OVERVIEW OF LINEAR COLLIDER TEST FACILITIES AND RESULTS

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Abstract

In order to promote realization of Linear Collider (LC), the formation of international co-operation for unified LC design and efficient R&D share are thought to be necessary. As a first step of this co-operation, the International Technology Recommendation Panel (ITRP) will recommend a technology for the global LC design to the International Linear Collider Steering Committee (ILCSC). Towards this recommendation, many efforts of the developments and the output results of each technology have been made to satisfy the requirements of the technical review committee report (TRC)[1]. The test facilities of each LC design are the place of the key technology demonstration and realization. The summarized overview of the LC test facility activities and outputs of TTF, NLCTA, ATF&GLCTA and CTF will give information of LC technology direction.

INTRODUCTION

Major laboratories in the world began to start LC developments in late 1980s. LC workshop and many related workshop have been held from that time, having R&D information exchange and design review. After about 15 years R&D, LC designs of each laboratory became more realistic based on the demonstrations of technologies in their test facilities. The test facilities in this overview are the active facilities conducted by the leading laboratories. By the order of the main linac frequency, TTF (TESLA Test Facility) conducted by DESY, NLCTA (NLC Test Accelerator) conducted by SLAC, ATF (Accelerator Test Facility)&GLCTA (GLC Test Accelerator) conducted by KEK, and CTF (CLIC Test Facility) conducted by CERN, are briefly summarized in this text.

TESLA TEST FACILITY (TTF)

The TTF at DESY includes infrastructure labs and shops for superconducting cavity treatment, test stands and the accelerator module assembly and a test linac for an integrated system test of the TESLA[2] accelerator prototype with beam. The functions of this facility are development of accelerating module compatible to TESLA, integrated system test of the TESLA linac components with beam and application of SASE FEL in the VUV wavelength regime[3]. The performance of the TESLA superconducting cavities are well advanced by the electro-polishing (EP) processing as well as chemical etching of the inner surfaces, high temperature treatment at 1400degC, and high pressure rinsing with ultra-pure water. The design gradient 23.8 MV/m has been attained on average with cavities of the standard treatment. By application of new EP method to 9-cell cavities, another 6 cavities have reached gradients between 31 and 35 MV/m. Some of them are assembled into the TTF cryomodule. TTF linac is now in the phase 2 stage construction, which is planned for 2μm emittance, 1nC electron beam by upgraded laser-driven photocathode RF gun, 1 GeV acceleration by 6 cryomodules each containing 8 superconducting 9 cell cavities, and 50μm RMS bunch length by 2 stage bunch compressors. A 6.4nm wavelength FEL light will be generated by modified 27m undulator magnets, and will be transported to the downstream user experimental area. The photocathode RF gun injector is capable of delivering bunch trains with parameters very close to the TESLA linear collider specifications in terms of beam current and pulse length. It also delivers bunches with sufficiently low emittance for successful operation of the FEL. The TTF-I program is being concluded in autumn 2002. The last tests are devoted to one more accelerator module (named module 1*, because it is the original module 1 equipped with new cavities), which is expected to yield an average accelerating gradient of 25 MV/m, and to a beam test with a first version of the so-called superstructure concept. In a superstructure, two cavities are fed with RF power by a single coupler, which saves length (the fill factor is increased by 6% in comparison with the present TTF modules) and cost by reducing the number of couplers. First beam tests with two superstructures at a gradient of 15 MV/m have been performed successfully, proving the principle of this concept and confirming very satisfactory damping of higher order modes in the structures. After completion of that experimental program, the linac is lengthened by three more modules (two of which contain only cavities which have reached 25 MV/m or more on the test stand) in an already completed additional tunnel, and the FEL installations is modified to prepare for phase 2 (TTF-II) of the user facility, commissioning of which will begin in the second half of 2004[4].

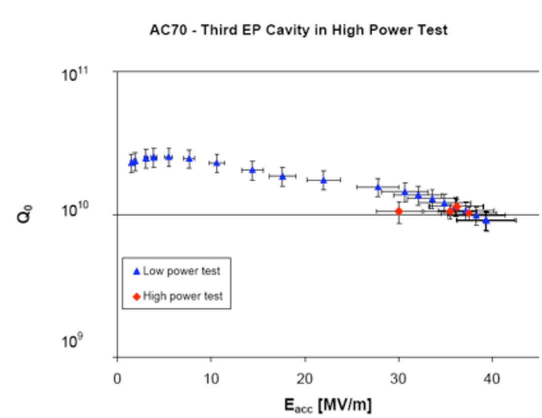

Figure 1: 35MV/m result of AC70 EP cavity.

For the start-up of TTF-II, emphasis is on achieving lasing and saturation at a wavelength of 30 nm, which requires beam energy of 461.5MeV. With a slice emittance of 2mmmrad, the saturation length will be less than 20m well within the undulator length of 27 m. Later, lasing at longer and shorter wavelengths and finally down to 6 nm will follow, where stronger requirements on the emittance apply.

Figure 2: 35MV/m AC72 cavity installation.

NLC TEST ACCELERATOR (NLCTA)

The NLCTA of SLAC is a testing ground for the X-band RF system components and has been demonstrating the viability of the NLC RF system[5]. It has 4 RF stations and beam supply from the DC gun. The first RF station is used to power the injector, which was designed to generate beams with NLC-like currents (~1 A) by the thermionic DC gun and bunchers, except the bunch spacing of 88 ps. To improve the bunching efficiency, the first structure has a low beta section in its upstream end and is preceded by two pre-bunching cavities, all powered from the single 50MW solenoid focused klystron (1.5μs pulse length) and the SLED-II pulse (factor 4 gain in peak power). The structure testing for the gradient program has been done exclusively at NLCTA using the four accelerator slots in the two linac RF stations. To date, 12 structures have been tested in the two RF stations, which have been run in parallel for about 7000 hours at 60 Hz. As part of this testing, the SLED-II pulse compression systems have operated stably, producing up to 280 MW, 240 ns pulses. The fourth station is used for the 8-Pack system.

Designs for a future TeV scale electron-positron Xband linear collider (NLC/GLC) require main linac units, which produce and deliver 475 MW of RF power at 11.424 GHz to eight 60 cm accelerator structures. To demonstrate such high power RF, four 50 MW X-band klystrons, powered by a common 400 kV solid-state modulator, are used to drive a dualmoded SLED-II pulse compression system (the 8-Pack system). The three times compressed power is delivered to structures in the NLCTA beam line by an over-moded transmission and distribution system. Four 60 cm accelerator structures are currently installed and powered, with four additional structures and associated high power components available for installation late in 2004. Full GLC/NLC prototype structures with the short-range and long-range wake field control (HDDS1/HDDS2) are tested to verify the gradient performance 65MV/m. The system was run at 500-510 MW for 200 hours at 30 Hz and 100 hours at 60 Hz to measure RF breakdown rates in the system. During the 30 Hz operation, 11 RF breakdowns were observed in the SLED system and in the over-height high power waveguide, while none were measured during the 60 Hz running. The average rate of 0.06 breakdowns per hour (60 Hz equivalent) is better than the NLC/GLC requirement of < 0.16 per hour (for 475 MW operation), and the improvement during the last 100 hours indicates the breakdown rate was decreasing. Beam was then accelerated with the four accelerator structures powered by the 8-Pack system and the four previous structures on the NLCTA beam line. They have been operating at the NLC/GLC design accelerating gradient of 65 MV/m for 850 hours. The breakdown rate, averaged over the eight structures, during the most recent 150 hours of operation, is 0.085 per hour. This rate is better than the <0.1 breakdown per hour NLC/GLC goal.

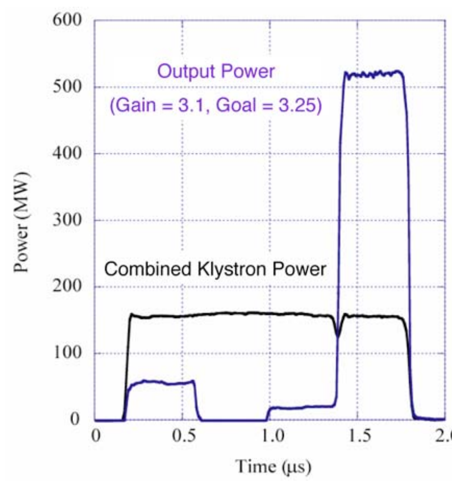

Figure 3: 510MW, 400ns power from 8-pack system.

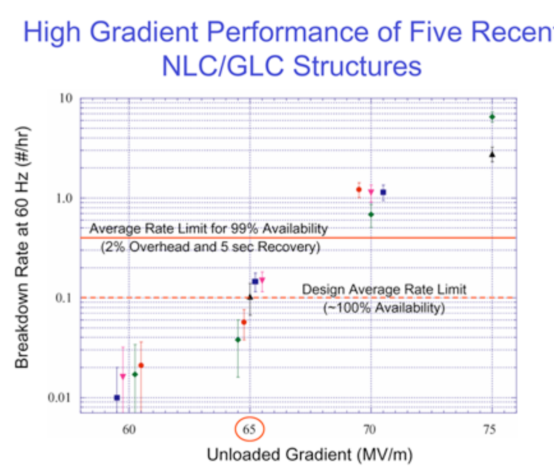

Figure 4: Structure breakdown rate at 65MV/m.

As for PPM (Periodic Permanent Magnet focused) klystron development[6], the XP3-3, which is the product of DFM (Design for Manufacture) strategy, was the first full-spec operational klystron operated at 75 MW, 120 Hz at 1.6μs pulse length. Due to the beam transmission, RF and thermal issues discovered with this DFM versions we decided to temporarily return to a design with pole pieces brazed directly to the drift tube. Next two tubes are currently under test. The first one, the XP3-4 was built and tested with air cooling rather than water cooling while the water cooling components were still under fabrication. The XP3-4 operated full spec at 120 Hz, 506 kV, 75 MW, 1.62μs RF, and 50 % efficiency with 60 dB gain. The beam transmission was 98.7 % during the full saturated RF pulse. The XP3-4 is currently under test at full power and has accumulated 60 hours at 120 Hz full-spec operation. The second one, XP3-5 is still processing up to the full pulse width and has reached 75 MW at 1μs and 120 Hz.

KEK ACCELERATOR TEST FACILITY (ATF) & GLC TEST ACCELERATOR (GLCTA)

ATF is the only LC facility devoted to the production of low emittance beams, a critical challenge in LC beam dynamics and technology. The ATF includes a 1.54 GeV S-band injection linac, a 138.6 m circumference damping ring and an extraction line for beam analysis. Technology development at ATF is centered on precision beam instrumentation, stabilization techniques and tuning methods. To achieve the low emittance goal, ATF operation has focused on the following investigations: (1) tuning techniques and error correction, (2) single bunch collective effects (e.g., intrabeam scattering), (3) wiggler performance, (4) damping ring acceptance, (5) extracted beam jitter, and (6) multibunch instabilities. The primary design goal of the ATF damping ring is to obtain a vertical normalized emittance less than $3\text{x}10^{-8}$ m.rad with a high intensity ($0.7\text{-}3.0\text{x}10^{10}$ e-/bunch) multibunch beam. The ATF damping ring currently operates at 1.28 GeV beam energy at a repetition rate of 0.7 Hz with one bunch train of 20 bunches with 2.8 ns bunch spacing and 0.7x1010 particles/bunch. Extremely low emittance studies have been done in single bunch mode, resulting in the smallest single bunch, low current emittance recorded in the world, 1.6x10-8 m.rad (normalized)[7]. The tuning procedure to obtain low emittance involves the successive application of orbit, dispersion, and coupling corrections. Considerable work has been done to characterize the damping ring optics, resulting in high confidence in the present model. For instance, beam-based magnet field measurements (lattice diagnostics) uncovered quadrupole field-strength errors on the order of 1%. Correcting the optics model to account for these errors produced a model accurate to 0.01%. To correct residual alignment errors, beam-based alignment of focusing and sextupole magnets has begun. In late 2002, using new high-resolution ring BPMs, a quick, accurate beam-based alignment procedure has been developed to provide insight into the nature of the optics corrections that are presently used for emittance optimization. This should make it possible to identify sources of instability and quantify the physical limits on the minimum vertical emittance. This is one of the highest priority beam studies. With respect to intrabeam scattering, single bunch studies have shown a dependence of the measured emittance on both the bunch current and the longitudinal emittance, indicating strong intrabeam scattering (IBS). In October 2002, the thermionic gun and buncher system were replaced by a Cs_2Te photo-cathode RF gun in order to increase the injection efficiency into the ring to ~100% and to improve performance during multibunch operation. The stored charge of multibunch beam in the ring was increased to $7\text{x}10^9$/bunch with 20 bunches without beam loss. After several days of scrubbing, observed instabilities at tail bunches of multibunch, which were seemed to come from fast ion effect, was disappeared. The measured emittance was still twice high compared to the single bunch by insufficient DR tuning at that time. The multibunch low emittance confirmation will be done in the next run. Additional studies at ATF have been aimed at developing the technology required to accurately measure very small beams. There are five wire scanners in the extraction line, a laser-wire monitor in the ring, SR interference monitor and X-ray imaging SR monitor in the ring, and Optical Transition and Diffraction Radiation (OTR and ODR) monitors under development in the extraction line. The ATF laser wire closely resembles a design, which is expected to be widely used in the LC. A laser beam with a very thin waist is generated in an optical cavity formed by nearly concentric mirrors. The laser intensity is amplified by adjusting the cavity length to meet the resonance condition. The cavity constructed for the ATF has produced a beam waist of 12 μm (2σ) and an effective power of 100 W, with good long-term stability. The laser wire is installed in the ring at a location with a transverse electron beam size of ~10 μm. It has been used over the last year to make accurate measurements of the vertical emittance of each bunch in the ring.

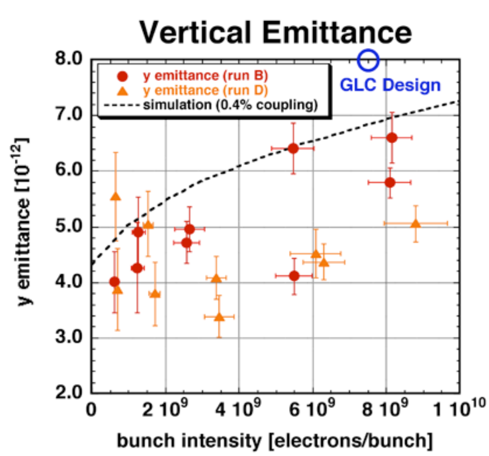

Figure 5: ATF vertical emittance in single bunch.

Since the LC design was similar between GLC and NLC, development of X-band technology has been done with close collaboration between KEK and SLAC from the beginning. The main collaboration area is the structure development and pulse compression component. They are installed and tested in NLCTA. In order to promote and demonstrate GLC main linac technology even in KEK, 3 years construction plan of GLCTA has been started from 2003. This is a realization of 1 main linac accelerator unit, which is the result of own GLC R&D and collaboration R&D with SLAC. For the beam acceleration demonstration, extracted ATF beam with additional bunch compression and/or additional photo-cathode RF gun beam with full GLC beam loading will be used. Construction is under way towards 2006 of beam acceleration demonstration.

CLIC TEST FACILITY (CTF)

CLIC[8] is a two beam-acceleration concept linear collider of a centre-of-mass energy of 3 TeV. It is based on the use of normal conducting accelerating structures operated at high gradient (150 MV/m), powered by 30 GHz high power RF pulses generated from a high current drive beam accelerator of low RF frequency. Since the overall efficiency is critical, the drive linac will be operated in the "full beam loading" condition, where the beam extracts almost all the power from the structures, expecting an overall transfer efficiency of about 98 %. A phase 3 of CLIC Test Facility (CTF3)[9] is being built at CERN in order to demonstrate this drive beam generation scheme and also to serve as a 30 GHz RF power source, necessary to develop CLIC RF components. CTF3 will consist of a 70 m long linac followed by two rings, where the bunch manipulations will be carried out by a 42 m long delay loop and an 84 m combiner ring. The 30 GHz high power test stand is also included for testing CLIC module and a test decelerator. The generation of 1.5 μs long drive beam pulse is done by a 140 kV thermionic gun and phase-coded bunching system followed by two travelling wave structures. It provides bunches spaced by 10 cm, at energy of 20 MeV. The CTF3 linac will be composed of 11 modules. The 3 GHz structure, have a total length of 1.22 m and operate at a loaded gradient (nominal current) of 6.5 MV/m. In order to suppress the transverse Higher Order Modes (HOMs) the structures (called SICA, for Slotted Iris Constant Aperture) use four radial slots in the iris to couple out the HOMs to SiC loads. The klystron RF power is compressed by a factor 2 with programmed phase ramp to provide rectangular 30MW over 1.5 μs pulses at each structure input. After the linac, a first stage of electron pulse compression and bunch frequency multiplication of the drive beam is obtained using a transverse RF deflector at 1.5 GHz and a 42 m long delay loop. The phase-coded 140 ns long sub pulses are first separated and then recombined by the deflector after half of them have been delayed in the loop. An 84 m long combiner ring is then used for a further stage of pulse compression and frequency multiplication by a factor of 5, through injection with 3 GHz transverse RF deflectors. The drive beam pulse is then transported to the 30 GHz test area. A 30 GHz decelerating structure, optimized for maximum power production, will be used in a high power test stand where CLIC prototype accelerator structures and RF components can be tested at nominal power and beyond. The probe beam is generated in a 3 GHz RF photo injector. It can be accelerated further to about 500 MeV in 30 GHz CLIC accelerator structures powered by the drive beam, operated at a maximum gradient of 150 MV/m.

In 2003 the injector and the first three linac modules were installed in CTF3. Beam commissioning started in June 2003[10]. The design beam current and pulse length were reached without beam break-up under full beam loading. The observation of the RF signals at the structures' output coupler allowed to adjust easily the beam-to-RF phase by maximizing the beam loading. When the beam is on, it extracts more than 90 % of the energy contained in the useful part of the RF pulse (1.5 μs). The RF signals were also used to assess the RF-to-beam efficiency. The RF-to-beam efficiency evaluated is 94 %. During the winter 2003 shutdown more modules were installed, bringing the total number of accelerating structures to 10. A dogleg transport line was installed after the instrumentation module, together with a new 30 GHz power test stand, where the drive beam can be used to generate 30 GHz RF power in a special Power Extraction and Transfer Structure (PETS). The commissioning of the newly installed hardware is presently under way, and the first 30 GHz RF pulses have already been produced, with moderate beam current. At present only a short PETS is installed, and preliminary measurements indicate a power above 100 kW, in accord to the expected value.

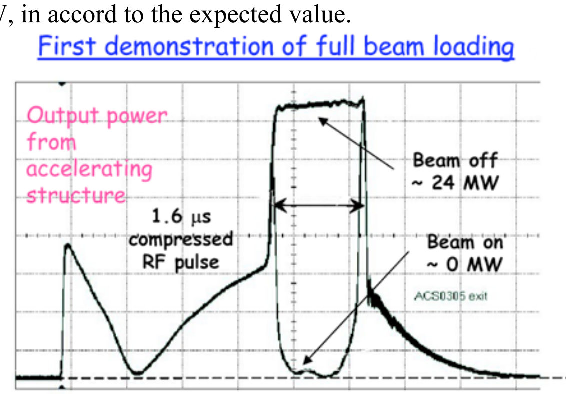

Figure 6: Beam loading of CTF3 injector structure.

As for CLIC structure development, CTF2 has provided 30 GHz RF pulses of up to 280 MW with a pulse-length variable from 3 to 15 ns. This pulse length was larger than the fill-time of the structures built so far, but was short compared to the nominal 130 ns pulse-length of CLIC. The constant impedance copper structures have reached mean accelerating gradients of 72 MV/m for a surface field of 317 MV/m. At these field levels, considerable surface damage is observed on the first iris.

The structure with an iris made of tungsten replaced the damaged region was tested applying a 160 MV/m gradient of 3ns long for 5x105 pulses, and no damage occurred on the tungsten iris.

The systematic comparison of the structure has been carried out during 2002 with reduced Esurf/Eacc ratio in the cells and in the coupler. The first structure made of tungsten with copper rings clamped in between showed that accelerating fields of 125 MV/m in average and of 152 MV/m in the first cell, were obtained in this structure without damage. The second structure entirely made from OFHC copper reached an average accelerating field of 102 MV/m and 114 MV/m in the first cell. This structure showed signs of surface damage on the first regular iris, where the surface E-field is highest. The third structure, with molybdenum irises, was reached to an average accelerating gradient of 150 MV/m, and 193 MV/m in the first cell without damage. Comparing results from these structures, importance of material rather than geometry effects should be stressed. The test facility CTF3 under construction will allow to produce 30 GHz RF power pulses of nominal length. 30 GHz structures testing with this new source will start in late 2004.

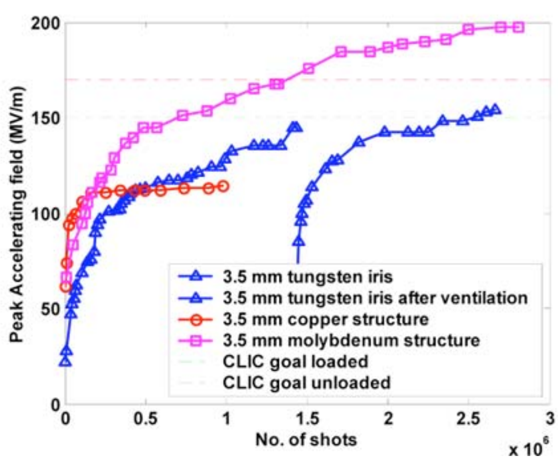

Figure 7: Peak accelerating field of Tungsten-iris and Molybdenum-iris in 30GHz structure.

SUMMARY

Major achievement and status of each test facilities are summarized briefly below;

TTF: Accelerating gradient of superconducting L-band cavity reached up to 35MV/m with applying EP method, cleared TESLA800 design goal. Acceleration demonstration with TESLA like beam loading was already done. SASE-FEL application using upgraded TTF is underway towards lasing at 30nm in September 2004.

NLCTA: RF power generation of 510MW, 400ns (design 475MW, 400ns) was achieved with 0.06 breakdowns per hour, better than the NLC/GLC requirement of < 0.16 per hour. The X-band structure also achieved 65 MV/m for 850 hours with 0.085 per hour breakdown, better than <0.1 breakdown per hour goal. The PPM klystron achieved the design rf output independent with test facility. The generated RF power by 8-pack will be delivered to 8 structures instead 4 in fall 2004.

ATF/GLCTA: The GLC vertical emittance goal of 2.0×10^{-8} rad.m was achieved in ATF damping ring with single bunch operation. Emittance of multibunch, which is suffered from ion effect, will be achieved in fall 2004. Beam instrumentation such as laser wire has been developed using very low emittance beam.

Complete RF unit demonstration of GLC is under construction at downstream of ATF towards 2006 commissioning.

CTF: More complete test facility for two-beam acceleration demonstration is under construction as CTF3. Delay loop and combiner ring for drive beam manipulation will be demonstrated in 2007. 94% RF-to-beam efficiency was demonstrated in CTF3 drive linac injector. 193MV/m gradient in 30GHz structure was reached using molybdenum irises in case of 16ns pulse length. CLIC nominal RF power will be available in 2007.

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