RECENT RESULTS ON CLIC X-BAND PROTOTYPE ACCELERATING STRUCTURES

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Abstract

The CLIC study is conducting an extensive testing program towards a prototype accelerating structure suitable for a liner collider. The requirements for CLIC are a loaded gradient of 100 MV/m for pulse duration of 240 ns with a trip rate below $3*10^{-7}$ per meter. These accelerating structures are designed, fabricated and tested in collaboration between KEK, SLAC and CERN.

Recent results from these experiments will be reported including a low group velocity accelerating structure which reached a gradient in excess of 100 MV/m with an acceptable breakdown rate.

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 luminosity sufficient 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 accelerating structure designs results from 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 for the structure described in this paper 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 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 detailed parameters of this structure named 'T18_vg2.6_disk' can be found in table 1 and [5].

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 a very similar rf design including HOM damping have been made out of clamped milled 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 of this structures series 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. Damped versions using four damping waveguides in each cell are currently under production.

This paper reports on the high power test results of the first T18 structure made out of disks as well as the first damped TD18 structure made out of quadrants. The disk version has been tested from both ends exploring the different input group velocities. For comparison a structure named 'T28_vg3.3_disk' was produced by SLAC and high power tested. This structure has a larger aperture and group velocity and has also a rising accelerating field along the structure.

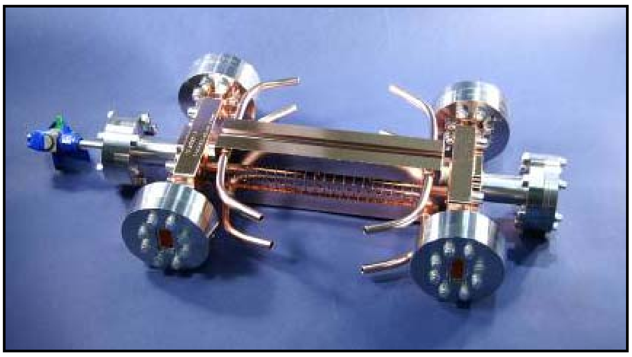

Figure 1: Photo of a KEK/SLAC made x-band accelerating structure called T18_vg2.6_disk (1).

EXPERIMENTAL RESULTS

Results of T18_vg2.6_disk

The first structure out of the KEK/SLAC production made out of disks 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

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 %
Phase Advace Per Cell	2π/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)

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. 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}. During the last 200 hours however the breakdown rate went slightly up again due to a problem in the middle of the structure.

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 (see figure 2). For completeness the distribution of all recorded breakdown is shown as well. Apart from these curious events the distribution shows that the end cells broke down more often which reach surface fields up to 300 MV/m.

More details about this experiment can be found in [8].

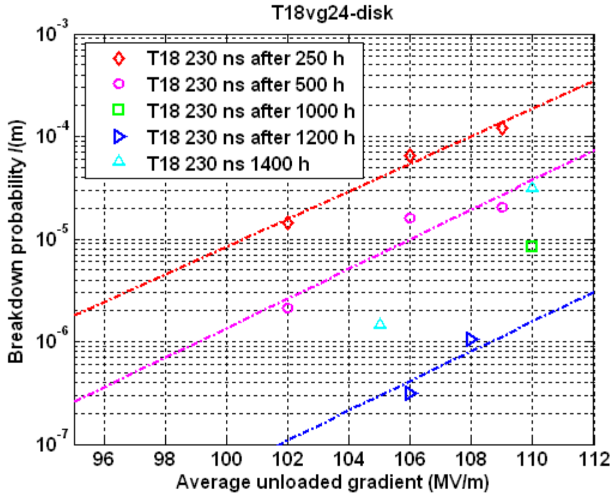

Figure 2: Normalized breakdown probability as a function of the average unloaded gradient measured different times during the experiment. The CLIC goal is a trip rate below 3 10^{-7} per meter.

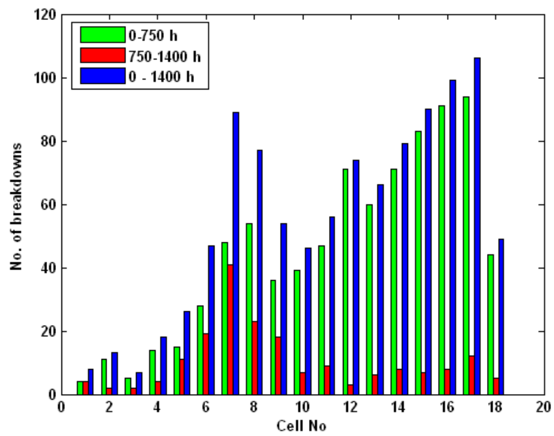

Figure 3: Breakdown distribution along the accelerating structure after 750 hours (green), for all recorded breakdowns (blue) and in the second half of the experiment (red).

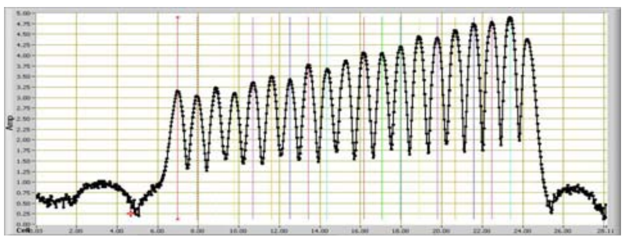

Figure 4: Bead-pull field measurement along the structure. The accelerating field is increasing from 100 MV/m in the first regular cell to 155 MV/m in the last cell corresponding to an average unloaded gradient of 109 MV/m.

Results of T18_vg2.6_disk tested form the backend

The structure was turned around and fed now with power from the back end to investigate the influence of the even lower group velocity and aperture. The group velocity of the last cell is only one percent. The gradient along the structure falls of very quickly in this mode of operation therefore this is essentially a single cell test.

The structure was tested only for a total of 110 hours from the back end at pulse lengths of 80 and 150 ns. The breakdown rate as a function of the gradient in the last cell can be compared with the previous results obtained from the forward experiment for 150 ns pulses. Figure 5 contains the forward data after 250 hours of conditioning when a breakdown rate was first measured systematically with the data points obtained form the backwards running. The influence of the conditioning time is a big uncertainty for the interpretation of this data. During the forward run of 1400 hours the breakdown rates improved by about a factor 50 which is indicated with the second blue line in figure 5. The backward breakdown rate data points are lying somewhat in between. Assuming that some memory but not all of the previous conditioning remains after vending the data seems consistent with the forward run. Basically all breakdowns happened in the last cell during the backward conditioning.

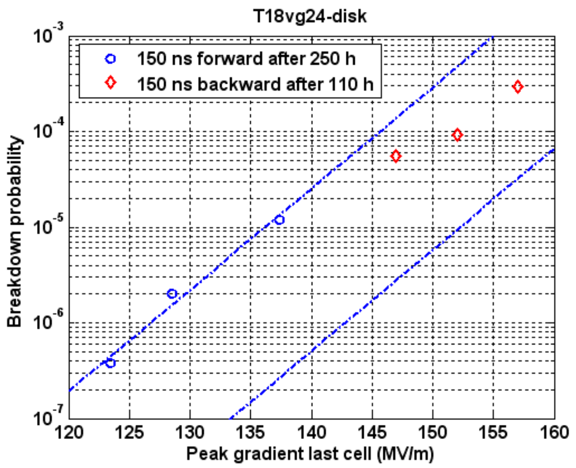

Figure 5: Comparison of the last cell gradient for the forward and backward feeding experiment.

The structure was inspected with a boroscope after the two experiments. In the area of the 'hot cells' in the middle of the structure nothing particular which could explain the curious behaviour was found. However it was clear that the output cells have been heavily pitted by the breakdowns. The last two irises have been mostly affected of which one is actually the matching iris of the mode launcher coupler with lower surface fields.

Results of TD18_vg2.4_quad

This structure has in principle an identical rf design compared to the T18_vg2.6_disk. The group velocity for each cell is only slightly lower because of the four damping waveguide opening in the outer diameter of the cells. The structure requires 3 % more input power for the same average gradient compared to the undamped disk version due to a lower cell Q. In addition this structure is made out of four quadrants produced by high speed milling instead of disks. The four quadrants (see figure 6) are than clamped together and form an accelerating structure. Since this assembly is not leak tight it is tested in a vacuum tank.

Figure 6: Photo of the four milled quadrants forming one structure before clamping.

The structure was designed and fabricated by CERN, heat treated, assembled and tested at SLAC. The quadrant version followed identical preparation steps as the disk structures with the exception that the final assembly was done in air after the baking in the vacuum furnace.

The high power testing was performed in NLCTA. The structure was tested for 50 hours up to a pulse length of 90 ns. The maximum gradient achieved during conditioning was 50 MV/m. About 2000 breakdowns have been counted in these 50 hours of conditioning. The structure released a lot of gas in case of a breakdown. The breakdowns were found to happen mostly in the middle of the structure a very different pattern than for the disk version.

Post mortem inspection indicated breakdown activity in the small gaps remaining in-between the quadrants in particular close to the iris tips. Clearly the structure performed much worse compared to the disk version despite an identical surface preparation and heat cycle. The damping waveguide which represent a significant difference between the two structures might be responsible for the failure even so the post mortem inspection did not point in this direction.

Results of T28_vg3.3_disk

This structure was designed during NLC/GLC R&D at SLAC for 65 MV/m and was originally twice as long 56 cells, named T53vg3_MC. This structure obtained previously the best performance at 100 MV/m. It turned out that taking out every second cells resulting in a 28 cells structure results in an attractive test piece for CLIC parameters. The structure is strongly tapered and changes from a constant unloaded gradient to a constant loaded gradient structure. Like this the structure needs 18 % less power for the same average gradient as the T56vg3_MC structure. The detailed parameters can be found in table 2. Although the tapering is a bit less aggressive (Eout/Ein = 1.28) this structure is similar to the T18 with 6% larger average a/λ. The structure was designed, fabricated and tested at SLAC. The fabrication procedure was the same as for the T18_vg2.6_disk described above.

Frequency:	11.424 GHz
Cells:	28+2 matching cells
Filling Time:	36 ns
Length: active acceleration	28 cm
Iris Dia. a/λ	0.15~0.12
Group Velocity: vg/c	3.3-1.6 %
Phase Advace Per Cell	2π/3
Power for <Ea>=100MV/m	82 MW
Unloaded Ea(out)/Ea(in)	1.28
Es/Ea	2.1-2

Table 2: Design parameters of T28_vg3.3_disk

The structure was conditioned in NLCTA for about 500 hours starting at 50 ns pulse and lengthening up to 200 ns pulse length. Breakdown rates as a function of gradient have been measured at 100 ns and 150 ns long pulses and can be compared to the previous T53vg3_MC results. It turns out that the performance of the shorter structure as a function of average gradient is about a factor 10 worse in breakdown rate for the same pulse length. The performance in terms of the peak accelerating gradient however is much more similar has shown in figure 7.

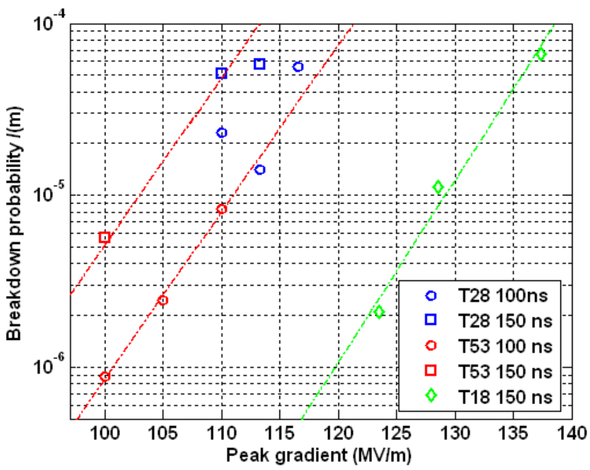

Figure 7: Normalized breakdown rate as a function of peak accelerating gradient for three different accelerating structures.

The breakdown distribution was measured and resembles the one of the T18 structure shown earlier. During the first half of the conditioning the number of breakdowns rises linearly along the structure. This pattern is somewhat shifted to a peak after two thirds of the structure during the second half of the structure.

Figure 7 contains also the breakdown rate dependence of the peak accelerating field in the last cell of the T18 structure. Clearly the performance of this cell which has a lower group velocity and aperture is superior to the cells of the other two structures. This results confirms nicely the assumption behind the optimization procedure used to design this structure that lower power flow reduces the breakdown probability even in the presence of a higher surface field.

CONCLUSIONS AND OUTLOOK

Design, construction and testing of these accelerator prototypes for CLIC is the result of a very successful collaborative effort between KEK, SLAC and CERN. The high power test of the low group velocity X-band structure T18_vg2.6_disk 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. However the linear rise in breakdown rate is not what one expect from a field emission dominated breakdown mechanism which has a exponential dependence on the electrical surface field.

The experiment of feeding the structure from the backend showed limitation at very similar field levels in this last cell including the matching cell thus confirming that the limiting field quantities are in this area. 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. A second structure which has seen an identical preparation is currently tested at KEK in the Nextef [10] facility.

The comparison between a structure made out of disks and a structure made of quadrants showed that the disk structure had a largely superior performance. However the reason for the bad result and the influence of the damping waveguides with this respect is still unknown. Virtual leaks in the clamping areas have been pointed out as a candidate to limit the performance.

The result of the T28_vg3.3_disk structure was somewhat a surprise. When the experiment was planned the structure was expected to me limited by power flow in the first cell and therefore should yield a higher average gradient because of the stronger taper compared to the T53vg3_MC structure tested before. The test can be interpreted that the structure was limited towards its end as well and therefore a careful balance for the tapering has to be found.

A rather clear result is the fact that the structure with the lower average group velocity and aperture shows the best performance. The latest version of the CLIC structure has been designed with an even lower group velocity of 1.7 % in the first cell and a constant unloaded gradient.

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