



A Review of the Q-Drop Phenomenon in High Gradient SRF Cavities

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Overcoming Q-drop is a crucial step toward reliable achievement of the 35 MV/m gradient in the superconducting RF cavities for the ILC project. Although a cure for Q-drop exists, consisting of a modest temperature heat treatment, the understanding of its cause(s) is still lacking. Many experiments have been conducted, providing us with a solid set of facts that need to be explained by one model. Many explanations have been proposed but none was thoroughly proven. The purpose of this review is to gather all the experimental evidence pertinent to the Q-drop phenomenon in niobium cavities. We also attempt to discuss the available models to explain it. This review is yet another step in the ongoing exploration of the Q-drop problem, one of the "hot topics" in SRF technology today.

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1) Introduction

A 35 MV/m average accelerating field in the main linac superconducting RF cavities is an aggressive design goal for the future International Linear Collider (ILC). According to the state of the art of niobium based SRF cavity fabrication and processing this ambitious gradient can only be achieved if the cavities are processed with an in-situ low temperature bake to remove the so-called Q-drop. The Q-drop is a precipitous decrease in cavity quality factor Q (or increase in surface resistance) when exceeding $\sim 20\text{-}30$ MV/m average accelerating gradient. The cause of this sudden increase in surface resistance is yet unknown. Figure 1 gives examples of Q-drop before and after baking as observed by various labs (CEA, J-Lab, DESY, KEK) involved in high gradient SRF cavity development. The dramatic improvement of cavity performance with baking is obvious from these data. Figure 2 shows with the example of the larger batch of cavities for the DESY TTF1 project that this is also true in a statistical sense [4].

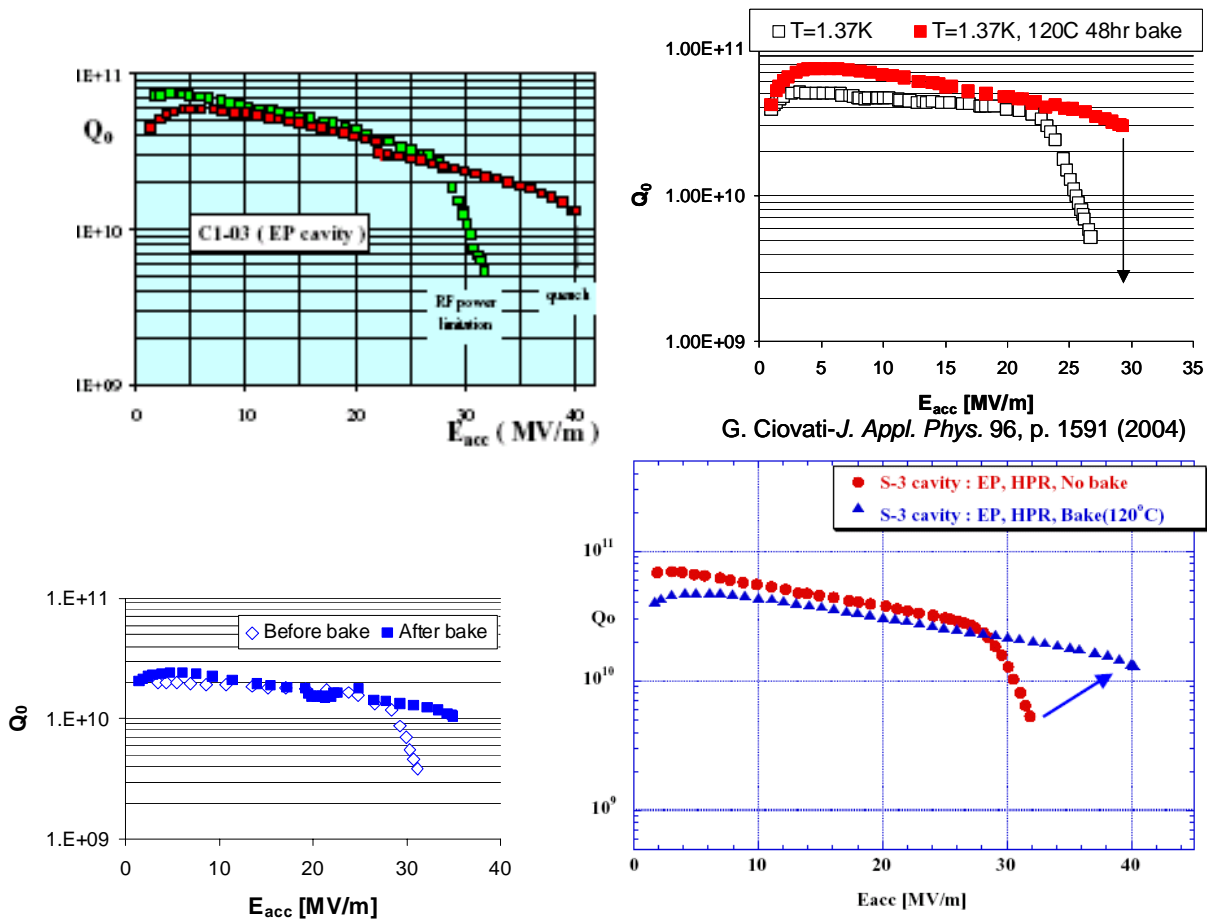


Figure 1: Examples of Q-drop and removed Q-drop after baking in cavities from CEA (C1-03, top left, [1]), Jlab (CEBAF 1-cell, top right, [2]), DESY (AC76 9-cell, bottom left, [3]) and KEK (S3, .

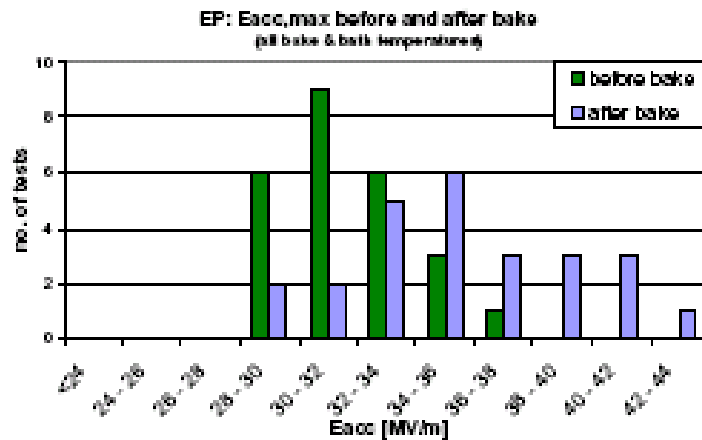


Figure 2: Improvement of average gradient in DESY TESLA Test Facility 1 cavities after baking from ~30 MV/m to ~37 MV/m [4].

The following will review the experimental evidence gathered thus far on the Q-drop as well as present the various models proposed to explain it. This summary draws heavily on the contributions from various national labs and university groups specialized in SRF cavity development and superconducting material science.

2) Review of Experimental Evidence on Q-Drop

The following is an attempt to summarize all the information in the SRF workshop publications related to the baking effect, starting with the Santa Fe workshop in 1999. The low temperature bake-out as a remedy for Q-drop was discovered in 1998 at CEA/Saclay. First we will review the experimental evidence that exists today on the baking effect. Then different explanations that were brought forward will be discussed.

2.1) Basics of Q-Drop and Baking

The “Q-drop” denominates the strong degradation of the quality factor of bulk niobium superconducting cavities at accelerating gradients of ~20 MV/m (which, in TESLA/ILC type accelerating mode cavities corresponds to peak surface magnetic fields of ~85 mT). Absence of electron emission or X-rays implies that field emission is not a major factor in these losses. Temperature array maps of the cavity reveal a global heating as well as local heating spikes all over the equator region (where the magnetic field is highest) in the Q-drop regime. A few years ago it was considered as a typical feature of BCP cavities since the KEK group could show that the electro-polishing process did not give significant Q-drop. The Q-drop was named the “European headache”. Later the CEA/Saclay group discovered that an in-situ bake at moderate temperatures between 90-120°C partially alleviated the Q-drop problem [5]. The same was shown later in electro-polished cavities, which at first had also shown Q-drop at DESY, a fact that created

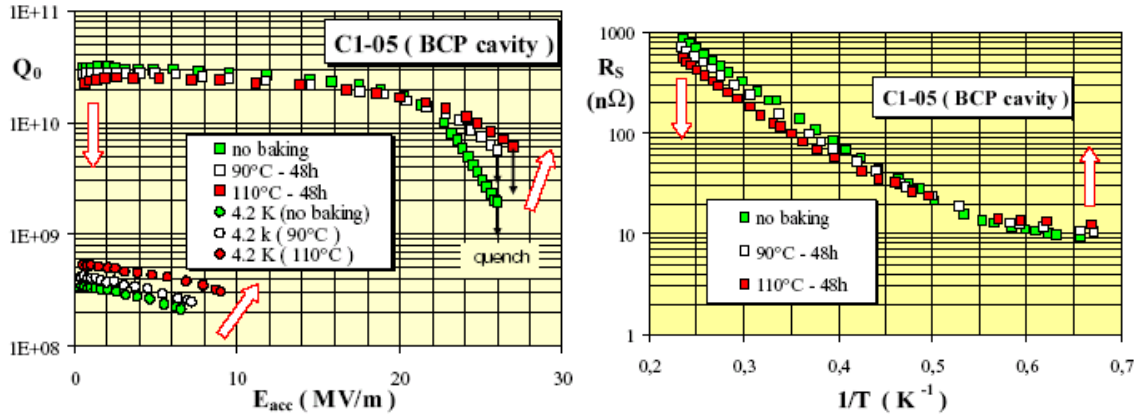


Figure 3: Example of the effect of the in-situ bake on the Q-drop (from [1]). Left: quality factor vs average accelerating field; Right: Surface resistance vs temperature (measured at low temperature).

confusion as to the claimed superiority of electro-polishing. It was later understood that a moderate temperature bake-out was part of the Japanese electro-polishing procedure. It has to be noted, however, that the baking effect (or “baking benefit”) is generally more pronounced in electro-polished cavities, i.e. often a small residual Q-drop remains in the chemically polished (BCP) cavities after baking. An example of Q-drop and its removal by baking in a chemically polished (BCP) cavity is shown in Figure 3. The graphs in the figure also show the reduction in BCS surface resistance and the increase in the residual (= temperature independent component of the) resistance that goes hand in hand with the baking [1]. The decrease in BCS resistance can clearly be seen in the 4.2 K measurements in Figure 3 because at “higher” temperature the surface resistance is BCS dominated. In the <2 K measurements the increase of the residual resistance as a result of baking explains the reduction of the quality factor at low and moderate fields after baking.

One has to note that Q-drop is not at all unusual. It can have many different origins. Low RRR material, for instance, shows higher resistance at low field, stronger Q-slope and earlier onset of Q-drop [6]. The lower the RRR the stronger the above features. There are exceptions to this rule, however. One example for such an exception is 9.56 GHz cavity that reached a 150 mT peak magnetic field with very little Q-drop, made from reactor-grade RRR (~ 50) material [Pfister Cryogenics 1976]. Cavities made from deep-drawn polycrystalline sheet material, which haven’t undergone the initial 100 micron etching to remove the “damage layer”, also show strong Q-slope and early onset of Q-drop.

Recently Visentin [7] showed that the Q-drop can also be “cured” with a heat treatment at 145°C for 3 hrs, rather than the established 48 hrs at 120°C . This is a significant technological advancement, which will allow shortening of the cavity processing time. Since both these baking conditions result in the same oxygen profile in the Nb surface, as calculated from a simple diffusion model, this finding also further hints at a possible role of oxygen in the Q-drop phenomenon. The involvement of oxygen was already suspected when measurements indicated that the reduction in BCS resistance that accompanies the

baking disappears after the removal of ~100 nm of material from the surface. This is consistent with the thermal diffusion length of oxygen (and with that of no other element) at the baking temperature and duration.

The baking effect on the BCS resistance remains after long-term exposure to air and high pressure water rinsing [8]. The baking effect on the BCS resistance saturates after a certain baking time [9]. When removing surface layers in a baked cavity in small steps by oxypolishing, the BCS resistance slowly rises again. After removal of 300 nm from the surface the BCS resistance of before baking is restored [9]. Recently Eremeev showed that Q-drop in fact re-appears after removal of ~10 nm from the Nb surface through anodization in a baked cavity [15]. This could indicate that the origin of the Q-drop effect is located in an even thinner surface layer. Possibly this could also hint at the change of BCS resistance with baking being just a secondary benefit of the baking, with both effects, BCS resistance change and Q-drop, actually having different origins.

2.2) Stability of the Baking Effect in Time

B. Visentin / CEA-Saclay [1] exposed a cavity to air for extended periods of time to verify if the baking effect would be reversed as a result of the ensuing transformation of the oxide layer (e.g. growth). After each cycle to (clean-room) air the cavities were high pressure rinsed. The baking benefit held throughout these experiments (Figure 4). This indicates that the source of the Q-drop is not located within or on the oxide, but below it. It could also indicate, however, that the oxide is very stable. Visentin conducted more tests of the same kind, one following a 4-year storage in air, again with no noticeable degradation of the baking benefit [10]. Similar findings were reported in [9]. These are remarkable results proving the stability of the baking effect in time. This is one of the arguments brought forward to contradict hydrogen-contamination theories. Four years at room temperature is sufficiently long for hydrogen to repopulate the near surface layers from where it could have been removed by the baking. It is believed that in this case the hydrogen would have to come from the bulk, however, since the oxide layer is not

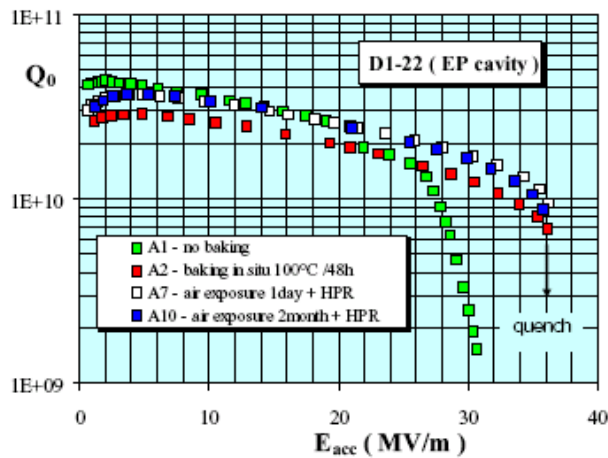


Figure 4: Effect of exposure to air [1].

transparent to hydrogen. Experiments in which the cavity was exposed to pure N₂ during up to three days after baking also did not reveal any reversal of the baking benefit either [11].

2.3) Thermal Maps

A very powerful diagnostics tool for superconducting cavities is a thermal sensor array covering the outer cavity surface during operation. L. Lilje's reported first [13] that before baking local heating appears along the equator region where the magnetic field (and thus the surface current) is highest. The data in fact indicate temperature "spikes", i.e. several localized regions operating at higher (~700 mK) temperature in the Q-drop region (Figure 5). These "hot-spots" along the cavity equator mostly disappear with the baking. This remarkable result first and foremost indicates that the cause of Q-drop is located in the region of high magnetic field (equator region). Secondly, it tells us that the source of Q-drop is further concentrated in smaller areas within the high field region. This could be interpreted as a hint toward non-uniform surface properties, as suggested by Gurevich in [28]. Similar thermal maps showing localized heating were also published by Ciovati [20] and Padamsee [14].

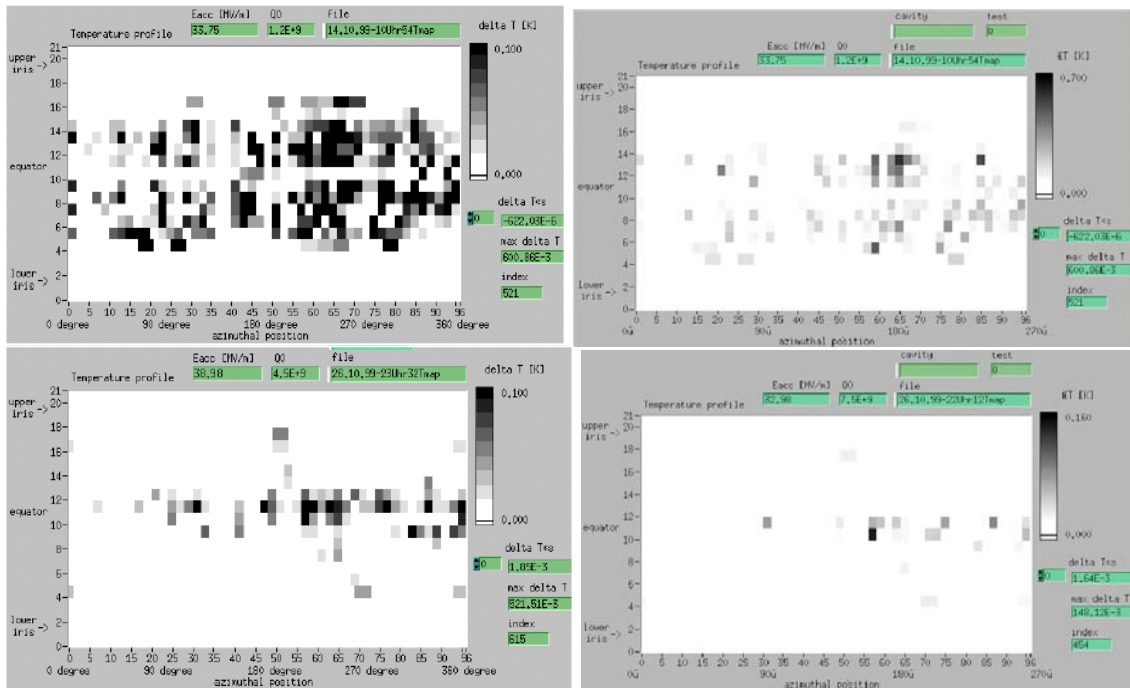


Figure 5: Thermal map of DESY TESLA cavity at 34 MV/m before baking (above) and 39 MV/m after baking (below). Left: 0.1 K scale, right: 0.7 K scale. Courtesy of L. Lilje [13]

2.4) Removal of Baking-Benefit Layer through Oxy-polishing and Anodization

When removing surface layers in a baked cavity in small steps by oxy-polishing the BCS resistance slowly rises again, indicating that the baking benefit is being gradually reversed in this process. During oxypolishing the Nb surface is electrochemically oxidized in a solution of 30% NH_4OH at a low voltage, where the thickness of the oxide layer produced is determined by the voltage (2 nm/V). The amount of oxide created can then be equated to the amount of bulk Nb “consumed” (starting from the surface) by this process, assuming that ~30% of the oxide formed contains Nb and that the oxide is ~3 times less dense than the bulk, so ~1 nm of Nb is converted for each ~10 nm of oxide.

After removal of 300 nm from the surface with this process Kneisel found that the BCS resistance of before baking is restored [9]. A similar experiment was recently performed by G. Ereemeev and H. Padamsee at Cornell University [15] (Figure 7). Instead of investigating the effect of the anodization on the BCS resistance at low power, however, they measured its effect on the Q-drop at high fields. After removing ~6 nm of the Nb from the surface via anodization, the Q-drop gradually re-appeared. This indicates that the baking benefit layer is actually thinner than what one could conclude from the Kneisel measurements shown in Fig. 6. This, however, is not necessarily a contradiction between the two results, because the BCS surface resistance reduction and removal of Q-drop are not necessarily related to the same process (see more on this in the separate discussion of the baking effect on the BCS surface resistance and of the Q-drop models). The slight improvement of the cavity performance after anodization with 5 V is an interesting, yet unexplained effect.

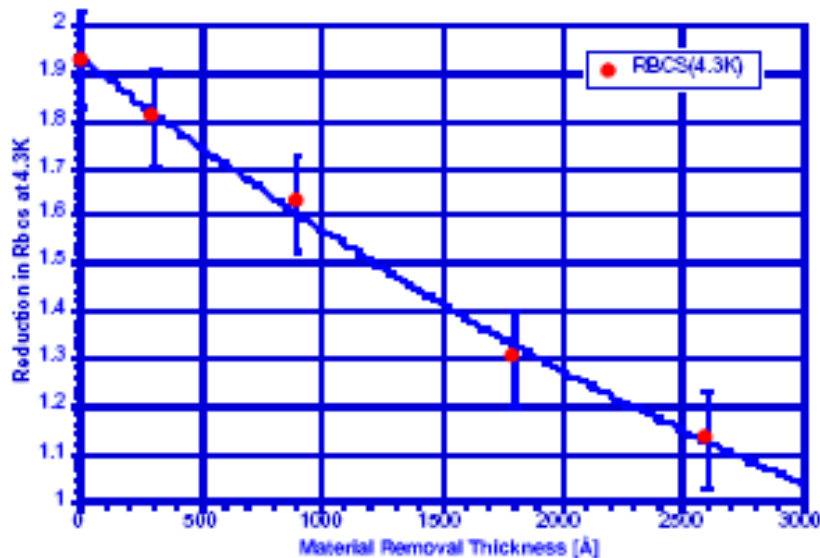


Figure 6: Dependence of BCS surface resistance as function of material thickness removed through oxy-polishing [9].

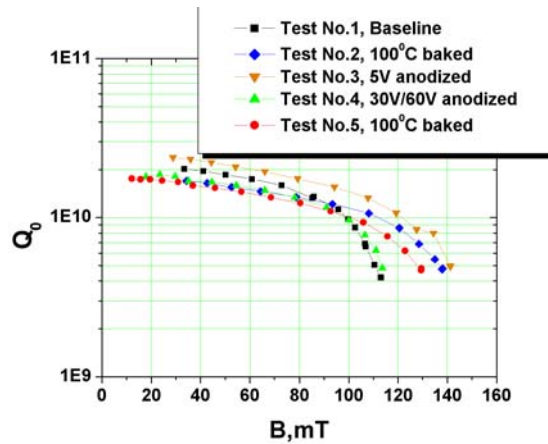


Figure 7: Cavity test result: original Q-drop is restored after 10 nm thick layer of surface-Nb was converted to oxide. Courtesy of G. Ereemeev [15].

2.5) Removal of Oxide

A treatment during ~20-50 mins with HF is believed to result in a completely rebuilt oxide layer, since HF dissolves Nb_2O_5 . Visentin processed a cavity that had undergone baking at 110°C with HF [10]. He could show that the Q-drop did not re-appear following the HF treatment (Figure 8). If he is right in thinking that the oxide layer is entirely rebuilt together with the near surface layer being replenished with oxygen in that process, this remarkable result would suggest that the source of Q-drop is neither related to a modification of the oxide layer, nor related to a purification of the first few nm in the bulk. Visentin also observed a change in the residual resistance at low field after the HF treatment, which he interprets as an effect related to the Nb-oxide interface. The change in residual resistance is often observed when the oxide layer is re-built or otherwise modified (grown thicker for instance) and is therefore not unexpected. This experiment is therefore most relevant to the “weak-layer” model (discussed further in 3.1) and 4.2)).

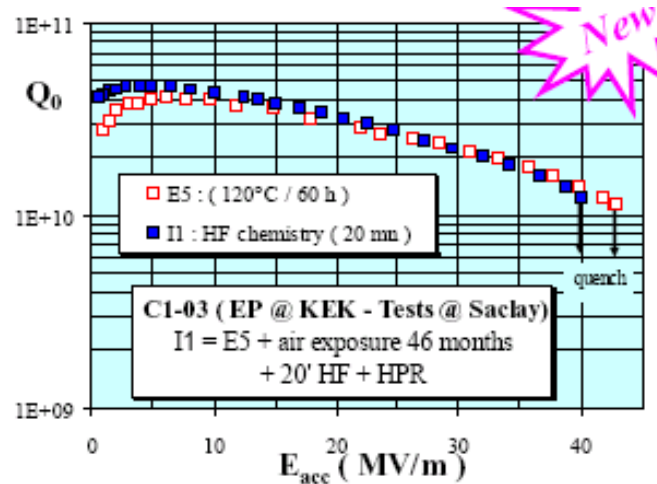


Figure 8: Q of single cell TESLA cavity after baking (E5) and after an additional HF treatment (I1). The Q-drop does not reappear after the HF chemistry [10].

2.6) TE vs TM Mode

Experiments with the operation of a CEBAF type single cell cavity in two different modes, the usual TM_{010} accelerating mode (1.5 GHz) and the special TE_{011} mode (~3 GHz), were conducted by G. Ciovati and P. Kneisel [16]. In the TE_{011} mode the peak magnetic field is higher than in the TM_{010} mode (and it is located in the iris region). Most importantly, however, the electric field is zero on the surface in the TE_{011} mode. As is clear from Figure 9 the cavity shows exponential Q-drop in both modes. The Q-drop partially disappears after baking in both cases also. These measurements are being interpreted in the sense that the Q-drop is not related to an electric field effect (as stipulated for instance by the ITE model, see further discussion in 3.4)). Another interesting aspect of the measurement in Figure 9 is that the cavity reaches to a higher peak field in the TE_{011} mode, despite (or because of?) the fact that the TE_{011} mode frequency is twice as high. An interesting observation in this context is that the high field region is approximately twice larger in the TM_{010} mode. Could therefore the higher Q-drop onset field in the TE mode cavity be the result of a smaller probability of encountering the Q-drop source, statistically distributed over the surface, because of the smaller surface? This observation could, in that sense, have some relevance for the so-called hot-spot model discussed further below. If this difference is the result of the difference in frequency, it could be most relevant to the flux penetration model discussed below as well.

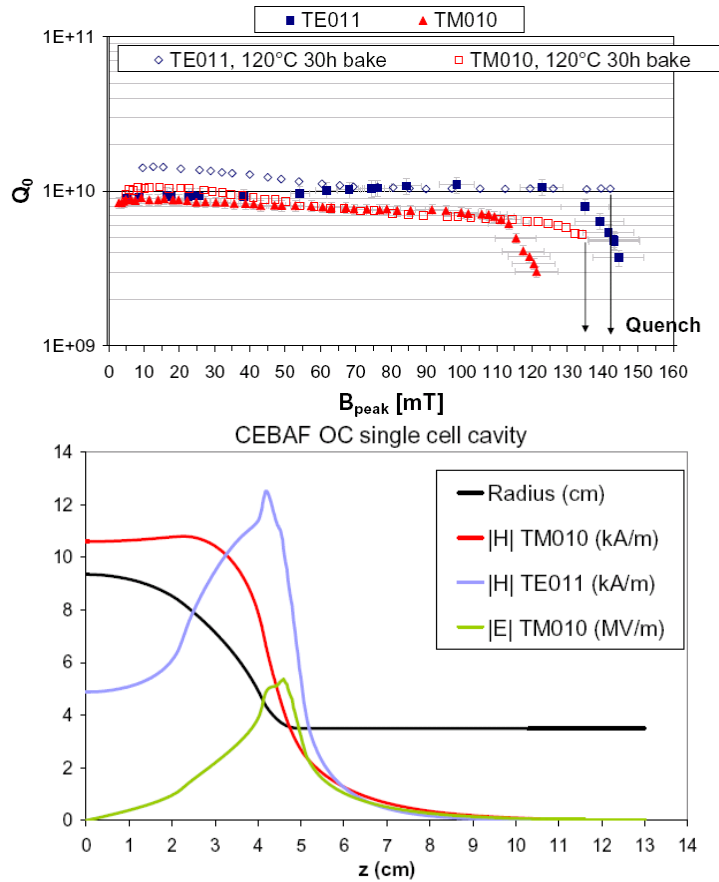


Figure 9: Above: Q before and after baking in CEBAF single cell cavity operated in the TM010 and TE011 modes. Below: Field-profiles in the TM and TE modes. Courtesy of G. Ciovati [16].

2.7) Special Cavities

The sputtered Nb on copper cavities produced by CERN show a strong Q-slope and rarely reach gradients beyond ~ 20 MV/m, where the Q-drop usually appears. It is therefore difficult to interpret these cases in terms of their relevance to the Q-drop phenomenon. The sputtering technology, however, is optimized for the exploration of the effect of different coatings. Some cavities were “dry-coated” with pure oxygen in the sputtering apparatus, which reduced the residual resistance [17]. Al-coatings, intended to substitute Nb-oxides, were also tested, showing no effect on the surface resistance [17].

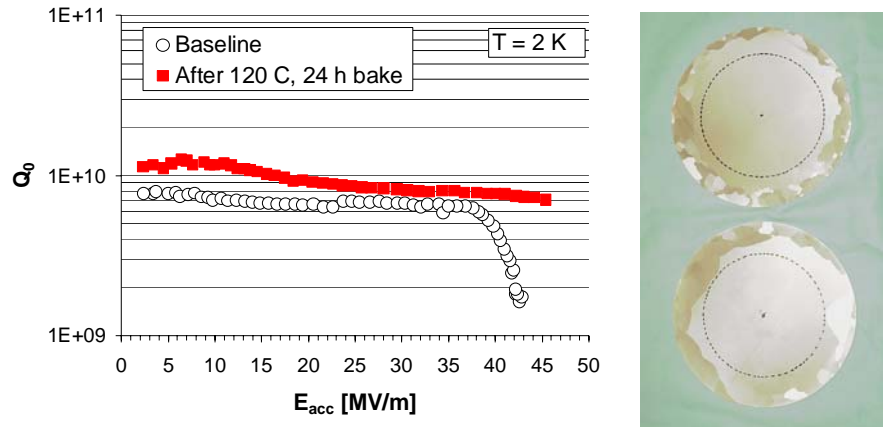


Figure 10: Test result of the single-crystal cavity at J-Lab. Courtesy of P. Kneisel [18]

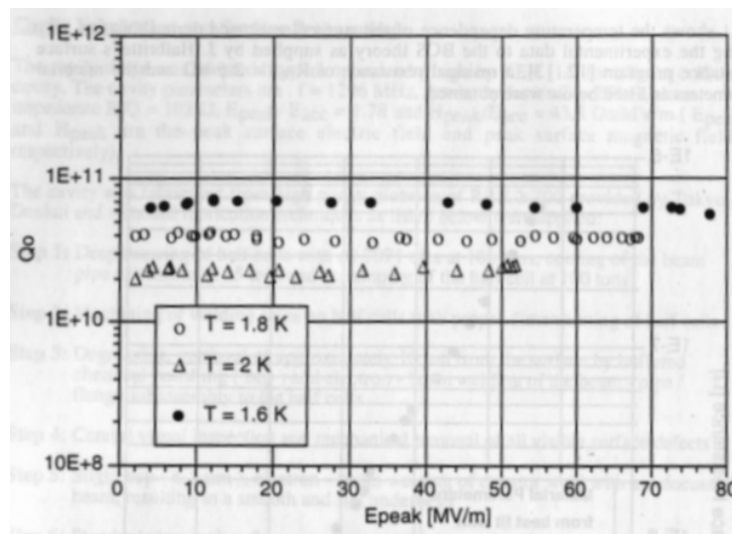


Figure 11: “Almost defect free” cavity as fabricated and tested by P. Kneisel [19].

Most important, however, are the recent single crystal cavities produced by J-Lab. Interestingly they as well showed Q-drop and baking benefit [18], possibly indicating that grain-boundaries do not play the central role in the Q-drop. The measurement result is shown in Figure 10.

Certain cavities, however, reached fields beyond the typical Q-drop onset field without showing Q-drop. Among them is the “defect-free” J-Lab cavity [19]. This particular world-record single-cell cavity was made from RRR 200 material from Tokyo Denkai. This measurement result is shown in Figure 11. Only a minimum of BCP etching and high pressure rinsing was applied. No heat treatments were performed.

2.8) Frequency Effect

Very little is known today about the frequency dependence of the Q-drop effect. Ciovati recently compiled data from cavities operating at different frequencies, indicating a general trend of increasing Q-drop onset field with frequency [20]. At frequencies beyond 3 GHz (and at the “usual” measurement temperature ~ 2 K) the thermal quench typically occurs before the Q-drop onset (see for instance the case of Fermilab’s 3.9 GHz cavities). Very low frequency cavities often battle Q-disease and the data on Q-drop are therefore scarce. A similar data compilation was prepared by Visentin (shown in Figure 12, right), indicating that the Q-drop onset field increases from 1500 to 700 MHz. This appears to contradict Ciovati’s plot. Visentin also notes that the Q-drops are more or less parallel in all cases [10]. With the possible interference of many other parameters (RRR, presence of damage layer,..etc) it seems such multi-cavity plots are to be considered with caution. Further study of the frequency effect is necessary.

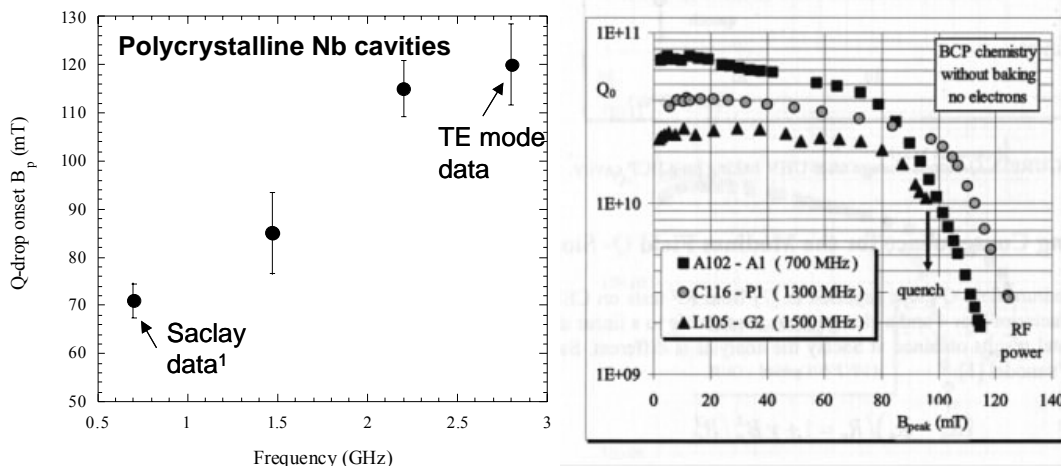


Figure 12: Left: Frequency dependency of Q-drop onset field, as compiled by G. Ciovati [20]. Q-drops at different frequencies as compiled by B. Visentin [10].

2.9) Baking Temperature-Profile Studies

Different baking procedures have been established at different laboratories. JLab heats N_2 gas blown at the cavity in the clean-room to $120^\circ C$ during 48 hrs (1.45 hrs ramp-up time). The DESY procedure is very similar ($120^\circ C$ during 48-70 hrs). At Saclay the helium gas surrounding the cavity in the cryostat is heated to $100-120^\circ C$ for 60 hrs. In special cases baking in air is also performed for single-cell prototypes (Fig. 13a).

As a general rule the baking temperature needs to remain below $\sim 150^\circ C$. Visentin’s systematic study of the effect of baking temperature indicates a gradual decrease in baking benefit (Q-curves are shifted more or less uniformly to lower values over the whole E-field range in the log scale) as shown in Fig. 13b. Beyond the $150^\circ C$ threshold



Figure 13a: CEA setup for baking in air [7].

the baking benefit disappears again (while things recover again above 300°C). It is also clearly established that (for a chosen temperature) there is an optimum baking duration, beyond which no further improvement is obtained. As is clear from the following figures the baking benefit is a gradual process that ultimately saturates.

Visentin performed the cavity-bake itself in air at 110°C for 60 hrs and again found that the Q-drop was removed, though not as thoroughly as when baked in vacuum (noted by Gigi) [1]. G. Ciovati’s experiment with baking in air at 120°C, 48 hrs did not show any improvement. A more recent experiment, in which he baked a cavity in air at 145°C for 3 hrs showed no substantial improvement of the Q-drop either [7]. The setup Visentin used for the baking in air is shown in Figure 13a. In a variant to these tests Visentin used plasma-coating (“cold” ECR discharge in pure oxygen) to grow the oxide layer toward the outside (as opposed to toward the inside as it occurs with anodization). The increase of the oxide layer by the cold plasma coating was confirmed by measurement on coupons. The plasma treated cavity had a similar Q-drop as those without. Again baking removed it.

A recent experiment by Visentin gave a strong boost to the oxygen diffusion hypothesis. The experiment consisted in applying a 145°C heat treatment for 3 hours instead of 110°C for 60 hrs, because both treatments gave the same calculated oxygen (Figure 15). Both heat treatments successfully removed Q-drop, although the procedure was less effective in the 145°C/3hrs case (possibly indicating that the parameters are not yet optimized)!

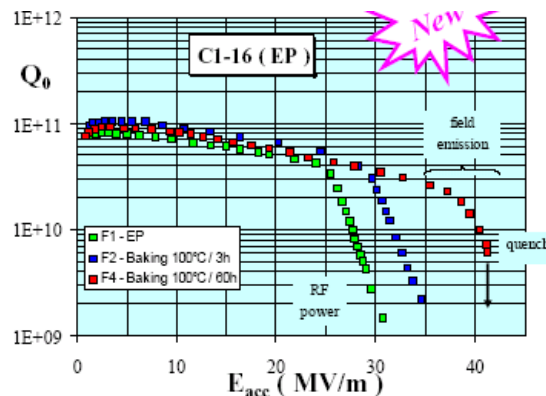


Figure 13b: Gradual removal of Q-drop with baking [10].

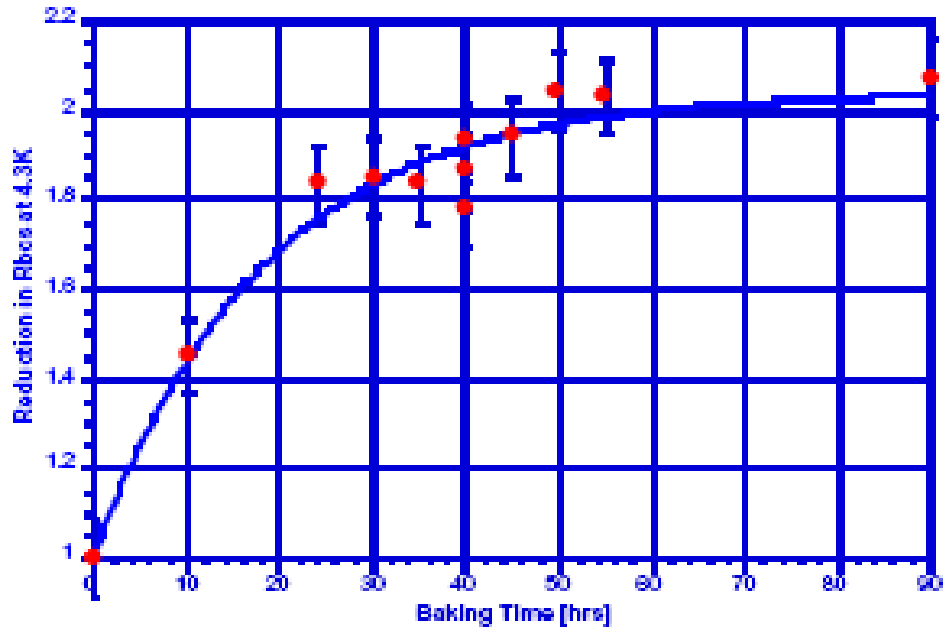


Figure 14: Reduction in surface resistance as function of baking time [9].

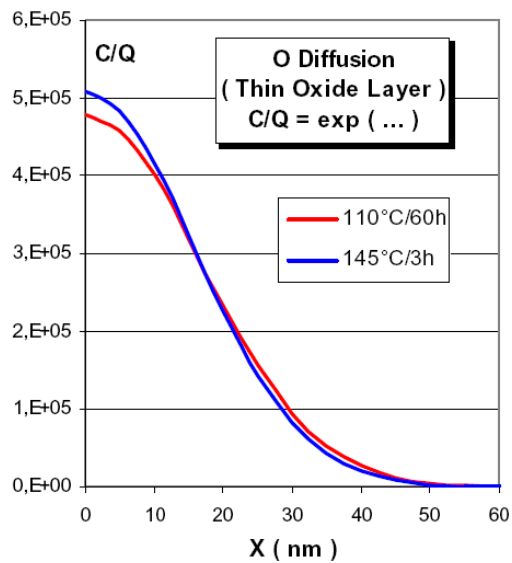


Figure 15: Oxygen profiles in Nb calculated for two different baking profiles [7].

The studies of the effect of baking temperature and duration therefore hint at a diffusion effect. As noted by Ereemev [15], the fact that after a 150-300°C heat treatment, the Q-drop reappears possibly could be explained by effects related to the decomposition of the oxide layer.

2.10) Magnetic Susceptibility and B_{c3} Measurements

AC susceptibility measurements between 10 Hz-1 MHz were recently conducted at Hamburg university to measure surface superconductivity beyond B_{c2} [21]. The main result of this series of measurements are that electro-polishing increases B_{c3} by ~10% (Figure 16). Baking at 144°C for $t > 48$ hrs increases B_{c3} another 20%. In all cases the measured ratio B_{c3}/B_{c2} (where B_{c2} is the measured bulk average) largely exceeded the theoretically expected DeGennes ratio of 1.695, hinting that the underlying effect is actually an increased B_{c2} in the surface layer of thickness λ as probed with this type of measurements. In the region of fields between B_{c2} and B_{c3} the susceptibility data clearly allow separation of a coherent and incoherent surface current regime. The coherent regime disappears at the same $0.81 B_{c3}$, independent of the preparation and it thus ensues that electro-polishing and baking also increase the field to which the coherent regime can be sustained (the surface currents measured in this case, however, were very small, three orders of magnitude smaller than the RF induced surface currents in a high gradient cavity). From this the authors conclude that the smooth EP surface is able to support higher, planar (two-dimensional) surface currents while the rough grain boundaries in a BCP surface enforce more complicated current patterns. Weak links in grain boundaries are also mentioned as possible cause for the “weaker” surface superconductivity in BCP samples with respect to EP samples. Finally paramagnetic susceptibility measurements at $B \gg B_{c3}$ (also shown in Figure 16) indicate larger density of paramagnetic impurities (oxygen?) after baking in BCP than EP samples (“..which may be an indication that the impurities in grain boundaries play an important role.”). The sample that was baked after electro-polishing was the one with the highest paramagnetic impurity (or oxygen) content. This finding is relevant to the oxygen contamination model discussed further below.

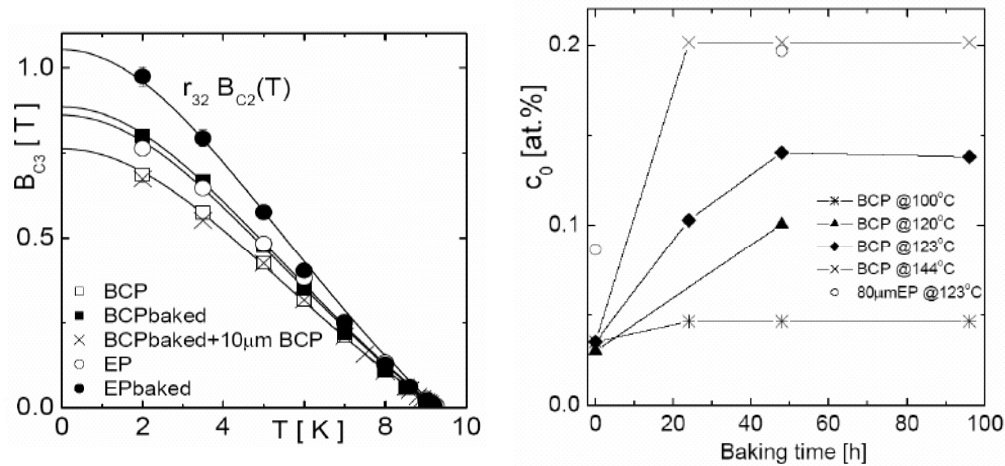


Figure 16: Left: B_{c3} measurements in electro-polished (EP), chemically polished (BCP) and baked samples. Right: Oxygen concentration derived from the paramagnetic moment [21].

3) Review of Q-Drop Models

Several models for the Q-drop and baking effect were presented. The most important among them are briefly introduced and discussed in the context of the experimental evidence gathered herein. The discussion of the models includes the arguments developed by Visentin in his similar, recent analysis [1].

3.1) Weak Superconducting Layer Model

H. Safa [6] proposed a two-superconductor model, with the high purity bulk Nb being covered by a thin (~2 nm) layer of “low-grade” (contaminated) Nb. The Q-drop arises when the critical magnetic field is reached in the “weak” layer, which, as a result of the contamination, has a low critical field. After baking the “weak layer” dissolves into the bulk (Figure 17). While this removes the Q-drop, it does so at the expense of a slight increase of surface resistance (and an increased quench field) because of the impurity content being distributed into the “purer” bulk. Both effects, as pointed out by Visentin [1], are not confirmed by experiments, which on the contrary reveal a decrease of the BCS surface resistance after baking and no effect of the baking on the quench field (at least in BCP cavities). This, however, is not necessarily inconsistent with an increase of contamination in the bulk layer, as will be discussed further in 4.2). In light of the facts known today the contaminant could be interstitial oxygen, which is known to strongly depress superconductivity in Nb in concentrations of several at%.

H. Safa’s two-superconductor model explains Q-drop with the transition of a nm thin layer on the surface of the Nb bulk into the normal state. He does not specify, however, the exact modus of this quench. Is it that vortex penetration occurs at lower fields because of a reduced B_{c1} in the “weak” layer? Note that the Abrikosov vortex nucleation time is believed to be longer than the RF period. Furthermore, shouldn’t a nm-thin layer adjacent to the pure and strong superconductor in the bulk be superconducting by proximity coupling? Surface chemistry studies have yet to support or refute the contamination model. Very little hard data exist on the chemistry of the first few nm in the bulk.

Visentin also points out that in his HF treatment experiment (discussed in 2.4) the Nb-oxide interface was completely re-built after dissolution of the oxide in HF, and with it the oxide-rich few nm thick layer on top of the bulk, i.e. “Safa’s weak layer”. Since after HF treatment the Q-drop is not restored, the oxygen rich surface layer could not have been its cause, so he argues. This was also pointed out by Ciovati [20]. Another issue, also mentioned by Visentin [1] is that the Safa model does not explain why the quench field is higher in EP than BCP cavities. All these questions need to be answered before this model can be seriously considered. A variation of this model was recently presented by V. Palmieri [22].

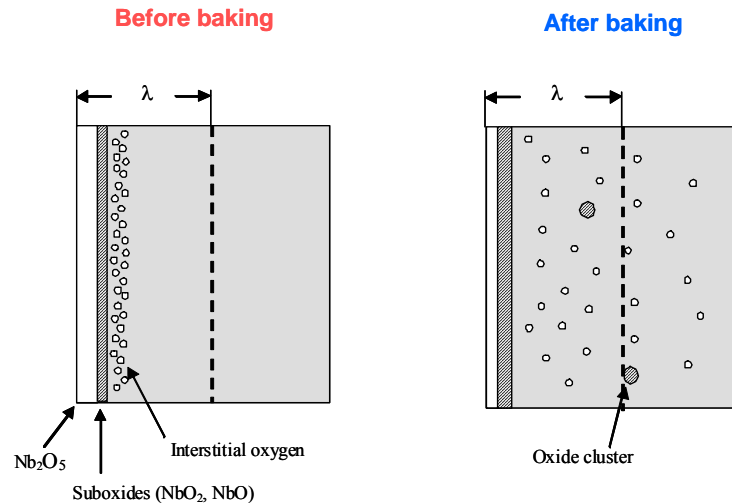


Figure 17: Schematic of oxygen distribution before and after baking. Courtesy of G. Ciovati [Ciovati-SRF05]. λ is the London penetration depth, i.e. the RF field penetration depth.

The strength of this model is that there is ample evidence that the diffusion of oxygen is playing a role in the Q-drop and baking effects. Should oxygen be the contaminant responsible for weakening the surface superconductor, then the purification of the Nb surface layer during baking is only possible if the oxide does not decompose at the baking temperatures. The lack of baking benefit for heat treatment at temperatures exceeding 150°C could very well be explained by it. The fact that the baking benefit is more pronounced in the EP cavities than in BCP cavities as well as other experimental findings (no effect of exposure to air,..etc) may also be related to the details of the oxide layer (de-)composition. Note, however, that some data (notably the susceptibility measurements at the University of Hamburg) appear to indicate an increase in oxygen content in the first 50 nm with baking.

The issue of oxide diffusion into the surface during baking will be discussed further later.

3.2) Grain-Edge Field Enhancement Model

Q slope can be explained by any surface resistance contribution with a strong field dependence. One such surface resistance contribution, proposed by J. Knobloch [23], is given by field enhancement at the sharp edges of grains. This contribution is characterized by a strong dependence on field above a given threshold ($\sim B^4$). Especially BCP etched surfaces are usually rougher, characterized by sharp grain-edges, which are believed to be the result of variations in the etching rate for different crystal orientations and preferential etching at the grain boundaries. FE computations reveal that sharp edges of grains can produce field enhancement factors of up to two. Localized quenching of

grain edges occurs whenever the enhanced fields reach the critical field. This of course occurs first in the high field (equator) regions of the cavity. Knobloch calculates the Q-drop from an estimate of the total surface of the quenched grain edges (in the normal state) at a given field in the cavity. An important input into this calculation is the distribution of field enhancement factors. One can argue that the field enhancement factor at which this distribution peaks is approximately related to the field at which the Q-slope starts (e.g. $B_{crit}/B_{slopestart} \sim 1.6$). The width of the distribution is bounded by the fact that enhancement factors above two are not consistent with typical surface topologies (so at least argues Knobloch). The distribution function proposed by Knobloch uses $\beta_0 \sim 1.44$ and $\sigma \sim 0.0068$. The surface resistance contribution due to quenched grains is a function of the normal state surface resistance ($\sim 1.5 \text{ m}\Omega$ at 1.3 GHz) and the “width” of the quenched grain edge (usually assumed to be $\sim 1 \mu\text{m}$).

The strength of the field enhancement model is that it naturally explains the difference between chemically polished and electro-polished cavities as a result of a difference in surface roughness. It is more difficult, however, to explain the effect of the low temperature bake with this model, since the bake does not appear to modify the surface roughness.

An additional, independent model therefore appears necessary to explain the effect of the bake. Such a model could be the 2-superconductor model discussed above. It could also be the fluxon penetration model (as noted for instance by Visentin). The later would be interesting because it does not contradict the fact that electro-polished cavities show less Q-drop than chemically polished cavities. This since, as a result of surface topology, the B_{c1} would also be reached earlier locally in the rougher (BCP) surface. In that sense the field-enhancement model is rather an addition to the Q-drop model and could be useful to explain the difference in response of BCP polished and electro-polished cavities to the baking. It could also represent be an “additional” Q-drop mechanism present in BCP-etched cavities and not removed by the in-situ bake. This would explain the weaker response of BCP etched cavities to the bake as compared to electro-polished cavities (i.e. the field enhancement effect is in this sense “uncovered” when the Q-drop is removed by baking). The fact that the Q-drop before baking is similar in the EP and BCP treated cavities, on the other hand, seems to completely contradict the field enhancement model. The fact that the quench field does not change in BCP cavities from before to after baking is also not explained by this model.

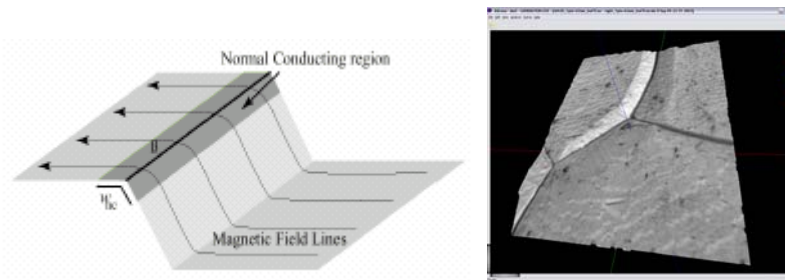


Figure 18: Left: Schematic drawing of quenched grain edge due to field-enhancement. Courtesy of J. Knobloch [23]. Right: 3D reconstruction of surface topology in e-beam weld region. Courtesy of P. Lee [42].

3.3) Fluxon Penetration Model

The fluxon penetration model is probably the oldest, but least developed of all Q-drop models. It was established early on that the finite nucleation times of Abrikosov vortices allow delaying fluxon penetration beyond the thermo-dynamic critical field, H_c , in a *perfect* surface (to the so-called “superheating” field). The flux penetration into a “realistic” surface, with field enhancement and reduced surface barrier, however, was not studied. This is a high priority task!

G. Ciovati [20] and many others suggest that the baking cures Q-drop because it raises the critical field, H_{c1} , thus delaying flux penetration. The H_{c1} of the surface layer can certainly be raised as a result of a purification of this surface. Recent experiments conducted by the University of Wisconsin [43] as well as those at the University of Hamburg [21] show that the H_{c1} of the surface is typically smaller than that of the bulk. A surface resistance model by Rabinowitz can be used to evaluate the surface resistance contribution by an Abrikosov vortex inside the bulk oscillating in the RF field. Some have issued doubt, however, whether, a single vortex could be sustained in the high field RF regime. Other vortex types, such as the Josephson or mixed Abrikosov-Josephson vortex need to be considered. They have shorter nucleation time, higher mobility and produce less loss. Geometrically they are not bound by the coherence length, but by the “size” of the weak region. Figure 19 shows a schematic of how a mixed vortex is created in a region of weakened superconductivity (i.e. with reduced de-pairing current J_d and critical field H_{c1}). Essentially the mixed type vortex is a “current deviation”.

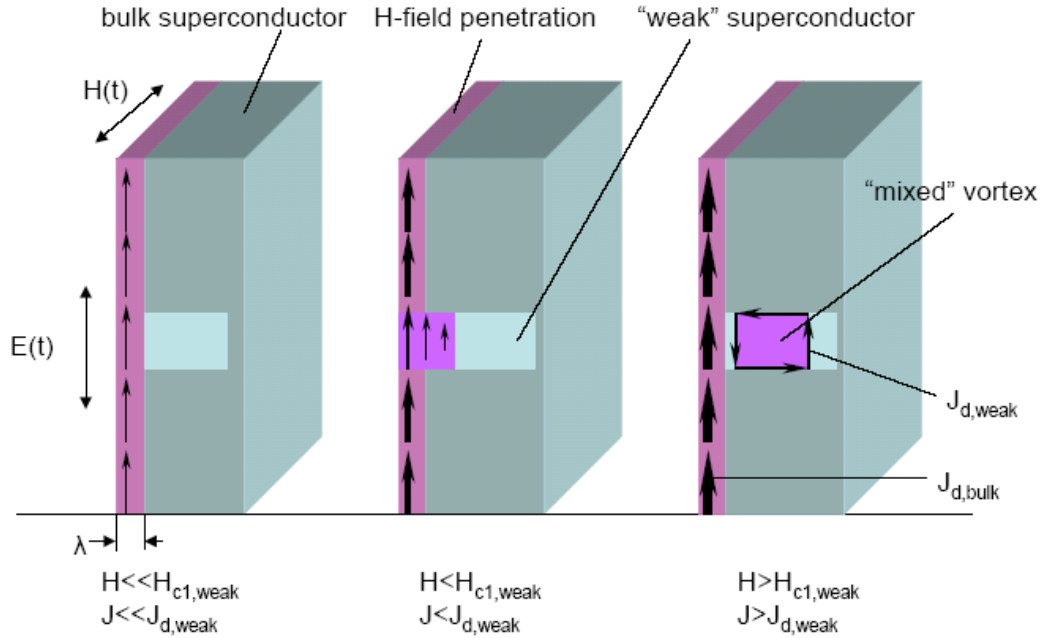


Figure 19: Schematic drawing showing the generation of a “mixed” vortex in a region of weakened superconductivity (lower depairing current density J_d and critical field H_{c1}).

One should note that the flux penetration model potentially could explain the case of Nb_3Sn film cavities, which showed Q-drop at much lower fields than bulk Nb, maybe as a result of the much lower H_{c1} in Nb_3Sn .

3.4) Wet-dry Oxide Model or ITE Model

Oxides in the surface dielectric provide localized states accessible to sub-gap electrons in the adjacent superconductor via tunneling. Once occupied, resonant absorption of RF fields and scattering on phonons generate the loss contribution (see schematic in Figure 17). This phenomenon is known from Josephson junctions. J. Halbritter describes the effect of ITE on the RF surface resistance with a phenomenological formula, assuming an exponential contribution when the threshold field for ITE is reached [24]. Some of the main predictions of the ITE model are that the Q-drop threshold field should increase by baking (because baking reduces the density of localized states) and decrease with a thicker oxide layer (because the number of localized states is increased). ITE could also explain why electro-polished cavities generally respond better to baking: the local electric

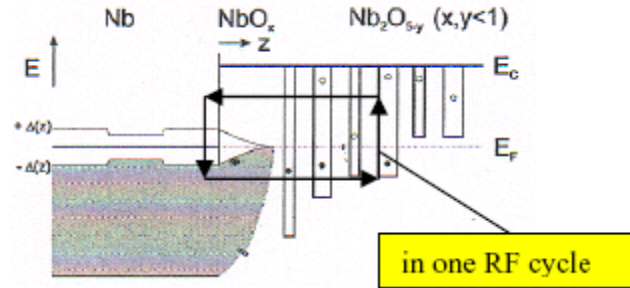


Figure 20: Schematic for loss mechanism causing Q-drop in SRF cavities [24].

field that drives ITE can also be enhanced by surface topology, less surface roughness in EP cavities hence increases the ITE threshold field. This argument, however, can also be turned around. If the local electric field is higher in chemically polished than in electro-polished cavities, one could also expect their Q-drop to be steeper. Unfortunately the ITE model is not quantitative at this point.

Two experimental results contradict this particular model: -1- thermal maps indicate that most heating during the Q-drop occurs at the equator and not where the electric field peaks (iris region) –2- Ciovati’s measurements on cavities in the TE-mode do also show Q-drop although the surface electric field is zero. The experiments which consisted of modifying the oxide layer and did not show a reversal of the baking benefit, such as baking in air [1], rebuilding the oxide after an HF treatment [10], growing thicker oxide by cold plasma coating [12], indicate further that the role of the surface oxide in the Q-drop phenomenon is of secondary order. One experimental fact that the ITE model explains, however, is the onset of Q-drop at approximately the same gradients in EP and BCP cavities [1].

3.5) Thermal Feedback – Global Heating vs Hot Spot Model

There is not much doubt about the fact that Q gradually decreases with applied fields as a result of thermal feedback. The exponential dependence of the BCS surface resistance of the superconductor on temperature, in feedback with the dependence of the RF power dissipation on the surface resistance drives this process, which ultimately leads to thermal runaway (thermal quench) of the RF exposed surface. A. Gurevich recently presented a thorough analysis of thermal feedback [25]. Most important for the agreement between model and reality, however, is what surface resistance contributions (beyond BCS) are included in the thermal feedback model. Although numerous surface resistance contributions are known, we believe today that the Q-slope in bulk Nb cavities in the medium field region is more or less understood (in the better cavities) with a mix of linear and non-linear BCS resistance (A. Gurevich and P. Bauer [26]) and/or some weak-link hysteresis (J. Halbritter and Ciovati in [27]).

Even these surface resistance contributions, however, are not sufficient to describe the very steep, ultimate Q-slope (or Q-drop) found before baking. This fact is clearly illustrated in the figure below, showing a comparison of data from a state of the art SRF cavity from CEA to a thermal feedback model calculation. This comparison shows that the thermal feedback model calculation based on linear, non-linear BCS and residual surface resistance (as measured at low field) does not predict the ultimate Q-drop. No “reasonable” set of thermal material parameters can explain this discrepancy. Expressed in terms of the Halbritter slope parameter γ^* ¹, the model on the basis of linear and non-linear BCS predicts $\gamma^* \sim 1-3$. The γ^* parameters that fit the experimental ultimate Q-drop data is ~ 500 . This is the fundamental problem of the thermal feedback model as discussed in [1].

The current understanding is that the thermal feedback model requires an additional surface resistance contribution, possibly due to the quench of a weak layer, fluxon penetration, ITE or early quenching of the grain edges as a result of field enhancement to predict the steep slope during the Q-drop.

A possible improvement of the thermal feedback model based on the “standard” surface resistance contributions (BCS and residual) is to assume non-uniform surface properties. Such a case was developed by Gurevich and called “hot spot” model [28]. The hot spot model assumes that some, possibly very small regions (<1 μm), operate at a higher loss rate, e.g. as a result of a locally depressed superconductivity (smaller gap,..etc) or a normal inclusion. The hot spots grow to a larger size as a result of thermal diffusion. Given the exponential factor in the BCS surface resistance these regions, although only

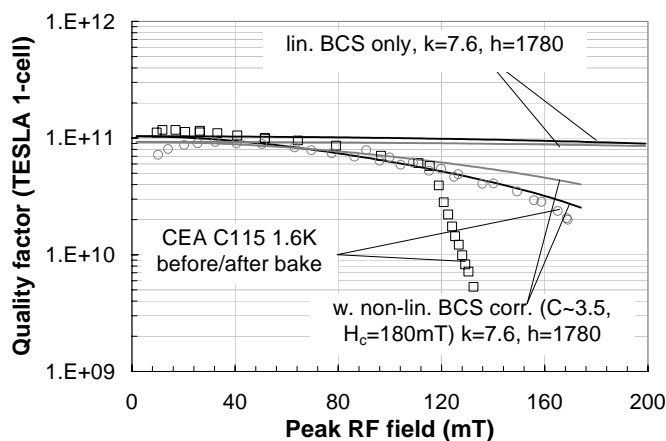


Figure 21: Comparison of measured and predicted quality factor of a CEA/Saclay single cell TESLA prototype cavity (C 115) before and after baking. Experimental data were obtained at 1.6 K. The cavity was electro-polished and post-purified and has a very small residual surface resistance Also shown are calculations for a case with residual and linear BCS resistance as well as a case with residual, linear and non-linear BCS resistance [26].

¹ The γ^* parameter is related to a surface resistance fit function of the type $R_s = R_{s0}(1 + \gamma^*(H/H_c)^2)$, with R_{s0} the surface resistance at the bath temperature and zero RF magnetic field H.

100 mK hotter than the others, can give a noticeable surface resistance contribution if present in large enough numbers. The hot-spot model is obviously consistent with the results of thermal mapping (Figure 22), indicating hot spots at 100-200 mK above background. Note that the temperature margin of the RF exposed surface is only 200-300 mK, before thermal feedback causes a thermal quench.

The hot-spot model, however, does not specify any further the cause of the non-uniformities. It could be fluxon penetration, normal conducting inclusions, hypersound,..etc [28]. Note also, that the hot-spot model has some commonality with the local defect model, which often limited cavities in the past. These local defects were ~10-100 μm size normal conducting regions that would heat to the critical temperature during RF operation and cause a sudden quench (with no prior “signature” in the Q characteristic). What is also not explained in the “hot-spot” model is the baking effect. This question, of course, is closely tied to the origin of these spots. The difference of the baking effect in EP and BCP cavities is also not explained with this model.

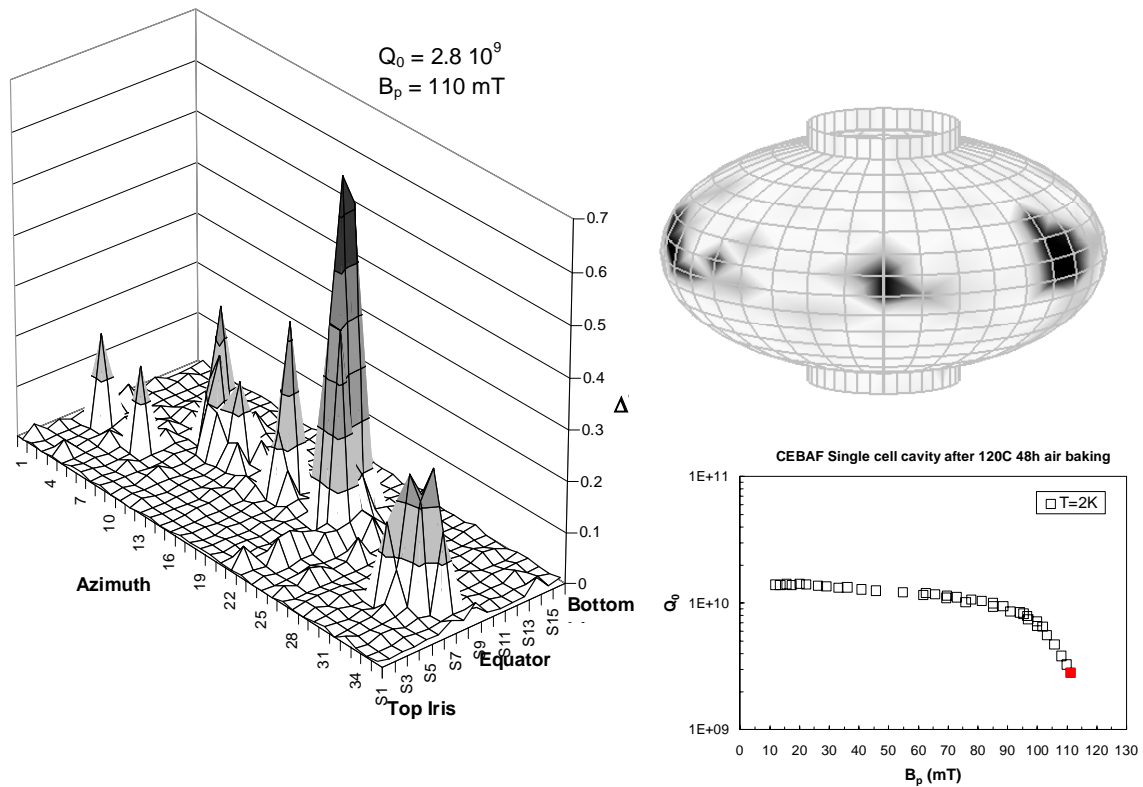


Figure 22: Example of hot spots recorded in thermal maps in the Q-drop region. Courtesy of G. Ciovati [20].

3.6) Weak-Link-Model

The strong Q-slope observed in sputtered Nb on Cu cavities is now believed to be in part the result of 100 times smaller grain-size as compared to poly-crystalline, cross-rolled bulk material. Possibly because of the effect of grain-boundaries on the RF surface resistance. Models used for the description of high-Tc superconductors in which the grain-boundaries are described as weak links, were adapted to the case of RF fields. Such a model was adapted to the case of Nb by H. Safa and B. Bonin [29]. The most important input parameter in this case is the grain boundary critical current density together with the weak-link lattice parameter, i.e. the grain size in this case. The de-pairing current density derived from the Meissner shielding condition is $\sim 3 \text{ MA/mm}^2$. The grain-boundary de-pairing current density is difficult to measure. The details of the interaction between the baking effect and the weak links remain to be explained also. Note that a different type of weak link effects was taken into account in the “hysteresis” loss as a contribution to the medium field Q-slope [27, 24].

The fact that today’s SRF cavities made from polycrystalline material achieve peak performances at or even above the thermodynamic critical field indicates that grain boundaries cannot be too disruptive, however. It is also not clear how this model explains the benefit of baking. One possible mechanism would be that baking increases the grain-boundary de-pairing current density, but this needs to be shown experimentally.

4) The Role of Oxygen

4.1) Oxygen Diffusion and Oxide Layer

Oxygen diffusion was quickly identified as a possible culprit for Q-drop because at the baking temperatures only oxygen and hydrogen have sufficient mobility to diffuse a London penetration depth ($\sim 40 \text{ nm}$) into the material. A diffusion process would also be consistent with the fact that the baking benefit first continuously increases with baking time and then finally saturates. According to the diffusion models the saturation of the baking benefit occurs at roughly the time at which the diffusion front has reached the edge of the London depth. Different variants of the diffusion model were applied. A major issue in these calculations is the assumption on the supply of atomic oxygen on the oxide-bulk interface. Calatroni [30] calculated the diffusion with the Fick equation and an experimental diffusion coefficient, assuming that there is no O in the bulk before the heat treatment, while the oxygen concentration in the surface layer is at the “solubility-limit” (=infinite). This model predicts that the $145^\circ\text{C}/50 \text{ hrs}$ profile drives oxygen up to 200 nm into the bulk². Recently Ciovati introduced an oxide-decomposition term into the

² Kneisel’s BCS surface resistance versus removed thickness data were used to estimate the solubility limit at 145 deg to be $0.33\% \text{at}$ of O. Ciovati’s surface resistance measurements in the normal state ($\sim 10 \text{ K}$) give RRR values of the order of 200 in the RF skin depth of the material. This RRR is consistent with a $0.017\% \text{at}$ oxygen content in the material [Ciovati-SRF03]. Calculations in which the supply of oxygen on the surface is limited have also been performed – they usually give smaller diffusion depths. The specified bulk value is $\sim 10 \text{ wtppm}$ ($=0.006\% \text{at}$).

calculation. As will be discussed next the oxide decomposition was observed in numerous surface chemistry studies. This process could explain why “overheating” or heating in air can destroy the baking benefit and restore the Q-drop.

Several studies were performed to quantitatively estimate the composition of the oxide layer using XPS. Most XPS studies conducted thus far have in common that after deconvolution of the Nb3d line four chemical states of oxidized niobium could be identified: Nb₂O, NbO, NbO₂ and Nb₂O₅. On top of these oxides there are adsorbates of carbon with C=O and C-OH bonds (also Nb-OH) [31].

Kowalski’s [32] XPS studies show decomposition of Nb₂O₅ into NbO and NbO₂ during baking (weak at 120°C, strong at 160°C), with the effect being more pronounced in the BCP treated sample than in the EP sample. This, however, could well be an artifact of the fact that the oxide layer was thinner following BCP treatment than after EP (XPS measurements give relative results). Kowalski argues (Figure 23) that at the typical baking temperatures the oxide layer decomposition is unlikely. His sketch illustrates a “dirty” limit case, in which the drop in BCS resistance after baking is the result of a decreased oxygen concentration in the λ-layer and thus an increase in mean-free-path. As will be discussed later this is not the currently preferred model. Kowalski also observes

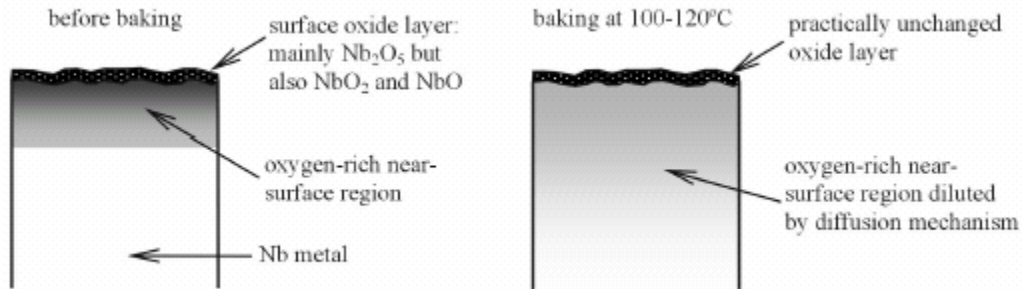


Figure 23: Oxygen contamination model as sketched by K. Kowalski et al. [Kowalski – SRF03]

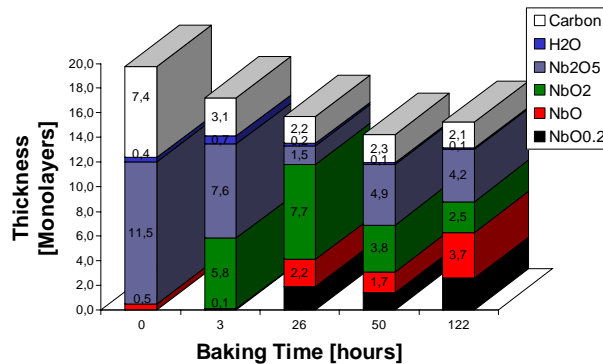


Figure 24: Natural oxide (Nb₂O₅) decomposes into sub-oxides (NbO, NbO₂), thinner oxide layer. Courtesy of A. Dacca [34].

a decrease of the oxide thickness during baking – therefore not everything is about pentoxide decomposition, some oxygen must also escape (into the bulk or into the furnace). Pentoxide decomposition and increased disorder was found by all groups performing XPS measurements.

Rosenberg [33] found a reduction of Nb_2O_5 and formation of NbO_x ($x < 2.5$) during baking at $\sim 100^\circ\text{C}$. At 170°C only a little Nb_2O_5 remained after > 70 hrs and substantial amounts of NbO_x formed. Heating at these temperatures caused hydrocarbon decomposition, leaving graphitic carbon on the surface.

Dacca found that during the heating phase, an irreversible transition took place near $200\text{-}300^\circ\text{C}$. It is characterized by a progressive reduction of Nb oxides from Nb_2O_5 to NbO_2 and finally to NbO . Work function measurements show that the values of Φ are strongly correlated with the chemical composition of the surface [34].

Antoine also saw a reduction of oxide layer thickness and transformation of the oxide layer composition from containing Nb mostly in the Nb-V state (as in Nb_2O_5) to the Nb-IV state (110°C , 48 hrs, 10^{-9} bar) [35]. Decomposition of Nb_2O_5 to sub-oxides (“increase of disorder”) during baking further confirmed in later XPS studies [36]. Furthermore she observed “injection of oxygen into the matrix”.

A famous experiment was performed in the 1980s by Palmer [37]. He fired X-band niobium cavities at 1400°C in UHV, which resulted in the dissolution of the native surface oxides as confirmed by AES. The residual resistances of these “oxide-free” cavities (they were never exposed to atmosphere prior to the test) were $5\text{-}10\text{ n}\Omega$ – comparable to oxidized surfaces. When oxide layers were carefully re-grown under controlled exposure to dry oxygen, the increase in resistance gave an additional contribution of $1\text{-}2\text{ n}\Omega$ for the oxide layer [31]. Studies of dry and wet oxides were also performed by [38]. Dry oxide was grown in the furnace following a 1950°C UHV firing, with no subsequent etching, improving the cavity (3 GHz) performance noticeably, in this case. The SRF community generally believes that dry oxides are thinner, better ordered and give better performance.

Summarizing the chemical analysis of the baking effect seems to indicate decomposition and restructuring of the oxide layer as well as dissolution of an oxygen-rich layer on top of the bulk into the purer bulk underneath. This finding is essentially consistent with all models. Some experimental data, such as the magnetic susceptibility measurements at the University of Hamburg and Visentin’s HF experiment are not consistent with it.

4.2) Effect of Baking on BCS Surface Resistance

Many authors, among them [8], [9], [39] report a substantial decrease of the BCS surface resistance (up to a factor of 2) and (sometimes) an increase of the residual surface

resistance after baking. An example is given in Figure 25, showing that a saturation of the effect occurs at baking temperatures exceeding $\sim 130^\circ\text{C}$. The BCS surface resistance contribution is derived from a fit of the experimental surface resistance obtained from a Q measurement at varying bath temperatures and at low field. The residual surface resistance is the value to which the surface resistance asymptotically tends toward very low temperatures.

Interestingly the change of BCS resistance is rather via the $A(\omega)$ factor in Eq. (1) rather than the α exponent [9]. This indicates that the effect is rather related to a mean-free-path issue than gap suppression. This is also confirmed by a detailed analysis of the change of BCS resistance with baking performed by Saito. He calculated the BCS resistance with the Halbritter program, which allows for a larger number of free parameters ($f_0, T_0, T_c, \alpha, \lambda_L(0), \xi_0, \Lambda_{mfp}$). Saito’s finding is that the leading parameter that is changed by the baking is Λ_{mfp} , which is decreased strongly [40] with baking. This finding supports the “contamination theory”.

$$R_{s,BCS}(T) = \frac{A(\omega, \Delta, \Lambda, \dots)}{T} e^{-\frac{\Delta}{k_b T}} \quad (\Omega) \quad (1)$$

Ciovati’s data (see right graph in Figure 25) also support this model. In addition, however, Saito found that it was also necessary to decrease $\lambda_L(0)$ and increase α . The latter was also shown in Ciovati’s analysis [39]. Since according to the two fluid model the mean free path reduction results in an increase of the effective penetration depth, this finding is consistent with the observed reduction in cavity resonance frequency after baking, as found by Visentin [8]. The last argument, however, applies only to the case of the so-called “dirty limit”, for which the two-fluid model applies.

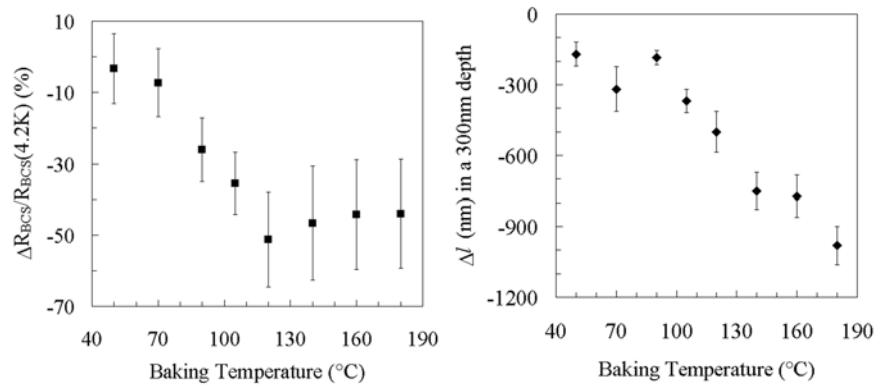


Figure 25: Left: change of BCS resistance after baking at different temperatures (baking time = 48 hrs). Courtesy of G. Ciovati [20]. Right: mean free path measurements in the superconducting state. Courtesy of G. Ciovati [2].

Ciovati’s analysis [39] on the basis of experiments conducted on a CEBAF single cell cavity – using the “free” parameters in the Halbritter-program $T_c, \alpha, \Lambda_{mfp}$ (λ_L, ξ_0 were kept fixed) and the residual resistance – showed an increase in α from ~ 1.81 to ~ 1.85 and decrease in electron mean free path (from ~ 750 nm to 500 nm) as a result of the baking process. Ciovati also measured the shift in cavity frequency with temperature at a temperature close to critical. He converted this information into an electron mean free path using Halbritter’s BCS resistance program, finding a decrease of the electron mean free path in the RF skin depth after baking. Note, however, that at 7-9 K, the measurement temperatures, the London depth is up to ~ 300 nm, and thus the mean free path obtained through this procedure is an average over this layer.

The most widely accepted explanation for the reduction in BCS resistance is that the first ~ 100 nm in the Nb bulk are clean and become dirty as the baking is performed [9]. In this case the BCS surface resistance is reduced because one is on the clean limit side of the minimum in the BCS resistance vs mean free path characteristic (Figure 25). Ciovati’s recent work (Figure 25) is also consistent with this model [39]. There is some doubt, however, whether there should be any noticeable dependence of the BCS surface resistance on the mean free path in the clean limit [25, 28]. Furthermore the case of clean-limit versus dirty limit is not unambiguously resolved yet. The BCS resistance as function of London depth (anti-proportional to mean free path) is shown in Figure 26, with a question mark next to the data under discussion on the clean limit side.

Furthermore, and this was pointed out by several authors ([7], [20]), one also needs to differentiate between the first few nms of the bulk and the rest of the ~ 50 nm into which the fields penetrate. The first few nms might be more relevant to the Q-drop problem, while the BCS resistance measurements probes the entire London depth layer. Ciovati, for instance, suggests that the former might be purified during baking, while the latter might be contaminated during baking. This suggests an alternate explanation for the

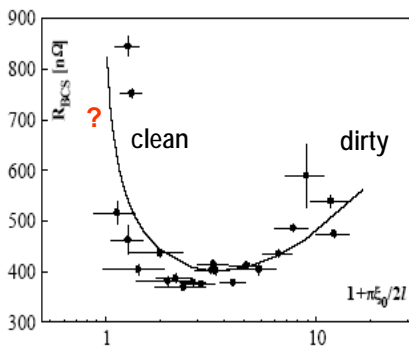


Figure 3. The BCS resistance at T=4.2K.

Figure 26: BCS resistance versus penetration depth. From H. Padamsee [41]. The question mark is from Gurevich who claims that an increase of the BCS surface resistance in the clean limit is unexpected.

reduction of the BCS resistance with baking, in analogy with Safa's weak layer model, assuming, as suggested by Ciovati [20], that the baking drives the interstitial oxygen out of the first few nm of the bulk, where the high oxygen content (10-15%) causes depressed superconductivity. One could imagine that, as a result of the gap-suppression, the weak layer also dominates the RF surface resistance before baking as a result of an increased BCS resistance (also note that the magnetic fields are higher in this area, possibly causing an additional contribution to the BCS surface resistance due to non-linearity). After purification of this layer the total BCS surface resistance drops, because the dirty layer is purified. The gain in BCS resistance due to purification of the first few nms can offset the slight increase in BCS resistance due to slight contamination of the remaining 50 nm. It is not clear, however, as with all weak layer models, how this model can be made consistent with the HF experiment by Visentin, if, as claimed by Visentin, oxygen is re-introduced in to the "weak layer as a result of the HF treatment (see the detailed discussion in 3.1)).

4.3) Summary Table

The following table is an attempt to collect the major experimental facts supporting or not supporting oxygen purification or contamination models. The task is obviously not simple given the sheer amount of data available as well as the difficulties related to their interpretation.

The main experiments listed in the table below are the experiments:

- measuring the effect of anodization on Q-drop and surface resistance in a baked cavity;
- varying the baking temperature and duration;
- applying an HF treatment after baking;
- measuring the effect of baking on BCS resistance and cavity resonance frequency;
- measuring the magnetic susceptibility of the λ surface layer;
- looking for possible non-linear BCS resistance contributions;
- measuring the surface chemistry before and after baking;

If any conclusions are permitted on the basis of this modest table, one could argue that the contamination models have the upper hand. The partial purification model as proposed by Ciovati, however, is also counted with the contamination models, because it assumes that the thicker, deeper portion of the λ surface layer is contaminated in the baking process.

Table 1: Summary of Q-drop and baking benefit data in the context of oxygen models. Four different hypotheses regarding the oxygen levels in the surface layer after baking are discussed in the context of the experimental data. “Mixed” refers to a case as proposed by Ciovati in which the top layer (first 1-10 nm) is purified while the rest of the first 100 nm are contaminated by the baking procedure.

Effects of Baking	Purification	Contamination	Mixed	Comment
Low field BCS-resist. decreases by up to 50% (Kneisel)	OK - if material starts from dirty limit	OK ? – if material starts from clean limit	OK ? – if material starts from clean limit	? Which mechanism causes decrease in BCS resistance when decreasing the mfp coming from the clean limit?
Reversal of baking benefit by anodization of first 10 nm (Eremeev)	OK	OK	OK	This experiment indicates that the top layer plays a significant role in the Q-drop
No reversal of baking benefit by HF treatment (Visentin)	OK	OK	NO	This experiment indicates that the top layer does not play a significant role
Decrease of mean free path in first 300 nm (Ciovati, Visentin reduction of cavity resonance frequency at 7-10K)	NO	OK	OK	-
Increase of surface-Hc2 and paramagnetic moment (Casalbuoni)	NO	OK	OK	Magnetic susceptibility measurements in the superconducting state is determined by processes taking place within the I-layer
Non-linear BCS resistance in medium field before and after baking not consistent with clean limit in most cases (Bauer)	NO?	OK	OK	? There is, however, the possibility that the purification model holds if the purification is bringing the surface from a very dirty to a moderately dirty state
Saturation of baking effect after a certain baking time (for a given temperature)	OK ? – O depletion	OK? – O supply from de-composing oxide or sub-oxide dries up	OK? – O-rich layer is depleted when purified	? Quantitative analysis would be needed here to differentiate the different scenarios.
No baking benefit for a baking temperature above ~150C	OK? – O contamination from de-composing oxide	OK? – excessive O supply from de-composing oxide	OK ? – excessive O supply from de-composing oxide	? Quantitative analysis would be needed here to differentiate the different scenarios.
XPS analysis	OK? – evidence of high oxygen content before baking	OK ? - Evidence of sub-oxides and oxide decomposition	OK ? evidence of high oxygen content before baking	? Experimental evidence goes both ways, although Kowalski concludes in favor of purification models

References

- [1] B. Visentin, “Q-Slope at High Gradients: Review of Experiments and Theories”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [2] G. Ciovati, “Effect of Low-Temperature Baking on the Radio-Frequency Properties of Niobium Superconducting Cavities for Particle Accelerators”, J. Appl. Phys. 96, p. 1591, 2004
- [3] L. Lilje, EPAC 04
- [4] J. Hao, D. Reschke, A. Brinkmann, L. Lilje, “Low Temperature Heat Treatment Effect on High-Field EP Cavities”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [5] B. Visentin, “Improvements of Superconducting Cavity Performance at High Accelerating Gradients”, EPAC 1998, Stockholm, Vol. III, p. 1885, TUP07B
- [6] H. Safa, “High Field Behavior of SCRF Cavities”, Proceedings of the 2001 workshop on RF superconductivity, Sept. 2001, Tsukuba, Japan
- [7] B. Visentin, “High Field Q-Slope and Oxygen Diffusion”, presentation at the 2005 workshop on RF superconductivity, July 2005, Ithaca, USA
- [8] B. Visentin, J.P. Charrier, B. Coadou, D. Roudier, “Cavity Baking: A Cure for the High Accelerator Field Q_0 Drop”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [9] P. Kneisel, “Preliminary Experience with in-situ Baking of Niobium Cavities”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [10] B. Visentin, “Low, Medium, High Field Q-Slopes Change with Surface Treatments”, Proceedings of workshop on Pushing the Limits of RF Superconductivity, Argonne National Laboratory, March 2005, Argonne, USA
- [11] K. Saito, E. Kako, T. Shishido, S. Noguchi, M. Ono, Y. Yamazaki, “Long Term Air Exposure Effect on the Electropolished Surface of Niobium Superconducting RF Cavity”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [12] B. Visentin, J.P. Charrier, D. Roudier, Y. Gasser, A. Aspart, J.P. Poupeau, B. Coadou, G. Monnereau, “High Gradient Q-Slope: Non “In-Situ” Baking, Surface Treatment by Plasma and Similarities Between BCP & EP Cavities”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [13] L. Lilje et al., “Electro-polishing and in-situ Baking of 1.3 GHz Niobium Cavities”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [14] G. Ereemeev, H. Padamsee, M. Liepe, R. Roy, “Effect of Mild Baking on High Field Q-Drop of BCP Cavity”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [15] G. Ereemeev, “New Results on the High Field Q-Slope”, presentation at the 2005 workshop on RF superconductivity, July 2005, Ithaca, USA
- [16] G. Ciovati, P. Kneisel, “Measurements of the High Field Q-Drop in TE011/TM010 Mode in a Single Cell Cavity”, Proceedings of workshop on Pushing the Limits of RF Superconductivity, Argonne National Laboratory, March 2005, Argonne, USA
- [17] A.M. Valente, C. Benvenuti, S. Calatroni, P. Darriulat, M. A. Peck, C.A. Van’t Hof, “Study of the Residual Resistance of Superconducting Niobium Films at 1.5 GHz”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [18] P. Kneisel, “Performance of Large Grain and Single Crystal Niobium Cavities”, presentation at the 2005 workshop on RF superconductivity, July 2005, Ithaca, USA
- [19] P. Kneisel, R.W. Roeth, H.G. Kuerschner, “Results from a Nearly Defect-Free Niobium Cavity”, Proceedings of the 1995 workshop on RF superconductivity, Oct. 1995, Gif sur Yvette, France
- [20] G. Ciovati, “Review of Frontier Workshop and Q-Slope Results”, presentation at the 2005 workshop on RF superconductivity, July 2005, Ithaca, USA
- [21] S. Casalbuoni, L. von Sawilski, J. Koetzler, “Superconductivity Above H_{c2} as a Probe for Niobium RF Cavity Surfaces”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany

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- [22] V. Palmieri, “Q-Drop, an Analysis Starting from Elementary Field Theory”, SRF05
- [23] J. Knobloch, R.L. Geng, M. Liepe, H. Padamsee, “High-Field Q-Slope in Superconducting Cavities Due to Magnetic Field Enhancement at Grain Boundaries”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [24] J. Halbritter, “Degradation of Superconducting RF Cavity Performances By Extrinsic Properties”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [25] A. Gurevich, “Thermal RF Breakdown of Superconducting Cavities”, Proceedings of workshop on Pushing the Limits of RF Superconductivity, Argonne National Laboratory, March 2005, Argonne, USA
- [26] P. Bauer, N. Solyak, G. Ciovati, G. Ereemeev, A. Gurevich, L. Lilje, B. Visentin, “Discussion of Possible Evidence for Non-Linear BCS Resistance in SRF Cavity Data to Model Comparison”, presentation at the 2005 workshop on RF superconductivity, July 2005, Ithaca, USA
- [27] G. Ciovati, “High Q at Low and Medium Field”, Proceedings of workshop on Pushing the Limits of RF Superconductivity, Argonne National Laboratory, March 2005, Argonne, USA
- [28] A. Gurevich, “Theoretical Advances in SRF”, presentation at the 2005 workshop on RF superconductivity, July 2005, Ithaca, USA
- [29] H. Safa, B. Bonin, “Power Dissipation at High Fields in Granular RF Superconductivity”, B. Bonin, H. Safa, *Superconductor Science Technology* 4, 257-261, 1991
- [30] S. Calatroni, C. Benvenuti, M. Hakovirta, H. Neupert, M. Prada, A.-M. Valente, “Cern Studies on Niobium-Coated 1.5 GHz Copper Cavities”, Proceedings of the 2001 workshop on RF superconductivity, Sept. 2001, Tsukuba, Japan
- [31] P. Kneisel, “Surface Characterization of Bulk Nb: what has been done, what has been learnt”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [32] K. Kowalski, A. Bernasik, W. Singer, X. Singer, J. Camra, “In Situ XPS Investigation of the Baking Effect on the Surface Oxide Structure Formed on Niobium Sheets Used for Superconducting RF Cavity Production”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [33] Q. Ma, R. Rosenberg, “Thermal and Electron-Beam Irradiation Effects on the Surfaces of Niobium for RF Cavity Production”, Proceedings of the 2001 workshop on RF superconductivity, Sept. 2001, Tsukuba, Japan
- [34] A. Dacca et al., “XPS Analysis of the Surface Composition of Nb for SRF Cavities”, *Appl. Surf. Sc.* 126, p.219, 1998
- [35] C.Z. Antoine, A. Aspart, M. Berthelot, Y. Gasser, J.P. Poupeau, F. Valin, “Morphological and Chemical Studies of Nb Samples after Various Surface Treatments”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [36] C.Z. Antoine, A. Aspart, S. Regnault, A. Chincarini, “Surface Studies: Method and Analysis and Results”, Proceedings of the 2001 workshop on RF superconductivity, Sept. 2001, Tsukuba, Japan
- [37] F.L. Palmer – “Influence of Oxide Layers on the Microwave Surface Resistance of Nb”, *IEEE Trans. Magn.* 23, N2, p. 1617, 1987
- [38] R. Ballantini, A. Dacca, G. Gemme, R. Parodi, “Improvement of the Maximum Field of Accelerating Cavities by Dry Oxidation”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [39] G. Ciovati, P. Kneisel, G. Myneni, W. A. Lanford, “Effect of Low Temperature Baking on Niobium Cavities”, Proceedings of the 2003 workshop on RF superconductivity, Sept. 2003, Luebeck, Germany
- [40] K. Saito, P. Kneisel, “Temperature Dependence of the Surface Resistance of Niobium at 1300 MHz – Comparison to BCS Theory”, Proceedings of the 1999 workshop on RF superconductivity, 1999, Santa Fe, USA
- [41] H. Padamsee, T. Hays, J. Knobloch, “RF Superconductivity”, Wiley & Sons?
- [42] A. Polyanskii, P. Lee, P. Bauer, C. Boffo, L. Bellantoni, H. Edwards, A. Gurevich, M. Jewell, D. Larbalestier, G. Perkins, A. Squitieri, “An Investigation of the Properties of BCP Niobium for Superconducting RF Cavities”, Proceedings of workshop on Pushing the Limits of RF Superconductivity, Argonne National Laboratory, March 2005, Argonne, USA
- [43] A. Polyanskii, A. Squitieri, M. Jewell, P. Lee, A. Gurevich, D. Larbalestier, P. Bauer, C. Boffo, L. Bellantoni, H. Edwards, “Inhomogeneous Flux Penetration in Niobium Sheet Sampled Across the Cavity Production Route”, 2005 workshop on RF superconductivity, July 2005, Ithaca, USA