REVIEW OF HIGH FIELD Q SLOPE, CAVITY MEASUREMENTS*

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Abstract

One of the most interesting phenomenon occurring in superconducting radio-frequency (SRF) cavities made of bulk high RRR niobium is represented by a sharp decrease of the quality factor above peak surface magnetic field of about 90 mT and is referred to as "high field Q-slope" or "Q-drop". This phenomenon was observed first in 1997 and since then some effort was devoted to the understanding of the causes behind it. Still, no clear physical interpretation of the Q-drop has emerged, despite several attempts. In this contribution, I will review the experimental results for various cavities measured in many laboratories and I will try to identify common features and differences related to the Q-drop.

INTRODUCTION

The most recent limitation discovered in SRF cavities made of high-purity (RRR > 200) bulk niobium manifest itself as a sharp, exponential reduction of the quality factor Q_0 for peak surface magnetic fields B_p above about 90-100 mT, without of X-rays [1, 2]. This phenomenon was named "high-field Q-slope" or "Q-drop" and it limits the attainable accelerating gradient E_{acc} to about 20-28 MV/m, depending on the cavity shape. Temperature maps of the outer cavity surface revealed non-uniform heating ("hot-spots") mainly in the equatorial, high magnetic field region of the cavity [3-5]. Fortunately, it was discovered that a low temperature bake (100-120 °C, 48 h, in ultra-high vacuum) helps in reducing these anomalous losses, improving both Q_0(2 K) at low field and the breakdown field by about 30% [6]. Efforts have been made in many laboratories over the last decade to explain the origin of the Q-drop and the baking effect by performing various cavity surface preparations, surface analytical studies on Nb samples and by developing theoretical models. Although progress has been made in all areas of investigation, a complete physical description of the Q-drop and the baking effect is still lacking. In this contribution we will focus on experimental results on SRF cavities and how they compare with existing models. We will cover topics such as surface roughness, surface oxidation, heat treatments, large-grain/single crystal Nb, baking time. A review of surface analytical studies related to the Q-drop is given at this Workshop by Romanenko [7].

SURFACE ROUGHNESS

Surface roughness is considered to be an important parameter of cavity preparation, influencing the Q-drop behavior, the effectiveness of surface cleaning by high-pressure water rinse (HPR) and the quench field. Surfaces obtained by buffered chemical polishing (BCP) are in general rougher than obtained by electropolishing (EP) (5-10 μm for BCP surfaces versus 1-5 μm for EP) for polycrystalline Nb. A model was proposed by Knobloch et al. [8] where the magnetic field enhancement due to surface roughness, in particular at pronounced grain boundary edges of BCP-treated surfaces, causes cumulative local quenches which drastically lowers the cavity Q_0. Nevertheless, not only does the Q-drop occur in smooth EP and single-crystal cavities, but very high B_p values (~ 170 mT) were obtained also in BCP-treated cavities with a very rough surface [9], as shown in Fig. 1. At Jefferson Lab we also experienced many cases of cavities with rough-looking surface achieving high B_p-values (~ 150 mT). In addition, as discussed later, low temperature baking, which does not affect geometrical surface roughness, strongly reduces the Q-drop.
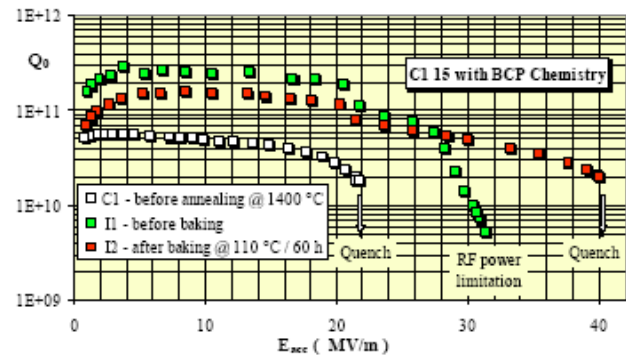

Figure 1: Q_0 vs. E_{acc} measured at 1.44 K at Saclay [9] on a 1.3 GHz single-cell cavity treated by BCP (top) and post-purified at 1400 °C, resulting in a rough surface with pronounced grain boundaries (bottom).

Another area of the cavity which received much attention is the equatorial weld, since it typically results in a "rough" underbead inside the cavity and a "heat affected zone" with reduced RRR, about 1-2 cm away from the

weld. Nevertheless, recent tests done by Kneisel on a seamless cavity made by hydroforming at DESY and treated by EP at KEK [10], was also limited by Q-drop, as shown in Fig. 2. Furthermore, centrifugal barrel polishing done at KEK, allows smoothening of the weld underbead (Fig. 3) but the Q-drop is still present.
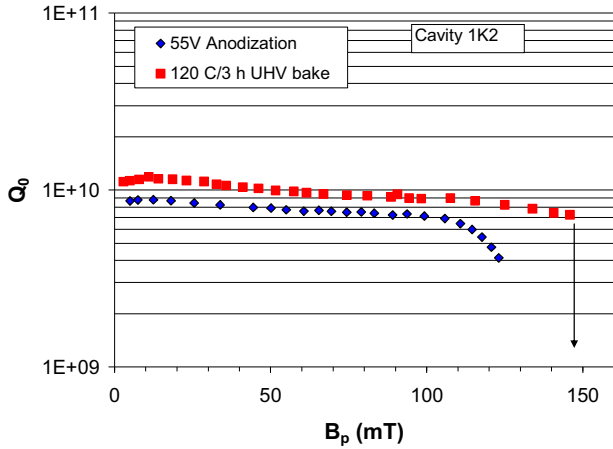

Figure 2: $Q_0(2$ K) vs. B_p measured at JLab on a hydroformed, electropolished 1.3 GHz cavity limited by Q-drop after anodization at 55V and by quench after "in-situ" baking at 120 °C for only 3 h [B_p/E_{acc} = 4.07 mT/(MV/m)].

Figure 3: Picture of the inner surface of the equatorial weld before (left) and after (right) removing 60 μm by centrifugal barrel polishing (Courtesy of T. Saeki).

LARGE GRAIN/SINGLE CRYSTAL VS. FINE GRAIN NIOBIUM

It recently became possible to fabricate cavities from large grain (~ cm^2 area) or even single crystal niobium [11], which enabled the investigation of the influence of grain boundaries on the Q-drop and to compare it with measurements on fine grain (~ 50 μm size, ASTM 5) material. Grain boundaries are regions where impurities tend to segregate, they can be filled with oxides and therefore a degradation of their superconducting properties, such as the critical field, is expected [12]. Experimentally, the Q-drop is also present in large grain and single crystal cavities (Fig. 4), although at typically ~ 10% higher onset.

As it was already reported in a previous review [13], cavities made of large grain/single crystal and fine grain Nb respond differently to the low temperature baking, depending on the chemical treatment applied: baking in ultra-high vacuum (UHV) at 120 °C for 48 h allows

recovering from the Q-drop in fine grain cavities treated by EP, while it is necessary to post-purify the cavity with Ti in a vacuum furnace at temperatures greater than 1200 °C for several hours (which allows growing mm-size grains) if BCP is used as chemical treatment. If large grain/single crystal Nb is used, it is sufficient to bake the BCP-treated cavity at 120 °C for only 12 h, as shown in tens of cavity tests done at JLab. If EP is used, longer baking times (48 h) seem to be necessary [14]. These "recipes" to overcome the Q-drop depending on the starting material are indicated schematically in Fig. 5. Of course, HPR is always a necessary step after chemical treatment for any cavity preparation, in order to avoid field emission.
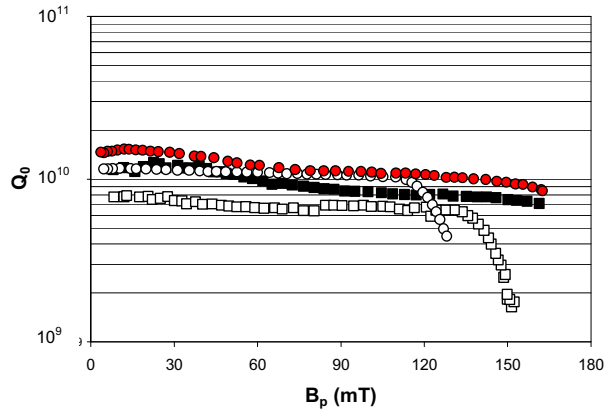

Figure 4: $Q_0(2$ K) vs. B_p measured at JLab on a single-crystal 2.36 GHz single cell (squares) from CBMM material and on a 1.47 GHz large grain single cell (circles) from Ningxia material before (empty symbols) and after (solid symbols) baking at 120 °C for 24 h and 9 h respectively. Both cavities were treated by BCP.
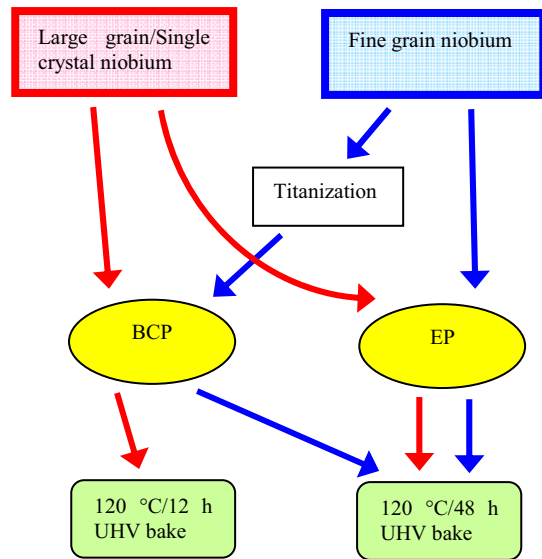

Figure 5: Schematic of the treatments necessary to overcome the Q-drop, depending on the starting material.

CAVITY OXIDATION

Role of the oxide layer

The presence of an amorphous niobium pentoxide layer 3-5 nm thick on the cavity surface and of thinner metallic suboxides at the metal/oxide interface have been suspected to be involved in the Q-drop effect. A model was proposed by Halbritter [15] where normal electrons tunnel from the metal into localized states in the oxide. In the presence of a strong electric field, electrons are resonantly excited above the energy gap of Nb and cycle through states above the gap, below the gap and back to localized states, following the changes of the RF field. This would result in an exponential increase of the surface resistance and additional power dissipation, amplified at the equator by high magnetic field. Changes in the oxide structure by baking would reduce the density of localized states and therefore the Q-drop.

Experiments were done at Saclay [16] where a previously baked cavity (no Q-drop) was rinsed with HF to remove the pentoxide and a new layer, with supposedly the same characteristics of one grown on an un-baked cavity, is grown by subsequent exposure to ultra-pure water and air. The Q-drop did not occur after this treatment, as shown in Fig. 6 on a fine grain single cell treated by EP. Similar results were obtained at JLab on large grain cavities treated by BCP [5].
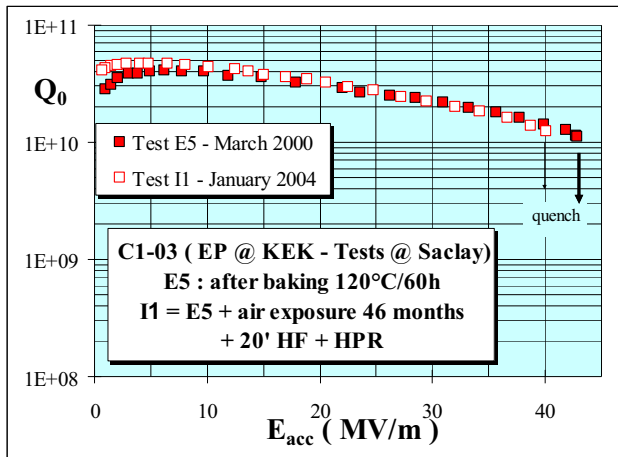

Figure 6: Q_0 vs. E_{acc} measured at Saclay on a fine grain 1.3 GHz single cell after EP and 120 °C bake (red symbols) and after HF rinse (white symbols) $[B_p/E_{acc} = 4.07$ mT/(MV/m)] [16].

Experiments were done at Cornell where a previously baked cavity was anodized, which allows growing a pentoxide layer whose thickness depends mainly on the applied voltage [17]. It was found that the Q-drop re-occurred after anodizing at 30V, corresponding to ~ 60 nm Nb_2O_5 thickness. Similar results were obtained at JLab on large grain cavities treated by BCP (Fig. 7) [5].

Experiments done at JLab on a single cell where $Q_0(B_p)$ was measured in the TE_{011} mode (which has no surface electric field), besides the standard TM_{010} mode, under the same surface conditions, showed Q-drop occurring in both modes, suggesting a mechanism activated by the surface magnetic field as responsible for the Q-drop [18].

Both anodization and HF rinse experiments showed that the baking effect is not limited to the oxide layer but affects the Nb metal up to a depth of ~ 20 nm. This conclusion is consistent with experimental results showing the stability of the baking effect after air exposure for several years and multiple water rinses [19].
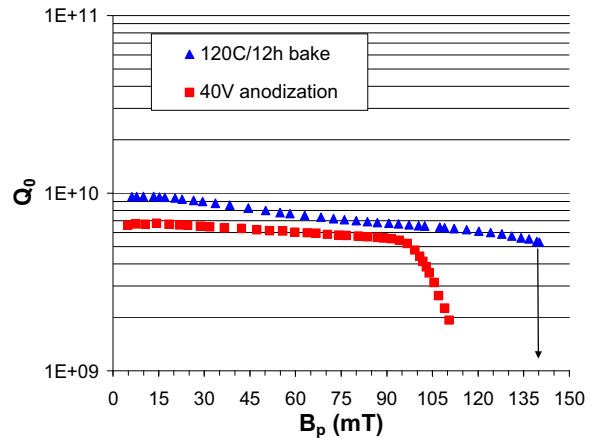

Figure 7: Q_0(2 K) vs. B_p measured at JLab on a 1.47 GHz large grain single cell after BCP and 120 °C/12 h bake and after 40 V anodization. The Q-drop re-occurs after anodization [5].

Role of interstitial oxygen

Besides the oxide layer, the presence of high concentrations of interstitial oxygen at the metal oxide interface as a result of the oxidation process was considered as a possible cause for the Q-drop [20]. High concentrations of interstitial oxygen in Nb may cause a local suppression of the surface barrier, allowing vortices to penetrate the surface under the action of the RF field and generating additional losses. Baking at 120 °C for 48 h allows oxygen to diffuse and dilute over a depth comparable to the RF penetration depth and consistent with the results from the anodization experiments [20]. Furthermore, by fitting $R_s(T)$ at low field with BCS theory code, it was found that the normal electrons mean free path is reduced to ~ 20 nm by baking at 120-140 °C for 48 h [21]. It was also found both at JLab [5] and Saclay [16] that the onset of the Q-drop is increased by baking at 100-120 °C for progressively longer time (Fig. 8) and both these results are consistent with the hypothesis of impurity diffusion.

In recent experiments done at Cornell [22], a cavity treated by EP was baked "in situ" at 400 °C for 2 h. A much thinner oxide layer was measured by XPS, and oxygen diffused to a depth larger than the RF penetration depth, as calculated using the model of Ref. [20]. The Q-drop did not improve and the cavity was limited by quench at lower field. The cavity was then re-oxidized by exposure to dry air for 5 min and baked again in UHV at 400 °C for 2 h, but the cavity was still limited by quench just at the Q-drop onset field (Fig. 9).
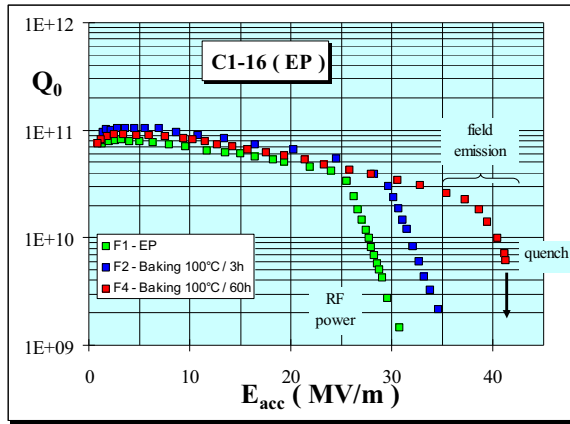
Figure 8: Q_0 vs. B_p measured at Saclay on a 1.3 GHz single cell after EP and baking at 100 °C for progressively longer time [16].
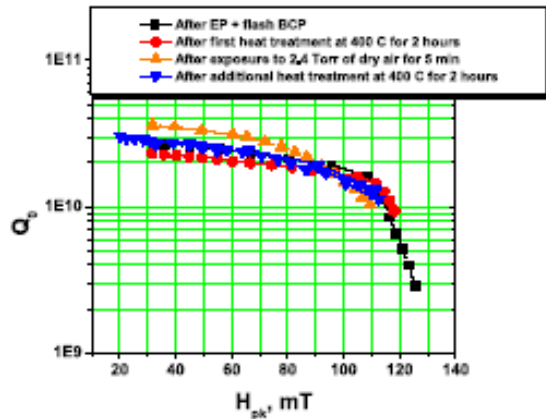

Figure 9: Q_0(1.5 K) vs. B_p measured at Cornell on a 1.5 GHz single cell treated by EP, "in situ" baked at 400 °C for 2 h, exposed to dry air and baked again at 400 °C/2 h.

Recent experiments were done at JLab [5] on a large grain single cell treated by BCP and baked, where it was attempted to restore the Q-drop by increasing the oxide thickness and oxygen concentration by baking the cavity in 1 atm of pure oxygen at 120 °C for 12 h and for 48 h. The Q-drop could not be re-established after those treatments. The cavity remained Q-drop free after additional baking in air at 120 °C and 150 °C for 12 h (Fig. 10). Both results at Cornell and JLab seem to contradict the explanation of the baking effect by the oxygen diffusion model.

Non "in-situ" baking

Early experimental results from Saclay [23] showed some improvements in the Q-drop by baking cavities in air at 145 °C for 3 h, which give similar oxygen diffusion depths as at 120 °C for 48 h. Nevertheless the Q_0 at high field was typically lower than achieved with "in situ", UHV baking. It was recognized that the higher temperature may facilitate the diffusion of oxygen from the atmosphere into the surface, reducing the effectiveness of baking. Therefore, baking at 145 °C/3 h in an argon atmosphere was pursued, using infrared sensors to rapidly

warm up the cavity. Results comparable to the standard UHV baking were achieved, as shown in Fig. 11 [24]. The results from these studies are consistent with the oxygen diffusion model.
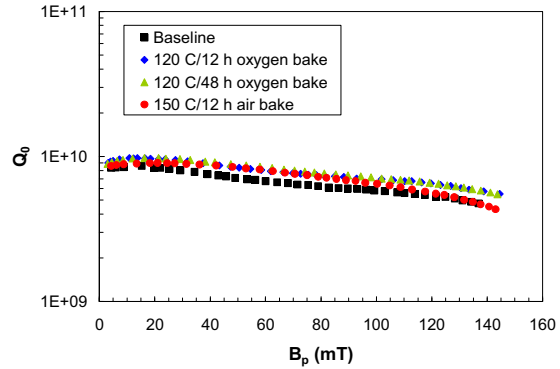

Figure 10: Q_0(2 K) vs. B_p measured at JLab on a 1.5 GHz large grain single cell after additional bakes in different conditions.
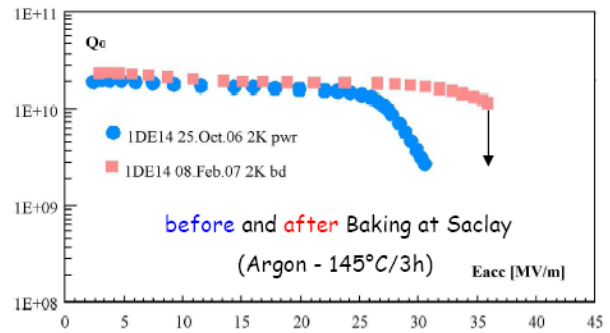

Figure 11: Q_0 vs. E_{acc} for a 1.3 GHz single cell measured at Saclay after EP and baking in argon atmosphere at 145 °C for 3 h [B_p/E_{acc} = 4.07 mT/(MV/m)].

DISCUSSION

The experimental results summarized in the previous sections show a wide variety of cavity treatments which improved the knowledge of the Q-drop phenomenon and the baking effect over the past years. Although it is recognized that surface roughness plays an important role on cavity performance, it cannot explain the majority of the experimental data on the Q-drop phenomenon. In addition, the low-temperature baking does not change the morphology of the cavity. The question to be answered is therefore to which length scale is roughness important.

The results showing that the effectiveness of baking and the baking parameters depend on the surface treatment and grain size are not clearly explained by any of the existing models.

There seems to be strong experimental evidence against the involvement of the natural surface pentoxide layer in causing the Q-drop. The role of the metal/oxide interface is quite unclear. In the recent cavity oxidation study done at JLab [5] on a large grain cavity treated by BCP, an interesting correlation was found between the value of the

energy gap and the Q-drop onset/quench field. By increasing the energy gap, as obtained by baking, the quench field increases, while reducing the gap value, as obtained by anodization or BCP, causes the Q-drop to occur at lower RF field. This correlation has been explained by considering the effect of changes of the energy gap Δ on the "breakdown" field H_{pb} in a thermal feedback model:

$$H_{pb} = H_{p0} e^{(\Delta - \Delta_0)/2kT_c} \qquad (1)$$

where H_{p0} and Δ_0 are the breakdown field and energy gap of pure niobium. The term "breakdown" is referred to as a breakdown of the Meissner state, which can result in the Q-drop at lower field or in a cavity thermal quench at higher fields. The changes in the energy gap could be explained by the presence of an interface metallic layer, whose nature is still unclear, formed between the superconducting niobium and the dielectric pentoxide after chemical treatments, which is dissolved by baking. In the same study it was shown that a model of the high field surface resistance recently developed by Gurevich [25] describes well the data on Q-drop. While not aiming directly to any particular physical or metallurgical cause of the phenomenon, this model describes $Q_0(B_p)$ by calculating the average surface resistance at high RF field in the presence of areas of reduced superconducting properties ("hot-spots" observed by temperature mapping).

The experimental results on the investigation of the role of interstitial oxygen and its diffusion by baking are quite contradictory in the sense that a diffusion process seems to be involved, but it is not yet clear whether oxygen is the only impurity involved in this process.

SUMMARY

This contribution provides an updated review of cavity test results on the investigation of the Q-drop and the baking effect. The main conclusions are:

- there seem to be no clear correlation between roughness on a μm scale and the Q-drop. The equatorial electron beam weld also does not seem to play a major role.
- The effectiveness of baking and the baking parameters depends on the chemical treatment (BCP or EP) and the state of niobium (fine grain, post-purified, large grain/single crystal).
- The niobium pentoxide layer does not seem to play a major role in causing the Q-drop.
- The role of interstitial oxygen and oxygen diffusion are still unclear: some results (baking at 400 °C, oxygen bake) contradict its involvement while (fast argon baking) others support it.
- A correlation was found between the energy gap and the Q-drop onset and the quench field, which can be interpreted on the basis of a thermo-magnetic instability, taking into account a depression of the gap at the surface.

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