SLAC – PUB – 4446
November 1987
(A)

LINEAR COLLIDER RESEARCH AT SLAC*

RONALD D. RUTH

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Invited talk presented at the
ICFA Seminar on Future Perspectives in High Energy Physics,
Upton, New York, October 5–10, 1987

⋆ Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.

1. INTRODUCTION

We, at SLAC, are in the process of preparing the SLC, the first linear collider, for the initial physics run in the spring of 1988. The present status of that process is covered in Ref. 1 and 2, and also in Ref. 3 which appears in these proceedings. Therefore, the time is ripe for initial investigation into the next generation of linear colliders.

Towards this end, Burt Richter has charged the Accelerator Department at SLAC to design a next generation linear collider by about 1990, so that the construction might start in the mid 1990's ± a couple of years. The general parameters of such a machine are listed in Table 1. The center of mass energy is taken to be about 1 TeV and the luminosity in the range $10^{33} - 10^{34}\text{cm}^{-2}\text{sec}^{-1}$. These two parameters force the design to be a non-simple extension of the SLC.

The other requirements in Table 1 are somewhat arbitrary but allow the machine to be built on a Stanford site with "reasonable" wall-plug power. The technology used in the machine must be realizable by the early 1990's. A possible site for such a machine is shown in Fig. 1. The Tev Linear Collider (TLC) is about twice as long as the SLC; however, the site shown in Fig. 1 is entirely on Stanford land.

A linear collider can be divided into 4 main subsystems: *Damping Rings* provide low emittance beams with the appropriate intensity and repetition rate. Next, to prepare a short bunch for injection into a high gradient accelerator structure, we need a section for *Bunch Rotation and Pre-acceleration.* The *Linac* is then used to accelerate the beams to high energy while maintaining the emittance of the beam. Finally, the *Final Focus* is used to focus the beams to a small spot for collision. This must yield a luminosity consistent with constraints on beam-beam effects (disruption and beamstrahlung).

Table 1. GENERAL PARAMETERS

Energy	2×0.5 TeV = 1 TeV in center of mass.
Luminosity	$10^{33} - 10^{34} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$, (preferably the latter).
Length	Each Linac $\lesssim 3$ Km.
Power	$\lesssim 100$ MW per Linac.
Technology	Must be realizable by 1990–92!

Before beginning the discussion of each of the subsystems, it is useful to present a possible parameter set for the next linear collider. This parameter set appears in Table 2 and was generated by Bob Palmer.[4] It is a self-consistent set in which there was an attempt made to optimize based on approximate formulae and scaling for the various subsystems. The repetition rate and number of particles per bunch are somewhat less than the SLC design. The accelerating structure for the example in Table 2 is at 4 times the SLC frequency and is powered to 10 times the SLC acceleration gradient. This leads to short filling times for the travelling wave structure and to quite high peak-power requirements. The final spot size is very much smaller than the SLC design. This is achieved by a combination of a much smaller emittance of the beam and a small beta function at the final focus. For this example the beamstrahlung parameter is about 1/3.

These self consistent solutions change depending upon the choice of frequency of the linac. Several other possibilities appear in Ref. 4. In this paper, this particular example is used to illustrate the general nature and scope of the various subsystems.

In the next section, we begin the discussions of the various subsystems at the final focus and interaction point since this is where we produce the physics. In subsequent sections, we work our way upstream to discuss qualitatively various features of each subsystem.

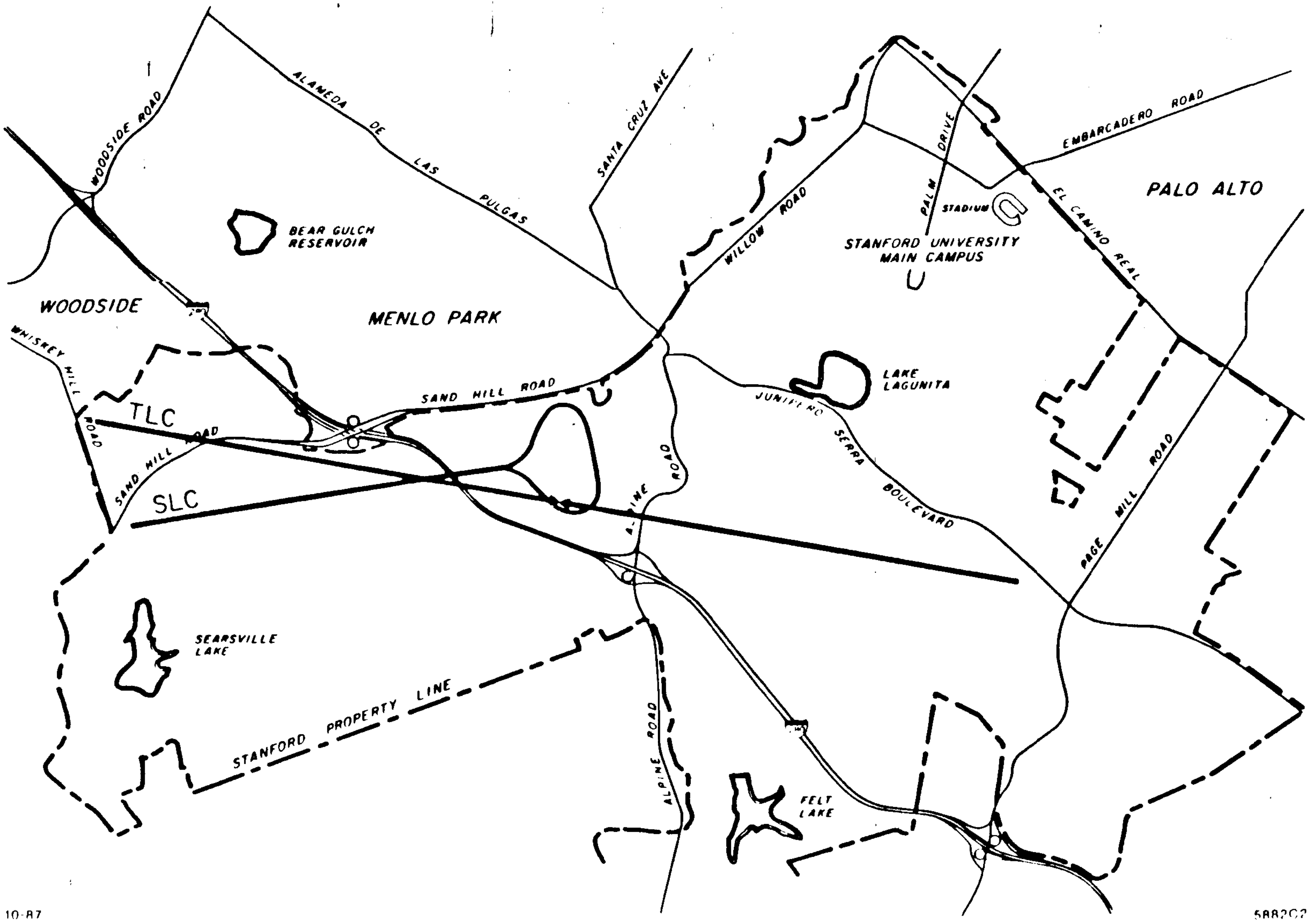

Fig. 1. A Possible Site for the TeV Linear Collider (TLC).

Table 2. SOME POSSIBLE PARAMETERS OF 1 TEV COLLIDER*

(Used in defining R&D Programs)

LUMINOSITY	
$\mathcal{L}$	$1.7 \times 10^{33} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$
AC Power/Wall Plug	100 MW
Repetition Rate	100 Hz
Number of particles per bunch	1.8×10^{10}
RF POWER	
Frequency	11.4 GHz
Acceleration Gradient	186 MV/m
Group Velocity β_g	.08
Pulse Length	45 nsec
Distance between feeds	1.2 m
Watts per meter	1.2 GW
FINAL FOCUS	
β_y^*	.05 mm
β_x^*/β_y^*	300
Final Focus Pole Tip Field	1.4 Tesla
σ_y	1.5 nm
σ_x	270 nm
σ_z	.04 mm
Disruption	14
Beamstrahlung δ	.33
DAMPING RINGS	
Vertical emittance ϵ_y	3.5×10^{-8} m rad
ϵ_x/ϵ_y	100
Energy	1 GeV
Damping Time	2.3 msec
Average Radius	15 m

*Not necessarily optimum, but self-consistent.

2. FINAL FOCUS

The final focus design from Table 2 assumes that flat beams collide with a small crossing angle. Why should the beam be flat?

The purpose of a flat beam is to increase luminosity while controlling beamstrahlung and disruption. As we move from round beams to flat beams, the beamstrahlung from the beam-beam crossing becomes independent of the vertical size. Thus we can increase the luminosity without affecting the energy loss due to beamstrahlung.

Why should we have a small crossing angle? If we allow the beams to cross at angles less than σ_x/σ_z where σ_x is the horizontal (wide) dimension and σ_z is the bunch length, then the luminosity is changed very little when compared to head-on collisions since there is almost complete overlap of the two distributions. However, this has the great advantage of allowing the disrupted beam, after collision, to follow a different path than the entering beam. Therefore, one can design the final quadrupole to accept the incoming emittance of the beam, and thus it can have a very small aperture. This leads to the reasonable pole tip field shown in Table 2. The quadrupole shape can allow a separate channel for the disrupted beam.

To achieve the small spot in an aberration free way, it is necessary to provide some chromatic correction upstream of the final quadrupole doublet. Bends are used to disperse the beam horizontally, while sextupoles provide the different focussing forces for different energy particles. These bends cause the beam to emit synchrotron radiation. This chromatic correction section must be designed so that the total energy radiated by these bends is quite small, and in addition so that the transverse emittance is not diluted by the diffusion caused by emission of the discrete photons of synchrotron radiation.

Finally, to conclude this section, we may need to correct higher order chromatic effects for the vertical dimension. This may not, however, be needed horizontally because of the much larger horizontal size.

3. LINAC

3.1 POWER SOURCES

The linac is envisioned to be similar to the SLAC disk-loaded structure with a frequency at least 4 times the present SLAC frequency. The irises will probably be relatively larger to reduce transverse and longitudinal wake fields. This would be driven by an RF power source with the capability of about 1 GW per meter of structure with a pulse length of about 50 nsec. The peak power can be reduced somewhat by using smaller irises in the structure and longer pulse lengths.[5] However, this increases the transverse wake fields and causes instability transversely. In either case this high peak power is difficult to obtain and is a key area for research.

Presently, the SLC klystrons produce 67 MW of power for about 3.5 μsec at 2.86 GHz. This is used to feed 12 m of structure. For the next linear collider, we are investigating two approaches.

RF Pulse Compression

In Fig. 2a, you see illustrated the basic principle of RF pulse compression. A long modulator pulse is converted by a high power, 'semi-conventional' klystron into RF power with the same pulse width. This RF pulse is then compressed by cleverly slicing the pulse and re-routing the portions through delay lines so that they add up at the end to a high peak power but for a small pulse width. This scheme was suggested by D. Farkas at SLAC and is presently under experimental investigation also.[6] With a factor of 16 in pulse compression, the method requires a 60 MW klystron with a 1 μsec pulse length for each meter of the accelerator.

The Relativistic Klystron

In Fig. 2b, you see the principle of the relativistic klystron illustrated. In this case, the pulse compression happens *before* the creation of RF. This technique makes use of the pulsed power work done at LLNL in which magnetic compressors are used to drive induction linacs to produce multi-MeV e^- beams with kiloampere currents for pulses of

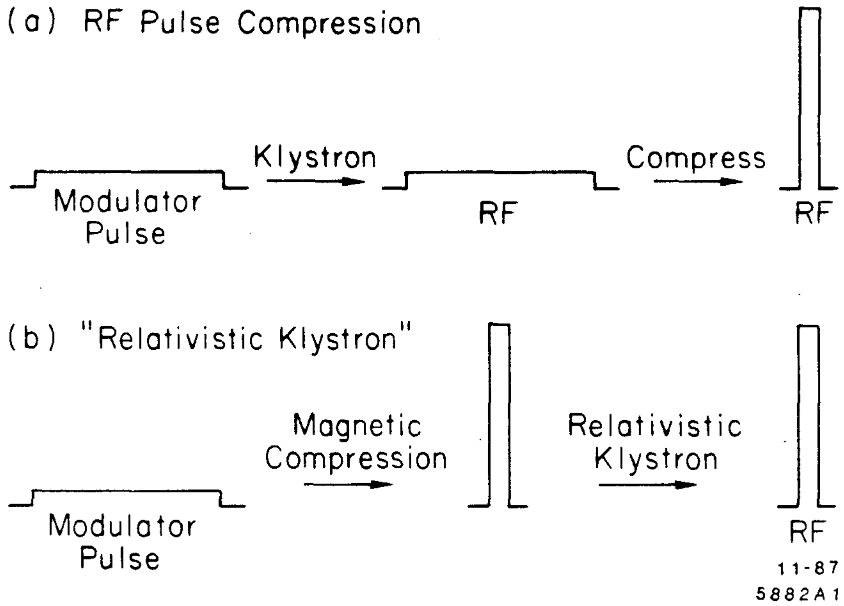

Fig. 2a. Illustration of RF Pulse Compression
2b. Illustration of the Relativistic Klystron With Magnetic Compression

about 50 nsec. These e^- beams contain gigawatts of power. The object, then, is to bunch the beam at the RF frequency to extract a significant fraction of this power. This can be done either by velocity modulation or by dispersive magnetic "chicanes". After bunching, the beam is passed by an RF extraction cavity which extracts RF power from the beam.

Presently, we are collaborating with LLNL on a relativistic klystron experiment which makes use of the ARC facility (e^- beams 1.2–4.5 MeV and 1–3 KA). This collaboration will continue on ETA II (e^- beams 7 MeV and 1–3 KA) later after it becomes operational. The present program has achieved 70 MW at 8.6 GHz in a test run at ARC. We hope to achieve about 500 MW at 11.4 GHz early in 1988. The purpose of these experiments is to first achieve significantly higher RF power than the SLC klystrons at a much higher frequency and secondly to drive an accelerator section to fields exceeding 200 MV/m to test breakdown and field emission.

A final power source along these lines might have a 10 GW beam (say 2 KA and 5 MV) which is RF modulated at some stage in the acceleration process. The RF might then be extracted with greater than 50% efficiency in 5 extraction gaps to drive about 5 meters of accelerator structure. Of course, there is a continuum of possible devices from a rather short relativistic klystron up to a full two-beam accelerator as envisaged by A. Sessler and S. Yu.[7]

3.2 TRANSPORT

Of course, the beam must be transported as well as accelerated in the linac. This is complicated by deflecting wake fields caused by the beam as it moves off axis slightly in the accelerator. For a single bunch, this leads to very tight tolerances on beam position measurement and on the alignment of quadrupoles. It also necessitates opening the irises of the structure to reduce the transverse wakefield to tolerable levels.

In order to obtain the highest luminosity, it will probably be necessary to have many bunches of particles per RF pulse. This allows a much more efficient transfer of energy and thus for little increase in wall-plug power, one can possibly increase the luminosity by a factor of 10 with about 10–20 bunches per pulse. Unfortunately, the transverse deflecting wakes are once again a problem. Each bunch induces a long-range wakefield which acts on many trailing bunches. This leads to the beam break-up of the bunch train. This is a very serious problem which so far has not been solved. However, for 2 or 3 bunches, the problem is not so severe, and indeed the SLC plans 3-bunch operation ($e^+e^-e^-$). For many bunches, one probably must damp the long-range transverse wake by clever cavity design.

4. BUNCH COMPRESSION AND PRE-ACCELERATION

In order to obtain the very short bunches necessary for the linac, it is necessary to perform at least two bunch compressions. A bunch length of 50 μm in the linac puts a tight constraint on the longitudinal emittance of the damping ring. In addition, during the bunch compressions, it is necessary to keep the energy spread small to avoid the dilution of the transverse emittance. If we assume that we can transport 1% energy spread without diluting either transverse emittance, then at least two bunch compressions are needed. For example if we consider a 1 GeV damping ring with energy spread $\Delta E/E = 10^{-3}$ and a bunch length of 5 mm, the two compressions are shown in Table 3. The first one decreases the bunch length by an order of magnitude. This is followed by a pre-acceleration section to decrease the relative energy spread in the beam by an order of magnitude. One must avoid an increase of energy spread due to the cosine of the RF wave (and also due to beam loading). If this pre-acceleration is done at the present SLAC frequency and if the bunch current is as shown in Table 1, then the additional energy spread induced is about 5×10^{-4}. Neglecting this small increase, the next bunch compression happens at 10 GeV and serves to reduce the bunch length to about 50 μm. This is suitable for injection into the high frequency, high gradient structure.

5. DAMPING RINGS

The damping ring emittances are shown in Table 1. For the horizontal, they represent a factor of 10 decrease in emittance (a factor of 3 in beam size) from the SLC. For the vertical, they reflect the fact that damping rings provide an asymmetrical emittance naturally.

This small vertical emittance will not, however, be trivial to achieve since it requires tight orbit tolerances and the control of coupling and the vertical dispersion. However, experience shows us that large emittance ratios are possible; PEP has achieved $\epsilon_x/\epsilon_y \simeq 100$, and the VUV ring at BNL has achieved $\epsilon_x/\epsilon_y \simeq 300$. Thus we expect these ratios to be possible also in the next damping ring.

In addition, we must control the longitudinal emittance, and thus, avoid bunch lengthening in the damping ring. This means that the impedance of the ring must be carefully

Table 3. BUNCH COMPRESSION

E	$\Delta E/E$	σ_z	Compress →	$\Delta E/E$	σ_z
1 GeV	10^{-3}	5mm	Compress →	10^{-2}	0.5mm
[pre-acceleration at long wavelength, $\lambda = 10.5$ cm]					
10 GeV	10^{-3}	0.5mm	Compress →	10^{-2}	50μm

controlled.

To gain experience with asymmetrical emittance, we are planning an experiment at the SLC which has the goal of achieving $\epsilon_{ny} = 3 \times 10^{-7}$ (an emittance ratio $\epsilon_x/\epsilon_y = 100$).

Recently, ICFA sponsored a workshop on low emittance production.[8] The general conclusion was that the emittances shown in Table 2 seem to be possible with only modest extensions of present techniques.

6. TOLERANCES AND MEASUREMENT PROBLEMS

Many of the key issues for the next linear collider are related to the tight tolerances required. In both the linac and damping ring, it will be necessary to measure the orbit position very precisely in order to be able to correct it. This will require a beam position monitor (BPM) precision of less than 10μm. Presently at the SLC, we measure beam position to about $50-100\mu$m, and in some cases, we can measure relative positions to about 20μm. Therefore, the next generation of BPM's should be about an order of magnitude more precise than the present generation. With smaller apertures and low noise designs, this will probably be possible.

In addition to careful measurement, we must also align the magnets very precisely. For the design in Table 2, this alignment tolerance is less than $10\mu m$ for magnet to magnet misalignments. This will require more careful survey techniques, and perhaps more importantly, the precise determination of the magnetic centers of all the focussing quadrupoles.

The problem of position measurement and correction is helped somewhat by pulse to pulse stability since for a stable beam one can average many successive measurements. This pulse to pulse stability is another key requirement to maintain the collision of the beams. Slow variations of the beam position can be corrected with feedback systems, therefore, much of the ground motion can be cured since it occurs at low frequency. However, variations of the beam at the repetition rate are uncorrectable except by vibration isolation techniques and careful power supply regulation.

In addition to the beam position, one must also measure the beam spot size. These measurements are used to check the optics and to measure the emittance of the beam. At the end of the linac in the example shown in Table 2, the spot sizes are

$$\begin{aligned} \sigma_y &\simeq 1\mu m \\ \sigma_x &\simeq 8\mu m \quad . \end{aligned}$$

Since these are typical throughout the linac, routine measurements of such spot sizes and aspect ratios must be addressed. Presently at the SLC, the final focus spot will eventually be about $1\mu m$; and, in fact, $5\mu m$ spots have already been measured with flying wire techniques. The SLC system is designed for the $1\mu m$ level, so for a future collider there is at least one option for spot size measurements in the linac.

The final focus spot is a completely separate question. In this case the spot sizes for the example shown in Table 2 are

$$\begin{aligned} \sigma_y^* &\simeq 1.5\mathrm{nm} \\ \sigma_x^* &\simeq 270\mathrm{nm} \quad . \end{aligned}$$

Thus far, there are no specific proposals for this measurement. It is certainly a challenging problem; however, it could be attacked with significant resources since it occurs only *once* in the entire linear collider.

7. OUTLOOK

What are the prospects for a linear collider with 1 TeV center of mass in the near future? We have briefly discussed a few of the problems in the previous sections to emphasize that the next linear collider will *not* be just a simple extension of SLC technology. In spite of this, experience with the SLC is an essential ingredient. Various topics for research and development have been specified and detailed studies on many of the subsystems are beginning. A key element is the power source. Just now the relativistic klystron seems to be a promising candidate; however, future experiments and cost studies will tell the true story.

In spite of the amount of work yet to be done, with the combined efforts of the various laboratories around the world we may see a detailed design of a TeV linear collider in the next 2 to 3 years.

REFERENCES

1. B. Richter and R. Stiening, *Proc. of 1987 International Symposium on Lepton and Photon Interactions at High Energies*, Hamburg, Germany, and SLAC-PUB-4367.
2. J. T. Seeman and J. C. Sheppard, *Proc. of the Workshop on New Developments in Particle Accelerator Techniques*, Orsay, France, and SLAC-PUB-4421.
3. R. D. Ruth, SLAC-PUB-4472 and these proceedings.
4. R. B. Palmer, *Proc. of the Workshop on New Developments in Particle Accelerator Techniques*, Orsay, France, and SLAC-PUB-4295.
5. P. B. Wilson, in *Proc. of the 1987 Particle Accelerator Conference*, Washington, D.C., and SLAC-PUB-4310
6. Z. D. Farkas, *IEEE Transcripts on Microwave Theory and Techniques*, **MTT-34**, No. 10 (1986) 1036, and also SLAC/AP-59.
7. A. M. Sessler and S. S. Yu, *Phys. Rev. Lett.*, **58** (1987) 2439.
8. J. B. Murphy and C. Pellegrini, Editors, *Proceedings of the ICFA Workshop on Low Emittance e^-e^+ Beams*, Brookhaven National Laboratory, 1987, BNL 52090.