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The Next-generation Linear Collider

The next-generation linear collider will require high-power microwave sources and accelerating systems vastly more challenging than its predecessor, the Stanford Linear Collider (SLC). Cost efficiency will demand high accelerating gradient to achieve beam energies five to ten times greater than in the SLC. Luminosity goals 10,000 times greater than the SLC demand efficient creation of the highest possible beam power without degradation of beam emittance.

The past decade of R&D has demonstrated the feasibility of two technical approaches for building a 500-GeV center-of-mass system (cms) collider with attractive options for future upgrade. The TESLA R&D program offers the prospect of 1.3-GHz superconducting rf (srf) linacs with 23.4 MV/m gradient that can be upgraded later to 35 MV/m gradient by doubling the number of klystrons and the cryo-plant, to reach 800 GeV cms [1]. The Next Linear Collider (NLC) and Japanese Linear Collider (JLC) R&D programs offer the prospect of 11.4-GHz room-temperature linacs that can later be extended to 1 TeV by doubling the number of structures and klystrons, and to 1.5 TeV by additionally increasing gradient or length [2–4]. Both programs offer a 500-GeV linear collider project start within the next few years (2–3 years for TESLA, 3–4 years for NLC) based on available technology validated by experiments at several complementary test facilities. Both offer their upgrades as a result of further progress in R&D that is already underway.

While both the 1.3- and 11.4-GHz approaches use klystrons to generate the accelerator rf power, a longer-range design study for a two-beam accelerator, the CERN Linear Collider (CLIC), is based on the concept of using klystrons to accelerate a low-energy drive beam that is subsequently compressed and de-accelerated to generate power at 30

GHz for accelerating a high-energy beam. This approach may offer a path to multi-TeV collisions after approximately six years of further R&D [5].

Motivated by the growing interest in building a 500-GeV cms linear collider in the near future, this report focuses on the status of the rf technology being developed for TESLA, NLC and JLC.

Power Sources

High-power sources of the longest possible pulse-width are desirable for high efficiency and low cost. The use of superconducting accelerator structures in TESLA reduces the peak rf power requirement, permits 1.5 millisecond pulse width, and allows large interbunch spacing and high rf-to-beam power transfer efficiency.

A seven-beam klystron has been developed with industry for TESLA [6]. It can operate with moderate high-voltage (110 kV) and high efficiency (70% goal) due to reduced space-charge forces in the vacuum tube. One of the initial tubes produced has operated at 65% efficiency at the 10-MW design power, 1.5-ms pulse length, and 5-Hz pulse rate (although 10 Hz will be required of some of the klystrons for FEL operation). This tube was used in the TELSA Test Facility at low power, and more have been produced. The full klystron output pulse in TESLA will be divided to feed 36 nine-cell superconducting cavities.

The push to higher gradients for the room-temperature machines has utilized higher frequencies and corresponding increases in field strength and decreases in pulse length and stored energy. The high frequencies allow the same rf-to-beam transfer efficiency to be achieved for a fixed current at a higher gradient with less rf energy per pulse. The cost-optimal unloaded gradient for the NLC is about 70 MV/m. CLIC studies for 3-TeV cms are based on 170-MV/m unloaded gradient.

The pulse-width required for the 11.4-GHz accelerator structures of the NLC and JLC is 400 ns. Klystrons have been developed, for efficiency and cost, to generate wider pulses (3.2 microseconds for NLC, 1.6 microseconds for JLC) that get compressed in time as they are delivered to the accelerator. The klystrons developed for this purpose during the past decade produce 75-MW output, which approaches the practical limit for single beam klystrons. A major advancement was the use of periodic permanent magnet focusing of the klystron beam instead of conventional power-consuming electromagnetic solenoids [7, 8] (a 50 MW tube of this type is also being developed for a C-Band linear collider [9]). Both NLC and JLC have produced klystrons that meet the peak power and pulse-width requirements with acceptable efficiency above 50%. The pulse width in testing to date has been limited by the high-voltage pulse modulators. However, widening the pulse would produce diminishing returns because of the increased cost of the pulse compression system. The current program is to continue to develop the klystrons in association with industry to improve manufacturability and cost, and to achieve reliable operation at the design pulse repetition rate (120 Hz for NLC, 150 Hz for JLC).

While klystron technology is satisfactory for linear collider applications at 11.4-GHz, novel sources are under study for higher power and higher frequency acceleration [10]. Multiple-beam and sheet-beam klystrons are being studied at SLAC and at Calabazas Creek Research (CCR), Inc. in Saratoga, California. Higher frequency sources in the 10-1000 MW peak power range are under investigation. Gyroklystrons at the University of Maryland have demonstrated 20–75 MW peak power at frequencies of 8–17 GHz. A 91-GHz gyroklystron is being built by CCR with a goal of 10-MW peak power. CPI, in Palo Alto, is designing a 50-MW gyroklystron at 30 GHz for CLIC studies (prior to the availability of drive-beam power generation). Innovative research is also underway on high-power magnicons at 11 and 34 GHz, at the U.S. Naval Research Lab (NRL), and at Omega-P, Inc., in New Haven, Connecticut.

The microwave pulse compression needed to transform the output of 11-GHz klystrons to the narrower pulse width and higher power required by NLC and JLC accelerator structures is challenging. The pulse compression and power distribution system must be efficient and inexpensive. The Delay Line Distribution System (DLDS), first proposed by KEK (the Japanese Laboratory for High Energy Physics), was adopted as the best of available choices [11]. Components of a two-mode version of the DLDS have been developed at SLAC to further reduce the net length of transmission line [12]. For the NLC, this system combines the power from eight 75-MW klystrons and routes it up-beam in a sequence of eight (shorter) pulses to feed eight separated sets of accelerator structures. The DLDS for JLC is similar; the narrower klystron pulses sequentially feed only four sets of structures. DLDS components have been tested at peak power levels up to 500 MW and a test of all the critical components of a full system at the nominal (600 MW) peak power, pulse width and energy is planned in the next two years.

Although passive components have been at the center of research for pulse compression systems, active components such as switches and phase shifters can be the basis of the next generation of more elegant, efficient and low-cost pulse compression systems. Research on the topology of active systems is being conducted at SLAC and some of its basic principles and scaling laws have been established. Overmoded active components based on semiconductor devices and magnetic materials have been designed and demonstrated at power levels around 10 MW at 11 GHz [13]. Researchers at the Institute for Applied Physics (Nizhny-Novogorod, Russia), Omega-P, and NRL have demonstrated pulse compression to 15 MW using a plasma switch. This work is in the early stages of development [14].

The CLIC study focuses on using low-frequency, long-pulse klystrons with high-frequency, 30-GHz room-temperature accelerator structures. In a novel form of pulse compression, the low-frequency rf is to be used to accelerate trains of bunches in a 1.2-GeV “drive linac” that produces 80-MW of average beam power; the train is to be compressed in a series of chicanes and combiner rings, and routed sequentially up-beam to decelerator structures that will transform the 30-GHz harmonic power from the train (230 MW per decelerator structure) to the high-gradient accelerator. Tests so far have generated low power (30 MW) in short (16 ns) pulses. At least six years will be required to demonstrate the feasibility of this technology sufficiently to pursue a CLIC-type collider.

Normal Conducting Accelerator Structures

The largest application of the normal-conducting rf accelerator structures to date is the 3-km long, 50-GeV SLAC Linac, which operates at 2.856 GHz (S band). Much experience has been gained from its 35 years of operation, during which it has been continuously upgraded for higher energy, higher intensity and lower beam emittance. Many linear accelerators built subsequently for energy research, industrial, or medical applications have been based on the SLAC technology. The NLC and JLC linear collider designs build further on this experience, but using 11.424 GHz (X-band) technology [2–4]. In these designs, about 6 km of X-band accelerator structures are required in each linac to increase the beam energy from 8 GeV at injection to 250 GeV for collisions at the interaction point. The four-times higher frequency results in accelerator structures with higher shut impedance and a shorter filling time. These changes lower the project cost due to the higher optimal gradient and the lower rf energy required per pulse. However, stronger transverse wakefields are generated by off-axis beams in the higher frequency structures, which act to increase the beam emittances. For this tradeoff, the NLC and JLC groups believe the choice of 11.424 GHz gains the major cost benefits of a higher-frequency rf system while allowing the achievable alignment tolerances associated with the stronger wakefields. Alternatively, a group at KEK is pursuing 5.7 GHz (C band) as an optimum technology choice [15] and the CERN CLIC group is developing 30-GHz technology as a cost-effective solution for multi-TeV colliders employing two-beam power sources [5].

Regardless of the frequency, there are four general requirements on the accelerator structure design: it must transfer the rf energy to the beam efficiently to keep the machine cost low; it must be optimized to reduce the short-range wakefields which depend on the average iris radius; it must suppress the long-range transverse wakefield to prevent multibunch beam breakup (the resonant amplification of bunch betatron motion by the bunch-to-bunch transverse wakefield coupling); and it must reliably operate at the design gradient. The design choices and R&D related to meeting these requirements for the NLC and JLC designs are discussed below together with comparisons with the C-band and CLIC approaches, which are less well developed.

Structure Design Considerations

The basic NLC/JLC structure parameters were determined mainly by the trade-off between high rf-to-beam efficiency and low short-range wakefield related emittance growth. The emittance growth is caused by the head-to-tail transverse wakefield deflections generated when the bunches travel off-axis through the structures. Resonant head-to-tail amplification is suppressed by introducing a correlated energy spread along each bunch (called BNS damping). The size of the remaining non-resonant emittance growth depends on a number of factors including the average iris radius, the bunch charge, and the achievable beam-to-structure alignment (the goal is about 10 microns). The average iris radius and the bunch charge also affect the rf-to-beam energy transfer efficiency. Higher efficiency comes at the expense of increased emittance growth. As a result of this basic trade-off and the constraints on related parameters, an average iris radius of 18% of the X-band wavelength was chosen for the linac structure design.

Defining the structure parameters required a number of other design choices. A traveling-wave structure was selected because standing-wave designs are generally more expensive. A disk-loaded waveguide geometry was used since disk-shaped cells are easy to manufacture. The iris surface field along the structure was held roughly constant to avoid having one region of the structure limit the gradient because of rf breakdown. The gradient profile was shaped by varying the rf group velocity along the structure, a common method for achieving a constant gradient. The phase advance was chosen to be 120 degrees per cell, the same as in the SLAC S-band structure. This value gives high shunt impedance per unit length, which improves efficiency. The structure filling time was chosen to maximize the rf-to-beam energy transfer efficiency, taking into account the length of the NLC bunch train. These choices constrained the basic structure geometry, and resulted in a 206-cell, 1.8-m long structure with a group velocity varying from about 12% to 3% c.

Later, a high-gradient damage problem was discovered to be associated with group velocities in excess of 4% c, as discussed below under the heading, “High Gradient Development.” This discovery is now leading to a reevaluation of the initial choices of phase advance, group velocity, and structure length.

Wakefield Suppression

Once the basic structure design had been selected, a method for suppressing the long-range transverse wakefield was needed. The long-range wakefields, which are generated as the multi-bunch beams traverse the accelerator structures, can strongly couple the motion of the bunches to one another. This coupling will resonantly amplify any betatron motion of the train, unless the transverse wakefield is reduced by about two orders of magnitude during the 1.4 ns between bunches. This difficult goal was met for the initial structure design by using a combination of cell detuning and damping [16, 17]. Detuning requires that each cell of the rf structure have a slightly different dipole frequency, such that the wakefields from the different cells have decohered significantly by the time the second bunch arrives. The frequency variation is made systematically along the structure to produce a gaussian distribution in the product of the mode density and the mode coupling strength to the beam. This detuning produces an approximately gaussian falloff in the net wakefield generated by each bunch. Detuning works well to suppress the wakefield for about the first 30 ns, after which the amplitude increases due to a partial recoherence of the mode excitations.

To offset this rise, weak mode damping was introduced by coupling each cell through longitudinal slots to four TE-11 circular waveguides (manifolds) that run parallel to the structure. The manifold damping works because the phase velocity of the manifold mode is greater than c and the detuning results in localized dipole modes in the structure that each have a phase velocity profile that varies from near c at one end (the pi-mode-like end) to infinity at the other end (the 0-mode-like end). Thus, a near-speed-of-light beam excites the dipoles modes near their pi-mode end. The energy propagates at the local group velocity until it reaches the region of the mode where the phase velocity matches that of the manifold mode, where it couples to the manifold. The damping is optimized when the coupling is adjusted so all of the energy in the dipole modes flows directly into the manifolds, as would be the situation for a perfectly terminated traveling wave.

Successful implementation of the damping and detuning required major advances on two fronts. One was the accurate modeling of wakefield generation in structures whose geometry varies from cell to cell. This was achieved using 3D finite-element calculations to obtain parameters for an equivalent circuit model of the cells [18]. Another key advance was in the precision machining of the cell shapes to produce the desired acceleration and dipole mode frequencies [19, 20]. The result of these two efforts produced structures with frequencies that matched design to better than 1 MHz. As a consequence, the long-range wakefield that was measured agrees well with prediction [21].

The manifold damping in the NLC/JLC structures reduces the dipole mode quality (Q) factors from about 6000 to 1000, limited by the propagation time of the dipole-mode energy through the cells. For the CLIC structures, stronger damping is required, which is leading to the development of local dipole mode damping. One approach that was successfully tested at 15 GHz uses four radial waveguides extending from each cell to transport the dipole mode energy to SiC loads [22]. These waveguides are cut off to the acceleration mode. Dipole mode Q's as low as 20 were achieved with a moderate loss (20%) in the acceleration mode shunt impedance. However, the pulse surface heating near the waveguide entrances in a 30-GHz cell would raise the copper temperature by 250 C at the CLIC design gradient of 150 MV/m. Changes to the cell and waveguide geometry are being studied to minimize this temperature rise.

Another approach being developed by the CLIC group uses radially slotted irises to transport the dipole mode energy outside the cell, which avoids the large pulse heating

[23]. To test this concept, a 3 GHz structure is being fabricated with slotted irises for the CTF3 drive beam. Finally, the C-band group has built a structure where an azimuthal choke joint prevents the acceleration mode fields, but the not the dipole mode fields, from extending into a SiC ring located at the outer cell radius. Wakefield tests of this structure showed that this damping configuration reduced the dipole modes Q's below 20 with about a 20% loss of shunt impedance [24].

High Gradient Development

During the period when the long-range wakefield-suppression techniques for the NLC/JLC were being developed, there was little concern about the feasibility of operating the 1.8-m structures at unloaded gradients in the 50–80 MV/m range. Earlier rf power tests with standing-wave cavities and short, low group velocity structures had achieved gradients above 100 MV/m. These first tests were limited to cavities and short structures because the rf power available at the time was insufficient for longer structures.

High-power testing of NLC and JLC prototype structures began in earnest about two years ago with the improvements to the high power testing capability at the NLC Test Accelerator (NLCTA). Systematic studies of several 1.8-m structures showed that damage began to occur at unloaded gradients above 45–50 MV/m [25]. The damage was manifested as an increase in the rf phase advance through the structures and was associated with severe pitting of the cell irises. In particular, the damage occurred mainly in the upstream ends of the structures where the rf group velocity is greatest. Such a dependence on group velocity may have occurred because the rf power required to achieve a given gradient increases with group velocity. Also, if the structure is viewed as a transmission line and rf breakdown as a load impedance, the fraction of incident power absorbed during breakdown increases with group velocity.

An aggressive R&D program was launched in Spring 2000 to develop lower group-velocity structures [26]. A series of structures with different lengths and group velocities was built to study the factors contributing to the damage. In addition, various improvements were made to the structure cleaning, handling and processing procedures to determine their impact on high gradient performance. A pre-processing procedure has been adopted that includes 'wet' and 'dry' hydrogen firing at 950 C, a two-week vacuum furnace bake-out at 650 C, and a one-week in-situ bake-out at 220 C.

Six structures have been processed at NLCTA to date as part of this program. Most recently tested were a pair of 53-cm long structures with group velocities of 5% c and 3% c, respectively, at their upstream ends. In contrast, the 1.8-m structures have 12% c initial group velocity. With 240-ns pulses, the 5% c structure was processed to 86 MV/m and the 3% c structure to 81 MV/m. During 1200 hours of operation at 60 Hz, the 5% c structure incurred a few degree phase shift while the 3% c structure showed no discernable phase change (less than 1 degree). Near the end of this period, the structures were run for about 100 hours with 400 ns pulses, the NLC design value. For the 3% c structure, the breakdown rate was about 1 per hour at 70 MV/m and 1 per 7 hours at 65 MV/m, which would be marginally acceptable for the NLC. These rates were dominated by breakdowns in the input coupler cell. One of the structures that will be tested next has an input coupler with lower fields and higher impedance in an attempt to suppress breakdown in this cell.

The results so far from the low group velocity structures are encouraging. However, the average cell iris radius in these test structures is too small to meet NLC/JLC short-range wakefield requirements. To increase the iris size while maintaining low group velocity, a higher phase advance per cell (150 degrees instead of 120 degrees) will be used. Also, long-range wakefield suppression will need to be added, which should be fairly straightforward given the decade-long experience gained in developing such techniques for the 1.8 m structures. Tests of structures with the higher cell phase advance will begin early in 2002.

Another approach being explored for achieving higher gradients is to use short standing-wave structures, which require much lower peak power than the traveling wave structures currently being studied [27]. The first pair tested showed frequency shifts of about 500 kHz after operation for over 900 hours at the NLCTA. A gradient of 82 MV/m was achieved with a 100 ns flattop pulse and a gradient of 74 MV/m was achieved with a 270 flat-top pulse, the NLC bunch train length. With the wider pulse, the breakdown rate was about two per hour in each of the 20 cm long structures when the gradient was lowered to 55 MV/m, the NLC loaded gradient (unlike the traveling wave structures, the standing wave structures would not need to operate above the NLC loaded gradient). The breakdown in these structures appears to occur mainly in the input coupler cells. As a result, the next pair of structures to be tested have been tuned to have a lower field in the coupler region. Other improvements are planned in future tests, so it is still early in the development of these structures to assess their viability for NLC/JLC.

The CLIC group also has a program of high-power structure testing. However, they are limited by the unavailability of a long pulse (130 ns), high power (230 MW) rf source at 30 GHz to achieve their goal of 170 MV/m unloaded gradient operation. The two-beam power sources developed thus far have produced pulses up to 16 ns long. Tests of prototype structures at this longest pulse length have achieved gradients up to about 70 MV/m, limited by breakdown [28]. Subsequent inspection of these structures showed damage to the input coupler region. The C-band group at KEK has yet to do systematic high-power structure testing at their design (unloaded) gradient of 44 MV/m.

Fabrication and Operational Experience

Over the past decade, manufacturing processes for X-band cells and structures have been developed by a SLAC-KEK collaboration, with participation by Lawrence Livermore National Laboratory and the involvement of several precision machining companies. In addition, the JLC group at KEK, in Japan, has made good progress toward developing industrial partnerships for fabricating cells and assembling structures, particularly with Ishikawajima-Harima Heavy Industries (IHI).

The process developed for building the 1.8-m structures begins with the rough machining of high-purity copper billets using conventional lathes and mills [3]. Rough machining leaves more than 40 microns of extra copper on all surfaces except for the coupling slots and manifolds. Follow-up precision turning, performed using single-crystal diamond tools, yields micron level accuracy and 50-nm (rms) surface finish. As the diamond turning is completed, microwave quality-control measurements are made of the acceleration and dipole-mode frequencies of each cell. If a systematic shift of the acceleration frequency by more than about 0.1 MHz is observed, adjustments are made to the nominal dimensions of the subsequent cells to offset the net phase-advance error. This feed-forward correction procedure yields structures with a net phase advance within a few degrees of the design value. The dipole-mode frequencies are checked to eliminate cells with values significantly different (by a few megahertz) from those of neighboring cells.

After careful cleaning and rinsing with ozonized water, the cells are stacked in a special V-block fixture and bonded together by a two-step diffusion bonding process: first at 180 C and then at 890 C. Then the complete structure is assembled---with flanges, vacuum ports, WR90 waveguides for the acceleration mode, and WR62 waveguides for the dipole modes---and brazed together in a hydrogen furnace at 1020 C. After a vacuum bake-out, the structure is installed on a strongback for final mechanical measurement and straightening guided by data from a Coordinate Measuring Machine. This procedure has yielded 1.8-m structures meeting the NLC/JLC straightness requirement of 10 microns rms.

The bulk of operational experience with X-band structures has come from the NLC Test Accelerator (NLCTA) at SLAC. This facility, which was commissioned in 1996, is a test-bed for X-band accelerator systems. The power sources (XL4 klystrons and SLED-II pulse compressors) have operated reliably, energizing 12 X-band accelerator structures for an integrated total of about 10,000 hours. The NLCTA has accelerated high-quality pulse trains with energy spread well within the NLC/JLC specification of 0.3% [2].

The new generation of improved X-band components will be added to the NLCTA over the next two years for a demonstration of the proposed NLC rf system. The components include 11 meters of high-gradient accelerator, elements of a delay-line distribution system (DLDS), eight 75-MW klystrons with periodic permanent-magnet focusing, and a solid state, high-voltage pulse modulator.

Fermilab will participate in the X-band system demonstration. After joining the NLC collaboration in 1999, Fermilab is focusing mainly on structure manufacturing. The Fermilab NLC group recently built its first X-band structure, working with off-site fabrication shops. In the next two years, it plans to develop sufficient production capability to produce high-gradient, low group velocity, X-band structures for the NLC rf-system demonstration at the NLCTA. The long-term goal is to develop the industrial partnerships needed to manufacture the full complement of X-band structures for NLC. Small Business Innovative Research (SBIR) funds, administered by the Division of High Energy Physics of the U.S. Department of Energy, are also supporting the development of industrial production methods for X-band structures in larger quantities.

Superconducting Accelerator Structures

The TESLA linear collider is based on 1.3 GHz, 9-cell standing wave cavities that are one meter long and operate in a superhelium bath at 2 K. The main goals of the TELSA international collaboration during the past decade have been to increase the achievable gradient by a factor of four from the 5–8 MV/m available ten years ago, and to decrease the cost per unit length of the superconducting cavities by a similar factor. Improved understanding of gradient limiting mechanisms, followed by new techniques to fabricate, treat and prepare cavities now reliably yield gradients improvement factors desired. In the most recent batch, more than twenty one-meter long niobium structures yielded an average gradient over 25 MV/m during CW operation. Eight 9-cell cavities, while operating with the TESLA pulse-length of one millisecond, reached gradients of 30–35 MV/m. Having met the gradient goals, the TESLA proposal is to build a 500 GeV cms energy linear collider with a 23.4 MV/m loaded linac gradient. An upgrade to 800 GeV cms energy requires operation at a loaded gradient of 35 MV/m.

R&D continues to improve cavity performance, as well as to reduce and qualify large-scale production costs. With further advances in cavity preparation techniques many laboratories in the TESLA collaboration are now reproducibly reaching accelerating fields of 40–42 MV/m with single cell cavities. Research is now focused on transferring the improved technology to 9-cell units. The number of cavities required, about 21,000, is well beyond the quantity used in any application to date. Therefore industrial studies have been carried out to analyze large-scale production costs, and to pin-point areas for major cost reduction. Several areas have been identified, major ones yielding reduction factors of ten over present fabrication costs.

Wakefield Suppression

One concern with any accelerator structure is the strength of the transverse wakefields generated when beams traverse them off-axis. These fields can act within a bunch (short-range) and on subsequent bunches (long-range) to degrade the beam emittance. Since transverse wakefields scale as the cube of the rf frequency [29], the low frequency choice of TESLA results in low wakefields, both long-range and short-range. Extensive studies have been carried out on the higher mode spectrum (related to the long-range wakefields) of 9-cell TESLA cavities using field computation codes, bench measurements on copper models and measurements with the TESLA Test Facility (TTF) beam. The frequency distribution of higher modes has been evaluated out to 200 GHz. Longitudinal wakefields, which scale as the square of the rf frequency [29], can cause energy spread and deposit power. Monopole higher-order modes responsible have also been carefully studied.

TESLA plans to prevent multi-bunch beam break-up in its millisecond-long, 3000-bunch train by damping the higher-order modes in the 1.3-GHz superconducting cavities using external loads, and by relying on the natural detuning of the modes that results from fabrication differences within the construction tolerances. HOM couplers have been developed and tested in TTF. In experimental tests, all but one of the modes have been successfully damped. Bench measurements on model structures show that a reorientation of the output coupler can damp the remaining mode. Very high frequency modes must be absorbed by suitable material inserted into the beam pipe between cryomodules to avoid additional heat load into the helium at 2 K. Concepts to intercept these modes are well under exploration.

High Gradient Development

At the DESY TTF site, a large number of industrially-produced nine-cell structures (1-m active length) have reliably reached gradients of 25–30 MV/m in cavity acceptance tests [1]. With high pulsed power (e.g., 200 kW per meter required for delivering beam power) gradients often exceed CW results. Eight 9-cell units have demonstrated gradients between 30–35 MV/m in the pulsed mode at the TESLA pulse length. With two cryomodules, the TTF linac has been run for short periods at gradients just above 20 MV/m. For FEL operation TTF ran for 9000 hours between 15–17 MV/m.

To reach high gradients, high-purity, high thermal-conductivity niobium is used to prevent thermal breakdown of superconductivity, while high pressure rinsing and clean room assembly techniques are used to reduce field emission and voltage breakdown [30]. In completed cryomodules of eight, nine-cell cavities for the TTF beam, one unit has reached 22 MV/m average gradient. Gradients for cryomodules have been steadily rising as final assembly techniques improve. Two new cryomodules have been assembled with sixteen cavities that exceed 25 MV/m. The maximum accelerating gradient for TESLA structures will be limited to 50–60 MV/m by the critical rf magnetic field.

Cleanliness in superconducting cavity surface preparation ensures that field emission current stays well below the microampere range, an important consideration for preserving beam quality along the linac. Another benefit of dust-free cleanliness is the absence of voltage breakdown in the cavities after first conditioning of isolated emitters is accomplished, a procedure that usually takes a few hours. The cavities are maintained clean by the use of rf windows.

Field emission is an important gradient limiting mechanism for all linear collider approaches. Extensive studies have been carried out on the causes of field emission (also referred to as dark current). Microparticle contamination has been determined to be the main cause of field emission in superconducting cavities [31]. Such emitters have been individually located using temperature-mapping techniques and identified after cavity dissection and surface analysis. DC field emission studies on 1 square-cm, room-temperature niobium cathodes also reveal micro-particles to be the main source of field emission [30, 31]. Following up on these discoveries, high pressure (approximately 100 atmosphere) water rinsing of superconducting cavities has been shown to be a highly effective tool to reduce field emission. Without high pressure rinsing, cavities show heavy field emission between 10 and 20 MV/m. With high pressure rinsing it is now possible to reliably achieve gradients between 20 to 30 MV/m in 9-cell cavities.

If dust enters a cavity during final assembly or accelerator installation, the emitters can be destroyed by pulsed high power processing (also known as conditioning) [31]. TESLA cavities will be equipped with high power couplers (for beam power). These can also provide the power necessary to process field emission in-situ, in case of accidental contamination [1].

Extensive studies have been carried out on the effectiveness of high power conditioning of superconducting cavities. Several 5-cell TESLA-geometry cavities that were not high pressure rinsed showed heavy field emission above 10 MV/m [32]. Using 1 MW of power at 250-microsecond pulse length it was possible to establish (after a few hours of conditioning) accelerating fields of 45 MV/m for about one microsecond, and destroy emitters at the high field. Subsequently it was possible to reach CW fields of 22 MV/m without any field emission, and 27 MV/m with less than a few microampere dark current. Similar tests were conducted with single cell niobium cavities, equipped with temperature mapping to locate individual emitters that successfully conditioned with high pulsed power [31]. Subsequently these cavities were dissected and examined under an electron microscope and Auger surface analysis. Micron-size molten craters were always found at the processed sites. In almost all cases, residues of foreign elements accompanied the craters, confirming the finding that emission takes place at contaminant sites. Intentional micro-particle contaminants placed inside superconducting cavities also broke down at high fields, and revealed craters coated with the original contaminant element.

To corroborate these findings, a major investigation is underway on room temperature niobium and copper cathodes using a DC high voltage spark gap to establish surface electric fields between 50 and 175 MV/m [33]. Voltage breakdown at many intentionally introduced microparticle contaminants showed craters and residues very similar to those found in superconducting cavities. These studies suggest that the voltage breakdown mechanism is very similar in room temperature and cold niobium, and also similar to the mechanism for warm copper cathodes.

Input couplers and rf window assemblies have been developed and tested to 1 MW at the TESLA pulse length [1]. Input coupler designs have been guided by the new calculation tools that show how to avoid multipactoring [34]. Applying a bias voltage to the center conductor of coaxial power couplers also suppresses multipactoring, a technique that has been extensively proven in LEP-II at CERN [35] and in HERA at DESY [36].

R&D is in progress to increase superconducting rf gradients. Electropolishing instead of the standard chemical polishing eliminates grain boundary steps so that gradients of 40 MV/m at Q values above 10^{10} are now reliably achieved in single cells at three laboratories (KEK, TTF/CERN and TJNAF) [37]. The highest gradient achieved was 42 MV/m. The same cavities when chemically etched show gradients below 30 MV/m, indicating that electropolishing is a fundamentally superior procedure. Preparations are underway to electropolish nine-cell cavities.

R&D is also underway on Q improvement, which will help lower the cost of the refrigeration system. For example, baking cavities at 140 C for 48 hours improves the Q by 50% due to lowering of the mean free path and thereby the BCS surface resistance. Such baking also improves the gradients, especially for electro-polished cavities [37]. For the TESLA upgrade path, lowering the temperature to 1.7 K and reducing the DC magnetic field inside the cryostat opens the option of increasing Q values to 10^{11}. In single cell 1300 MHz test cavities, Q values of 2 x 10^{11} have been reached and maintained above 10^{11} for gradients above 30 MV/m [38].

Fabrication and Operational Experience

An industrial base for superconducting cavity fabrication was established for LEP [39]. Industry has acquired the generic superconducting rf technology, which includes cavity chemistry, high pressure rinsing, cryomodule fabrication, and cryomodule assembly in clean rooms. Three companies have made cavities for the TTF. These are major steps toward industrialization of srf technology for TESLA, a time consuming process with a steep learning curve for all rf structure types. Cryomodules for the TTF have been made in industry. Industrial collaboration has been sought for making cost estimates for large-scale production [1].

There has been substantial progress in cost reduction by increasing the number of cells per cavity to nine, the number of cavities inside one cryomodule to twelve, and by integrating the cryogenic distribution system into the cryomodule [1]. An industry-based cost study of niobium cavities revealed that the largest cost component of niobium cavity fabrication comes from electron-beam welding. The study showed that the time required for beam welding could be reduced by more than a factor of ten by adopting a three-chamber welding machine, one for pump down, a second for welding and a third for cooling. A superstructure based on a nine-cell pair offers more cost reduction, and will be tested in the near future [1]. Further cost reduction efforts are forthcoming in new weld-free cavity fabrication techniques, such as spinning and hydroforming [40]. Copper-clad niobium cavities are under exploration to reduce material and fabrication costs as well as to attenuate Lorentz force detuning by using thicker material. Another cost benefit is likely to come from niobium material due to large scale production, a factor that was not included in the current cost estimate. An industrial study is underway to explore how to reduce the cost of high purity niobium.

Superconducting rf systems in HERA, JLAB, LEP-II, CESR, KEK-B and other projects have accumulated substantial operating experience over the last five years in the gradient range between 6 to 8 MV/m [41, 42]. Due to the intrinsic potential of superconducting cavities, the operating gradient for most of these installations has steadily risen well above the typical design value of 5 MV/m initially adopted for these projects during the late 1980's and early 1990's. CEBAF runs at 7.5 MV/m and LEP ran at 8 MV/m before decommissioning.

Other Superconducting Cavity Applications

Superconducting rf technology has made substantial inroads into a variety of accelerator applications for light sources [43] as well as neutron [44], neutrino, and muon sources [45]. SRF cavities are planned to separate kaon beams at Fermilab [46]. 500 MHz cavities for the Cornell Electron Storage Ring (CESR) have been adopted by two new light sources under construction. The TTF (and perhaps TESLA) will serve the FEL user community [1]. The U.S. Spallation Neutron Source (SNS) has changed its baseline to use srf cavities to accelerate beams from 200 MeV to 1 GeV [47]. In Europe the decision to use srf for ESS is still under consideration, but increasing in likelihood due user's requests for longer pulse length [48]. Los Alamos National Laboratory in the U.S. and INFN in Italy are developing srf technology for high-intensity proton accelerators for transmutation of nuclear waste [49]. CERN is studying the use of the LEP-II srf cavities for a high intensity proton linac (SPL) for advanced neutrino beams [50]. The Radioactive Isotope Accelerator will use srf technology being developed as a collaborative effort at Argonne National Laboratory, JLAB and Michigan State University (MSU) [51]. TRIUMF has adopted superconducting technology for producing radioactive ion beams for its project called ISAC-II [52]. JLAB in the U.S. and JAERI in Japan have operated infra-red FELs producing more than 2-kW average power for materials processing applications [53]. Feasibility Studies I and II in the U.S. for a Neutrino Factory are based on 200-MHz srf cavities; a prototype is under development. Subsystems of a future muon collider potentially will use srf.

In anticipation of these future projects the technology base for srf is widening. Los Alamos has installed complete new facilities for cavity fabrication, preparation and testing. MSU has installed brand new facilities. Fermilab has installed new srf capabilities for the photo injector [54] and kaon separator projects. Recently flat with large aspect ratios beams (desired for linear colliders) have been produced right after the photo injector. Transverse emittance ratios of 50 have been reached at Fermilab.

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