

# Q-SLOPE AT HIGH GRADIENTS : REVIEW OF EXPERIMENTS AND THEORIES

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## Abstract

The intrinsic quality factor of niobium superconducting cavities shows a strong degradation ( $Q_0$ -slope) at high fields.

By means of a simple baking around  $120^\circ\text{C}$  the  $Q$ -slope is removed. This improvement seems easier to achieve when the cavity is electro-polished (EP) than when it is etched by using a standard “buffered chemical polishing” (BCP).

Many experiments have been carried out and different theoretical models developed to explain the  $Q$ -slope origin. Comparison between experiments and theories leads us to believe that  $Q$ -slope and baking phenomenon are still not explained.

## INTRODUCTION

$Q$ -slope which appears at high fields in  $Q_0$  ( $E_{\text{acc}}$ ) curves for niobium superconducting cavities, can be removed by an empirical cure: the “in-situ” cavity baking at low temperature and under ultra high vacuum (UHV) conditions.

Cavity baking is useful in a variety of situations involving superconducting RF cavities:

- at high gradients ( $E_{\text{acc}} \sim 40$  MV/m)
- at moderated fields when a high  $Q_0$  value is required, because in both cases it decreases anomalous losses,
- at low fields, when cavities are cooled with He I, because it also decreases also  $R_{\text{BCS}}$  surface resistance.

Nevertheless, in spite of their importance, the baking effect and the  $Q$ -slope origin are not well understood. This is why an overall analysis of experiments and theories is required to know where we stand in 2003.

## EXPERIMENTAL OBSERVATIONS

### $Q_0$ -Slope Features

The  $Q$ -slope is defined as a strong degradation of the quality factor of niobium superconducting cavity when the peak surface magnetic field  $B_p$  becomes higher than 85 mT (Fig.1). This, for a 1.3 GHz TTF cavity, corresponds to an accelerating field  $E_{\text{acc}}$  above 20 MV/m. Absence of electron or X-ray implies that the field emission is not involved in these losses. The temperature map of the cavity shows a global heating all over the central part of the cavity where the peak magnetic field is maximum.  $Q$ -slope is limited by the available RF power

or by a classical thermal breakdown due to a defect on the surface.

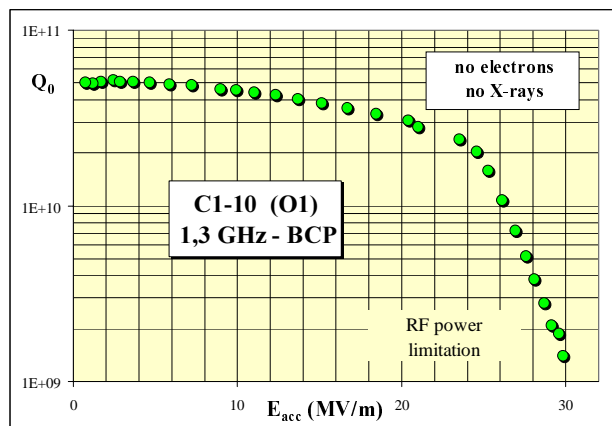


Figure 1:  $Q_0$  ( $E_{\text{acc}}$ ) curve for mono-cell BCP cavity.

Few years ago, it was considered as a typical feature of BCP cavities and our Japanese colleagues could claim the superiority of electropolishing [1-2], because this chemical treatment did not induce such a slope. The  $Q$ -slope phenomenon was nicknamed the “European or BCP Headache”.

### Baking of BCP Cavities

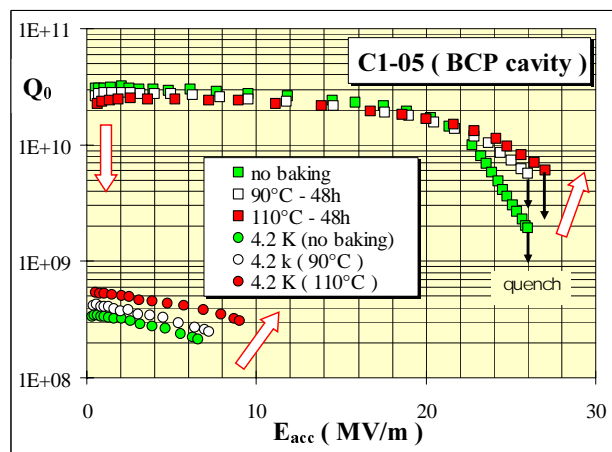


Figure 2: Modifications of  $Q_0$  after “in-situ” baking for BCP cavity.

One year later at Saclay, we discovered [3] that a simple ‘in-situ’ baking at moderated temperature ( $90 < T < 120^\circ\text{C}$ ) improved the Q-slope of BCP cavities (Fig.2). Baking modifies also surface resistances through the strong decrease of  $R_{BCS}$  (32%) and the slight increase of  $R_{res}$  (Fig.3). The quench limit is unaffected (Fig.2-6).

$$R_S = R_{res} + R_{BCS} = R_{res} + A(\lambda_L, \xi_F, \ell) \frac{\omega^2}{T} e^{-\Delta/kT} \quad (1)$$

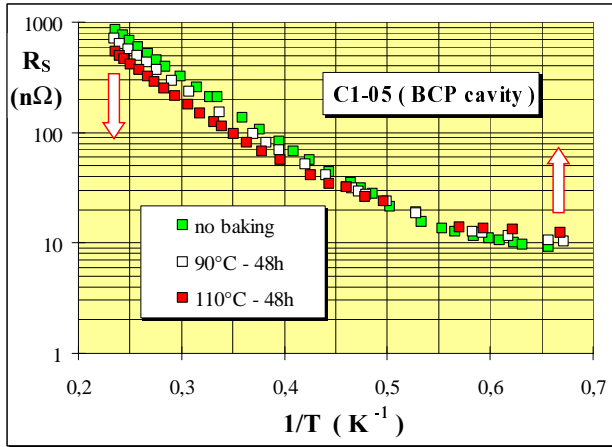


Figure 3: Modification of surface resistances after baking.

### Baking Effect on EP Cavities

Later on, several papers reported on a similar behaviour for electropolished cavities [4-5-6-7]:

- before baking, electropolished cavities show the same Q-slope than BCP ones [8],
- after baking the Q-slope is improved with modifications of surface resistances (Fig.4).

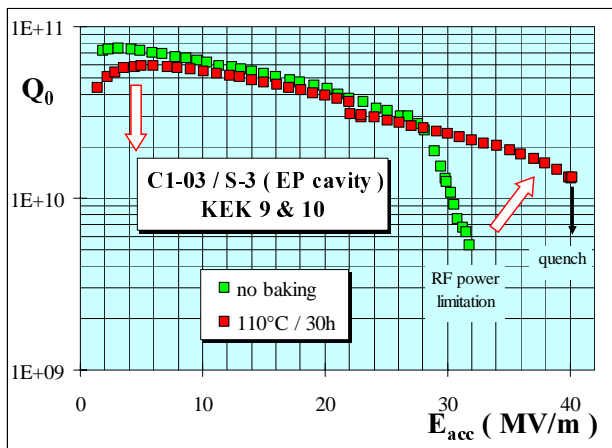


Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].

As for the apparent superiority of EP cavities already mentioned, it is in fact due to the cleaning procedure:

after a high pressure rinse, the wet cavity is directly pumped out and baked at  $85^\circ\text{C}$  during 20 hours to accelerate the pumping [2]. In summary, whether it is electropolished or not, any cavity can reach 40 MV/m without baking.

### Re-oxidation after Baking

After baking, Q-slope improvement is unaltered by the cavity aperture to air [6-7]. In Fig.5, the cavity has undergone five RF tests after the only baking following the initial electropolishing treatment (green and red data points). Between each RF tests, the cavity was opened to air, submitted to a high pressure rinse (HPR) and dried during 3 hours in the clean room under laminar flow without additional baking.

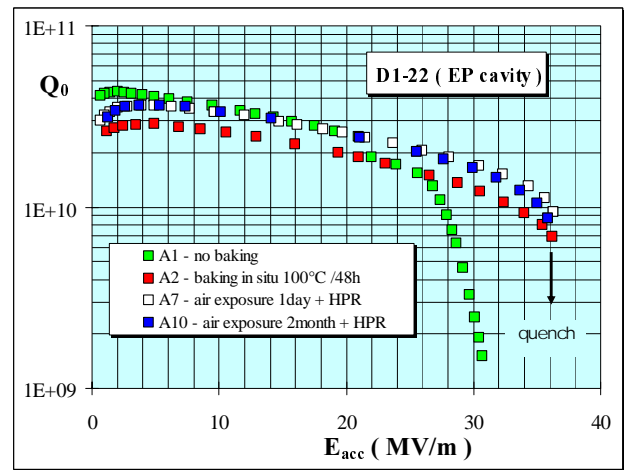


Figure 5: Baking effect is preserved from air exposure and surface re-oxidation.

Several air exposures of the cavity have been performed in different conditions (Fig.5):

- an artificial leak was created on a flange to refill with air the cavity, still attached to the test bench, during 3, 8 or 24 hours (white data),
- the cavity dismantled from the test bench stayed open to air under laminar flow (class 10), in the clean room, during 9 days,
- the cavity, opened to air, remained during two months on a laboratory shelf (blue data).

### Non ‘in-situ’ Baking

UHV conditions are not necessary to observe the baking effect on cavities. A subsequent Q-slope improvement has recently been observed (Fig.6) [8]: wet BCP cavity was directly baked after HPR ( $110^\circ\text{C}/60\text{h}$ ) inside a drying oven working under atmospheric air pressure without any pumping system. Results are similar to those achieved after a classical ‘in-situ’ baking in UHV conditions.

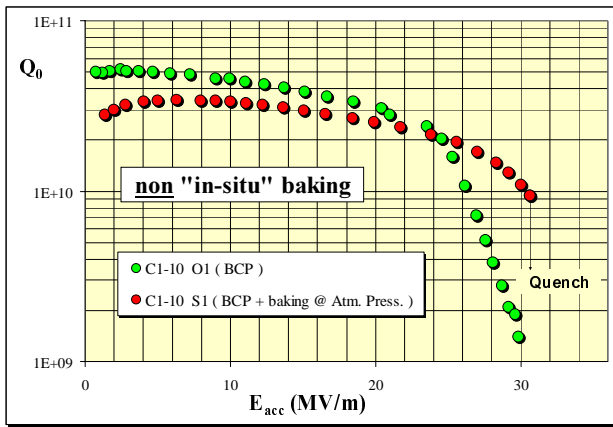


Figure 6: Modifications on  $Q_0$  after “non in-situ” baking for BCP cavity [8].

### Comparison of BCP and EP cavities

In spite of Q-slope improvement on BCP cavities, electropolishing superiority still exists due to the higher efficiency of the cavity baking: for EP cavities, a subsequent Q-slope improvement can be noticed from 85°C while on BCP cavity residual Q-slope is observed, even after baking at 120°C (Fig.2 & 6).

Another undeniable advantage of electropolishing is that gradients of 40 MV/m can be obtained routinely.

Surface roughness also is different between the two chemical treatments: a smoother surface is obtained with EP, with an average height of steps from 2 to 5  $\mu\text{m}$  instead of 5 to 9  $\mu\text{m}$  with BCP [10].

### Some Exceptional Results

Nevertheless, BCP cavities in some cases reach similar performances to electropolished ones. Apart from the Jefferson Lab “defect free” cavity [11] for which no baking is mentioned, three other cases are known:

- one DESY NbCu clad cavity (INC2) [12],
- two Saclay Nb cavities (C1-15 and C1-16) [13-8].

In these cases, Q-slopes were totally removed (Fig.7) after baking with a quench field value around 40 MV/m, or 32 MV/m for C1-16. However, their inner surface is not particularly smooth: large grains (2-3  $\text{mm}^2$ ) and high steps (8  $\mu\text{m}$ ) were measured on C1-15.

## NIONIUM SURFACE MODIFICATIONS

In addition to its influence on the Q-slope, baking also modifies surface resistances and in particular the BCS resistance is strongly decreased (Fig.3).  $R_{\text{BCS}}$  decrease with baking time leads to a saturation [4], involving a diffusion process through the RF niobium surface on a 300 nm depth.

Since Palmer’s publications [14], we know that oxide layers ( $\text{Nb}_2\text{O}_5 - \text{NbO}_x$ ) influence the Nb surface resistance and that oxygen diffusion at very low temperature can be experimentally observed. More recent papers [15-16-17-

18] report observations, achieved by XPS analysis on Nb samples, about the modification of oxide structure after baking with reduction of niobium pentoxide and formation of  $\text{NbO}_x$  ( $0.2 < x < 2.5$ ).

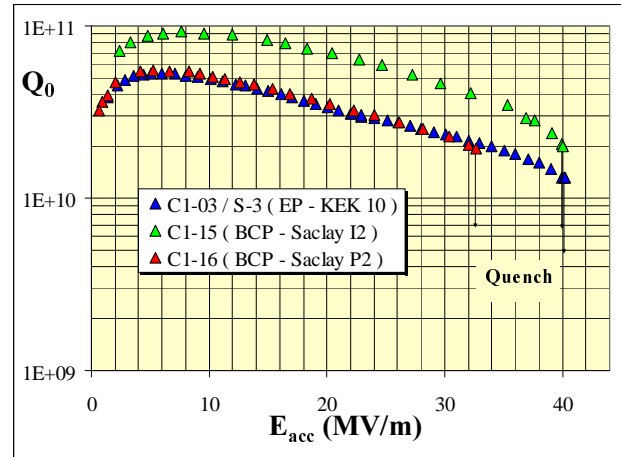


Figure 7: Exceptional results on BCP cavities after baking (red and green data points) with no residual slopes. Possible comparison with EP cavity after baking (blue).

From  $\chi$  susceptibility measurements on Nb samples [19-20] the critical magnetic field value on the surface is found higher than bulk value ( $B_{\text{C3}}^{\text{surf}} \sim 1.7 B_{\text{C2}}^{\text{bulk}}$ ). These measurements show also that  $B_{\text{C3}}^{\text{surf}}$  and  $B_{\text{C2}}^{\text{bulk}}$  values are higher for electropolished samples and these values increase after baking with any of the chemical treatments (EP and BCP).

## THEORETICAL MODELS

Except for high field Q-slope improvement, modifications induced by baking can be structured into three categories:

- the differences observed between EP and BCP cavities linked to the surface roughness and the grain boundaries,
- the modification at the interface between oxide and metal through the oxygen diffusion,
- the change of surface superconducting parameters ( $R_{\text{BCS}}$ ,  $R_{\text{res}}$ ,  $B_{\text{C}}$ ,  $T_{\text{C}}$  [21], ...).

Different theoretical models, described below, used one or several of these observations to establish their validity. Obviously they should be able to explain several essential points summarized in Table1:

- the Q-slope similarity for EP and BCP cavities before baking,
- the Q-slope improvement after baking,
- the unchanged benefit of the “in-situ” baking after surface re-oxidation and similar results observed with “non in-situ” baking,
- the residual slope only observed on BCP cavities after baking,

- the exceptional results achieved with BCP cavities,
- the higher quench limit for EP cavities,
- the unchanged quench limit for BCP cavities before and after baking.

### Magnetic Field Enhancement (M.F.E.)

Microstructures on RF surface, particularly observed on BCP cavities, roughness of which is characterized by step heights around 10  $\mu\text{m}$ , induce a magnetic field enhancement  $\beta_m H$  [22]. When this local value becomes higher than  $H_C$ , the region becomes normal conducting (Fig.8). This is the Q-slope origin according to this model. As for the quench, it is caused by the most dissipative grain boundary. For a BCP cavity, the value of  $\beta_m$  MFE factor is estimated between 1.6 and 2.5.

By using this model, an electromagnetic code and thermal simulations, it is possible to well fit the  $Q_0(E_{\text{acc}})$  curve before baking for BCP cavity (Fig.9). Q-slope improvement after baking can be understood in reminding  $\chi$  measurements on samples with the increase of  $B_{C3}^{\text{surf}}$  after baking. Better slope for an EP baked cavity, compared to a BCP one, is also explained with lower  $\beta_m$  value ( $\sim 1$ ).

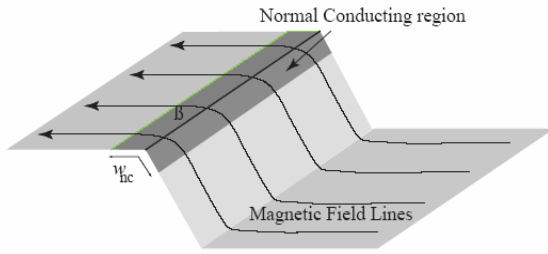


Figure 8: Schematic of area after quench due to MFE at grain boundary [22].

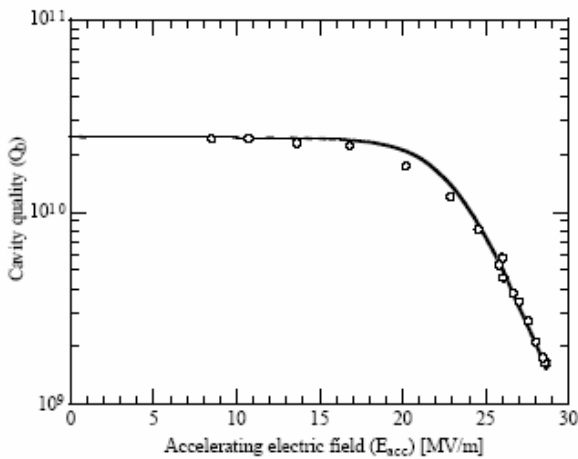


Figure 9: Experimental data fit using  $H_C=2000$  Oe [22].

Unfortunately this model can not explain why EP cavities have before baking Q-slopes similar to BCP ones, in spite of lower  $\beta_m$  and higher  $H_C$  ( $\chi$  measurements). It

cannot either explain exceptional results of BCP cavities (Fig.7) with high quench limits and no residual Q-slopes: surface roughness with measured step heights of 8  $\mu\text{m}$  implying a high  $\beta_m$  value. This is the same inability to explain the unchanged quench limits, experimentally observed after baking for BCP cavities ( $H_C$  increasing with cavity baking).

### Interface Tunnel Exchange (I.T.E.)

In his model, Halbritter [23-24] explains that RF field on metallic surface can be decomposed in two parts: a magnetic field component ( $H^{\parallel}$ ), parallel to the metallic surface and a perpendicular electric field component ( $E^{\perp}$ ). The latter implies electric field impedance  $Z^E$  negligible for clean metal. However, due to dielectric oxide layer on the surface,  $Z^E$  could be enhanced by interface tunnel exchange (ITE) between localized states of  $\text{Nb}_2\text{O}_{5-y}$  and the density of state of Nb, with additionally electron diffusion at the  $\text{NbO}_x - \text{Nb}_2\text{O}_{5-y}$  interface (Fig.10). The dielectric surface resistance is exponentially dependent on  $E^{\perp}$ :

$$R^E \propto e^{-C/\beta^* E^{\perp}}$$

where  $\beta^*$  is the field enhancement factor. This exponential increase becomes predominant at high fields, starting at the  $E^{\circ}$  onset value.

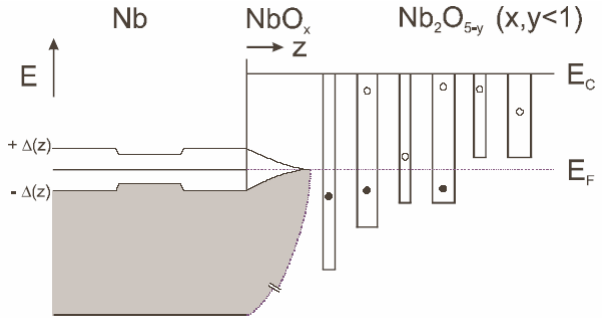


Figure 10: Band structure in niobium-oxide interfaces [23].

According to this model ITE gives a quantitative description of the Q-slope and the experimental data are conventionally fitted by

$$R^E = R^0 (E^{\perp})^8$$

I.T.E. mechanism can be reduced by:

- surface smoothing (EP cavities) with low  $\beta^*$  and high  $E^{\circ}$ ,
- baking because of localized states decrease due to  $\text{Nb}_2\text{O}_{5-y}$  reduction and better oxide interface.

As M.F.E., I.T.E. model fails to explain some experimental observations, like:

- similarity between EP and BCP cavity Q-slopes in spite of their different surface roughness ( $\beta^*$ ),

- unaltered Q-slope after surface re-oxidation (or non “in-situ” baking) where niobium pentoxide is built up again,
- exceptional results on BCP cavities (high  $\beta^*$ ) without residual Q-slopes.

### Thermal Feedback

This theory takes into account the temperature dependence of surface resistance (see Eq.1) [25-26]. The power, dissipated because of the magnetic field on the inner surface of the cavity, leads to a temperature increase followed by a resistance increase: more power is then dissipated. A real thermal feedback is implemented:

$$\Delta T = R_{therm} \Delta P \propto \frac{R_S H_S^2}{2}$$

Surface resistance can be expressed using the accelerator field [7]:

$$R_S(T) = R_S(T_0) / (1 - C \cdot E_{acc}^2)$$

where  $C (\approx 2 \cdot 10^8 \cdot \partial R_S / \partial T)$  is the fit factor (Fig.11). In this model, the baking effect is taken into account through the  $\partial R_S / \partial T$  term with the decrease of the parameter A (see Eq.1).

Fit parameter C can be expressed analytically by means of niobium thermal properties. Unfortunately the calculated value ( $C_{calc} \approx 2 \cdot 10^9 \cdot \partial R_S / \partial T$ ) is higher than the experimental value and contributes to raise doubts about the model validity.

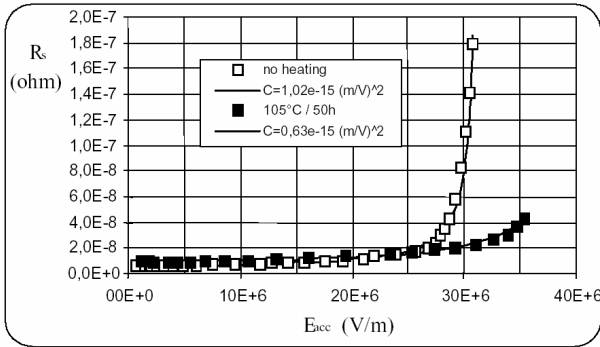


Figure 11: Thermal feedback fit on EP cavity experimental data (before and after baking) [7].

### Magnetic Field Dependence on the Energy Gap

The  $R_S$  behaviour at high fields could be due to its exponential variation with the energy gap  $\Delta$  (see Eq.1). Theories mention a possible magnetic field dependence of  $\Delta$  [27-28-29]:

$$\Delta(H) = \Delta(0) \left(1 - H^2 / H_C^2\right)^\alpha \quad (2)$$

$\alpha = 1/2$  when  $T \sim T_C$ , or in our case  $\alpha = 1$  ( $T \sim 0$ ).

Using this formula, it is possible to fit the  $Q_0$  versus  $E_{acc}$  curve (Fig.12) with  $H_C$  as the only fitting parameter [3].

Unfortunately, the magnetic field dependence of  $\Delta$  according to equation (2), is only rigorously and experimentally proved for thin superconducting films. For thick and bulk superconducting materials,  $\Delta(H)$  variation is less than 1%. For this reason this model cannot be considered as valid.

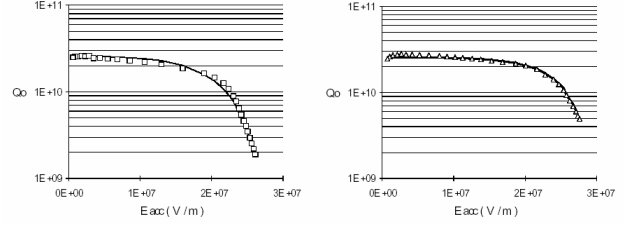


Figure 12: Experimental data fit on BCP cavity before ( $B_C=182$  mT) and after baking ( $B_C=195$  mT) [3].

### Granular Superconductivity

Due to the polycrystalline nature of niobium, grain boundaries can contribute to surface resistance. In this case the grain boundary is considered as a weak link of Josephson junction [30]. But as in the previous model the theory is only valid for thin films. The effect is negligible for bulk niobium with grain size around  $10 \mu m$ .

Exception could be made if segregation of impurities is located at grain boundaries of bulk niobium. Even in this case, the model cannot explain the baking effect: because it is difficult to apprehend a possible impurities cleaning at such a low temperature ( $120^\circ C$ ) where only oxygen diffusion can be considered. Nevertheless an experiment was started to measure the grain boundary specific resistance [31].

### Others Models

Kenji Saïto [32] gives a new expression for  $R_{BCS}$  by using a mix of several previous models described above:

$$R_S = R_{res} + A \frac{\omega^2}{T^*} e^{-\Delta^*/kT^*}$$

- thermal dependence:

$$T^* = T + C \cdot E_{acc}$$

- magnetic field dependence of  $\Delta$  :

$$\Delta^* = \Delta_0 \sqrt{1 - H^{*2} / 2H_C^2}$$

- magnetic field enhancement :  $H^* = \beta_m H$

Using this model with  $C$ ,  $\beta_m$  and  $H_C$  as free parameters, Q-slopes can be well fitted for EP and BCP baked cavities (Fig.13). An explanation has been found for the residual slope observed on BCP cavity through the field enhancement factor value ( $\beta_m=2.34$ ) in agreement with the MFE theoretical model. Same criticisms separately made above for each theoretical model can be applied to this one.

The “Bad Superconducting” model described in [33] takes into account presence of oxygen at the Nb<sub>2</sub>O<sub>5</sub>/Nb interface to define a highly degraded resistive layer. This layer is, even so, superconducting at low field ( $B_p < B_{C1}$ ) by the “proximity effect” and becomes again normal conducting at higher field (blue curve on Fig.14).

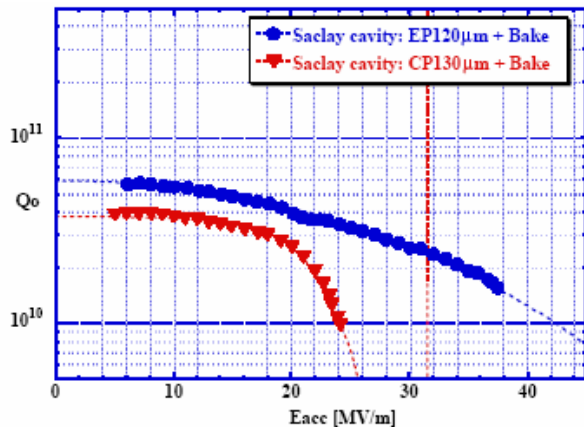


Figure 13: Q-slope fits after baking on EP and BCP cavities [32].

Baking at low temperature dilutes this “pollution” in depth (oxygen diffusion), giving an averaged slight slope (red curve).

Unfortunately this model does not explain the exponential characteristic of the Q-slope before baking.

Moreover, it is unrealistic because it does not consider the experimental shapes observed on  $Q_0(E_{acc})$  curves:

- before baking, the “middle field” part is not flat, a slope already exists (Fig.4-5-6),
- after baking, this slope is not more degraded than before baking like the model suggests: on the contrary the experiments show a slight improvement (Fig.2-5-6),
- according to this model,  $B_{C2}'$ , the critical magnetic field of niobium after baking, is lower than  $B_{C2}$ . This is not corroborated by the XPS measurements [19-20] and does not explain why the quench limit is unchanged for BCP cavities before and after baking (Fig.2-6).

Because of these too strong discrepancies with the experimental observations, this model can not be reasonably taken into consideration.

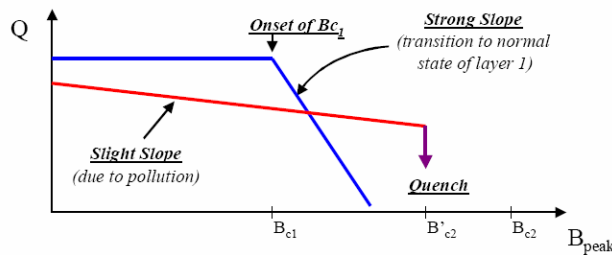


Figure 14: Schematic description to explain  $Q_0$  behaviour before and after baking [33].

Table 1: Summary statement of comparison between experiments and theoretical models (Yes or No: theory can or can't explain experimental result).

	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 ( $\beta_m$ et $H_C \neq$ )	Y ( $H_C \uparrow$ )	Y ( $\beta_m < ; H_C >$ )	-	N (high $\beta_m$ )	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 $\Delta$	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
Bad SC Layer	N	Y (n.c. layer)	Y (dilution)	N	N (bad layer $\uparrow$ )	-	N	N ( $H_{C2}' \downarrow$ )	N (unrealistic)

## CONCLUSION

A summary of the experiment-theory confrontation is given in Table 1. As we see, none of the theoretical models can explain all of the Q-slope characteristics. This is particularly true for second and sixth column which underline the similarities between EP and BCP cavities.

Models must be refined in order to provide a right and indisputable explanation.

Many more experiments are probably also necessary to differentiate the different models. An experimental program is started in this direction at Jefferson Laboratory [34] to understand the Q-slope mechanism by studying the electrical and magnetic fields influence on the cavity surface.

Finding the correct explanation is not only an intellectual goal: it is necessary because slope is not definitively cured by baking even for EP cavities [8]. If the present quench limit is moved above 40 MV/m, the Q-slope will come back again.

## ACKNOWLEDGEMENT

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