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RF-Breakdown in High-Frequency Accelerators

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RF Breakdown in High Frequency Accelerators*

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Abstract

RF breakdown in high-frequency accelerators appears to limit the maximum achievable gradient as well as the reliability of such devices. Experimental results from high power tests, 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 issues. The dependence of the breakdown phenomena on rf pulse length, operating frequency and fabrication material will be described. Since reliability is extremely important for large scale accelerators such as a linear collider, the measurements of breakdown rate as a function of the operating gradient will be highlighted.

I. Introduction

The complex physics associated with rf breakdown still lacks a full theoretical understanding despite five decades of experience with rf accelerators. Nonetheless, there is clear experimental evidence in a frequency range of 100 MHz to 3 GHz that the gradient limit due to breakdown increases as the square root of frequency (Kilpatrick type behavior [1]). Linear collider projects aimed at the high energy frontier therefore chose high rf frequencies to take advantage of the cost reduction associated with the higher possible gradients. The Next Linear Collider (NLC) collaboration based at the Stanford Linear Accelerator Center (SLAC), together with the Global Linear Collider (GLC) collaboration lead by KEK (High Energy Accelerator Lab) in Japan, are based on X-band (11.4 GHz) rf technology. The design accelerator gradient is 65 MV/m unloaded (52 MV/m loaded) and the rf pulse length is 400 ns [2]. The Compact Linear Collider study (CLIC) at CERN (European Center for High Energy Physics) aims for a 170 MV/m unloaded gradient (150 MV/m loaded) with 130 ns pulses using 30 GHz accelerators [3] (the design pulse length for CLIC is likely to be changed to about 60 ns). Each of these groups encountered problems achieving the design gradient and required reliability in the first accelerator structures developed for these projects, and they subsequently launched extensive R&D programs to overcome the limitations [4,5,6].

Since there is no simple understanding as to what causes rf breakdown, we will summarize the experimental observations associated with this phenomenon, in particular, the dependence of achievable gradient and breakdown rates on key parameters such as rf frequency, pulse length and fabrication material.

II. Phenomenology

RF breakdown produces a very fast and localized dissipation of stored energy in a structure. The time scale for the energy dissipation is between 10 ns and 100 ns and the absorbed energy ranges from 1 J to 10 J. A breakdown is accompanied with the emission of electron bursts, acoustic waves, visible light and vacuum activity. Breakdowns are observed to occur in areas of both high surface electric field and magnetic field, as well as in areas with local defects or contamination with large particles.

Craters with 10-100 micron diameters are observed on the surfaces in high electric field regions. They clearly show melting has occurred, and are consistent with a field emission driven process. While damage observed in the CERN structures at very high surface field and short pulses (16 ns) is clearly correlated with the surface electric field distribution in the structures, this is not the case for the X-band structures at a lower fields and longer pulses (400 ns). Here the rf power levels appear to affect the achievable gradient.

In simulations of rf breakdown using particle-in-cell codes, a large amount of gas or metal ions are needed in addition to massive electron emission (kA) to reproduce the nearly full absorption of the incident rf pulse that is observed experimentally [7]. The origin of these ions is not clear from experimental observations.

Besides craters in high electric field regions, damage in the form of melting and surface cracking has been observed along sharp edges in the X-band structure input couplers where the surface magnetic field is high. Simulations of rf pulsed heating on these edges indicates a pulsed temperature rise of at least 130 K, which is above the copper stress limit. A likely scenario to explain the damage is micro-cracking due to fatigue followed by higher temperature increases due to the surface discontinuities. Recent coupler designs that limit the temperature rise to below 50 K have not had this problem.

Finally, in a few cases, contamination consisting of large (100 micron) metallic particles was found to be the origin

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of enhanced breakdown activity in high surface magnetic field regions.

III. Gradient Limitations

A. Frequency dependence

Experimental data in the range of 100 MHz to 3 GHz show a clear square-root dependence of the attainable surface field on rf frequency. However, there is limited data at higher frequencies. Early measurements at SLAC between 3 and 11 GHz suggest a weaker cubic-root dependence on frequency [8] while a recent experiment at CERN found no significant frequency dependence in the 20 to 40 GHz range [9]. The results from this latter experiment are shown in Figure 1. These measurements were made using single cell, standing-wave (SW) cavities driven by a high charge beam. The surface field that is plotted is the peak field just after beam excitation. The field then decays exponentially, governed by the cavity quality factor, and the resulting effective pulse length should be interpreted as fairly short (< 10 ns).

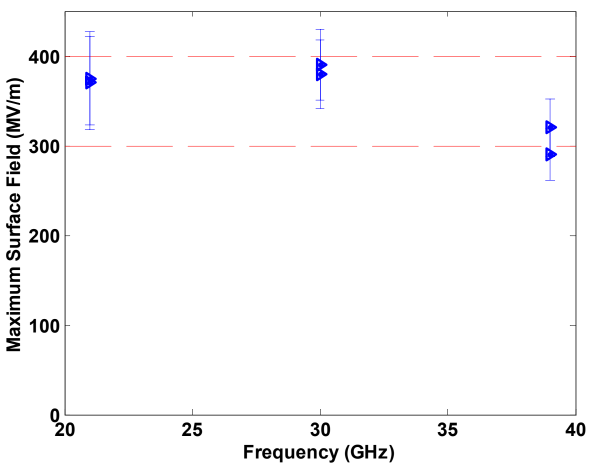

Figure 1: Frequency dependence of the maximum achievable surface gradient in single cells.

Experiments at SLAC at 11 GHz achieved ~ 300 MV/m surface fields in multi-cell, traveling-wave structures at short pulses and ~ 400 MV/m in single cell SW cavities [10]. The leveling-off of the gradient dependence on frequency at large values most likely indicates a change in the limiting physics. The Kilpatrick-like square root dependence is explained by rest gas ions getting accelerated and bombarding the cavity wall. RF pulse heating follows a $\nu^{1/8}$ dependence with frequency (ν) due to the 'natural' pulse length scaling with frequency. Field emission is rather frequency independent.

B. Pulse length dependence

The typical method to condition a high voltage device is to start at a lower voltage and a shorter pulse length than desired, then to increase the voltage and finally widen the pulse length. The dependence of the achieved structure gradient on pulse length measured for NLC/GLC structures is shown in Figure 2. The maximum surface gradient, which is on the iris tips, is a factor of 2.1 higher for these structures. The red data points (top set) are the maximum gradient the structure was processed to. These values are at the onset of saturation in the conditioning process, but are below the copper damage threshold (no significant damage was found after processing). The blue data points (bottom set) are gradients where the structure breakdown rate is 0.1 per hour. The fit to both data sets (solid lines) assumes a gradient dependence on pulse length of $G \sim t_p^{-1/6}$. Note that the surface fields achieved in 30 GHz copper structures at CERN at a pulse length of 16 ns fit well on the upper curve shown in Figure 2 for X-band structures. The breakdown times at each pulse length were observed to occur uniformly along the pulse. The temperature rise due to rf pulse heating is proportional to power and increases with the square root of pulse length. Therefore one would expect a quarter root behavior in gradient if pulse heating was the source of breakdown. Assuming a plasma spot multiplication as the physical mechanism for rf breakdown could explain the observed pulse length dependence according to [11].

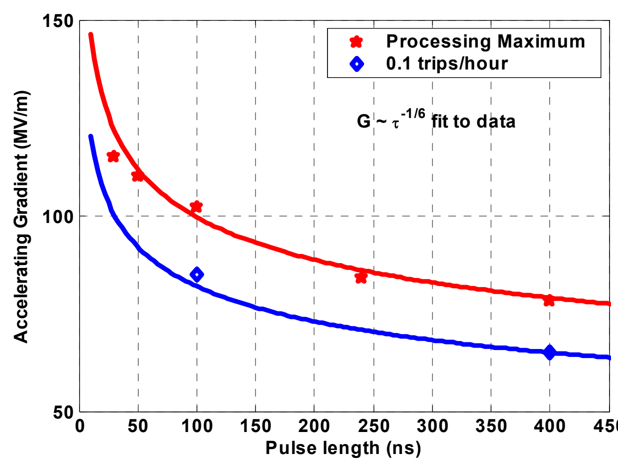

Figure 2: Pulse length dependence of the achievable gradient in X-band structures.

C. Material dependence

Copper is the material traditionally used for accelerators because of its superior conductivity and machinability. Inspired by the high-voltage switch industry, which uses refractory metals to reduce erosion, both the CLIC study and the NLC/GLC group are investigating alternative materials for accelerator structures. The CLIC group has compared the high gradient performance of three electrically identical structures made out of tungsten, molybdenum and copper [5]. The copper structure was made using the traditional brazing technique while the tungsten and molybdenum versions consisted of irises of these materials clamped between copper rings (the entire assembly was then installed in a vacuum container). Thus, the high electric field regions, which showed damage in previous tests of copper structures, are on high melting-temperature metals in these latter structures. Results from tests of these 30 GHz structures at the CLIC Test Facility are shown in Figure 3. The copper structure processed very fast and hit its saturation value at a peak accelerating

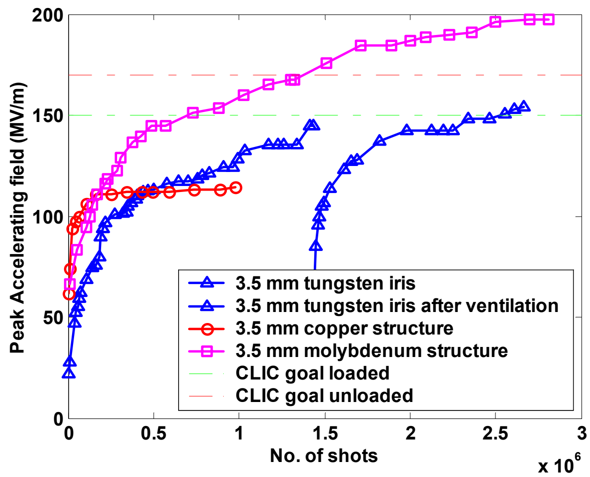

Figure 3: Peak accelerator field obtained for different materials at 30 GHz and 16 ns pulse length.

field of 110 MV/m, corresponding to a 250 MV/m surface field. The tungsten and molybdenum structure exceeded by far the values achieved with copper. The molybdenum structure reached a 190 MV/m peak accelerating field and thus sustained a 430 MV/m surface field. These values represent the onset of damage as melting and micro-cracking were revealed in a post-mortem inspection of these structures with a SEM.

Encouraged by the high gradients achieved, an X-band version of a molybdenum structure was built. It was tested at the Next Linear Collider Test Accelerator (NLCTA) at SLAC where longer rf pulse lengths (30 - 400 ns) are possible. The clamped structure processed very slowly compared to the X-band copper structures, and after more than 700 hours, it did not exceed the gradients shown in Figure 2. Unfortunately the experiment couldn't be extended due to time constrains and therefore no final conclusion could be drawn as to the ultimate sustainable gradient [12]. The SLAC group also tested X-band waveguide made out of different materials including stainless steel, copper and gold [13]. The corresponding surface fields achieved at a pulse length of 800 ns are 75, 65 and 50 MV/m, respectively. The conditioning was done using pulse lengths up to 1.5 μs.

The results with different materials seem to indicate that properties like melting temperature, yield strength, vapor pressure or the energy needed to vaporize a certain volume of the material are important for achieving a higher 'breakdown resistance'. Using alternative materials to push the performance of accelerators further is very tempting but more research has to be done to understand which material property is relevant for high gradient performance.

D. Reliability constraints

A large-scale implementation of high-gradient accelerator technology such as in a linear collider imposes challenging reliability requirements. The NLC/GLC design has ~18,000 accelerator structures powered in groups of 8 (rf unit). A 2% overhead of rf units is included to provide 'hot-swappable' spares to temporary replace those units with structures that break down (a 10 second recovery time is assumed after a trip, which was empirically determined). With these parameters, the breakdown rate needs to be less than 0.1 per hour at 60 Hz to rarely (less than once a year on average) deplete the pool of spares. At this limit, there would be one breakdown every second among all the structures. The measured trip rate as a function of gradient has a strong exponential dependence as shown in Figure 4. A detailed study of trip rates for NLC/GLC structures shows this dependence to be similar at different pulse lengths [4] and even for different structure designs. The trip rate increases exponentially with pulse length at a fixed gradient.

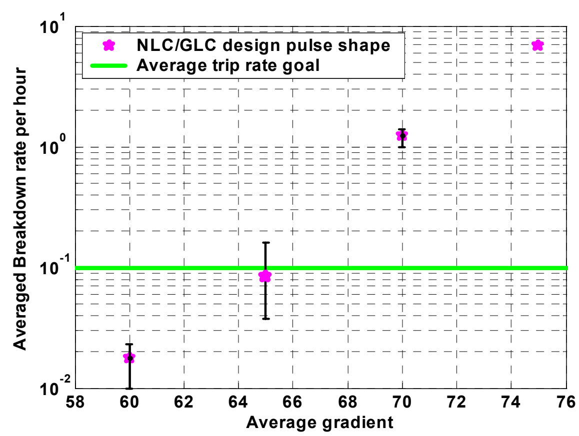

Figure 4: Average breakdown rate versus gradient in five recent NLC/GLC structures. The error bars reflect the range of rates for these structures (not all structures were measured at all gradients plotted).

The spread in the rates in Figure 4 is most likely due to variations within the fabrication, assembly, surface treatment and handling procedures that are used. This variation can be probably be reduced by more thorough quality control and strict adherence to handling procedures.

E. Surface treatment

The goal when making the structures is to produce rf surfaces as smooth, clean and particle-free as possible. NLC/GLC structures parts are made of OFC copper, machined without solvents, etched (5 μm), joined together in a few high-temperature brazing steps (800-1000 °C), and finally baked at 500 °C in vacuum. Initially, a 220 °C in-situ bake out was performed after installation in

NLCTA. Omitting this step recently resulted in a much faster processing time and better final performance of the structures. Below a certain vacuum quality (10^{-7} Torr), no correlation between bulk gas pressure and performance has been seen. Occasionally a 'hot' breakdown spot in a structure can be traced to a large (100 micron) metallic particle as its cause. However no correlation between micron size particle contamination and breakdown locations has been established in post-mortem examinations.

IV. Conclusions

RF breakdown is one of the main limitations in high-frequency accelerators. Unfortunately a consistent theory of rf breakdown has not been established despite 50 years of study. Higher frequencies are still probably the right choice for future high-gradient accelerator applications due to the cost benefits. However, the advantage of being able to operate a higher gradient at higher frequency seems questionable above X-band. Understanding the physics behind the experimental observations will be crucial to advancing this field.

The melting temperature of copper seems to be a factor in limiting the gradient and therefore new materials should be investigated for applications aiming at high gradients. Initial tests with tungsten and molybdenum show promise but more study needs to be done.

The NLC/GLC collaboration has demonstrated reliable operation of X-band accelerator structures running at 65 MV/m with a pulse length of 400 ns. This represents a major milestone for the whole accelerator community to be able to provide a technology suitable for the next generation high-energy physics machines. In addition, the CLIC group's development of alternative structure materials and novel rf technology may provide a path to multi-TeV energies.

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