INVESTIGATION OF THE SURFACE RESISTIVITY OF SRF CAVITIES VIA THE HEAT AND SRIMP PROGRAM AS WELL AS THE MULTI-CELL T-MAP SYSTEM*

M. Ge#, F. Furuta, D. Gonnella, G.H. Hoffstaetter, M, Liepe, H. Padamsee,
Cornell University, Ithaca, NY, 14853, USA

Abstract

The thermal feedback model with the linear BCS resistance which were believed not strong enough to explain medium-field Q-slope (MFQS) is still valid. The HEAT and SRIMP program (H&S program) which adopted the SRIMP code for BCS resistance calculation allows inputting full material parameters, hence is able to simulate different cavity cases e.g. baked, unbaked, BCP'd, EP'd, and so on. The results agree with the measurement data from the low-field up to the hot-spots onset field. With the T-map data, it's a clear view that the localized hot-spots occur above MFQS region and caused high-field Q-slope.

INTRODUCTION

The surface resistance of superconductor under RF field is a critical topic, because it determines the Q-value of SRF cavity in accelerating fields. The thermal feedback model with the linear BCS resistance was developed for Medium-Field Q-Slope (MFQS) study [1]. However, the thermal feedback model was believed not strong enough to account for the observed MFQS [1-3]. In this work, we explain that the thermal feedback model with linear BCS model is still valid for MFQS and the localized hot-spots cause the Q-slope in high fields.

HEAT AND SRIMP PROGRAM

The surface resistance of superconductor under RF field includes two parts, one is BCS resistance (R_{BCS}) and the other is residual resistance (R_0), shown in equation (1). And equation (2) is the simplified R_{BCS} forms.

$$R_s = R_{BCS} + R_0 \tag{1}$$

$$R_{BCS} = A\left(\frac{1}{T}\right) f^2 \exp\left(-\frac{\Delta}{kT}\right) \tag{2}$$

Here, the factor A is a constant which determined by material property such as mean free path (l) *etc.*, Δ is the energy gap, f is the frequency.

The traditional HEAT program [4] uses Pippard approximation [5]:

$$R_{BCS}(T) = (2.78\times10^{-5}\Omega)\frac{\nu^2}{t}\left(\frac{148t}{\nu}\right)\exp\left[-\frac{1.81g(t)}{t}\right] \tag{3}$$

$$t = \frac{T}{T_c},\quad \nu = \frac{f}{2.86GHz},\quad g(t) = \left[cos\left(\frac{\pi t^2}{2}\right)\right]^{1/2} \tag{4}$$

where f is the frequency of the RF field, T is the temperature. However in equation (3) and (4), it doesn't consider the Nb property. Comparison between baked and un-baked cases, the mean free path l is reduced by baking. Hence the factor A in equation (2) is changed and decreases the BCS resistance after baking. But equation (3) and (4) are unable to reflect the changes.

The improved HEAT program, HEAT and SRIMP code (H&S code), uses SRIMP [6, 7] to replace the equation (3) and (4). The SRIMP was written by Jurgen Halbritter for the BCS surface resistance calculation. The method of calculation incorporates the full BCS theory. Five material parameters are required to describe the superconductor:

- The superconducting transition temperature T_c;
- The energy gap (entered as Δ/kT);
- The London penetration depth, λ at T=0;
- The coherence length, ξ at T=0;
- The electron mean free path, l, at 4.2 K.

MULTI-CELL T-MAP SYSTEM

The T-map system is known as a powerful tool for surface resistance research. It's able to detect tiny heating on exterior wall on cavities. Cornell University developed a multi-cell T-map system [8] shown in Figure 1 with 1 mK temperature resolution.

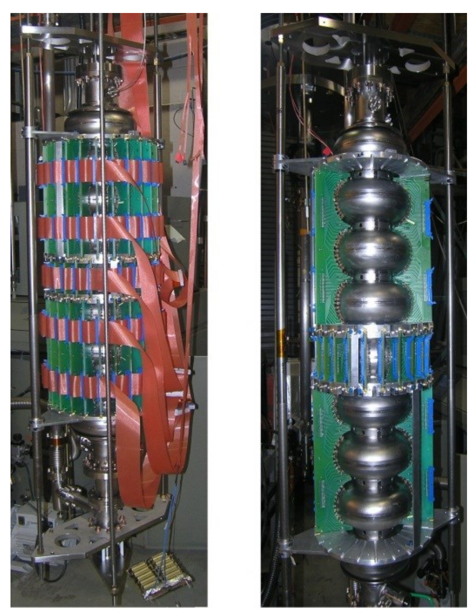


Figure 1: Picture of the Cornell multi-cell T-map system.

*Work supported by NSF award PHY-0969959 and DOE award DOE/SC00008431
#mg574@cornell.edu

SURFACE RESISTANCE ANALYSIS

The EP'd and BCP'd Cavity Cases

Figure 2 is the comparison Q vs. E curves between H&S program calculation and RF measurement from 1.7 to 2K. The plot shows the calculation agrees with the measurement results well. The cavity is TELSA single-cell cavity NR1-3. The cavity was EP'd and 120°C baked. During the test, the cavity was FE and quench free.

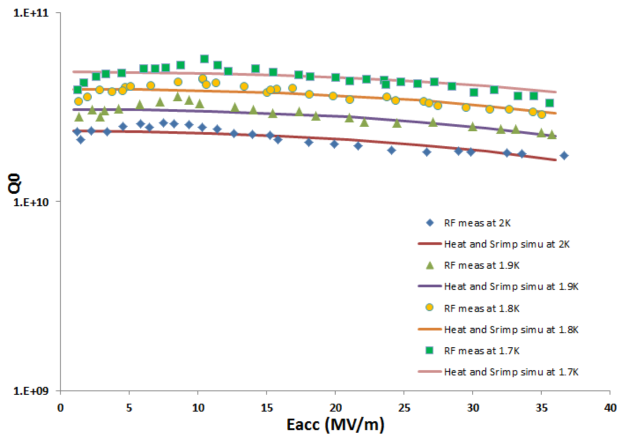


Figure 2: Comparison of H&S calculation and RF measurement at different temperatures for EP'd cavity.

The Q_0 versus Temperature data measured at low accelerating field was fitted by the SRIMP to obtain the material parameters mentioned in previous section. Figure 3 is the Q-T fitting curve of the cavity NR1-3. In the fitting, we use surface RRR value to represent electron mean free path [9]. The parameters are shown in table 1.

Table 1: Material Parameters

Parameters	value
T_c (K)	9.2
Energy gap	1.891
λ(A)	360
ξ(A)	640
Surface RRR	4.4
Residual resistance (R_0) ($n\Omega$)	4

Here we selected the residual resistance, energy gap, and surface RRR as fitting parameters. The cavity was 120°C baked; therefore the surface RRR was reduced. Converted the surface RRR to electron mean free path, the value is about 119 Angstrom. The detail of the conversion is discussed in the reference [9].The BCS resistance is minimum when mean free path is around 120 Angstrom [1].

The figure 4 shows the comparison of the BCP'd cavity case. The cavity is the 7-cell cavity ERL 7-4 for Cornell ERL project. The cavity was BCP'd more than 100 μm; then the cavity was furnace treated under 650°C vacuum;

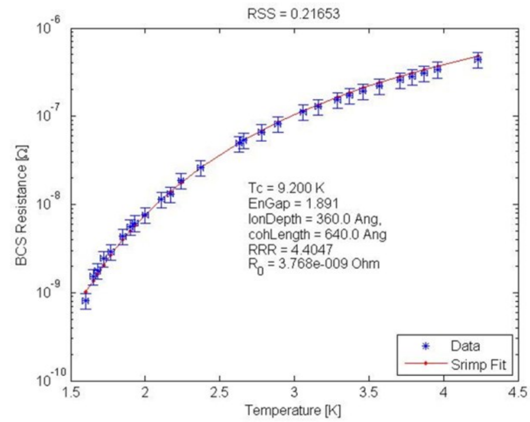


Figure 3: Q vs. T curve fitted by the SRIMP code.

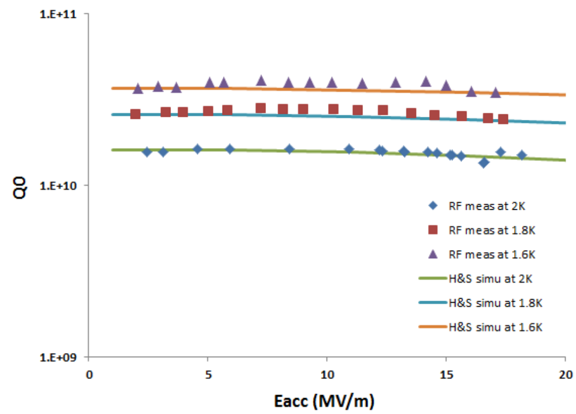


Figure 4: Comparison of H&S calculation and RF measurement at different temperatures for BCP'd cavity.

after light-BCP, the cavity was 120°C baked in furnace followed by HR rinsed; and then the cavity was HPR'd and assembled in class 10 cleanroom.

The SRIMP code fitting from the Q_0 versus Temperature data indicates that the R_0 is about 5.6 $n\Omega$; the energy gap is 1.825; and the surface RRR is about 4.56. Using these parameters as the input of H&S program, the result agrees with the RF measurement very well at different temperatures.

The Baked and Unbaked Cavity Cases

In EP'd and BCP'd cavity cases, it suggests that 120°C baking plays an important role in reducing the BCS resistance to minimum. The H&S program is able to reflect the baking effect. In the figure 5, there is the comparison between the cavity NR1-2 baked and un-baked cases. The NR1-2 cavity was EP'd about 30 μm, and was tests before and after 120°C baking. The table 2 shows the material parameters comparison fitted by SRIMP. The surface RRR was reduced from 38 to 6.9, and energy gap was increased from 1.86 to 1.956. The changing of the parameters reduced BCS resistance from 13.78 $n\Omega$ to 6.02 $n\Omega$ at the accelerating gradient equalling 2 MV/m; however the residual resistance was increased from 4.5 $n\Omega$ to 10.16 $n\Omega$; the total surface resistance was reduced from 18.27 $n\Omega$ to 16.18 $n\Omega$ at 2 MV/m, which is shown in table 3.

ISBN 978-3-95450-143-4

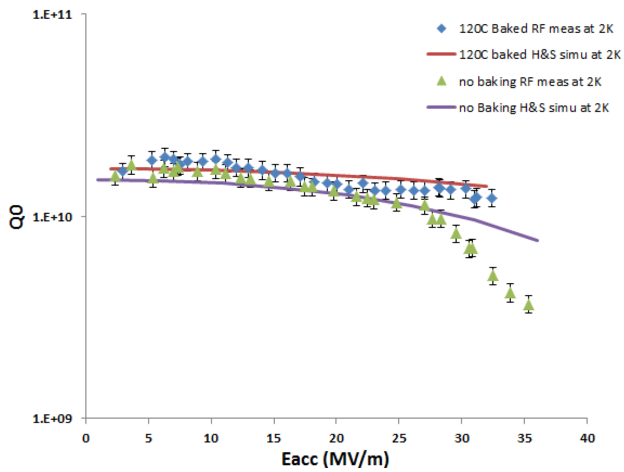


Figure 5: Comparison of H&S calculation and RF measurement between the baked and the un-baked cavity.

Table 2: Material Parameters Comparison of NR1-2

Parameters	Baked	Un-baked
T_c (K)	9.2	9.2
Energy gap	1.959	1.86
λ(A)	360	360
ξ(A)	640	640
Surface RRR	6.9	38
Residual resistance (R_0) ($n\Omega$)	10.16	4.5

Table 3: Surface Resistance Comparison of NR1-2

Parameters	Baked	Un-baked
BCS resistance at 2MV/m ($n\Omega$)	6.02	13.78
Residual resistance ($n\Omega$)	10.16	4.5
Surface resistance at 2MV/m ($n\Omega$)	16.18	18.27
Q_0 at 2MV/m	1.72×10^{10}	1.52×10^{10}

In the un-baked cavity case, the H&S program's calculation agrees with the measurement data up to 25 MV/m above which the obvious discrepancy occurs. The cause of the discrepancy is the localized hot-spots based on the T-map data which will be shown in next section.

The Localized Hot-spots and High-field Q-slope

From the cavity NR1-2 measurement data (the un-baked case), we found that all the hot-spots present above the 25 MV/m where the onset of the Q-slope is. The figure 6 shows the temperature map at 25 MV/m, which has no hot-spots.

Figure 7 (a) is the temperature map of the cavity NR1-2 at 32MV/m, and (b) is the temperature map after the baking. By the contrast, we clearly see the hot-spots were suppressed by the baking, and the Q-value was recovered. Before the baking, the cavity was no quench; and the performance limited by RF power source. After the baking, the cavity limited by the hard quench at 32MV/m.

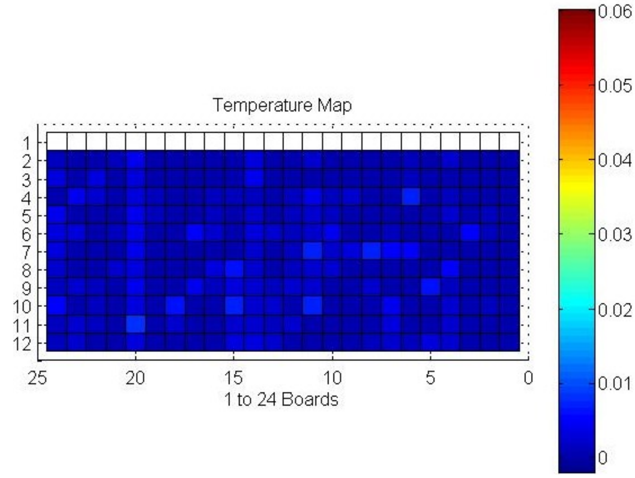
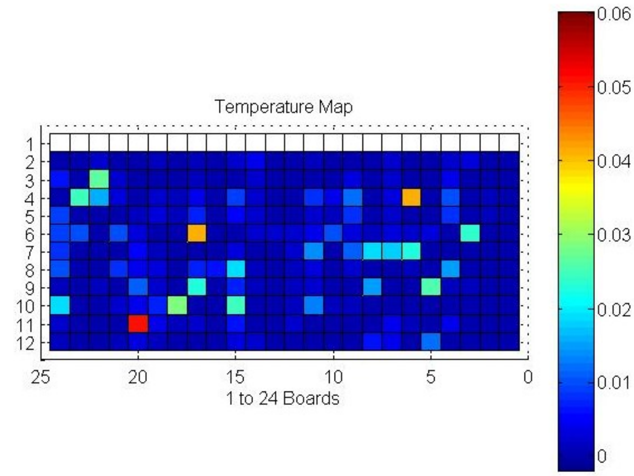
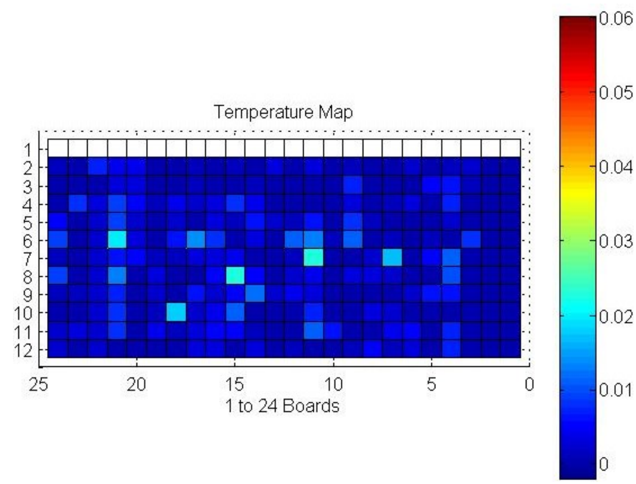


Figure 6: the temperature map at 25 MV/m



a) The temperature map of before the baking at 32 MV/m



b) The temperature map of after the baking at 32MV/m

Figure 7: Temperature map comparison of NR1-2 before and after the baking at 32 MV/m.

ISBN 978-3-95450-143-4

The sensor in 11th row and 20th column shows the highest temperature increase in the figure 7 (a), and the value is closed to 0.11K. The figure 8 shows the heating versus accelerating gradient (E_{acc}) of the sensors (11, 20), (4, 6), (6, 17), (3, 22). The comparison curve from the sensor (3, 3) was selected because the sensor located in non-heating region.

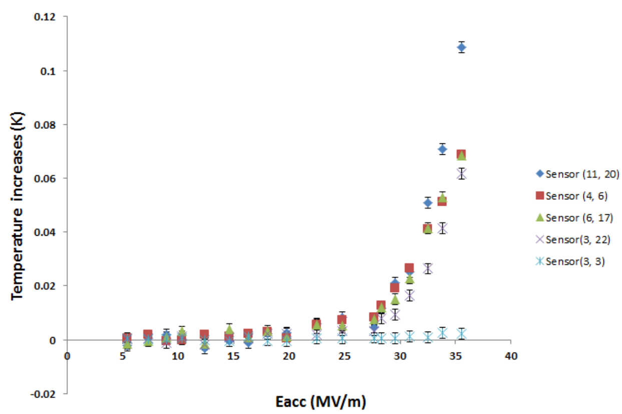


Figure 8: the temperature increases vs. accelerating gradient.

The H&S program is able to calculate the surface resistance of the hot-spots based on the T-map data. The program treats the residual resistance within one sensor coverage area as uniformed; in other words, the program utilizes the average residual resistance value within one sensor. To obtain the power loss on one hot-spot, the program gradually increases residual resistance thus increase the heating on exterior wall. The calculation ceases when the heating on exterior wall matches the T-map data. The power loss in none hot-spots region is mainly caused by BCS heating. Summing the power loss on each sensor region, the cavity Q_0 is obtained. The figure 9 depicts the calculated Q_0 of NR1-2 compared with the RF measurement data. The scattering of the calculated result depends on the quality of the T-map data, e.g. the quantity of the broken sensors which miss the hot-spots detection.

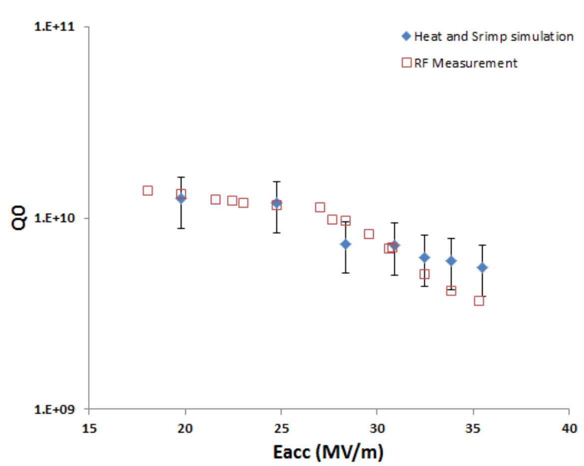


Figure 9: the Power loss on the Hot-spots comparison between H&S program and RF measurement.

CONCLUSION

The thermal feedback model with linear BCS resistance is valid for the medium-field Q-slope analysis. The H&S program's calculation indicates that the residual resistance is field-independent below the hot-spots onset field (25MV/m for NR1-2), and the residual resistance became field-dependent after the onset.

The distribution of the residual resistance isn't homogeneous. The high residual resistance region formed the hot-spots which degraded the Q-value in high-field.

The H&S program's calculations match up the measurement data perfectly. In this paper we checked the BCP and EP case as well as baked and un-baked case. It can be used to estimate the best performance of SRF cavities.

REFERENCES

[1] H. Padamsee, *RF Superconductivity, Vol. II Science, Technology, and Applications*, WILE-VCH, 2009.

[2] A. Gurevich, "Multiscale Mechanisms of SRF Breakdown", Proceedings of the 12th Workshop on RF superconductivity, Ithaca, (2005), p. 156.

[3] A. Gurevich, "Multiscale Mechanisms of SRF Breakdown", Physica C 441, 38 (2006).

[4] J. Vines, Y. Xie, H. Padamsee, "Systematic Trends for the Medium Field Q-Slope", Proceedings of SRF 2007, 2007, TUP27, p.178Beijing, China.

[5] H. Padamsee. Calculations for breakdown induced by "large defects" in superconducting niobium cavities. CERN/EF/RF82-5, 1982.

[6] J. Halbritter, Zeitschrift für Physik 238 (1970) 466.

[7] J. Halbritter, "Fortran Program for the Computation of the Surface Impedance of Superconductors", Internal Notes KFZ Karlsruhe 3/70-6. June 1970.

[8] M. Ge, a temperature-mapping system for multi-cell SRF accelerating cavities.

[9] B. Bonin, Materials for superconducting cavities. (cds.cern.ch/record/399568/files/p191.pdf)

ISBN 978-3-95450-143-4