ULTRA HIGH GRADIENT BREAKDOWN RATES IN X-BAND CRYOGENIC NORMAL CONDUCTING RF ACCELERATING CAVITIES*

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Abstract

RF breakdown is one of the major factors limiting the operating accelerating gradient in rf particle accelerators. We conjecture that the breakdown rate is linked to the movements of crystal defects induced by periodic mechanical stress. Pulsed surface heating possibly creates a major part of this stress. By decreasing crystal mobility and increasing yield strength we hope to reduce the breakdown rate for the same accelerating gradient. We can achieve these properties by cooling a copper accelerating cavity to cryogenic temperatures. We tested an 11.4 GHz cryogenic copper accelerating cavity at high power and observed that the rf and dark current signals are consistent with Q_0 changing during rf pulses. To take this change in Q_0 into account, we created a non-linear circuit model in which the Q_0 is allowed to vary inside the pulse. We used this model to process the data obtained from the high power test of the cryogenic accelerating structure. We present the results of measurements with low rf breakdown rates for surface electric fields near 500 MV/m for a shaped rf pulse with 150 ns of flat gradient.

INTRODUCTION

Future large scale rf accelerator facilities depend on large accelerating gradients to be economically feasible, since larger gradients decrease the required accelerator length. The major factor that limits accelerating gradient is rf breakdown. The statistical nature of rf breakdowns was discovered during work on NLC/GLC [1–4]. For large linacs, the breakdown probability needs to be very small, $< 10^{-6}$/pulse/meter[5], since if a single accelerating structure breaks down at the entire facility, the electron bunch will not be usable. X-band structures are currently the most studied in terms of rf breakdowns [4, 6–9] and the experiment described in this paper builds upon this work. Recent studies show that breakdown rate correlates with pulse heating [10] and a numerous list of other factors, such as the peak electric field, the peak magnetic field [11, 12], and the peak Poynting vector[13].

Our current theory is that the properties of rf breakdown rates are consistent with the movement and generation of dislocations[14]. At cryogenic temperatures, the material properties of copper change, increasing the electrical conductivity and hardness [15, 16]. We speculate that the lower temperature will reduce the mobility of the dislocations, decreasing the rf breakdown rate [17]. Our testable hypothesis is that rf breakdown rates in cryogenic acclerating structures will be lower than breakdown rates in room temperatures structures with the same geometry and accelerating gradient[17]. We tested two copper cryogenic accelerating structures, 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#1 and 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2, at high rf power. In the test of 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#1 the rf performance was worse than for a room temperature structure. We speculate that gases from the cryostat contaminated the high field surface [18]. We rebuilt the structure and separated the vacuum of the high gradient structure from the vacuum of the cryostat. During the test of 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2 we measured low breakdown rates for gradients significantly higher than in room temperature structures with the same geometry.

Analysis of the results from 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2 shows an inconsistency between low and high power measurements of the internal quality factor (Q_0). Low power measurements using a network analyzer measured $Q_0 = 30,400$ at 45 K [19], while at high power the rf signals were consisten with smaller Q_0, on the order of 20,000 [20]. We systematically studied this discrepancy and we will publish the results of this study in the future. We found that the Q_0 decreases during a high power rf pulse and returns to the larger Q_0 value after the rf pulse ends. We speculate that most of the Q_0 degradation is caused by beam loading from field emission electrons expelled from the copper surfaces, (these electrons will be referred to as dark current). We developed a model that uses the measured dark current signal in addition to measured rf signals to estimate the dependence of Q_0 in time and calculate the accelerating gradient. We present the measuremnets of the rf breakdown rates for accelerating gradients calculated using this nonlinear Q_0 model.

EXPERIMENTAL METHODS

The cryogenic accelerating cavity, is a single cell structure, of which about 50 similar structures have been tested at SLAC. The design, approach and methods for these experiments can be found in [5, 17, 21–23]. 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2 has an iris radius of 2.75 mm frequency, resonant frequency of 11.425 GHz at 96 K, and the surface electric fields are shown in Figure 1.

In these numerous experiments with normal conducting room temperature cavities, the high power rf and dark current signals were well explained by a linear circuit model with a constant Q_0. The data 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2 does not match simulations from the linear circuit model

* Work Supported by DOE/SU Contract DE-AC02-76-SF00515, US NSF Award PHY-1549132, the Center for Bright Beams, and DOE SCGSR Fellowship. Travel to IPAC'17 supported by the Div. of Phys. of the US NSF (Accel. Sci. Prog.) and the Div. of Beam Phys. of the APS
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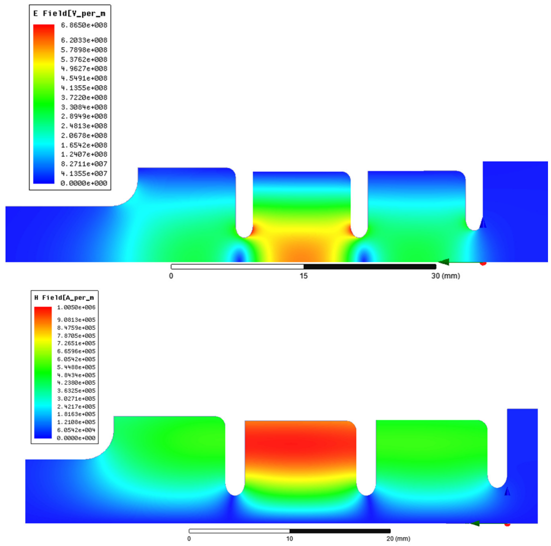

Figure 1: Surface electric and magnetic fields for 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2. Fields are normalized to 10 MW rf input power for a $Q_0 = 20,000$. The maximum surface electric field is 687 MV/m, and maximum surface magnetic field is 101 kA/m

and requires a different model. Also because of this added difficulty, in this experiment we used the rf phase information for added precision, which was not necessary in previous experiments.

There is no field probe in 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2, since a field probe distorts and amplifies surface fields and can degrade high power performance. Dark current is exponentially dependent on electric gradient, therefore the dark current signal is a sensitive measurement of accelerating gradient. Therefore, we used the measured dark current signal in lieu of a field probe signal.

Calculation of Accelerating Gradient

During high power measurements we noticed that the measured signals could not be predicted using a linear circuit model. The change in Q_0 during the rf pulse makes the linear circuit model invalid. We performed a systematic study of the change in Q_0 for varying rf pulse lengths and rf input powers, the results of which will be published in the future. Using this data we were able to create a model that describes the high power data from our rf breakdown rate experiments.

In our model, the electric field inside a resonant cavity for which the Q_0 is changing is governed by the following equation, where $Q_0 >> 1$ is assumed [24]:

$$\frac{d\tilde{E}}{dt}\left(\frac{\omega_0}{Q_E} + \omega\left(\frac{1}{Q_0} - 2i\right)\right) + \tilde{E}\left((\omega_0^2 - \omega^2\right)$$
$$-i\omega\left(\frac{\omega}{Q_0} + \frac{\omega_0}{Q_E}\right)\right) = \sqrt{\frac{8P_{\text{in}}\omega_0^3}{\mu_0 Q_E}},$$

where $\tilde{E}$ is the electric field inside the accelerating cavity, ω_0 is the resonant angular frequency of the cavity, ω is the

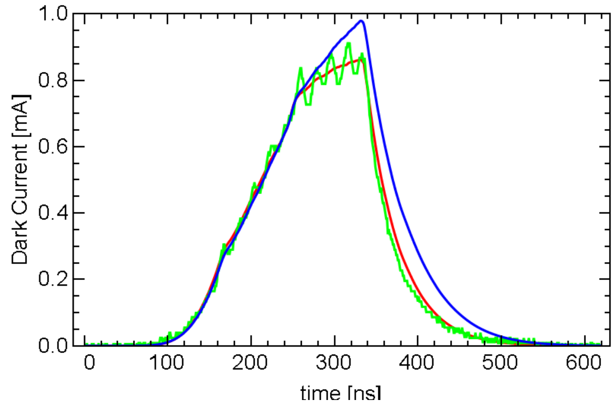

Figure 2: Dark current versus time. The measured signal is green, the signal simulated with the linear model is blue, and the signal simulated with the dynamic Q_0 model is red. For this pulse, in the constant Q_0 model the gradient is calculated to be 247 MV/m. In the dynamic Q_0 model, the gradient is 237 MV/m and the Q_0 decreases to 20,00 from 30,400.

driving frequency of the input rf, μ_0 is the permeability of free space, P_{in} is the input rf power, and Q_E is the external quality factor. The dependence in time of Q_0 is chosen such that the calculated accelerating gradient creates a dark current signal that matches the temporal shape of the measured dark current signal. Figure 2 shows the dark current signal from a typical rf pulse. In this example, the Q_0 drops to 20,000 from 30,400 at the beginning of the pulse, and calculated gradient for the linear fit is 247 MV/m, which is reduced to 237 MV/m in the model where the Q_0 degrades. The graidnet change is relativley small for such a large Q_0 degradation, which we believe is because the Q_0 is still large as the resonant cavity is being filled with fields, thus reaching nearly the same accelerating gradient as the constant Q_0 case.

RESULTS

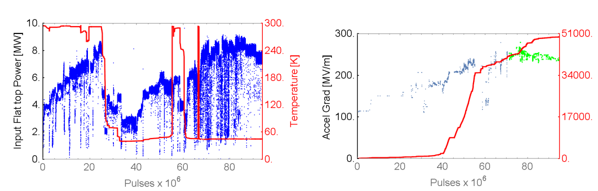

Figure 3: The processing history for 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2. Left) Blue is the input flat power and red is the temperature. Right) Red the number of recorded breakdowns. Blue is the gradient at a breakdown while the structure is processing, and the green shows the calculated gradient during measurements of the rf breakdown rate, with 150 ns flat gradient

Figure 3 shows the processing history of 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#2, including the temperature, number of breakdowns and the accelerating gradient in the structure

ISBN 978-3-95450-182-3

at the time. We performed measurements after allowing the structure to process for 70 million pulses.

We calculated the rf breakdown rates for the period of 70-95 million pulses, Figure 4 shows a zoom in on this time period. Breakdown rate was measured for periods of time

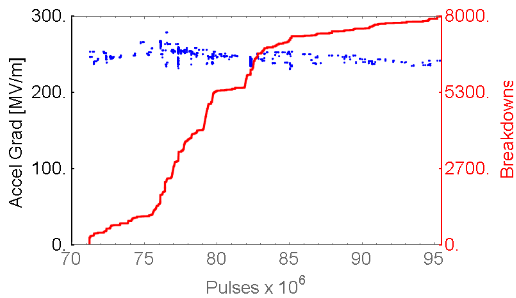

Figure 4: Breakdowns and calculated accelerating gradient for the processed structure that is used to measure rf breakdown rates.

where the gradient was relatively constant and the breakdown rate was in steady state for 1-3 million pulses. We measure first (or "trigger") breakdown rates and total breakdown rates as discussed in [21–23]. As stated in the previous sources, rf breakdowns can create breakdown chains, where a trigger breakdown will cause a number of breakdowns that are at the same or lower accelerating gradient. The first breakdown rate only counts the rate of the trigger breakdowns. Total breakdown rate counts all breakdowns, including the ones in breakdown chains.

The measured value for the first breakdown rate is 2×10^{-4} breakdowns/pulse/m at 250 MV/m and shaped pulse with 150 ns flat gradient. The total breakdown rate is 10^{-3} breakdowns/pulse/m for accelerating gradients of 250 MV/m at 150 ns pulse length. The 250 MV/m accelerating gradient corresponds to a 500 MV/m peak surface electric field for this accelerating structure. Figure 5 compares these measured rf breakdown rates to previous measurements in room temperature copper accelerating structures of the same shape (2.75 mm aperture radius).

In the future, we plan to find the dependency of rf breakdown rate on accelerating gradient. The preliminary data suggests that the dependence is steeper than that of room temperature cavities, that the rf breakdown rate will decrease rapidly as the accelerating gradient is decreased. In the described experiments we were not able to reliably measure very small breakdown rates.

CONCLUSION

We performed high gradient and rf breakdown rate measurements on a cryogenic copper single cell accelerating structure. In these experiments, we observed at high input rf power and very high gradients that the Q_0 changes during the rf pulse. The data suggests that one of the major reasons for the dynamic Q_0 degradation is dark current beam loading. To calculate the accelerating gradient we developed a method that takes into account the dynamic Q_0. We measured an rf breakdown rate of 2×10^{-4}/pulse/m at 250 MV/m accelerating gradient or 500 MV/m peak surface electric surface field for a shaped rf pulse with 150 ns of flat gradient. We are currently planning to use this improved high gradient performance of cryogenic accelerating cavities for an rf photoinjector[25], where a very large gradient could help to produce electron bunches with high brightness and low transverse emittances. The improved high gradient performance of cryogenic accelerators opens up other new possibilities for accelerator applications which require extreme gradients.

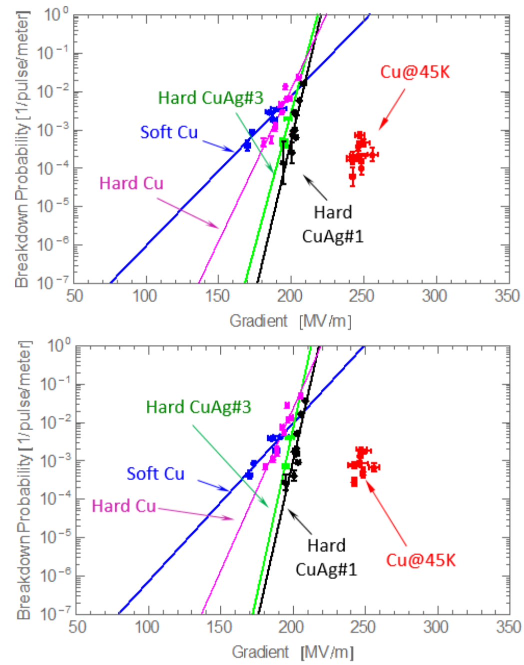

Figure 5: Breakdown rate vs. gradient: top) first, trigger rf breakdowns; bottom) all rf breakdowns. For the breakdown probability 10^{-3} – 10^{-4} 1/pulse/m cryo structure clearly outperforms record data from hard CuAg obtained in initial stages of conditioning. CuAg on final stages of conditioning very similar to hard Cu.

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