HIGH FIELD Q-SLOPE AND THE BAKING EFFECT*

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Abstract

The performance of SRF cavities made of bulk Nb at high fields (peak surface magnetic field greater than about 90 mT) is characterized by exponentially increasing RF losses (high-field Q-slope), in the absence of field emission, which are often mitigated by a low temperature (100-140 °C, 12-48h) baking. In this contribution, recent experimental results and phenomenological models to explain this effect will be briefly reviewed. New experimental results on the high-field Q-slope will be presented for cavities that had been heat treated at high temperature in the presence of a small partial pressure of nitrogen. Improvement of the cavity performances have been obtained, while surface analysis measurements on Nb samples treated with the cavities revealed significantly lower hydrogen concentration than for samples that followed standard cavity treatments.

INTRODUCTION

The most outstanding issue related to the basic understanding of the superconductivity of high-purity, bulk Nb in strong radio-frequency (RF) fields is the occurrence of a sharp increase of the RF losses when the peak magnetic field, B_p, reaches about 90 mT; consequently limiting the operational accelerating gradient of SRF Nb cavities for particle accelerators to about 25 MV/m. This phenomenon was discovered in 1997, after the development of improved surface cleaning techniques allowed the preparation of cavities which achieved high surface fields, without being limited by “extrinsic” losses, such as those caused by field emission.

Experiments showed that the onset of the newly discovered “anomalous” losses, which are commonly referred to as “high field Q-slope” or “Q-drop”, range between 80 – 110 mT (it has been established that the Q-drop is a magnetic field phenomenon), depending on the particular material-processing combination. Lower onset of the Q-drop is typically associated with “rougher” surfaces.

Currently, two types of high-purity (residual resistivity ratio greater than 200) Nb material are used for cavity fabrication: fine grain (ASTM 5), and large (cm^2 size) grain or even single crystal. The two techniques currently used for the final surface polishing of Nb cavities are Buffered Chemical Polishing (BCP) or Electropolishing (EP).

An empirical “cure” for the Q-drop had already been discovered in 1998 and consisted of a low-temperature (100-140 °C, 48h) baking of the cavities in ultra-high vacuum. Later experiments showed that the benefit of baking and the baking parameters (time and temperature) depend significantly on the cavity material-processing combination. These findings are summarized in Ref. [1].

A model which describes all the experimental results related to the Q-drop and the baking effect is yet to be found. The solution to this problem will help devising new, possibly cheaper, ways of improving the overall performance of Nb cavities. In addition, it will give important clues to the understanding of loss mechanisms in high-temperature superconductors, comparatively more difficult to understand than Nb, which are being investigated for future SRF applications.

Several models to explain the Q-drop and the baking effect had been proposed over the last decade, but strong contradictions between each one of them and experimental results were found, as more experiments to test their assumptions had been carried-out over the past years. Reviews of such models and experimental results can be found in Ref. [1].

Temperature mapping of the cavity surface during high-power RF tests at 2 K consistently show strong, non-uniform heating occurring in the high-magnetic field area of the cavity, causing the Q-drop. The regions of the cavity where the strong heating occurs are referred to as “hot-spots”.

In this contribution we will briefly review two models which give a good description of the observed $Q_0(B_p)$ dependency, without making any particular assumption on the physical origin of the hot-spots. In addition, we will review the latest model (so called “oxygen pollution model”) concerning the Q-drop and recent experimental results which contradict some of its hypothesis. We will then review recent theoretical and experimental results indicating a connection between the Q-drop and magnetic vortices pinned or entering the Nb surface. Finally, we will present some new experimental results on the attempt to reduce surface defects and impurities in Nb by “passivating” it with a thin nitride layer.

MODELS THAT DESCRIBE THE $Q_0(B_p)$ CURVES

One model which provides a good description of the $Q_0(B_p)$ curves was proposed by Gurevich [2] and is based on an analytical solution of the 2D thermal diffusion equation which includes the extra power localized in a small defect region. The results show that a hot-spot of radius much larger than the defect size is produced. The sum of N non-overlapping hot-spots yield an expression for the global surface resistance of the cavity, which is then used in the heat balance equation for the temperature of the cavity surface exposed to RF field. The solution of

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such equation is expressed in the following parametric dependence $Q_0(B_p)$:

$$u(\theta) = \theta e^{1-\theta}$$

$$\frac{2B_p^2}{B_{b0}^2} = 1 + g + u(\theta) - \sqrt{\left[1 + g + u(\theta)\right]^2 - 4u(\theta)} \quad (1)$$

$$Q_0(B_p) = \frac{Q_0(0)e^{-\theta}}{1 + g\Big/\left[1 - \left(B_p/B_{b0}\right)^2\right]}$$

where g, $Q_0(0)$ and B_{b0} are fit parameters. g is a parameter which is related to the number and intensity of hot-spots, $Q_0(0)$ is the Q_0-value at low field and B_{b0} is the thermal breakdown field in absence of defects.

A recent model proposed by Weingarten [3] gives an expression for a field-dependent surface resistance obtained assuming that defects of density n_{s0} with smaller values of the lower critical field (B_0) than Nb are present on the surface and that the size of the normal conducting regions increases with increasing magnetic field, above B_0. The field-dependent surface resistance given in [3] is an infinite product expansion:

$$R_s^{nl}(B_p) = \frac{4}{3}\pi\mu_0\lambda^3 f n_{s0}\left\{\left(\frac{B_0}{B_p}\right)^2 + \right.$$
$$\left. + \frac{1}{2}\left(\frac{B_p}{B_c}\right)^2\left[1 + \frac{2}{3}\kappa^2\left(\frac{B_p}{B_c}\right)^2\left(1 + \frac{3}{4}\kappa^2\left(\frac{B_p}{B_c}\right)^2 \cdots\right)\right]\right\} \quad (2)$$

where the first term in the sum describes the low-field Q-increase while the second term describes the medium and high-field Q-slopes. λ is the penetration depth, B_c is the thermodynamic critical field at the He bath temperature, f is the resonant frequency and κ is the Ginzburg-Landau parameter. The expression in Eq. (2) is added to the BCS and residual resistance to determine the total surface resistance, $R_s(B_p)$. The cavity quality factor is then calculated through the usual relation $Q_0 = G/R_s$. κ, n_{s0}, B_0 and the residual resistance, R_{res}, are used as fit parameters.

Figure 1 shows, as an example, the $Q_0(B_p)$ data at 1.4 K for a typical bulk Nb cavity affected by the Q-drop and the curve fits using the two models mentioned above. The data are taken from [4]. The fit parameters of the two models and the fit correlation factor, r^2, are reported in Table 1. Both models provide a good description of the data with reasonable values of the fit parameters. It should be mentioned that 25 terms of the product expansion in Eq. (2) were needed for a good fit using Weingarten model [5].

Although both models mentioned in this Section give a good description of the $Q_0(B_p)$ curves, the question of what are the "defects" which cause the hot-spots remains unanswered. In the next Section we will briefly review the latest model which tries to answer this question and recent experimental results which contradict it.

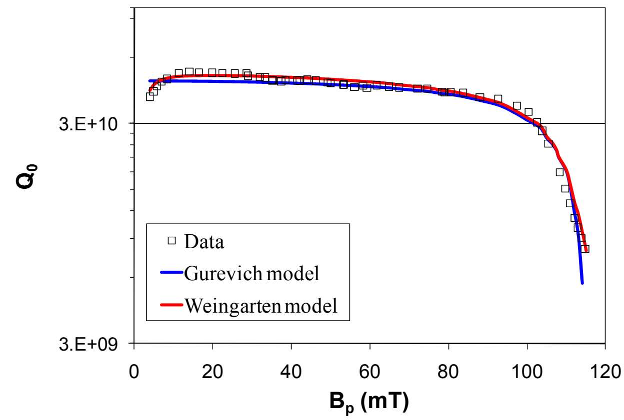

Figure 1: Typical $Q_0(B_p)$ curve of a bulk Nb cavity limited by the Q-drop fitted with Gurevich and Weingarten models. The data are from a CEBAF single-cell measured at 1.4 K [4].

Table 1: Fit parameters and fit correlation factor for Gurevich and Weingarten models applied to the data shown in Fig. 1. Values of λ = 36 nm and B_c = 190 mT were used in Eq. (1)

Gurevich model		Weingarten model	
$Q_0(0)$	5.5×10^{10}	R_{res} (nΩ)	5
B_{b0} (mT)	115	B_0 (mT)	1.5
g	0.18	n_{s0} (1/m^2)	2×10^{10}
r^2	0.960	κ	1.767
		r^2	0.985

"OXYGEN POLLUTION" MODEL

A recent model which attempts to explain the physical origins of the hot-spots causing the Q-drop is the so-called "oxygen pollution" model. The idea that a pollution layer at the Nb surface is involved in the Q-drop and the baking effect had been already put forward by Safa in 2001 [6]. Oxygen is the impurity whose diffusion length in Nb is comparable to the RF penetration depth, for the typical baking parameters. Oxygen concentrations high enough to change the superconducting properties of Nb had been measured at the Nb/oxide interface by surface analytical methods. A refinement of the model includes the effects of both oxygen diffusion and oxide decomposition in determining the oxygen concentration at the metal/oxide interface, after the low-temperature baking [7]. The calculation shows a minimum of the oxygen concentration in the temperature range 120°-150°C for a 48 h long bake-out, in good agreement with the baking parameters which give the highest improvement of the cavity performance. The diffusion mechanism is also consistent with the following experimental results:

- The onset of the Q-drop increases continuously by increasing the baking time from 3 h to 60 h [8].
- The BCS surface resistance decreases continuously by increasing the baking time from 3 h to 48 h [9].

According to the oxygen pollution model, the hot-spots are caused by magnetic vortices being pushed in the Nb surface at a B_p-value corresponding to the onset of the Q-drop. Regions with high concentration of interstitial oxygen (grain boundaries, for example) result in a local reduction of the surface barrier, from the value of H_{c1} of pure Nb (~ 170 mT at 2 K) down to the Q-drop onset, at about 100 mT. Another mechanism which is also known to lower the surface barrier is roughness: this may explain why the Q-drop onset is typically lower in BCP-treated cavities than EP-treated ones (for fine-grain Nb).

Baking at 120 °C, for 12 h to 48 h, depending on the grain boundary density, dilutes the interstitial oxygen near the surface over a larger volume, effectively lowering its concentration within the RF penetration depth. This effect will push the surface barrier against vortex penetration to higher values, toward H_{c1} of pure Nb.

In the last two years, experiments were carried out at various laboratories to further test the oxygen pollution model and the results are in contradiction with the model predictions. In particular, the following results have been reported:

- The Q-drop was not re-established in a previously baked cavity, after additional baking at 120°C/48 h in 1 atm of pure oxygen. Measurements on samples by Secondary Ion Mass Spectroscopy (SIMS) confirmed the presence of a higher oxygen concentration at the Nb surface after baking in oxygen atmosphere [10].
- The Q-drop did not improve after baking a cavity "in-situ" at 400 °C/2 h, although the interstitial oxygen should have diffused deeper into the bulk by baking at such high temperature [11].
- Measurements of the sub-surface oxygen profile by diffuse X-ray scattering on a single-crystal Nb sample revealed a diffusion length of only about 2 nm after baking at 145 °C/5 h, in spite of the 40 nm diffusion length as calculated using the diffusion equation [12]. This result is shown in Fig. 2.

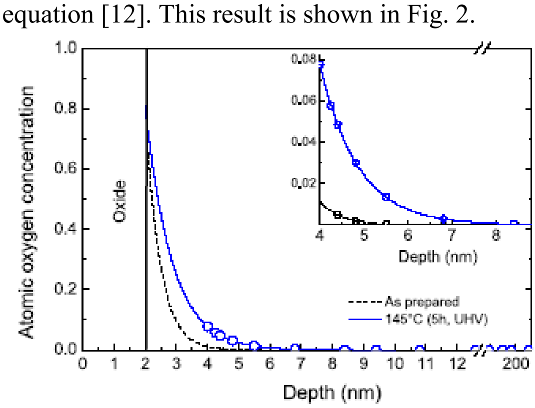

Figure 2: Atomic oxygen concentration profile as a function of depth into Nb below the oxide layer, measured on a single-crystal Nb sample before and after baking. The figure is taken from Ref. [12].

While the role of oxygen as the impurity leading to the Q-drop is significantly diminished by the experimental results mentioned above, recent theoretical and experimental work [13, 14] still support the idea of the hot-spots being caused by magnetic vortices oscillating at the Nb surface under the action of the RF field. These findings will be briefly reviewed in the next Section.

HOT-SPOTS DUE TO MAGNETIC VORTICES

Theoretical calculations show that RF losses due to the motion of vortices at the Nb surface can certainly generate hot-spots at high field, which cause the cavity quality factor to drop. There are two possible ways in which vortices can cause losses at the Nb surface:

- Vortices with segments pinned near the surface oscillate under the Lorentz force given by the RF field, causing losses.
- Vortices can be pushed into the surface when the amplitude of the RF field exceeds the local surface barrier. The periodic motion of such vortices produces losses.

Losses Due to Pinned Vortices

Because of the incomplete Meissner effect in technical Nb, trapped vortices are always present upon cooling a Nb cavity below T_c, in the presence of a residual DC magnetic field. The resulting distribution of pinned vortices can be highly inhomogeneous and the pinning efficiency depends on the treatments applied to the Nb. Figure 3 shows a schematic representation of a vortex pinned near the surface: the pinned vortex segments oscillate under the action of the RF field. By solving the equation of motion of the pinned vortex segments, the dissipated power can then be calculated [13].

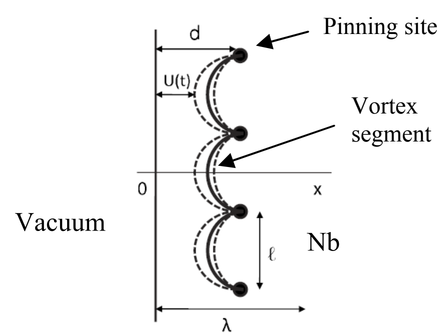

Figure 3: Vortex pinned by a chain of defects near the surface. The solid line shows the equilibrium vortex shape due to competition of pinning and image attraction forces. The dashed lines show instantaneous vortex profiles for $B(t)=B_p$ and $B(t)=-B_p$, between which the vortex line oscillates. The figure is taken from Ref. [13].

Magnetic vortices move under the action of a thermal force, proportional to the product of the vortex entropy times the local thermal gradient [15]. Pinned vortices can therefore be de-pinned if a thermal force greater than the pinning force is applied. The pinning strength in pure Nb is fairly weak, compared to other technical superconductors such as NbTi and Nb_3Sn, making it feasible to displace vortices by applying moderate thermal gradients. An estimate of the thermal gradient $|\nabla T|_c$ needed to de-pin vortices at 2 K is given by [16]:

$$\left|\nabla T\right|_c \cong \frac{J_c \mu_0 T_c^2}{2B_{c1}T} = 1.5\,K/mm \qquad (3)$$

where J_c = 1 kA/cm^2 is the critical de-pinning current density, B_{c1} = 170 mT is the lower critical field at 2 K, T_c = 9.25 K is the critical temperature and T = 2 K is the He bath temperature.

The hypothesis of hot-spots being caused by pinned vortices can therefore be tested by applying a thermal gradient of the order of the value calculated with Eq. (3) across the 3 mm thick walls of a Nb SRF cavity and look for changes in the thermal maps of the cavity, before and after applying the thermal gradient. Such kind of experiments were done recently at JLab [14] and clearly showed changes in the intensity of the hot-spots, after a thermal gradient of about 0.5 K/mm was applied by heaters glued to the outer surface of a large-grain cavity. Although a proof of principle for pinned vortices as being one of the causes for the hot-spots was achieved, the applied thermal gradient was not high enough to really push vortices away from the RF surface. Most likely, what happened was a re-distribution of the pinned vortices over a larger area.

In order to fully test the hypothesis of pinned vortices generating hot-spots and the possibility of improving the cavity performance by applying a high enough thermal gradient, a series of experiments are planned at JLab where a scanning laser light, directed on the inside surface of a Nb cavity, will act as a "thermal broom" to push trapped vortices deeper into the bulk.

Losses Due to Vortex Penetration

At high peak surface magnetic fields, approaching the lower critical field of Nb, vortices overcome the surface barrier, locally depressed in some areas, and enter the Nb surface. The simplest way to describe this is to solve the equation of motion of a vortex subjected to the Lorentz force generated by the RF field, the image force, attracting the vortex to the surface, and the viscous drag force, opposing the motion [13]. The solution of such equation is shown, as an example, in Fig. 4: a single vortex enters the surface when B_p exceeds the local penetration field, B_v. As the RF field changes sign, the vortex is pulled toward the surface, while an anti-vortex is pushed in, when $-B_p = -B_v$, and annihilates with the vortex inside the surface. This phenomenon repeats for each RF period. It is important to notice that the calculation shows that the characteristic time, τ, it takes for the vortex to travel a distance of the order of the penetration depth is much smaller than the RF period. The maximum power, P_0, dissipated by this mechanism is twice the work done by the Lorentz force to bring a vortex from the surface deeper into the bulk:

$$P_0 = \frac{2\,\omega\phi_0 B_v}{\pi\mu_0} \qquad (4)$$

P_0 = 1.4 W/m at 1.5 GHz and B_v = 140 mT.

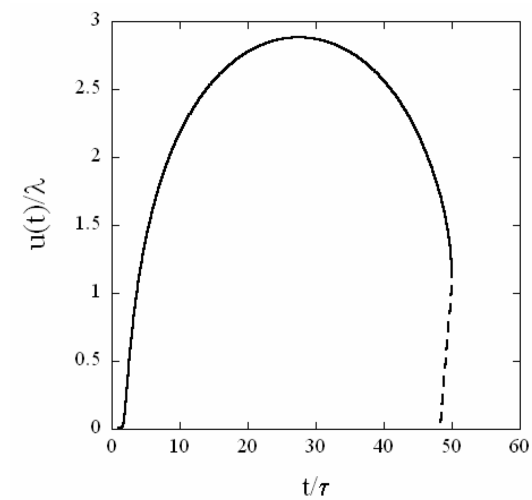

Figure 4: Trajectory $u(t)$ of a vortex entering the surface at $B_p = B_v$ during one RF period. The dashed line shows the trajectory of an anti-vortex entering the surface at $-B_p = -B_v$. The figure is taken from Ref. [13].

High-Field Losses Due to Vortices

Theoretical calculations show that the local dissipation due to pinned vortices produces a long-range temperature distribution, which spreads out on the scale ~ $2d/\pi$ (d is the cavity wall thickness). Even if these temperature variations are weak, they can nevertheless produce strong variations in the surface resistance R_s of the surrounding areas, because of the exponential dependence of R_{BCS} on temperature [13]. This non-linear R_s can be estimated as follows:

$$R_s(r) = R_{BCS}(T_0,\omega)\coth^{\sigma}\left(\frac{\pi r}{4d}\right) \qquad r > r_0 \qquad (5)$$

$$\sigma(B_p,T_0,\omega) = P_0(B_p,T_0,\omega)\frac{\Delta}{k_B\pi\kappa(T_0)T_0^2} \qquad (6)$$

where P_0 is the dissipated power at the local heat source of size r_0 , κ is the thermal conductivity, Δ is the energy gap and T_0 is the He bath temperature.

NEW RESULTS ON NIOBIUM SAMPLE MEASUREMENTS

While experiments and calculations highlight the contribution of magnetic vortices to high-field losses, what impurity or defects on the Nb surface are involved in this process and how the low-temperature baking affects them is still unclear. Niobium samples had been cut from the "hot" and "cold" spots of a single-cell cavity and have been analyzed at Cornell using a variety of surface analytical tools [17]. The results showed no difference in terms of surface roughness, oxide structure or crystalline orientation between the two types of samples. What was found is that "hot" samples had a larger local misorientation angle than "cold" ones, as measured by Electron BackScatter Diffraction (EBSD). The local misorientation angle is related to the density of lattice defects (vacancies and/or dislocations) near the surface. In addition, it was found that the local misorientation angle in "hot" samples is reduced by the low-temperature baking (120 °C/ 40 h).

Samples characterization by Point-Contact Tunneling (PCT), have been done at Argonne on Nb samples prepared by EP, before and after baking [18]. The results show that unbaked samples have a high zero-bias conductance value, indicating the presence of quasiparticle states inside the superconducting energy gap. The zero-bias conductance value is significantly reduced by the low-temperature baking. This reduction was explained by the less scattering by magnetic impurities near the surface. Oxygen vacancies in the non-stoichiometric niobium pentoxide were proposed as the source of magnetic impurities. This interpretation somehow contradicts experimental results showing that the Q-drop does not re-occur in a baked cavity after the oxide is removed with hydrofluoric acid and a new one is grown by water rinses [8]. In addition, measurements of the magnetic susceptibility in Nb samples done at DESY showed an increase of the Curie constant after baking. This was interpreted as an increase of the concentration of localized magnetic moments [19].

THE ROLE OF HYDROGEN

Hydrogen is one of the main impurities in Nb and it is known to suppress superconductivity when the bulk H concentration is greater than about 10 wppm (a phenomenon referred to as "Q-disease"). Cavities affected by the Q-drop do not show Q-disease and therefore the bulk hydrogen concentration is expected to be low. Nevertheless, several surface analysis methods revealed a high concentration of hydrogen in a few nanometer region at the metal/oxide interface. Hydrogen may segregate and be "trapped" near the surface by impurities (for example oxygen) lattice defects and stress fields. In what follows, we indicate several observations found in the literature which may link hydrogen to the surface measurement results described in the previous Section:

- Thermal desorption studies showed two hydrogen desorption peaks at 130 °C and 198 °C, interpreted as hydrogen desorption from surface and subsurface sites [20]. This observation may explain the reduction of surface hydrogen concentration by baking, as measured by Nuclear Reaction Analysis (NRA) [4].
- Measurements by Positron Annihilation Spectroscopy (PAS) show that the defect density (vacancies) increases with hydrogen concentration in Nb samples [21]. Hydrogen readily enters Nb during chemical etching or mechanical polishing, possibly being the source of the high defect density in the "hot-spot" samples.
- Hydrogen affects the magnetic behavior of Nb by lowering the magnetic susceptibility for increasing H concentration [22]. It is possible that hydrogen is the magnetic impurity invoked by the PCT results.

Although it is not yet clear how hydrogen can explain all the wealth of experimental results related to the Q-drop and baking effect, the findings mentioned above certainly suggest that it should be considered carefully.

Because hydrogen has a high affinity and mobility in Nb and is the main residual gas in ultra-high vacuum (UHV) systems, state-of-the-art surface analytical methods are necessary to well characterize its presence in Nb. In fact, this might have been one of the factors which discouraged surface scientist in the past to strongly pursue this research in relation to the Q-drop. In addition, little is known about the magnetic interaction of hydrogen in Nb and how it may affect the superconducting behavior of Nb. Further studies on this topic would be beneficial.

NEW RESULTS ON CAVITY HEAT TREATMENTS

From what was discussed in the previous Sections, it is clear that a significant improvement of the cavity performance, both in terms of quality factor and maximum accelerating gradient, could be achieved by reducing the amount of impurities and defects within a few hundred nanometers from the Nb surface. One way to accomplish this is to heat treat the cavity at high temperature (~ 800 °C) for a few hours in a UHV furnace. Such heat treatment would reduce the density of lattice defects, such as dislocations and vacancies, reduce the amount of interstitial hydrogen, and dissociate the oxide layer, leaving only 1-2 monolayers of NbO on the surface.

One problem with this approach is that residual gases inside the furnace would be re-absorbed by Nb upon cool-down and subsequent exposure to air and water. A way to overcome this had been already proposed at SLAC in 1971 and consists of forming a thin (~ 10 nm thick) nitride layer on the surface at some intermediate temperature (~ 400 °C) by thermal diffusion of nitrogen during cool-down [23]. The expectation is that the nitride layer would "passivate" the Nb surface and prevent hydrogen and oxygen absorption from the atmosphere. The nitride layer should be thin enough not to change significantly the superconducting properties of Nb. Of course, no chemical etching should be done afterwards.

We attempted this process first on a large-grain single cell cavity (CEBAF shape; Nb from OTIC, Ningxia, China). The main residual gases in the furnace and the temperature profile during the heat-treatment are shown in Fig. 5. A nitrogen partial pressure of about 10^{-5} mbar was maintained in the furnace at 400 °C for about 15 min by regulating the opening of a needle valve, connected to the furnace through a vacuum line. Semiconductor grade nitrogen was supplied at the inlet of the needle valve through a regulator. Large-grain niobium samples were prepared following standard cavity preparation techniques (150 μm removal by BCP, 600 °C/10 h heat treatment in the vacuum furnace, 10-15 μm removal by BCP) and the surface was nano-polished at Wah Chang. The samples were heat-treated in the furnace with the cavity, and a depth profile of the major impurities (N, O, C, H) was measured by SIMS at North Carolina State University [24]. In the same setup, a sample which was not heat-treated was also measured. The only noticeable difference between the heat-treated versus non heat-treated samples was a lower hydrogen concentration by about two orders of magnitude in the heat treated sample. Nevertheless, no nitride layer was found on the heat-treated sample.

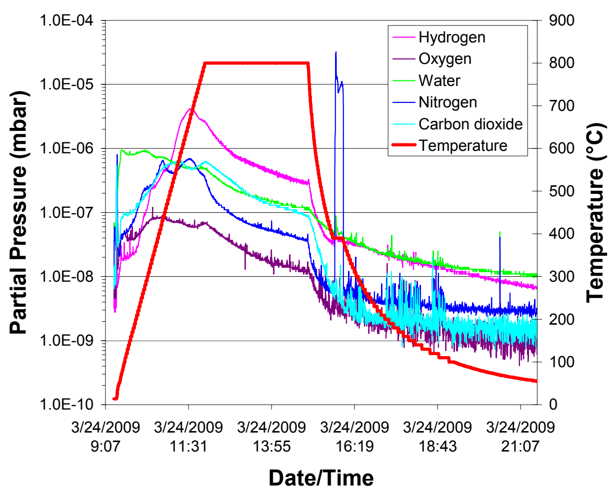

Figure 5: Partial pressures and temperature profile during the first attempt at surface passivation of a Nb cavity. The temperature was maintained at 800 °C for 3 h, then dropped to 400 °C in about 45 min, hold at 400 °C for 20 min while nitrogen was admitted into the furnace, followed by cool-down at 30 °C.

After the heat-treatment, the cavity was degreased in a ultrasonic tank filled with water and detergent for about 1 h, followed by standard high-pressure water rinse (HPR) for 1 h, drying in a class 10 clean room, flange assemblies and evacuation on a vertical test stand. The high power RF test results at 1.7 K are shown in Fig. 6: the Q_0 at low field improved by about 50%, the Q-drop is still present but the onset increased by about 15%. The cavity was then baked on the test stand at 120 °C/12 h in UHV and the following RF test showed no Q-drop, up to a quench field of 136 mT (corresponding to an accelerating gradient of 31.9 MV/m in a 9-cell ILC cavity).

A new baseline was established by removing about 5 μm from the inside cavity surface by BCP. The cavity was limited by Q-drop starting at B_p = 98 mT. The heat-treatment procedure was repeated, although this time the cavity was held at 120 °C for 12 h inside the furnace, before the final cool-down. Again, the cavity was only degreased and high-pressure water rinsed afterwards. The Q_0 at low field improved by about 25%. No Q-drop was observed up to a quench field of about 118 mT. Still, the sample measurements showed no nitride layer being formed on the Nb surface.

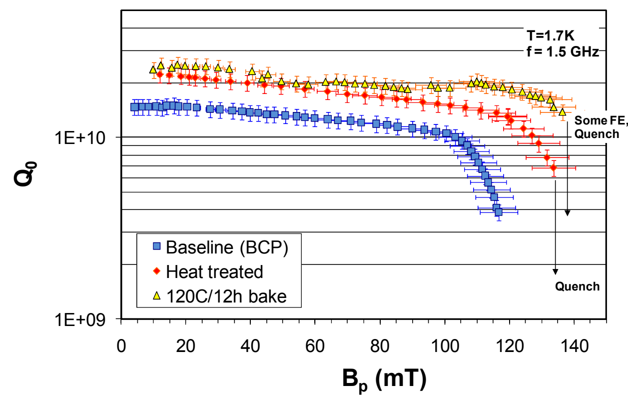

Figure 6: $Q_0(B_p)$ curve measured at 1.7 K on a CEBAF single-cell cavity made of large-grain Nb before and after the heat-treatment shown in Fig. 5 and additional low-temperature baking.

In the following set of measurements, no nitrogen was admitted in the furnace at 400 °C, yet similar improvements of the cavity performance, as mentioned above, were obtained. At the moment it is not clear why no nitride layer was formed on the Nb surface.

Another set of measurements was done on an ILC single-cell built by AES with fine-grain (Wah Chang) Nb. The baseline was measured at 2 K after about 120 μm removal by vertical EP (done by C. Crawford at JLab) and showed Q-drop starting at about 107 mT. The cavity was heat-treated using the same parameters as shown in Fig. 5, but without N_2 injection. No chemical etching was done afterwards. The RF test results at 2 K showed an improvement of the low-field Q_0 by about 30% and of the Q-drop onset by about 15%. The high-field performance drastically improved after additional “in-situ” baking at 120 °C for 24 h: the cavity quenched at B_p = 180 mT (corresponding to an accelerating gradient of 42 MV/m in a 9-cell cavity), as shown in Fig. 7.

Similar improvements of the cavity performance as described above were measured on another large-grain cavity (ILC shape; Nb from Tokyo Denkai, Japan). The experimental results on both cavities and samples will be described in more details in a forthcoming publication.

The preliminary work described in this Section showed that an improvement of the cavity performance can be obtained by a high-temperature heat-treatment, without subsequent chemical etching. The furnace cleanliness and vacuum level are most likely very important conditions to achieve such improvement. Although somewhat improved, the Q-drop could not be eliminated without the low-temperature baking.

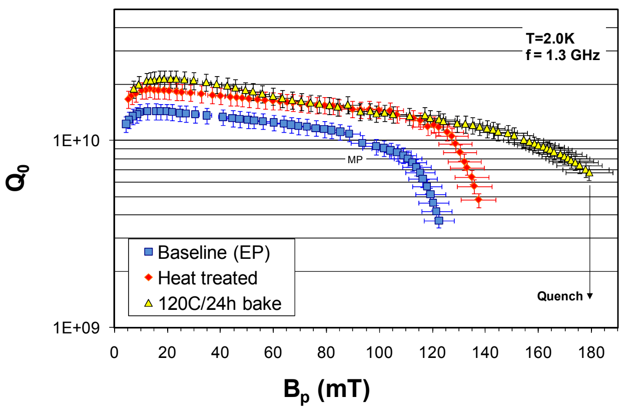

Figure 7: $Q_0(B_p)$ curve measured at 2.0 K on an ILC single-cell cavity (AES001) made of fine-grain Nb before and after the heat-treatment shown in Fig. 5 (but without N_2 injection at 400 °C) and additional low-temperature baking.

SUMMARY AND CONCLUSIONS

The occurrence of strong RF losses causing the Q-drop in bulk Nb cavities is a phenomenon which still lack a clear explanation. It is known that these losses are non-uniform ("hot-spots") and occur in the high magnetic field region of the cavity. Two models exists which describes well the $Q_0(B_p)$ curves, based on the calculation of the surface resistance with the inclusion of "defects".

Which kind of "defects" are involved in the Q-drop and the baking effect is still an open question: recent experimental results, both on cavities and samples, contradict the predictions of an "oxygen pollution" model. This model had provided a fairly good description of other experimental results.

Recent experimental and theoretical calculations indicate that magnetic vortices, either pinned or entering the RF surface, may be the source of the hot-spots. New experiments to push pinned vortices deeper into the bulk by laser heating are being planned at JLab.

Recent sample measurements indicate that a high density of lattice dislocations and/or vacancies near the surface is related to the hot-spot locations. In addition, quasiparticle states have been measured inside the superconducting energy gap of electropolished Nb samples. The density of these states is reduced by baking.

Experimental results reported in the literature suggest a possible role of hydrogen in the Q-drop and the baking effect. More high-quality research in this direction is needed. Improvements of the cavity performance have been achieved by high-temperature heat treatments, without subsequent chemical etching. A new type of furnace with cleaner conditions and flexibility towards admission of various gases is being designed at JLab, in collaboration with local companies. This furnace will be used to fully test the idea of surface passivation, in order to reduce the density of lattice defects and impurities.

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