

## A DEMONSTRATION OF HIGH-GRADIENT ACCELERATION

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### Abstract

One priority of the CLIC (Compact Linear Collider) accelerating-structure development program has been to investigate ways to achieve accelerating gradients above 150 MV/m. Two main concepts to achieve such high gradients have emerged: reduced surface field geometries and the use of alternative materials. An experimental demonstration of these two concepts has been made in CTFII (CLIC Test Facility) using three 30 GHz accelerating structures: one made entirely from copper, one with copper cavity walls and tungsten irises and one with copper cavity walls and molybdenum irises. A peak accelerating gradient of over 190 MV/m was achieved using the molybdenum-iris structure. The effect of pulse length on achievable gradient was investigated using a novel 'pulse stretcher'.

### INTRODUCTION

The CLIC linear-collider design envisages the use of the rather high accelerating gradient of 150 MV/m, resulting in an input power of 130 MW to the 30 GHz accelerating structures [1]. Such an accelerating gradient, with the nominal 130 ns CLIC pulse length, has already been demonstrated with two small aperture copper X-band structures [2,3]. However the limiting breakdown gradients achieved in subsequent tests of X-band and 30 GHz structures [4,5] have been much lower. Although the exact reason for the higher performance of the early test structures is not yet clear [6,7], it seems to be related to their very low  $a/\lambda$  ratio of 0.11. One aspect of low  $a/\lambda$  geometries, a low ratio of peak surface field to accelerating gradient, has been used as a design criteria for CLIC accelerating structures [1]. The reduction of  $a/\lambda$  is however limited by short range wakefields, which grow cubically as the beam aperture becomes smaller, leading to unacceptable beam emittance growth.

The use of alternative materials to copper is consequently under investigation by the CLIC study as an additional way of obtaining very high accelerating gradients. Desirable characteristics of a candidate material include the ability to support a high surface electric field before breaking down, to resist damage from the arc that occurs once the breakdown has begun, and high electrical conductivity. Three refractory metals, tungsten, molybdenum and rhodium, are clear potential candidates and are used in low frequency (DC-50/60 Hz), high power and high voltage applications. Initial high gradient 30 GHz rf tests with tungsten yielded extremely encouraging results [8].

This report describes recent results of a systematic investigation of the relative high-gradient rf performances

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of copper, tungsten and molybdenum obtained from tests of structures with a common rf design that were tested using a standardized conditioning procedure. The structures are shown in Fig. 1.

The materials investigation was carried out in CTFII using 15 ns pulses, which are produced using the longest possible drive bunch train. In order to also investigate pulse length dependence a special rf pulse stretcher was designed and fabricated. This allowed the test of the copper structure with a 30 ns pulse and to address the issue of pulse length dependence of rf breakdown



Figure 1: The copper, tungsten iris and molybdenum iris accelerating structures (10 cm active length).

### THE STRUCTURES

The structure characteristics and fabrication techniques were chosen to provide, within the final year of CTFII operation, as direct a comparison between the high-gradient properties of copper, tungsten and molybdenum as possible. Structure parameters are summarized in Table 1. All the structures had identical clamped-on 'mode launcher' couplers [9] which have a peak surface field at least 20% lower than anywhere in the disk-loaded-waveguide part of the structure. In this way couplers are expected neither to limit nor complicate the tests.

The body of the copper structure was vacuum brazed while the tungsten and molybdenum structures were entirely clamped. The configuration of the clamping can be found in [8]. The copper structure was cleaned before brazing using the CERN standard chemical procedure. The tungsten irises were only degreased. The molybdenum irises were also vacuum fired at 800 °C before assembly. This was motivated by the observation of substantial degassing of the tungsten structure during conditioning. All three structures were tested in a vacuum can for best vacuum and minimum experimental turn-

around time. None of structures were in-situ baked, due to lack of time.

Table 1: Structure parameters. The bottom two values are for the cell geometry, i.e. are local values.

Frequency	29.984 GHz
Number of cells	30+2 matching cells
Phase advance	$2\pi/3$
Beam aperture	3.5 mm (constant)
Group velocity, $v_g/c$	4.6 %
Fill time	8.3 ns
$E_{\text{surface}}/E_{\text{accelerating}}$	2.2
Power for $E_{\text{accelerating}}=150$ MV/m	56 MW

### MATERIAL INVESTIGATION

The structures were conditioned with 15 ns rf pulses and a repetition rate of 5 Hz by maintaining a nearly continuous, but controlled, level of breakdown. Breakdowns were identified using emitted current bursts, vacuum activity and missing rf energy. Periodically a measurement was made of the operating gradient and the results obtained are plotted in Fig. 2. These results show a clear influence of material on achievable accelerating gradient, with a substantial gain in gradient for the refractory metals. The final field values are summarized in Table 2. It should be noted that the tungsten-iris and molybdenum-iris tests were both stopped due to lack of testing time.

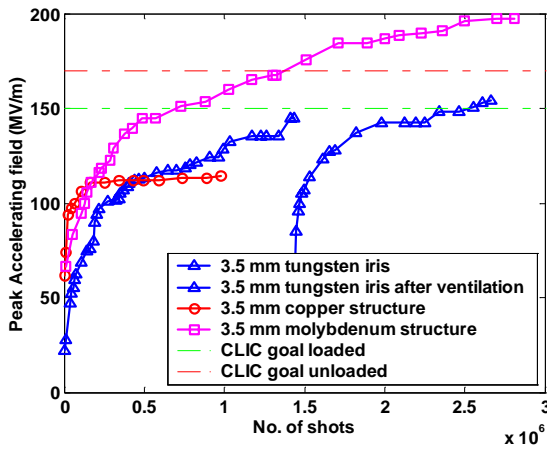


Figure 2: Conditioning history of the three structures.

Table 2: Final gradient values in MV/m.

Structure	Peak accelerating	Average accelerating	Peak surface
Copper	110	100	260
Tungsten	150	125	340
Molybdenum	193	153	426

A roughened surface and a slight erosion of material was observed, using an endoscope, in the copper structure on the surfaces with the highest electric field, which are located on the first irises of the copper structure. The tungsten and molybdenum structures were unbolted after the tests and were inspected by eye and electron microscope (SEM). SEM images show surface melting in the iris tips in the first few cells in both structures. Sub-micron cracks can be distinguished in the junction between melting regions, which are themselves about 10 microns in size. However, no erosion has taken place to a level that affects the rf characteristics of the structure. This has been confirmed by a comparison of rf measurements made before and after the tests. Further inspections are underway.

Evidence of arcing in some of the clamped cell to iris contacts was observed in the tungsten structure. This appeared as spots of roughened surface on the copper disk and corresponding plated copper spots on the tungsten iris. More care was taken to ensure an adequate contact pressure when assembling the molybdenum structure, and no traces of contact arcing was observed in it after testing.

It should be stressed that the ultimate and relative high gradient performances of tungsten and molybdenum may not have been determined yet because: neither the tungsten nor the molybdenum tests were taken to the point where the conditioning curves showed a clear saturation, there is evidence of contact arcing in the tungsten structure and only the molybdenum irises where vacuum fired.

The transition from stable to unstable operation was also investigated during the tests. Breakdown rate has been clearly identified as an important issue for a linear collider with many thousands of accelerating structures [10]. The transition from stable to unstable operation is remarkably smooth as illustrated in Fig. 3. For the conditioning curves shown in Fig. 2, a gradient of 130 MV/m would be quoted for this data. A gradient stable enough for a linear collider would need to be distinctly lower.

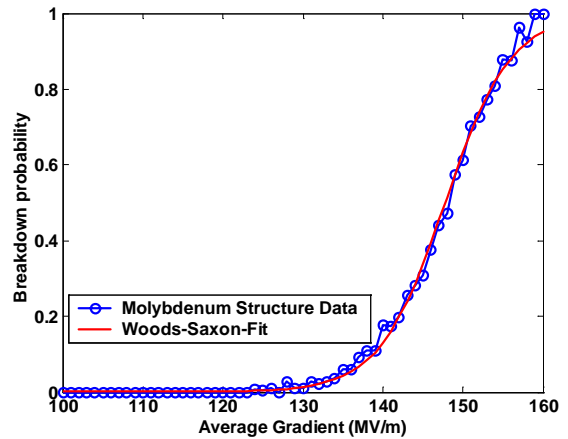


Figure 3: Breakdown probability as a function of gradient for the partially conditioned molybdenum structure.

## PULSE-LENGTH DEPENDANCE

Although the high-gradient values described in the previous section are very encouraging, it should be stressed that the gradients were achieved with 15 ns pulses, while the CLIC nominal pulse length is 130 ns. The pulse length dependence of rf breakdown, and its origin, remains an open question. Achievable gradient is generally assumed to decrease with increasing pulse length. The 15 ns pulse length is fixed by the maximum electron bunch train length that CTFII can produce. In order to investigate pulse length, a novel rf ‘pulse stretcher’, which doubles the pulse length, was built [11]. The rf pulse produced by the stretcher in CTFII is shown in Fig. 4.

The stretcher was only used to condition the copper structure because the tungsten and molybdenum structures would have required more power than CTFII could deliver. The structure was conditioned with an additional one million 30 ns pulses after the initial one million 15 ns pulses. The encouraging result was that the same 120 MV/m gradient was achieved with both pulse lengths. The achievable gradient was also measured for 4 and 8 ns, to probe the turn-on time of an rf arc. The pulse length results are summarized in Fig. 5

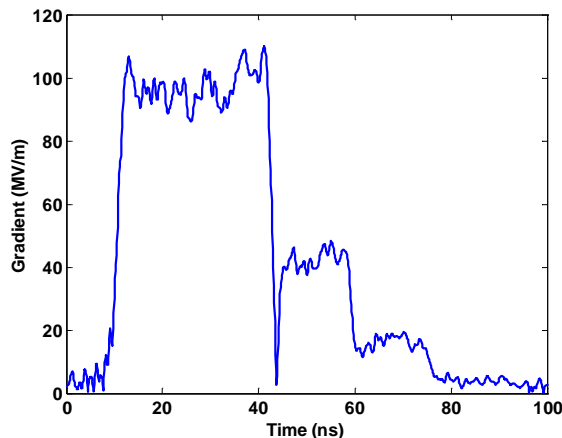


Figure 4: Rf pulse from stretcher.

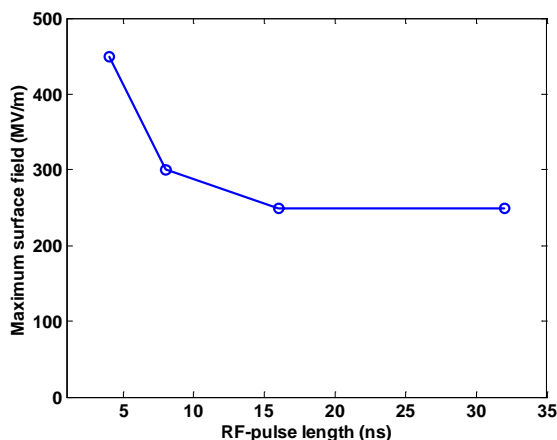


Figure 5: Pulse length dependence of the copper structure.

## CONCLUSIONS

These tests have established that refractory metals can substantially increase the rf-breakdown limit in accelerating structures. Of course a consequence is that new structure fabrication techniques are required, but these test structures already represent a first step towards development of these techniques. Judging from the state of surfaces after conditioning, only the tips of the irises, where the surface electric field is highest, need to be made from new materials. In this case, composite accelerating structures would only be slightly less efficient than all-copper structures. The need to fabricate composite structure may also be motivated by pulsed surface heating, which may also require new materials. Although the highest gradient at which 30 GHz structures can run reliably at the full CLIC 130 ns pulse length has not yet been determined, a path with substantial potential has been identified.

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