SLAC–PUB–9906
September 2003

Normal-Conducting RF Structure Test Facilities And Results [*]

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Expanded version of paper presented at the 2003 Particle Accelerator Conference, Portland, Oregon, May 12-16, 2003

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[*] Work supported by Department of Energy contract DE–AC03–76SF00515.

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INTRODUCTION

During the past six years, the major R&D on normal-conducting accelerator structures has been in support of two linear collider initiatives [1]. The SLAC, FNAL and KEK based NLC/GLC group proposes 11.4-GHz rf technology as a ‘modest’ extrapolation of that of the 2.9 GHz SLAC Linac. The CERN-based CLIC group aims at multi-TeV operation, proposing a higher rf frequency, 30 GHz, at the limit to which conventional copper fabrication techniques can still be used. The desire for a higher operating frequency results from the associated cost benefits of having lower rf energy per pulse (hence fewer rf sources) and a higher operating gradient with reasonable structure efficiency (hence a shorter linac).

Higher frequencies have several drawbacks including the large transverse wakefields generated in the structures by the beam. The structure designs are strongly influenced by the need to keep short-range wakefields small to limit emittance growth in the linacs. In particular, this requirement tightly constrains the allowed minimum average structure iris radius (a), which would otherwise be reduced to improve efficiency. The average radii currently being considered by both groups are about 17% of the rf wavelength (λ). This constraint has had implications for the structure high-gradient performance, as will become evident below.

The long-range transverse wakefields also need to be suppressed, and both groups use a combination of dipole-mode detuning and damping for this purpose. For the NLC/GLC structures, moderate damping is achieved by coupling the cells to four circular waveguides (manifolds) that run parallel to the structure. The CLIC design achieves stronger damping with four terminated, transverse waveguides attached to each cell. In each approach, there is enhanced pulsed heating near the openings in the cells required for this purpose. The designs of these regions need to limit the heating below a level that produces stress-induced cracks, which can lead to rf breakdown.

An even greater challenge related to the choice of high rf frequency has been to achieve stable operation at the design gradients. Both groups propose constant-gradient, traveling-wave structures where the upstream ends of the structures operate near the unloaded gradient. The design unloaded gradient for NLC/GLC is 65 MV/m (52 MV/m loaded), and for CLIC, it is 170 MV/m (150 MV/m loaded). The rf pulse length is tied to the frequency choice through the Q’s of the structure cells. For efficiency, the pulse length is several times the structure fill time, and the fill time is roughly equal to the attenuation time, $Q/\omega \sim \omega^{-3/2}$. For NLC/GLC (CLIC), the rf pulse length is 400 ns (130 ns) and the structure fill time is 110 ns (30 ns).

Both groups had similar initial experiences in developing structures to meet these goals. In the mid-to-late 1990s, each group built and commissioned a test facility aimed at demonstrating basic rf system performance (for CLIC, the CLIC Test Facility II, or CTF II, at CERN, and for NLC, the NLC Test Accelerator, or NLCTA, at SLAC). During this time, achieving the required gradients was not a major concern since earlier results showed >100 MV/m gradients were attainable at X-band, and that higher gradients seemed possible at higher frequencies [2]. However, when the test facilities came into full operation in 1999-2000, it became clear that the structures tested at that time, which required higher input powers and longer pulse lengths than those in the earlier tests, would not meet performance requirements due to breakdown-related damage.

In the following sections, the NLC/GLC and CLIC high-gradient programs, facilities and test results are reviewed with the emphasis on the past year’s findings.

NLCTA STRUCTURE TESTING

The first structures installed in the NLCTA linac were NLC prototypes built in part to test wakefield detuning and damping. They are 1.8-m long (206 cells), traveling wave ($2\pi/3$ phase advance per cell), nearly constant gradient (the group velocity varies from 12% to 3% c), and have an a/λ = 18% aperture. At the completion of NLCTA commissioning in 1997, four such structures

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* Work Supported by DOE Contract DE-AC03-76F00515.

had operated concurrently at unloaded gradients of 40 MV/m to 45 MV/m, close to the 50 MV/m requirement for the 0.5 TeV NLC design at that time. During 1997-99, the two linac power sources were upgraded to allow 70 MV/m operation, which had become the 0.5 TeV and 1 TeV NLC/GLC design unloaded gradient. It was during this period that performance limitations due to breakdown were fully realized, which initiated the high-gradient structure development program that is ongoing today. Since 2001, power from the two linac rf stations has been used to test 21 structures (up to four at a time), with over 10,000 hours of operation logged at 60 Hz [3].

Nearly all the cells in these structures are circularly symmetric, without the wakefield damping slots. Most of the cells were fabricated either at KEK using single-crystal diamond turning or at a precision machining company near SLAC using poly-crystal diamond turning. After machining, the former (latter) cells were etched to remove a 0.3 µm (3 µm) surface layer. During assembly, the cells were first diffusion bonded and then the couplers and water-cooling hardware brazed on in an hydrogen environment. After assembly, the structures went through a heat treatment that included ‘wet’ and ‘dry’ hydrogen firing at 950 ºC, a two-week vacuum bake at 650 ºC, and a one-week in-situ bake at 220 ºC. No significant performance difference has been seen between structures with single and poly-crystal diamond-turned cells.

The rf conditioning protocol used for the structures is typical in that the power is slowly increased until a breakdown is detected. In this case, the rf is normally shut off for 60 s, then brought back to full amplitude in 20 s at a reduced pulse width, and finally ramped to full pulse width in 20 s. A lower amplitude is used if the period between breakdowns is shorter than a preset limit. The main trip criterion is a loss in transmitted power through the structure (about 50% initially and 10% in the later stages of processing). Using this protocol, structures are normally conditioned to a target gradient (75 MV/m to 80 MV/m) with a series of progressively longer pulses (50 ns, 100 ns, 170 ns, 240 ns, 400 ns), and then run at a lower gradient to measure the breakdown rate.

Various types of signals are monitored during structure operation including rf, acoustic, vacuum pump current, and dark current. The basic characteristics of the breakdown events (e.g., time during the pulse, location in the structure and absorbed energy) are derived mainly from phase and amplitude measurements of the reflected and transmitted rf. A 2-ns-long beam is used to verify the structure gradient and to induce rf to monitor any phase advance changes. A bead-pull phase measurement is also made before and after each run.

The important structure performance metrics are (1) the time it takes to process to an unloaded gradient about 10% higher than nominal, (2) the breakdown rate at the nominal unloaded gradient and (3) the damage incurred during normal operation. With the large number of structures required for NLC/GLC, the processing time per structure needs to be less than a few hundred hours if they are to be conditioned during the five-year production period envisioned for the linear collider. Structure damage is characterized by the change in net phase advance through the structure and a few-degree shift per year would likely be acceptable, although much less is expected with stable operation.

An acceptable trip rate has been defined as one that would rarely (once a year) deplete the planned 2% reserve of NLC/GLC accelerator units assuming a 10-s recovery period after a trip (such periods have been shown feasible). For the 60-Hz operation at NLCTA, this requirement translates to < 0.1 trip per hour for a 60-cm structure. To be conservative, the structures are qualified at the 65 MV/m unloaded gradient with 400-ns square rf pulses. The corresponding NLC/GLC trip rate would likely be lower since the pulse length is effectively shorter (due to the 100-ns ramp for beam loading compensation) and the gradient lower (21% on average from beam loading, which increases roughly quadratically along the structure).

NLC/GLC TEST RESULTS

The past year saw the transition from testing experimental structures (so called T-Series structures) to testing those designed for use in the NLC/GLC (so called H-Series structures). The former had been built to examine how performance depends on structure length and group velocity. This study was motivated by the pattern of damage observed in the 1.8-m structures: the high group velocity (> 5% c) portions incurred extensive pitting and phase change with operation above about 50 MV/m, while the low group velocity portions remained relatively unscathed.

Seven T-Series structures were built with different lengths (20, 53 and 105 cm) and initial group velocities (5% c and 3% c). By mid-2002, six structures had been tested and showed that breakdown-related damage decreased significantly at lower group velocity and that structure length had little effect on performance. However, the breakdown rates in the input and output coupler cells were noticeably high. At 70 MV/m in the 3% c structures, the coupler breakdown rates were generally > 0.3 per hour while for the other 59 cells combined, they ranged from < 0.1 per hour to 0.3 per hour.

An autopsy of the input couplers revealed melting on the edges of the waveguide openings to the cell and extensive pitting near these edges and on the coupler iris. It was subsequently realized that the waveguide edges see large rf currents and the associated pulse heating can be significant if the edges are sharp. By design, the edges in the T-Series structures were much sharper (76-µm radius) than those in the 1.8-m structures (500-µm radius) where this problem was not seen. Simulations showed that the pulse heating for the T-Series structures was in the 130-270 °C range, well below the copper melting temperature, but high enough to produce stress-induced cracks, which can enhance the heating.

To see whether reducing the pulse heating would help, a structure was built using an input coupler design with lower peak surface currents (a 'mode-converter' type [4]) and an output coupler with larger radius (3 mm) edges. For the regular cells, a previously tested T-Series design (53 cm, 3% c) was used. This structure performed very well, with no enhancement of the coupler breakdown rates relative to the other cells. For the full structure, the breakdown rate at 90 MV/m with 400-ns pulses was about 1 per 25 hours. All structures have since been made using similar couplers.

Although the T-Series structure results were encouraging, their average cell iris radii ($a/\lambda = 13\%$) would produce unacceptably large short-range transverse wakefields in a linear collider. In parallel with the T-Series tests, the structure design efforts focused on developing NLC/GLC-compatible versions. The first task was to increase the iris size while keeping the group velocity low and maintaining a reasonable shunt impedance. This required both thickening the irises (from about 2 mm to 4 mm) and increasing the phase advance per cell (from 120º to 150º). The structures were also detuned and their lengths were optimized for efficiency. The resulting designs (H-Series) require higher input power relative to comparable T-Series structures (about 50% more at 3% c). This increase is more than that expected from just the larger iris diameter because the thicker irises also reduced the shunt impedance. To date, six such structures have been tested at high gradients.

The first test was of a pair of structures, one 60 cm, 3% c (designated H60VG3), and the other 90 cm, 5% c (designated H90VG5). These structures were built before the coupler problem was remedied and have the sharp-edged design. Also, the pulse heating is higher for the H-Series structures due to the larger stored energy. During processing, coupler breakdowns did indeed limit the gradients to values below those achieved with the T-Series structures. In addition, at short pulse lengths where the coupler events did not dominate, the processing rate was much slower than that for the T-Series structures. The thicker H-Series irises may have been a contributing factor because of their larger (times two) high-field surface area. Nonetheless, the H60VG3 structure did eventually process to 72 MV/m, and excluding the input coupler, the breakdown rate was < 1 in 10 hours at 65 MV/m.

The next four structures processed to 70 MV/m much faster than the first two, and in one case, faster than most of the T-Series structures. None of these structures showed an enhanced coupler breakdown rate. However, at gradients > 70 MV/m with 400-ns pulses, the processing was slowed considerably by what are aptly called 'spitfests.' These are a series of breakdowns close to each other in location and in time (in many cases, they occur during the ramp-up sequence in power and pulse width that follows a breakdown). The damage caused by the initial breakdown in these sequences is likely creating additional breakdown sites. Such correlated breakdowns were observed in the 1.8-m structures at lower gradients, and in the T-Series structures at higher gradients. In all cases, they become noticeable at roughly the same structure input power level (60-80 MW).

Two of the four structures are H60VG3 designs built by the FNAL structures group, which are the first ones they produced for testing [5]. Problems with the brazing furnace used for assembly caused a slight oxidation to the copper, which was removed from the second structure using a hydrogen bake. At NLCTA, the first structure would not process above 70 MV/m due to the large number of spitfests. The second structure performed much better, with a breakdown rate of about 1 per hour at 65 MV/m during a relatively short run. Future structures will be brazed in a custom-designed vacuum furnace at FNAL.

Another of the four structures is a 90-cm, 3% c design (H90VG3), which was built to test the feasibility of longer structures. It requires 30% more power for the same average gradient as H60VG3. When processed, it reached 75 MV/m with 400-ns pulses before being limited by spitfests. At 65 MV/m, the breakdown rate was about 1 per hour, but the spitfest nature of the events was still apparent. About 70% of the breakdowns occurred within 5 minutes of the previous one, although there were periods of up to 25 hours without any breakdown. Fig. 1 shows the dependence of the trip rate on gradient and pulse width after processing. At a fixed

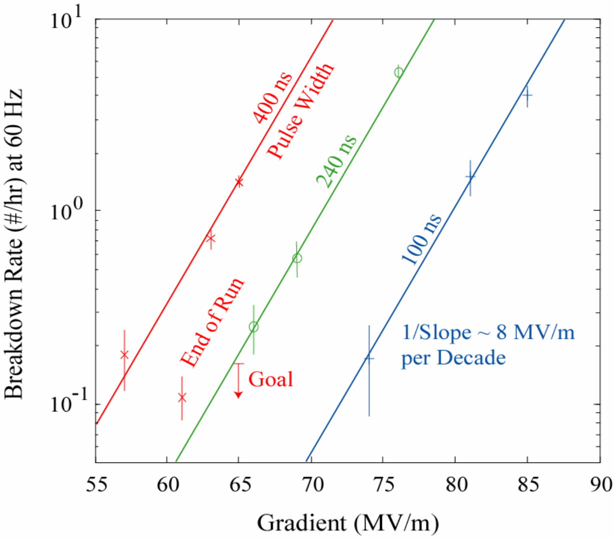

Fig. 1: Breakdown rate versus gradient and pulse width for the H90VG3 structure.

breakdown rate, the gradient scales as the -1/6 power of the pulse width. Near the end of the run, a breakdown rate of about 1 in 10 hours was achieved at 61 MV/m (less than 1 in 6 hours is required for this longer structure).

Roughly half of the breakdowns at 65 MV/m occurred in a few cells (three near the front and one in the middle). After the run, these 'hot' cells were examined using a boroscope. In the interior cell, a 100-µm wide piece of material that was pitted by breakdown was seen on the outer wall (a similar-looking contaminant in an earlier structure turned out to be aluminum). No obvious foreign material was seen in the upstream cells and a more thorough autopsy is underway.

The last of the four structures is an H60VG3 design whose middle six cells have manifold slots for wakefield damping. They were included to test whether pulse heating near the slot openings leads to breakdowns such as those in the sharp-edged couplers. To reduce this possibility, the slot openings were rounded to minimize the heating. A 43 °C temperature rise is expected at 65 MV/m with 400-ns pulses, which is believed to be safe based on the sharp-edged coupler operation experience.

This structure processed fairly quickly (≈ 50 hours) and achieved 80 MV/m with 400-ns pulses before spitfests began to limit further gains. During this period, there was no obvious breakdown rate difference between the slotted and non-slotted cells. At lower gradients, a few hot cells became apparent, including a slotted one. These cells accounted for a sizeable fraction of breakdowns, as shown in Fig. 2. Since only one of the six slotted cells was hot and hot cells occurred elsewhere, the breakdown enhancement in the slotted cell is probably not slot related.

During a 32-day run at 65 MV/m, the average trip rate was 0.21 per hour. Large day-to-day fluctuations occurred (up to 0.7 per hour) from 'flare-ups' in the hot cells. The spitfests were much reduced at this gradient, with 25% of breakdowns occurring within 5 minutes of the previous one. At 60 MV/m, the breakdown rate was well below 1 in 10 hours. This structure will be autopsied as well.

NLC/GLC SUMMARY AND OUTLOOK

The H-series results show that in structures with essential NLC/GLC features, reasonable processing times are possible and that breakdown rates close to those required can be achieved (damage rates also appear acceptable). Nonetheless, more operating overhead is desired, and a new version of the 60-cm structure design was recently adopted that has a smaller average iris radius ($a/\lambda = 17\%$) than the present structures ($a/\lambda = 18\%$). Decreasing the radius increases efficiency and will likely improve high-gradient performance due to the lower (7%) input power required. The transverse wakefield is about 20% larger, which is not expected to significantly increase emittance growth in the NLC/GLC linacs.

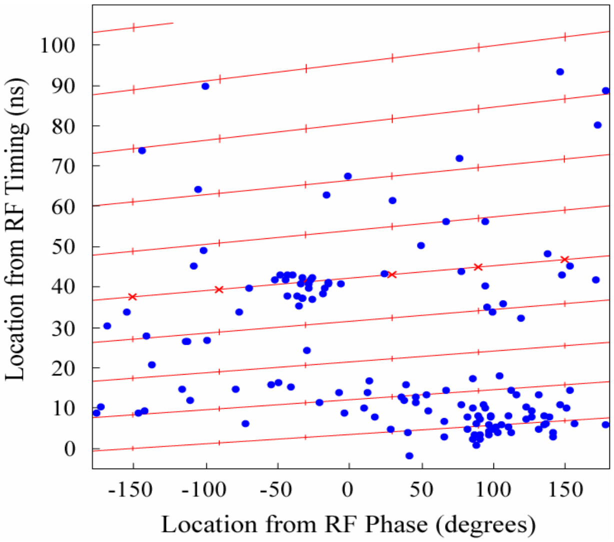

Fig. 2: H60VG3 breakdown locations (dots) at 65 MV/m inferred from reflected and transmitted RF. The cross hatches along the lines are cell locations (crosses are slotted cells) with the first upstream cell at the lower left.

The main goal within the next year is to operate eight such structures at 65 MV/m in the NLCTA. Tests of experimental structures will also continue, including ones aimed at achieving significantly higher gradients. One test will be of CERN-built, X-band structures with molybdenum and tungsten irises (part of the CLIC program described below). Another test will be of standing-wave structures with rounded-edged couplers. Earlier versions were limited to about 60 MV/m gradients, which may have been the result of their sharp-edged couplers [6].

At a more fundamental level, many questions remain such as the origin of breakdown and the large (×10) variation in processing rates. Surface analyses such as SEM, EDS, and AES have not found contaminants linked to breakdown sites, and residual gas analyses have not revealed any unexpected impurities. Also, the link between field emission and breakdown is unclear since the size of emitters would have to be very small (« micron) to explain the low dark currents (≈ 1 mA) that have been measured. Finally, the relationships among pulse heating, surface melting and breakdown are poorly understood. Not all couplers with high pulsed heating broke down so other conditions may be required, such as some minimum surface electric field. These and other questions will continue to be explored in future structure, waveguide and single-cell tests.

CLIC STRUCTURE DEVELOPMENT

The CLIC Test Facility II (CTF II) basically consists of two parallel beam lines (drive and probe) separated by about a meter [7]. It was designed when the CLIC linac required shorter rf pulses (12-18 ns) and lower gradients (80 MV/m). The drive-beam injector produces 16-ns-long trains of 48 bunches with several nC per bunch, and the probe-beam injector generates single, 0.6-nC bunches. Both beams are first accelerated to about 45 MeV in individual S-band linacs. The drive beam is then deaccelerated in transfer structures to generate 15 ns, 30-GHz rf pulses. This power is fed locally to 30-GHz structures in the probe linac to accelerate the probe bunch.

When CTF II commissioning concluded in 1999, the probe linac contained five CLIC Accelerator Structures (CAS), each constant impedance, 28-cm long (86 cells) with a $2\pi/3$ phase advance, 8.6 % c group velocity, and an $a/\lambda = 20\%$ iris aperture. A constant-impedance design was used to simplify cell fabrication, but has the disadvantage that only the upstream cells ‘see’ the highest gradient (the gradient decreases by 20% along the structure). Moreover, the single-feed power coupler used in the CAS design enhances the surface field on the coupler irises across from the waveguide opening by about 40%.

The basic results from the CAS testing were that processing plateaued after a 250-MV/m peak surface field was attained on the input coupler irises, and that rf breakdown severely eroded (≈ 100-μm deep) the high field surfaces on these irises. The corresponding first cell gradients were about 60 MV/m with the 15-ns pulses, far from the 170 MV/m required with 130-ns pulses.

Most of the copper cells for these and subsequent structures were fabricated by industry using single-crystal diamond turning. At CERN, they were degreased (but not etched) and then assembled using a vacuum brazing and bonding procedure at 820 °C. No high-temperature vacuum bake was performed after assembly. For structures that included poly-crystal diamond turned cells, the processing results were not significantly different, and as discussed below, a coupler iris that did not go through any high temperature process performed similarly to those that did.

In dedicated tests that followed in 2000, the structures were operated with improved breakdown monitoring and vacuum quality (from a 120 °C in-situ bake). For the processing then, as now, the power is increased while vacuum, missing power and structure currents are monitored. The power is not shut off after a breakdown, but the drive beam current is lowered to limit the breakdown rate, which can be a large fraction of the pulses. Typically a processing ‘plateau’ is reached within a few million pulses. The more systematic CAS testing again showed that the coupler iris surface fields were limited to about 250 MV/m.

With these and other tests showing little gain from improving iris surface quality, the use of other iris materials was considered, in particular those with melting temperatures higher than that of copper (1100 °C). For the structure to be practical, a reasonable conductivity (> 1/3 of copper) was required. Tungsten (W) was the first material chosen to test because of its very high melting temperature (3400 °C) and its use in high-voltage switching applications. For the initial tests, only the CAS input coupler irises were changed: a copper iris and three differently prepared tungsten irises (ground, electropolished and W/Cu matrix) were used (none of the irises were baked). In each case, the coupler iris was clamped between the same input coupler body and copper structure, and the whole unit mounted in a vacuum chamber for high power operation. While the copper coupler iris performed similarly to those in previous all-brazed structures, all three tungsten coupler irises sustained higher surface fields (320 MV/m) before the processing gains leveled off due to breakdowns elsewhere (mainly on the copper output coupler irises after a 250 MV/m surface field was reached there). The W iris tips showed no erosion at the high field regions, although there was some indication of melting.

Encouraged by these results, a new structure was designed to exploit the higher possible surface fields. For the couplers, a mode-converter design was used that has a 15% lower peak surface field than in the neighboring cells [8]. For the regular cells, the surface to on-axis field ratio was reduced from 2.8 to 2.2 by making the irises thicker and their radii smaller ($a/\lambda = 17.5\%$). The smaller radius is acceptable for CLIC, but it cannot be reduced much further due to wakefield-related limitations. The success of the clamped-on couplers led to the adoption of a fully ‘clampable’ design where four bolts run through the structure to hold it together. The cells are made of copper and include a 10-mm OD slot to accommodate snugly fitting, interchangeable irises. With the smaller structure group velocity (4.6% c), the structure was shortened to 30 regular cells (10 cm) to keep the same 20% gradient attenuation along an all-copper structure.

Three such structures have been tested to date, one with ground tungsten irises, one with ground molybdenum (Mo) irises, and for comparison, one with standard, brazed copper cells [9]. When processed, the all-copper structure performed as expected, with little gain after a 250 MV/m surface field was reached on the first cell iris (later visual examination showed some erosion at the highest field regions of this cell). With the lower surface to on-axis field ratio, the first cell gradient was 110 MV/m at this limit, almost twice the CAS result.

The gradients achieved in the other structures were limited by the allowed processing time. After about three million pulses, the gradient reached in the first cell of the W structure was 150 MV/m (340 MV/m surface), and in the Mo structure, it was 193 MV/m (426 MV/m surface). As a candidate iris material, molybdenum was chosen because it is relatively easy to machine and has good HV hold-off properties at DC. Its melting temperature (2600 °C) is midway between copper and tungsten, so its faster processing is somewhat surprising. However, this may be a consequence of the Mo iris heat treatment (900 °C vacuum firing), which was done to prevent the high out-gassing that occurred with the non-heat-treated W irises. When disassembled, the high-field regions on both the W and Mo first cell irises showed surface-layer melting but no obvious erosion; a more thorough examination is underway.

While the Mo structure results showed that CLIC-like gradients are possible, many challenges remain to achieve a 'CLIC-ready' structure. First, an acceptable breakdown rate at 170 MV/m needs to be shown at the 130-ns design pulse width in longer (≈ 80 cell), constant-gradient structures. Also, if Mo or W irises are ultimately used, their surface area must be made smaller or else the Q loss would be prohibitive. If only the high field regions (> 50% of maximum) of the irises are made with these materials, a modest Q loss (5%) could be achieved, although the fabrication of such tipped irises may be difficult. Finally, four radial waveguides need to be added to the outer region of each cell for wakefield damping. Pulse heating near the waveguide openings to the cells is of particular concern, given the high rf frequency and required field levels. In the latest design aimed at minimizing the heating, a 120 °C pulse temperature rise would occur under CLIC operating conditions, while a temperature rise below 60 °C is desired.

As for future testing, CTF II was decommissioned in October, 2002, and its components are being used for CTF 3. This facility will produce longer (130 ns), higher current (35 A), higher frequency (30 GHz) drive beams using the type of combiner rings envisioned for CLIC. High-power testing should resume in spring 2004 using the 5-A, 3-GHz injection beam for CTF 3. In the meantime, versions of the clamped structure scaled to X-band will be tested at NLCTA with Mo and W irises.

SUMMARY

The results from three generations of NLC/GLC structure tests show the need to operate at power levels below the regime where damage occurs (60-80 MW at 400 ns). At this limit, the peak iris surface fields vary significantly: about 110 MV/m in the 1.8-m structures, 140 MV/m in the H-Series structures and up to 195 MV/m in the T-Series structures. In contrast, operation of the copper CLIC structures with 15-ns pulses appears to be surface-field limited (at about 250 MV/m). At this limit, the input power differs significantly for the two structure designs tested (23 MW and 35 MW). This insensitivity to power compared to the NLC/GLC structures may be due to the higher surface fields, shorter pulses and the much higher breakdown rates at which they were operated.

In regard to demonstrating a feasible design, the NLC/GLC group has operated structures with essential linear-collider features that basically meet the 65 MV/m performance requirements (at 60 MV/m, breakdown rates well within spec have been achieved). A lower-power structure design has been adopted recently that should prove more robust. The CLIC group has attained over 300 MV/m surface fields on W and Mo irises with 15-ns pulses. Although CLIC-level gradients were achieved in a Mo iris structure, significant challenges remain to demonstrate acceptable performance with 130-ns pulses in longer, damped, efficient structures.

ACKNOWLEDGMENTS

The impressive gains that have been made in improving high gradient performance are the result of the dedicated efforts of a large number of people working on the design, construction and testing of structures at SLAC, FNAL, KEK and CERN. The authors thank Walter Wuensch and Steffen Doebert for providing detailed and insightful information on the CLIC R&D program for this report.

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