GRADIENT LIMITATIONS FOR HIGH-FREQUENCY ACCELERATORS*

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Abstract

The main gradient limitation for high frequency accelerators is rf breakdown. While the physics of this gradient limitation still lacks a full theoretical understanding, a fairly complete empirical picture has emerged from the experimental work done in the past few years to characterize this phenomenon. Experimental results obtained mostly in the framework of the NLC/GLC project at 11 GHz and from the CLIC study at 30 GHz will be used to illustrate the important trends. The dependence of achievable gradient on pulse length, operating frequency and fabrication materials will be described. Also, the performance results most relevant to linear colliders will be presented in some detail. Specifically, these related to the requirements that the structures sustain a certain gradient without incurring damage, and that more importantly, they run reliably at this gradient, with breakdown rates less than one in a million pulses. In this context, long term operation results will be discussed as well as the result of controlled venting experiments. Finally, a very brief idea of the theories related to rf breakdown will be presented.

INTRODUCTION

Choosing a high rf operating frequency offers the advantage of a more compact accelerator design and less rf energy per pulse for efficient acceleration. Drawbacks include the difficulty of generating high peak powers at higher frequency and the tighter alignment tolerances required to cope with the higher transverse wakefields. However, these impediments can be overcome, and high rf frequencies were chosen by normal-conducting linear collider projects, specifically, NLC and GLC [1] and by CLIC [2], which aims for multi-TeV energies. The NLC/GLC collaboration has developed accelerating structures at 11.4 GHz with an unloaded design gradient of 65 MV/m with 400 ns long pulses. The CLIC group studies structures at 30 GHz aiming for an unloaded gradient of 170 MV/m at a pulse length of 130 ns (recent optimization studies suggest a much shorter pulse length of about 60 ns). These gradient choices were motivated in part by early measurements that showed achievable gradient increases monotonically with frequency. Recent results suggest that this assumption is probably not valid anymore at frequencies above X-band [3]. Beyond just achieving these gradients, the structures must operate reliability for decades in a linear collider, which makes it imperative that rf breakdown limitations be well understood. Although a dynamical model of rf breakdown has yet to be fully developed, the phenomenon can be sketched from an empirical view as follows: rf breakdown is a fast and local dissipation of stored energy. Several Joules of rf energy can be absorbed in a single cell, and in the process, surface melting and evaporation occurs in an area of a few 100 μm^2. Strong electron emission, acoustic waves, gas desorption, X-rays and visible light is observed during a breakdown event. The majority of breakdowns are concentrated in areas of high surface electric fields. However a strong exponential correlation between surface field distribution and breakdown location is not always observed, as would be expected from a purely field emission driven process. In areas with high surface currents but not necessarily high electric fields, surface defects like particles, voids and contaminants have been found to be sources of breakdown. The stress imposed on the copper surface by pulsed heating resulting from high surface currents alone is also believed to lead to breakdown. Structure designs with a pulsed temperature rises < 50 K appear to be safe in this respect.

HIGH GRADIENT PROCESSING

High frequency accelerators have to be conditioned to their high operational gradients. The process of rf conditioning is not well understood but it is believed to be a combination of physically smoothening, degassing and cleanup of the surface as a result of the energy dissipated during breakdown. Clean fabrication and assembly procedure seem to speed up rf conditioning but never eliminate it. Typically, the conditioning starts with a pulse width much shorter than the design value. The structure is processed to a field 10-25% above the design gradient and then this process is repeated with progressively longer pulses. As an example, Figure 1 shows the processing

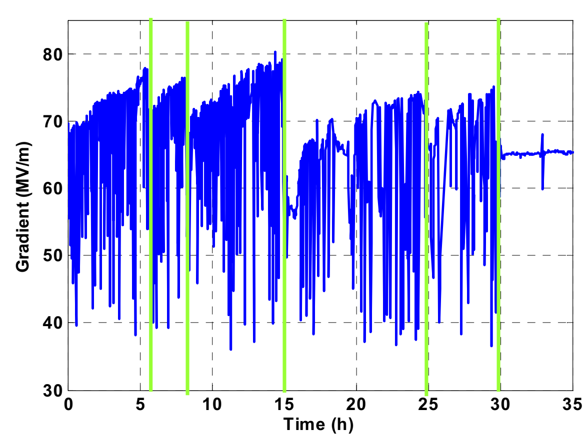

Figure 1: Processing history of a pair of 60 cm structures. The green vertical lines indicate changes in the rf pulse length (50, 100, 170, 240,400 ns).

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history for a pair of NLC/GLC structures tested in the Next Linear Collider Test Accelerator (NLCTA). After about 30 hours of processing in this case, the structures where operated at the design gradient (65 MV/m) and pulse length (400 ns).

The conditioning times and final performance of the structures do not seem to depend on the differences in the fabrication methods used. Most of the NLC/GLC structures have been built by two groups using somewhat different procedures. The FNAL group starts with cells fabricated by poly-crystal diamond turning, assembles them using conventional brazing in low a pressure argon atmosphere and then vacuum bakes them at 500 °C for 72 hours [4]. The KEK/SLAC group starts with cells fabricated by single-crystal diamond turning, diffusion bonds them in a hydrogen furnace and then vacuum bakes them for 15 days at 650 °C. In each case, the structures are back-filled with nitrogen after assembly. A 250 °C in-situ bake had been performed after the structures were installed in NLCTA for testing, but it was eliminated after faster conditioning times were achieved without it.

A series of venting experiments were recently conducted to determine the influence of gas exposure to the conditioning process. Venting and purging a pair of previously processed structures with filtered, boiled-off nitrogen resulted in almost no degradation of structure performance. Both structures came up to the design gradient with only a few breakdowns and the subsequent breakdown rate was unchanged for one structure and a factor of 2 higher for the other during the first 24 hours. The structures were then exposed to filtered laboratory air. In this case, they came up to the design gradient after a few dozen breakdowns and continued to breakdown at a rate (~ 0.5/hr) that is 10 times higher than the pre-test levels. However, after 50-100 hours, the rates came down to the earlier values. It appears that the addition of water vapor and the thin oxide layer that results enhances breakdown activity, but only temporarily as these sites are quickly processed. More importantly, a rf conditioned surface doesn't loose this quality after a exposure to filtered nitrogen or air.

RELIABILITY

Due to the large number of components in a linear collider, the reliably requirements are very demanding. The NLC/GLC linacs contain about 18,000 X-band structures, so the trip rate from rf breakdown needs to be very small to not impact accelerator availability and emerged therefore to a figure of merit for their performance. Also, the transverse fields generated during breakdown will deflect the beam so there concern as to the magnitude of the kicks (e.g., do they cause beam loss).

As for availability, the NLC/GLC design assumes that after breakdown in any structure in an rf unit (which contains 8 structures), the unit would be shut off for 10 seconds. During this time, another unit from a 2% pool of spares (overhead) would be turned on so there would be a reduction in beam energy for a single rf pulse only.

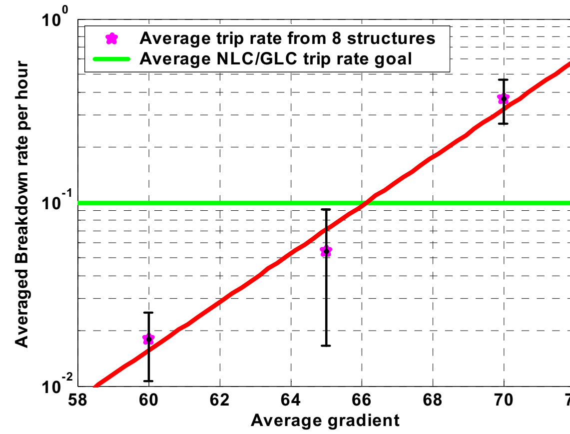

Figure 2: Average breakdown rate for 8 NLC structures as a function of average gradient.

Measurements of the beam kicks show them to be large enough to cause some luminosity loss from off-center beam collisions, but not large enough to cause the beams to hit the collimators. These considerations have lead to the adoption of a breakdown rate limit of 1 in 10 hours per structure at the 60 Hz rate used for testing (the collider rate is 120 Hz). For NLC/GLC operation, this would ensure that the pool of spares would rarely be depleted (once a year) and the luminosity loss from beam deflections would be well below 1%.

To achieve this very low trip rate at the design gradient of 65 MV/m required several years of structure development by the NLC/GLC groups. The breakdown rates obtained this year in an ensemble of 8 structures tested together in NLCTA is shown in figure 2. The breakdown rate is an exponential function of the average gradient. The slope of the fitted curve is one decade in breakdown rate for 7 MV/m of average gradient independent of pulse length. The breakdown probability also grows exponentially with pulse length at a fixed gradient [5]. The observed spread in performance is most likely reflecting the variability in the current structure production. More rigorous quality control and monitoring should improve the reproducibility.

Tests done in NLCTA indicate that most of the breakdowns are single events and the field recovers for the following pulse. Therefore it may be not necessary to shut off the rf unit in case of a single breakdown. The ensemble of 8 structures has been operated for about 1600 hours at the design gradient of 65 MV/m. A very encouraging observation during this period was that the breakdown rates steadily decreased (see figure 3). The reduction is compatible with a 1/sqrt(t) behavior. This is similar to the outgassing rate dependence in a diffusion limited vacuum system, which makes one wonder if the two phenomena are related (although other time dependencies fit the statistics-limited rate data just as well). Similar trends in the breakdown rate dependence on operation time have been observed in the proton linac at FNAL [6].

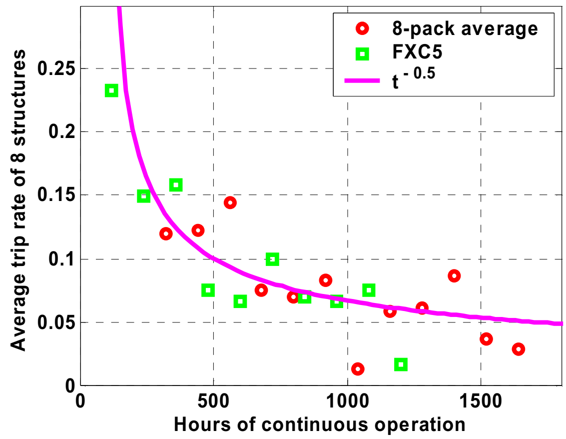

Figure 3: Long term operation of multiple NLC accelerating structures at 65 MV/m and 400 ns. The reduction of the breakdown rate with time is shown.

PULSE LENGTH DEPENDENCE

The dependence of the maximum gradient in a high frequency accelerator on the rf pulse duration is shown in figure 4 for NLC X-band structures. The presented data follows a $G \sim t_p^{-1/6}$ dependence. The upper data points represent the onset of saturation in the processing curve and correspond to a breakdown rate of a few tens per hour while the two lower data points have a breakdown rate of 0.1/h. It is interesting to note that a 30 GHz copper cavity at CERN measured at 16 ns matches the trend in terms of surface field (see figure 6) [7]. The observed dependence on pulse length is predicted by a plasma spot multiplication model [8] and has been observed experimentally for vacuum surface flashovers involving a dielectric insulator [9]. Pulse length dependences following a $G \sim t_p^{-1/4}$ law have been reported by other experiments and suggest that pulsed heating may determine this dependence [10]. The breakdowns in the X-band structures occur fairly uniformly during the pulse, which is true even immediately after the pulse length is increased. The dependence of the achievable gradient as a function of pulse length might well be the most restricting limitation for high frequency accelerators.

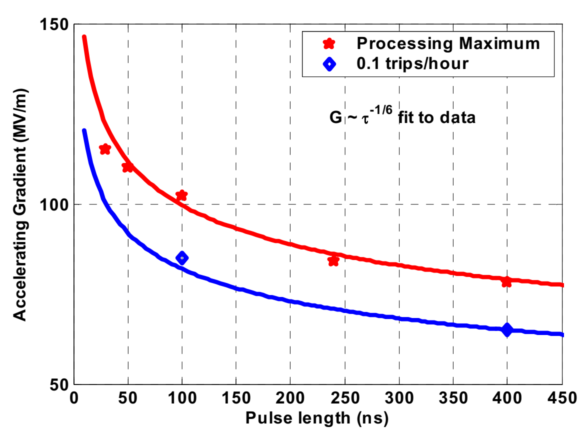

Figure 4: Pulse length dependence of the achievable gradient in X-band structures.

FREQUENCY DEPENDENCE

At frequencies below S-band one finds the empirically well established square-root frequency dependence of the attainable surface field. This dependence first established by Kilpatrick could be explained by rest gas ions being accelerated and bombarding the cavity wall, although the field limits predicted have been largely exceeded [11]. Until about five years ago, it was believed that this trend continued at higher frequencies where there were few measurements for comparison. Newer experiments however suggest that the increase in gradient with frequency is much weaker in this regime. A frequency scaling experiment conducted at CERN using single cells between 20 and 40 GHz did not see an increase of the attainable surface field in this frequency range [3]. The same limiting surface fields were found for copper cavities at 30 GHz by the CLIC study and by the NLC group at 11 GHz.

Currently there is no model of the limiting mechanism describing the available. Figure 5 shows data from copper cavities in a frequency range between 3 and 40 GHz obtained by various groups (KEK [12], SLAC [5, 10], MIT [13], and CERN [3, 7]). Two eye-guiding curves have been added to suggest certain trends in an otherwise confusing data landscape. The straight line at 350 MV/m is meant to indicate the ultimate limit in copper that is determined by breakdown-related damage. Surface fields this high can be obtained over the entire frequency range using low power cavities and brut-force processing. Subsequent autopsies of these cavities however revealed serious erosion and melting on the high field surfaces. Practical structures on the other hand group around the second curve ($G \sim f^{1/4}$), which follows from the observed pulse length dependence on gradient ($G \sim t_p^{-1/6}$) for a fixed breakdown rate, and structure fill time dependence on frequency ($t_p \sim f^{-3/2}$) assuming the 'natural' pulse length scales with the fill time. Thus the data appear to be bounded by material limits and pulse length dependent effects.

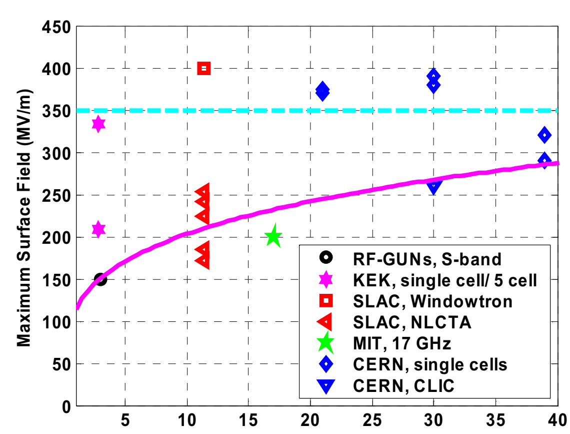

Figure 5: Maximum surface field as a function of frequency. The data points are measured at different pulse lengths (see further explanation in text).

CHOICE OF MATERIALS

Copper is the most common material choice for high voltage applications due to its superior conductivity. However many applications suffer from erosion due to local melting during breakdown events. This shortcoming has prompted the high voltage switch industry, for example, to look at alternative materials to enhance switch lifetime. Materials combining both a higher melting point and reasonable conductivity such as tungsten, molybdenum and their alloys with copper have been investigated and successfully implemented. The CLIC group likewise tried to use these materials to achieve higher gradients, and have had spectacular success [7]. As part of this program, three electrically identical 30 GHz constant impedance accelerating structures were built using copper, tungsten and molybdenum and tested in the CLIC Test Facility at the maximum available rf pulse length of 16 ns. The copper structure was built the traditional way, while for the other two structures, the irises were made out of the refractory metals and then clamped between copper disks to form the cells (hence the highest fields are only on the new materials). These structures were then mounted in a vacuum container for high power testing. The copper structure reached a surface field of 260 MV/m on the first iris while the tungsten and the molybdenum structure went up to 340 MV/m and 430 MV/m respectively. Post-mortem inspections of the irises revealed local melting and micro cracking therefore, indicating that these fields are close to the damage limits for these materials.

High power tests using X-band waveguides made out of copper, gold and stainless steel have been conducted at SLAC [14]. The results favor stainless steel over copper and gold with respect to the achievable surface fields. The measured surface fields ranging between 50 and 100 MV/m are not comparable with those obtained in X-band accelerating structures.

Inspired by the success of the 30 GHz experiments, the CLIC group built an X-band structure with molybdenum irises for testing at NLCTA, where longer pulse lengths are possible. The structure is a scaled version of the 30 GHz constant impedance structure discussed above. It was processed for more than 700 h and conditioned very slowly compared to NLC/GLC copper structures. Furthermore the structure did not exceed field values obtained for X-band copper structures. When the test ended due to time and program constraints, the gradient was still slowly increasing, which may mean higher gradients are still possible. More details about the experiment and the post analysis could be found in [15, 16]. The maximum surface fields achieved with different materials at various frequencies are plotted in figure 6 as a function of pulse length. It is remarkable that the copper results connect at short pulse length despite the different structure designs at different frequencies.

The molybdenum X-band structure shows the same pulse length dependence as the copper structures, but lower field levels. This contrasts with the 30 GHz results and DC spark experiments, which show molybdenum to be superior to copper in the field levels that can be achieved [17]. At pulse lengths of 30 ns and smaller, it should be noted that the molybdenum results were power limited. With only one test, it would be premature to drawn a definite conclusion as to the performance of molybdenum at X-band.

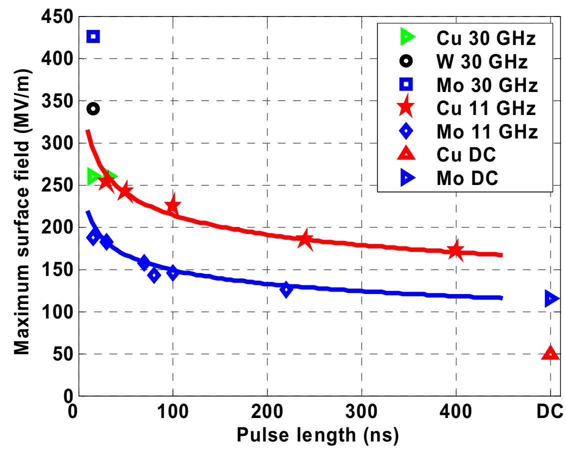

Figure 6: Pulse length dependence of the maximum surface field for different materials.

Material properties such as the melting point, yield strength, vapor pressure and vaporization energy seem to be important in determining gradient limits. Which parameter or combination of parameters is the most relevant is not yet understood and clearly more work has to be done to be able to use the full potential of alternative materials.

REMARKS ABOUT THEORY

Currently there is no consistent theoretical description of rf breakdown. The theory of explosive electron emission which was developed for DC breakdown is certainly also relevant for the rf case too, but it cannot describe all the aspects of the rf breakdown [18]. Field emission is most likely the starting point of rf breakdown. A long standing mystery in this regard is the field enhancement factors (β) in the Fowler-Nordheim theory of field emission. Without this enhancement the local surface fields are not high enough to generate the observed emission currents. The measured β-values should probably be considered as fudge-factors that account for multiple surface properties such as roughness, oxide layers, grain boundaries etc. During breakdown, local plasma has to be created and maintained to account for the amount of charge observed and the erosion. This plasma can consist out of copper ions from melting or vaporization processes and out of gas ions desorpted by particle bombardment or local heating. A plasma spot model has been developed which can predict pulse length, gradient and material dependencies [9]. An alternative to field emission as the trigger of breakdown is surface fracturing directly from the high surface field forces [19].

The surface magnetic field seems to play a role in the breakdown dynamics as well. Large surface currents can provide additional local heating that enhances field emission and subsequent melting. Also, the application of an external magnetic field may enhance damage by confining the breakdown induced plasma.

The potential damage to the surface from a breakdown should be related to the available energy therefore a limit for breakdown proportional to power and square-root of pulse length ($G \sim P\, t_p^{1/2}$) was suggested [20].

One of the most puzzling aspects of rf breakdown is its stochastic nature. That is, why is there breakdown in a particular pulse after millions of non-breakdown pulses? This must involve a yet unknown, low probability dynamical process.

CONCLUSIONS

The NLC/GLC collaboration has demonstrated that normal-conducting high-frequency accelerator technology is suitable for a large scale linear collider. An ensemble of eight accelerating structures has been operated reliable at the design gradient of 65 MV/m at 400 ns for more than 1500 hours with a breakdown rate below 0.1/h. In addition, experience from venting experiments and long term operation shows the structures to be rather robust and easy to maintain. These results are a major milestone in the quest for a next generation linear collider.

The results from various high gradient studies show there is little margin to increase the operating gradient in practical structures made of copper. Nevertheless, the choice of higher frequencies for the linear collider application still appears to be the right one due to the cost benefits of a more compact machine and the lower rf energy requirements.

Rf breakdown still lacks a complete understanding and therefore there might be still some room for optimizations and performance improvements. On the other hand the experimental data presented encircles a large fraction of the available parameter space for copper structures. One can almost predict the expected performance as a function of gradient, frequency and pulse length. Among those the pulse length dependence is probably the most limiting and the most interesting to understand better in the future.

The only hard physical limit seems to be the melting point of copper. Therefore the exploitation of alternative materials is very appealing but challenging at the same time. New fabrication methods have to be developed and material quality standards have to be defined. Yet it is not clear which material parameters are most relevant for better breakdown resistance. The first results obtained are very promising and might be therefore the right way towards gradients above 100 MV/m necessary for multi-TeV energies.

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