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# HIGH POWER TESTING OF A PROTOTYPE CLIC STRUCTURE: TD26CC R05 N3

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## Abstract

Testing of high gradient accelerating structure prototypes for the Compact Linear Collider is ongoing at CERN. High power testing of the baseline structure CLIC-G, also known as TD26CC R05, from the most recent concept design review was conducted on CERN's second X-band test stand, Xbox 2. Several months of conditioning resulted in an ultimate unloaded gradient of 110 MV/m, the highest achieved for a structure with higher-order mode damping, with a 170ns flat-top RF pulse and operating with a breakdown rate of 2 ×10−5 breakdowns/pulse/metre. Investigations of the breakdown distribution demonstrated homogenous breakdown behaviour throughout the structure when fields were below 110 MV/m. After high power testing, a measurement of the RF parameters of the structure illustrated a significant change in the S-parameters consequential of a detuning of the cells, equating to a 1 MHz shift in the frequency.

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# High Power Testing of a Prototype CLIC structure: TD26CC R05 N3


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Testing of high gradient accelerating structure prototypes for the Compact Linear Collider is ongoing at CERN. High power testing of the baseline structure CLIC-G* , also known as TD26CC R05, from the most recent concept design review was conducted on CERN's second X-band test stand, Xbox 2. Several months of conditioning resulted in an ultimate unloaded gradient of 110 MV/m, the highest achieved for a structure with higher-order mode damping, with a 170 ns flat-top RF pulse and operating with a breakdown rate of $2 \times 10^{-5}$ breakdowns/pulse/metre. Investigations of the breakdown distribution demonstrated homogenous breakdown behaviour throughout the structure when fields were below 110 MV/m. After high power testing, a measurement of the RF parameters of the structure illustrated a significant change in the S-parameters consequential of a detuning of the cells, equating to a 1 MHz shift in the frequency.


## I. INTRODUCTION

High gradient testing of accelerating structures for the Compact Linear Collider (CLIC) is ongoing at CERN's X-band test stands. Current testing involves structures designed around the CLIC-G (3 TeV) design. Three prototypes using the CLIC-G* (TD26CC) design, with internal edge rounding of 0.5 mm (R05), were produced at CERN for the purpose of understanding their high power performance. Below we will review the high power testing of one of these structure demonstrating the achieved unloaded gradient and pulse length, as well as reviewing the RF breakdown behaviour within the structure. Following that we will discuss the RF parameter of the structure after high power testing, investi-


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gating structure RF property changes possibly caused by high power operation.

## II. STRUCTURE OVERVIEW

Submitted as the baseline structure for CLIC 3 TeV design in the most recent Concept Design Report, the TD26CC structure has an operational frequency of 11.994 GHz and a phase advance per cell of $2\pi/3$ [1]. Tapering of the irises offers a constant gradient across the 26 regular cells, once one accounts for beam loading. Two additional coupling cells, designed using the compact coupler design, input the high power RF [2]. Achieving the 100 MV/m loaded gradient requires a peak power of 61.3 MW [1]. For machining purposes the inner edges of these structures' cells are rounded with a regular rounding profile and 0.5 mm diameter. Three iterations of this design were produced at CERN, the structure in question was the third to be produced (N3) and second to be tested at high power.

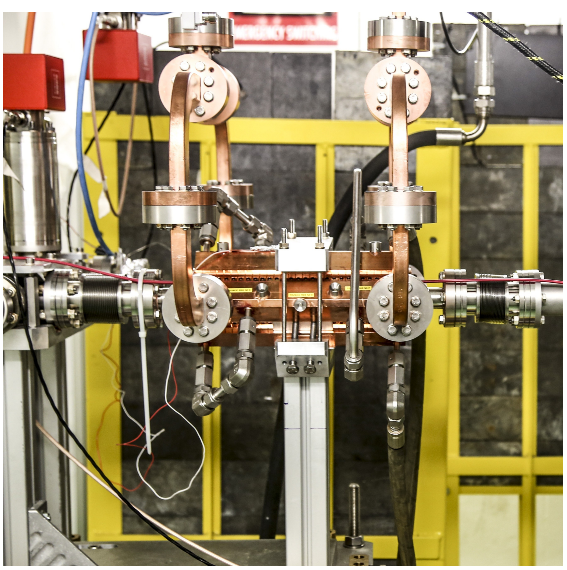


FIG. 1. The TD26CCR05 N3 installed on the Xbox 2 X-band test stand.

## III. CONDITIONING HISTORY

Commencing in December of 2015, the TD26CC R05 N3 structure was installed on Xbox 2. Commissioned in 2014, Xbox 2 is the second X-band test stand at CERN (Figure 1). The infrastructure of Xbox 2 have been extensively reviewed in [3]. The RF conditiong history is depicted in Figure 2 which will be used to describe the entire history in detail below. RF Conditioning began with a short 70 ns RF pulse length (red), the BDR limit of the conditioning algorithm was set to $8 \times 10^{-5}$ breakdowns per pulse (bpp) for 50 million pulses in which the structure conditioned to 60 MV/m, where the unloaded gradient is depicted in blue. It was found that a greater BDR limit led to periods of clustered breakdowns seen in the BDR's variation of 60% (magenta). This was considered undesirable for the structure and the BDR limit was reduced to $3\times10^{-5}$ bpp, seen clearly in the gradient reduction of the cumulative breakdowns plot(black). Continuing to condition, the structure reached 105 MV/m after 300 million pulses. Investigations into the power curves observed an uncharacteristically linear behaviour and further investigations found that this was the result of the conditioning algorithm retard-

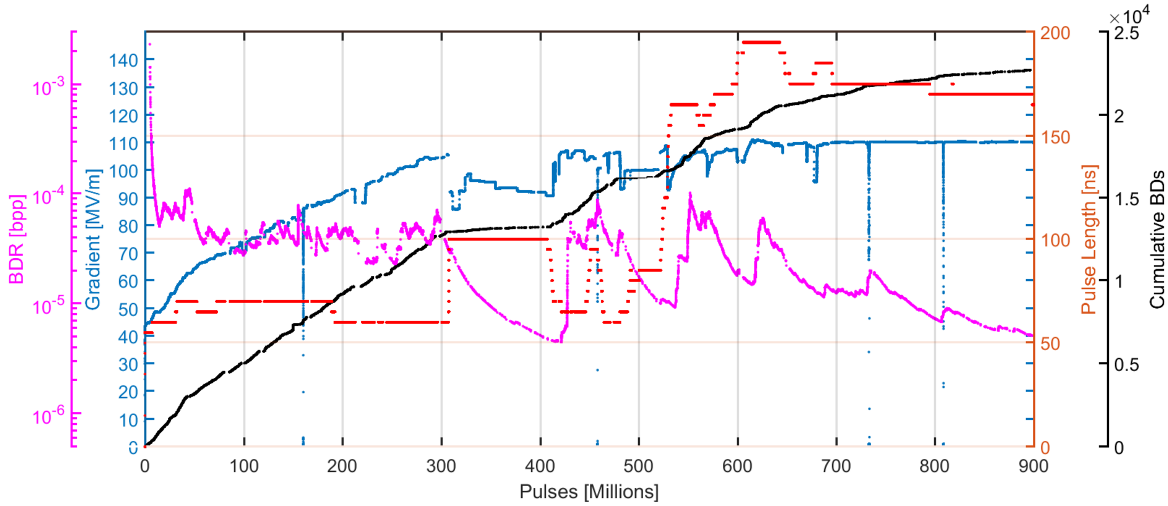



FIG. 2. Conditioning history of the TD26CCR05 N3 structure in Xbox 2.

ing progress [4]. At 105 MV/m, and just above 300 million pulses, the safe limit of radiation outside the test bunker was exceeded and temporarily prevented further increases in the power. During these periods, where power changes were not permitted, a test of the gradient dependence of the BDR was performed. During this time, the pulse length was set to the second pulse length of 100 ns to increase the BDR, allowing the increase in the number of breakdowns and therefore improving statistics. Scanning through peak electric fields of 187.5 MV/m followed by 182.6 MV/m and 180.25 MV/m, the BDR depedency is seen in Figure 3. Past tests have found a dependence of $E^{30}$ which fits well within the error bars of the measured values [5].

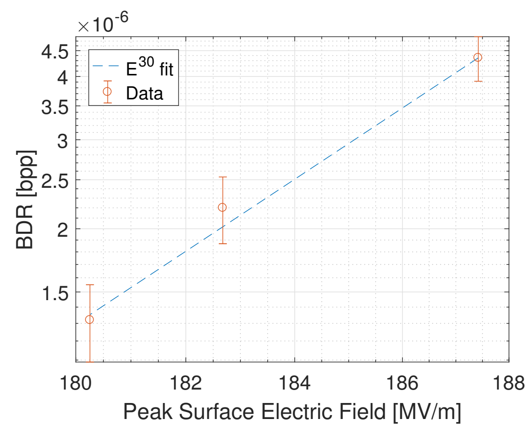
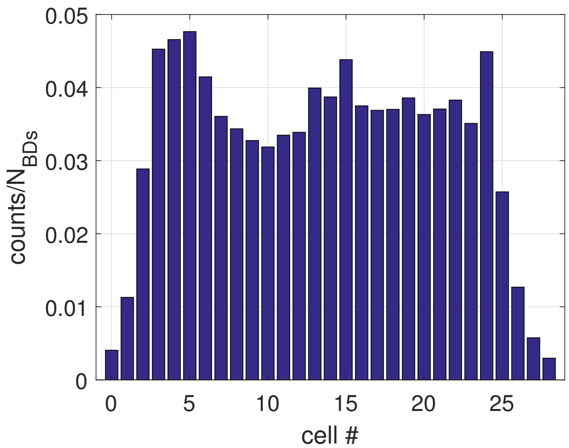
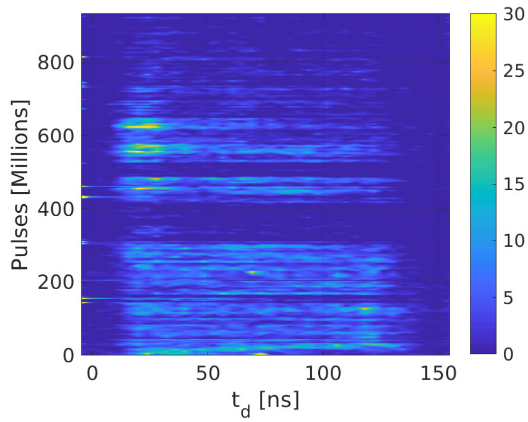



FIG. 3. Test of the BDR dependency on the surface electric field.

At 415 million pulses into the high power testing, the structure resumed power ramping with the RF pulse parameters set to those used at 300 million pulses. Between 415 and 500 million pulses, the structure was pushed to an unloaded gradient of 107 MV/m, at this time it was found that a reflection from the structure caused an undesirable peak in the pulse's flat top. It was determined that this peak came from a reflection from the start of the structure which interfered with the klystron pulse and led to excess power being extracted from the klystron [7]. A change to the phase profile allowed the pulse amplitude to be flattened. At 540 million pulses, a new pulse length and shape was estalished to

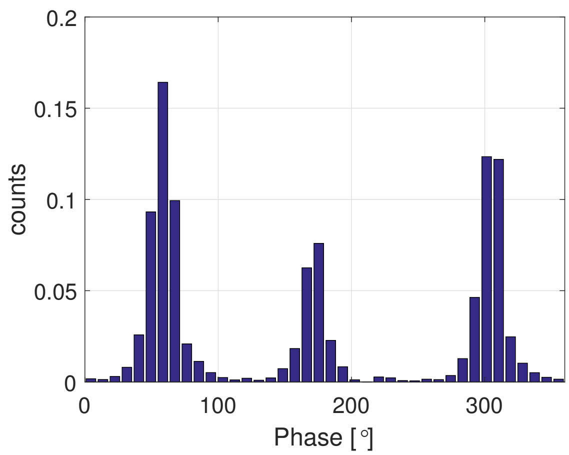



(a) Cumulative Breakdown Distribution.

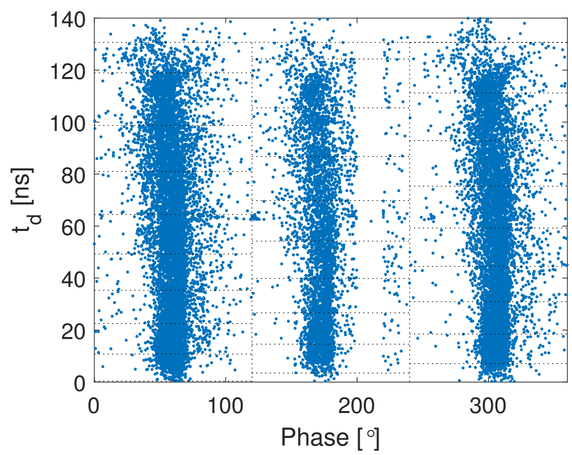



(b) Breakdown distribution per day.

FIG. 4. Breakdown distibution along the structure.




(a) Phase differential for breakdowns.




(b) Phase differential vs breakdown position.

FIG. 5. RF breakdown distribution in the structure.

flatten the pulse by reducing the reflection from the start of the structure. Up to 600 million pulses, the structure was pulsed with a "CLIC-like" pulse shape with a power ramp at the start of the pulse and a 160 ns pulse flat top [8]. Conditioning was able to reach 113 MV/m though an excess of breakdowns at the beginning of the structure was observed and will be elaborated on in the coming setion.

At 600 million pulses the structure was increased to a 200 ns pulse and ran with the undesirable peak in the otherwise flat pulse. From 650 to 700 million pulses, the pulse shape was changed to a CLIC pulse, totalling 240 ns with 180 ns flat-top [8]. This allowed testing with the nominal CLIC pulse shape while removing the undesirable peak in the pulse. Setting the unloaded gradient to a constant 110 MV/m, the structure ran with the intention of reducing the BDR for the last 200 million pulses.

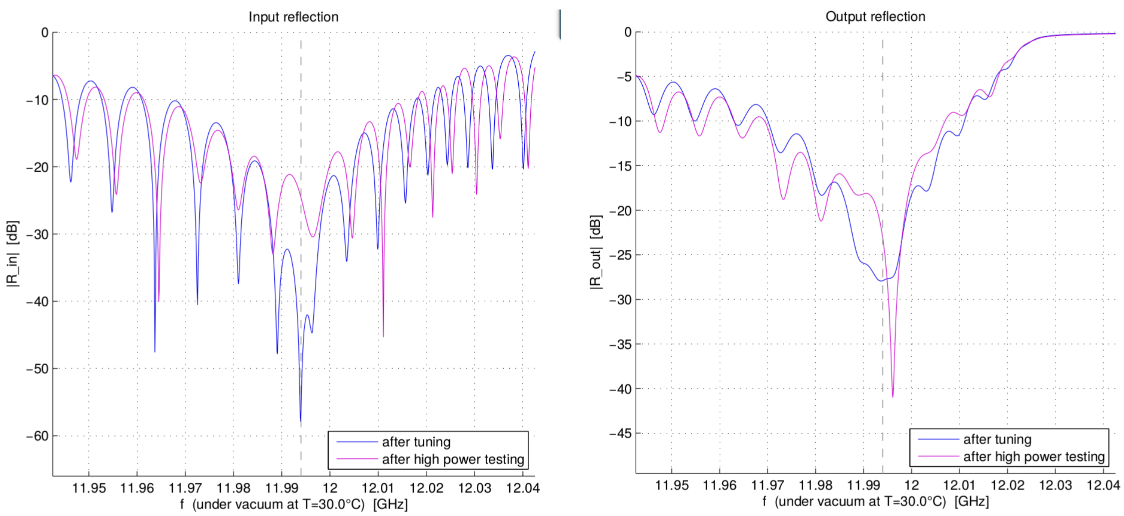
A small change in the pulse length is seen at 800 million caused by a reconfiguration of the phase control after a power outage. At the end of conditioning, the CLIC-G* had reached 110 MV/m with 170 flat top and a breakdown rate of $4 \times 10^{-6}$ bpp, equivalent to $2 \times 10^{-5}$ breakdowns/pulse/metre, which is the highest gradient achieved on a higher order mode damped CLIC structure.

## IV. BREAKDOWN DISTRIBUTION

An analysis of the breakdown distributions revealed further information about the structure's performance. Figure 4(a) depicts the breakdown distribution within the structure plotted against the cell number. A close to flat distribution demonstrated the health and field flatness of the structure as the breakdowns are expected to occur more frequently in regions of greater surface electric field strength [5, 6]. A small peak developed at the start of the structure which required further investigation. To understand the excess breakdowns at the start of the structure we plot the breakdown distribution against the number of pulses of conditioning (Figure 4(b)). For the first 300 million pulses of conditioning the breakdowns were evenly distributed across the structure. From 300 to 415 million pulses, the structure ran at a reduced power due to the radiation outside the bunker exceeding the maximum safe level. After 415 million pulses, the structure continued with another power reduction occuring at 475 million pulses. Resuming the RF conditioning after 540 million pulses, the gradient was increased to the 113 MV/m which resulted in an excess of breakdowns in the start of the structure. A reduction in power reduced the total number of breakdowns though the breakdowns continued to predominantly occur at the input of the structure. These results led to the conclusion that once a breakdown site is developed due to excessive fields it will remain despite the field reduction. Looking at the phase distribution, the expected three peaks occured in accordance with the peak surface fields occuring at the iris each separated by 120° (Figure 5(a)) [10]. When plotting the phase difference against the breakdown position a small curvature is visible in the three vertical clusters. This curvature is indicative of cell detuning which can occur during transport but also may result from high power operation(Figure 5(b)).

## V. RF TESTING AFTER HIGH POWER

After the structure was removed from the test stand it was taken for low power testing. For long term operation, it is important to understand changes in the structure's RF parameters due to high power operation. In Figure 6 the reflection from the input and output ports are displayed before (labelled "after tuning") and after high power testing. Before testing the structure can be seen to be well tuned to the oper-




(a) Input coupler reflection.

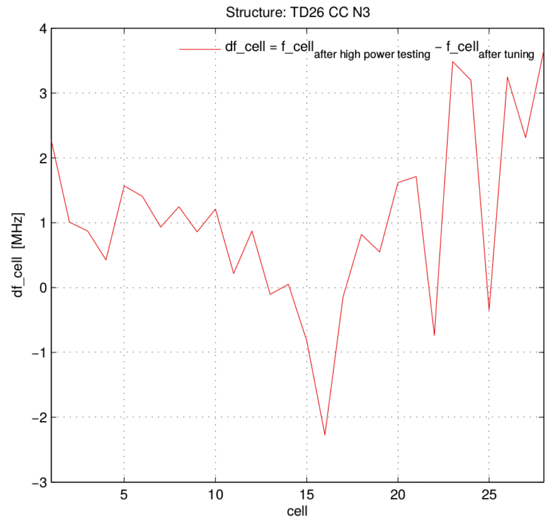
(b) Output coupler reflection.

FIG. 6. S-parameter measurements of the structure before and after high power testing.

ational frequency of 11.994 GHz with a reflection from the input coupler of −58 dB. After the RF conditioning, the reflection at the operational frequency of 11.994 GHz can be seen to jump to −26 dB. Using a non-perturbative beadpull method the cell detuning due to high power could be determined. In Figure 7(a) we observe an average frequency change of about 1 MHz (corresponding to 1° in phase advance) [9]. Such significant detuning resulted in a significant change in electric field profile's amplitude and phase, seen in Figures 7(b) and 7(c), as the standing wave ratio increased. The variance of the field amplitude and phase can be seen to increase after high power testing. It has been previously observed that structures field properties change after high power testing and this provides further evidence supporting the detuning of structures due to RF conditioning.

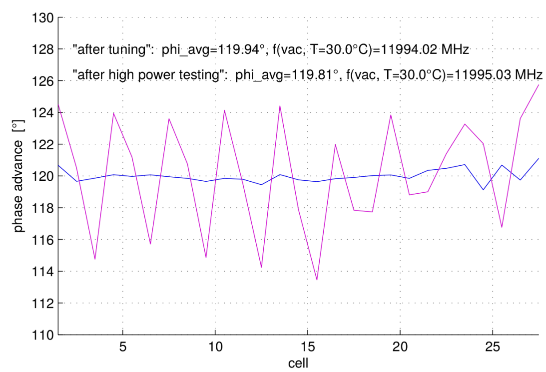
## VI. CONCLUSION

A CLIC baseline structure operating at 11.994 GHz underwent high power testing at CERN's X-band test stand (Xbox 2). After 900 million pulses the structure was able to achieve an ultimate unloaded gradient of 110 MV/m for a 170 ns RF pulse and conditioning down to a BDR of $2 \times 10^{-5}$ breakdowns/pulse/metre. Breakdown distributions along the structure demonstrated that the breakdowns occured homogeneously across the structure before occurring predominantly at the beginning of the structure when the gradient was pushed above 110 MV/m. Testing of the structures field distribution and S-parameters after high power testing illustrated significant detuning, averaging 1 MHz over the structure, expected to be the result of high power testing.




(a) Electric field profile along the structure.


(b) Cell detuning along the structure.




(c) Phase advance per cell.

FIG. 7. Electric field properties along the structure before and after high power testing.

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