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# A HIGH-POWER TEST OF AN X-BAND MOLYBDENUM-IRIS STRUCTURE

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*Abstract*

In order to achieve accelerating gradients above 150 MV/m, alternative materials to copper are being investigated by the CLIC study. The potential of refractory metals has already been demonstrated in tests in which a tungsten-iris and a molybdenum-iris structure reached 150 and 193 MV/m respectively (30 GHz and a pulse length of 15 ns). In order to extend the investigation to the pulse lengths required for a linear collider, a molybdenum-iris structure scaled to X-band was tested at the Next Linear Collider Test Accelerator (NLCTA). The structure conditioned to only 65 MV/m (100 ns pulse length) in the available testing time and much more slowly than is typical of a copper structure. However the structure showed no sign of saturation and a microscopic inspection of the rf surfaces corroborated that the structure was still at an early stage of conditioning. The X-band and 30 GHz results are compared and what has been learned about material quality, surface preparation and conditioning strategy is discussed.

## INTRODUCTION

The CLIC accelerating gradient specification is 150 MV/m, indisputably high, and a substantial development program is underway to achieve it [1]. One aspect of the program is an rf design study with the objective to design and optimize structures within experimentally determined high-power rf and simulated beam-dynamics constraints [2]. Another aspect is an experimental study which seeks to find alternative materials to copper which are able both to sustain a higher surface electric field and to resist damage during breakdown. A significant success of this experimental study has been the demonstration in CTF2 of a 193 MV/m, 15 ns peak accelerating gradient in a molybdenum iris structure [3].

The logical next step is to repeat the test at a longer pulse length since the CLIC design pulse length is 150 ns. However 30 GHz power will only become available for testing (in CTF3) at the end of 2004. In order make the test as soon as possible and to utilize the highly-developed NLCTA test area, an agreement was made to test a CERN-built molybdenum iris structure scaled to 11 GHz at the NLCTA at SLAC.

## THE STRUCTURE AND INSTALLATION

The 11 GHz structure geometry was exactly scaled from the 30 GHz test in order to be able to make as direct a comparison to the previous test and also to provide frequency scaling of gradient data. The structure characteristics are summarized in table 1. The same mode-launcher coupler was used as in the 30 GHz test with only slight dimensional changes to match to WR-90 rather than WR-28 waveguide.

In addition, the irises were manufactured from the same 99.95% purity sintered and forged molybdenum bar produced by the same supplier as those of the 30 GHz test. Finally the method of assembly by clamping, a cell and iris are shown in fig.1, was maintained to keep to a minimum the number of differences between the structures.

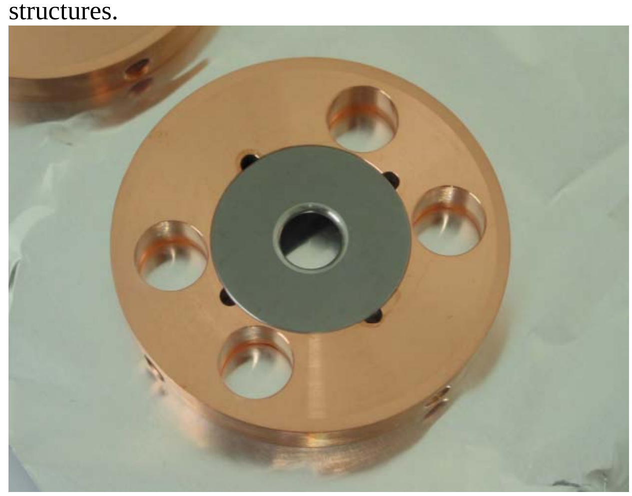

Figure 1: A molybdenum iris mounted in the copper disk which forms the cell.

Table 1: Structure Specifications

| | |
|---|---|
| Frequency | 11.424 GHz |
| Number of cells | 30+2 matching cells |
| Phase advance | 2π/3 |
| Beam aperture | 9.19 mm (constant) |
| Group velocity, $v_g/c$ | 4.6 % |
| Fill time | 20 ns |
| $E_{surface}/E_{accelerating}$ | 2.2 |
| Power for $E_{accelerating}$=100 MV/m | 175 MW |

The structure was assembled and installed in a dedicated vacuum tank at CERN and shipped to SLAC under vacuum. However the structure arrived vented and was therefore purged with hot (100$^o$C) nitrogen for 72 hours in an attempt to reduce the water content in the rest gas. The structure vacuum level was measured by a gauge mounted directly on the tank and operated with a static pressure of the order of $10^{-8}$ mbar.

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## CONDITIONING

The high power test was performed using a single 50 MW klystron and a SLED II pulse compression system delivering a maximum of 140 MW X-band power to the structure at a pulse length of up to 240 ns. Directional couplers in the input and output waveguide were used to monitor the relevant rf power signals.

The structure was conditioned using the standard NLCTA automated processing loop. The primary pulse-to-pulse interlock on rf was a user-defined percentage of missing forward energy (integrated incident power minus transmitted power). In addition, structure vacuum and reflected power interlocks were used to protect the klystron output windows. The missing energy trip level, which is normally set to 10% for (copper) NLC structures, was set for most of this experiment to about 50%.

The conditioning was started using a pulse length of 30 ns. The conditioning curve, accelerating gradient in the first cell as a function of testing time, for the entire test is shown in fig. 2. Progress was initially limited by heavy vacuum out-gassing and the structure processed slowly to about 70 MV/m (first cell). Progress was then limited by rf breakdown. Initially most breakdowns were 'soft', missing energy below 15%, but towards the end of the processing the more typical 'hard', missing energy above 50%, breakdowns dominated.

The pulse length was changed a number of times during conditioning, which produced the abrupt changes in gradient that appear in the conditioning curve. The reasons it was changed were to investigate the behaviour near the CLIC nominal pulse length, to try to optimize conditioning speed and in order to compare directly to the 16 ns data at 30 GHz. The klystron/pulse compressor power limit of roughly 140 MW, producing 85 MV/m in the first cell, was reached for pulse lengths of 16, 25 and 30 ns.

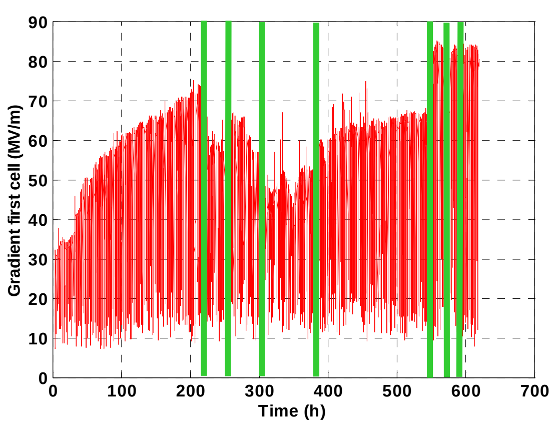


Figure 2: The conditioning curve gradient in the first cell vs processing time. A green vertical line indicates a change in pulse length and the sequence of pulse lengths was: 30, 100, 70, 240,100, 16, 25 and 30 ns.

In addition to the processing, about 100 h of testing time was used to make a number of basic high power rf measurements. More details on these measurements can be found in [4]. The dependence of breakdown rate on gradient and pulse length was similar to that observed in copper X-band structures [5]. The dependence of gradient on pulse length was $\tau^{-(1/6)}$ and thus very similar to that measured with copper structures. A Fowler-Nordheim field enhancement factor of $\beta = 30$ was measured.

The locations of breakdown in the structure were determined by timing measurements using the transmitted and reflected rf pulses. They were uniformly distributed over the length of the structure with some enhancement in the last five cells or so. The stable gradient did not change when the repetition rate was changed from 60 Hz to 10 Hz, which indicates that the cooling of the structure was sufficient – a concern in a clamped structure.

## COMPARISON TO 30 GHZ AND COPPER RESULTS AND CONCLUSIONS

Although the structure ran to the available power limit for pulse lengths of 30 ns and below, it must be clearly stated that the 65 MV/m achieved for longer pulses in the nearly five week long test was a disappointment. The test has raised the questions: are the 11 GHz results consistent with the 30 GHz test, what new issues does this test highlight and do the results call into question the potential of molybdenum?

Direct comparison of the maximum achievable gradient is impossible because of the power-source limit of the 11 GHz gradient at the 16 ns 30 GHz test pulse length. In addition, the conditioning curve of the 11 GHz structure shows no sign of saturation at longer pulse lengths which indicates that it had not been taken to its ultimate gradient - more evidence follows below.

An obvious difference between the two structures is that the 11 GHz structure conditioned much more slowly with respect to testing time, even allowing for the longer pulse lengths. However since the conditioning was controlled so differently in the two tests, the 11 GHz test was interlocked and the 30 GHz test was not, comparing testing time is arguably not relevant.

One comparison which may be physically relevant is the number of breakdowns per rf surface area that the structures were subject to. This comparison is motivated by the supposition that breakdowns during conditioning improve rf surfaces by removing dirt, oxides, asperities or mechanical stresses. The surface area which individual breakdowns affect is small and not a function of rf frequency and a certain number are needed per unit area to prepare a given type of surface for a specific gradient.

A counterargument can be found by applying this logic to copper and extrapolating NLC results to 30 GHz structures. This implies conditioning within 100 breakdowns, which has not been observed [3]. Still copper and molybdenum may need a very different type of conditioning, and the numbers are considered.

In CTF2 the 30 GHz structure was driven to breakdown on approximately every fourth rf pulse (exact statistics are not available) giving nearly a 1 Hz conditioning pulse rate and resulting in a total of about 500,000 breakdowns. In NLCTA the requirement to protect the driving klystron restricted the rate to about two per minute and resulted in a total of about 100,000 breakdowns. Normalizing by the ratio of surface areas, the 11 GH structure saw an equivalent of 15,000 breakdowns, a very early stage of conditioning from the 30 GHz data.

A microscopic analysis of the irises, shown in fig. 3, corroborates the hypothesis that the 11 GHz structure surface was subject to a much lower number of conditioning breakdowns and consequently that it was conditioned comparatively little. Taken together these two analyses imply that the two tests differed mainly in conditioning procedure – and does not indicate a specific problem with the 11 GHz structure nor a frequency dependence of breakdown.

The images also show that the surface finish of the molybdenum parts was not good and that the 11 GHz structure was the poorer of the two. Substantial progress must be made in improving both the molybdenum bulk and the surface in order to provide a more practical rf material since rf conditioning is bound to be a costly activity for a linear collider – although a more robust material may always be more difficult to condition.

Higher purity and smaller grain molybdenum than the sintered 99.95% purity used in the tests described in this report are being investigated. Both the higher purity and especially the smaller grain size should improve surface finish (and tolerances) which should speed conditioning. The higher purity may also be better with respect to breakdown.

Demonstrating these suppositions with experiments with positive results is a very high priority of the CLIC structure development program. A repeat of the 30 GHz test, but now in CTF3 with longer pulses, will be the next test of molybdenum. The test of a tungsten-iris structure will also be redone.

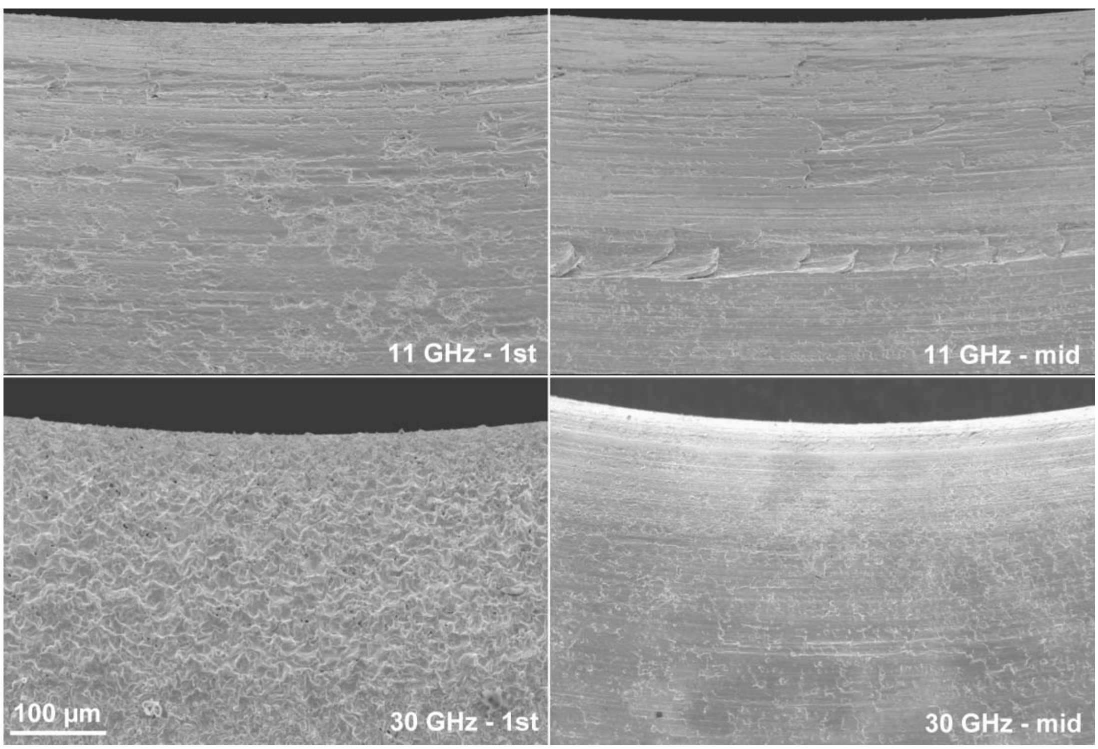


Figure 3: SEM analysis of the high electric field region of the molybdenum irises after test. The same magnification is used for all the photographs. Images of cells from the middle of the structure are shown for reference. The relative difference in conditioning is easily observed from the much higher density of melted spots on the 30 GHz iris.

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