SLAC-PUB-5295
June 1990
A

PROGRESS TOWARDS THE DESIGN OF A NEXT LINEAR COLLIDER*

RONALD D. RUTH
Stanford Linear Accelerator Center
Stanford University, *Stanford, California 94309*

INTRODUCTION

The purpose of this paper is to review the ongoing research at SLAC towards the design of a next-generation linear collider (NLC). The energy of the collider is taken to be 0.5 TeV in the CM with a view towards upgrading to 1.0 TeV. The luminosity is in the range of 10^{33} to 10^{34} $cm^{-2}sec^{-1}$. The energy is achieved by acceleration with a gradient of about a factor of five higher than SLC; which yields a linear collider approximately twice as long as SLC. The detailed trade-off between length and acceleration will be based on total cost. A very broad optimum occurs when the total linear costs equal the total cost of RF power.

The luminosity of the linear collider is obtained basically in two ways. First, the cross-sectional area of the beam is decreased primarily by decreasing the vertical size. This creates a flat beam and is useful for controlling beamstrahlung. Secondly, several bunches (-10) are accelerated on each RF fill in order to more efficiently extract energy from the RF structure. This effectively increases the repetition rate by an order of magnitude.

An overall layout of one half of the collider is shown in Fig. 1. In the next several sections, we trace the beam through the collider to review the research program at SLAC. More details of ongoing work at SLAC and throughout the world can be found in Refs. 1-5.

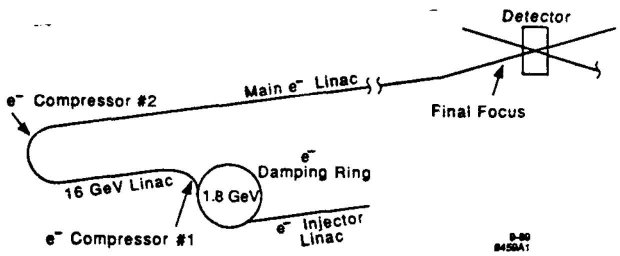

Fig. 1. Schematic of a Next Linear Collider.

DAMPING RINGS & BUNCH COMPRESSION

Initial designs for damping rings and bunch compression systems have been completed and are discussed in Refs. 6-9. The emittances required are an order of magnitude smaller than those achieved at the SLC. In addition, the design exploits the natural asymmetrical emittances of electron storage rings with $\epsilon_x/\epsilon_y = 100$. The rings are about five times the circumference of the SLC ring and have a design energy of 1.8 GeV. The damping time to achieve 360 Hz is obtained through the use of wigglers in straight sections; however, if the repetition rate is dropped to 180 Hz, these wigglers can probably be eliminated from the design.

The bunch length in the damping ring is about 5 mm. In order to reduce transverse wakefields in the high gadient linac and also to keep the bunch length less than the depth of focus at the IP, we must compress the bunch to about 50 μm. As discussed in Refs. 8 and 9, this is achieved by using two compressors separated by a 16 GeV pre-accelerator linac. This combination serves to reduce the bunch length by two orders of magnitude, while keeping the relative energy spread below about 1%. The second compressor may also be used to bend the beam by 180° as shown in Fig. 1. This bend is useful for possible upgrades in length and also allows the use of direct feedback to control injection jitter in the linac.

LINAC

The linac is envisioned to be similar to the SLAC disk-loaded structure with a frequency of four times the present SLAC frequency. The irises in the-design are somewhat larger (relative to the wavelength) to reduce transverse wakefields. The structure will have other modifications to damp long-range transverse wakefields. This will be driven by a power source capable of about 220 MW/m in order to obtain an accelerating field of about 100 MV/m.

The remainder of this section is divided into three subsections. In the first subsection we discuss structures, the second deals with RF power sources, and the third treats emittance preservation.

Structures

The first question that arises for the RF structure is breakdown. This question is treated in Refs. 10 and 11. where G. Loew and J. Wang present results from many experiments at various frequencies. If the scaling laws thus obtained are extrapolated to 11.4 GHz, the breakdown-limited surface fields obtained are 660 MV/m. To convert this to an effective accelerating gradient, a reduction factor of 2.5 is typically used, which yields an accelerating gradient above 200 MeV/m. However, the measurements also indicated significant "dark currents" generated by captured field-emitted electrons. The question of the effects of dark current on loading and beam dynamics is not yet resolved and may provide the ultimate limit to the acceleration gradient.

As mentioned in the Introduction, in order to make efficient use of the RF power and to achieve high luminosity, it seems essential to accelerate a train of bunches with each fill of the RF structure. This leads to twoproblems: (1) the energy of the bunches in the train must be controlled and (2) the transverse stability of the bunch train must be ensured.

The problem of energy control is studied in Ref. 12. Provided that the higher longitudinal modes are damped, it seems possible to extract up to about 25% of the energy in the structure while still maintaining a small bunch-to-bunch energy spread. Transverse effects are treated in Refs. 13 and 14. The most severe problem is beam breakup in the linac; however, if the transverse modes are damped to Q's ~10–50 and (with the higher Q's) if the first dipole mode can be tuned, then there is no beam breakup in the linac. Thus, both problems can be solved by damping higher modes (both transverse and longitudinal) in the RF structure.

In Ref. 15, R. Palmer describes a technique of using slotted irises coupled to radial waveguides to damp these modes: Q's as low as 10-20 were measured in model structures. This encouraging evidence has led to a development program at SLAC to do more detailed studies of slotted structures. Recently at SLAC, Q's as low as 8 have been measured in low-power models at 2.8 GHz.[16,17] Several different techniques are being explored and experiments are also ongoing at high frequency.[16]

RF Power Sources

Before discussing results on power sources, it is useful to contrast and compare two basic approaches, RF pulse compression and magnetic pulse compression.

RF Pulse Compression and Conventional Klystrons: Prior to RF pulse compression, a long modulator pulse is converted by a high-power, "semi-conventional" klystron or some other power source into RF power with the same pulse width. This RF pulse is then compressed by slicing the pulse using phase shifts and 3 db hybrids 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 invented by D. Farkas at SLAC and is presently under experimental investigation.[18] With a factor of 6 in pulse compression, a 100 MW klystron could power about 3 m of structure to achieve an accelerating gradient of about 100 MV/m.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Presented at the 2nd European Particle Accelerator Conference, Nice, *France, June 12-16, 1990*

In Ref. 19, P. Wilson describes RF pulse compression in some detail including estimates of efficiencies. An experimental test, at SLAC of a low-loss, low-power system has been completed which yielded a factor of 3.2 power gain.[20] Recently, a high-power RF pulse compressor, designed to yield a power gain of 6, has been completed at SLAG. This has been tested at low power and has achieved a gain of 5.5.[21] This will be powered with a high-power 11.4 GHz klystron designed to yield 100 MW peak power. An initial prototype of this klystron has achieved 65 MW in short pulses and 25 MW in long pulses.[22]

Magnetic Pulse Compression and the Relativistic Klystron: 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 about 50 nsec. These e^- beams contain gigawatts of power. The object, then, is to bunch the beam at the RF frequency and the&o-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.

Experiments on the relativistic klystron are described in Ref. 23. The best power output achieved to date is 330 MW.[22] Although higher acceleration gradients have been achieved, the best breakdown-free acceleration gradient in this experiment is 84 MV/m with 80 MW of RF power input into a 30 cm long accelerator structure.

Other RF Sources: It is also possible to consider other sources driven by magnetic pulse compressors which directly produce short, high-power RF pulses. One example is a cross-field amplifier (CFA). This device has the geometry of a magnitron but is configured as an amplifier rather than an oscillator. SLAC has completed the construction of a CFA designed to produce 100 MW. This initial prototype has achieved about 10 MW peak output power.[22] Although it is a large extrapolation from existing sources, it holds the promise of being less expensive than an equivalent power klystron.

The "cluster klystron" is another interesting possible RF source. In Ref. 24, R. Palmer and R. Miller describe a multiple beam array of "klystrinos" which when coupled together can give impressive results. By dividing a single beam into many beams shielded from each other, the problems of space charge are effectively eliminated. This source could be used as a driver for RF pulse compression. Alternatively, with the addition of a grid and an oil-filled transmission line for energy storage, the device could directly produce short RF pulses. Thus far, there has been no experimentation, but calculations and cost estimates are encouraging.

To conclude this section, if high-power tests of RF pulse compression show positive results, and if the 100 MW klystron achieves its design power, this combination could provide a power source for a Next Linear Collider.

Emittance Preservation

In order to achieve the desired luminosity, we must preserve the emittance of the beam during acceleration. Much experience is being gained at SLC, where BNS[25] damping has been successfully tested and is routinely used in normal operation.[26] For the NLC as conceived at SLAC, chromatic dilution of the bunch has limited tolerances to about 10–20 μm for vertical misalignments. Recently, a new trajectory correction technique, which eliminates the chromatic dilution, has been invented which increases the tolerances on misalignments to values greater than 200 μm rms.[27,28] Using this technique combined with BNS damping, we hope to control the emittance growth during acceleration.

FINAL FOCUS

The final focus is a flat beam which crosses at a small angle to the oncoming beam. The purpose of the flat beam is to increase the luminosity while controlling beamstrahlung and disruption. The crossing angle is to allow different size apertures for the incoming and outgoing beam. Another invention, "crab-wise crossing", discussed in Ref. 29, allows a much larger crossing angle than the diagonal angle of the bunch. This type of geometry may now be essential due to the production of e^+e^- pairs by beamstrablung photons in the field of the bunches.

Final Focus Optics and Tolerances

The first job in the final focus is to demagnify the beam to provide a small spot for collision. A design for such a system is presented in Ref. 30 by K.. Oide. This is a flat beam final focus which achieves a vertical and horizontal beam size of about 1 nm and 200 nm, respectively. The vertical size is limited by a fundamental constraint, the "Oide limit", due to the synchrotron radiation in the final doublet coupled to the chromatic effect of a quadrupole. The quadrupole gradients necessary are very high, and in Oide's design are obtained by conventional iron magnets with 1 mm pole-to-pole distance. Tolerances are very tight in such a final focus. The most restrictive vibration tolerance is on the final doublet which must be stable pulse-to-pulse to about 1 nm.

Since vibration of the final doublet is the most serious problem, it is considered in some detail in Ref. 31. In this paper, it is shown that passive vibration isolation seems to be more than adequate to handle the vibrations above 10 Hz at the high frequency end. For low frequencies, an interferometric feedback system can be used to control motion down to about 1 μm. Beam steering feedback can then be used to control slow variations in the 1 nm to 1 pm region.

Final Focus Test Beam

In order to address the issues of the final focus, a Final Focus Test Beam is being constructed at SLAC.[32] This is supported by a collaborative effort of SLAC, INP, KEK, Orsay, and DESY. The test beam is being constructed in the old C-line at SLAC and consists of a chromaticity-corrected final focus with a non-interlaced sextupole correction.[33] The goal is to produce spots which are 60 nm high by 1 μm wide, and, in the process, to test alignment, stability, and instrumentation necessary to achieve this goal. Further details of this effort are presented in these proceedings.[32]

Beam-Beam Effects

When a small bunch of electrons collides with a small bunch of positrons, the fields of one bunch focus the other causing disruption. Since the opposing particles are strongly bent, they also emit radiation called beamstrahlung. These are the two basic beam-beam effects. The disruption enhances the luminosity by a small amount, while the beamstrahlung causes significant energy loss during collision and increases the effective momentum spread for physics. These issues are discussed in detail in Ref. 34.

In addition, there are several other important effects which should be mentioned here. If the beams are offset relative to each other, a kink instability develops. For small disruption, this effect actually causes the luminosity to be less sensitive to offsets because the beams attract each other and collide anyway. There is also a multibunch kink instabilitv. which is more serious since it can cause the trailing bunches to "miss each other entirely. This places restrictions on the product of the vertical and horizontal disruption per bunch.

It has been discovered that beamstrahlung photons pair-produce in the coherent field of the bunch.[35–38] The corresponding incoherent process has been known for some time, but its importance has only just been realized.[39] The problem is that low energy e^+e^- pairs are produced in an extremely strong field, which then deflects the charge of the appropriate sign while confining the other.

These stray particles can lead to background problems, which must be addressed by detailed interaction point design. In Ref. 29, it is suggested that crab-crossing combined with large crossing angles and solenoidal fields would allow one to channel these electrons out through a large exit hole to a beam dump. Further studies of this option have indicated that crossing angles in the range 30-100 mrad would be necessary to avoid particle impact in the detector.[40]

The measurement of the final spot size is an extremely important, but as yet unsolved, problem. From SLC experience, it is probably possible to use beam-beam effects to minimize spot sizes. However, for the initial tune-up of the final focus, a single-beam method is almost essential. Initial studies of this problem use the energy and angular distribution of ions from a gas jet which is intercepted by the beam? However, there is clearly much more work needed in this area.

SUMMARY

Research at SLAC is focused on the two key parameters of a Next Linear Collider, the energy and luminosity. On the energy side, we have demonstrated damped structures, RF pulse compression, and have tested initial prototypes of high-power klystrons. On the luminosity side, we have designed damping rings and bunch compressors and have studied preservation of emittance, both theoretically and experimentally. New studies bring the alignment tolerances for thelinac into the range greater than 100 μm. The Final Focus Test Beam is being constructed and will test the optical demagnification necessary for an NLC. We look forward to a design in the early to mid-1990's.

REFERENCES

1. Proceedings of the Workshop on Physics of Linear Colliders, Capri, Italy, June 1988.
2. Proc. of the Summer Study on High Energy Physics in the 1990's, Snowmass, Colorado, July 1988, World Scientific, Singapore, 1989.
3. Proceedings of the International Workshon on Next Generation Linear Colliders, SLAC, Stanford, CA, Dec. 1988, SLAC-Report-335.
4. Linear Collider Working Group Reports From Snowmass '88, Ed. R. D. Ruth, SLAC-Report-334.
5. Proceedings of the 1990 Workshon on Next Generation Linear Colliders, KEK, Tsukuba, Japan, March 1990.
6. T. 0. Raubenheimer, L. Z. Rivkin and R. D. Ruth, "Damping Ring Designs for a TeV Linear Collider" 'SLAC-PUB-4808, 1988, and in Refs. 2 and 4.
7. T. 0. Raubenheimer et al., "A Damping Ring Design for Future Linear Colliders" 'Proc. of 1989 IEEE Part. Acc. Conf., Chicago, Ill., p. 1316, and in SLAC-PUB-4912.
8. S. A. Kheifets, R. D. Ruth, J. J. Murray and T. H. Fieguth, "Bunch Compression for the TLC. Preliminary Design," SLAC-PUB-4802, 1988, and in Refs. 2 and 4.
9. S. A. Kheifets. R. D. Ruth and T. H. Fieguth, "Bunch Compression for the TLC," Proc. of Int. Conf. on High Energy Acc. Tsukuba, Japan, 1989, and in SLAC-PUB-5034.
10. G. A. Loew and J. W. Wang, "RF Breakdown Studies in Room Temperature Electron Linac Structures," SLAC-PUB-4647, 1988, and in Refs. 2 and 4.
11. G. A. Loew and J. W. Wang, "Field Emission and RF Breakdown in Copper Linac Structures," Proc. of the 14th Int. Conf. on High Energy Acc., Tsukuba, Japan, 1989, and in SLAC-PUB-5059.
12. R. D. Ruth, "Multibunch Energy Compensation," SLAC-PUB-4541, 1989, and in Ref. 1.
13. K. A. Thompson and R. D. Ruth, "Controlling Transverse Multibunch Instabilities in Linacs of High Enerny Linear Colliders," Phvs. Rev. D, 41, p. 964, 1990, and in SLAC-PUB-4801, 1989.
14. K. A. Thompson and R. D. Ruth, "Multibunch Instabilities in Subsystems of 0.5 and 1.0 TeV Linear Colliders," SLAC-PUB-4800, 1988, and in Refs. 2 and 4.
15. R. B. Palmer, "Damped Accelerator Cavities," SLAC-PUB-4542, 1988, and in Refs. 2 and 4.
16. H. Deruyter et al., "Damped Accelerator Structures,," Proceedings of the 2nd European Part. Acc. Conf., Nice, France, June 1990, and in SLAC-PUB-5263.
17. N. M. Kroll and D. U. L. Yu, "Computer Determination of the External Q and Resonant Frequency of Waveguide Loaded Cavities," SLAC-PUB-5171, to be published.
18. Z. D. Farkas, "Binary Peak Power Multiplier and its Application to Linear Accelerator Design," IEEE Transcripts on Microwave Theory and Techniques, MTT-34, No. 10, p. 1036, 1986, and also SLAC-PUB-3694.
19. P. B. Wilson, "RF Pulse Compression and Alternative RF Sources," SLAC-PUB-4803, 1988, and in Refs. 2 and 4.
20. Z. D. Farkas, G. Spalek, and P. B. Wilson, "RF Pulse Compression Experiment at SLAC," Proc. of 1989 IEEE Part. Acc. Conf. 1989, Chicago, Ill., and in SLAC-PUB-4911.
21. T. L. Lavine et al., "Binary RF Pulse Compression Experiment at SLAC," Proceedings of the 2nd European Part. Acc. Conf., Nice, France, June 1990, and in SLAC-PUB-5277
22. M. A. Allen et *al.*, "RF Power Sources for Linear Colliders," Proceedings of the 2nd European Part. Acc. Conf., Nice, France, June 1990, and in SLAC-PUB-5274.
23. M. A. Allen et al., "High Gradient Electron Accelerator Powered by a Relativistic Klystron," Phys. Rev. Lett. 63, p. 2472, 1989.
24. R. B. Palmer and R. Miller, "A Cluster Klystron," SLAC-PUB-4706, 1988, and in Refs. 2 and 4.
25. V. Balakin, A. Novokhatsky, and V. Smirnov, Proc. of the 12th Int. Conf. on High Energy Accelerators, Fermilab, 1983, p. 119.
26. J. Seeman, SLAC-PUB-4968, 1990, to be published.
27. T. 0. Raubenheimer and R. D. Ruth. "A New Trajectory Correction Technique for Linacs," Proc. of the 2nd European Part. Acc. Conf., Nice, France, June 1990, and in SLAC-PUB-5279.
28. T. 0. Raubenheimer and R. D. Ruth, "A Dispersion-Free Trajectory Correction Technique for Linear Colliders," SLAC-PUB-5222, 1990, submitted for publication.
29. R. B. Palmer, "Energy Scaling, Crab Crossing and the Pair Problem," SLAC-PUB-4707, 1988, and in Refs. 2 and 4.
30. K. Oide, "Final Focus System for TLC," SLAC-PUB-4806, 1988, and in Refs. 2 and 4.
31. W. W. Ash, "Final Focus Supports for a TeV Linear Collider," SLAC-PUB-4782, 1988, and in Refs. 2 and 4.
32. J. Buon, "Final Focus Test Beam for the Next Linear Collider," Proc. of the 2nd European Part. Acc. Conf., Nice, France, 1990.
33. K. Oide, "Design of Optics for the Final Focus Test Beam at SLAC," Proc. of 1989 IEEE Part. Acc. Conf., Chicago IL, p. 1319, and in SLAC-PUB-4953.
34. P. Chen, "Disruption, Beamstrahlung, and Beamstrahlung Pair Creation," SLAC-PUB-4822, 1988, and Refs. 2 and 4.
35. R. Blankenbecler, S. D. Drell, and N. Kroll. "Pair Production From Photon Pulse Collisions," Phys. Rev. D, 40, p. 2462, 1989, and SLAC-PUB-4954.
36. P. Chen and V. I. Telnov, "Coherent Pair Creation in Linear Colliders," Phvs. Rev. Lett., 63, p. 1796, 1989, and SLAC-PUB-4923.
37. M. Jacob and T. T. Wu, "Pair Production in Bunch Crossing," Phvs. Lett. B, 221, p. 203, 1989.
38. V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, Proc. 14th International Conf. on High Energy Particle Accelerators, Tsukuba, Japan, 1989.
39. M. S. Zolotarev, E. A. Kuraev and V. G. Serbo, "Estimates of Electromagnetic Background Processes for the VLEPP Project," Inst. Yadernoi Fiziki, Preprint 81-63, 1981; English Translation SLAC TRANS-0227, 1987.
40. J. Irwin, Private communication.
41. J. Buon, Proceedings of the 14th International Conference on High Energy Accelerators, Tsukuba, Japan, 1989.