Status of studies and tests on the CLIC high-gradient accelerating structures

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Abstract

This document aims at giving the status at mid-2006 of some studies and tests on the CLIC high-gradient accelerating structures, by gathering together the content of two papers which have been published in the 2006 European Particle Accelerator Conference, in Edinburgh. This summary concerns the study carried out on the fatigue data for copper alloys in the particular stress pattern present in RF cavities on the one side, and on the RF tests made at 11.4 and 30 GHz with identical-geometry structures of different materials on the other side. Both efforts tend to find ways to reach the high accelerating gradients desirable for the future multi-TeV e+e- Compact Linear Collider (CLIC).

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STATUS OF THE FATIGUE STUDIES ON THE CLIC ACCELERATING STRUCTURES

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Abstract

The need for high accelerating gradients for the future multi-TeV e+e- Compact Linear Collider (CLIC) imposes considerable constraints on the materials of the accelerating structures. The surfaces exposed to high pulsed RF (Radio Frequency) currents are subject to cyclic thermal stresses which are expected to induce surface break up by fatigue. Since no fatigue data exists in the literature up to very large numbers of cycles and for the particular stress pattern present in RF cavities, a comprehensive study of copper alloys in this parameter range has been initiated. Fatigue data for selected copper alloys in different states are presented.

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Abstract

The need for high accelerating gradients for the future multi-TeV e^+e^- Compact Linear Collider (CLIC) imposes considerable constraints on the materials of the accelerating structures. The surfaces exposed to high pulsed RF (Radio Frequency) currents are subject to cyclic thermal stresses which are expected to induce surface break up by fatigue. Since no fatigue data exists in the literature up to very large numbers of cycles and for the particular stress pattern present in RF cavities, a comprehensive study of copper alloys in this parameter range has been initiated. Fatigue data for selected copper alloys in different states are presented.

INTRODUCTION

The current design of the 30 GHz CLIC accelerating structures is based on the HDS-type (Hybrid Damped Structure) geometry. The instantaneous surface temperature rise in the outer wall of the cavities due to 68 ns long RF pulses is 56ºC for Copper Zirconium (C15000) alloy [1]. This sudden anisotropic temperature profile corresponds to 155 MPa compressive stress. Between the pulses all the heat is rapidly conducted via the bulk leading to stress relaxation and thus to thermal cycling. The fatigue loading is a cyclic compressive stress with stress amplitude of 77.5 MPa and mean stress of -77.5 MPa for C15000 [2]. The design lifetime of CLIC is 20 years and the pulse repetition rate is currently fixed to 150 Hz, which result in a total number of thermal cycles of $7*10^{10}$.

The experiments under way in order to qualify the material resistance to this stress pattern are based on high frequency ultrasonic excitation to study the bulk fatigue behaviour at the high cycle regime and pulsed laser irradiation to simulate the thermal surface fatigue phenomena at low cycle regime. A complete RF fatigue experiment of CLIC parameters is very expensive and time consuming to proceed. Only few low cycle RF experiments are foreseen to cross check the results of the other experiments.

In order to simulate the total CLIC lifetime it is important to find the connectivity between data of the high cycle and the low cycle experiments. The specimens for the different experiments are produced from same materials and go through the same manufacturing processes.

Materials and preparation

The induced thermal stress in the CLIC parameter range is inversely proportional to the electrical and thermal conductivities of the cavity material. High electrical conductivity is also important for the overall efficiency requirement of the CLIC machine, and a good fatigue performance is of course required. The candidate materials for the fatigue experiments have thus been selected from the group of high conductivity, high strength copper alloys, which are presented in Table 1 [2]. The state of the material plays a significant role on its mechanical properties, so a number of techniques to prepare the material have been investigated.

Table 1: Candidate alloys

Alloy	UNS C	Electrical conductivity [%IACS]	Cold-Working Ratio [%]
CuZr	C15000	93	40
CuCrZr	C18150	75	20
Cu-OFE	C10100	101	30
GlidCop® Al-15	C15715	90	0

Peening of the metallic material's surface is known to improve its fatigue strength [3]. It introduces a compressive residual stress over a thin surface layer which blocks the opening of cracks and it also work hardens the surface layer to be mechanically stronger. In the CLIC RF-cavities the critical area for the fatigue is a 10 μm deep surface layer affected by the pulsed heating due to the surface magnetic fields. Different peening methods are considered to be interesting for the CLIC fatigue studies and here classical shot peening and new cavitation shot-less peening [4] techniques have been studied.

TEST SET-UPS

High cycle fatigue data, of up to $7*10^{10}$ cycles, at various stress ratios have been collected in high frequency bulk fatigue tests using two commercial ultrasonic generators, which operate at 24 kHz. In this way the CLIC lifetime can be simulated in 30 days. The method has been presented in detail in references [2] and [5].

By default the loading condition in ultrasonic testing is fully reversed tension-compression with zero mean stress. In the cavities the thermal cycling causes fully compressive loading. Only few fatigue data exist in the literature for compressive mean stresses, whose effect for copper alloys at high number of cycles is not well known. To study this issue a special pre-compressed test specimen has been designed.

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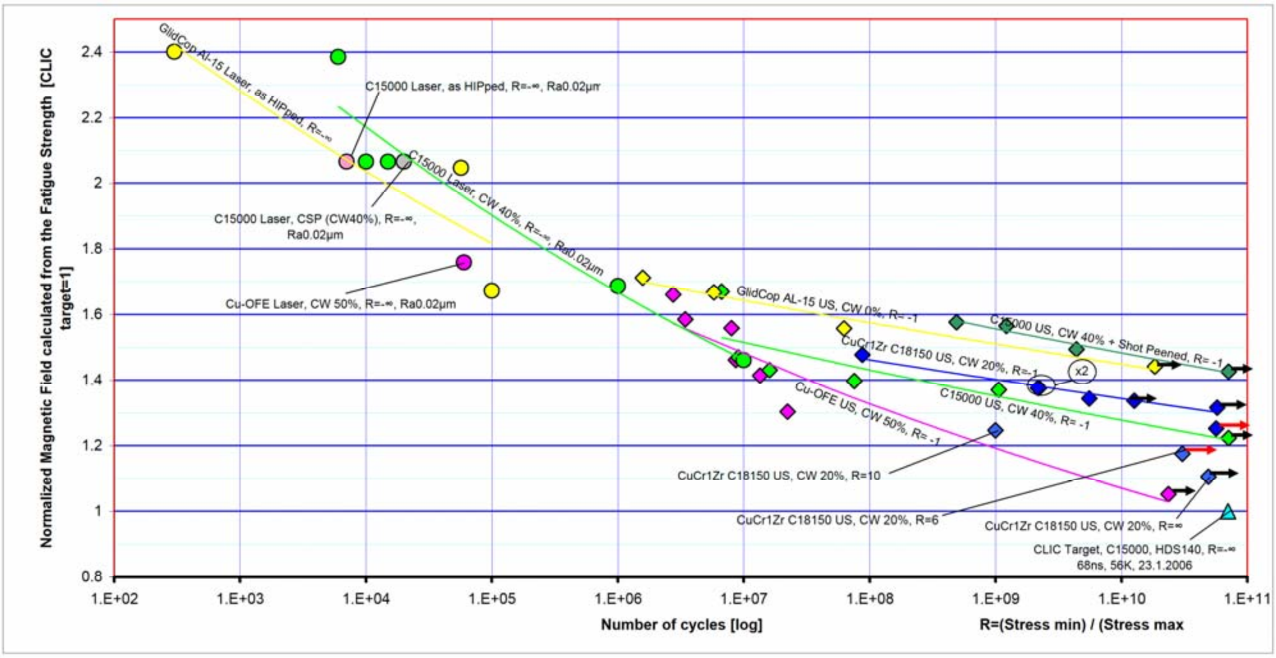

Figure 1: The fatigue data collected by the Ultrasonic- and Laser techniques. For ultrasound a data point is given by the number of cycles up to fracture and for laser it is up to an induced surface roughness Ra of 0.02 μm. Incomplete ongoing experiments without a fracture are marked with an arrow. The y-axis values represent the corresponding magnetic field on the surface based on the applied stress amplitude. In this way the mechanical stress amplitude is converted to surface magnetic field on a RF cavity's surface, which is then normalized to CLIC target value. The Circles are data points for Laser fatigue experiment and the diamonds are data points for Ultrasonic fatigue experiment. The triangle is the current CLIC target value based on the HDS140 accelerating structure design. The solid lines are fitted curves for the data points of the same colour and shape. The R parameter indicated close to the data points is equal to (Stress min)/ (Stress max). R=-1 corresponds to fully alternating stress condition and R=∞ corresponds to fully compressive stress condition.

Low to medium cycle fatigue data (up to 10^7 cycles) of fully compressive cyclic surface thermal stress has been collected by means of a pulsed UV laser surface heating apparatus. The surface damage has been characterized by SEM observations and roughness measurements. The method has been presented in detail in reference [6].

EXPERIMENTAL RESULTS

Ultrasonic testing

US fatigue experiments up to high cycle regime have been made for all the candidate alloys: the results are presented in Figure 1. The data for commercially pure copper, Cu-OFE C10100, is not complete yet, but the early stage results show that the CLIC target value cannot be achieved with a proper safety margin. CuZr C15000, CuCrZr C18150 and shot peened CuZr C15000 reached the CLIC lifetime without crack initiation with the safety margins of 22%, 32% and 43% respectively. However these specimens did experience some unexpected fatigue effects. A significant development of surface roughness was observed on the surface at the point of maximum stress amplitude at a number of cycles of about $3*10^{10}$-$5*10^{10}$. This is probably due to the Persistent Slip Band movement under cyclic loading. The irreversibility of shear displacements along the slip bands results in the 'roughening' of the surface where the persistent slip bands emerge from the surface causing intrusions and extrusions [6]. Unlike in the US tests, the RF induced stress in the CLIC accelerating cavities increases with the surface roughness. So the phenomenon of surface roughening under cyclic deformation is probably unacceptable for CLIC. To study this in more detail lower stress amplitude experiments need to be performed in order to find the thresholds for the surface roughness development.

The GlidCop® specimens show a high fatigue strength especially in the soft, non-cold worked, state. GlidCop®'s clear advantage is that its strength does not decrease dramatically when reducing the cold-working ratio. However its fracture toughness is lower than for the other alloys. It was observed that after the crack was initiated, the crack development behaviour is faster in GlidCop®, while for the others it has more stable behaviour. The crack propagation speed was measured to be an order of magnitude higher for GlidCop® than for CuCrZr. The ITER R&D programme reported similar observations when they studied the physical and mechanical properties of copper alloys. For this reason GlidCop® was rejected as a candidate material for components of ITER [7].

The early stage of US experiments with pre-stressed specimens show that the mean stress has an effect on fatigue strength. A highly pre-stressed CuCrZr specimen cracked at significantly lower stress amplitude than a specimen with a fully alternating stress. Pre-stressing is likely to limit the acceptable cyclic stress amplitude because the yield strength of a material is approached with lower stress amplitudes than under fully alternating loading conditions. This is an important issue for the CLIC RF cavities where the loading is fully compressive. On the other hand tensile mean stresses are known to decrease the fatigue strength of a material [6].

Classical shot-peening was studied as a surface hardening method. On 40% cold worked CuZr specimens shot peening increased significantly the fatigue strength. The surface quality after shot peening is not acceptable for the CLIC RF cavities, but a possible solution could be a re-machined shot peened surface.

Laser testing

It is expected that as soon as fatigue damage appears in RF, it leads to increased surface resistance and thus surface heating resulting very rapidly in a catastrophic effect. It seems thus logical to set the fatigue damage threshold at the first appearance of surface break-up. Laser testing was carried out on diamond machined specimens, having a surface roughness R_a of 10 nm (close to the sensitivity limit of the measuring device). The criterion for identifying the first fatigue damage induced by laser irradiation, i.e. deviation from flatness, is $R_a = 20$ nm. All data are reported in Figure 1. It is worth commenting that, for a given stress level, surface break-up appears first for C15000 in its softest state (HIP-treated), followed by 40% cold worked specimens and then by cavitation shot-less peened ones, with GlidCop® showing damage at the larger number of cycles. However upon further irradiation the roughness increases at a rate which ranks the materials in exactly the opposite order. This is in agreement with what was mentioned in the previous section.

Connectivity between the methods

From the data it is clear that surface fatigue thresholds, identified as when surface damage starts to appear in the laser experiments, and fatigue cracks appear in the bulk specimen, happen at similar stress levels for similar numbers of cycles [2]. This allows the two experimental techniques to be connected and to predict the surface damage at a high number of cycles. Fit to the data with the classic Woehler formula $\sigma=N^{-b}$ [3] where $N=Log_{10}$ (*number of cycles*) gives a similar exponent in both tests, with an average value, for example, for C15000 40% cold worked of $b = 1.2 \pm 0.1$.

CONCLUSIONS AND PERSPECTIVES

GlidCop® and Shot-Peened C15000 have given the best results so far. Compared with the CLIC design value they show that the current CLIC parameters could be achieved with existing materials with a reasonable safety margin, however more studies are needed for the final conclusion. In the CLIC RF cavities the fracture toughness is probably not as critical as the crack initiation fatigue, because a small crack already causes a rapid failure of the structure. The GlidCop®'s fatigue experiments were interrupted due to parallel studies, aimed at assessing its resistance to electrical breakdown when exposed to high electric fields, of prime importance in the CLIC machine.

The manufacturing process of the CLIC accelerating cavities is not defined yet, so the final material state is still unknown. For this reason in the fatigue studies the whole range from annealed soft state to highly cold worked hard state plus the surface hardened alloys have to be taken into account. High cycle surface roughening is a critical issue and needs more studies. An RF fatigue experiment is under way.

Further pre-stressed US experiments are foreseen to study the effect of stress ratio in more detail. An experiment is under way to test whether the re-machining affects the fatigue performance achieved by shot peening. Different peening techniques are also foreseen in the test program.

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A HIGH-GRADIENT TEST OF A 30 GHZ MOLYBDENUM-IRIS STRUCTURE

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Abstract

The CLIC study is actively investigating a number of different materials in an effort to find ways to increase achievable accelerating gradient. So far a series of rf tests have been made with a set of identical-geometry structures: a W-iris 30 GHz structure, a Mo-iris 30 GHz structure (with pulses as long as 16 ns) and a scaled Mo-iris X-band structure. A second Mo-iris 30 GHz structure of the same geometry has now been tested in CTF3 with pulse lengths up to 350 ns. The structure was conditioned to a gradient of 140 MV/m with a 70 ns pulse length and a breakdown rate slope of 13 MV/m per decade has been measured.

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INTRODUCTION

The CLIC study has been investigating a number of different materials through both rf and dc-spark tests as part of an effort to determine if alternative material to copper can be found which will allow higher accelerating gradients [1, 2]. An initial part of this study was to test a series of identical-geometry 30 GHz structures with Cu, W and Mo irises in CTF2, but limited to 16 ns pulse length [1], and identical-geometry but scaled 11 GHz structures with W and Mo irises at NLCTA [4]. The 30 GHz Mo-iris test has now been repeated with a new but identical structure in the new test stand at CTF3 [3], which has allowed testing to pulse lengths up to and beyond the current CLIC pulse length of 70 ns. Details of the Mo test structure (fig. 1), its design, rf parameters and fabrication method can be found in [1].

Figure 1: 30 GHz Molybdenum-iris structure.

EXPERIMENTAL SETUP

The 30 GHz RF power used to test the molybdenum-iris structure is produced in CTF3. An electron beam (typically ~ 100 MeV and ~ 5 A) is decelerated using a Power Extracting and Transfer Structure (PETS). Part of the kinetic energy of the beam is transformed into 30 GHz RF power [3]. The RF power is transported using a low loss transfer line to a contiguous building which hosts the structure test stand.

Fig. 2 shows a picture of the test stand including the most relevant diagnostics elements. The rf power coming from the PETS is feed to the accelerating structure after going through a first measurement directional coupler, a variable power splitter and a second directional coupler. The power transmitted though the structure is dissipated in a water cooled load after going though a third directional coupler.

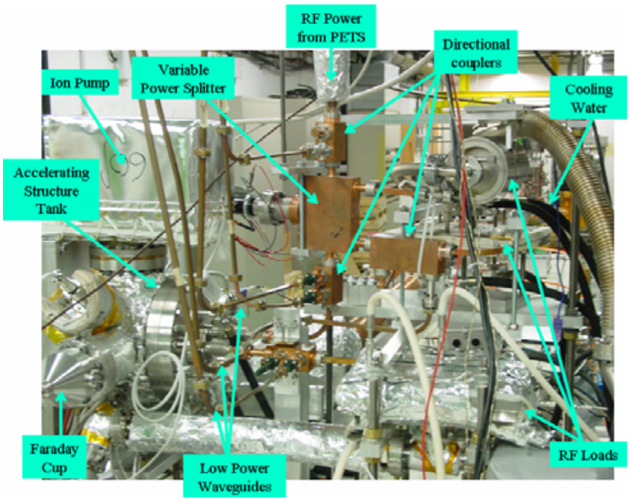

Figure 2: Structure test stand.

Signals picked up by these couplers are down-mixed and digitized. The first coupler is used to measure the power available to test the structure. The percentage of the available power used to test the structure is changed by moving the stepper motor that controls the variable power splitter and it is measured using the second coupler. This coupler is also used to measure the reflected power from the structure while the third is used to measure the transmitted power.

The other important diagnostic elements of the test stand are the Faraday cups located up and down stream of the molybdenum-iris structure. These Faraday cups collect the electron current that makes it through the irises of the structure when a breakdown occurs. That current together with the measured reflected power and the transmitted power (or lack of transmitted power) was used to determine whether or not the structure was able to hold the gradient produced by the rf pulse.

There are also several vacuum gauges distributed along the system including one in the tank that hosts the PETS and another one in the tank of the accelerating structure.

The characteristics of the rf pulses can be reproduced using the digitized signals picked up with the different directional couplers. The calibrations of the lines were performed before and after the experiments were carried out.

EXPERIMENTAL RESULTS

Conditioning of the structure

The conditioning history of the structure is shown in fig. 3. The data is plotted as a function of time rather than the number of rf pulses to include periods when rf pulsing was interrupted to allow the system to pump back down after a breakdown. This is an important distinction especially in the early stages of conditioning molybdenum when a significant amount of gas is released during breakdown. Dead times caused by external factors like maintenance and shutdowns of CTF3 have been removed from the data. The structure was conditioned with an rf repetition rate of 10 Hz.

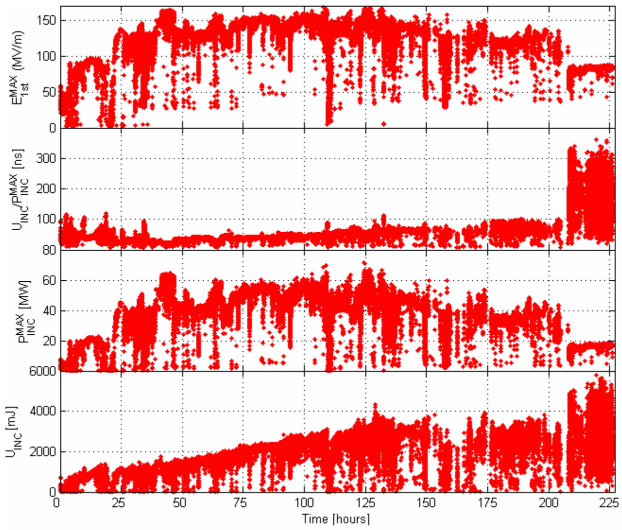

Figure 3: Conditioning history of the structure. From top to bottom are: peak accelerating gradient in the first cell, pulse length (computed as the pulse energy divided by the incident peak power), peak incident power and pulse energy.

The conditioning data shows that the energy of the pulses that the structure was able to hold increased steadily during the first 125-150 hours of conditioning, during which the pulse lengths were kept shorter than 100 ns. The structure conditioning was only interlocked on vacuum level, otherwise it was allowed to break down repeatedly. Despite this rather aggressive conditioning strategy, Mo was again observed to condition very slowly [2, 4].

The highest gradient / pulse length combination which was achieved was 140 MV/m and 70 ns. For this value, the gradient is defined as the average gradient over the 70 ns pulse length. As a consequence the value is lower than the peak gradient which is plotted in fig. 3.

The long-pulse running during the last 20 hours of the test were made to investigate the performance of the entire rf system [3]. During that time the breakdowns occurred more in the PETS and high-power transfer line than in the molybdenum-iris structure itself but the data is included for completeness.

The input power versus pulse length for the entirety of stable rf pulses observed during the conditioning process is plotted in fig. 4. The best point reached in CTF2 with the Mo structure is shown as an orange star, 93 MW and 16 ns. The three lines show plausible pulse length dependencies: constant pulse energy, constant peak power times square root pulse length and constant peak power times cube root pulse length. All three dependencies show that the most recent test achieved as high or higher performance than that performed in CTF2 [1].

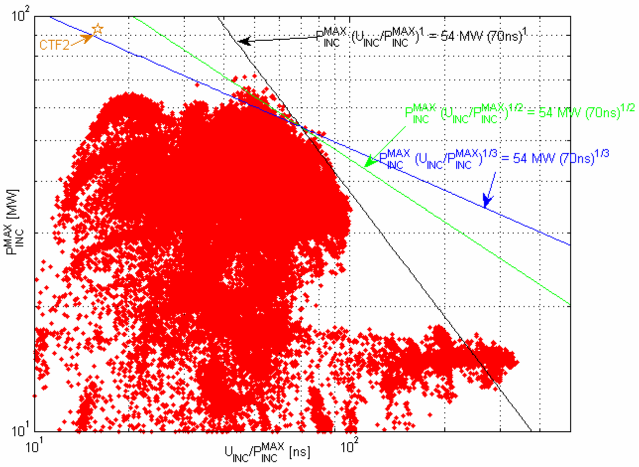

Figure 4: Peak power vs. pulse length. The red points were reached with the structure. The available power limited the achievable gradient for short pulses (<60 ns). Breakdowns in the PETS and the transmission line limited the achievable pulse length for low gradient. The region where the limit in achievable gradient was due to the molybdenum structure itself was between 60 and 100 ns.

Breakdown Rate

The gradients quoted in the previous sections are all for the conditioning limit of the structure, i.e. the typical value of gradient at which a breakdown occurs when the gradient is raised steadily from a low value. The breakdown probability at the conditioning limit is quite high but becomes lower as the gradient is lowered. The breakdown probability requirement for CLIC structures is not yet determined since it depends on the detailed machine configuration and some unknown parameters (like the transverse kick the main beam would receive when a breakdown occurs). But, since CLIC will contain about 10^5 accelerating structures, it is expected to be of the order of 10^{-6}. In order to help estimate the required gradient back-off from conditioning to stable gradient, the breakdown probability as a function of gradient for different pulse lengths has been measured near the end of the conditioning process, and the data is shown in fig. 5.

The data has been fitted with lines that give constant pulse dependence for all breakdown probabilities – which means that the slopes are inversely proportional to the gradient at a fixed breakdown probability. This same inverse proportionality fits well with data of the X-band Mo-iris structure [4].

The data show that a back-off of about 40% is needed to go from the conditioning gradient to the gradient which gives a breakdown rate of the order of 10^{-6}. The breakdown rate slope appears to be lower by a factor of two than for copper NLC structures [5]. Some possible causes for the lower slope, and consequently larger required back-off, have been identified: the slope is material dependent, the slope is material purity or preparation dependent, the low slope of the Mo iris structure is a consequence of assembly by clamping, or the slope is a consequence of the rather extreme surface state created during conditioning (discussed in the next section). A clear priority for the CLIC high gradient testing program is to determine the origin of this lower slope. A consequence may be that although higher conditioning gradients can be achieved with Mo than with Cu, at low breakdown rates the advantage from Mo may be small or non-existent.

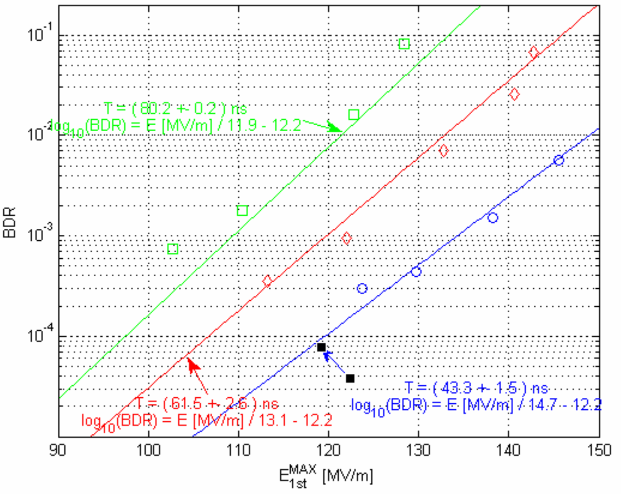

Figure 5: Breakdown probability for different pulse lengths.

Structure Inspection after Conditioning

The irises and cells were systematically inspected at the end of the experiment and scanning electron microscope (SEM) images of the first and last irises of the structure are shown in fig. 6. SEM images of previously tested Mo irises can be found in [4]. The first iris shows dramatic re-melting and a modified surface while the last iris shows re-melting but with little change to its shape.

It is not known when during the tests the surfaces were modified. The surface modification may be due to an excessively aggressive conditioning strategy (which was adopted to speed the slow conditioning of Mo), it may have occurred only during the period when the structure was conditioned and the gradient did not improve or it may o gths.
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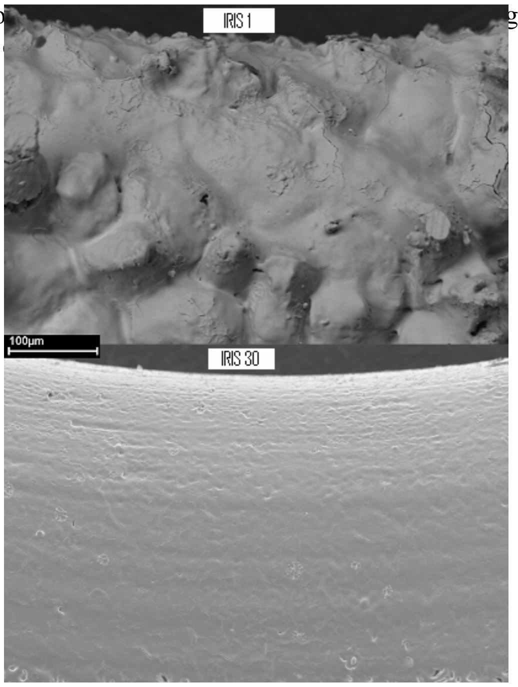

Figure 6: SEM picture of the first and last iris.

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