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PERSPECTIVES ON LARGE LINEAR COLLIDERS*

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I. INTRODUCTION

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.

I want to discuss three main items with you. The first is the interrelation of energy and luminosity requirements. These two items impose severe constraints on the accelerator builder who must design a machine to meet the needs of experimental high energy physics rather than designing a machine for its own sake. Next, I will give an introduction to linear collider design, concentrating on what goes on at the collision point, for still another constraint comes here from the beam-beam interaction which further restricts the choices available to the accelerator builder. Then, I want to give my impressions of the state of the technology available for building these kinds of machines within the next decade. Finally, I will conclude with a brief recommendation for how we can all get on with the work faster, and hope to realize these machines sooner by working together. Before going on to those topics I will talk a little bit about the past and how the linear collider concept came to be so popular.

The linear collider idea has been discussed casually for some time. Indeed, I remember Karl Brown of Stanford talking to me about the possibility in the

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early '60s when we were still building the first of the storage rings, the Princeton–Stanford Electron–Electron Collider. The first reference to linear colliders that I have been able to find in the literature is a paper by Maury Tigner of Cornell[1] which appeared in Nuovo Cimento in 1965. In this paper, Tigner talks about a system using colliding linac beams as an alternative to storage rings for studying electron-electron collisions. He talks about the benefits of superconductivity and how to lower the operating power by using energy recovery, where a beam gives its energy back after the collision point to the cavities of the accelerating structure that accelerated the other beam. He lists the luminosity requirements for low energy machines and concludes that it would be difficult but possible to make an effective electron-electron collider in the few GeV energy range.

The next paper I found is by Amaldi in *Physics Letters*[2] in 1976. Amaldi independently reinvented Tigner's scheme of superconducting electron linacs with energy recovery. He also considered electron-positron colliders, but could not find a solution that satisfied him for the production of positrons in a sufficiently small phase space to make high luminosity electron-positron colliders a practicality.

In between these two papers, I believe there was some discussion by Budker at the 1972 meeting of Laboratory Directors in Morges, Switzerland. I have not been able to find any written version of Budker's comments, but one or two of those who attended the meeting have told me that he did talk about it as a possibility but had no specific scheme in mind at the time.

I began to think about alternatives to storage rings after writing my paper on storage ring scaling laws while I was on sabbatical at CERN. Those scaling laws[3] were so unfavorable for machines much larger than a Z^0 machine that it became clear to me that some alternative to storage rings was required if we were going to go on with the highly important and productive electron-positron colliding beam studies at energies much above the Z^0 mass. I was on sabbatical at CERN when I wrote that paper, and it may be that discussions on the limitations of storage rings stimulated both Amaldi and Albert Hofmann of CERN to start thinking in new directions as well.

I believe the seminal event in the birth of the linear collider idea occurred at the ICFA Workshop on "Possibilities and Limitations of Accelerators and Detectors" which was held at Fermilab in October of 1978. I had continued thinking about alternatives to storage rings after I returned to SLAC from my sabbatical, and had done some calculations on the design of such machines. None was really satisfactory. The ICFA workshop brought together Dikansky and Skrinsky from Novosibirsk, Tigner from Cornell, and John Rees and myself from SLAC, for two weeks away from distractions. Skrinsky, Tigner and I discovered that we had all been thinking about linear colliders. During the course of the workshop we, with the help of a few others, wrote the paper[4] which set out all the criteria for linear colliders, including their scaling laws, the effect of synchrotron radiation on the beam-beam collisions, the emittance requirements, etc. For those who say that the International Committee for Future Accelerators never accomplished anything, I respond, they gave birth to linear colliders at that workshop.

When I returned to SLAC I pulled together a small group, and we began working on the conceptual design of what became the SLC. A second ICFA workshop was held in Switzerland in 1979, and the same group from the '78 workshop got together to refine the work. Skrinsky presented the conceptual design of the VLEPP project they were thinking about at Novosibirsk, and I got the help of many people in criticizing the state of our own design as it was then.

At SLAC we began pressing the Government for serious funding for the project in 1979, and made an extensive presentation to the U. S. High Energy Physics Advisory Panel in late '79 and early '80. It took us another year or two to finally convince our colleagues in the Government funding agencies that we really could build the device, and in the fall of 1983 construction of the SLC began. It is ready to do physics very shortly, and I think the fact that we were brave enough — or foolhardy enough, depending on your point of view — to start this machine has a lot to do with world interest in future projects.

The birth of the linear collider is not an untypical story in accelerator physics. Ever since the first accelerators were built, we have seen cycle after cycle where a particular accelerator technology reaches maturity and must be replaced by something else if high energy physics is to continue probing matter to ever smaller distances. Like most of the previous cases of the introduction of new technology, not too much is written because the practitioners are too busy working to write papers. The historians will be unhappy at the sloppy documentation of the physicists, but so be it. If any of you know of early papers which I have not been able to locate I would appreciate it if you could send me references.

Now let me turn from my perspective on the past of linear colliders to my perspectives on their future.

II. PHYSICS GUIDEPOSTS

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 are 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

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

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 table below.

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

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

I now turn to a brief description of some physics experiments that one might do to try to give you some feeling for the minimum energy that might be chosen for the NLC. If we look first at searches for the standard Higgs boson we see that if its mass is less than about 40 GeV it should be found at either LEP or the SLC; if its mass is less than about 80 GeV it should be found at LEP II; if its mass is between 80 and 160 GeV (twice the mass of the W) it will be very hard to find at proton machines (at least according to SSC and LHC studies to date) while it should not be hard at the NLC; and if the mass is greater than 160 GeV it should be discoverable at the proton collider (though there are background problems) or with the NLC.

The standard Feynman graph for neutral Higgs production associated with the Z^0 is shown in Figure 1(a), and this process leads to a production cross section of a few tenths of a unit of R. There is another process which is more important at high energies illustrated in Figure 1(b). This process, which might be called W fusion, has a cross section of 0.1–1.0 unit of R depending on the energy and the

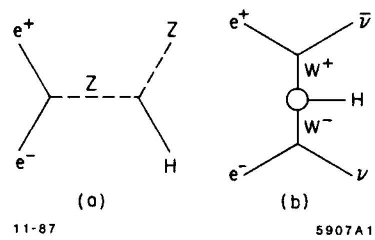

Fig. 1. Feynman diagrams for neutral Higgs boson production; (a) radiative Z^0 production, (b) W fusion.

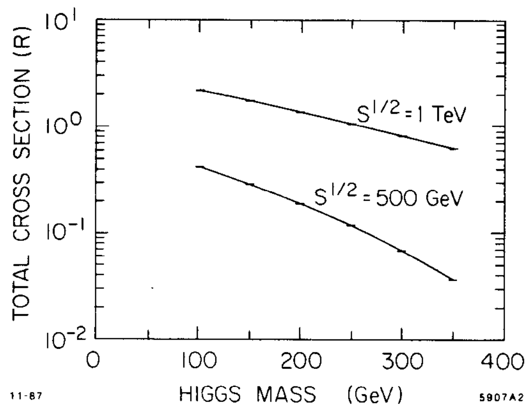

Fig. 2. Cross section in R units for Higgs production as a function of Higgs mass.

mass. Figure 2 shows the W fusion cross section as a function of Higgs mass for two different center-of-mass energies.

The detection of charged Higgs bosons seems to be very difficult at proton machines because of background problems. At e^+e^-machines it is much easier. For low-mass Higgs, the branching fraction of the Z^0 into charged Higgs is given by

$$\Gamma(Z \to H^+H^-) \approx 0.01\beta_H^3 \tag{3}$$

while for heavier charged Higgs production at the NLC the R value is given by

$$R_{H^+H^-} \approx 0.3\beta^3 \quad . \tag{4}$$

Charged Higgs can be detected by their decays into jets, though there is a significant amount of background.[5]

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). These models would tell us that machines to search for new quarks must have center-of-mass energies from 500 GeV to 1 TeV.

Most supersymmetric models predict the existence of supersymmetric leptons in the mass range from 100 to 400 GeV, requiring a machine energy of from 200 to 800 GeV.

Technicolor models usually predict the existence of technipions around 800 GeV which would push the machine energy up to around 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. The cross section over the entire energy range is shown in Figure 3. 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.

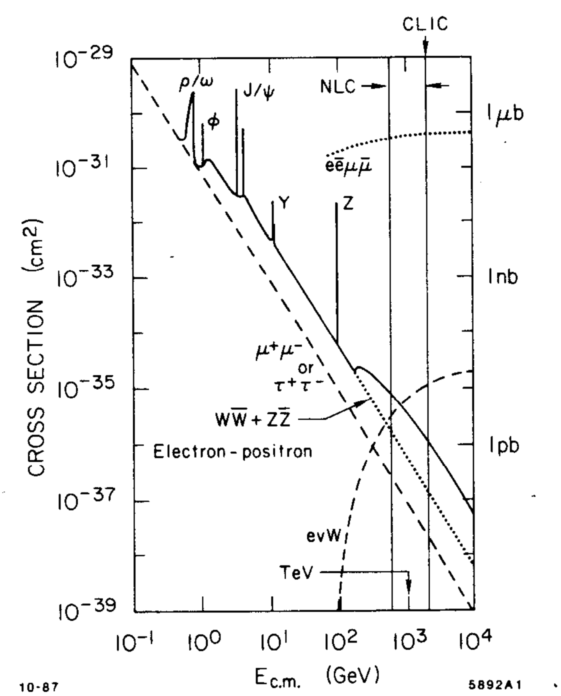

Fig. 3. Cross section as a function of energy.

III. LINEAR COLLIDERS FOR EXPERIMENTALISTS

The technique used up to now for all electron-positron colliding-beam physics experiments is that of the colliding-beam storage ring. This technology is well understood, for it has been in use for nearly thirty years since the start of the first electron storage ring, the Princeton–Stanford Storage Ring, at the Stanford High Energy Physics Laboratory. Indeed, the culmination of this technology is the 27 km. circumference LEP storage ring at CERN. Since the technology is so well understood it is possible to write a set of scaling laws which quite accurately describe the size and cost of such facilities. It turns out that the cost of storage rings at fixed luminosity scales as the square of the center-of-mass energy[3] , and so cost and size get to be very large at energies beyond LEP. To go to what one might call LEP–1000, a storage ring with 1 TeV in the center of mass, the size increases by a factor of 100 over LEP, and laid on a map of Europe, for example, a diameter of the machine would stretch roughly from Geneva to London, making two channel crossings on the way. Machines that big do not seem to be fiscally feasible, and there is some reason to believe that there are technical problems as well.

A technique with somewhat different scaling laws is the linear collider which seems to have the potential to achieve high center-of-mass energies at much lower cost than that of an equivalent storage ring. However, linear electron colliders are new and we are still learning to understand them, and so it is not possible right now to write down a simple set of equations which will predict the costs of an optimized facility. Indeed, the first linear collider, the SLC at SLAC, is just now coming into operation and will only begin to be used for physics experiments in 1988. There is still a lot to learn about the technology and optimization of these kinds of machines. In this section of my talk I will give a brief introduction to what goes on in the collision region in a linear collider. There are problems here which affect the experimenter's abilities to do experiments, and questions which require answers that cannot be determined solely by the accelerator physicists.

The beam-beam interaction in linear colliders can be much stronger than in a storage ring. The reason is that, since the beam is only used once, one can allow the electromagnetic fields of the two beams to disrupt their phase space to a much larger extent than is allowable in a storage ring where the beams must continue to circulate in a magnet ring for a very long time. In an electron-positron collider the collective fields of one beam will focus a single particle in the other beam, as illustrated in Figure 4. The strength of the interaction is measured by a dimensionless parameter (D), the disruption parameter, which is the ratio of the bunch length to the focal length of an equivalent lens. For round trigaussian beams D is given by

$$D = \frac{\sigma_z}{F} = \frac{r_e \sigma_z N}{\gamma \sigma_{r_0}^2} \tag{5}$$

where the bunch has a longitudinal standard deviation σ_z, a radial standard deviation of σ_{r_0}, a number of particles N, and an energy γ in rest-mass units; r_e is the classical electron radius and F is the small amplitude focal length of an equivalent thin lens.

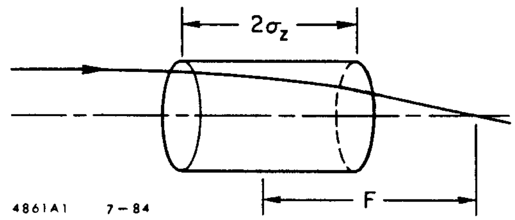

Fig. 4. The focusing effect of one beam on an oppositely charged particle in the other beam.

The effective fields in a linear collider tend to be very large, and the focal lengths can be very small. For example, in the SLC project at SLAC the fields are on the order of megagauss, F is on the order of millimeters, and D is about one. In the high-energy machines being discussed now at many places in the world the fields are tens of megagauss, F is tens of microns, and D is 5–10.

The luminosity of a linear collider is given by

$$\mathcal{L} = \frac{N^2 f}{4\pi}\left\langle \frac{1}{\sigma_r^2} \right\rangle = \frac{N^2 f}{4\pi\sigma_{r_0}^2} \quad H \tag{6}$$

where the charge in the two bunches is assumed equal, f is the collision frequency, σ_{r_0} is the radial standard deviation before the collision, and H is an enhancement factor which measures the effect of the beam-beam interaction on the transverse dimensions of the bunch during the collision. The beam-beam interaction in linear colliders can be so strong that a kind of mutual pinch occurs, reducing the radius of both beams during the collision period and hence enhancing the luminosity. H has been calculated by means of a computer simulation first by Hollebeek[6] and more recently by Yokoya[7] . Hollebeek's results, which are similar to Yokoya's for a round gaussian theme, are shown in Figure 5. H is by definition one as small values of the disruption parameter and rises to an asymptotic value of around 6 for disruption parameters greater than two. For flat beams the mutual pinch occurs in the thin dimension and the maximum value of H is around three.

The very large effective fields in the collision region can generate extremely intense synchrotron radiation. At high luminosities the synchrotron radiation called "beamstrahlung" dominates the energy spread in the beam. In the region that might be called the classical regime, where all synchrotron light sources

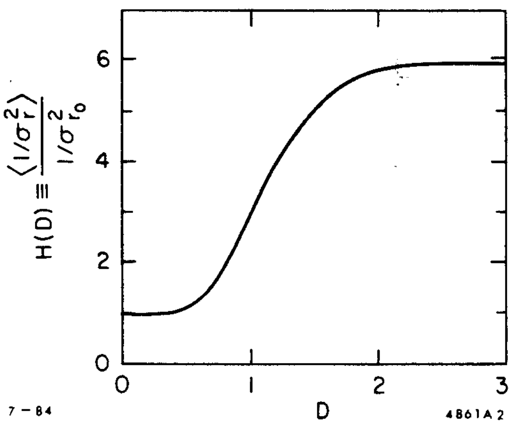

Fig. 5. Luminosity enhancement factor as a function of the disruption parameter.

and storage rings operate, the synchrotron radiation spectrum is a universal function of the radiated photon energy, divided by a parameter E_c called the critical energy. A sketch of the classical spectrum is shown by the heavy line in Figure 6, where the variable x is the photon energy divided by the critical energy. The critical energy itself is given by

$$E_c = 3\hbar c \frac{\gamma^3}{2\rho} \tag{7}$$

where h is Planck's constant, c is the velocity of light, and ρ is the bending radius of the particle in the particular field. The classical spectrum rises to a maximum at $x = 1$, and decreases exponentially for $x > 1$.

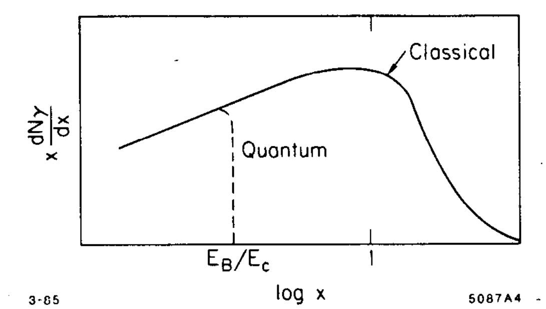

Fig. 6. Synchrotron radiation power spectrum as a function of the ratio of the radiated photon energy divided by the critical energy. The solid line is the "classical" case, while the dashed line shows the cut off in the extreme quantum limit.

Clearly, the classical spectrum can no longer be correct if the energy of the incident electron is itself small compared to the critical energy, and this is the case in extremely high-energy linear colliders where γ is large and ρ is small. Himel and Siegrist[8] were the first to analyze this case for linear colliders, and their work showed that to a good approximation that one could simply use the classical spectrum up to a value of the parameter x which was equal to E_B/E_c where the spectrum cut off. More recently, Blankenbecler and Drell[9] have done a complete quantum mechanical calculation good for any value of E_B/E_c, and in good agreement with the Himel–Siegrist calculation for very large values of E_B/E_c.

It turns out that all low-energy machines like the SLC are in the classical regime, and all interesting very high-energy machines are in the quantum mechanical regime. The machines that I have called NLC are in a transition region, and whether they are quantum mechanical or classical depends on the details of the design.

What is important to the experimenters, and hence to the machine designers, is the spread in center-of-mass energy generated by this beamstrahlung phenomena. Particles in one beam lose energy to synchrotron radiation photons as they pass through the other beam and so, even for the case of zero energy spread in the incident beams, there can be long tails on the energy distribution of the colliding beams if this synchrotron radiation is sufficiently intense. Naturally, it turns out to be easier for the machine designer to make machines with very large values of this center-of-mass energy spread, while it turns out to be difficult for the experimenters to do experiments if this energy spread is too big.

Qualitatively, for small values of δ, a parameter approximately equal to the mean loss in energy of a particle in one beam in traveling through the other beam, the center-of-mass collision energy distribution is sharply peaked around the initial center-of-mass energy, while for large values of δ the distribution has long tails stretching out toward low center-of-mass energy. Figure 7 shows the integral distribution of center-of-mass energies. I have plotted three cases which show the fraction of the time that S/S_0 is greater than a given value, versus that value. For $\delta = 0.26$, only about 30% of the time is the center-of-mass energy within 2.0% of the maximum energy. This can give rise to a strange looking spectrum of events. In Figure 8 I have plotted the yield at a 1 TeV collider with $\delta = 0.26$ for a mythical process which has a cross section one unit of R for a 1 TeV NLC operating at a luminosity of 10^{33} for 10^7 seconds. This cross section depends on energy as S^{-1} down to the Z mass where it is simply assumed on the resonance to be about 20% of the hadron cross section. Though the tails on the center-of-mass energy distribution are small, there are approximately as many events around the Z peak as there are within 2.0% of the maximum value of S, and there is a long flat tail in between. Determining the allowable maximum value of δ is a job for the experimenters.

I conclude this section by noting that the choice of center-of-mass energy, luminosity and beamstrahlung parameter tightly constrains the choice of design of the machine, for most of the parameters of the accelerator itself will be determined

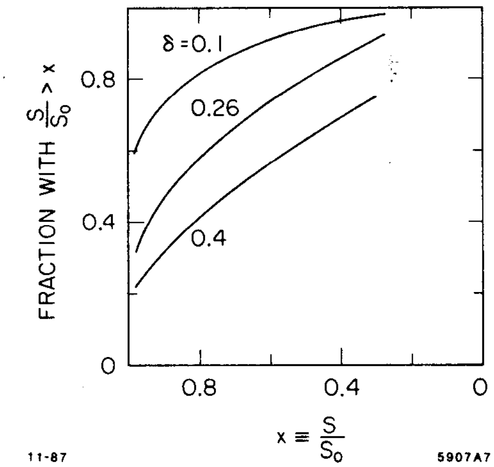

Fig. 7. Probability that a collision takes place with a value of S/S_0 greater than a given value for 3 values of the beamstrahlung parameter, δ.

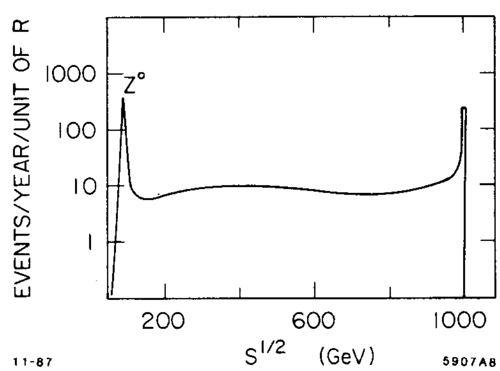

Fig. 8. Yield in a 1 TeV collider of $\mathcal{L} = 10^{33}$ for 10^7 seconds of operations at $\delta = 0.26$ for a hadron-like process with a cross section of one unit of R.

by these choices. Of course, the technology to be used in boosting the required number of particles to the required energy within the beamstrahlung constraints is what the accelerator builder has to worry about. The higher the energy, the higher the luminosity, and the lower the beamstrahlung parameter, the more difficult the accelerator builder's job becomes, and the further we go from the region of the SLC, where we are now getting some experience.

IV. A QUALITATIVE PICTURE OF ACCELERATOR TECHNOLOGY

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 multi-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 9, 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 some new kinds of approaches. The physics requirements for the NLC push us toward the "new approaches" region.

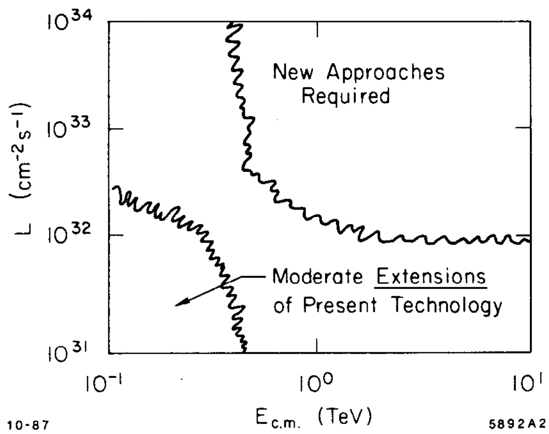

Fig. 9. A qualitative view of the accelerator technology required for a linear collider in the luminosity-energy plane.

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 — 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 surely be superconducting, though some work is going on using plasma lenses which can be made even stronger than superconducting magnets for final focus elements. 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 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. 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 are 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.[10] Thus, high accelerating gradients also seem to benefit from higher RF frequency.

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. Of course, 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. Everyone now seems to be talking about systems with frequencies from 10 to 30 GHz.

The power sources for these 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 in the world 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. 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 almost 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 Berkeley/Livermore/SLAC collaboration uses induction linacs to produce beams of several kiloamp current at energies of several MeV, with klystron-like bunching and energy extraction cavities. We hope to demonstrate a 500 gigawatt, 50 nanosecond pulse length RF source sometime next year.

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 years' 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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