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Abstract

In recent years evidence has been found that the maximum sustainable gradient in an accelerating structure depends on the rf power flow through the structure. The CLIC study group has consequently designed a new prototype structure for CLIC with a very low group velocity, input power and average aperture ($<a/\lambda> = 0.13$). The 18 cell structure has a group velocity of 2.6 % at the entrance and 1 % at the last cell. Several of these structures have been made in a collaboration between KEK, SLAC and CERN. A total of five brazed-disk structures and two quadrant structures have been made. The high power results of the first KEK/SLAC built structure is presented which reached an unloaded gradient in excess of 100 MV/m at a pulse length of 230 ns with a breakdown rate below 10^{-6} per meter active length. The high-power testing was done using the NLCTA facility at SLAC.

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HIGH POWER TEST OF A LOW GROUP VELOCITY X-BAND ACCELERATOR STRUCTURE FOR CLIC

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In recent years evidence has been found that the maximum sustainable gradient in an accelerating structure depends on the rf power flow through the structure. The CLIC study group has consequently designed a new prototype structure for CLIC with a very low group velocity, input power and average aperture ($<a/\lambda> = 0.13$). The 18 cell structure has a group velocity of 2.6 % at the entrance and 1 % at the last cell. Several of these structures have been made in a collaboration between KEK, SLAC and CERN. A total of five brazed-disk structures and two quadrant structures have been made. The high power results of the first KEK/SLAC built structure is presented which reached an unloaded gradient in excess of 100 MV/m at a pulse length of 230 ns with a breakdown rate below 10^{-6} per meter active length. The high-power testing was done using the NLCTA facility at SLAC.

INTRODUCTION

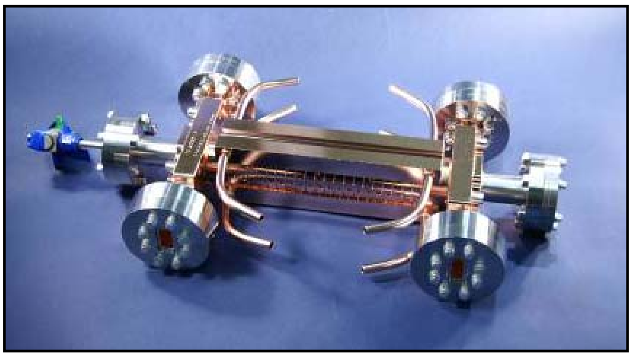
The CLIC study [1] aims to demonstrate a prototype accelerating structure suitable for a linear collider with an average loaded gradient of 100 MV/m at 12 GHz. To reach a sufficient luminosity for the collider a bunch train of 312 bunches with 3.7 10^9 electrons each has to be accelerated with a reasonable rf-to-beam efficiency. Therefore the structure needs to be equipped with heavy higher order mode damping and the gradient should be sustainable for 230 ns. The present structure is the result of a sophisticated optimization procedure to maximize the overall collider luminosity taking into account rf constraints like surface fields, input power, pulse length dependence and pulse heating as well as beam dynamics constraints for short and long range wake fields [2]. The rf constraints used in the optimization are the result of a comprehensive analysis of the available data mostly from the NLC/GLC program [3] and from 30 GHz tests at CERN. The rf power flow characterized by $P/C*\tau^{1/3}$ (P= input power, C= circumference of the first iris, τ = pulse length) was identified in this analysis as a possible limitation [4] and is therefore limited to previously demonstrated values in the optimization. The structure obtained is strongly tapered resulting in a quasi constant gradient with beam loading and a constant ratio of power over circumference along the structure. The unloaded gradient rises linearly towards the end of the structure due to this design. The structure needs only 55 MW for an average unloaded gradient of 100 MV/m due to its low group velocity- starting at 2.6 % and reaching 1% in the last cell. The detailed parameters of this structure can be found in table 1 and [5].

Frequency:	11.424 GHz
Cells:	18+2 matching cells
Filling Time:	36 ns
Length: active acceleration	18 cm
Iris Dia. a/λ	0.155~0.10
Group Velocity: vg/c	2.6-1.0 %
S11/ S21	0.035/0.8
Phase Advace Per Cell	$2\pi/3$
Power for <Ea>=100MV/m	55.5MW
Unloaded Ea(out)/Ea(in)	1.55
Es/Ea	2
Pulse Heating ΔT: (75.4MW@200ns)	16 - 25 K

Table 1: Design and measured parameters of T18_vg2.6_disk (1)

Four of these structures have been made in collaboration between KEK and SLAC using the NLC/GLC fabrication technique which comprises single crystal diamond turning of the cells, high temperature bonding (1000 C°) in a hydrogen furnace followed by extensive vacuum baking at 650 C° . CERN has made one more of this structure out of disks but using a vacuum furnace just above 800 C° for the bonding. In addition two structures with HOM damping are being prepared made out of clamped quadrants, one by CERN in OFC Copper and one by KEK in CuZr. More information about structures made out of clamped quadrant can be found in [6]. The aim is to compare different fabrication technologies and preparation techniques. A photo of the first structure tested made by KEK/SLAC is shown in figure 1. The high-power prototypes made out of disks do not include high order damping which will be added in subsequent versions. The higher order mode damping for this structures consists out of four damping waveguides in each cell which change the rf parameters slightly but in particular enhances the pulsed heating temperature rise by about a factor 2.

Figure 1: Photo of a KEK/SLAC made x-band accelerating structure called T18_vg2.6_disk (1).



EXPERIMENTAL RESULTS

The results reported here are from the first structure out of the KEK/SLAC production which was tested in NLCTA [7] at SLAC. The structure was high power tested for a total of 1400 hours using an automated conditioning system which detects missing transmitted energy pulse by pulse and switches off the rf input in case of a breakdown. A total of 2148 breakdowns were accumulated during the entire experiment. The initial conditioning started with 50 ns pulses up to just above 110 MV/m. The pulse length was then extended in several steps to a maximum pulse length of 230 ns. This pulse length corresponds to the flattop pulse length needed for the structure to accelerate 312 bunches and happens to be the length of the available SLED 2 pulse compressor used in NLCTA. After roughly 250 hours of conditioning breakdown rate measurements were started in order to characterize the performance of the structure. The main result of the experiment is summarized in figure 2 where the breakdown probability is plotted as a function of the average unloaded gradient along the structure for a pulse length of 230 ns. The breakdown probability has been normalized by the active length of the structure. The CLIC goal for a 3 TeV machine is a trip rate of 3 10^{-7} per meter at 100 MV/m loaded gradient. An average unloaded gradient of 109 MV/m corresponds to a loaded gradient of 100 MV/m for the present CLIC beam parameters [1]. The breakdown rate at a fixed working point continued to improve almost until the end of the experiment with a time-dependence proportional to t^{-2}.

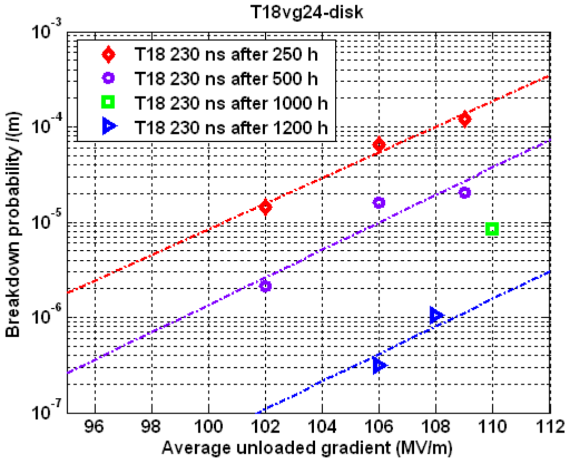


Figure 2: Normalized breakdown probability as a function of the average unloaded gradient measured different times during the experiment. The CLIC goal is a trip rate below 3 10^{-7} per meter.

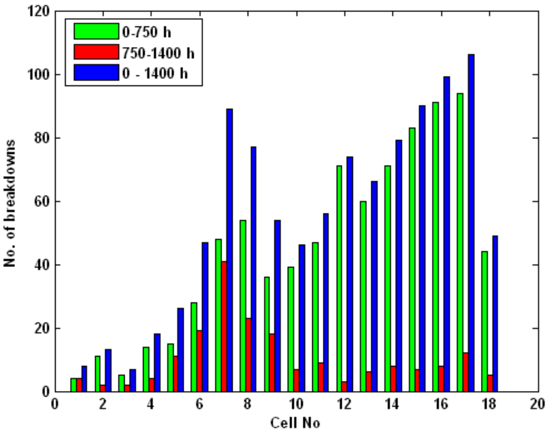


Figure 3: Breakdown distribution along the accelerating structure after 750 hours (green), for all recorded breakdowns (blue) and in the second half of the experiment (red).

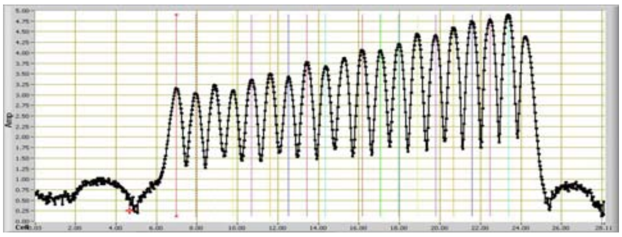


Figure 4: Bead pull field measurement along the structure. The accelerating field is increasing from 100 MV/m in the first regular cell to 155 MV/m in the last cell corresponding to an average unloaded gradient of 109 MV/m.

The data taken at NLCTA allows determining the location of breakdowns in the structure by analysing the timing of the reflected rf and the pulse shortening of the transmitted rf signals. About half of the breakdown events have been recorded and analyzed. The distribution of the breakdown along the structure is shown in figure 3. During the first 750 hours where more than 80% of the breakdowns occurred, the number of breakdowns per cell rises linearity towards the end of the structure. This rise is consistent with the rise in surface field (see figure 4). The last 650 hours of the experiment during which less than 20 % of the breakdown occurred the distribution changed suggesting a 'hot spot' in cell No. 7 or 8. The breakdown rate actually went up slightly in the last 200 hours of the experiment (not shown in figure 2) due to this hot spot. For completeness the distribution of all recorded breakdown is shown as well. The suspicious cells will be inspected to understand this behaviour. Apart from these curious events the distribution indicates that the structure was limited by the end cells which reach surface fields above 300 MV/m. The pulse heating is also highest in the end cells but is only around 25 C°. The effect of pulse shape on gradient was studied with a special experiment using a 200 ns pulse and varying the power during the first 100 ns. This experiment showed a sudden increase in breakdown rate when in the first 100 ns the gradient exceeded 80% of the gradient in the second 100ns. The breakdown then happened more often during the first 100 ns indicating that the change in gradient is more relevant than the change in pulsed heating. These results can be found in more detail in [8].

The pulse length dependence of the accelerating gradient at a fixed breakdown probability was found to follow the usual $G \sim \tau^{-1/6}$ behaviour after the structure was fully conditioned.

CONCLUSIONS AND OUTLOOK

Design, construction and testing of this accelerator prototype for CLIC is the result of a very successful collaborative effort between KEK, SLAC and CERN. The high power test of this low group velocity X-band structure for CLIC demonstrated an unloaded gradient in excess of 100 MV/m with a breakdown rate below the CLIC goal of $3\ 10^{-7}$. The structure seems to be limited at the far end of the taper where several rf parameters like the electrical and magnetic surface fields have their maximum. Even so pulsed heating originating from the magnetic field seems not to be the critical parameter. The complex Poynting vector at the surface combining magnetic and electrical fields has recently been found to describe well the limits of several test structures [9] and it rises also towards the end of the structure. The former power flow parameter ~P/C originally used to design the structure is constant along the structure and seems therefore less relevant. However the general concept to optimize for low input power and low group velocity in the CLIC structure design proved to be very successful. The fabrication techniques developed by the NLC/GLC program have once again been very reliable and further test in this structure series should give much more insights into the issues of fabrication technology.

This prototype structure for a high-gradient test does not include yet the necessary features for HOM damping. Therefore the next step therefore is clearly to test a similar structure but which has HOM damping. In addition the mode launcher type couplers used are not compatible with the desired filling factor for CLIC and therefore need to be replaced by shorter couplers. The present high-power test structure would have an rf to beam efficiency of ~ 17% when used with CLIC parameters. These issues have to be addressed in the next generation of test structures already under preparation.

A second structure which has seen an identical preparation will be tested soon at KEK in the Nextef [10] facility. The aim is to check the reproducibility of the results for different structures and test facilities. Two more sets of cells have been machined and will be assembled using slightly different preparation techniques. For one structure the time consuming high-temperature vacuum bake after bonding will be skipped. In addition two structures with the same rf circuit made out of quadrants are under construction. The quadrants will be clamped together and installed in a vacuum tank for testing. This technique allows for more flexibility in the choice of materials and does not need a heating cycle for joining the parts together which might compromise the otherwise favourable properties against fatigue from pulsed heating. One particular interesting material is CuZr. However several accelerating structures have been tested already using this technique and showed inferior results compared to similar structures made out of brazed disks.

The latest version of the CLIC accelerating structure is the result of optimizing with lower surface field constraints (Es < 250 MV/m) and trying to keep the local complex pointing vector below a critical value [2]. This new design has a superior rf to beam efficiency of 27 % and is expected to exceed even the results reported in this paper.

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