EVIDENCE OF MAGNETIC BREAKDOWN ON THE DEFECTS WITH THERMALLY SUPPRESSED CRITICAL FIELD IN HIGH GRADIENT SRF CAVITIES*

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Abstract

At SRF 2011 we presented the study of quenches in high gradient SRF cavities with a dual mode excitation technique [1]. The data differed from measurements done in 80's that indicated a thermal breakdown nature of quenches in SRF cavities [2]. In this contribution we present analysis of the data that indicates that our recent data for high gradient quenches is consistent with magnetic breakdown on defects with thermally suppressed critical field. From the parametric fits derived within the model we estimate the critical breakdown fields.

INTRODUCTION

One of the fundamental questions about RF properties of superconductors is the ultimate limitation in RF fields. The best SRF cavities lose their superconductivity at about B$_{peak}$ = 180 - 200 mT, which is close to niobium thermodynamic critical field. How the cavity breakdown field relates to the material critical field is not evident, because RF fields heat up the surface and magnetic and thermal effects on the superconducting RF breakdown become entangled.

To distinguish between thermal and magnetic effects on the superconducting RF breakdown, simultaneous excitation of two modes have been preformed in the past [2]. The data was fitted with the expected behavior for thermal breakdown. Our data deviates from the the behavior observed in the past. Here, we show that the data can be explained within a model, in which the critical magnetic field is adjusted for RF surface temperature change due to RF dissipation.

RF BREAKDOWN MODEL

Temperature mapping results on superconducting RF cavities show that in the medium field region the field dependence of the measured temperature is approximately quadratic, so we will assume that RF surface temperature can be expressed as:

$$T_{\rm RF} \cong T_0 + C \cdot H^2, \tag{1}$$

In the case when two modes are mixed, the product of two fields will vanish when averaged over time due to different resonant frequencies, and so the temperature can be expressed as:

$$T_{\rm RF} \cong T_0 + C \cdot (H_1^2 + H_2^2) \tag{2}$$

We will assume that the magnetic breakdown occurs when the sum of RF field amplitudes exceeds the RF critical field, i.e., $H_1 + H_2 = H^{\rm RF}_{\rm crit}(T)$, and we will use the quadratic approximation for the temperature dependence of the thermodynamic critical field [3] to model the temperature dependence of RF critical field:

$$H_c(T_{RF}) = H_c\left(1 - \left(\frac{T_{RF}}{T_C}\right)^2\right), \tag{3}$$

where H_c is $H_c(0)$, the critical field at zero temperature, T_c is the critical temperature, and T_{RF} is the temperature of the RF surface. Lastly, we will assume that, if two RF fields are applied, then the critical condition is when the sum of the field amplitudes of two modes is equal to the critical magnetic field:

$$H_1 + H_2 = H_c\left(1 - \left(\frac{T_0 + C\cdot(H_1^2+H_2^2)}{T_C}\right)^2\right), \tag{4}$$

where T_c and H_c are the critical temperature and the magnetic field, and we used (1) for RF surface temperature. When only one field is applied:

$$H_{\rm max} = H_c\left(1 - \left(\frac{T_0 + C\cdot H_{\rm max}^2}{T_C}\right)^2\right), \tag{5}$$

where $H_{\rm max}$ is the breakdown field amplitude. Equations (4) and (5) can be reduced to:

$$\begin{aligned}&\left(\frac{H_1}{H_{\rm max}} + \frac{H_2}{H_{\rm max}}\right) + \\ &\frac{2H_cT_0H_{\rm max}C}{T_c^2} \times \left(\left(\frac{H_1}{H_{\rm max}}\right)^2 + \left(\frac{H_2}{H_{\rm max}}\right)^2\right) + \\ &\frac{H_cH_{\rm max}^3C^2}{T_c^2} \times \left(\left(\frac{H_1}{H_{\rm max}}\right)^2 + \left(\frac{H_2}{H_{\rm max}}\right)^2\right)^2 \\ &= 1 + \frac{2H_cT_0H_{\rm max}C}{T_c^2} + \frac{H_cH_{\rm max}^3C^2}{T_c^2}\end{aligned} \tag{6}$$

If we define $1/\alpha = 1 + \frac{2H_cT_0H_{\rm max}C}{T_c^2} + \frac{H_cH_{\rm max}^3C^2}{T_c^2}$ and normalize the fields H_1 and H_2 to H_{max}, the resulting equation

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can be written in terms of α, T_0, T_c and normalized fields $\tilde{H}_1$ and $\tilde{H}_2$ as:

$$\alpha(\tilde{H}_1+\tilde{H}_2)+ \\ 2\frac{T_0^2}{T_c^2-T_0^2}\left(\sqrt{\frac{T_c^2}{T_0^2}(1-\alpha)+\alpha}-1\right)(\tilde{H}_1^2+\tilde{H}_2^2)+ \\ \frac{T_0^2}{T_c^2-T_0^2}\left(\sqrt{\frac{T_c^2}{T_0^2}(1-\alpha)+\alpha}-1\right)^2(\tilde{H}_1^2+\tilde{H}_2^2)^2=1 \tag{7}$$

To understand the physical meaning of α quantitatively, we expand the equation (4) and, after combining with equation (6) and the definition of α, the fitting parameter α can be re-written as:

$$\alpha=\frac{H_{\max}}{H_c\left(1-\left(\frac{T_0}{T_C}\right)^2\right)} \tag{8}$$

This expression illustrates the physical meaning of the fitting parameter α. The fitting parameter quantifies how much the material critical field is suppressed due to RF surface temperature increase over the liquid helium bath temperature. In analogy with geometrical field enhancement factor, α can be called *the thermal suppression factor*.

Let us consider two limiting cases. First, we will assume that α is close to 1, that is $\alpha = 1-\delta$, where $\delta << 1$. Expanding equation (7) and dropping quadratic and higher order terms in δ, we obtain the following expression for mode-mixing:

$$\alpha(\tilde{H}_1+\tilde{H}_2)+(1-\alpha)(\tilde{H}_1^2+\tilde{H}_2^2)=1 \tag{9}$$

From this equation we can see that $\alpha = 1$ means a purely magnetic quench. As α departs from one, the thermal effects become more pronounced.

Let us assume that α is close to 0, that is $\alpha = o(1)$. Combining eq. 8 and eq. 5, we can reduce eq. 1 to:

$$H_{\max}=\sqrt{\frac{T_c-T_0}{C}}, \tag{10}$$

which resembles the expression for the thermal breakdown in [4].

EXPERIMENTAL DATA FITS AND DISCUSSION

Measured mode-mixing data is normalized to the quench field in each mode and presented on an x-y plot. Each data point on the x-y plot corresponds to a single RF breakdown event during mode-mixing. The abscissa of the point is equal to one of the mixed fields' normalized amplitude; the ordinate of the point is equal to the other field's normalized amplitude. As the result, an x-y dependence connecting points (0,1) and (1,0) is plotted. To fit the experimental

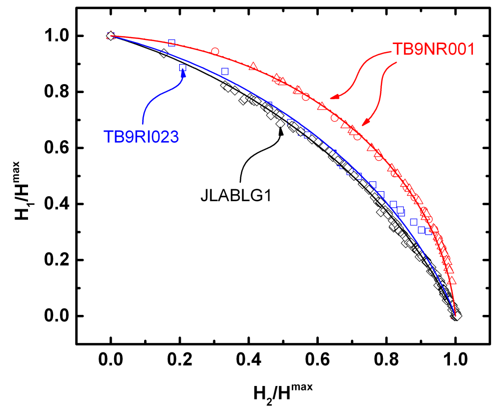

Figure 1: RF mode-mixing measurements of TB9NR001, TB9RI023, and JLab-LG-1. Open blue squares present the data for 6π/9 and 5π/9 mode mixing in TB9RI023; the blue solid line present the best fit using (7) with the best fit α of 0.58 ± 0.02. Open red circles and triangles present the data for π & 7π/9 and 3π/9 & 7π/9 of TB9NR001 mode mixing; the best fits are presented with solid and dot red lines; the best fits for α are 0.20 ± 0.01 and 0.19 ± 0.01 respectively. JLab-LG-1 π & 6π/9 mode-mixing results are shown with black rhombs. The best fit α = 0.63 $\pm$ 0.00 is shown with the solid black line.

data we used:

$$\alpha(\tilde{H}_1+\tilde{H}_2)+ \\ 2\frac{T_0^2}{T_c^2-T_0^2}\left(\sqrt{\frac{T_c^2}{T_0^2}(1-\alpha)+\alpha}-1\right)(\tilde{H}_1^2+\tilde{H}_2^2)+ \\ \frac{T_0^2}{T_c^2-T_0^2}\left(\sqrt{\frac{T_c^2}{T_0^2}(1-\alpha)+\alpha}-1\right)^2(\tilde{H}_1^2+\tilde{H}_2^2)^2=1, \tag{11}$$

where α is a fitting parameter and $\tilde{H}_1$ and $\tilde{H}_2$ are the field amplitudes of each mode normalized to the maximum field amplitude measured with single-mode excitation. The critical temperature T_c is set to 9.25 K, and the bath temperature T_0 is set to 2 K.

In Fig. 1 the results from dual mode excitation measurements of π & 7π/9 and 3π/9 & 7π/9 modes along with the best fits are presented. More details on the measurement can be found in [1]. The TB9NR001 measurements best fit for π & 7π/9 is 0.20 $\pm$ 0.01, the best fit for 3π/9 & 7π/9 is 0.19 $\pm$ 0.01. The TB9RI023 measurements best fit for 5π/9 & 6π/9 is 0.58 $\pm$ 0.02. JLab-LG-1 was limited in π mode by a defect in the sixth cell at B_{peak} = 86 $\pm$ 5 mT. The same limitation was encountered in 6π/9, 4π/9, and π/9 modes. The results for $\pi(f^{\pi}_{\text{TM}_{010}} \cong 1.30054$ GHz) and 6π/9($f^{\pi}_{\text{TM}_{010}} \cong 1.29365$ GHz) mode-mixing are shown in Fig.1. The best fit yields 0.63 $\pm$ 0.01.

Using the equation (8), the quench fields, and the fitting parameter α we can infer the material critical field at the

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quench site for the three quenches. From the quench field in TB9NR001 of $\approx$ 70 mT and α = 0.2, we infer the material critical field in TB9NR001 is $\approx$ 350 mT. This value is about 50 percent higher than 240 mT at 2 K, typically assumed to be the limiting superheating field of niobium [5, 6]. We speculate that the discrepancy stems from the assumption that the breakdown is magnetic, whereas in TB9NR001 the quench is likely to be a thermal quench from a normal conducting inclusion[7]. If the quench in TB9NR001 is in fact thermal then equation (4) does not describe the breakdown condition and equation (8) is not applicable. From the quench field in TB9RI023 of $\approx$ 140 mT and α = 0.58, we infer the material critical field in TB9RI023 is $\approx$ 241 mT. This value compares well with 240 mT for the generally accepted value of the superheating field. We note that in the case of TB9RI023, the quench site was off the equator, and therefore the derived quench field, which is the calculated peak magnetic field in the cell, is overestimated. From the quench field in JLAB LG-1 of $\approx$ 86 mT and α = 0.63, we infer the material critical field in JLAB LG-1 is $\approx$ 137 mT. This value is about 40 percent lower than 240 mT, which can be understood, if we take into account a geometrical field enhancement factor of the large grain cavity. We note that in JLAB LG-1 a sharp feature was found at the quench location[8].

CONCLUSION

We have developed a model to analyze the RF breakdown of superconductivity in multicell superconducting radio frequency cavities. Within our model, the mode-mixing experimental data in several cavities is explained by a magnetic breakdown distorted by heating on the RF surface. The mode-mixing data can be fit with one fitting parameter. The fitting parameter within our model indicates how strongly the magnetic breakdown is distorted by the heating on the RF surface. From the measured quench field and the best-fit fitting parameter, we estimated the critical field at the quench sites.

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