TECHNOLOGIES FOR ELECTRON-POSITRON LINEAR COLLIDERS

S. D. Holmes, Fermi National Accelerator Laboratory*, Batavia, IL 60510, USA

Abstract

High energy electron-positron Linear Collider designs based on room temperature and superconducting technologies have been developed and are currently under consideration by the International Technology Recommendation Panel. This paper will review the state of development of technologies required to support a linear collider meeting the performance goals outlined by the world high energy physics community. In addition it will summarize aspects of the cold/warm study completed in the U.S. with particular emphasis on design alternatives relative to the warm and cold baseline designs.

THE INTERNATIONAL CONTEXT

An internationally constructed and operated electron-positron Linear Collider (LC), with an initial center-of-mass energy of 500 GeV, has received strong endorsement from advisory panels in North America, Europe, and Asia as the next large facility in support of elementary particle physics. Under the auspices of the International Committee on Future Accelerators (ICFA) an international panel has established performance goals for the LC as meeting the needs of the world community. The published [1] international goals are as follows:

- Initial maximum energy of 500 GeV, operable over the range 200-500 GeV for physics running.
- Equivalent (scaled by 500 GeV/√s) integrated luminosity for the first four years after commissioning of 500 fb^{-1}.
- Ability to perform energy scans with minimal changeover times.
- Beam energy stability and precision of 0.1%.
- Capability of 80% electron beam polarization over the range 200-500 GeV.
- Two interaction regions, at least one of which allows for a crossing angle enabling γγ collisions.
- Ability to operate at 90 GeV for calibration running.
- Machine upgradeable to approximately 1 TeV.

Over the past few years technologies capable of supporting such a facility have developed rapidly. Two approaches are being pursued: one based on room temperature ("warm") rf structures operating at 11.4 GHz; and another based on superconducting ("cold") rf structures operating at 1.3 GHz. Performance parameters of these two approaches, consistent with the international requirements, are given in Table 1 [2]. An International Technology Recommendation Panel (ITRP) has been convened by ICFA to make a recommendation on which technology base should be pursued for the LC. The ITRP recommendation is due by the end of 2004.

*Operated by Universities Research Association under contract to the United States Department of Energy

Table 1: Performance Parameters for the TESLA (superconducting) and NLC/GLC (room temperature) linear collider designs.

	TESLA		NLC/GLC		
Center of Mass Energy	500	800	500	1000	GeV
Design Luminosity	34	58	20	30	10^{33}cm^{-2} sec^{-1}
Linac rf frequency	1.3		11.4		GHz
Unloaded/loaded gradient	24/24	35/35	65/50		MV/m
Pulse repetition rate	5	4	120		Hz
Bunches/pulse	2820	4886	192		
Bunch separation	337	176	1.4		nsec
Particles/bunch	2	1.4	0.75		$\times 10^{10}$
Bunch train length	950	860	0.27		μsec
Beam power	11	18	7	14	MW/beam
$\gamma\epsilon_H/\gamma\epsilon_V$ at IP	10/.03	8/.02	3.6/.04		mm-mrad
σ_x/σ_y at IP (before pinch)	554/5	392/3	243/3	219/2	nm
Site AC power	140	200	195	350	MW
Site length	33		32		
Tunnel configuration	Single		Double		

TECHNICAL REQUIREMENTS: ENERGY

Delivery of beams at the desired collision energy requires both accelerating structures that can support the desired gradients and an rf generation and distribution system capable of delivering the power required to sustain the design gradient. The requirements are for 500 GeV in the initial stage, with an upgrade capability to approximately 1 TeV. The parameter lists given in Table 1 meets these requirements for both the warm and cold designs. The cold design is based on the installation of accelerating structures capable of supporting 35 MV/m, but operating at 24 MV/m initially. The energy is then upgraded by upgrading the rf sources to support 35 MV/m. In the warm design the installed structures are capable of supporting 65 MV/m in the absence of beam, which results in 52 MV/m in the presence of beams at intensities sufficient to produce the desired luminosity. Sufficient tunnel length is constructed in the initial stage to allow populating the second half of the tunnel (which contains bare beam transport initially) to achieve an upgraded energy of 1000 GeV. The initial arrangement also allows some flexibility for running at energies higher than 500 GeV by sacrificing beam current, i.e. luminosity.

Several test facilities have been constructed and operated to develop and demonstrate the required technologies. Included are the TESLA Test Facilities (TTF-I and TTF-II) at DESY, the NLC Test Accelerator (NLCTA), and the NLC 8-pack test, both at SLAC.

NLC/GLC Structures and RF Sources

The basic rf unit of the NLC/GLC is composed of a solid state induction modulator, two PPM-focused klystrons, a dual-moded SLED-II pulse compressor, and eight 60 cm long accelerating structures. Approximately 2000 such units are required to reach 500 GeV center-of-mass energy.

The NLC/GLC structure has evolved considerably over the last several years in response to difficulties encountered with structure damage after several hundreds of hours of operations. The newly designed structure is shorter (60 cm), with a lower group velocity (3%), and newly designed input couplers reducing the peak fields. This design results in significantly less stored energy in the structure as well as a reduced ability for energy to flow within the cavity (in response to an incipient breakdown). Operational breakdown criteria for the structure are based on providing 99% availability of the linac in the presence of a 5 second recovery time and 2% energy overhead. This translates to <0.4 breakdowns/structure/hour when operated at 60 Hz (in the NLCTA), and at the full pulse width (400 nsec) and gradient (65 MV/m unloaded). The corresponding performance specification has been established at 0.1breakdowns/structure/hour. Structure testing at the NLCTA (Figure 1) is now showing the full complement of 8 structures operating at 65 MV/m with a trip rate of 0.085/structure/hour—somewhat better than the performance specification. It is worth noting that these structures have been built at three different laboratories: Fermilab, SLAC, and KEK.

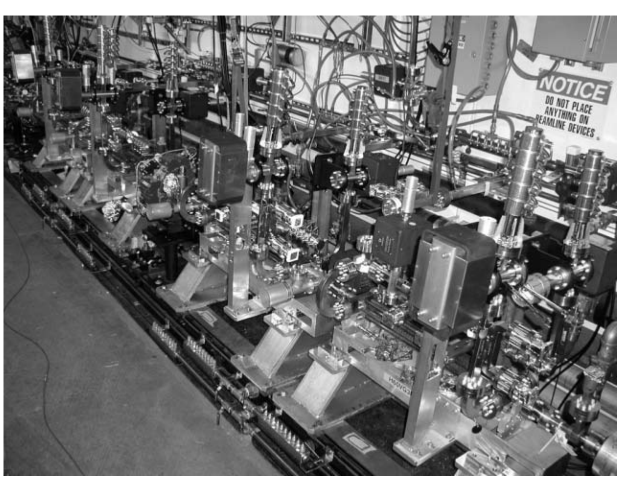

Figure 1: The NLCTA at SLAC, with eight 60 cm accelerating structures under testing.

The NLC/GLC structure is driven by a 75 MW Periodic Permanent Magnet (PPM) focused klystron. The klystron is required to generate a 1.6 μsec pulse at 120 Hz for NLC/GLC operations. The klystrons are being developed both at SLAC and at KEK. Two prototypes have met the performance specification but a great deal of work is still required as success is not highly reproducible at this stage. The klystron is driven by a 500 kV solid state induction modulator, and the klystron output is compressed (compression ratio of ~4) with a dual-mode SLED system. The modulator and pulse compression have been demonstrated, and are working well, in the “8-pack” test setup at SLAC. The desired rf characteristics have been achieved into an rf load, utilizing four solenoid focused 50 MW klystrons. This system has operated reliably for 500 hours at 500 MW output pulse as shown in Figure 2 [3].

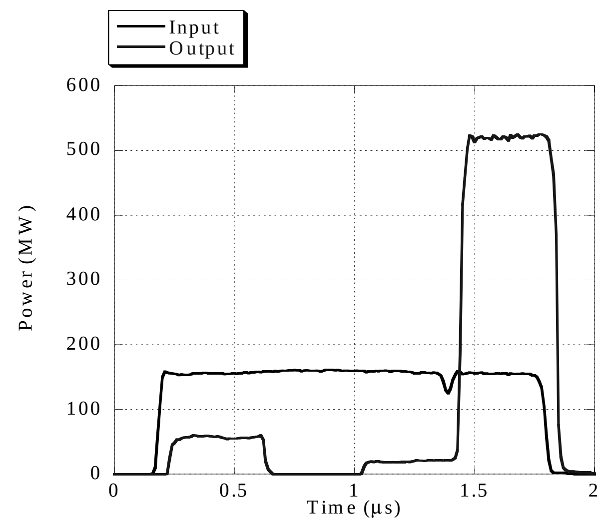

Figure 2: Pulse compression utilizing the dual-mode SLED II system in the 8-pack test facility.

TESLA Structures and RF Sources

The basic rf unit of TESLA is composed of a conventional modulator and a multi-beam klystron feeding directly into 36 accelerating structures via a hybrid coupler based distribution system. The 36 structures are contained in three cryomodules, each about 10 m in length. Approximately 570 such units are required to reach 500 GeV center-of-mass energy.

The structure proposed to support a 500 GeV linear collider is required to operate at 24 MV/m. This performance has been demonstrated previously in the 1999-2000 cavity production run for the TTF-I facility [4]. These cavities have been in operation for roughly 13,000 hours, although not all at 24 MV/m. The goal is to develop structures capable of 35 MV/m allowing the 800 GeV upgrade to proceed via additional rf power installation rather than replacement of the accelerating cavities. Significant progress has been made over the last several years based on development of effective techniques for surface processing and quality control. Buffered chemical polishing (BCP) and electro-polishing (EP) techniques have been the key elements. Using these techniques several single cell cavities have exceeded 40 MV/m and five nine-cell cavities have reached 35 MV/m. Figure 3 shows performance of four EP cavities as measured in the low power, CW, vertical test facility at DESY [5]. High pulsed power performance is found to be completely consistent with the low power tests. It is very important to control/minimize field emission and dark current in the superconducting cavities. Operational criteria for dark current have been established at <50 nA/cavity based on limiting the increase in the cryogenic heat load to 10%. Dark current in a complete 25 MV/m cryomodule is measured to be about 15 nA/cavity, while measurements of radiation backgrounds on the vertical test stand indicate that electro-polished cavities operating at 35 MV/m emit about a factor of ten less dark current than BCP cavities at 25 MV/m. Figure 4 shows the electro-polished accelerating structure AC72 being installed in a cryomodule in TTF-II. This structure has accelerated beam at 35 MV/m with no measurable field emission.

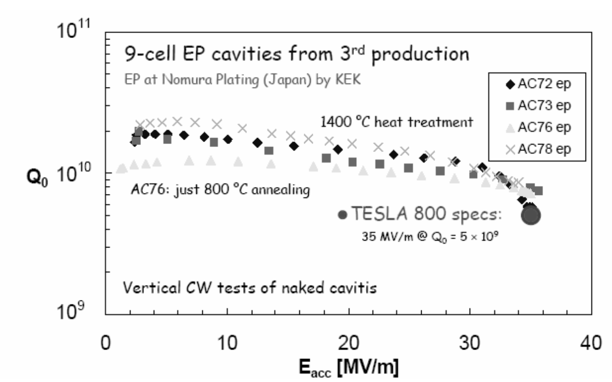

Figure 3: Performance of four electropolished superconducting accelerating cavities in the vertical test facility at DESY.

The TESLA accelerating structures are driven directly by a 10 MW klystron via a hybrid distribution system with 36 cavities/klystron. The required pulse width is 1.5 msec and repetition rate 5 Hz. The initial development has been done by Thales and three units meeting the performance specification have been produced. Independent development efforts have also been initiated with CPI and Toshiba. The klystron is driven by a conventional modulator. Ten modulators have been built, three by Fermilab and seven by industry, with seven in operation for nearly a decade at TTF-I.

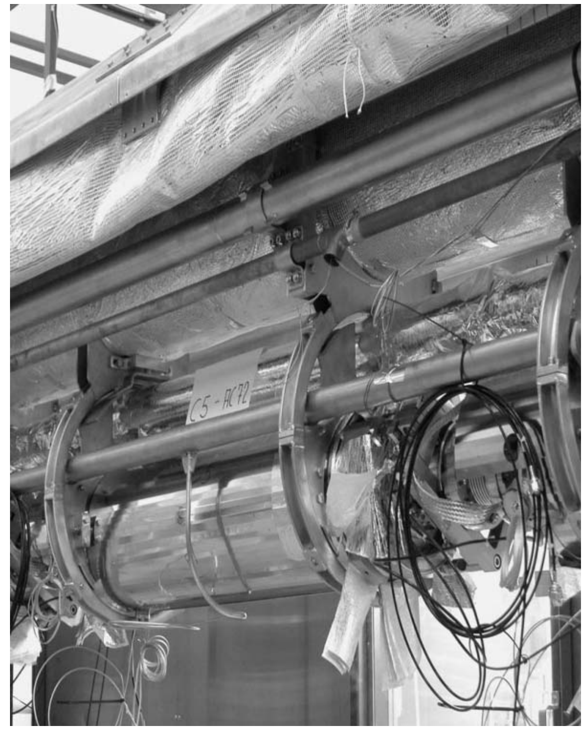

Figure 4: Installation of the electro-polished cavity AC72 in a TTF-II cryomodule at DESY

TECHNICAL REQUIREMENTS: LUMINOSITY

The desire to integrate 500 fb^{-1} in the first four years of operation leads to a required instantaneous luminosity well in excess of 10^{34} $cm^{-2}sec^{-1}$, as indicated in Table 1. Attaining these luminosities requires the production of extremely small beam emittances in the electron and positron sources, and preservation of the emittance through the linac and into collisions. The damping rings are the key element in the production of the required emittances, while control and mitigation of wakefields is key to preserving the beam emittance into collisions. Two R&D facilities have been constructed to address these issues: the Accelerator Test Facility (ATF) at KEK, and the ASSET facility at SLAC.

Damping Rings

The ATF is a full scale model of the NLC/GLC damping ring. It has been in operation at KEK for several years and the most recent performance for vertical emittance is indicated in Figure 5. [6] The ATF has achieved the NLC/GLC design criteria for vertical and horizontal emittance with single electron bunches. Operations in this mode do not probe electron cloud, ion, or other multi-bunch effects. Nonetheless, the observed performance represents a significant achievement. As indicated in the figure, the growth of emittance with intensity is consistent with intrabeam scattering (IBS).

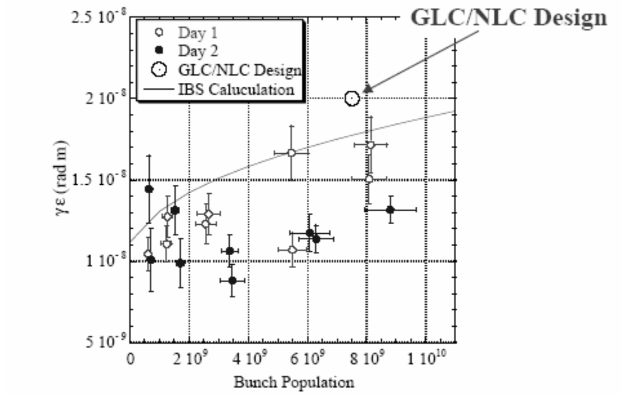

Figure 5: Vertical emittance measured with single electron bunches in the ATF at KEK.

The damping ring required for TESLA is very different from that required for NLC/GLC. The difference is a consequence of the requirement of storing the much longer TESLA beam pulse. The total length of the TESLA pulse (2820 bunches × 337 nsec bunch spacing) is 285 km. By spacing the bunches with 20 nsec separation the resulting damping ring circumference can be reduced to 17 km. However, operations requires a fast cycling kicker (3 MHz) with a 20 nsec rise/fall time to bring the bunches out with the correct spacing, and the excessive damping ring length raises a number of issues not normally encountered in electron damping rings of this energy. Most notable among these is the non-negligible space-charge tune shift experienced by the electrons due to their electromagnetic self-interaction. The TESLA TDR [7] includes design concepts for dealing with these issues, but no specific test facility is contemplated. It would seem prudent to examine alternative implementations and some thinking along other lines has begun [8].

DESIGN VARIANTS

A U.S. study comparing warm and cold designs was released in the spring of 2004 [9]. Among other things, the study looked at a number of variants to the baseline NLC/GLC designs that are worthy of consideration as the design based on the ITRP recommended technology evolves through its next iteration.

Luminosity vs. Energy

The opportunity exists to construct a "500 GeV" linear collider in which luminosity can be sacrificed for higher energy operations. This happens naturally in the warm machine because beam loading is an inherent part of the design, i.e. the gradient rises as the beam current decreases. In the current NLC/GLC design the unloaded gradient is 65 MV/m, with a loaded gradient of 52 MV/m at the design current. This means the collision energy at zero beam current is 625 GeV.

One could consider a similar tradeoff in a cold design by installing superconducting cavities capable of 35 MV/m, but only providing power to support 28 MV/m at the design current. Again one could support higher energies at reduced current, i.e. reduced luminosity. For this particular example the maximum collision energy is again 625 GeV. Figure 6, taken from the U.S. study illustrates this particular implementation.

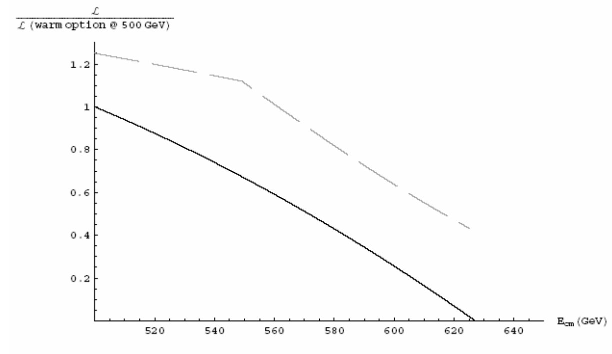

Figure 6: Evolution of luminosity with energy for the specific case described in the text. The upper/lower curve is the cold/warm linear collider.

One vs. Two Tunnels

The TESLA design features a single tunnel, shared by the klystrons and the linear accelerator, with the modulators in surface buildings. The NLC/GLC design uses two tunnels as it is impractical to do otherwise because of the significant space required for the rf system. Through the use of a single tunnel the TESLA design reduces construction costs, but at the expense of having equipment requiring maintenance within the accelerator enclosure. The U.S. study attempts to estimate both the cost savings and the impact on machine availability in this configuration. Availability is estimated using a Monte Carlo model described in the study. The conclusion is that use of a single tunnel reduces the overall construction cost of the linear collider by roughly 5%, and reduces overall machine availability by about 10% for the same component reliability. This trade-off should be reexamined in the next design round of the cold machine. It is possible that the optimum configuration will be site specific.

Undulator vs. Conventional Positron Source

The positron source in the TESLA design utilizes the high energy electron beam, passing through an undulator on its way to the collision point to produce high energy photons. These photons are then separated from the electron beam and impinge on a target from which positrons are collected. The system has the advantage of offering the possibility of producing polarized positrons. This option does not exist utilizing the conventional (defined as modest energy electrons striking a high-Z material) source in the NLC/GLC design. However, the scheme has the disadvantage of requiring the high energy electron beam to be up and running in order to operate the positron source. The U.S. study looked both at the feasibility of a conventional positron source for the cold machine and at the overall availability of a linear collider based on both undulator and conventional sources. The study concludes that a conventional source is feasible for the cold machine, but availability is sacrificed by utilizing the undulator source during the commissioning period. As such, the study suggests starting up a linear collider with a conventional source, but providing space in the accelerator enclosure for eventual upgrade to an undulator source. This conclusion is warm/cold independent.

LONGER TERM PROSPECTS

Because the physical length of a linear collider is at least the collision energy divided by the accelerating gradient, it appears likely that energies in the multi-TeV range will require a technology that can generate more than 100 MV/m. The Compact Linear Collider (CLIC) concept may offer such a possibility [10]. CLIC is a two-beam accelerator in which a high current, low energy electron beam transfers energy to the high energy, low current beam to be brought into collision. Acceleration gradients in the range 150-200 MV/m have been achieved in molybdenum structures and in copper structures with tungsten irises in the CTF-II (CLIC Test Facility) at CERN (Figure 7). Current operations are at much shorter pulse lengths than required in a linear collider, and the full mechanism for generating the low energy drive beam has yet to be demonstrated. These developments are likely to take the remainder of the decade, along with further investigations into the very challenging problems of controlling wakefields and preserving beam emittances in such a machine. Nonetheless, the recent results are impressive and indicate that a 0.5-1 TeV linear collider is not necessarily the end of the line.

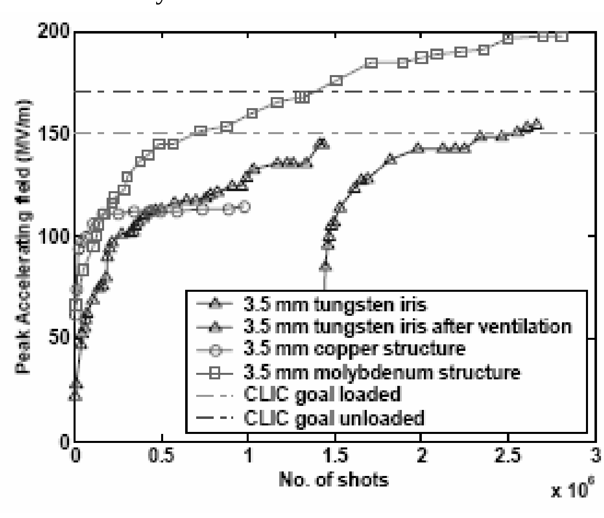

Figure 7: Recent structure performance in the CLIC Test Facility, CTF-II

CONCLUSIONS

The technologies required to support either a room temperature or superconducting rf-based linear collider have made substantial progress over the last two years. It is my conclusion that a linear collider meeting the needs of the world HEP community could be built and operated based on either technology. As such, I believe our community should be very happy if given the opportunity to construct and operate a 500-1000 GeV linear collider based on either technology, no matter where it is situated in the world. So, let us support the decision of the ITRP when it is released later this year and do everything in our power to realize this forefront machine.

ACKNOWLEDGEMENTS

The work described in this presentation was carried out by a large number of people in the major linear collider collaborations throughout the world: TESLA, NLC/GLC, and CLIC. The author would like to acknowledge these contributions in addition to the following people who provided input: D. Burke, J.P. Delahaye, G. Dugan, K. Kubo, T. Markiewicz, C. Pagani, and N. Walker.

REFERENCES

[1] Parameters for the Linear Collider, September, 2003 www.fnal.gov/directorate/icfa/LC_parameters.pdf

[2] International Linear Collider Technical Review Committee, Second Report, 2003 www.slac.stanford.edu/xorg/ilc-trc/2002/2002/report/03rep.htm

[3] T. Markiewicz, Update on X-band LC, International Conference on Linear Colliders, Paris, 2004

[4] P. Castro, Performance of the TESLA Test Facility, Proceedings of the 2002 European Particle Accelerator Conference, Paris, p. 876

[5] C. Pagani, Present Status of R&D for the Superconducting Linac, International Conference on Linear Colliders, Paris, 2004

[6] K. Kubo, Present Status of R&D for the Warm Linacs, International Conference on Linear Colliders, Paris, 2004

[7] TESLA Technical Design Report, March 2001

[8] See, for example, www.hep.uiuc.edu/LCRD/YSED_posters/ITRP_DESY_FNAL_small_damping_ring.ppt

[9] U.S. Linear Collider Technology Options Study, March 2004, www.slac.stanford.edu/xorg/accelops/Full/LC_opts_full.pdf

[10] J.P Delahaye, The Compact Linear Collider Study, International Conference on Linear Colliders, Paris, 2004