Vacuum radio-frequency (rf) breakdown is one of the major factors that limit operating accelerating gradients in rf particle accelerators. The occurrence of rf breakdowns was shown to be probabilistic, and can be characterized by a breakdown rate. Experiments with hard copper cavities showed that harder materials can reach larger accelerating gradients for the same breakdown rate. We study the effect of cavity material on rf breakdowns with short X-band standing wave accelerating structures. Here we report results from tests of a structure at cryogenic temperatures. At gradients greater than 150 MV/m we observed a degradation in the intrinsic cavity quality factor, $Q_0$. This decrease in $Q_0$ is consistent with rf power being absorbed by field emission currents, and is accounted for in the determination of accelerating gradients.

The structure was conditioned up to an accelerating gradient of 250 MV/m at 45 K with $10^8$ rf pulses and a breakdown rate of $2 \times 10^{-4}$/pulse/m. For this breakdown rate, the cryogenic structure has the largest reported accelerating gradient. This improved performance over room temperatures structures supports the hypothesis that breakdown rate can be reduced by immobilizing crystal defects and decreasing thermally induced stresses.

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I. INTRODUCTION

Accelerating gradient is one of the major parameters that determine the cost and viability of accelerator projects, such as large scale linear colliders for high energy physics and high brightness electron sources of free electron lasers (FELs), for example the Linac Coherent Light Source (LCLS) [1]. The major factor limiting larger accelerating gradients is vacuum rf breakdown [2–5], therefore breakdown physics is an active field of study with many contributors.

The accelerating gradient of the long-lived SLAC S-band linac is about 17 MV/m [6]. During development of the Next Linear Collider (NLC)/Global Linear Collider (GLC), an X-band test accelerator operated at 65 MV/m unloaded gradient [4,7]. The CERN based Compact Linear Collider (CLIC) design requires 100 MV/m loaded gradient at 12 GHz in accelerating structures with heavy wakefield damping [8]. Advances in understanding limitations on accelerating gradient go beyond linear colliders. rf accelerators are used in applications such as inverse Compton scattering gamma ray sources [9], compact free-electron lasers (FELs) [10,11], compact medical linacs for hadron therapy [12], photo-rf guns [13], 4-th harmonic linearizers for FELs [14], rf deflectors [15–17], and rf undulators [18,19], all may benefit from larger accelerating gradients. For example, if an S-band rf photoinjector that operates with sustained rf surface electric fields of 250 MV/m on the cathode is used as the electron source for LCLS [1], the required undulator length could be reduced by over 50% [20].

Early work by Loew et al. [21] and Balakin et al. [22] considered the rf breakdowns to be directly linked to peak electric field. Later, during the NLC/GLC work the statistical nature of rf breakdown became apparent [4,7,23,24]. For most accelerating structures at comparable rf power and pulse shape, the number of rf breakdowns per pulse is nearly steady or slowly decreasing over $10^5 - 10^7$ pulses. The breakdown rate (BDR) became one of the main quantitative requirements characterizing high gradient performance of linacs. For example: the CLIC linear collider requires rf breakdown probability to be less than $4 \times 10^{-7}$/pulse/m for a loaded accelerating gradient of 100 MV/m.

As technology progressed, sophisticated manufacturing and surface preparation techniques and systematic rf processing methods were developed [25–27]. As a result of this
R&D, practical 11.4 GHz Traveling Wave (TW) accelerating structures, which are CLIC prototypes, run at breakdown rates of about $10^{-3}$/pulse/m at unloaded gradients up to 120 MV/m and $\sim 200$ ns pulse length [28]. TW structures that include wakefield damping work at about 100 MV/m for similar breakdown rates [28,29]. Small copper standing wave (SW) structures at 11.4 GHz have reached 175 MV/m accelerating gradients with breakdown rates of $10^{-3}$/pulse/m.

### A. Properties of rf breakdowns

Presently, X-band structures are the most studied in terms of rf breakdowns [5,24,30-32]. We know that breakdown statistics depend on pulsed surface heating [33] and a numerous list of other factors, such as the peak electric field, the peak magnetic field [34], the peak Poynting vector [35], and hardness of the cavity material [36].

Typically, rf breakdowns can be separated into two categories: trigger and secondary breakdowns [37]. The secondary breakdowns occur in a chain after and appear to be caused by the trigger breakdowns. A secondary breakdown will occur within a short period of time after the trigger breakdown and can occur at significantly lower field levels. Commonly, the trigger breakdown rate is understood to be dependent on material properties and structure geometry, and secondary breakdowns are associated with damage caused by the trigger breakdowns. A publication analyzing the statistics of rf breakdowns in CLIC TW structures, showed the distribution of breakdowns in time can be analyzed by a double Poisson distribution and that pairs of breakdowns that are close temporally are also close spatially [38].

A review of existing experimental data with the goal of determining parameters that scale with the BDR of accelerating structures is reported in [35]. First, the BDR was empirically found to be dependent on accelerating gradient, $G$, as $\text{BDR} \propto G^{30}$ for many TW structures. Second, the BDR increases for longer pulse lengths, $t_p$, with BDR $\propto t_p^{\frac{3}{2}}$ for the same accelerating gradient. It was found that the modified Poynting vector is correlated with the BDR [35]. A recent review of the conditioning process of several TW structures showed that they conditioned at the same rate and to the same gradients with the same number of rf pulses, but not with the number of accumulated breakdowns [39].

A study of SW structures with varying geometries showed that breakdown rates correlate with peak rf pulsed heating rather than with peak rf electric fields [40]. This motivated work on the physics of periodic rf pulsed heating. At SLAC, a cavity was designed such that sample disks were not exposed to surface electric fields, but had enhanced surface magnetic fields [41]. The results were that harder materials, such as non-annealed CuAg, CuCr, and CuZr, exhibited significantly less damage than annealed copper samples, and also damage was apparent when the temperature of peak pulse heating reached greater than 50 K. Subsequently, short SW structures constructed from hard CuAg achieved accelerating gradients of 200 MV/m with breakdown rates near $10^{-3}$/pulse/m [36].

In another study, reported in [42], copper samples were prepared with the same heat treatment process as for accelerating structures, and then mechanically stressed for the same number of pulses as used for conditioning of accelerating structures. Comparison of the copper samples and autopsy of accelerating structures showed similar damage and mechanical hardening on the surface.

The current consensus is that vacuum rf breakdowns are caused by movements of crystal defects induced by periodic mechanical stress. The stress may be caused by pulsed surface heating and large electric fields. There are theoretical models [43,44] that predict the empirical $\text{BDR} \propto G^{30}$ power law dependence for room temperature copper structures. The same theory predicts that for lower temperatures the power law $\text{BDR} \propto G^\zeta$ has an exponent $\zeta$ greater than 30, and thus stronger gradient dependence than at room temperature.

Therefore, from the current understanding of rf breakdown physics, decreasing crystal mobility and reducing thermally induced stress should lower breakdown rates. This can be accomplished by operating accelerating structures at cryogenic temperatures.

### B. Cryogenic accelerators

One possible method to increase sustained electric fields in copper cavities is to cool them to temperatures below 77 K, where the rf surface resistance and coefficient of thermal expansion decrease, while the yield strength (which correlates with hardness) and thermal conductivity increase [45,46], all of which can affect the limits of sustained surface fields. The changes in rf surface resistance, coefficient of thermal expansion, and thermal conductivity decrease the pulsed surface heating and mechanical stress applied to the cavity material, the peak rf pulsed heating will decrease by over a factor of three by decreasing the temperature from room temperature to 45 K [47], and mechanical stress is proportional to the coefficient of thermal expansion times the peak pulsed heating. Increasing the yield strength decreases crystal mobility, while the changes in the other material properties decrease thermal stresses.

Of these properties, the decrease in rf surface resistance has been studied the most, which in cryogenic copper is well described by the theory of anomalous skin effect [48]. Measurements of the rf losses are in agreement with this theory to within 10% at a range of frequencies: 1.17, 1.4, 3, 5.7, 9.3, 11.4, and 35 GHz [49-57]. These experiments used the intrinsic quality factor, $Q_i$, of copper resonant cavities at very low fields and sub Watt rf power to measure the rf surface resistance.

However, there is little data on the sustainable electric fields of copper cavities at temperatures below 100 K with high input rf power, corresponding to surface electric fields greater than 75 MV/m. The results of an experiment at
9.3 GHz, 77 K, with 150–300 kW input peak power found surface electric fields up to 50 MV/m [55]. In another study conducted at 5.7 GHz, 20 K, showed surface fields up to 65 MV/m [51]. However, an experiment at 3 GHz, 77 K with surface electric fields up to 300 MV/m showed a decrease of $Q_0$ with increased fields [57]. The authors report that the decrease in $Q_0$ is correlated with surface magnetic fields and is possibly caused by multipactor discharge [58].

In the experiments above, the breakdown rate was not considered. A study conducted at CERN attempted to show the relation between rf breakdown rate and decreased temperatures. Cavities with frequencies between 21 and 39 GHz showed no dependence of breakdown rates on temperature between 100 and 800 K [59].

In our experiments we found that lowering the temperature of copper accelerating cavities allows them to sustain larger rf surface electric fields with decreased probability for vacuum rf breakdowns [60,61]. We also observed that the $Q_0$ decreases when accelerating gradients increase above 150 MV/m. We found that the explanation for the $Q_0$ degradation is dark current beam loading [62]. In this paper we present experiments conducted with a cryogenic accelerating structure, and the measured rf breakdown rates.

II. CAVITY DESIGN

Our cryogenic accelerating cavity is designed to have high fields in a single, middle cell. Fifty similar structures have been tested at SLAC [40,63–66]. The shape for the cryogenic cavity, 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC, was based on the geometry with the smallest aperture, $a = 2.75$ mm, which has the highest-shunt-impedance out of those tested at room temperature. The irises have an elliptical shape with thickness 2.0 mm. We use the same geometry to directly compare our room temperature results with those presented here. The structure is made of three cells with the highest fields in the middle cell, to localize rf breakdowns to that cell. The middle cell shape is designed to mimic the properties of a longer periodic accelerating structure.

The cryogenic cavity does not include a field probe, as they distort and amplify surface fields and degrade high power performance. To determine the electric fields we instead use the measured input rf power to the cavity (forward power), rf power reflected from the cavity, and signals from the current monitors which intercept the field emission currents.

rf power is coupled into the structure using a TM$_{01}$ mode launcher [67]. For the design of the structure, we used properties of cryogenic copper measured in previous experiments [54]. The structure was designed to be critically coupled, $\beta = 1$, at 96 K with $Q_0 = 19$, 100. At 45 K, the cryogenic cavity is over-coupled with $\beta = 2.12$, and at 293 K undercoupled with $\beta = 0.45$. The resonant frequency of the accelerating mode is 11.424 GHz at 150 K.

The rf parameters for a periodic structure with dimensions of the middle cell for 45 K and 293 K are in Table I, and the measured parameters for the tested cryogenic cavity at 45 K are in Table II. The electric and magnetic fields are shown in Fig. 1 and the surface fields are shown in Fig. 2. The peak pulsed heating is calculated using the following equation:

![FIG. 1. Electric and magnetic fields for the cryogenic cavity. The fields are scaled to 3.46 MW dissipated in the cavity walls. T = 45 K and $Q_0 = 30,263$. (a) shows the surface electric fields, with a maximum 507 MV/m. (b) shows the surface magnetic fields, with a maximum 736 kA/m.](image-url)

Here is the table for comparison:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>293 K</th>
<th>45 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-Value</td>
<td>8,590</td>
<td>29,000</td>
</tr>
<tr>
<td>Shunt impedance [MΩ/m]</td>
<td>102.891</td>
<td>347.39</td>
</tr>
<tr>
<td>$H_{\text{max}}$ [MA/m]</td>
<td>0.736</td>
<td>0.736</td>
</tr>
<tr>
<td>$E_{\text{max}}$ [MV/m]</td>
<td>507.8</td>
<td>507.8</td>
</tr>
<tr>
<td>$E_{\text{acc}}$ [MV/m]</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>$H_{\text{max}}Z_0/E_{\text{acc}}$</td>
<td>1.093</td>
<td>1.093</td>
</tr>
<tr>
<td>Losses in a cell [MW]</td>
<td>7.97</td>
<td>2.36</td>
</tr>
<tr>
<td>Peak pulsed heating (150 ns) [K]</td>
<td>86.9</td>
<td>21.9</td>
</tr>
<tr>
<td>$a$ [mm]</td>
<td>2.75</td>
<td>2.75</td>
</tr>
<tr>
<td>$a/\lambda$</td>
<td>0.105</td>
<td>0.105</td>
</tr>
<tr>
<td>Iris thickness [mm]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Iris ellipticity</td>
<td>1.385</td>
<td>1.385</td>
</tr>
</tbody>
</table>

Here is the table for full Cryo-Cu-SLAC-#2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$ [GHz]</td>
<td>11.4294</td>
</tr>
<tr>
<td>Q-Value</td>
<td>30,263</td>
</tr>
<tr>
<td>$H_{\text{max}}$ [MA/m]</td>
<td>0.736</td>
</tr>
<tr>
<td>$E_{\text{max}}$ [MV/m]</td>
<td>507.8</td>
</tr>
<tr>
<td>$E_{\text{acc}}$ [MV/m]</td>
<td>250</td>
</tr>
<tr>
<td>Coupling $\beta$</td>
<td>1.97</td>
</tr>
<tr>
<td>Power lost in walls [MW]</td>
<td>3.46</td>
</tr>
</tbody>
</table>
\[ \Delta T = |H|^2 \sqrt{\tau_p} \frac{R_s}{\sqrt{\pi \rho c_s k}}, \]

where \( \tau_p \) is the rf pulse length for a square pulse, \( R_s \) is the rf surface resistance, \( \rho \) is the density, \( c_s \) is the specific heat capacity, and \( k \) is the heat conductivity. We assume these parameters do not change during the pulse.

III. METHODS

A. Experimental setup

The cavity was placed inside a vacuum cryostat and cooled by a pulse tube cryocooler, the Cryomech PT-415. The cold head of the cryocooler was in thermal contact with the cavity. The input waveguide is fed from the outside of the cryostat by a TM01 mode launcher [67].

A heat shield separates the SW structure from the rest of the cryostat. A diagram and photo of the cryostat are included in Figs. 3 and 5.

We performed two experiments with identical structures, Cryo-Cu-SLAC-#1 and Cryo-Cu-SLAC-#2. The difference between the two was the following; in the first experiment the mode launcher was connected to the cavity with two rf chokes in a circular waveguide as described in [68]. These rf chokes create a gap in the circular waveguide that functions as a thermal break, preventing heat conduction from the room temperature waveguide to the cryogenic structure. However, the rf flanges and the current monitor shown in Fig. 3 connected the cryostat vacuum to that of the accelerating structure. This structure showed no improvement with decreased temperature and performed worse than previously tested structures. We speculated that gases from the vacuum of the cryostat contaminated the accelerating structure, causing and increase in the breakdown rate.

Following this experience, the feeding waveguide was modified to separate the cryostat vacuum from the accelerating vacuum. In the second experiment, we separate the cryostat and accelerator vacuum in the following ways; the rf chokes were removed and a thin 0.015 inch copper foil was introduced before the current monitor as shown in Fig. 3. The metal foil is thin enough to not significantly affect the near MeV field emitted electrons.

For low power measurements, we used a vector network analyzer (VNA), a Keysight N5242A. With the VNA we measured the dependence of the reflection coefficient on the rf frequency. Knowing this dependence we calculated \( Q_0 \) and other rf parameters using a linear equivalent circuit [69]. For high power tests, the rf source was a SLAC 50 MW XL-4 klystron, which was pulsed with a repetition rate of 5, 10, or 30 Hz and pulse length up to 500 ns. The rf pulses are shaped in a specific way for this experiment, and we will use \( t_1 \) and \( t_2 \) as shown in Fig. 6 to describe the pulse, where the input rf pulse is the green curve in Fig. 6(a). The initial 150 ns is at high power, and then the power is dropped to a lower at time \( t = t_1 \) value that

![FIG. 3. (a) Solid model of the cryostat and (b) zoom in on Cryo-Cu-SLAC-#2 in same model. (1) Cold head of cryocooler; (2) current monitor; (3) brazed metal foil; (4) Cryo-Cu-SLAC-#2; (5) rf flange; (6) thermal shield; (7) Cu-plated stainless steel waveguide; (8) rf input.](image-url)
The rf signals were sampled by two directional couplers (4) directly before the mode launcher. The forward and reflected signals were measured with a Keysight N9121A peak power meter (14) and downmixed to 115 MHz (15) to be read by a fast digitizer (13). Two current monitors (3) on both sides of the cavity intercept the field emission electrons, and were connected via coaxial cables to the digitizer. The dark current measured will be a small portion of the dark current inside the cavity.

### B. Data processing and gradient reconstruction

In our numerous previous experiments with room temperature cavities, the rf and dark current signals were well described by a linear equivalent circuit with a constant $Q_0$ [69], determined from VNA measurements. We will refer to this equivalent circuit as the linear model. However, during experiments with Cryo-Cu-SLAC-#2, we found that $Q_0$ degrades during the rf pulse, which will lower the peak accelerating gradient. We developed a model to account for the $Q_0$ degradation [62], which we will refer to as the nonlinear model. The decrease in $Q_0$ was found to be consistent with beam loading from the field emission currents.

To find the behavior of the electric field, we start with an eigensolution for electromagnetic fields in a perfectly conductive cavity with a resonant frequency of $\omega_0(t)$. Here, we assume that $\omega_0(t)$ is time-dependent. The magnitude of the electric field for the eigensolution is proportional to $\tilde{E}(t)$. Then there are two perturbations to the eigensolution, one the finite losses characterized by a time dependent quality factor $Q_0(t)$, and second one is a coupling to a waveguide with an external quality factor $Q_E$. We did not assume any specific model to describe the time-dependent losses or changing of the resonant frequency. Then we define a time dependent phasor of input power, $P_{in}(t)$, with constant frequency $\Omega$. Any time dependence of input frequency is contained in $P_{in}(t)$. For a detailed derivation of this equation, see [71].

When $Q_0$ and $\omega_0$ are time-dependent, $\tilde{E}(t)$, a variable proportional to the electric field inside the cavity, is governed by the following equation derived from the assumptions stated previously:

$$
\sqrt{\frac{8P_{in}(t)\omega_0(t)^3}{\varepsilon_0 Q_E}} = \frac{d\tilde{E}(t)}{dt} \left[ \frac{\omega_0(t)}{Q_E} + \Omega \left( \frac{1}{Q_0(t)} - 2i \right) \right] + \tilde{E}(t) \left\{ [\omega_0(t)^2 - \Omega^2] - i\Omega \left( \frac{\Omega}{Q_0(t)} + \frac{\omega_0(t)}{Q_E} \right) \right\},
$$

where $\Omega$ is the driving frequency of the input rf, $P_{in}$ is the input rf power, $Q_E$ is the external quality factor, $\varepsilon_0$ is the vacuum permittivity, and $i = \sqrt{-1}$. Here we assumed $Q_E$ is constant in time and that $Q_0 \gg 1$. The variation of input phase is contained in the complex function $P_{in}(t)$, so $\Omega$ is
also constant for this calculation. The behaviors of \( Q_0(t) \) and \( \omega_0(t) \) are described in detail in [62].

This equation is derived directly from Maxwell’s equations for electromagnetic fields in a resonant cavity. In the case that the quality factor and resonant frequency are constant, this equation can be reduced to the standard linear equivalent circuit [71]:

\[
\frac{d^2}{dt^2} + \frac{\omega_0}{Q_L} \frac{d}{dt} + \omega_0^2 \tilde{E}(t) = -\sqrt{\frac{8 \mu_0 \omega_0^3 \mu_0 Q_L}{\delta \omega}}. \tag{2}
\]

Using the nonlinear model, we were able to successfully reconstruct the accelerating gradient, proportional to \( \tilde{E}(t) \), using the measured rf and dark current signals. We present an example of the accelerating gradient reconstruction in Fig. 6. In this figure, the difference between the linear and nonlinear models are apparent in the reconstructed dark current signal.

The model does not include any assumptions to what physical phenomenon causes the frequency shift presented in the nonlinear model. Our hypothesis is that the presence of strong currents inside the resonant cavity will not only absorb rf power but will also drive the fields in the cavity. This beam driven power may manifest as a frequency shift in the measured signals. Study of this phenomenon is outside the scope of this paper, but in the future, to test this hypothesis, we will perform self-consistent particle in cell simulations of dark currents in the rf structure similar to [31].

IV. RESULTS

A. Low power measurements

We performed two sets of low power measurements, one before and one after the high power test. In the initial low power set, we measured the resonant frequencies of the three modes for Cryo-Cu-SLAC-#2, and performed a bead pull measurement at room temperature. Results of these tests are included in Fig. 7. The procedure for bead pull measurements is outlined in [72]. In the second set of tests, we used the VNA to measure the \( Q_0 \) of all three modes from 10 to 250 K. The results are shown in Fig. 8.

B. High power measurements

Figure 9 shows the processing history of Cryo-Cu-SLAC-#2, including the temperature, number of accumulated rf breakdowns, and the accelerating gradient in time. In Fig. 9(b) the nonlinear model was used to calculate the accelerating gradient after \( 70 \times 10^6 \) pulses. For pulses before that the linear model was used and may overestimate the gradient. Figure 10 shows a zoom in after \( 70 \times 10^6 \) pulses. We used data from this time period to calculate the rf breakdown rate. Breakdown rate was measured for periods of 1-3 million pulses where the gradient and rate of breakdowns were relatively constant. We measured both trigger breakdown rates and total breakdown rates as discussed in [63–65].

The measured value for the trigger breakdown rate is \( 2 \times 10^{-4} \)/pulse/m and total breakdown rate of...
\[10^{-3}/\text{pulse/m both for } 250 \text{ MV/m and a shaped pulse with } 150 \text{ ns flat gradient. } 250 \text{ MV/m accelerating gradient corresponds to a } 507 \text{ MV/m peak surface electric field for this accelerating structure. Figure 11 compares these rf breakdown rates to previous measurements in room temperature copper, hard copper, and hard CuAg accelerating structures of the same shape (2.75 mm aperture radius) \text{[36]. The data shows that for a given breakdown probability near or below } 10^{-4}/\text{m/pulse the sustained accelerating gradient increases going from soft Cu to hard Cu and to hard CuAg structures. Finally, the copper structure at cryogenic temperatures reaches larger accelerating gradients for the same breakdown rate, and is the highest recorded gradient in X-band rf structures for this breakdown rate. This behavior is different than that found in \text{[59], where temperature did not have an effect on the rf breakdown rate.}

Due to conditions of this experiment, it is very difficult to obtain enough data to fully characterize the statistical behavior of the phenomenon. A zoom in on the graph will give the impression that there is a fine structure in the data, which is not present.
A. Effect of dynamically changed quality factor on calculated gradient

This is the first of our experiments where the field emission current beam loading has become a significant factor. We developed a model to account for the resultant emission current beam loading has become a significant factor on calculated gradient. We optimize input rf pulse by making dark current flat in a second part of the pulse, between \( t_1 \) and \( t_2 \) on Fig. 6. At high gradient the \( Q_0 \) is decreased by loading from field emission currents, and the pulse shape is optimized for this decreased \( Q_0 \). If for the same pulse shape, we use the unchanged \( Q_0 \), the calculated gradient would not increase significantly. In the example pulse shown in Fig. 6, \( Q_0 \) decreases from 30,300 to 17,900, but the average gradient (average over \( t_1 \) to \( t_2 \)) of the resonant cavity only changes from 248 MV/m to 237 MV/m when comparing the constant \( Q_0 \) linear and time-dependent \( Q_0 \) nonlinear models. The change in gradient is relatively small for two reasons: the external quality factor \( Q_e = 15347 \) is smaller \( Q_0 \) at this temperature and the decrease in \( Q_0 \) changes the coupling closer to critical \( \beta = 1 \). For the same power level, we would only expect the asymptotic accelerating gradient to increase by about 20% for this drop in \( Q_0 \). Second, the forward rf pulse is optimized to create a flat gradient for the smaller \( Q_0 \). For this same pulse, a cavity where the \( Q_0 \) does not decrease would not reach the asymptotic gradient. Thus the average over where the gradient should be flat is instead an average over a growing function of gradient, and is lower than the asymptotic gradient.

B. Structure damage

The low power measurement of \( Q_0 \) at cryogenic temperatures, shown in Fig. 8, occurred after Cryo-Cu-SLAC-#2 had been exposed to large accelerating gradients. The design value of \( Q_0 \) at 45 K, obtained from our previous low power cryogenic copper experiments, is near 36,000, but the measured value is only 30,263. We conjecture that the smaller \( Q_0 \) was caused either by damage during high power operation, or by surface degradation when the tested cavity was vented to perform low power measurements. This conjecture is further supported by the lower \( Q_0 \) in the \( \pi \) mode when compared to the other resonant modes. The \( \pi \) mode would be the most affected by damage or surface degradation to the middle cell, where the \( \pi/2 \) mode would be affected the least, which we see in Fig. 8.

We performed an autopsy on the structure. The preliminary results are reported in [73]. We did not find any unusual concentrations of breakdown damage. The breakdown pits are mostly located in area of high electric and high peak Poynting vector. This pattern is typical for structures of the same geometry [74]. What was unusual for this particular structure, is an absence of damage due to pulse heating in areas of maximum rf magnetic field, typically observed at similar gradients and rf pulse lengths [74]. We speculate that the absence of the damage is related to the properties of the copper at cryogenic temperatures. We also speculate that the lower \( Q_0 \) mentioned in the previous paragraph stems from surface degradation from exposure to air, rather than damage from high power operation.

C. Future directions

Next, we plan to confirm reproducibility of the high power results with a third identical structure, Cryo-Cu-SLAC-#3, that has been manufactured and the geometry was successfully verified via a bead pull test. The current experiment was limited to running in day-long increments and thus we were not able to accurately measure BDRs less than \( \sim 10^{-4} \)/pulse/m, which corresponds to a few breakdowns per day, due to a lack of statistics. The next installation will be operated continuously for many days and will be able to measure the BDR for lower gradients.

This continuous operation will allow us to measure the exponent, \( \zeta \) for the power law dependence BDR \( \propto G^\zeta \) and repeat this measurement at different operating temperatures from 25 K to 77 K. This enables us to verify the theory proposed in [43], which predicts a stronger power law dependence between BDR and accelerating gradient for both harder and colder structures.
We plan to continue experiments at cryogenic temperatures with structures of different materials, such as CuAg, and at a lower frequency, S-band. The details of the S-band experiment are presented in [75].

VI. CONCLUSION

We studied the physics of vacuum rf breakdown using 11.4 GHz cryogenic normal conducting accelerating cavities. Decreasing the temperature of copper causes an increase in hardness and thermal conductivity, while decreasing the coefficient of thermal expansion and rf surface resistance. These changes of the material properties decrease both thermally induced stress and crystal defect mobility, which may lead to the decreased rf breakdown rate. The structure was processed to 250 MV/m and corresponding peak surface electric fields of 500 MV/m with $10^8$ rf pulses and had a trigger breakdown rate of $2 \times 10^{-4}$/pulse/m for a shaped pulse with 150 ns flat gradient. For the same breakdown rate, the accelerating gradient is larger than that of room temperature structures of the same geometry. These results are different than those presented in [59], where decreased temperature of the accelerating structure did not affect the rf breakdown rate. The better performance observed in the cryogenic accelerating structure supports the hypothesis that rf breakdowns are caused by movement of crystal defects.

A factor of two increase in accelerating gradient over the current copper accelerators of the same frequency will enable a multitude of applications. One compelling application is, if the peak surface electric field of an rf photo-injector for LCLS was increased by a factor of two, the required undulator length could be reduced by more than a factor of two and increase the X-ray photon energy [20].

ACKNOWLEDGMENTS

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