Q DROP AT HIGH GRADIENT, PROSPECT OF HIGHER Q FOR CW, CRITICAL RF SC FIELD

Chaired by K. Saito[#]

From the heat loading to cryogenics point of view, the future SRF applications like TESLA (long pulse) or ERL(cw) are eager for high-Q & high gradient in superconducting cavities. Now we have a very confirmed scope on the high gradient: Eacc=40MV/m by electropolishing technology for niobium cavities. The discussion of the fundamental critical has been already started in this workshop. However, the high-Q issue is not yet well understood. Usually one observes three kinds of Q-slope in Qo-Eacc excitation curve shown in Fig.1. The Q-slop III, which often limits the high gradient, is most concerned since the last SRF workshop in Santa Fe in 1999, where the baking effect was discovered. One objective in the WG1 is to make the common understanding for the mechanism on this Q-slope. Baking can eliminate the Q-slope especially with EP cavities, and then Q-slope II becomes the next issue to get high-Q at high gradient. However, with BCP cavities we need to discussion the baking effect on the Q-slope III. The Q-slope I, which is now commonly observed in many laboratories and is never a mistake in the cavity measurement, shows very storage behaviour. Investigation on this slope has been just started but it is the future discussion in this working group. WG1 mainly concentrated discussion on the Q-slope III because of the limited discussion time.

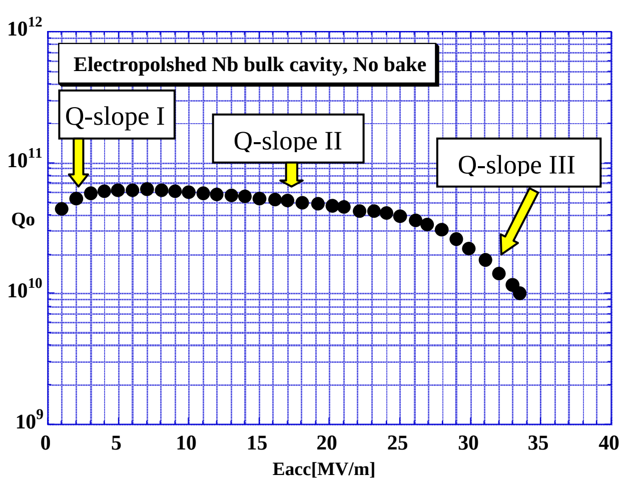

Figure 1: Q-slopes in the electropolished and none baked cavities.

GUIDE PRESENTATION

The discussion was started by the guide presentation by B.Visentin. He summarized 5 models for Q-slope III.

ksaito@post.kek.jp

- **Magnetic Field Enhancement Model by J.Knobloch (H-E model here)**

This model thinks the origin of Q-slope III is as the dissipation by the normal conducting niobium on the grain steps by the breaking superconductivity due to the field enhancement [1].

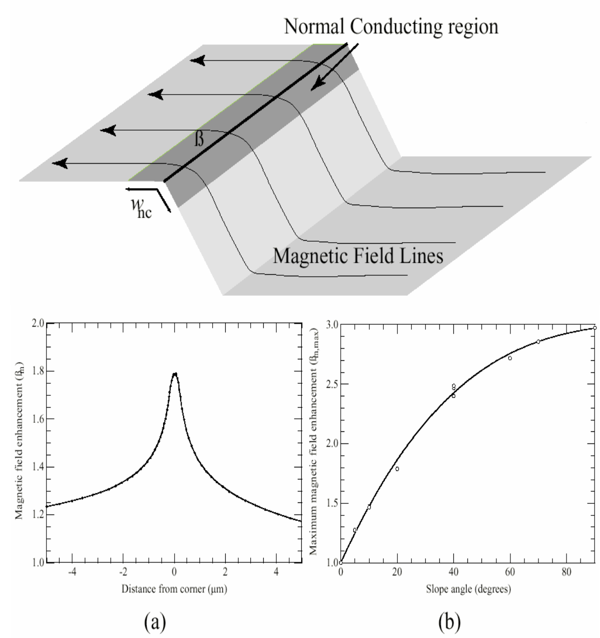

Figure 2: Magnetic field enhancement at the grain step.

β_m: ***field enhancement*****factor**

$\beta_m \cdot H > H_c$ ⇒ **normal conducting** ⇒ **heating**

$1.6 < \beta_m < 2.5$ **(BCP)**, $\beta_m < 1.5$ **(EP)**

Seamless cavity, which has no EBW seam on equator, has a trend to have flat-Q.

Explains the Q-slope appearance by BCP after EP.

X No explains the baking effect on EP or BCP cavities.

- **Interface Tunnel Exchange (ITE Model) by J.Halbritter**

The global loss mechanism is the electron tunnel exchange in one RF cycle in the interface of Nb/ NbO_X-Nb_2O_{5-y} [2].

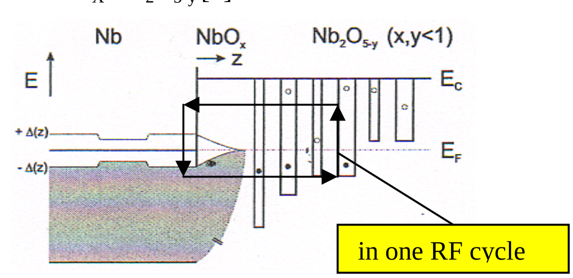

Figure 3: ITE model.

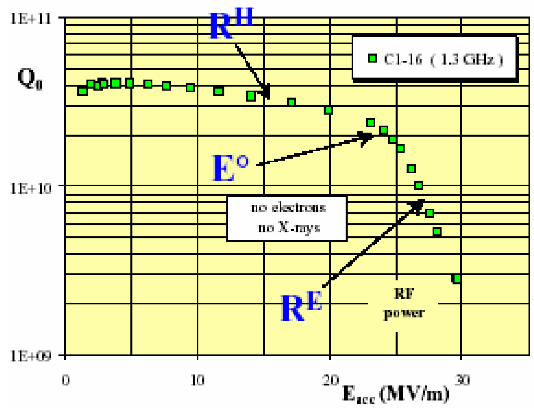

Figure 4: The loss mechanism for Q-slope II and III by J.Halbritter.

$$\textbf{Dielectric oxide} \Rightarrow R^E$$

β^*: ***field enhancement factor***

$$\beta^* \cdot E^{\perp} \Rightarrow R^E \propto exp[-\frac{C}{\beta^* E^{\perp}}]$$

Explains baking effect in both BCP and EP.
Have the on set Field E_O.
Field enhancement in E-field promotes the heating.

X Why the similar on set field ($\beta^* E_o^{\perp}$) in both BCP and EP before bake ?
X Why heating in the high H area of the cavity in the T-mapping ?
X Why no change in flat-Q after baking with a long term air exposure

- **Thermal Feedback Model (Global Heating Model) by V.Kurakin, E.Haebel et al.**

The Global Q-slope is caused by the increase of BCS surface resistance due to the very poor thermal conductivity in the superconductor [3, 4, 5, 6].

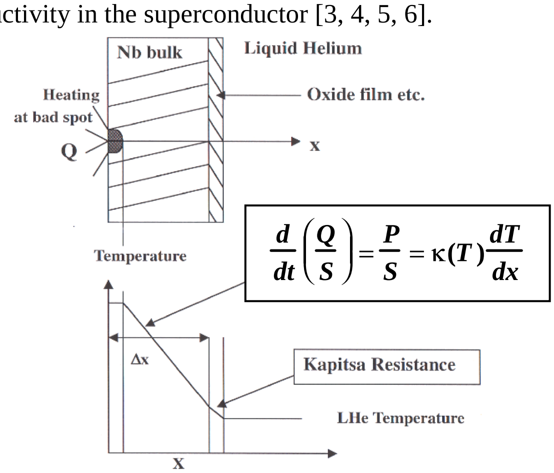

Figure 5: Poor thermal conductivity in superconductors.

$$R_{BCS} = \frac{A\omega^2}{T_s} \cdot \exp(-\frac{\Delta}{k_B T_s})$$

$$T_S = T_B + \Delta T: \quad \Delta T \Rightarrow \Delta R_{BCS} \Rightarrow \Delta T$$
$$\Uparrow \Leftarrow \Downarrow$$

$$R_s(T) = \frac{R_s(T_B)}{1 - C \cdot E_{acc}^2} \quad \text{by B.Visentin}$$

$$R_{BCS} = \frac{A\omega^2}{T_B + C \cdot E_{acc}} \cdot \exp\left[-\frac{\Delta}{k_B(1 + C \cdot E_{acc})}\right] \quad \text{by K.Saito}$$

X No explain the baking effect

- **H-Dependent Energy Gap by B.Visentin, K.Saito**

The band gap of the niobium surface might be influenced by the RF magnetic field. That causes the global heating.

$$\Delta(H) = \Delta(0) \cdot \left[1 - \left(\frac{H}{H_c}\right)^2\right] \quad \textbf{by V.Mathur et al. and B.Visentin [7]}$$

$$\Delta(H) = \Delta(0) \cdot \sqrt{1 - \left(\frac{H}{H_c}\right)^2} \quad \textbf{by K.Saito [6]}$$

Explains the baking effect with EP cavities
lower Hc before bake → higher Hc after bake

Explains the baking effect with BCP cavities, if combined with the field enhancement model
lower Hc before bake → higher Hc by the bake but limited by the field enhancement due to the rough surface

Consistent with T-mapping, i.e. heating at high H area

X Δ(H) is observed only with film superconductors, why happens in bulk niobium?

- **Granular Superconductivity by B.Bonin and H.Safa [8]**

Polycrystalline nature of Nb has a heating due to the Josephson junction resistivity.

Only available to Nb film coated cavities
X Difficulties to understand the baking effect on the clean surface.

Table 1 is his comparison among these models.

DISCUSSIONS

H-E Model

H-E model cannot explain the baking effect with Q-slope III. It is not the definite model but is still convenient for some explanations, for example 1) different baking effect in BCP and EP cavities, 2) flat-Q in seamless cavity, 3) Q-slope by BCP after EP, and so on. This model might be needed to complement other models.

Baking Effect

That the baking effect on the Q-slope III is due oxygen diffusion from the oxygen-contaminated surface into the underneath is commonly agreed between surface analysis and SRF measurement.

IET Model

ITE model, which relates to electric field loss, is promising. By Jlab's data analysis, Q-slope III is well described by this model. However, it is in conflict with some experimental observations. For example, when taking the T-mapping, the heating is observed over a wide region with high H-field before baking and it concentrates on the equator weld after baking [9].

Halbritter showed the other result [2], in which a remarkable $E^{\perp}$-loss appears in spun cavity in high E-field area. However the spun cavity has a lot of cracks in the iris section and might be the special case.

Global Heating Model

By G.Ciovati et al in Jlab [10], the global heating model proposed by B.Visentin also can well describe the Q-slope III, This model is related to magnetic field. This model cannot explain the difference in the baking effect on the gradient of BCP and EP cavities.

H-dependent Energy Gap Model

The H-dependence of the band gap is established in both theory and experiment only for film superconductors with several 1000 Angstroms [11]. The bulk superconductivity is not expected to have such a property. However, as RF cavity measurement picks up characteristics in the skin depth, it might be worth to investigate the property by other methods. It is the future issue. This model is so attractive because the combination of this model and the H-E model can nicely explain many observations.

Q-slope II

As seen in Fig.4, J.Halbritter proposes the analysis of the Q-slope II by the following Taylor series of the surface resistance [12]:

$$R^H = R_{so} \cdot [1 + \gamma \cdot \left(\frac{H_p}{H_c}\right)^2 + O(H_p^4)]$$

However, this is principally the same of the Taylor expansion of the BCS surface resistance with H-dependent energy gap [6]. This resistance also happens an exponentially increased heating at high gradient region. In the Q-slope III, why he neglects this effect?

Baking Effect on High Gradient

Baking often improves remarkably the high gradient in case of EP cavity, but it has small effect on the BCP cavity. This is confirmed with a defect free cavity in KEK [13]. For instance, the cavity reached 40MV/m by EP was treated by BCP and observed the appearance of Q-slope before baking and the gradient was not improved so much after the baking (100^{O}C for 2 days). The cavity was made EP and the gradient was improved up to 40 MV/m after 100^{O}C baking. There are similar observations in Saclay and Jlab [14,10]. Therefore the question appears why the gradient is not improved so much with BCP cavities. Does it suggest the oxygen contamination is different between BCP and EP?

Baking Temperature

Cornell got a depredated performance after 140^{O}C 48 hr baking [15]. Have other labs such an experience? By the Jlab experience, even by 160^{O}C bake Q-slope disappears [10]. The surface residual resistance has a trend to increase at such a temperature. Baking effect is remarkable at higher temperature than 100^{O}C.

Q-slope I

By the analysis in Jlab, Q-slope I can be present also both before and after baking. The surface resistance is fitted as [10]:

$$R_s = \frac{a}{B_p^2} + b$$

which is well explained by Halbritter's model of NbO_X cluster. not in thermal equibrium with the surrounding niobium.

Interesting Experiment on Q-slopes

P.Kneisel is making an interesting experiment on Q-slopes [16]. He excited the TM010 and TE011 modes in a cavity. He is investing the H/E effect in the same cavity. Such a experiment will disclose the Q-slope mechanism more clearly in the future.

CONCLUSION

Every model is still imperfect to explain consistently the experimental observations. And don't forget the exception of 40MV/m by BCP. This is another very important information. We have to work for next two years very hardly on this issue.

Enjoy SRF physics!

RELATED PAPERS ON WG1

Q-Slope

1)A Review of High-Field Q-Slope Studies at Cornell, H.Padamsee et al., MoP14.

2) Why does the Q-slope of a Nb cavity change?, I.V. Bazarvo et al., ThP02.

3) Q-slope Analysis of niobium SC RF cavities, K.Saito, ThP19.

4) Q-Slope: Comparison BCP and EP-Modification by Plasma, B.Visentine at al., MoP19.

Baking Effect

1) A Pleasant Surprise: Mild Baking Gives Large Improvement G.Eremeev et al., MoP18.

2) Low temperature heat treatment effect on high-field EP cavities, J.Hao et al., MoP16

3) Effect of low temperature baking on niobium cavities, G.Ciovati et al., WeO14.

Surface Analysis

1) In situ XPS investigation of the baking effect, K.Kowalski et al., ThP09.

2) Near-Surface Composition of Electropolished Niobium, A.M. Valente et al., MoP15.

3) Grain boundary specific resistance and RRR measurements, S.Berry et al., ThP03.

ACKNOWLEDGEMENTS

The author greatly thanks to B.Visentin for his nice guideline presentation in the WG1 and great help for me. He also thanks P.Kneisel for his help during the WG1.

REFERENCES

[1] J.Knobloch et al., " High-Field Q Slope in Superconducting Cavities Due to Magnetic Field Enhancement at Grain Boundaries ", Proc. of 9th Workshop on RF Superconductivity, Santa Fe, USA, Nov. 1-5, 1999, pp.77-91.

[2] J.Halbritter, " Material Science of Nb RF Accelerator Cavities: Where Do We Stand 2001? ", Proc. of the 10th Workshop on Superconductivity, Tsukuba, Japan, Sep. 6 – 11, pp. 292 – 301.

[3] V.Kurakin, EPAC94, London [4]

[4] E.Haebel, TTF Meeting, 1998.

[5] B.Visentin, SRF99, Santa Fe

[6] K.Saito, in this workshop, ThP17.

[7] B.Visentin, EPAC98, Stockholm.

[8] B.Bonin and H.Safa, Superc. Sci. Tech.4, 1991.

[9] L.Lilje et al, " Electropolshing and in-situ Baking of 1.3 GHz Niobium Cavities", SRF'99, Ppp.74- 76.

[10] G.Ciovati et al., in this workshop, WeO14.

[11] e.g. in the textbook, " Superconductivity" 1 edited by Parks, Marcel Dekker Inc., New York 1969, pp.150-152.

[12] J.Halbritter, "RF Residual Losses, High Electric and Magnetic RF Fields in Superconducting Cavities", Proc. of the 38th Eloistron Workshop, Erice, Italy, 1999.

[13] K.Saito, PAC2003, Portland

[14] B.Visentin, in this workshop, MoP19.

[15] G.Ermeev et al., in this workshop, MoP18.

[16] G.Ciovati, P.Kneisel et al., "Preliminary Studies of Electric and Magnetic Field Effect in Superconducting Niobium Cavities", Proc. of the PAC2003, in Portland, USA, pp.1374 – 1376.

Table: Evaluation of the various models for the Q-slope III by B.Visentin

8

Similarities EP / BCP

	Q-Slope Fit	Slope before baking (EP = BCP)	Slope Improvement after baking	Slope after baking (EP < BCP)	No change after 2 m. air exposure	Exceptional Results (BCP)	Quench (EP > BCP)	BCP Quench unchanged after baking	Validity
Magnetic Field Enhancement	Y	N (β_m et $H_C \neq$)	Y ($H_C \uparrow$)	Y ($\beta_m <$; $H_C >$)	-	N (high β_m)	Y ($\beta_m <$; $H_C >$)	N ($H_C \uparrow$)	Y
Interface Tunnel Exchange	Y (E^8)	N ($\beta* \neq$)	Y ($Nb_2O_{5-y} \downarrow$)	Y (low $\beta*$)	N ($Nb_2O_{5-y} \uparrow$)	N (high $\beta*$)	-	-	Y
Thermal Feedback	Y (parab.)	Y	Y ($R_{BCS}\downarrow$ $R_{res}\uparrow$)	N	-	N	-	-	N (coeff. C)
Magnetic Field Dependence of Δ	Y (expon.)	N ($H_C \neq$)	Y ($H_C \uparrow$)	Y ($H_C >$)	-	N	-	-	N (thin film)
Segregation of Impurities	-	N ($\neq$ segreg.)	N (only O)	-	-	Y (cleaning)	-	-	Y

SRF'2003 (11 th Workshop) Q-Slope at High Gradients Bernard Visentin