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TEST FACILITIES FOR FUTURE LINEAR COLLIDERS*

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I. Introduction

For many years now there has been active research around the world towards a future linear collider with an energy of about 1 TeV. This research has led to several test facilities around the world that seek to test key aspects of the various approaches. A comparison of the approaches to the design is given in these proceedings [1]. The purpose of this paper is to review the status of the test facilities.

In Fig. 1 you see a layout of a future linear collider that illustrates all the subsystems common to the various designs. The test facilities focus on three primary areas in the linear collider: creating the low emittance beams in the injector and damping rings, accelerating the beams in the high energy linac, and focusing the beams to a small spot in the final focus.

The damping ring ring and injection is the primary focus of the Accelerator Test Facility (ATF) at KEK. The accelerator technology is the primary focus of the Tesla Test Facility Linac, the S-Band Test Facility, the NLC Test Accelerator and the CLIC Test Facility. Lastly, the Final Focus Test Beam (FFTB) [2] addresses the problems in the final focus system.

We will discuss all the test facilities above except the FFTB which has a paper devoted to it [3]. In addition to all the test facilities above it is very important to note the key experience that has been and is being gained at the SLAC Linear Collider (SLC). Most of the SLC experience is directly applicable to future linear collider designs. For example, in the NLC design the positron source, injector linac, bunch compressors and the preaccelerator linac all draw heavily on the SLC experience. In a sense the SLC is the most important test facility of all! The current status of the SLC is covered in a separate paper in these proceedings [4].

Before beginning the review of the test facilities it is useful to note that their are several other papers in these proceedings (PAC 95) that address each linear collider design, test facility and/or related technology development. We refer the reader to these more detailed accounts. The following should be considered an overview.

II. The JLC: the Accelerator Test Facility (ATF)

The Japanese Linear Collider (JLC) design is based on normal-conducting linac technology. Although several options are being kept open, the initial choice of frequency was 11.424 GHz with accelerating gradients of about 100 MeV/m. Because this technology was not yet developed in the mid 1980s, the initial work began with estabilished S-band technology at 2.8 GHz.

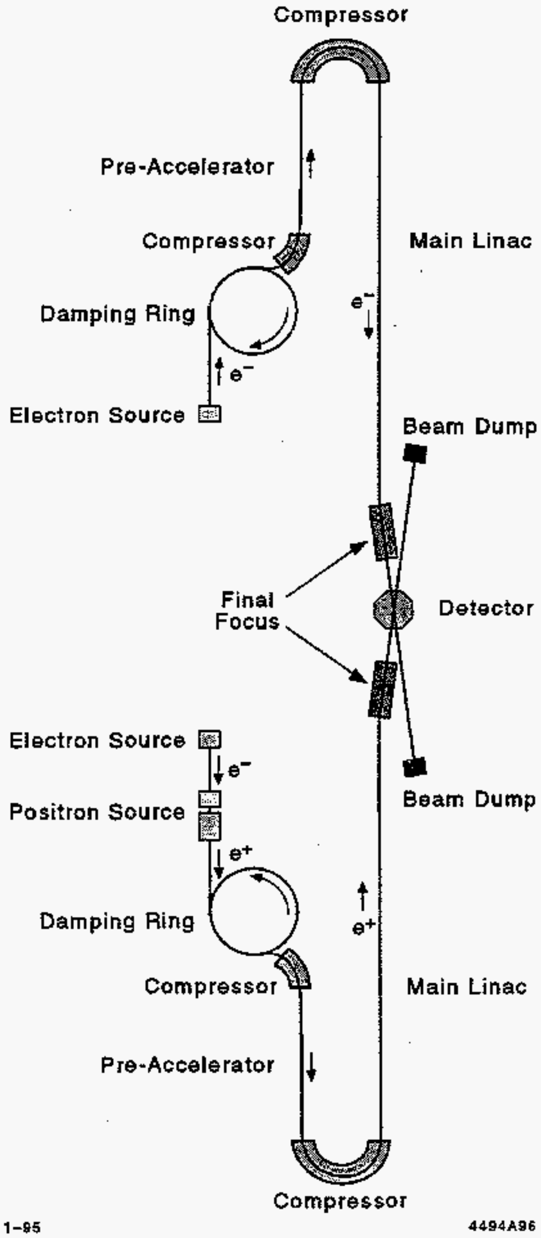

Figure. 1. Schematic layout of a future e^+e^- Linear Collider.

An Accelerator Test Facility (ATF) was founded at KEK in 1988 in order to promote the linac R&D work. At first an S-band rf system was established with several 5045 klystrons sent from SLAC. High gradient tests were carried out for S-band structures. Based upon this infrastructure, R&D work for X-band linac technology was then started. Power source work has been devoted mostly to develop X-band klystrons of 100 MW class. High-gradient tests of

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X-band structures also were carried out, as klystrons of a few tens of megawatts became available.

In the course of the X-band work and miscellaneous studies, the main purpose of the ATF gradually became construction of a test damping ring. Its energy was chosen to be 1.54 GeV. The injector is an S-band linac of the same energy. Construction of the accelerator complex was started in 1991. The ring is expected to provide electron bunches with their normalized emittance as small as a required value of 5×10^{-8} rad m.

The damping ring must provide beams with the small vertical emittance given above with a repetition rate as high as 150 Hz. A lattice of the FOBO type seems promising to attain the low emittance according to simulations. A long wiggler magnet section is necessary to ensure a fast damping time. The specifications are much more stringent than those for conventional rings; therefore, it is quite desirable to verify the feasibility by constructing a test ring. A fine alignment system for magnets is a key ingredient, since the coupling between vertical and horizontal betatron oscillations must be minimized to achieve the low emittance. The emittances, both transverse and longitudinal, should be as uniform as possible among the bunches for the beam dynamics in the main linac. For this sake, the ring rf system must use damped cavities and energy-compensating cavities. Those technologies will be developed in the ATF damping ring .

Shield walls for both the injection linac and the test ring were completed in 1993. Radiation safety systems were also completed. Construction of high power AC lines and cooling water pipings for the ring was completed by the end of 1994. The injector and the first 3-m accelerator section of the linac have undergone initial tests with beam. Various beam monitors and a choke cavity structure have been also been tested with the beam. In parallel with commissioning, the construction of the linac has continued. Almost all of the accelerator structures, modulators, and klystrons for the injector linac are installed.

In the damping ring one unit section of the arc has been fabricated, comprised of a defocusing dipole magnet, a quadrupole, a sextupole, and steering magnets set on a common table with precision movers. A few wiggler magnets have also been fabricated. Prototype vacuum chambers are under fabrication and a cold test of a damped cavity was completed. A 50 kW, 714 MHz klystron has also been successfully tested. The construction of the damping ring and tests of the injector linac will be continued through 1995 and 1996; at the end of 1996 the damping ring should be completed and ready for initial tests with beam.

III. CLIC: The CLIC Test Facility

CERN is studying the feasibility of building a 0.5–2.0 TeV e^+e^- linear collider, using classical normal-conducting traveling-wave rf accelerating sections, powered by a superconducting drive linac.

The 3–5 GeV high-intensity electron drive linac runs in parallel with the main linac. The bunched drive beam is decelerated in so-called transfer structures where 30 GHz rf power is generated and fed via standard waveguide to the accelerating structures.

Periodic replacement of the energy lost by the beam to the transfer structures is made by short sections of 6 MV/m superconducting cavities driven by 350 MHz 1 MW klystrons. The superconducting cavities and klystrons already developed by CERN for LEP are ideal for this application. Generation of the rf power by a drive linac, rather than by thousands of individual klystrons, is a distinctive feature of the CLIC design and results in a particularly simple tunnel cross-section.

An obvious design aim is to make the linacs as short as possible to keep the cost down. This implies high accelerating gradients, which would normally result in a higher power requirement, but is compensated for by operating at a high frequency to maximize the rf-to-beam power conversion efficiency. CLIC has chosen to work at 80 MV/m and 30 GHz. At this frequency, wakefield effects, alignment tolerances, and fabrication problems seem just manageable, but demand state-of-the-art technology.

Limiting the emittance blowup along the main linacs in the face of strong transverse wakefields is a concern, and sets tight tolerances on the transverse alignment of the components (typically 5 μm on BPMs and accelerating sections for 50 μm initial offsets of the quadrupoles). Such tolerances can only be achieved with a beam-based active alignment system and require in particular micron resolution BPMs. Prototype BPMs based on simple E_{110} cylindrical cavities have been built and their ability to resolve such small displacements has been evaluated on the bench by exciting them with an antenna to simulate the passage of an off-axis electron bunch. The output E_{110} signal as a function of antenna position over a range of ± 1 μm clearly shows a resolution capability of $<$ 10 nm.

CERN has built, and is currently operating, a test facility for linear collider studies (the CLIC Test Facility or CTF) to (i) study the production of short, high-charge electron bunches from laser illuminated photocathodes in rf guns, (ii) generate high-power 30 GHz rf pulses by passing bunch trains through transfer cavities for testing CLIC prototype components, and (iii) test beam position monitors.

Significant amounts of 30 GHz power can only be extracted from the CLIC section by using bunch trains. 76 MW has been generated by a 24-bunch train containing 72 nC of total charge or 3 nC per bunch. This power level corresponds to a decelerating field in the section of 123 MV/m (more than the CLIC nominal accelerating gradient). The charge per bunch which can be transmitted through the structure is at this moment limited by wakefields in the traveling wave accelerating section. The accelerating field in the second CLIC structure is determined from the difference between maximum and minimum energy gain of the beam as its phase with respect to the beam-induced rf accelerating field is varied. An average accelerating gradient of 73 MV/m was measured in this way for the best performance so far. Plans to increase the

30 GHz power generation include (i) raising the gradient in the accelerating section to reduce the effect of wakefields (ii) making shorter bunches using a magnetic bunch compressor (iii) building a new 100 nC/bunch rf gun.

CLIC Alignment Test Facility. An active alignment test facility has been built in an unused underground tunnel at CERN to study the feasibility of making controlled submicron displacements and to try out alignment systems.

The structures to be aligned, dummy accelerating sections for the moment, are supported by V–blocks on 1.4-m-long silicon carbide girders. The ends of two adjacent girders sit on a common platform which ensures continuity of position between units.

The platforms are activated by three stepping-motor-driven precision jacks (two in the vertical plane for vertical displacement and axial rotation, and one in the horizontal plane). The setup is equipped with linear and angular displacement transducers (0.1 μm and 10 μ-rad resolution respectively) and is piloted remotely from a small computer. After deliberate misalignments of 1 mm, the system which is programmed for automatic alignment with respect to the transducers, settles back to nominal positions within < 1 μm.

The CESTA Test Facility. A collaboration to study the use of an FEM to create the CLIC drive beam exists between CERN and the Centre d'Etudes Scientifiques et Techniques d'Aquitaine (CESTA) in Bordeaux. The aim is to use a helical wiggler to bunch a beam from an induction linac, and in a later phase to use this beam to generate power in a CLIC transfer structure. A preliminary experiment to measure the bunching produced by a helical wiggler using the beam from a gun-diode is already underway.

The MIT Test Facility. CERN is collaborating with MIT to test CLIC prototype components. MIT has a gun- diode driven FEL that produces 20-ns-long, 60 MW power pulses at 33 GHz. This facility is at present being used to test a 25-cell prototype CLIC accelerating section.

IV. The SBLC: the S-Band Test Facility

Among the different design studies for a next generation e^+e^- linear collider, the SBLC approach follows the concept of a relatively low rf-frequency $\omega_{\rm rf}$ and a moderate accelerating gradient g. In the SBLC, conventional traveling wave accelerating structures at 3 GHz are used running at a gradient of 17 MV/m. The SBLC linear collider study is pursued at DESY in the frame of an international collaboration with institutes in China, France, Germany, Japan, Netherlands, Russia, and USA contributing to the technical R&D and/or the design of the 500 GeV collider.

The goal of the SBLC test facility under construction at DESY is to construct and test the basic components required for the 2×250 GeV linear accelerators. The test linac consists of an injector providing bunch trains similar to those to be used in the collider. Two 150 MW klystrons (built by SLAC) power four 6-m-long accelerating structures. A beam diagnostics station is foreseen to measure bunch to bunch offsets as well as single and multibunch energy-spread. The injector provides a 6 A pulse out of a 90 kV gun with a duration of 2 ns. This pulse is compressed longitudinally by more than a factor of 200 resulting in a bunch length of ≈ 3 mm. Although longer than the final design bunch length, this value is sufficient to study most multibunch and beam dynamics effects. The subharmonic cavities and the vacuum system will be assembled and installed during 1994 and be commissioned early 1995.

Recently, the first klystron has reached its full design parameters in rf tests at SLAC. Conventional line-type modulators are foreseen for pulsing the klystrons. As an alternative solution a hard tube switching device is also under study at DESY. A klystron test stand for the 150 MW klystron with water loads and further required infrastructure is under construction.

The design of the accelerating sections concentrates on the first series production of 5.2-m-long structures for the DESY injector linac, which are very similar to the test facility structures. Nine-hundred cells for 6 sections (from overall 14) have been ordered from industry and are being brazed at DESY. Horizontal or vertical brazing, vacuum- or hydrogen-atmosphere ovens or inductive heating are still being investigated. A cup-tuning machine to match the structure for the accelerating wave after brazing and before final installation is now operating.

Low power test models of the symmetric high power couplers have been manufactured and matched to an accelerating structure while the high power versions are scheduled autumn 1994. Different types of additional couplers required for the HOM damping and/or measurement of the beam induced higher order mode power are being investigated. After brazing and tuning, the sections for the test facility will be mounted on different types of temperature insensitive girders (glass ceramics, carbon fiber composite and heat shielded stainless steel) to keep the six meters of copper waveguide straight within 15 μm rms. Every girder is equipped with micromovers at both ends to allow for ±1.5 mm offset in both directions.

Magnets, structure supports, and precision movers, as well as methods to compensate ground vibrations, are investigated. The design of the linac quadrupoles completely decouples the coil windings from the iron yoke, which automatically minimizes the vibration effects due to cooling water flow. Although the effects which have been described before will not affect the final emittance in the test accelerator, feedback systems and control loops will be tested on the supports and girders, which have been designed to fit the tunnel requirements and the minimum height for final installation.

V. TESLA: The TESLA Test Facility Linac (TTFL)

The TESLA [5] approach uses a superconducting RF system to accelerate the beam to high energy. The important issues that need to be addressed in the Tesla Test Facility Linac (TTFL) are somewhat different than those in the normal conducting case. There are both cost and technical factors to be considered. On the cost side the achievable gradients need to be raised from the 5 MeV/m typical of existing storage ring cavities to 20 or 25 MeV/m. The cost per unit length of the accelerating cavity plus cryostat needs to be lowered a factor of five to bring the price to about 50k$/m to give a competitive cost per MeV figure. Another source of concern is the relative delicacy of the superconducting state. How reliable would such a system be in the face of the realities of vacuum and cryo system failures? Will it be possible to recover from such a failure by in situ processing? At the long rf wavelength, which is a strength of the SC approach, electrons present in the accelerator vacuum can be more easily captured from rest to make parasitic beams. These parasite beams could perhaps sap energy from the main beam and perhaps cause unwanted cryo losses and beam background in addition to instabilities of the wanted beam. Because of the very high Q of the cavities, small changes in dimension can make large changes in amplitude and phase of the accelerating wave. The pressure caused by the growing stored energy during the pulse can make such changes, the so-called Lorentz detuning. Can an economical cavity stiffening with active control scheme be found? Finally, the large beam power which is on the one hand a virtue implies the need for the most powerful positron source of all the approaches and gives the challenge of safe disposal of the high beam power in addition. Progress in all of these areas has been made and a plan to demonstrate solutions to many of them put in place.

A 500 MeV TESLA Test Facility Linac (TTFL) is now under construction at DESY. It will consist of four cryomodules of a type that could be used in a linear collider. Each module contains eight 1 m, nine-cell cavity units, plus a focusing doublet assembly with beam monitors. Each cavity subunit has its own couplers. Two cryomodules are driven by one klystron/modulator set. An injector section brings the initial beam up to 15 MeV nominal before introduction into the TTFL proper. A beam analysis station will be installed both after the injector and at the high energy end of the TTFL. The linac will be installed in Halle 3 at DESY adjacent to the recently completed cavity chemical processing area, with cleanrooms, vertical test cryostats, and rf power supply for cavity testing and high power pulse processing (HPP). The first cavities and cryostats have for the first cryomodule have arrived at DESY and initial cavity tests have begun. In a prototype processing and test setup at Cornell, several multicell cavities have been chemically processed and subjected to HPP. Initial tests with HPP at DESY have also been started. HPP has been quite effective in raising the achievable gradient. After exposure to air, HPP was successful in recovering the gradient. How this will apply in a linac environment must await the completion and operation of the TTFL now expected in the 1997–1998 time frame. Experience with the facility will yield information about many of the critical issues cited above; for example, dark current, Lorentz detuning, cost, robustness against vacuum or cryogenic failures, and so on.

Table I
NLCTA rf System Parameters.

Parameter	Design	Upgrade
Linac unloaded energy gain	540 MeV	1080 MeV
Linac active length	10.8 m	10.8 m
Unloaded accelerating gradient	50 MV/m	85 MV/m
Injection energy	90 MeV	90 MeV
rf frequency	11.424 GHz	11.424 GHz
Number of klystrons	3	6
Klystron peakpower	50 MW	75 MW
Klystron pulselength	1.5 μs	1.5 μs
rf pulse compression power gain	4.0	4.0
Phase advance/cell	2 $\pi/3$	2 $\pi/3$

VI. The NLC: The Next Linear Collider Test Accelerator (NLCTA)

The NLC uses positron and electron sources similar to those in the SLC. Much of the early acceleration is done with S-Band as in the SLAC linac. The Damping Ring is similar to the ATF Damping Ring described earlier. The FFTB is addressing the Final Focus system issues. The acceleration in the NLC is accomplished with an 11.4 GHz RF system (X-Band) designed to accelerate the beam with gradients in the range of 50-85 MV/m. The purpose of the NLC Test Accelerator is to bring together all the separate developments on X-band in a model of a section of the NLC linac.

The NLCTA is a high-gradient X-band linac consisting of six 1.8 m-long accelerator sections. These sections are fed by three 50 MW klystrons, which make use of SLED–II pulse compression to increase the peak power by a factor of four. This yields an acceleration gradient of 50 MV/m, so that the total unloaded energy gain of the beam in the X-band linac is 540 MeV. The NLCTA parameters are listed in Table 1. The right-hand column of Table 1 lists the parameters for an upgrade of the X–band linac to 100 MV/m by the use of six 100 MW klystrons.

The NLCTA injector will consist of a 150 kV gridded thermionic cathode gun, an X–band prebuncher, a capture section with solenoid focusing, and a rectangular chicane magnetic bunch compressor.

The high-gradient accelerator will be fed with rf power through overmoded circular waveguides which penetrate the shielding blocks above the accelerator. Four 50-MW klystrons will be positioned along the accelerator, outside the shielded enclosure. Each klystron is powered by an independent modulator, allowing the flexibility needed for multibunch energy control and adequate power for an upgrade to a 85-MV/m accelerating gradient with six 75-MW klystrons, as indicated in Table 1. Each klystron feeds a SLED–II pulse compressor. The pairs of delay lines of the SLED–II pulse compressors are overlapped, parallel to the accelerator, outside the shielding. The output of each SLED–II is split to feed two accelerator sections. In the case of the injector, the SLED–II output is split to feed the two short injector sections to provide overhead for beam loading. The first three klystrons have exceeded NLCTA specifications (50 MW, 1.5 μs), and one is presently in regular operation testing the NLCTA pulse compression system and the 1.8 m accelerator section described below.

For the NLCTA, we plan to use a detuned structure which is a $2\pi/3$ "constant-gradient-like" structure modified every half meter to include four symmetric pumping holes. These holes lead to parallel vacuum manifolds, which provide sufficient pumping speed despite the small beam aperture. The cavities are machined to provide a precise mechanical reference from the inside dimensions to the exterior of the structure.

In order to achieve the reduced wakefield, the structure is configured to be very nearly constant gradient. The decoherence of the wakefield between bunches will be achieved by a Gaussian distribution of HOM frequencies with a standard deviation of 2.5%, which results in a Gaussian decay in time for the initial wakefield. This distribution can be obtained by tailoring a constant-gradient section so that more cells are near the central frequency, while fewer are near the ends of the frequency band. This choice results in a structure in which the iris size along the structure first decreases rather quickly, then decreases slowly in the middle, and finally decreases quickly along the structure towards the output end.

With this distribution of HOMs, the wakefield decoheres to less than 1% of its peak value. This decoherence is sufficient to eliminate beam breakup in the NLC or NLCTA. Because of the low injection energy, the NLCTA has a sensitivity to transverse wakefields comparable to the much longer NLC linac. The NLCTA will permit the verification that detuned structures can indeed suppress wakefields to the levels necessary for stable acceleration.

The first detuned accelerator structure has been completed and tested successfully at high gradient. In addition, the resulting wakefield was measured in ASSET in the SLC and was found to agree quite well with theoretical predictions. The second structure plus the two injector structures are presently in fabrication.

A magnetic spectrometer has been designed that will analyze the bunch train after acceleration in the linac in order to determine beam energy, beam-energy spread, and bunch-to-bunch offsets. The optics in the beam analysis region allow for the measurement of emittance in both transverse planes. A vertical kicker magnet upstream of the spectrometer provides a method for separating the bunches vertically so that the energy, energy-spread, and horizontal offsets can be independently measured along the bunch train. After initial commissioning, an extensive set of experiments is planned to verify that the NLCTA can indeed stably accelerate trains of low-emittance bunches suitable for a full-scale NLC.

The NLCTA is proceeding on schedule. The accelerator shielded enclosure is complete and all infrastructure is in place (girders, cable trays, water, lights, racks, and control room). All the magnets are complete and installed in the enclosure, power supplies are installed. The prototypes for the klystron and accelerator structure have performed at NLCTA specifications. Additional klystrons and structures are in fabrication. The prototype of the pulse compression system has been tested up to full power. The injector tests are planned for the fall of 1995, and the full NLCTA should be complete by end of 1996.

VII. Summary and Conclusion

During the past several years there has been a tremendous amount of progress on Linear Collider technology world wide. This research has led to the construction of the test facilities described in this report. Some of the facilities will be complete as early as the end of 1996, while others will be finishing up around the end 1997. Even now there are extensive tests ongoing for the enabling technologies for all of the test facilities. At the same time the Linear Collider designs are quite mature now and the SLC is providing the key experience base that can only come from a working collider. All this taken together indicates that the technology and accelerator physics will be ready for a future Linear Collider project to begin in the last half of the 1990s.

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