HIGH GRADIENT PERFORMANCE OF NLC/GLC X-BAND ACCELERATING STRUCTURES*

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Abstract

During the past five years, there has been an concerted program at SLAC and KEK to develop accelerator structures that meet the high gradient (65 MV/m) performance requirements for the Next Linear Collider (NLC) and Global Linear Collider (GLC) initiatives. The design that resulted is a 60-cm-long, traveling-wave structure with low group velocity and 150 degree per cell phase advance. It has an average iris size that produces an acceptable short-range wakefield, and dipole mode damping and detuning that adequately suppresses the long-range wakefield. More than eight such structures have operated at a 60 Hz repetition rate over 1000 hours at 65 MV/m with 400 ns long pulses, and have reached breakdown rate levels below the limit for the linear collider. Moreover, the structures are robust in that the rates continue to decrease over time, and if the structures are briefly exposed to air, the rates recover to their low levels within a few days. This paper presents a summary of the results from this program, which effectively ended last August with the selection of 'cold' technology for an International Linear Collider (ILC).

INTRODUCTION

For the NLC/GLC [1] normal conducting linear collider schemes, the performance of the X-band accelerator structure was a key-issue throughout the study. It turned out that the structures are limited by rf breakdown. Given the large number of accelerating structures for NLC the breakdown rate at a given gradient became the figure of merit to characterize the structure performance. With 18000 structures in the machine, 2 % operational overhead and a 10s trip recovery, the maximal allowable trip rate to guaranty 100 % availability turns out to be one trip in 10 hours at 60 Hz. The design gradient for the NLC/GLC is 65 MV/m unloaded at 11.4 GHz with a 400 ns rf pulse length. The rf design of the structure has to result in both a very good high gradient performance and an acceptable wakefield to insure low emittance beam transport. Controlling the wakefield means in particular to restrict the minimal aperture (short range wakefields) and the need of coupling slots in each cell to damp the higher order modes (HOM) locally (to suppress long range wakefields). The iterative design process resulted in a practical structure for linear collider applications which represents a trade off between, wakefield suppression, high gradient performance and cost. The design gradient of 65 MV/m is close to the cost optimum for the NLC.

The main limitation to maintain a high gradient is rf breakdown, leading to pulse shortening and eventually to damage in the structure. The phenomenon of rf breakdown is not completely understood, but there is experimental evidence that electric and magnetic surface fields and input power should be reduced as much as possible to reduce the breakdown probability. The surface condition itself matters obviously. Parameters like particle contamination, excess oxidation and grain structure seem to play a role for rf breakdown. More details about rf breakdown can be found in [2].

A picture of a 60 cm long damped and detuned NLC/GLC structure [3, 4] is shown in figure 1 fully equipped with fundamental mode power couplers and HOM output couplers. These structures a made out of high precision machined OFHC copper, bonded and brazed together. After brazing under Hydrogen (SLAC) or Argon (FNAL) the structures are degassed for several days at 500^{o}C in a vacuum furnace (see [5, 6] for a detailed description of the manufacturing processes).

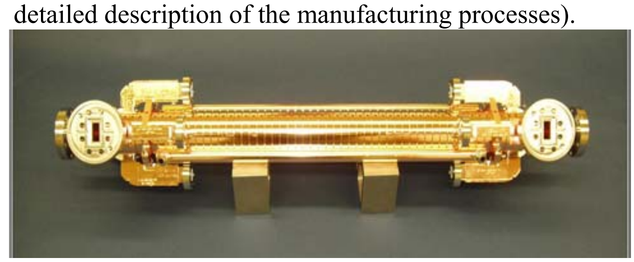

Figure 1: NLC accelerating structure with power couplers and HOM couplers on each side.

HIGH GRADIENT PERFORMANCE

The structures were installed and rf processing started without in situ baking. The processing sequence started with short pulses (50 ns) up to about 20% over the nominal field of 65 MV/m. The pulse length was then widened and the structure processed up again slightly above the target field. It took about 30 hours to process a

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structure to 70 MV/m at 400 ns pulse length. The rf power was switched off after each breakdown or vacuum trip during processing and than ramped up again in pulse length and power within 30 s. Typically about 1000 breakdowns were recorded during processing. While running already fairly quiet at the nominal working point just after processing it took a few 100 hours of operation to reach the NLC design trip rate of 0.1/h. Furthermore a continuous improvement of the breakdown rate over time was observed, roughly following a $t^{-0.5}$ dependence. This observation is illustrated in figure 2 for a single structure as well as for the average of another 3 structures.

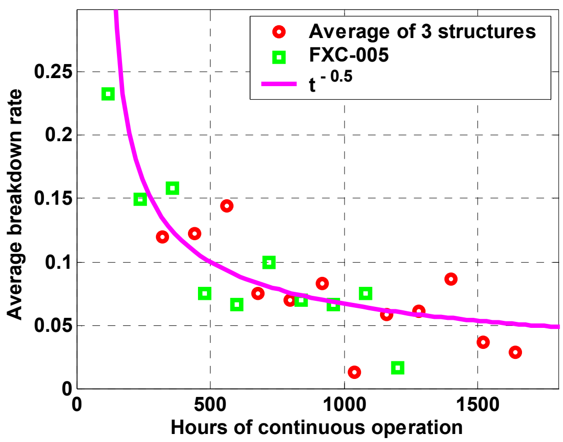

Figure 2**:** Breakdown rate as a function of time.

This type of time dependence is found for the pressure of diffusion limited vacuum systems.
A total of 9 out of 14 NLC structures tested during the last year of the development have been operated at 65 MV/m with a pulse length of 400 ns and a trip rate below the magic 0.1/h. In a full system test a string of 8 such structures were operated for 1500 hours meeting the NLC design specifications (more details about the overall rf system can be found in [4]). The breakdown rate was studied as a function of gradient and an exponential behavior was found, as shown in figure 3. The data points are the average of 8 structures while the error bars mark the best and worst performance. The breakdown rate increases one decade every 7 MV/m. This slope is quite universal even for different pulse length and structure designs. The second improved data point at 65 MV/m marks the performance after 1500 hours of operation, while the initial performance at different gradients was determined after about 500 hours. No indication of damage was found for these structures. The NLC/GLC structures were built by FNAL and by KEK/SLAC using different manufacturing processes. FNAL used conventional machining and brazing under Argon while the SLAC/KEK process used single point diamond turning and high temperature bonding under Hydrogen. However no correlations between this processes and the resulting high gradient performance was found.
The probability for breakdown dependents strongly on pulse length, specifically an exponential increase of the breakdown rate was measured for a fixed gradient. This dependence is plotted in figure 4 in the range of 100 to

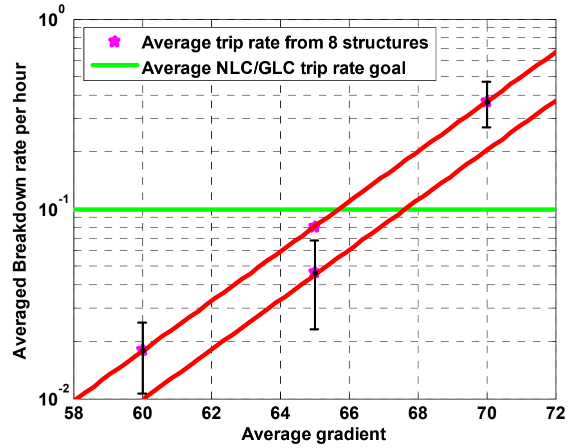

Figure 3: Average breakdown rate as a function of accelerating gradient.

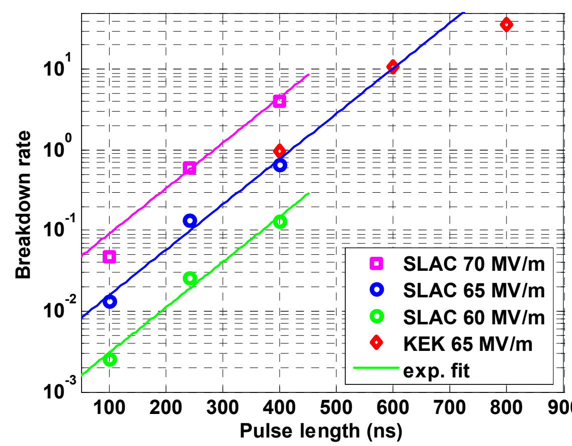

Figure 4: Pulse length dependence of the breakdown rate.

800 ns for different gradients. The set of straight lines have the same slopes determined form a fit to the SLAC 65 MV/m dataset, illustrating the 'universal' pulse length dependence even for different structures and a wide gradient and pulse length range. The accelerating gradient itself scales as $\tau^{-1/6}$ with pulse length for a fixed trip rate. These dependences allow for some operational flexibility where one can trade off gradient against pulse length. For example the NLC/GLC structures performed equally well in terms of trip rate at 85 MV/m with a pulse duration of 100 ns.
The maximum tolerable breakdown rate of 0.1/h is mainly based on operational arguments but it is also necessary to reduce the total number of breakdowns to insure a certain lifetime for the structure since every breakdown potentially erodes the surface. A worst case estimate from phase advance measured done for the NLC/GLC structures, 5000 breakdowns result in a 2 deg phase shift. For lifetime of 20 years, several breakdowns per hour would compromise severely the machine performance (5% energy loss).
During the NLC/GLC structure development program the influence of gas exposure at various steps of the production and handling procedures was often discussed and procedures like in situ baking have been adapted and discarded. Therefore a series of controlled venting

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experiments have been carried out. A pair of structures running at design values have been vented with dry nitrogen and left backfilled for 24 hours before pumping down and resuming operation. Both structures would run just fine at their design values after this procedure. In similar experiments venting with filtered and unfiltered air as well as purging with nitrogen or air didn't seem to compromise the structures performance. In the worst case of purging with air for an hour, it took 24 hours to restore the 0.1/h trip rate.

HIGH GRADIENT CONSTRAINS

The limitations of the achievable gradient as a function of the rf parameters is empirically well studied. Despite the fact that it is still difficult to give absolute threshold values on parameters like the maximal sustainable surface fields, pulse length or input power it is clear that one has to minimize those 'usual suspects' for a good high gradient performance. The ultimate restriction however seems to be the structure material itself. As a matter of fact rf breakdown results in surface melting, even if the detailed nature of the process is not well defined. Therefore exploring materials with a higher melting point for structure construction seems very attractive to achieve higher gradients. Very promising results at 30 GHz with a rf pulse duration of 16 ns have been obtained by the CLIC group at CERN using Molybdenum and Tungsten [7]. Waveguides made out of different materials were studied by the NLC group, exploring Copper, Gold and Stainless [8]. Experiments investigating DC breakdown and dark

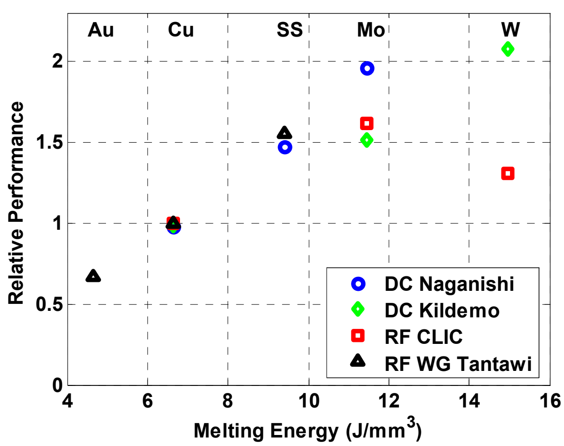

Figure 5: Material dependence of the maximum achievable surface field [7, 8, 9, 10].

current confirmed the potential for those materials [9, 10]. Each of these experiments used different criteria to determine the maximum sustainable fields and have been performed at different frequencies and pulse lengths. In order to identify trends the mentioned data was normalized by the copper result within each experiment and plotted as a function of the energy needed to melt a mm^3 of each material (see figure 5). The parameter chosen to characterize the materials might not be the only relevant one but is clearly well correlated with the maximal surface fields achieved. The large spread in the performance of Mo and W could be related to the bigger variability in material quality for those kinds of refractory metals. Facing the challenges involved with the application of new materials for rf structures might overcome high gradient constrains experienced for NLC/GLC structures made out of copper.

CONCLUSION

The NLC/GLC X-band structures have to be considered as a viable and mature accelerator system for a linear collider at the end of its successful development program. The required design specifications concerning their high gradient performance have been demonstrated. A total of 8 structures were operated for more than 1500 hours at 65 MV/m with a pulse length of 400 ns and a breakdown rate below 0.1/h. The normal conducting NLC/GLC structure turned out to be a very robust device. Once the design was fixed 70 % of the structures produced, met the design specifications. For the structure production at FNAL [6] all parts were manufactured in industry and assembled in the lab at a rate of 2 per month. Venting experiments showed that the structures are quite insensitive to potential vacuum problems and therefore easily maintainable. The design parameters however should be considered as close to the limits of any practical accelerator structure. Increasing the pulse length or the gradient would result very quickly in an intolerable high trip rate. The NLC/GLC development program explored a good fraction of the rf design parameter space for practical copper structures, therefore investigating new materials to push the gradient further seems to be the most promising approach.

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