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Breakdown Characteristics Study on an 18 Cell X-band Structure

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Abstract. A CLIC designed 18 cells, low group velocity (2.4% to 1.0% c), X-band (11.4 GHz) accelerator structure (denoted T18) was designed at CERN, its cells were built at KEK, and it was assembled and tested at SLAC. An interesting feature of this structure is that the gradient in the last cell is about 50% higher than that in the first cell. This structure has been RF conditioned at SLAC NLCTA for about 1400 hours where it incurred about 2200 breakdowns. This paper presents the characteristics of these breakdowns, including 1) the breakdown rate dependence on gradient, pulse width and conditioning time, 2) the breakdown distribution along the structure, 3) relation between breakdown and pulsed heating dependence study and 4) electric field decay time for breakdown changing over the whole conditioning time. Overall, this structure performed very well, having a final breakdown rate of less than 1e-6/pulse/m at 106 MV/m with 230 ns pulse width.

Keywords: X-band, RF, Breakdown, Gradient, Pulse Width, Pulsed Heating.
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INTRODUCTION

A CLIC designed 18-cell structure (T18) was designed by CERN based on all empirical laws developed experimentally, its cells were built at KEK and, it was bonded, processed and tested at SLAC. Instead of a constant accelerator field or constant impedance, T18 has a taper gradient, which could increase the efficiency of the structure. Its unloaded gradient in the last cell is about 50% higher than in the first cell. Tab.1[1,2] shows some of the structure parameters and test profile, where pulsed heating is calculated based on the structure powered by a squared RF pulse of 75.4MW with 200ns pulse.

TAB1. T18 structure parameters.

Parameters	Unit	Value
Frequency	GHz	11.424
Cells		18+input+output
Filling Time	ns	36
Total Length Including Beam Pipe	cm	29
Iris Dia. a/λ	%	15.5~10.1
Group Velocity: v_g/c(%)		2.61-1.02
S_{11}/ S_{21}		0.035/0.8
Phase Advace Per Cell	rad	2π/3
Power Needed $\langle E_a\rangle$=100MV/m	MW	55.5
E_a(out)/E_a(in)		1.55
E_s/E_a		2
Pulse Heating ΔT	K	16.9-23.8
High Power Test Time	Hrs	1400
Total Breakdown Events		~2200

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Fig.1 and Fig.2 shows RF conditioning history of the T18 over 1400hrs. The solid line is the average unloaded gradient for the full structure and the dash line is the breakdown rate normalized to the total length of T18. And the numbers in the plots indicate the RF pulse width during that period of conditioning. Basically, in the initial 500hrs conditioning, we limit the unloaded gradient of structure below 110MV/m to protect the structure from breakdown damage, and push the structure to higher gradient of 120MV/m in the following 900hrs conditioning. Totally the structure has been RF conditioned about 1400hrs incurred ~2200 breakdown events; hence it is ~ 120 events per cell over the full structure for average. As a whole, the structure ran very well, having a final breakdown rate around 7e-7/pulse/m operating at average unloaded gradient of 106MV/m with 230ns flat RF pulse for 140hrs.

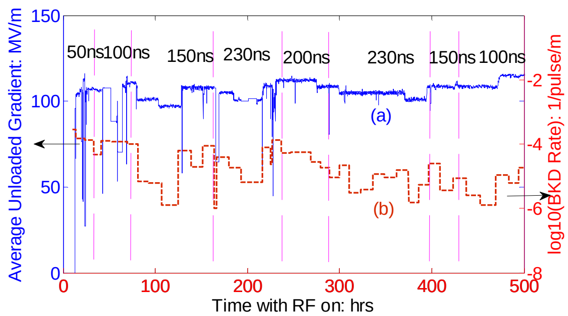

FIG. 1. T18 RF Conditioning history for the first 500hrs.The numbers in the figure shows the flat top pulse width during that period of conditioning. (a) stands for the unloaded gradient of the structure and (b) is the logged breakdown rate.

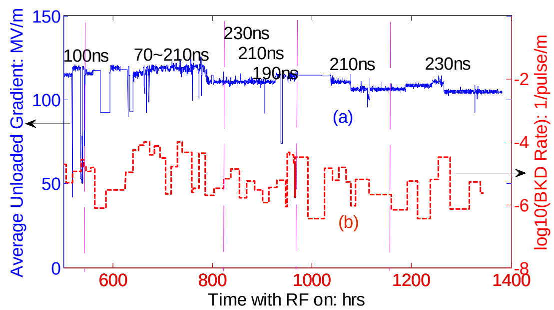

FIG. 2. T18 RF Conditioning history for the following 900hrs, which has the same description as for FIG. 1.

BREAKDOWN RATE DEPENDENCE ON GRADIENT AND PULSE WIDTH CHANGING OVER RF CONDITIONING

a) Gradient Dependence

T18 structure breakdown rate of accelerator gradient dependence at 230ns pulse width has been studied at different stage during the whole RF conditioning period. Fig.3 shows structure breakdown rate dependence of gradient at 230ns of flat RF pulse at different conditioning stage. The numbers on the figure indicates that the data are taken at what time of conditioning. The solid line shows that the breakdown rate has a gradient dependence of E_a^{32} from experiment data, where E_a is the average unloaded gradient of the full structure.

Fig.4 is the structure operational unloaded gradient at different conditioning time for a constant breakdown rate of 2e-6/pulse/m with 230ns flat pulse width. The circle data points are taken from initial 1400hrs conditioning in Fig.3. It shows that for a constant breakdown rate the operational gradient of the structure is increasing with further conditioning until something happened during 1200hrs to 1400hrs. Fig.5 is the breakdown distribution along the structure for the last 200hrs. The cross indicates the cell position. And the dot points are the breakdown position from data. It is clearly that for the last 200hrs the breakdowns are certainly dominated the individual cells. That is could be why the gradient dropped so much in Fig.4.

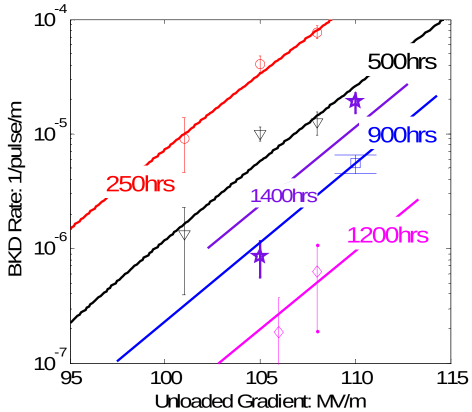

FIG. 3. Breakdown rate gradient dependence for 230ns flat pulse at different stage of RF conditioning.

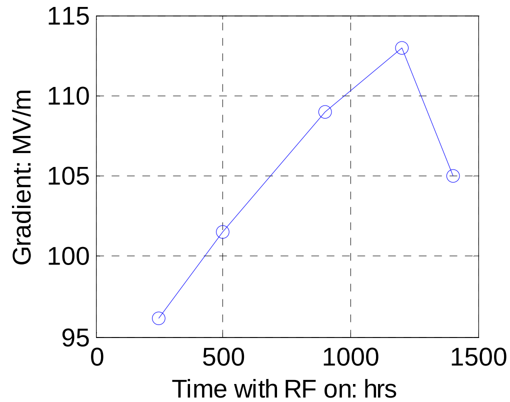

FIG. 4. T18 gradient with 230ns pulse for a contant breakdown rate 2e-6/pulse/m at different RF condition stage.

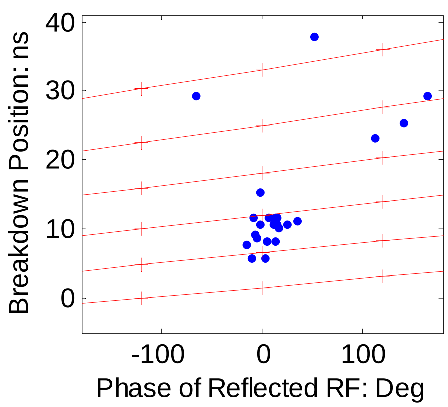

FIG. 5. Breakdown location in the structure for the last 200hrs conditioning.

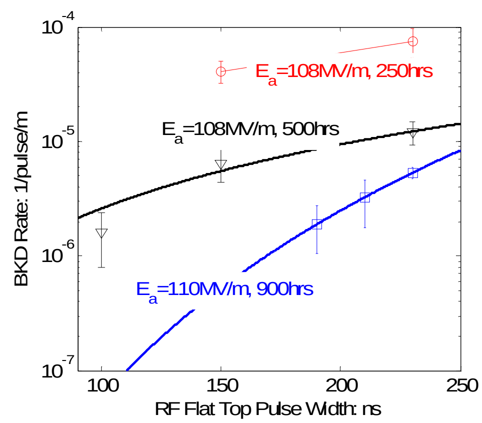

FIG. 6. Breakdown rate pulse width dependence at different conditioning stage.

b) Pulse Width Dependence

The breakdown rate dependence of pulse width has also been studied at certain gradient for different conditioning stage. It is found that the pulse width dependence becoming stronger with further condition as shown in Fig. 6, where the solid line are the power fit for the experiment data. Finally, it has pulse width dependence with exponent of 5.5.

BREAKDOWN DISTRIBUTION IN THE STRUCTURE

Since the gradient in the structure is tapered and the breakdown has a strong gradient dependence, naturally one may think that the breakdown will have very strong cell dependence. However it turned out that the position dependence is very weak as shown in Fig.7, which gives the breakdown distribution for cell-cluster over time. It is clearly that for the first cluster (cell 1~4) the conditioning doesn't affect much on these cells, for the second cluster (5~10) it seems these cells are going to be damaged with further conditioning and for the last cluster (11~18) conditioning help to reduce the breakdown rate.

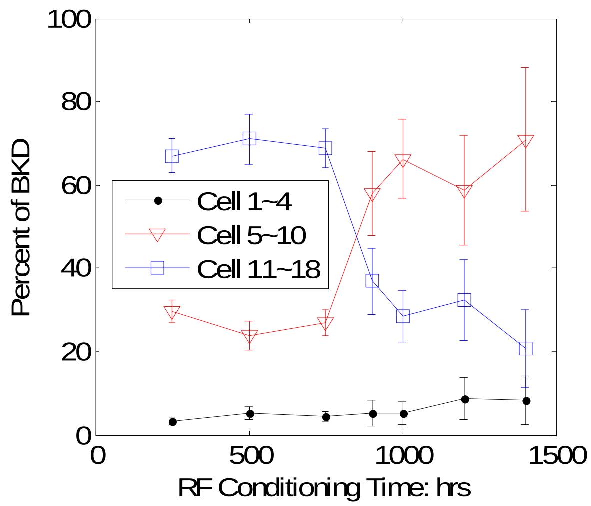

FIG. 7. Fraction of breakdown in cell-cluster changes with RF conditioning time.

BREAKDOWN PULSED HEATING DEPENDENCE

To study how the pulsed heating related to the breakdown, a step pulse is sent to the structure as shown in Fig.8. The small after pulses are generated by SLED system, which can't be removed. By changing the pre-pulse power level and fixed the main pulse power level to study how the breakdown rate will be affected by the whole pulsed heating. During the experiment, the main pulse is fixed to 100ns with a gradient of 119MV/m, and the pre-pulse is also set to 100ns pulse width with gradient (MV/m) of 0, 81, 97, 111, and 119.

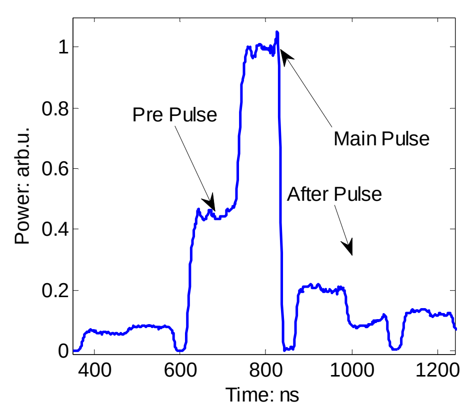

FIG. 8. SLED output of step pulse to the structure.

The number of pulse to damage the surface at certain pulsed heating is expressed as the following[3],

$$n \propto \exp\left(\frac{U}{6(T_0 + \Delta T)}\right) \quad (1)$$

where U is a constant and T_0 is the surface temperature without pulsed heating. The data points in Fig. 9 are the experimental result of number of pulses needed to generate a breakdown at different step pulsed heating in the last cell, where T_0 is set to 318K. The solid line is the fit to the eq. (1). Basically, it shows that the breakdown rate in the structure can not be simply explained to the pulsed heating as eq. (1).

Fig.10 shows the breakdown distribution during the pulse with different pre-pulse power level, which is expressed as the total pulsed heating of the last cell. When pre-pulse gradient is above 90 percent of main pulse gradient, the breakdown turned to happen very random between the pre-pulse and main pulse. It probably indicates that the heating during the pulse has very weak relation with breakdown at this case.

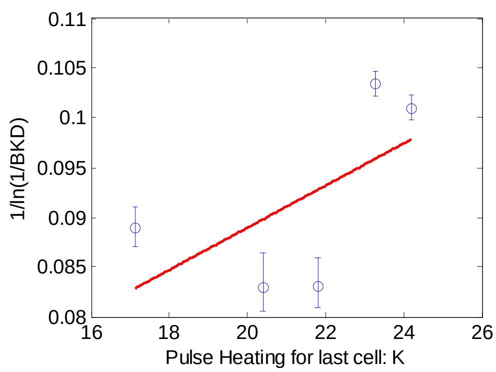

FIG. 9. Experimental data of number of pulse for a breakdown with different step pulse heating in the last cell

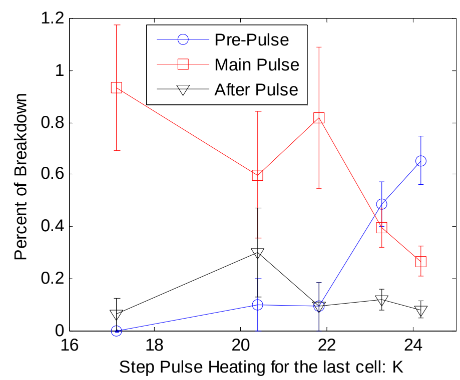

FIG. 10. Breakdown distribution during step pulse experiment versus pulse heating in the last cell

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FIELD DECAY TIME AT BREAKDOWN

When the breakdown happened, the field in the structure will be collapsed in a very short time as shown in Fig.11. The sold line is the normal structure field time evolution and the dash line is the field collapse at breakdown. Field decay time at breakdown t_e is defined as the time for the field collapse to 5% of the field just before the breakdown happened.

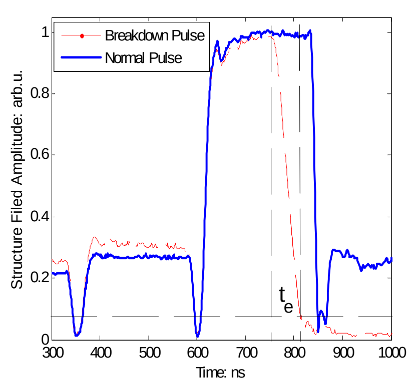

FIG. 11. Definition of field decay time for breakdown event.

Fig.12 is the field decay time distribution for T18 structure with 1139 events. The solid line is the non-centered and non-normalized Gaussian distribution fit with mean of 53.9ns and standard deviation of 17.8ns. Fig.13 shows the field decay time at different stage of RF conditioning. The last two points indicate that the decay time increase a lot, which could be related to the breakdown in the damaged cells as shown in Fig.5.

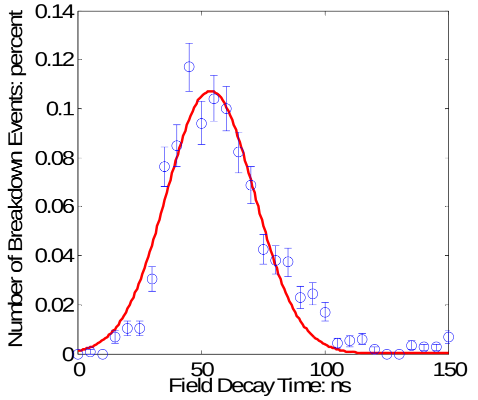

FIG. 12. Breakdown field decay time distribution for T18 structure with Gaussian Fit.

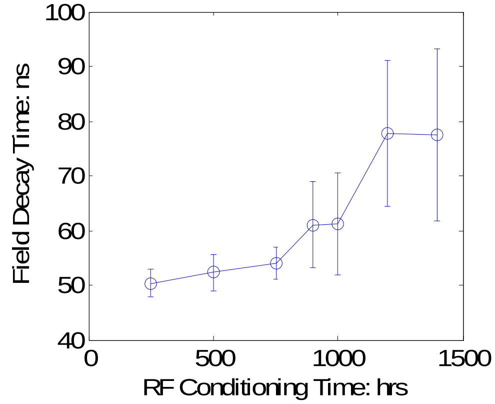

FIG. 53. Field Decay Time at different stage of RF conditioning

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DISCUSSIONS

Based on the breakdown rate gradient dependence and pulse width dependence of the structure, we have the following relation of the power P and pulse width τ for a constant breakdown rate,

$$P\tau^{5.5/16} \approx P\tau^{1/3} = const. \quad (2)$$

For the assumed pulsed heating caused breakdown, at a constant breakdown rate, it should has the constant pulse heating ΔT, thus it has

$$P\tau^{1/2} = const. \quad (3)$$

A latest paper shows that[4] for a constant number of pulse to damage a surface the pulse heating and pulse width will satisfy $\sqrt{\tau}\Delta T^2 = const.$ and $\frac{\Delta T^2}{\sqrt{\tau}} = const.$ for different pulse width, which can be rewritten in the term of power and pulse width as,

$$P\tau^{3/4} = const. \ , \quad (4)$$

$$P\tau^{1/4} = const. \quad (5)$$

where $\tau \sim 3ns \leftrightarrow 3\mu s$ and $\tau \sim< 3ns$ for eq. (4) and eq .(5) respectively. So far, there is still not a good model to explain the special heating related breakdown in eq.(2). This could mean that the power and pulse width relation in eq.(2) for a constant breakdown rate is just mathematically not physically related to pulsed heating, in other words the damage caused by pulsed heating on the surface has very weak relation with field breakdown.

Fig.14 shows RF conditioning history of the pulsed heating for the first cell and last cell of the structure at the scale of accumulated breakdown events. For other cells, the pulsed heating is just between the two cells. Based on the experience on the NLC/GLC structure H60VG3, which has a pulsed heating temperature of 43K at 65MV/m with 400ns pulse[5], it will not damage the surface on the scale of pulsed heating of T18 structure.

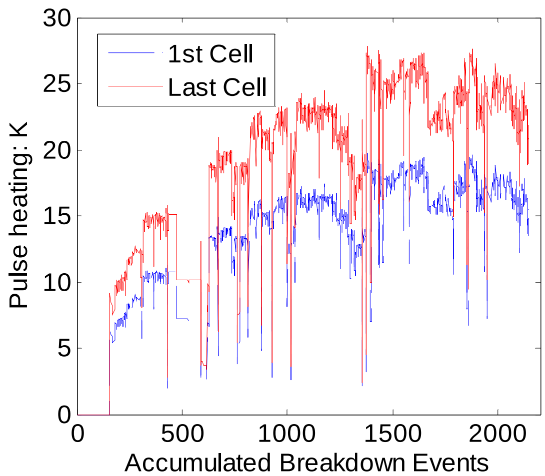

FIG. 14. Conditioning history of pulsed heating on the scale of accumulated breakdown events.

CONCLUSIONS

For the breakdown study, there are still many things that are not clear such as why the damaged cells are in the middle of structure and breakdown distribution has a linear like along the full structure.

Overall, this structure performed very well, with a quiet low breakdown rate of less than 1e-6/pulse/m at 106 MV/m with 230 ns pulses at the end of conditioning, which maybe a good enough structure for a collider of 100MV/m, however, it doesn't yet have all necessary features such as wake field damping and higher efficiency.

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