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Results from the CLIC X-Band Structure Test Program at NLCTA [*]

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Abstract

As part of a SLAC-CERN-KEK collaboration on high gradient X-band structure research, several prototype structures for the CLIC linear collider study have been tested using two of the high power (300 MW) X-band rf stations in the NLCTA facility at SLAC. These structures differ in terms of their fabrication (brazed disks and clamped quadrants), gradient profile (amount by which the gradient increases along the structure, which optimizes efficiency and maximizes sustainable gradient) and HOM damping (use of slots or waveguides to rapidly dissipate dipole mode energy). The CLIC goal in the next few years is to demonstrate the feasibility of a CLIC-ready baseline design and to investigate alternatives that could increase efficiency. This paper summarizes the high gradient test results from NLCTA in support of this effort.

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As part of a SLAC-CERN-KEK collaboration on high gradient X-band structure research, several prototype structures for the CLIC linear collider study have been tested using two of the high power (300 MW) X-band rf stations in the NLCTA facility at SLAC. These structures differ in terms of their fabrication (brazed disks and clamped quadrants), gradient profile (amount by which the gradient increases along the structure, which optimizes efficiency and maximizes sustainable gradient) and HOM damping (use of slots or waveguides to rapidly dissipate dipole mode energy). The CLIC goal in the next few years is to demonstrate the feasibility of a CLIC-ready baseline design and to investigate alternatives that could increase efficiency. This paper summarizes the high gradient test results from NLCTA in support of this effort.

INTRODUCTION

The linac operating frequency of the proposed Compact Linear Collider (CLIC) design was changed from 30 GHz to 12 GHz (X-band) in early 2007 based on results of a scaling study [1], and to take advantage of the resources and lessons learned from the 11.4 GHz accelerator structure program for NLC/GLC. With the CLIC drive-beam based rf source still under development, 11.4 GHz CLIC prototypes are being tested at the NLCTA facility at SLAC where there are two X-band rf stations available that produce up to 300 MW, 250 ns long pulses at 60 Hz. In fact, such testing started in 2003 when scaled versions of the CLIC 30 GHz structures were evaluated to see how performance depends on frequency.

During the past two and a half years, seven tests at NLCTA were performed on five CLIC structures having two basic rf designs, called HDX and T18, whose parameters are listed in Table I. The HDX design is a scaled version of a structure from the CLIC 30 GHz program and features thin irises and a low phase advance per cell to reduce the Es/Ea ratio (at the cost of a lower Q). The T18 design was a first attempt at an ‘optimized’ X-band structure based on empirical surface field and pulse heating constraints, and on the observed breakdown rate dependence on pulse length. It features a 55% ramp up in gradient along the structure, and with the lower group velocity and higher r/Q, it requires about a third of the input power for the same gradient as the HDX structure. The goal is to use a lower group velocity, smaller aperture and shorter pulse length (230 ns vs 400 ns for NLC/GLC) - all of which have generally yielded higher gradients - to achieve at least 100 MV/m unloaded gradients reliably (compared to 65 MV/m for the NLC/GLC structures). However, the smaller average a/λ (13% vs 17-18% for NLC/GLC) produces stronger transverse wakefields that require tighter structure alignment tolerances. Also, to recover the efficiency loss at the higher gradient, a shorter bunch spacing will be used, which requires more aggressive long-range wakefield control, in particular, having local HOM damping with Q’s of order 10.

Besides the differences in rf design, two fabrication techniques, quad and disk, were used for the structures. The disk fabrication technique is typical where structures are made by brazing stacks of disk-like cells. For the quad fabrication, four bars that run the length of the structure are each milled along one edge to form a quarter of the inner cell geometry, and then bolted together. This technique is appealing because large-scale production may be less expensive, the irises can be made thinner, azimuthal gaps (slots) can be introduced between the irises for HOM damping and no brazing is involved so different materials can be easily tried.

QUAD STRUCTURE RESULTS

The first X-band quad structure tested was an HDX design, which is shown in Figure 1. The details of this test can be found in reference [2], but basically it would not process above about 80 MV/m with 50 ns pulses during a 400 hour run. With the bolted assembly, it could be easily disassembled for inspection after the run. An SEM analysis showed that whisker-like copper protrusions had grown off the sides of the irises (see Fig. 2), and such growth was much more pronounced in the upstream cells. Nothing like this has been seen in the NLC/GLC structures where the breakdowns only produce pits on the

	HDX	T18
Regular Cells	11	18
a/λ (%)	16	15.5 - 10.1
Phase Adv/Cell (deg)	60	120
Group Velocity (% c)	5.1	2.6 - 1.0
Iris Thickness (mm)	1.4	2.8 - 1.3
Q	3760	6830 - 7240
r/Q (kΩ/m)	13	11.9 - 17.8
Es/Ea	1.6	1.95 - 1.85
Ea (out) / Ea (in)	0.97	1.55
Power for 100 MV/m (MW)	164	56

Table 1: Properties of the HDX and T18 structures

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iris tips (which were also observed on the HDX iris tips). However, protrusions like this have been seen in the output sections of X-band klystrons, which also have a narrow iris spacing of about 5 mm. Perhaps dark current hot spots originating on one wall led to stress fatigue on the opposite iris wall due to the close spacing, and this instigated the observed melting.

Other factors in the preparation of the structure may also have contributed to its poor performance so it was decided to refurbish it and make improvements. First, the quadrants were electropolished to smooth the breakdown pits and remove the whiskers. This worked well (but unfortunately cannot be done with disk structures). The quadrants were then hydrogen fired at 1050 °C to braze on new water fittings. This grew the copper grain size, which seemed to have benefited the NLC/GLC structure performance. When reassembling the quadrants, the relative iris alignment was improved from about 100 microns to 50 microns. Finally it was re-installed in NLCTA with the orientation reversed so the end that had been lightly damaged was upstream.

The second run started off well, and after 100 hours of processing with 50 ns pulses, the structure was operated at 105 MV/m over a 24 hour period in which the breakdown rate was about 1e-5 per pulse. However, when processing through 100 MV/m with 70 ns pulses, the performance degraded abruptly, and after 70 hours more of processing, only 80 MV/m could be achieved with 50 ns pulses. A subsequent SEM exam revealed that one quadrant of the first regular upstream cell had extensive whisker growth like that seen in the first run. The rest of the structure was fairly pristine, although there was noticeable copper splatter around the growth area.

A molybdenum version of the HDX structure was also tested at NLCTA and its performance was similar to that of the copper HDX structure during the first run [2]. A detailed postmortem has not yet been done on this structure. Also, four 30 GHz copper quad structures with and without slots were tested at CERN [3]. They have group velocities from 2.5% to 8.0% of c, a/λ from 17.5% to 19% and 60 deg and 120 deg phase advances. The gradients achieved were below about 80 MV/m for a 1e-3 per pulse breakdown rate with 70 ns pulses. Similar 30 GHz disk structures without slots did somewhat better, reaching 95 MV/m for the same conditions. Examination of the quad cells after processing showed that the irises were heavily pitted but no whisker growth was seen.

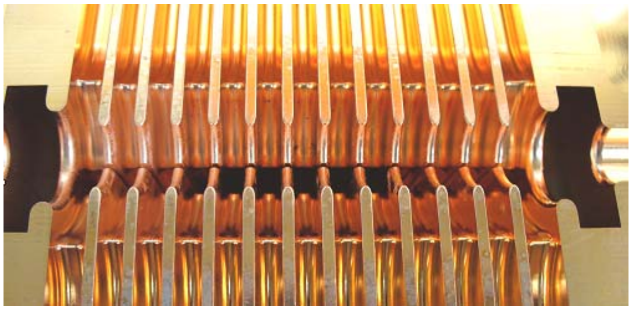
Figure 1: Photo showing the bottom two quadrants of the HDX structure after testing. There are slots between the regular irises but not the matching cell irises on each end.

More recently, a copper quad version of the T18 was tested at NLCTA. This structure has no iris slots but has four openings in the outer wall of each cell for HOM damping. Also, the iris spacing is twice that of HDX given its 120 degree phase advance. While a disk version of this structure did very well (see below), this quad version would not process above 50 MV/m with 90 ns pulses. It produced large gas bursts when it broke down, and at one point, the sustainable gradient dropped in half.

The structure was examined with an optical microscope as it is too long for the SLAC SEM. There is light pitting on the iris tips but no whisker growth on the iris sides. However, careful examination shows small clusters of pits at the iris edges where they contact azimuthally. At some joints, there are 10-50 micron copper ‘sheets’ protruding from the contract regions, and the nearby area is surrounded by intense pitting and melting. The quadrants were misaligned at the 50 micron level, which may be factor in the breakdowns as some azimuthal current will then flow across the joints. Another factor may be virtual leaks at the iris joints, which would explain the large gas bursts accompanying breakdown.

The next quad structure to be tested will also have contacting irises, but the edges will have a 50 micron radius to reduce the field enhancement from misalignments. However, the slotted approach may be better as it eliminates the virtual leaks in the high field region. Such an X-band structure with a 120 degree phase advance per cell may be the best chance to ‘redeem’ the quad fabrication technique.

DISK STRUCTURE RESULTS

As noted above, the T18 structure is an attempt at an ‘optimal’ X-band design. The cells for the first structure were made at KEK and the structure was assembled and tested at SLAC. During a 1400 hour run, it indeed preformed well. With 230 ns pulses, it operated at 105 MV/m for 48 hours with a breakdown rate that meets the linear collider spec of < 5e-7/pulse/m [4]. The breakdown rate within the structure increased only linearly toward the downstream end despite the large (55%) increase in gradient. However, a ‘hot’ cell midway through the structure became more prominent at high gradient, and

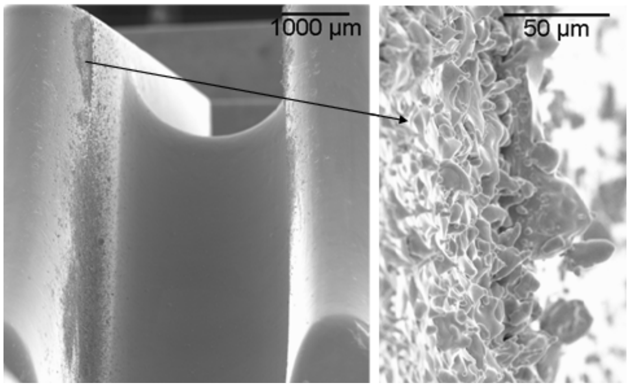

Figure 2: SEM Photo of a HDX cell 7 quadrant after the run. The right photo is a blowup of the triangular patch on the left and shows the growth of melted nodules.

when the structure was pushed past 114 MV/m, it ‘flared-up,’ causing a drop in performance (see Fig. 3). A boroscope examination after the run did show any indication as to the cause, although this was typical for hot cells in the NLC/GLC structures.

The T18 structure was then operated backwards to see how the highest gradient cell performed when powered directly. With 80 ns pulses, 163 MV/m was achieved in the first cell with a 2e-5 breakdown rate, which is roughly consistent with its forward operation performance. In other tests at SLAC, a similar rate at this gradient was achieved in a single SW cell with the same 10% a/λ as the highest gradient T18 cell, but with 200 ns pulses [5].

Two other T18 structures have since been tested. One was assembled the same way as the first, but processed at KEK. It also achieved gradients above 100 MV/m with low breakdown rates [6]. The second structure was assembled at CERN using cells from a European vendor. Figure 4 shows this structure mounted on the top plate of the vacuum can in which it is installed for high power tests (the HDX structures were also operated this way). At NLCTA, it processed very slowly and reached only 60 MV/m with 70 ns pulses after 35 hours. With the rf on, the structure vacuum pressure would rise over a factor of 10, which is unusual. Eventually, breakdowns in two hot cells near the middle of the structure dominated the total rate. The breakdowns were of the ‘soft’ type where the rf energy absorbed after breakdown is lower (30%) than typically seen (70%).

The structure was subsequently sent back to CERN were it was cut into sections. A detailed autopsy is now underway. Of note is the presence of sulfur rich particles in the bulk copper and at the grain boundaries. The relatively low braze temperature (800 °C) may have increased the diffusion of the sulfur into the grain boundaries. Although breakdowns are somewhat enhanced at these boundaries, only some show sulfur residue. More interesting is a contaminant found near the hot cells. Figure 5 shows a 200 micron long calcium and carbon rich object that appears to have caused breakdown related surface melting over a 1 mm wide area on the iris, and thus is likely one of the main contributors to the poor structure performance. In future CERN structures, more care will be taken to ensure better surface quality, including pre-firing the cells to 1000 °C to increase the gain size.

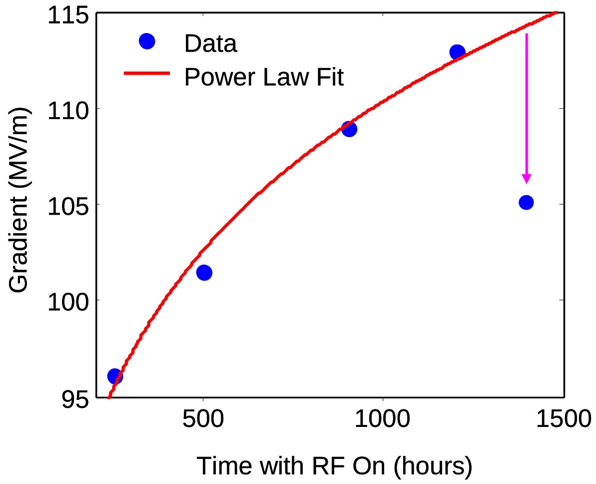

Figure 3: CERN/KEK/SLAC T18 disk structure gradient over time with 230 ns pulses and a breakdown rate of 2e-6 pulse per meter.

ACKNOWLEDGMENTS

We thank the Test Facilities and PCD groups at SLAC for their tireless efforts at keeping the NLCTA running.

REFERENCES

[1] A. Grudiev et al., ‘Optimum Frequency and Gradient for the CLIC Main Linac Accelerating Structure,’ EPAC06 Proceedings, June, 2006.
[2] S. Dobert et al., ‘High Power Test of an X-Band Slotted-IRIS Accelerator Structure at NLCTA,’ SLAC-PUB-12788, Sep 2007.
[3] S. Dobert, ‘Recent 30 GHz High Gradient Results’ CLIC08 Workshop, Oct 2008.
[4] S. Dobert et al., ‘High Power Test of a Low Group Velocity X-band Accelerator Structure for CLIC,’ CERN-AB-2008-069, Nov 2008.
[5] Valery Dolgashev, ‘Status of High Gradient Tests of NC Single-Cell Structures’, ANL High Gradient Collaboration Workshop, March 2009.
[6] Shuji Matsumoto, ‘Update of KEK X-band Research Activity,’ ANL High Gradient Collaboration Workshop, March 2009.

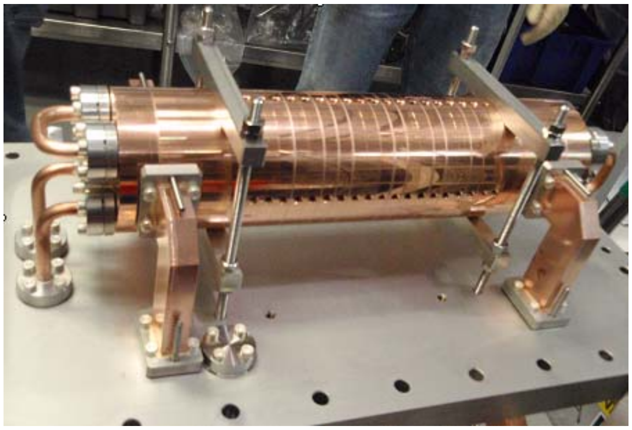

Figure 4: Photo of the T18 CERN structure mounted on the top plate of a vacuum can.

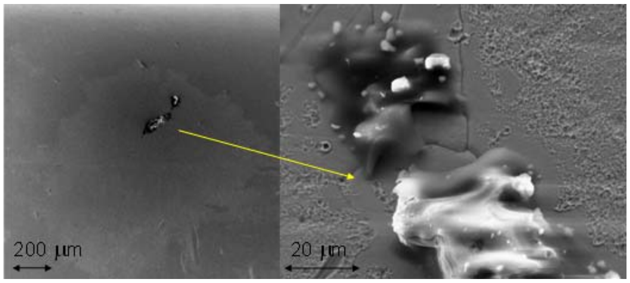

Figure 5: SEM photos of a calcium and carbon rich object on iris 12 of the CERN T18 structure.