HIGH GRADIENT PROPERTIES OF A CLIC PROTOTYPE ACCELERATING STRUCTURE MADE BY TSINGHUA UNIVERSITY

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Abstract

A CLIC prototype structure, T24_THU_#1, was recently high-gradient tested at KEK X-band test stand, Nextef. The copper parts of this 24-cell TW structure were delivered from CERN, were bonded and brazed, bench-tested and tuned in Tsinghua University. The aim of this test was not only to verify the cavity high-gradient properties under 100 MV/m but also to study the breakdown phenomenon in high gradient. High power test results were presented and breakdown rate under 100 MV/m was compared to previously-tested CLIC prototype structures. The assembly capability of Tsinghua University for X-band high gradient structures was validated by the good high gradient performance of T24_THU_#1.

INTRODUCTION

T24_THU_#1 uses the same dimension as the CLIC-G undamped structure [1, 2], which includes 24 regular travelling wave cells and 2 matching cells. It works at 11.424 GHz with 2pi/3 mode. “T24” refers to its tapered cell design and the number of cells, while ‘THU’ means that it is made in TsingHua University. Nextef [3] which stands for New X-band Test Facility was proposed in 2006 as a reassembled facility of GLCTA [4] to be a 100 MW high power station for X-band accelerating structure study.

In order to demonstrate the feasibility of one of the most crucial rf performance of CLIC [5], the high-power test target of T24_THU_#1 was the stable operation of the structure at an acceleration gradient of 100 MV/m with the nominal pulse width of 250 ns, keeping the breakdown rate (BDR) below the CLIC requirement. This experiment was also supposed to verify the assembling and bonding technology at Tsinghua University. During the high gradient test extending to 8 months, various measurements such as the BDR and the change of RF pulse shape related to the breakdown had been done.

FABRICATION AND BENCH TESTS

After the cleaning and etching the disks, the diffusion bonding and brazing for T24_THU_#1 were carried out in a hydrogen furnace at Tsinghua University. An uni-axial pressure of 0.1 MPa was applied during bonding.

Bench tests were done in a clean room before and after the diffusion bonding to check whether any significant deformation happened in the structure during the bonding. The two bench tests’ kept consistent with each other and tuning was then performed in a Nitrogen environment at 25 °C. Then it was tuned to 11.424GHz at the working temperature of 30°C which fits the environment of Nextef. A good tuning was obtained after the careful tuning.

The final vacuum baking was performed at 500°C for 5 days in Tsinghua University before shipping. The baking effect on the high power performance is still under study. The structure was kept under vacuum being closed by a valve and then shipped to KEK.

HIGH POWER TEST AND DATA ANALYSIS

Test Stand and RF Processing of T24_THU_#1

A maximum of pulsed rf power can reach 100 MW by combining two X-band periodic-permanent-magnet focused klystrons’ power. Peak power of 50 MW with 252 ns pulse width and 50 Hz repetition rate is the nominal power level for testing CLIC prototype structures. The high rf power is transferred into a concrete bunker with the structure inside. More details of Nextef can be found in [3].

To the way until reaching the nominal peak power and the pulse width, the operation was started with the lowest rf power with the shortest pulse width. Keeping the pulse width, we ramped the power little by little until it reached the nominal accelerating gradient (Eacc) of 100 MV/m. The pulse width was then expanded a little once Eacc reaches the nominal value or our preferred value around the nominal one. Eacc would ramp from zero again in the new pulse width processing. The whole processing of T24_THU_#1 is shown in Fig. 1.

Breakdown Rate Analysis

The breakdown rate which was evaluated from time to time during the experiment is one of the key parameters in the processing stage and also that characterizing the high-gradient quality of the structure. It is defined as the rate of breakdown per pulse per meter (1/pulse/m). We keep the input power constant, which gives the fixed gradient inside the structure during the period of operation time to evaluate the BDR. It is calculated by counting the breakdown events occurred in the given period of rf-on time.

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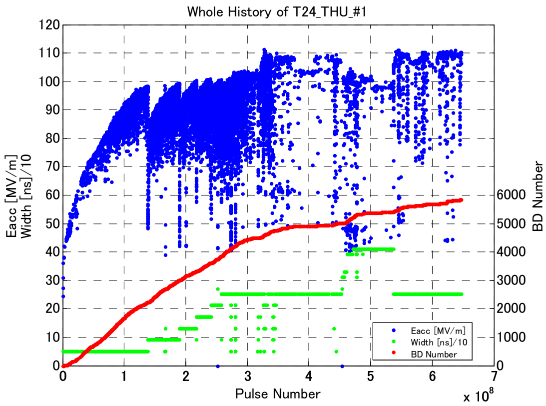

Figure 1: Summary of T24_THU_#1 processing. Blue and green dots represent the Eacc and the pulse width. Red solid line is the accumulated number of breakdowns with right axis.

BDR has a strong relationship with Eacc and rf pulse width. The dependencies which have been observed in many CLIC prototype structures and are reported in [6, 7]. It can be approximated with the relation,

$$\frac{BDR}{E_{acc}^{\ 30}\cdot\tau^{5}} = constant\,, \quad (1)$$

where E_{acc} is the accelerating gradient and τ is the rf pulse length. Based on this scaling law, we can calculate the normalized BDR (BDR*) by the formula shown below:

$$BDR^{*} = \frac{BDR}{E_{acc}^{\ 30}\cdot\tau^{5}}\,. \quad (2)$$

The normalized BDR results are shown in Fig. 2. The BDR* decreases as the total operation time increases. The decreasing feature of the BDR* (red line in Fig. 2) is obtained by fitting BDR* as an exponential function of rf-on time. It gives a “decay time” of three hundred hours which is similar to those of the former tested structures [8].

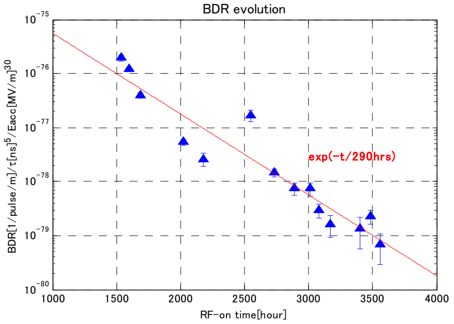

Figure 2: BDR* evolution versus to rf-on time.

As shown in Eq (1), BDR has strong dependence on Eacc which is 30th power of Eacc. In order to evaluate the dependence, we need to measure BDR at different Eacc. However, this cannot be perfectly done at the time close to each other especially when the BDR is fairly low so that the measurement at a given Eacc would cost more than 100 rf-on hours. During the time among the BDR measurements at different Eaccs, the additional conditioning effect will be added and it will affect the high-gradient characteristics of the structure in the later time. The “decay time” presented above was applied to complement the effect in our analysis on Eacc dependence shown in Fig. 3. The solid dots are the BDR values simply obtained from the raw data while hollow dots are those calculated by applying the time transient factor. As shown in the figure, the BDR dependence on Eacc became closer to Eacc^{30}. This indicates the smooth decrement of BDR as operation time.

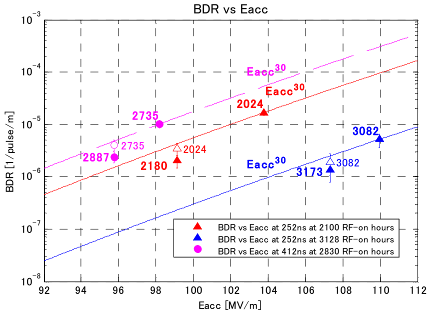

Figure 3: BDR as a function of Eacc for pulse width of 252 ns (red at 2100 rf-on hours and blue at 3128 rf-on hours) and 412ns (pink).

Normalized Eacc

Based on the dependencies of BDR on Eacc and pulse width, we can define the normalized Eacc [7]:

$$E_{acc}^{\ *} = \frac{E_{acc}\cdot\tau^{1/6}}{BDR^{1/30}}\,. \quad (3)$$

We used this parameter to replot the processing of T24_THU_#1, as shown in Fig. 4. The normalized Eacc curve became smoother and increased continuously compared with the Eacc curve in Fig. 1. The normalization equation (3) links all the different pulse width operations together and the resulting smooth curve indicates that the successive conditioning was well given to the structure.

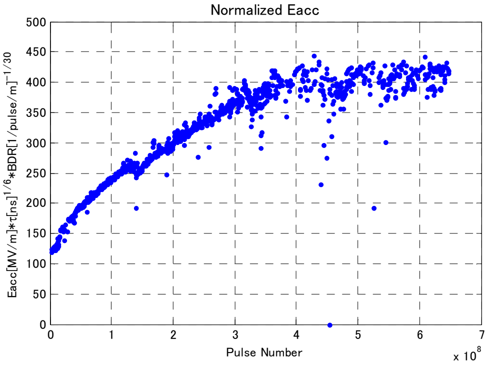

Figure 4: Normalized Eacc of T24_THU_#1.

Breakdown Timing Distribution

Breakdown timing here is defined as the time delay from the arrival of the RF pulse at the breakdown location until the breakdown occurs. When the structure is operated at the pulse width of 252 ns, the delay should be from 0 ns to 252 ns. The beginning of collapse of transmitted power was used to obtain the breakdown timing. In order to study whether there is any "hot time" when the breakdown occurs more frequently in an rf pulse, the distribution of breakdown timing was analyzed.

The breakdown events are classified into two categories, one the normal breakdown which is called "acc breakdown" and the other the special breakdown which is called "first pulse breakdown". The "first pulse breakdown" is the breakdown event happened in the very first pulse after the last breakdown event. The breakdown timing distribution of 252 ns operation (nominal pulse width operation) of T24_THU_#1 is shown in Fig. 5. "Acc breakdown" events have the uniform distribution over the rf pulse, while "first pulse breakdown" events have very high probability at the beginning of the rf pulse. One possible explanation is that something which contributes to a high field enhancement factor is left in the cavity after the previous breakdown and increases the local field. It will trigger the "first pulse breakdown" in the beginning of next rf pulse.

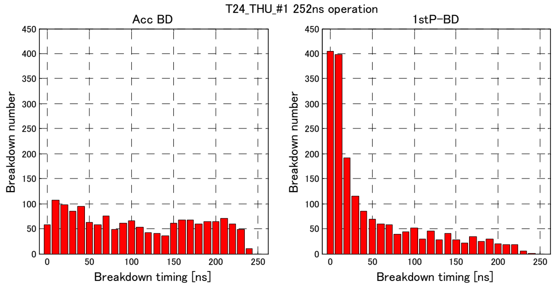

Figure 5: Breakdown timing distribution of 252ns operation. Left is the statistics of 1561 acc breakdown events while right is the statistics of 1859 first pulse breakdown events.

Comparison with Other CLIC Prototypes

The final breakdown rate of T24_THU_#1 was 1.27 × 10^{-6} breakdown per pulse per meter at the gradient of 110 MV/m and the pulse width of 252 ns. The breakdown rate comparison with previous CLIC prototype structures tested in KEK is shown in Fig. 6. The squares are the measured points, while the circles are normalized to CLIC pulse width and the crosses are the Eacc normalized to CLIC standard breakdown rate. Compared with other CLIC prototype structures, T24_THU_#1 (pink) showed a good performance and met the CLIC requirement. Note that some of the previous tested structures' data were obtained in their ending period of operation but not the final result so that such comparison still needs to be carefully checked and reviewed taking the time evolution in mind.

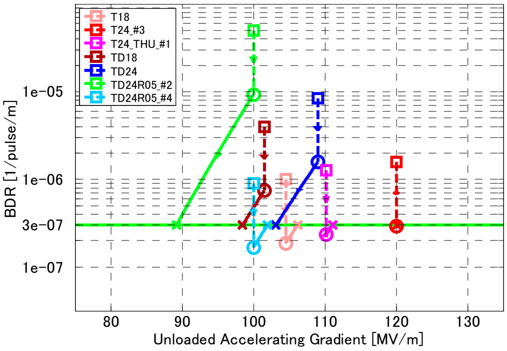

Figure 6: Comparison with previous CLIC prototypes.

FUTURE PLAN

Based on the same technology of manufacturing T24_THU_#1, a new sets of standing-wave single cell choke-mode cavities have been fabricated, assembled and bench tested. The high power test has now started at Nextef. The fabrication and test of 24-cell travelling-wave choke-mode damped structure is the next step for CLIC prototype study in Tsinghua University.

CONCLUSION

A CLIC prototype structure, T24_THU_#1, was bonded and brazed, bench-tested and tuned in Tsinghua University and then high-gradient tested at KEK. A good high power performance that T24_THU_#1 can run at 110 MV/m with the pulse width of 252 ns stably was seen after conditioning. Final breakdown rate evaluation showed that the breakdown rate at 110 MV/m and 252 ns pulse width was 1.27 × 10^{-6} breakdown/pulse/m which met the CLIC requirement. The testing results indicated that Tsinghua University has a good and reliable technology and capability of assembling and diffusion bonding for X-band structures.

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