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FUTURE LINEAR COLLIDERS*

BURTON RICHTER
Stanford Linear Accelerator Center,
Stanford University, Stanford, CA 94309

INTRODUCTION

At the La Thuile Workshop, I spoke about both the SLC and about the next generation of Linear Colliders. However, the SLC is a rapidly evolving machine and its status is very different at the time of this writing (April 1988) from what it was at the time of speaking (March 1988). It will be different still at the time of publication of these proceedings, and since there is little point in writing about what is already obsolete, I will limit my written report to the future of this new accelerator technology. More about history and concerns for the future experimenters can be found in reference 1.

LINEAR COLLIDERS

The accelerator community now generally agrees that the Linear Collider is the most cost-effective technology for reaching much higher energies in the center-of-mass than can be attained in the largest of the e^+e^- storage rings, LEP. Indeed, even as the first linear collider, the SLC at SLAC, is getting ready to begin operations, groups at SLAC, Novosibirsk, CERN and KEK are doing R&D and conceptual design studies on a next generation machine in the 1 TeV energy region. In this "perspectives" talk I do not want to restrict my comments to any particular design, and so I will talk about a high-energy machine as the NLC, which is shorthand for the Next Linear Collider, and taken to mean a machine with a center-of-mass energy someplace in the 0.5 to 2 TeV energy range with sufficient luminosity to carry out a meaningful experimental program. Also, calling the machine the NLC, I hope, will avoid offending anyone who does not see the name of his particular project mentioned frequently in the text.

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Energy and Luminosity Requirements

As energies increase, cross sections for the production of high-mass states go down like $(\text{mass})^{-2}$. This is a disadvantage for all kinds of accelerators, but cross section limitations for electron-positron machines are somewhat more restrictive than for those of proton colliders because the electroweak coupling constant is smaller than the strong coupling constant. However, electron-positron machines have two advantages over proton colliders:

1. Democracy: all nonperipheral cross sections are about the same if the particles produced have electromagnetic or weak charge.
2. Cleanliness: lepton and hadron production are comparable, and peripheral processes are small at large p_T and distinguishable from the processes of interest with simple cuts.

In order to talk realistically about future large electron-positron liner colliders it is necessary to specify the luminosity of the machine as a function of energy for many of the technical challenges in this kind of accelerator come from the need to achieve high luminosity. The reference cross section that we will use is that of muon pair production which is

$$\sigma_\mu = \frac{4\pi\alpha^2}{3S} = \frac{87 \times 10^{-39}}{S(\text{TeV}^2)} \quad , \tag{1}$$

where α is the fine structure constant and S is the square of the center-of-mass energy. This reference cross section is defined as one unit of R. Some "background" cross sections in R units coming from old physics at $S^{1/2}$ around 1 TeV are given in the following table.

Final States	R
six quarks	10
three leptons	3
W^+W^-	20
$Z^0\gamma$	10

To set the luminosity for a machine we have to specify a required yield. I will assume that a satisfactory yield is 1000 events per 10^7 seconds per unit of R. This yield is of course somewhat arbitrary, but 1000 events seems reasonable, and while 10^7 seconds is actually only one-third of a year, by the time one takes inefficiencies into account it is not an unreasonable estimate to use for the actual data collection time in a particular year. This yield implies that the luminosity must be

$$\mathcal{L} = 10^{33} \quad S(\text{TeV}^2) \quad . \tag{2}$$

Figure 1 shows the electron-positron cross section as a function of center-of-mass energy from 0.1 GeV to 10^4 GeV. The dashed line labeled "$\mu^+\mu^-$" represents one R unit. Some other R values of interest are charged Higgs $\approx 0.3\ \beta^3$, neutral Higgs $0.1 - 1$ (via W fusion), a new generation of quarks 2, etc.

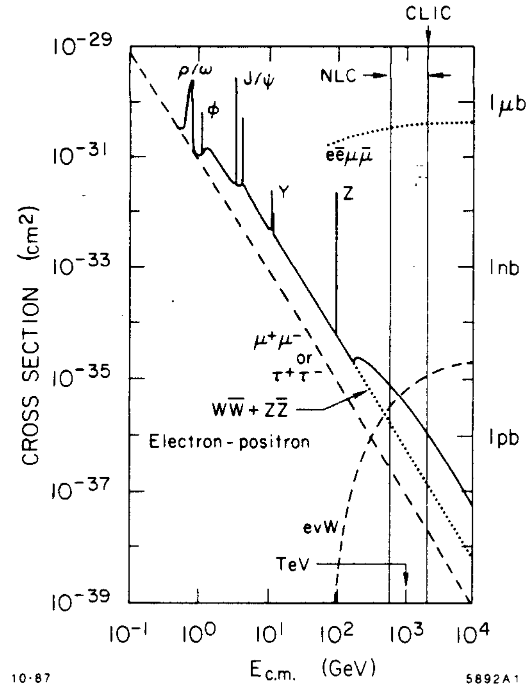

Fig. 1. Cross section as a function of energy.

There are many other physics processes which one might talk about, but these give few landmarks for a choice of machine energy. For example, there are whole collections of theoretical papers on possible masses of new quarks which give answers ranging from 200 GeV (Pasco's fixed point) to 500 GeV (perturbative unitarity bound from Higgs exchange). Most supersymmetric models predict the existence of supersymmetric leptons in the mass range from 100–400 GeV, requiring a machine energy of from 200–800 GeV. Technicolor models usually predict the existence of technipions around 800 GeV which would push the machine energy up to around 1 TeV. These models would tell us that machines to search for new quarks must have center-of-mass energies from 500 GeV to 1 TeV.

There is not much specificity in all of this, but taken together and including the fact that the next machine should be a significant advance over LEP II, I conclude that the NLC should probably be in the 500 GeV to 2 TeV center-of-mass energy range with a luminosity ranging from 3×10^{32} at the lower energy to 4×10^{33} at the upper energy. As we will see, nature and the taxpayer are at odds over the choice of energy — the higher energy being the more "conservative" choice from what we know now about the discovery potential while being technologically much more difficult and considerably more expensive.

How to Get There from Here

The only linear collider now operating is the SLC. The beam power in this machine is around 100 kilowatts; the beam radius at the collision point is about 1 micron; and the bunch length of the beam at the collision point is around 1 millimeter. It is simple to turn the crank and to find the equivalent parameters for very high-energy machines, and if one goes to the many-TeV region, one finds beam powers of many megawatts; beam radii at the collision point of tens of angstroms, and bunch lengths of microns. I believe that this is simply too big a jump in parameters to make in a single step in such an unexplored technology. Fortunately, for both the experimenters and the machine builders, the needs of high-energy physics seem to indicate an intermediate set of parameters. My own view of the technology situation is crudely shown in figure 2, where I have plotted luminosity versus center-of-mass energy. The region in the lower left of the figure is very roughly the region that can be reached with moderate extensions of existing technology. The region in the upper right requires new kinds of approaches. The physics requirements for the NLC push us toward the "new approaches" region.

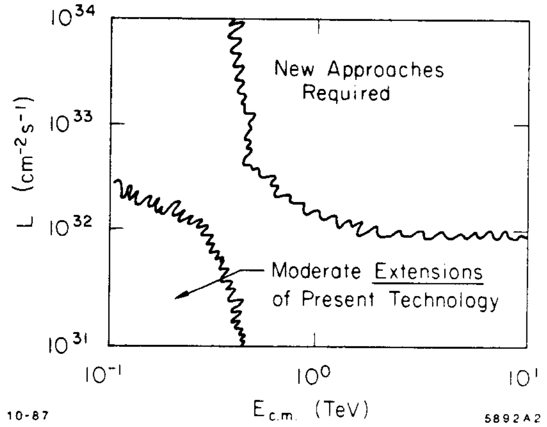

Fig. 2. A qualitative view of the accelerator technology required for a linear collider in the luminosity–energy plane.

The reason that new approaches are required is simply the costs of construction and operation of large machines. It is perfectly possible to build an NLC using present SLC technology. If we do that we will use an accelerating gradient of 20 MV per meter, giving us a 50-kilometer long linac and a total power into the laboratory of about one gigawatt. On the other hand, we know that for short accelerator sections, even at the frequency of SLAC (near three gigahertz), we could sustain an accelerating gradient of 150 MV per meter and can have higher accelerator gradients with still higher RF frequencies. As best we can tell now, an NLC of 5–20 kilometers with a total power input of 100–200 megawatts might be realized if we can develop the appropriate technologies. These technologies look reasonable but will need a lot of R&D.

There are four main areas that need considerable research and development before we will be ready to build a machine. These are the electron and positron sources where the beams are born, the accelerators that boost them to the required high energy, the final focus system that squeezes them to an exquisitely small size, and the beam dynamic studies that will tell us how all of these systems interact with each other. The largest and most expensive part of the NLC will be the accelerators, and so I will spend most of my time on that topic. It is, however, worthwhile to say a few words about the other three.

It is easier to make a small beam at the collision point if the beam has been born small at its source. The term "small" in this context means that we require a source of low emittance (the invariant emittance of the beam is proportional to the energy times the transverse size times the transverse angular spread). The NLC will require sources with an invariant emittance no more than about 10% of that used in the SLC. I think we understand how to do that job, at least for machines with repetition rates of no more than one or two kilohertz. We can use existing storage ring technology, but must pay a great deal of attention to the details to make sure that the emittance does come out as small as it can, in principle, be. The damping storage rings will be somewhat different in design from that used now, but it looks like the energy of these damping rings will be in the GeV region.

The final focus system will be difficult. The beam sizes are much smaller than they are in the SLC, while the energies are much higher so that the focusing system requires much stronger elements. The final focusing magnets will probably be superconducting, though some work is going on using plasma lenses which can be made even stronger than superconducting magnets. This focusing system becomes more difficult the larger the energy spread in the incoming beam will be, and regrettably, the smaller the required energy spread at the end of the accelerator the harder the accelerator is to build. This area needs a great deal of work, which can be theoretical for awhile, but eventually we are going to have to build some prototypes.

More detailed beam dynamic studies are required everywhere. The interaction of the beam with the accelerating structure (wakefields) must be better understood, and a lot of work is required on tolerances, stability requirements, etc. There is more than enough to do to keep the theoreticians in the accelerator community busy for some time.

As mentioned earlier, the accelerators and their power sources will be the most expensive part of the new machine, and it is here that most of the R&D work is now concentrated. The accelerators must be energy-efficient, stable, and able to preserve the small emittance of the beam from the sources through the full acceleration cycle. If one doesn't care about a few billion dollars here or there, one could probably use the SLAC linac technology for the NLC. The machine would be long, expensive and a terrible power hog. New developments in this area will strongly affect not only the construction costs of the machine, but its operating costs as well.

Four main approaches have been under discussion. These are:

1. Laser accelerators
2. Plasma accelerators
3. Wakefield accelerators
4. Conventional RF structures with either conventional or exotic power sources.

I think all of us who are active in this field (SLAC, Novosibirsk, KEK, CERN) have come to the conclusion that the NLC can only be built via the fourth method. It is the only one where in the foreseeable future we can see how, at least in principle, to get the required stability and energy conversion efficiency.

The stability requirement is very severe for we want to make a colliding-beam device, and not a fixed-target device. Beams from two independent accelerators must meet each other reliably and reproducibly within tolerances of a tiny fraction of a micron. A crude calculation indicates that the random transverse kick per stage of acceleration must be less than about 10^{-6} of the longitudinal kick. The first three methods all have severe problems — intensity fluctuation and mode structure (lasers), laser drivers and plasma uniformity (plasmas), and azimuthal asymmetry of drive beams (wakefield). All of them seem to suffer from serious inefficiency problems as well. I believe they are not for the next generation of linear colliders, though it may well be that new approaches and new technology may make these kinds of systems viable in 15–20 years.

The most promising system appears to be the conventional linear accelerator with some kind of high-power driver, which itself will have to be some new technology. The machines will probably use much higher accelerating gradients than are used now, and will almost surely be considerably shorter RF wavelengths than are used in the SLAC machine. The push toward high accelerating gradients is driven by the costs of the accelerator structure itself. The higher the accelerating gradient, the shorter the machine and its civil construction can be. At SLAC we have shown that for about one microsecond pulses at 3 kMHz, copper structures can stand accelerating gradients of more than 100 MV per meter at 3 kMHz, and more than 300 MV per meter at 10 kMHz.[2] Figure 3 shows the results. Note that for typical structures the accelerating gradient is about one-half of the maximum surface field. Thus, high accelerating gradients also seem to benefit from higher RF frequency.

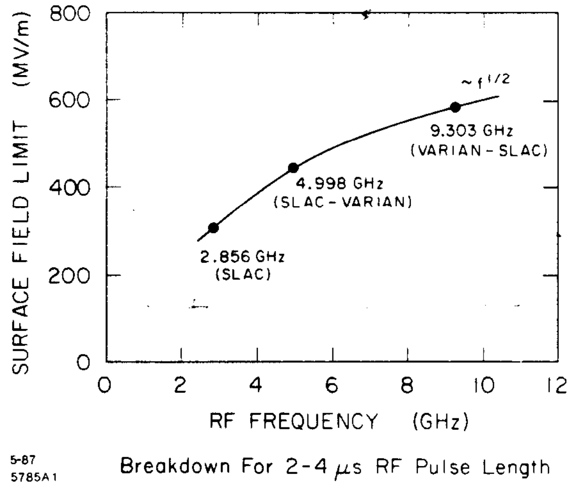

Fig. 3. Breakdown for 2–4 μs RF pulse length.

The electrical efficiency of the accelerating system also benefits from higher RF frequencies. For a given accelerating gradient, the stored energy per unit length in an accelerator is proportional to the square of the RF wavelength. Thus, for a given charge per bunch, the fraction of the energy stored in the accelerating structure that can be extracted by the bunch increases as the wavelength decreases.

There are two factors at work in the opposite direction. Transverse wakefields, which can increase the emittance of the beam, scale for given alignment tolerance as the reciprocal of the RF wavelength cubed, thus favoring larger wavelengths. Mechanical fabrication tolerances stay fractionally the same as the wavelength is reduced, but get absolutely more difficult to achieve at smaller wavelengths. In a situation where some factors favor short wavelengths while others favor long wavelengths, there is clearly an optimum. This optimum depends upon relative costs (power versus structure costs, for example), and the groups that have studied the issue believe that at our present state of knowledge the optimum is probably between one and three centimeter wavelength and is probably also relatively flat in that range.

If one had a superconducting accelerator structure, one would not have to worry about the fraction of stored energy extracted, for the leftover energy could be used to accelerate the next bunch. However, superconducting systems cannot attain very high accelerating gradients, and so the cost of a main accelerator done with superconductivity will be very high, as will be the power required to run the compressors of the refrigerator unless the Q of these systems can be significantly increased.

Table 1 shows the length and power consumption of a superconducting NLC of 1 TeV center-of-mass energy, assuming a Q of 5×10^9 at 2.3°K for an S-band structure with the refrigeration efficiency of 10^{-3} and a heat leak of two watts per meter. Both length costs and power consumption will be horrendous unless both the maximum accelerating gradient and the superconducting Q can be increased. Direct acceleration with a superconducting linac will have to wait for vastly improved cavities.

Table 1. Power requirements for a 1 TeV superconducting linear accelerator for various accelerating gradients. The refrigeration power is given for power dissipated in the structure (P_Q), for heat leaks (P_L), and total power.

G(MV/m)	L_{TOT}(km)	P_Q(MW)	P_L(MW)	P_{TOT}(MW)
2	500	80	1000	1080
5	200	210	400	610
10	100	420	200	620
20	50	840	100	940
50	20	2100	40	2140

The power sources for room temperature machines will require something new. Very high accelerating gradients go with high peak power in the accelerating structure. The machines under discussion at various laboratories use peak powers on the order of 1/2 to 1 gigawatt per meter of accelerating structure. Generating these high peak powers will be quite a challenge. Fortunately, the average power is not much higher than we deal with today, for these high peak powers are associated with short pulse lengths (typically 50 nanoseconds, or so) and so the average power required is not much different than that which comes from conventional klystrons.

One method that has been investigated at SLAC to generate high peak power from conventional klystrons is pulse compression. By combining multiple power sources through low-loss delay lines, with proper phase manipulation at the power sources, it is possible to get pulse compression ratios of ten or twenty to one. These systems are complicated, delicate, and require an enormous amount of plumbing for the delay lines, but they do seem workable.

Of more interest are the variants of what might be called two-beam accelerator systems. One beam with low energy and high current in one accelerator structure is used to generate RF power which drives a second accelerator structure. Two variants of this are currently under investigation. One being pursued by a SLAC/Livermore/Berkeley collaboration uses induction linacs to produce beams of several kiloamp current at energies of several MeV, with klystron-like bunching and energy extraction cavities.

The relativistic klystron concept is shown schematically in figure 4. A simple two-cavity system like that illustrated is only capable of producing power gains of around 100, but multiple-cavity systems like those used in our klystrons can produce power gains of 10^5 to 10^6. A proof-of-principle experiment was conducted last fall, which in essence removed the gun structure from an 8.6 GHz SLAC R&D tube and mounted the structure in an induction linac at LLNL. A peak power of 80 megawatts was produced in this system, which was far from optimized for operation at the high energy of the induction linac. A second-generation experiment will start soon using an 11.4 GHz structure optimized for the energy of the induction linac. We hope that this system will produce several hundred megawatts of peak power. If it does, we intend to use the power source to drive a multi-cavity accelerating structure in order to see whether one can hold as high a voltage gradient in such a multi-cavity system as can be held in a single-cavity system. We hope for results by the fall.

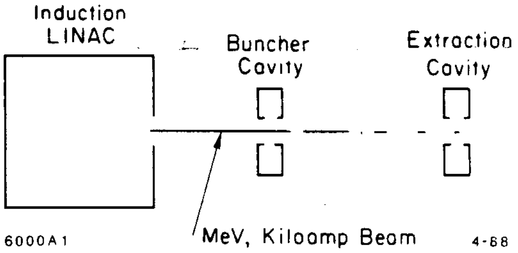

Fig. 4. Schematic of a relativistic klystron.

A different approach is being pursued at CERN. The CLIC group is investigating the use of superconducting cavities like those already designed and tested to increase the Tristan or LEP energy for the high current, low energy accelerator. A train of short, high-current bunches rides in this low-frequency accelerator and interacts with a high-frequency cavity structure to produce RF power which is used to charge the high-energy accelerator. The CLIC group is interested in frequencies of around 30 GHz for the high-energy machine, and are modeling the energy extraction cavities for tests at a lower RF frequency.

This field is moving very fast, and I think in a few year's time there is a very good chance that a practical power source/accelerator combination will be available.

CONCLUSION

The NLC is a goal being pursued by groups all over the world. The most intense efforts are underway in the U.S. and the U.S.S.R., and there is rising interest and increasing programs in both Europe and Japan. Everyone's goal is basically the same — to achieve a viable conceptual design in the early 1990's and to start construction on a real machine as soon as possible after that. In the preceding section I have outlined some of the work that has to be done. I believe there is clearly too much for any one laboratory or region to pursue on its own. This being the case, I conclude with a proposal.

We should do our research and development internationally with a mixture of coordinated and collaborative work. No single group can investigate all of the promising alternatives, and we will all move faster by cooperating. There are no secrets in accelerator physics anyway.

Governments and circumstances will determine who builds the first machine of the NLC class. Since no one yet has a good idea on how to make one of these machines with multiple interaction regions, there is a very good case to have more than one of them in any event.

We can argue about "where" later and collaborate now to all of our advantage. As difficult as international cooperation is, it will be a much easier task to carry out than to actually build the machine.

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