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# HIGH GRADIENT TESTING OF AN X-BAND CRAB CAVITY AT XBOX2

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## Abstract

CERN's Compact linear collider (CLIC) will require crab cavities to align the bunches to provide effective head-on collisions. An X-band quasi-TM<sub>11</sub> deflecting cavity has been designed and manufactured for testing at CERN's Xbox-2 high power standalone test stand.

The cavity is currently under test and has reached an input power level in excess of 40MW, with a measured breakdown rate of better than 10<sup>-5</sup> breakdowns per pulse. This paper also describes surface field quantities which are important in assessing the expected BDR when designing high gradient structures.

## INTRODUCTION

At the CLIC interaction region electron and positron bunches collide with a 20 mrad crossing angle and have an elongated shape (45 μm long and 45 nm wide). These two factors cause a 90% reduction in luminosity compared to a head on collision. Crab cavities on each linac are required to rotate each of the bunches before the interaction point. The luminosity can be restored to within 98% of which is attainable for a head on collision [1].

For cavities placed just before the final quadrupole doublets, the required voltage kick is 2.55MV per cavity. In order to reduce wakefields, a structure with a low cell count is preferred. Therefore, to obtain the required kick a high gradient design is needed. An 11.9942 GHz design was chosen in order to utilise the expertise and RF infrastructure already available within the CLIC project.

## RF DESIGN

The cavity was designed at Lancaster University/Cockcroft Institute, UK. It is a travelling wave structure employing a quasi-TM<sub>11</sub> dipole mode with 2π/3 phase advance per cell. There are ten regular cells and two coupling cells. The cavity's specifications were finalised by considering the limits upon beam loading sensitivity, wakefields and peak power available from the high power RF network.

The iris radius is 5mm and was chosen to keep short range wakefields within acceptable limits. For long range wakefields, the same order mode (SOM) is actively damped by using a racetrack cell shape. The frequency of the SOM is shifted such that every other bunch damps the unwanted mode. The shifted frequency must be a factor of 3n/2 of the bunch repetition rate (2 GHz). A SOM frequency of 13GHz was chosen to this effect. In the final design, the lower order monopole mode and higher order modes also require damping. Studies have been conducted to design cavities with choke mode or waveguide damping. Waveguide damping was found to

be superior [2] and two prototype cavities were commissioned to be built and tested at CERN; an un-damped prototype and a damped prototype (albeit without silicon carbide absorbers). The un-damped prototype has been built and is currently under high power test at CERN.

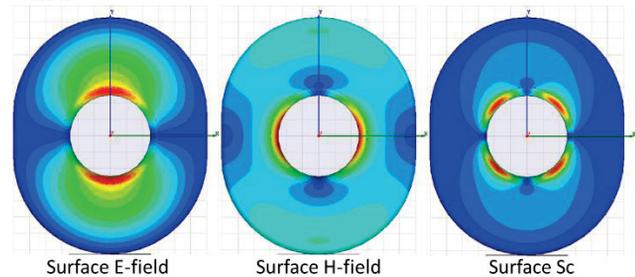


Figure 1 shows the cell geometry and the E-field, H-field and the modified pointing vector 'Sc' [3] of the un-damped crab cavity as simulated in HFSS.

As shown in Figure 1, the surface quantities affect breakdowns have peaks at different locations around the iris. For monopole mode structures all of the quantities shown in Figure 1 are distributed evenly around the iris. Therefore, this cavity provides an opportunity to test which surface quantities (electric field, magnetic field or power flow) contribute most strongly towards causing breakdowns. This can be achieved through a post-mortem inspection using optical and/or electron microscopy. A so called 'dark current spectrometer' can be used to look at the geometric source of emitted electrons during a BD in real-time. Both of these methods will be used with the latter being described in the following paper [4].

Table 1 shows the characteristics of the CLIC T24 un-damped accelerating structure, the LCLS deflector [5] and the CLIC crab cavity

Property	CLIC T24 (unloaded)	LCLS deflector	CLIC Crab (un-damped)
Input Power	37.2 MW	20 MW	13.35 MW
Transverse Kick	-	24 MV	2.55 MV
Peak surf. E-field	219 MV/m	115 MV/m	88.8 MV/m
Peak surf. H-field	410 kA/m	405 kA/m	292 kA/m
Peak Sc	3.4 MW/mm <sup>2</sup>	-	1.83 MW/mm <sup>2</sup>

Group Velocity	1.8-0.9% <i>c</i>	-3.2% <i>c</i>	-2.9% <i>c</i>
# Cells	24	117	12

Table 1 shows the parameters for the structure compared to the CLIC accelerating structure and the LCLS deflector, a similar X-band cavity with the same TM011 mode structure. In order to produce a 2.55MV kick with 13.35 MW available 12 cells are required. At the nominal operating power, the crab cavity has surface field quantities that are much lower than both the LCLS deflector and T24 accelerating structure. The breakdown rate (BDR) in this structure should therefore be extremely low. Attenuation across the structure is only 0.61 dB, allowing for a constant impedance design with a relatively constant kick voltage along the structure.

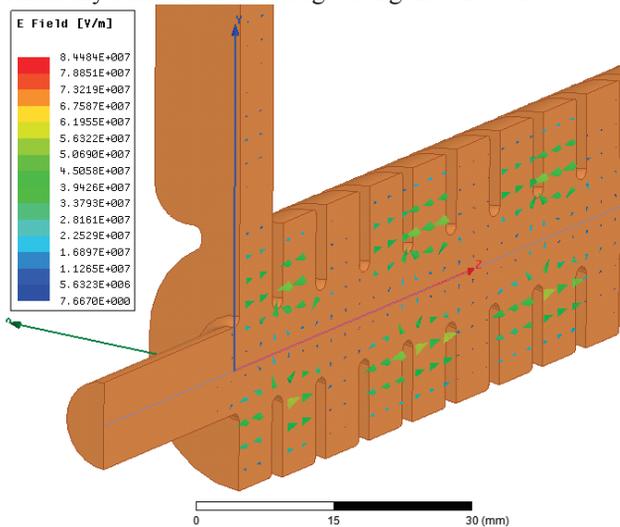


Figure 2: Shows the input coupler and the first 9 cells of the un-damped crab cavity prototype. The electric field is plotted for an input power of 13.35 MW.

As shown in Figure 2, a standard single feed coupler was chosen for the un-damped cavity to simplify the design. Although small monopole and quadrupole field components are introduced by the coupler, they will have no effect during the un-loaded high power RF test because there is no beam. For the final CLIC design, dual feed or mode launcher couplers are preferred in order to eliminate unwanted field components.

### FABRICATION AND TUNING

The mechanical design and fabrication were coordinated by CERN, based on techniques developed as part of a collaboration with SLAC and KEK. The discs were manufactured from OFHE copper at VDL using micron precision CNC milling and turning. The discs were then etched before being stacked and clamped into position. A pre-bonding RF test was performed to check the S-parameters. After the RF properties are verified, the stack is diffusion bonded in a hydrogen atmosphere at a temperature of 1020 °C. The waveguides and water cooling system are then brazed to the stack. The final

stage is a vacuum bake out at 650 °C for 10 days. A more detailed description of the process can be found in reference [6]. Tuning was performed using an iterative bead pull method described in reference [7]. The structure was successfully tuned, showing good field flatness and a cell to cell phase advance of 120° ±0.1°.

### HIGH POWER TEST

#### Xbox-2

The crab cavity is the first structure to be tested at the newly commissioned Xbox-2 test stand at CERN. The test stand is based on the same XL5 type klystron and Scandinova modulator design as Xbox-1 [8]. Improvements include an upgraded control system, a more compact waveguide network and a new pulse compressor. The new pulse compressor can be fully detuned through the use of mechanical pistons.

During the initial stages of processing a faulty XL5 klystron was being used. This limited its power output to about 10 MW before klystron gun arcs interrupted its operation. Due to the low power output, the pulse compressor was used to allow up to 30MW of incident power into the structure.

#### Breakdown Detection and Diagnostics

Xbox-2 uses RF directional couplers and Faraday cup signals, in order to detect breakdown events. Threshold detection on the reflected signal from the structure and the dark current signals are used to establish if a BD has occurred. As shown in Figure 3, when a BD occurs, the reflected signal goes from being 30 dB below the incident signal to about 50% of the incident signal level. A large ejection of charge is also measured by the Faraday cup, whereas during a normal pulse the dark current is too small to detect.

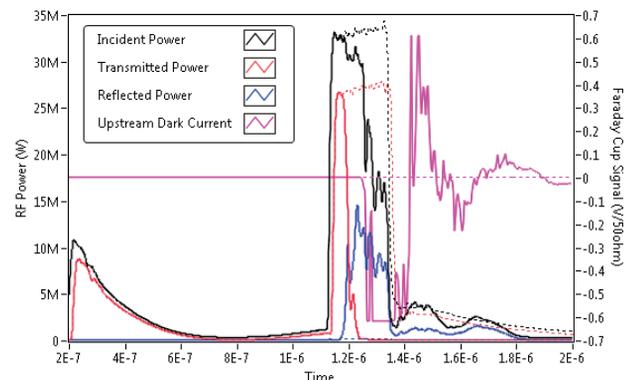


Figure 3: shows a normal compressed pulse (dotted lines) and a breakdown pulse (solid lines) inside the crab cavity.

#### Processing Method

The initial conditioning process followed that as for the TD26CC tested at Xbox-1 in 2014 [9]. The power was ramped while maintaining a constant BDR of about 6×10<sup>-5</sup>. An initial pulse width of 120 ns was used until the power increased to 15.5 MW. A pulse width of 210 ns was then chosen and the power ramped again to 15.5 MW. A

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data point was taken slightly above the nominal operating power, at 14.3 MW in order to validate the structure's performance. After 133 hours of RF on time, a breakdown rate of  $2 \times 10^{-6}$  was measured, corresponding to one breakdown every 2.8 hours. Considering there will be only 2 crab cavities at CLIC, this BDR is acceptable.

As shown in Figure 4, the BDR was decreasing while taking data at the nominal power level; a clear sign that the structure was still conditioning. In order to push the structure further the automatic conditioning algorithm was reactivated and the pulse width lowered to 120 ns. After 25 million pulses, the power level started to plateau at 27 MW, with a large increase in breakdown cluster events. The power was lowered to 20 MW, and an average BDR of  $(1.9 \pm 0.3) \times 10^{-6}$  was measured before the faulty klystron was replaced with a new CPI VKX-8311A tube.

During the installation of the new klystron the structure and network were exposed to air for one week. After a 2-day period of re-conditioning the structure to 20 MW, a second point was taken but with the pulse compressor detuned. A BDR of  $(1.1 \pm 0.2) \times 10^{-6}$  was measured, showing that there is evidence that the pulse compressor pre-pulse can contribute towards increasing the BDR.

The pulse compressor was re-activated and a series of points were taken in order to determine the BDR behaviour as a function of input power. However, as of the time of writing the structure has reached a power level of 40 MW with a BDR of  $10^{-5}$ . This implies that the structure has continued to condition. For a fully conditioned structure one would expect the BDR to be proportional to input power raised to the 15<sup>th</sup> power [3].

At the current power level of 40 MW the peak surface E, H and Sc are 154 MV/m, 505 kA/m and  $5.48 \text{ W}/\mu\text{m}^2$  respectively. Compared to CLIC T24 accelerating structure, the peak surface electric fields are 30% lower, while the magnetic field and modified pointing vector are 23% and 60% higher respectively.

## CONCLUSION

The crab cavity has been successfully fabricated, tuned and tested beyond its nominal operating conditions. Testing will continue for another few weeks in order to further understand breakdown phenomena in deflecting structures. We hope to continue to accumulate damage from BDs, such that the separate effects of electric and magnetic fields and power flow across the surface can be studied via a future post mortem analysis.

## ACKNOWLEDGMENT

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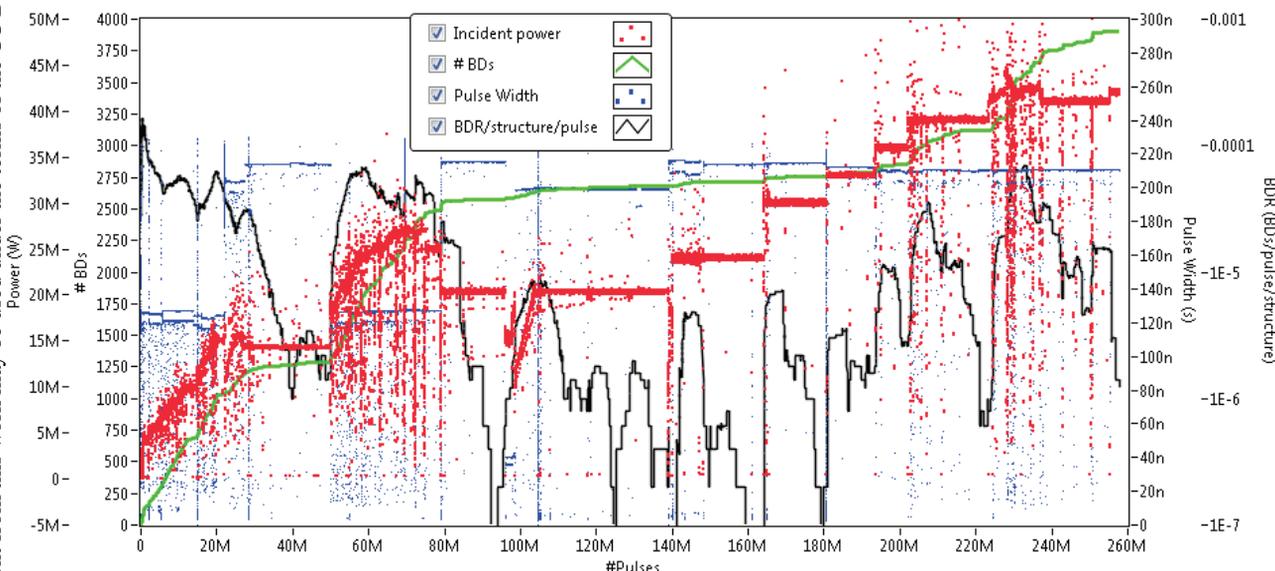


Figure 4 shows the full processing history of the crab cavity.

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