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High Gradient Test of a Clamped, Molybdenum Iris, X-band Accelerator Structure at NLCTA

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Abstract

Inspired by the very high gradients (150-195 MV/m) achieved at CERN in 30 GHz accelerator structures made with tungsten and molybdenum irises and operated with short (16 ns) rf pulses [1], an X-band (11.4 GHz) version of this structure design was built at CERN and tested at SLAC. The goals of this experiment were to provide frequency scaling data on high gradient phenomena at similar pulse lengths, and to measure the structure performance at the longer pulse lengths available at SLAC (the CLIC test facility, CTF II, could provide only 16 ns pulses for high power operation and 32 ns pulses for medium power operation). Earlier high gradient tests of 21 GHz to 39 GHz standing-wave, single cells indicated no significant frequency dependence of the maximum obtainable surface field [2]. The X-band scaling test would check if this was true for travelling-wave, multi-cell structures as well. For the experiment, the CLIC group at CERN built a 30 cell accelerating structure that consisted of copper cells and molybdenum irises that were clamped together. The structure was mounted in a vacuum tank and installed in the Next Linear Collider Test Accelerator (NLCTA) beam line at SLAC where it was operated at high power for more than 700 hours.

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HIGH GRADIENT TEST OF A CLAMPED, MOLYBDENUM IRIS, X-BAND ACCELERATOR STRUCTURE AT NLCTA

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INTRODUCTION

Inspired by the very high gradients (150-195 MV/m) achieved at CERN in 30 GHz accelerator structures made with tungsten and molybdenum irises and operated with short (16 ns) rf pulses [1], an X-band (11.4 GHz) version of this structure design was built at CERN and tested at SLAC. The goals of this experiment were to provide frequency scaling data on high gradient phenomena at similar pulse lengths, and to measure the structure performance at the longer pulse lengths available at SLAC (the CLIC test facility, CTF II, could provide only 16 ns pulses for high power operation and 32 ns pulses for medium power operation). Earlier high gradient tests of 21 GHz to 39 GHz standing-wave, single cells indicated no significant frequency dependence of the maximum obtainable surface field [2]. The X-band scaling test would check if this was true for travelling-wave, multi-cell structures as well. For the experiment, the CLIC group at CERN built a 30 cell accelerating structure that consisted of copper cells and molybdenum irises that were clamped together. The structure was mounted in a vacuum tank and installed in the Next Linear Collider Test Accelerator (NLCTA) beam line at SLAC where it was operated at high power for more than 700 hours.

DESIGN AND FABRICATION

The design of the original 30 GHz tungsten and molybdenum structures was driven by the need to test the potential of these new rf materials with a minimum amount of technological development. The solution for assembly that was adopted was to fabricate only the irises of the accelerating structures using the refractory metal and to longitudinally clamp them between copper cells and place the entire structure inside a vacuum tank. The achieved gradient at 30 GHz and a microscopic analysis of the refractory metal to copper joints both indicate that the solution was adequate and consequently it was carried over to the X-band structure. In this way the structure geometry could be exactly scaled from the 30 GHz test in order to be able to make as direct a comparison to the previous data as possible. A cell and iris is shown in Figure 1 and the structure characteristics are summarized in Table 1. The same single-feed mode-launcher coupler was used as in the 30 GHz test with only slight dimensional changes for matching to WR-90 rather than WR-28 waveguide.

The irises were manufactured by the same supplier from the same sintered and forged bar (99.95% purity) that was used to fabricate the irises for the 30 GHz test. The precision machined copper parts were degreased prior to assembly. The molybdenum irises were degreased and vacuum fired at 800 °C in an attempt to degas the material. However it is not known if the firing was necessary or even effective (especially since the irises were exposed to air for some weeks after the firing). The whole question of optimal material and surface preparation methods and assembly technology has not been addressed in any depth.

The assembled accelerating structure was held inside the vacuum tank by a copper support. The accelerating structure was cooled through clamped contact with the support, which was itself water cooled. The effectiveness of this solution for cooling was verified through tests with an electric heating element. There was however some doubt whether the clamped assembly could be baked, so to limit risk, it was decided not to bake the structure. The structure and vacuum tank assembly was then shipped to SLAC.

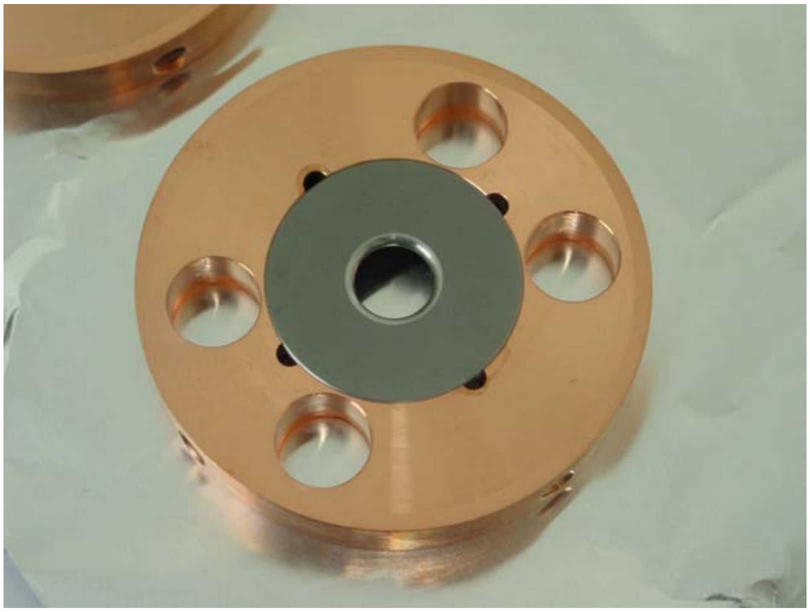

Figure 1. A molybdenum iris mounted in a copper disk, which forms a cell. The holes near the outer radius are used to bolt the cells together. The semi-circular holes just outside of the molybdenum disk allow gas to escape.

Table 1: Structure Parameters

Frequency	11.424 GHz
Number of cells	30+2 matching cells
Phase advance per cell	$2\pi/3$
Iris diameter	9.19 mm (constant)
Group velocity, v_g/c	4.6%
Fill time	20 ns
$E_{\text{peak-surface}} / E_{\text{acceleration}}$	2.2
Input Power for 100 MV/m Average Gradient	175 MW

EXPERIMENTAL SET UP

The structure was installed in its tank into the RF-Test Station 1 in NLCTA. A photo of the vacuum tank assembly in the NLCTA beam line is shown in Figure 2. In an attempt to reduce the water vapour that dominated the rest gas spectrum in the tank after installation in the beam line, it was purged with hot (100 ^{o}C) nitrogen for 72 hours. During operation of the structure, the

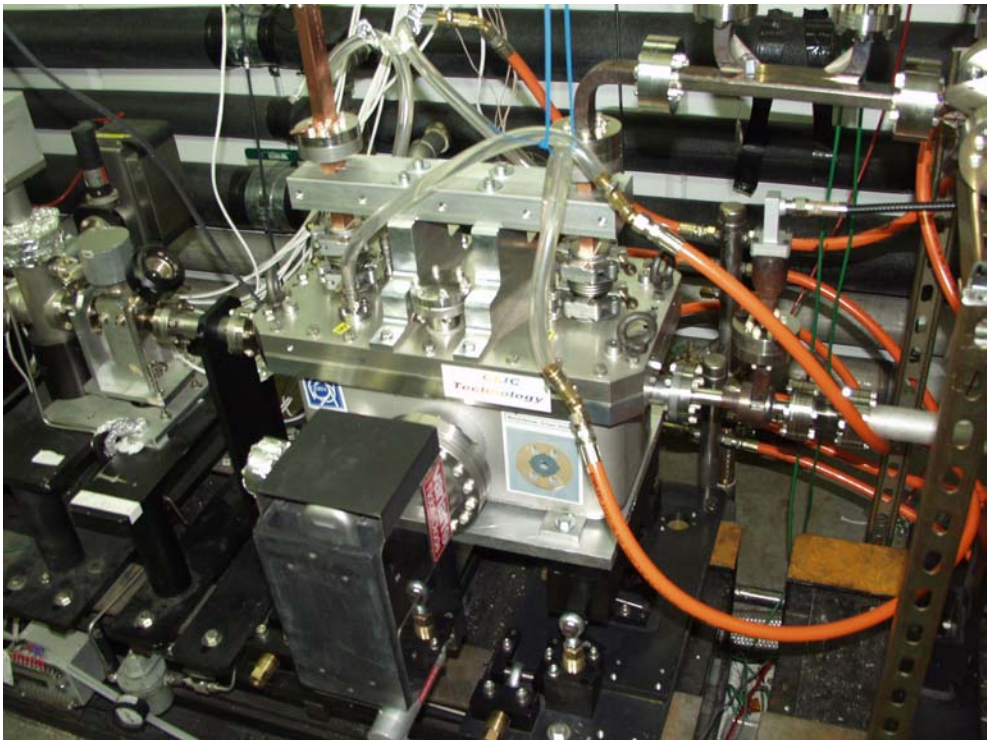

Figure 2. Photo of the test setup in the NLCTA beam line. The rectangular box (vacuum tank) in the center of the picture contains the accelerator structure. Also shown are a light monitor to the left and a current monitor to the right.

pressure achieved was of the order of 10^{-8} mbar as measured by a vacuum gauge directly on the vacuum tank. Directional couplers in the waveguide that transported power into and out of the structure were used to monitor the transmitted and reflected power. Upstream of the tank, a view port equipped with a mirror was available to measure visible light emission during rf conditioning, and downstream a current monitor was installed to allow dark current measurements.

The power source that was used for this test was unfortunately limited to 140 MW for pulse lengths up to 240 ns due to some unforeseen technical limitations during the scheduled time for the experiment. At this maximum power level, the gradient in the first cell of the test structure was 85 MV/m. The output power from the structure was split and transported to two water-cooled loads.

HIGH POWER TEST

The structure was rf conditioned using the standard NLCTA automated processing loop. This loop determines the missing energy (input power – transmitted power) on every pulse and switched off the rf if this quantity exceeded a user-defined threshold (the transmitted power typically decreases rapidly after a breakdown). In addition, there were vacuum and reflected power interlocks that were nominally used to protect the klystron output windows. The missing energy trip threshold, which was typically set to 10% for NLC/GLC structures, was set to about 50% for most of the experiment in order to speed up processing. The initial conditioning was done using 30 ns pulses and at first was limited by heavy out-gassing. The structure processed slowly and no attempt was made to increase the pulse length until a gradient of approximately 70 MV/m was achieved in the first cell (see Figure 3). During the early processing, many 'soft'

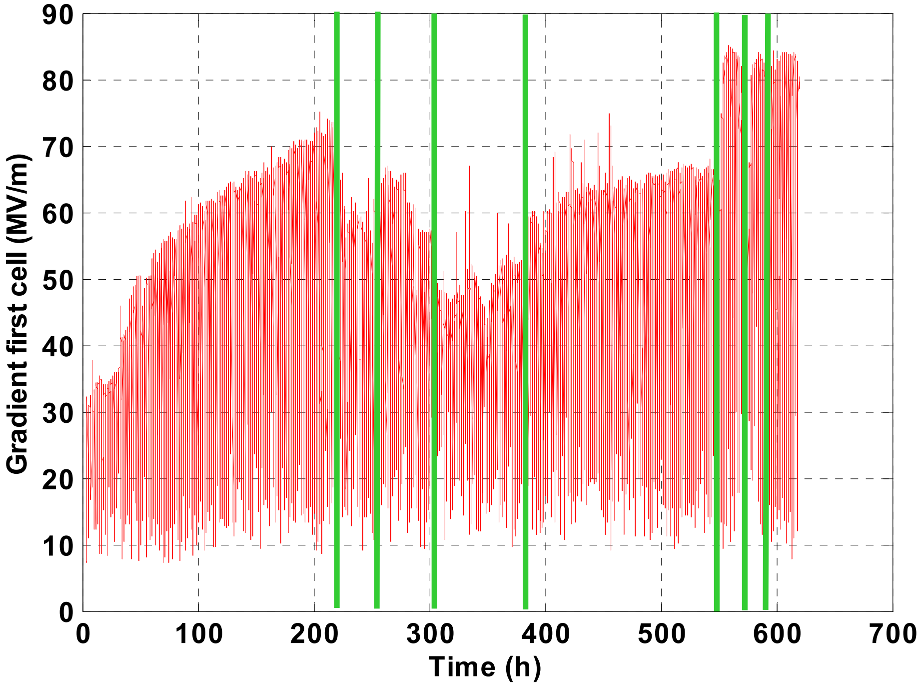

Figure 3. Gradient achieved in the first cell versus processing time (the gradient in the last cell was about 26 % lower). The green vertical lines indicate changes in pulse length. The sequence of pulse lengths was: 30, 100, 70, 240, 100, 16, 25 and 30 ns.

(missing energy below 15%) breakdowns were observed while later on ‘hard’ (missing energy > 50%) breakdowns dominated. As noted above, one of the objectives of the experiment was to assess the performance of the molybdenum structure at longer pulse lengths. Since the CLIC design pulse length is about 100 ns, the structure was operated with comparable pulse lengths for some time, despite very slow gains in sustainable gradient. Shorter pulses were then used to obtain data that could be compared with those from operation of the 30 GHz CLIC structures with 16 ns pulses. At pulse lengths of 16 ns, 25 ns and 30 ns, the power-limited gradient of 85 MV/m in the first cell of the structure was reached. Thus it was not possible to check whether values much closer to the 195 MV/m achieved at CERN were possible at X-band with short pulses.

The last 100 hours of operation were used to measure breakdown rates as a function of gradient at different pulse lengths to compare with the NLC/GLC copper structure results. Also, the repetition rate was lowered from 60 Hz to 10 Hz for a brief period to see if average heating effects were a factor (the pressed contact between the molybdenum and copper disks made this a particular concern). No measurable difference in high gradient performance was observed.

Data from a typical breakdown event during 100 ns pulse operation is shown in Figure 4. Relative to non-breakdown pulses, the transmitted power pulse was shortened and the reflected power was significantly higher. In addition, an electron burst was emitted as was visible light. Note that the input pulse also included low amplitude (< -20 db), 100 ns long ‘after-pulses’ which occurred in 240 ns intervals after the main pulse (these result from the SLED II system that is used to compress the klystron pulse). Both the reflected power and light pulse showed the after-pulse pattern, indicating that the plasma generated during breakdown lasts well beyond the

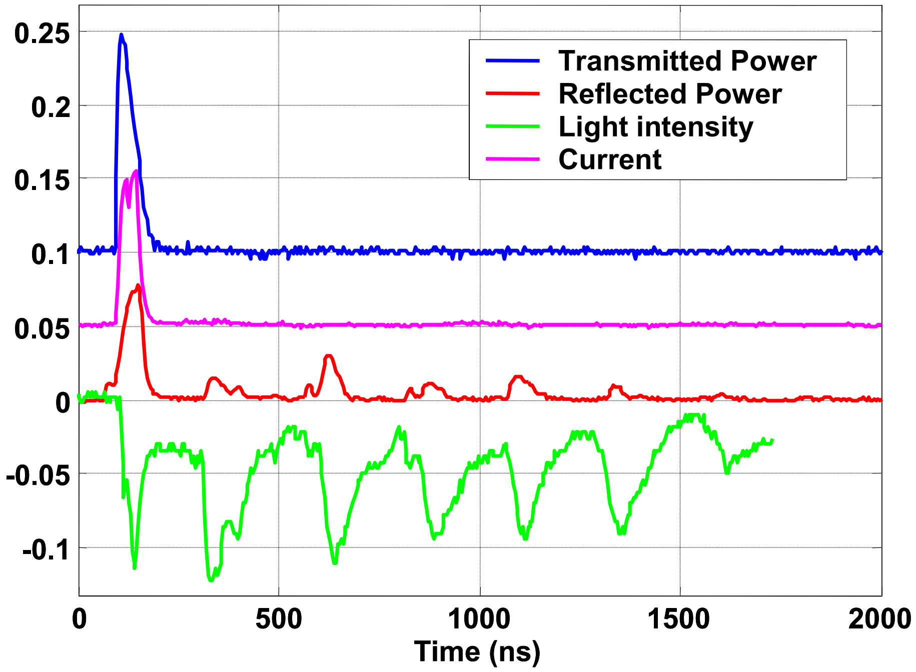

Figure 4. Diagnostic signals in arbitrary units as a function of time during a pulse in which a breakdown occurred. The incident pulse length was 100 ns and was followed by 100-ns-long, low-power after-pulses every 240 ns, which are described in the text.

main rf pulse (earlier measurements in copper structures showed that the after-pulses are not fully transmitted until about 10 microseconds after the main pulse). The low power after-pulses seemed to be capable of reigniting the plasma to emit visible light but were not large enough to generate detectable emission currents. Also, the plasma density was apparently high enough to reflect a significant fraction of the incident rf power. The total running time during the experiment was about 700 hours. The number of breakdowns registered by the processing loop counter was 28500 but the actual number was a factor 4 to 5 higher because the trip threshold was set rather high. After the run, the structure was removed from the vacuum tank and sent to CERN where a detailed surface analysis of the structure was made.

RESULTS

The rf breakdowns that occurred during processing showed ‘classical’ characteristics. These events were accompanied by vacuum bursts, electron bursts and light emission. A Fowler-Nordheim field enhancement factor (β) as low as 14 was measured at the beginning of the processing, while near the end of the run, measured values of 30 were typical. The dark current decreased by almost one order of magnitude between these two sets of measurements (no absolute measurement of the dark current was made however). The breakdown locations in the structure as determined by timing measurements of the transmitted and reflected rf pulses show a fairly flat distribution over the length of the structure with some enhancement in the last five cells. This was somewhat surprising given the 26% variation of surface field along the structure

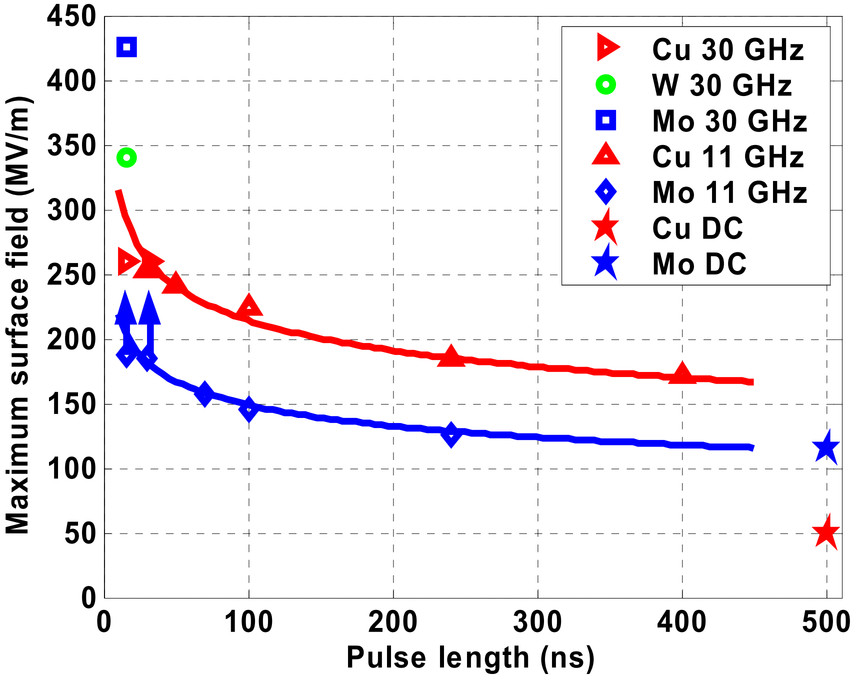

Figure 5. Pulse length dependence of the maximum surface field achieved in structures with different frequencies (11 GHz and 30 GHz) and different iris materials (Cu, Mo and W). The upper line is a fit (see text) to the Cu 11 GHz data and the lower line is a fit to the Mo 11 GHz data. Note that the Mo 11 GHz data points at 16 ns and 30 ns were power limited and therefore represent a lower limit.

and the strong (exponential) dependence of the average breakdown rate on gradient. However, it is not atypical of the distributions seen in X-band copper structures that have a 40% surface field variation along their length.

Figure 5 shows the gradient achieved at various pulse lengths for different frequency structures and different iris materials. For the molybdenum data from this experiment, the pulse length (τ) dependence follows a $\tau^{-(1/6)}$ behaviour that is similar to that for copper X-band structures (see the curves in Figure 5). It is remarkable that the short pulse, 30 GHz copper data points are roughly consistent with the trend of the 11.4 GHz copper data even though the structure designs differ significantly (the NLC/GLC structure is longer and quasi-constant gradient). Unfortunately the 11 GHz molybdenum result at 16 ns is somewhat inconclusive because the power was limited at this pulse length. However, the similar pulse length dependence at longer pulses suggests a similar cause for this behaviour, independent of iris material.

At the end of the experiment, the breakdown rate as a function of gradient was measured for pulse lengths of 50 ns and 100 ns. The data are shown in Figure 6 together with power-law fits. Each data point was derived from about 12 hours of operation. The inverse of the fitted slopes are 10.6 MV/m per decade for the 50 ns data and 6.1 MV/m per decade for the 100 ns data. For NLC/GLC copper structures, a typical inverse slope was 8 MV/m per decade, independent of pulse length [3].

No evidence of significant damage to the structure from the conditioning was found. The checks were made by monitoring the phase of the reflected rf signal during breakdown measurements and by doing cold testing at SLAC. In addition, bead-pull and dimensional measurements have been done at CERN. Therefore the breakdowns did not cause significant erosion of the iris material as has been observed in copper structures near their gradient limits. Typical processing

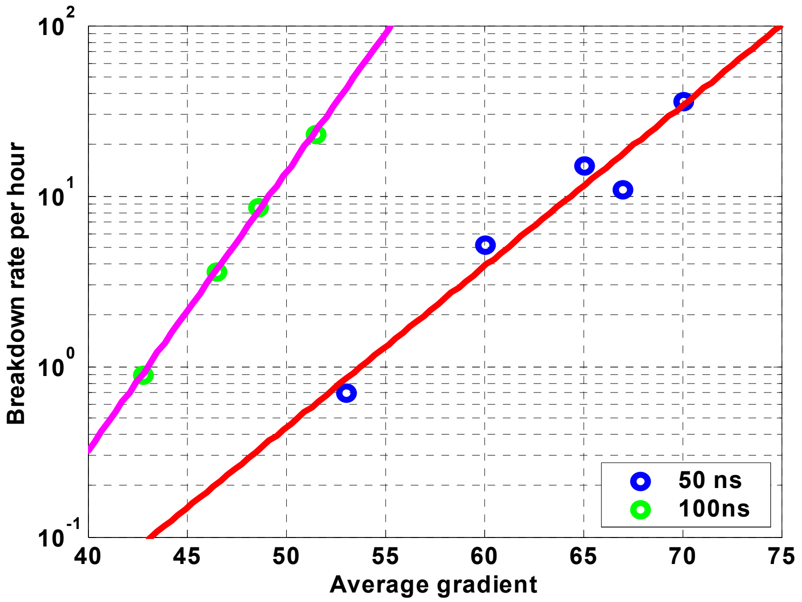

Figure 6. Breakdown rate as a function of gradient for 50 ns and 100 ns pulses. The inverse of the fitted slopes are 10.6 and 6.1 MV/m per decade, respectively.

results for the copper NLC/GLC- structures can be found in reference [4].

DISCUSSION

The structure conditioned extremely slowly compared with the NLC/GLC copper structures. After 700 hr, the 30 cm structure reached only 65 MV/m in the first cell with a pulse length of 100 ns. For comparison, typical NLC/GLC 60 cm long copper structures reached 75 MV/m with 100 ns pulses after about 5 hours, and reached 70 MV/m with 400 ns pulses after about 30 hours.

From the examination of the Mo iris surfaces at CERN, it was found that only the first few irises showed signs of melting and the melted regions were fairly small (see Figure 7). In contrast, the first few irises in the 30 GHz structure showed much more extensive melting, indicating that the gradients achieved at CERN are likely close to the material limits. Thus the conditioning limit for the X-band structure was probably not reached. The CERN group believes that conditioning depends on number of breakdowns per unit surface area [5]. With this metric, the 11 GHz Mo structure was far from conditioned as it experienced the equivalent of 15 thousand breakdowns (~100,000 divided by $(30/11.4)^2$) compared to 500 thousand in the 30 GHz Mo structure (note that the power to the structure at CERN was not shut-off after a breakdown, which allowed much higher breakdown rates during processing: this was not possible at NLCTA with longer pulses due to the pressure build-up that would occur from breakdown induced out-gassing).

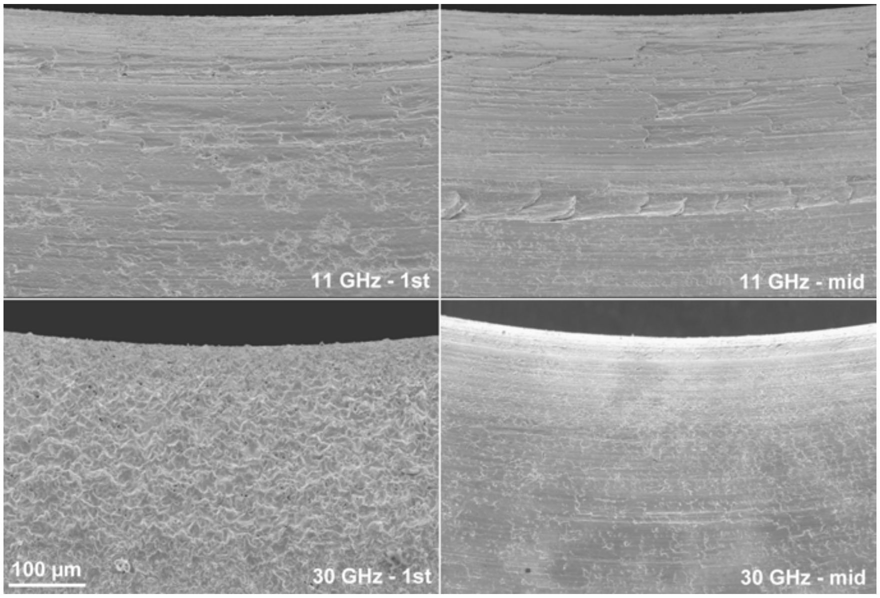

Figure 7. SEM photos of high electric field regions on the molybdenum irises after the test. The same magnification is used in all photographs. Images of the first and middle cells are shown, and for comparison, the same cells from the 30 GHz structure test. The relative degree of conditioning can be seen from the difference in the melting on the first cell iris.

Since the average power was much higher during this test than in the previous ones at 30 GHz, the molybdenum-to-copper joints were inspected after the test. With the exception of a few regions, nothing suspicious was found so these contact areas were not likely the cause of the slow conditioning. A general inspection also found that the surface finish of the 11 GHz molybdenum irises was rougher than that in the 30 GHz structure despite the fact that the same material and manufacturer were used.

Unfortunately it was not possible to measure the short pulse performance of the structure to see if it matches the 30 GHz data, as it does reasonably well in the Cu case (see Figure 5). Note however that DC experiments showed a superior voltage hold-off for molybdenum compared to copper [6,7].

Finally, it should be noted that the performance measured in one test is not always indicative of the typical result. For example, several NLC/GLC copper structures have preformed much worse than average for reasons that have not been understood. Clearly more tests of accelerator structures made with refractory metals should be done. SLAC plans to do experiments with single cells made of such materials and CERN has provided another X-band structure, this time with tungsten irises, that will be tested at NLCTA in the near future. The 30 GHz structure program at CERN will continue tests of molybdenum and tungsten structures when the new CTF3 power source is complete in 2005. This source will have a longer pulse length capability so more direct comparisons can be made with the X-band results. Another goal of the CERN program is to improve the quality of the structure materials and their surface preparation techniques and to optimize the conditioning strategy.

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