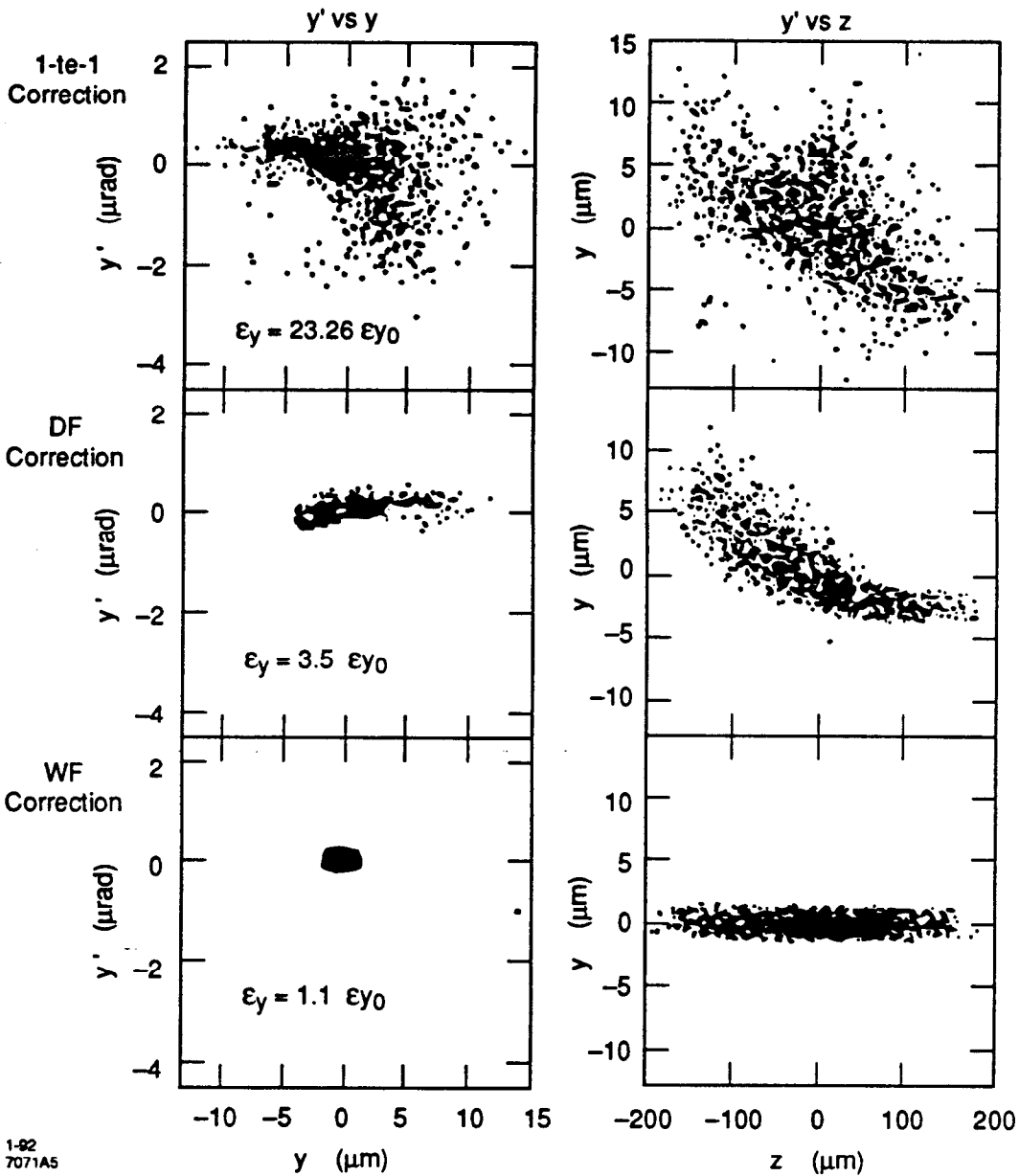
wake to within acceptable limits for the final focus system. It is this that defines the required minimum momentum passband of the final focus.

The short-range transverse wake can be controlled by sufficiently precise alignment of the accelerator coupled with what is called "wake-cancelling steering," which periodically introduces deliberate offsets designed to cancel out the accumulated effect of the short-range wake through portions of the accelerator. The effect is shown in computer simulation in Figure 8, which shows the effect on the beam emittance for an accelerator aligned to 70 micron rms tolerances. The upper part of Figure 8 shows the effect of simply measuring the beam position and steering it back towards the axis as it travels down the accelerator. The emittance blows up by a factor of 23 by the time the end of the accelerator is reached. The middle part of Figure 8 introduces dispersion-free steering which reduces the emittance blow-up to a factor of 3-1/2. The lower part of Figure 8 introduces periodic wake field cancellation and reduces the emittance blow-up to 10%.

The long-range wake has been a subject of considerable worry, for in multibunch accelerators it can build up from bunch to bunch giving intolerable energy spreads to the entire beam or intolerable transverse shifts in the bunches, so that they may miss each other at the collision point. There has recently been a breakthrough in accelerator design that I believe eliminates this concern. The technique is to deliberately introduce a spread of frequency in the higher-order-mode resonances of the accelerating structure so that the long-range wake cancels out as the beam travels through many cells of the accelerator. This technique has been experimentally demonstrated by a SLAC/Argonne group working with an Argonne test accelerator. The test accelerator allows a high intensity bunch to be run through an accelerating structure (to excite the wake fields), followed by a lower intensity "witness bunch" whose time delay can be varied behind the main bunch and which allows the effect of the wake fields to be measured. Figure 9 shows a calculation and an experiment with the system on a standard accelerating structure. Theory and experiment agree very well, and the long-range transverse wake lasts a very long time. Figure 10 shows theory and experiment for a structure with a spread of higher-mode frequencies and demonstrates that the long-range wake dies out because of this frequency spread soon after the passage of the main bunch. I believe that it has now been demonstrated that multibunch accelerators are workable.

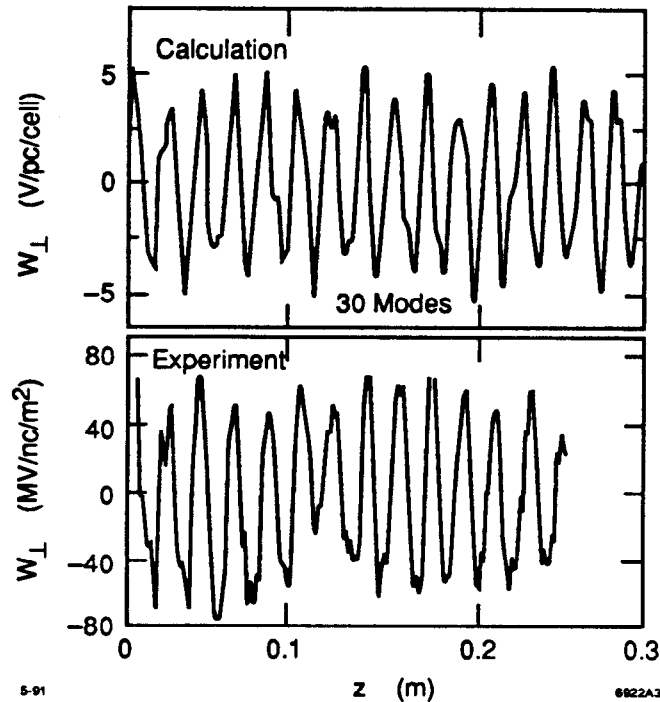
3.4 *Status of the Accelerator Work*

There are four main approaches to the high-energy booster required for the NLC. One that I will call the mainstream approach is exemplified by the work of SLAC, KEK, and Novosibirsk, using technology at four to five times the SLAC linac frequency. DESY is investigating the possibility of using standard SLAC linac technology. CERN is investigating a two-beam technology at very high frequency. The Tesla collaboration (Cornell, CEBAF, DESY and others) is looking at the possibilities of superconducting RF. I will comment on the status of each of these.



8. Emittance growth with one-to-one steering, dispersion-free steering, and wake field cancellation steering.

For the mainstream approach, I believe that the problem of the accelerator structure is solved with the demonstration of the mode-frequency-spread structure mentioned earlier. The limiting accelerator gradient is not yet known with any confidence. Very high gradients, up to 200 MV/m, have been demonstrated in short test cells. However, work at Orsay and KEK at S-band has shown that one can probably not work at the break-down limit. Both laboratories' S-band structures have been driven



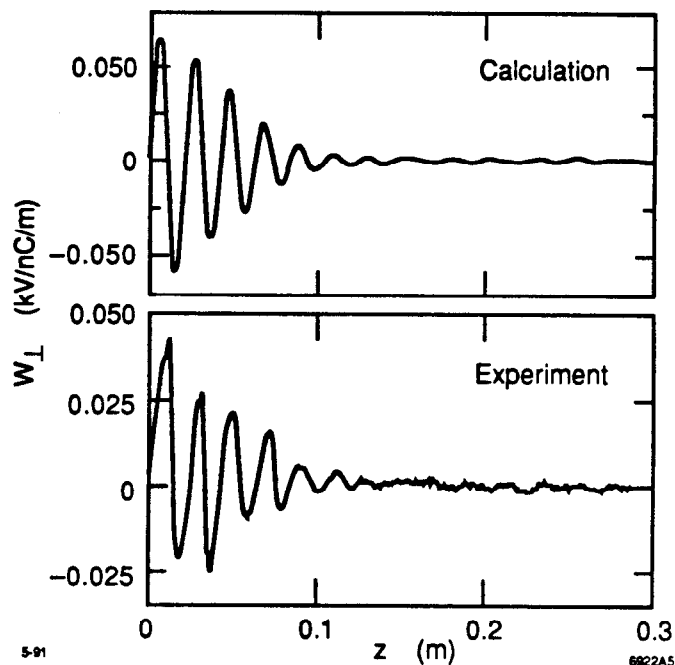
9. Calculated and measured transverse wake potential in a standard linear accelerator section.

at 100 MV/m, but high levels of field-emission current have been seen. At both laboratories, below about 70 MV/m, this so-called dark current dies away. Work on testing X-band sections at very high gradient is beginning, and I expect that we will know within a year what the upper limits to the accelerating gradient really are. They should be considerably higher than at S-band.

A 50 MW X-band klystron with one microsecond pulse length has been demonstrated at SLAC, and somewhat lower power levels have been attained at KEK. Work is continuing toward developing 100 MW klystrons at this high frequency. A new high efficiency pulse-compression technology has been demonstrated at SLAC, that allows the peak power to be increased by a factor of four to six, while the pulse length is reduced. The power source required for 11.4 GHz is almost here.

Both SLAC and KEK designs use ten microbunches per accelerator pulse, while the Novosibirsk design uses a single bunch of much higher current. In the single-bunch case, alignment tolerances are much tighter because wake-field effects are much stronger.

DESY and a rather skeptical SLAC are investigating the possibility of using the existing SLAC accelerator technology for the main booster. Here the principal problem is one of costs. It appears that the 3 GHz technology yields a total system cost for the high energy booster about two to three times as much as the 11.4 GHz technology. When one is talking of accelerators in the billion dollar class that can

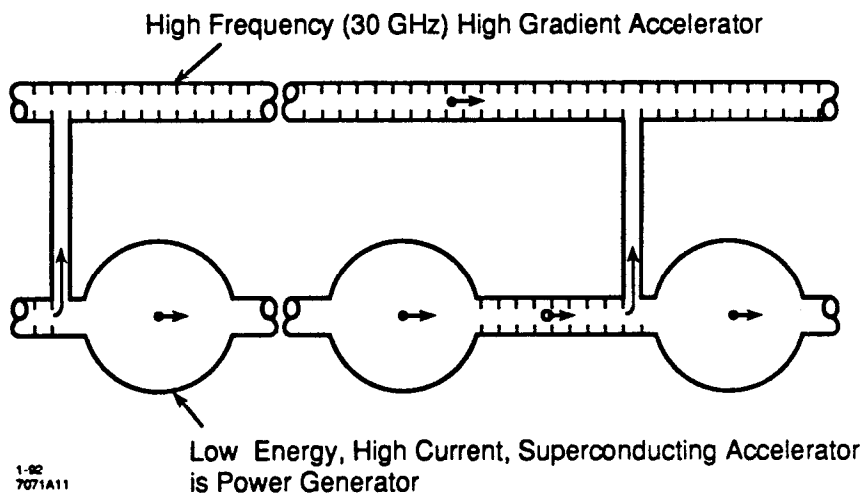


10. Calculated and measured wake potential in a structure with a spread in higher-mode frequencies.

amount to a lot of money. However, all the evidence isn't in yet, and so studies are continuing. The advantage of this approach is that we have 40 years of experience with 3 GHz technology and have very high confidence in the performance of all components.

The Tesla collaboration is pursuing superconducting RF based on the large amount of experience in such systems attained in the last few years. They feel that an accelerating gradient of 25 MV/m is attainable, although the best results today in large systems are about 7 MV/m. Even with $Q \approx 10^9 - 10^{10}$, power dissipation in the accelerating structure is prohibitive for CW operation, and so the design work concentrates on accelerators with duty cycles on the order of one percent. Within each pulse, approximately 400 bunches are accelerated, but the bunches are spaced so far apart that there is little concern about long-range wake effects. Also, at the design frequency of 1.5 GHz the accelerator apertures are so large that it is believed that there is little concern about short-range wake fields. Finally, the superconducting systems are so energy efficient that one can relax some of the beam-size constraints at the interaction point, using somewhat larger beam cross-sections which, coupled with a very large number of bunches, relaxes requirements on the final focus system and reduces beamstrahlung problems.

The main problem with the superconducting approach is cost. The CEBAF accelerator can be looked at as a 1 GeV superconducting linac, and I have the costs of the superconducting system from them. The system includes refrigerators, transfer lines, cryostats, accelerating structure supports, tuners, etc., and is priced at about



11. Schematic of a two-beam linear accelerator.

\$100M per GeV of energy. This is prohibitive and will have to come down by a factor of 50 before the superconducting approach can be competitive. The protagonists believe that, with a higher gradient and with re-engineering based on the experience today at CEBAF, they have a chance of reducing cost by the required amount. If they can do so, this is a very attractive approach.

Finally, the most exotic technology, the two-beam accelerator, is being worked on at CERN. This concept is illustrated schematically in Figure 11. One of the accelerators is a low-energy, high-current device made with low-frequency superconducting cavities of the type used at KEK, DESY and CERN in their storage rings. This accelerator drives a short high-intensity bunch which generates RF power in a traveling-wave structure that is then transferred to a 30 GHz high-gradient accelerator. This is the newest technology, and there is still a great deal to learn about it. In particular, there are questions about the stability of the beam in the low-frequency accelerator with its frequent energy extraction and reacceleration of a high-intensity beam, and also about tolerances in the high-gradient accelerator. The attractiveness of the approach comes from the apparent increase in sustainable accelerating gradient at higher frequencies, together with the energy efficiency of the power generator.

4. How to Get There From Here

I believe that in the next few years, sufficient R&D will have been done to allow the accelerator community to converge on a single technology for the NLC. The R&D program is very well coordinated, and the present effort seems to me to be a model of world-wide collaboration toward a common goal.

It is clear that whatever the technology chosen, the NLC accelerator will be in the billion dollar class, and I personally believe that it is much more likely to be realized

as a world-wide collaboration than as a regional project. Our accelerators are getting so expensive that I think it extremely unlikely that there will be more than one of any given kind in the world. That is going to create a problem, for all the participants in the R&D program are very happy to have world-wide collaboration in R&D — as long as the facility ends up in their own backyard.

The high energy physics community needs to develop a consensus on the parameters of the NLC, and international meetings like this one at Saariselkä are a very important part of the development of that consensus. There will be many regional meetings investigating the physics issues further, and the next world-wide meeting on these issues will take place in the spring of 1993 in Hawaii.

In parallel with the efforts to set the parameters of the machine, we need to begin to build a consensus among the scientific community that will lead to a true inter-regional collaboration in its construction. We have to do better than we have done with the SSC and the LHC, where there has been more rivalry than cooperation. The laboratories that now work so effectively together in a highly informal collaboration on accelerator R&D should begin to take the first “baby steps” toward a more formal and structured collaboration that will eventually lead to an inter-regional proposal to construct the facility. Given Europe and the United State’s commitment to large proton machines at the moment, such a construction project can probably not start till the second half of the nineties. That’s not a bad match to the pace of the R&D program. Settling the site issue will be contentious and will most probably be done as part of a process where very large global facilities in different fields of science are allocated to different regions of the world.

If we do our R&D well and our politics well, we may see this very important science facility running sometime in the early 2000’s.

Table 1
Parameters of Various Reference Designs

	C.M.		Length km	Frequency GHz	Repetition		Luminosity $\text{cm}^{-2}\text{s}^{-2}$
	Energy GeV	Gradient MV/m			Rate Hz	Number Bunch/Pulse	
SLAC	500	50	13	11.4	120	10	2×10^{33}
KEK	1000	100	13	11.4	200	10	6×10^{33}
Novosibirsk	1000	85	12	14.1	100	1	1×10^{33}
DESY	500	17	35	3.0	50	170	2×10^{33}
CERN	2000	80	26	30.0	1700	1	2×10^{33}
TESLA	500	25	25	1.5	20	400	2×10^{33}