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# HIGH GRADIENTS IN SCRF CAVITIES

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The two main limitations for achieving high gradients in superconducting radiofrequency cavities are the quench field level and the field emission threshold. This paper shows the successful progress obtained these last years while struggling to improve both figures. Field emission free cavities are now currently obtained up to 60 MV/m peak electric field and quench fields are pushed up to above 120 mT. While improving, a new unexpected limitation is starting to show up. At surface magnetic field levels over 100 mT, most cavities exhibit a strong slope in $Q$ with increasing field. This $Q$-degradation will be the next step to overcome before reaching the theoretical limit on niobium cavities.

*Keywords:* Superconductivity; Radiofrequency; Cavities; High gradients

## INTRODUCTION

Achieving high gradients in superconducting radiofrequency (SCRF) cavities was stumbling on two main limitations: quench and field emission. We will describe the significant progress that has been made recently to understand and overcome these phenomena. Moreover, the understanding of the residual resistance of niobium has enabled us to measure cavities routinely having a quality factor above $7 \times 10^{10}$ at low fields, while still being limited by the BCS resistance even at temperatures as low as 1.5 K. After demonstrating these improvements, a new limitation encountered at high fields will be described: A strong slope in the $Q$ vs $E_{acc}$ curve, showing up at magnetic field levels over 100 mT.

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## THE QUENCH

When slowly increasing the energy in a SCRF cavity, a sudden "breakdown" is observed at a given field, reducing drastically the accelerating field while damping almost all the stored energy. This is defined as the quench field and is mainly a thermo-magnetic physical process specific to superconductors. It can be understood while looking at the phase diagram of niobium (Figure 1). A transition to the normal state can occur if the magnetic field exceeds the critical field at a given temperature: $B_c(T) = B_{c0}[1 - (T/T_c)^2]$.

Heat flux generated by the RF field ($Q = \frac{1}{2} R_s H^2$) has to be conducted through the niobium wall to be removed by the helium bath. If $t$ is the wall thickness, $\Lambda$ the thermal conductivity and $h_k$ the Kapitza conductance, the inner surface temperature will be a solution of the equation

$$(T - T_b) = Q\left[\frac{t}{\Lambda} + \frac{1}{h_k}\right].$$

Both the surface resistance $R_s$ and the thermal conductivity $\Lambda$ are rapidly varying with temperature and the above equation might give no solution in the superconducting state above a given field. That gives the "uniform" quench field level which will be in all cases

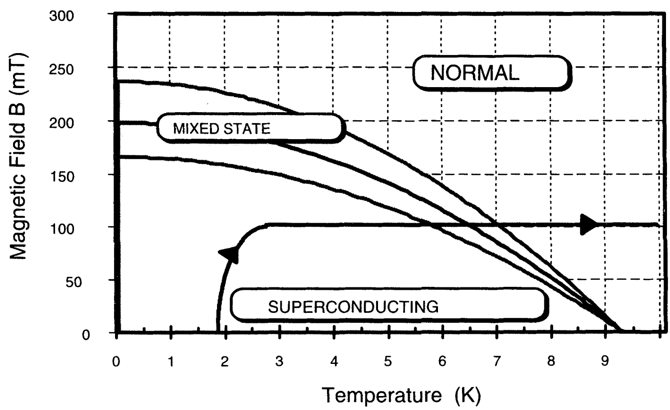


FIGURE 1 Phase diagram of niobium giving the critical magnetic fields ($B_{c1}$, $B_c$, $B_{c2}$) as a function of temperature.

lower than the critical magnetic field ($B_{c1} = 155\,\mathrm{mT}$ at $T = 2\,\mathrm{K}$ or $B_{c1} = 129\,\mathrm{mT}$ at 4.2 K). The use of $B_{c1}$ as the critical magnetic field can be justified by the fact that the measured superheating field $B_{sh}$ is not exceeding $B_{c1}$ at low temperatures.[1]

However, the quench field observed on actual cavities is somewhat lower than the expected one given by the uniform case. The experimental evidence of very localized heating spots as shown by temperature mappings supports the idea that thermal instabilities are driven by micron-size defects. A more complete thermal analysis, either analytical[2] or using computer codes,[3–5] can then be derived to evaluate the quench field value (assuming, for example, a normal conducting defect). Figure 2 gives an example comparing the computed quench field as a function of the bath temperature in the uniform case and for a given defect. Notice that in the defect case, the quench field can be significantly lower (80 mT) than the critical field (155 mT). This is mainly driven by a thermal instability: At the $\lambda$ transition of liquid helium (at 2.17 K, from normal fluid HeI to superfluid HeII), the cooling mechanism changes, resulting in a strong difference in the quench field value that is observed. While in the defect-free case, the quench is mainly a magnetic transition due to the intrinsic superconducting properties of niobium.

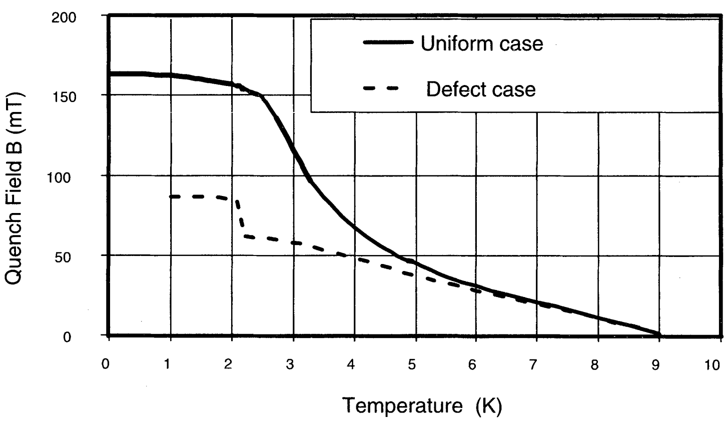


FIGURE 2 Calculated quench field value for a niobium RRR 200 cavity, thickness 2.5 mm at a frequency of 1300 MHz in the uniform case and in the case of a normal defect (size = 20 µm, $\sigma = 10^7\,\Omega^{-1}\,\mathrm{m}^{-1}$).

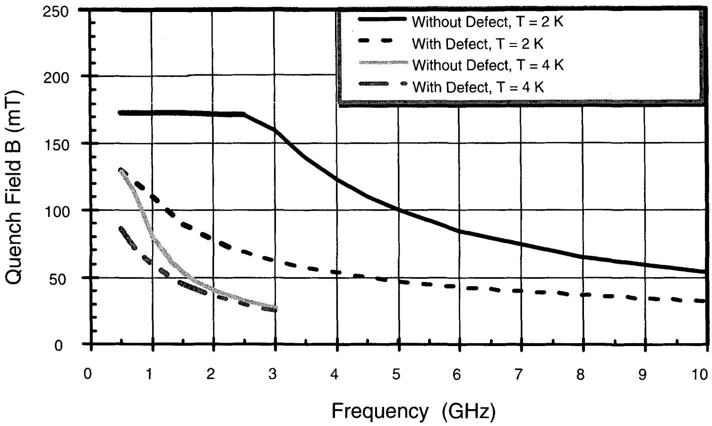


FIGURE 3 Calculated quench field value with and without defect as a function of frequency for a RRR 250 niobium cavity and helium bath in the superfluid state ($T = 2$ K) and normal state ($T = 4$ K).

Another fact that supports the defect-induced quench statement is the decrease in field observed while increasing the cavity area. As a matter of fact, a statistical analysis can be developed assuming a random probability for having a given defect size on a given surface. This will predict a distribution of quench field values that are in relatively good agreement with the present experiences. From there, a more detailed discussion concerning the variation with frequency can be deduced. While Figure 3 is showing the quench field value for a given defect as a function of frequency which definitely favors lower frequencies, the cavity surface increase at lower frequencies will tend to reduce that benefit.[6]

## Heat Treatment

A major breakthrough in SCRF cavity quench performance has been achieved through the use of high temperatures (800–1400°C) vacuum heat treatment. The process of purification of the niobium using a getter has been studied in detail.[7–10] When properly purified, cavities end up with much higher RRR than the initial sheet. This results in a

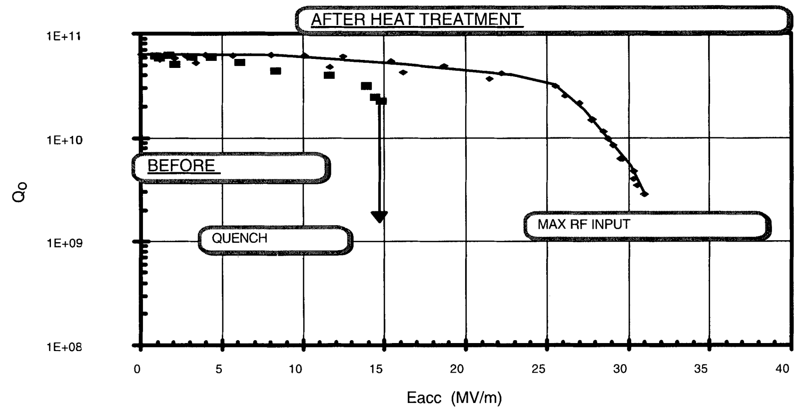


FIGURE 4 Single-cell cavity C101 (initial RRR 250), quenching at 15 MV/m before heat treatment. The improvement after heat treatment is impressive (> 31 MV/m without quench).

higher thermal conductivity (and eventually a lower heat flux) which helps thermally stabilizing the defects. Consequently, the quench field is improved (Figure 4).

Even though annealing is done at moderate temperatures (800–1000°C), where no purification process occurs, quench improvement can be experimentally observed. Possible explanations might be the material homogenization or dissolving local defects in the bulk thus reducing their resistivity. It has been shown that the higher the initial RRR, the lower the annealing temperature needed.[11] As an example, an improvement in accelerating field has been obtained after an 800°C annealing only, on a cavity made from initial RRR 400 niobium sheets (Figure 5).

Other benefits of the heat treatment are the relieving of mechanical stress (especially after the cold work of the half-cells during stamping or hydroforming) and the release of the embedded hydrogen (getting rid, at the same time, of the $Q$-disease). One important drawback of the very high temperature heat treatment (> 1200°C) is the softening of the material. Yield strength might decrease from 70 to 40 MPa and some cavity shapes have to be stiffened, either by increasing their wall thickness or by additional features.

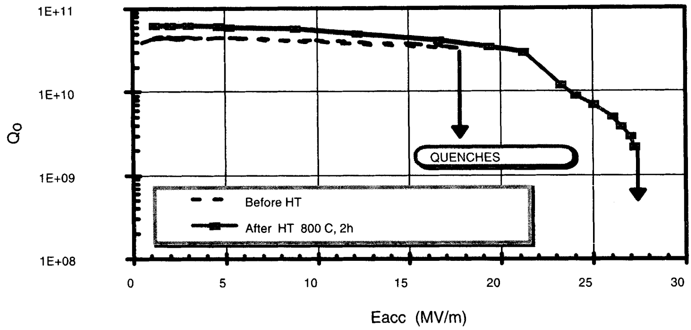


FIGURE 5 The cavity C110 made from niobium RRR 400 sheets improved its quench field after only an 800°C, 2 h annealing.

## THE FIELD EMISSION

Important progress has been made recently in the understanding of the mechanism of field emission at the levels of peak fields obtained in SCRF cavities (< 100 MV/m). The main point is that the limitation is essentially due to field enhancement from contamination particles, the protrusion on protrusion model being established.[12] More complete descriptions of specific studies are reported in other papers.[13–15] As a result, an effective experimental procedure for fighting particle contamination has been the combination of a very clean assembly followed by a high pressure rinsing with ultrapure water.[16] The effectiveness of the high pressure rinsing has been explained.[16] Histograms of the field emission thresholds obtained in vertical tests at Saclay and shown in Figure 6 clearly demonstrate the improvement resulting from these studies. While most cavity tests (> 50%) were limited by field emission before 1996, cavities with peak fields as high as 60 MV/m without field emission have been observed since then.

## THE RESIDUAL RESISTANCE

Another improvement of the RF superconductivity effort is the understanding of the residual resistance term (the non-BCS part) in

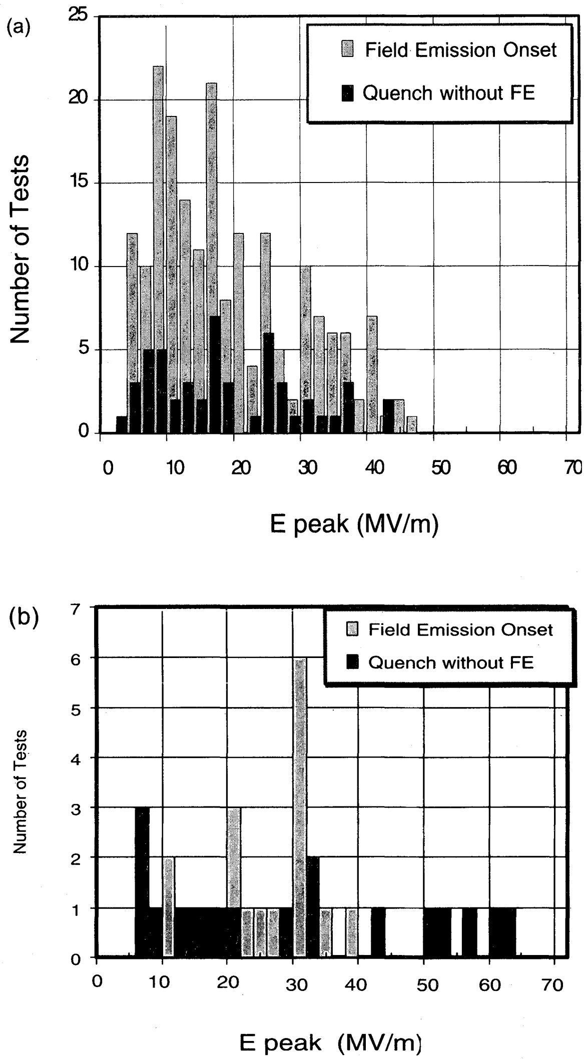


FIGURE 6 Field emission thresholds statistics on 320 tests performed at Saclay before (a) and after (b) January 1996. Cavities without FE are now obtained with peak fields exceeding 60 MV/m.

cavities. After nailing down each term contributing to this residual resistance, namely the 100 K effect ($Q$-disease due to hydrogen),[17,18] the influence of the static magnetic field,[19] the granular superconductivity[20] (resistance due to inter-grain boundaries) and the

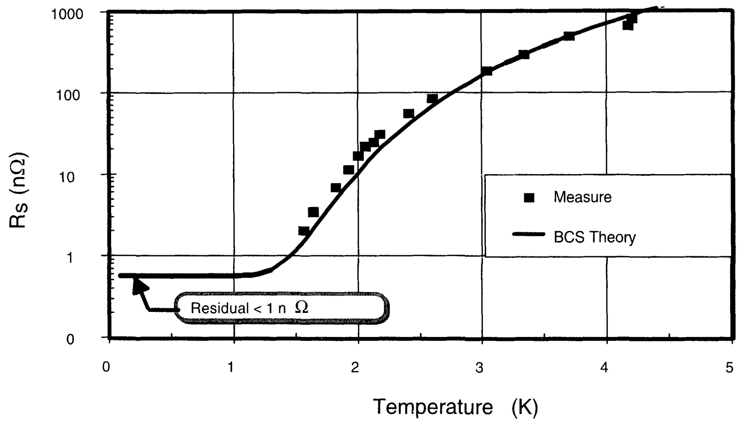


FIGURE 7 Surface resistance measured on a single-cell cavity at a frequency of 1300 MHz and an accelerating field of 0.5 MV/m. The theoretical fit is obtained with the BCS theory and a residual resistance of 0.57 nΩ.

impurities (or RRR) effect,[21] very small residual resistance can be achieved. Figure 7 shows an example of a cavity where $Q$-values higher than $10^{11}$ are effectively measured. The residual resistance left is smaller than 1 nΩ. This small part can be understood when one starts taking into account physical effects that are generally neglected, such as the RF losses in the end-flanges (in stainless steel), the surface roughness (very important at high frequencies) and the dielectric losses of the oxide layers or the coupling losses. Moreover, some residual static magnetic field still remains at low temperatures.

## SUMMARY

To summarize, the use of a high RRR niobium material combined with an optimized heat treatment has allowed to break through the quench field limit. On the other hand, very careful clean assembly combined with high pressure water rinsing pushed the average field emission limit to higher values. From there, the road to reaching the ultimate theoretical fields limit was cleared – at least until a new limitation arose.

## A new Limitation: Anomalous Losses at High Fields

Let us first describe the experimental observations associated with this new limitation. It is mainly characterized by a $Q$-degradation (or additional losses) appearing in the $Q$ vs $E_{acc}$ curve above a given field (80–100 mT). As a matter of fact, the higher the $Q$-value at low field, the earlier this effect can be observed (typically, with a $Q$ of $10^{11}$, it may start as low as at 65 mT, while with a $Q$ of "only" $10^{10}$, it will not show up before 110 mT). The general feature is that the drop in $Q$ is almost exponential. Figure 8 show a typical example of such a behavior. Although this behavior is similar to the field emission one, there are no X-rays detected, nor are there electrons detected on the probe antenna, the two specific signatures associated with field emission. Moreover, when performing a temperature mapping at these high fields, heating is observed to be almost uniformly distributed on the cavity surface (Figure 9). This is quite different from the field emission mapping type where the heating is generally seen along one meridian line. This first confirms that the losses are actually inside the cavity. Second, it indicates that the surface resistance itself is exponentially increasing with field.

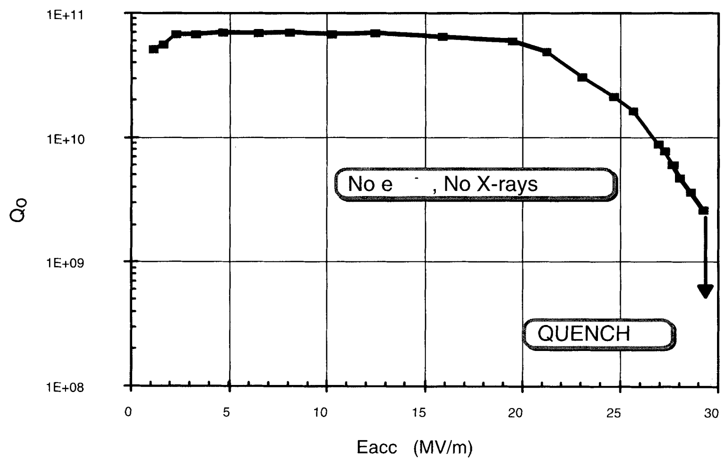


FIGURE 8 Example of anomalous losses obtained at high fields with no field emission. The $Q$-degradation is observed above 20 MV/m (cavity C105, f = 1300 MHz, $T$ = 1.7 K).

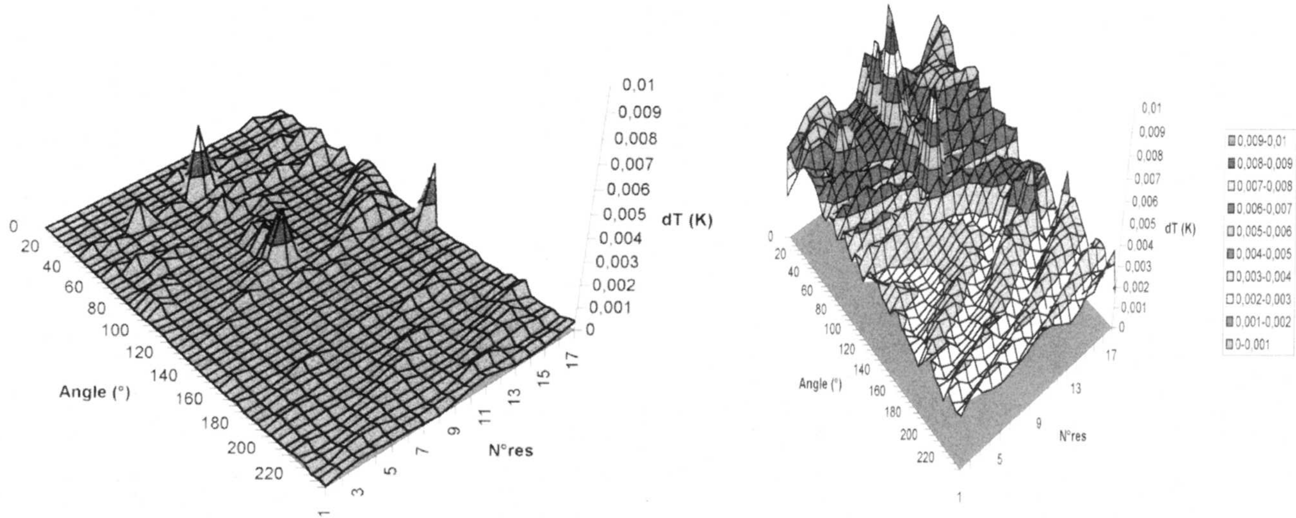


FIGURE 9 Temperature mappings for C105 measured at field levels of $E_{acc} = 25$ MV/m (left) and $E_{acc} = 30$ MV/m (right) indicating that the anomalous losses are almost uniformly distributed on the cavity surface. (See color plate V).

At this time, there is no obvious explanation for these anomalous losses. One plausible suggestion is the presence of a damage layer on the niobium inner surface caused either by a mechanical action (for example, during high pressure rinsing, if the pressure is too high, the material yield strength might be exceeded[22]) or by chemistry (it seems that electrochemistry does not induce that effect while standard buffer chemical polishing does[23]). Other suggestions would be the induced losses across grain boundaries or a residual tiny 100 K effect (also caused by chemistry after annealing).

## CONCLUSION

In conclusion, tremendous effort has been successfully devoted to the understanding of the surface resistance, the quench field and the field emission limitations in SCRF cavities. This enabled us to study then define some experimental procedures and techniques (heat treatment, high pressure rinsing) that allowed achieving accelerating fields in excess of 20 MV/m ($B > 80$ mT) and $Q$-values above $7 \times 10^{10}$ routinely and reliably on niobium cavities. While pushing for even higher gradients, a new limitation arose: Anomalous losses are appearing at magnetic fields higher than 100 mT. The physical mechanism of these losses is yet to be understood in order to steadily approach the intrinsic theoretical limits of the material.

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