Thermal stability of superconducting Nb cavities at 3 GHz

R. W. Röth, H.-G. Kürschner, G. Müller, H. Piel, and D. Reschke
Fachbereich Physik, Bergische Universität Wuppertal, Germany

Abstract

Even in field emission free cavities the expected fundamental field limit $H_c(T_B)$ cannot be achieved, yet. This is due to a local or global transition of the critical temperature $T_c(H)$, caused by anomalous loss mechanisms like geometrical surface defects, foreign material, adsorbed gases, etc. This paper presents the results of model calculations, simulating the temperature distribution in the niobium sheet with varying magnetic surface field. Especially, the influence of the thermal conductivity of the niobium is studied. Finally the calculated data are compared to some experimental results at 3 GHz. To fit the observed $Q_0(E_{acc})$ dependence, several assumptions about the local and global part of the anomalous losses are discussed.

1 INTRODUCTION

For the construction of a superconducting linear collider for electrons in the 300 GeV regime (TESLA-project [1]), cavities with acceleration gradients in excess of $E_{acc} = 20\,\mathrm{MV/m}$ are desirable. Such values are within reach today, even in multicell cavities [2, 3]. However, the reproducibility suffers from the breakdown of superconductivity, thermally induced by local surface defects or by field emitted electron currents [4]. Since 1989, niobium with a very low Ta-concentration is available in Russia [5]. As received, this sheet material has a residual-resistance-ratio of $RRR \approx 500-800$. Postpurification (solid state gettering of interstitial oxygen) can increase this value to $RRR \approx 2000$ [5]. Thus, the thermal stability of superconductivity can be increased significantly compared to today's cavities with a typical $RRR \approx 300-500$.

To quantify the improvements, which the new material provides with respect to maximum surface field and minimum decrease of the unloaded quality-factor $Q_0(E)$, we have developed a computer simulation code [6]. It solves the heat flow equation on a two-dimensional lattice, assuming a rotational symmetric temperature distribution in the vicinity of local defects. The temperature dependences of the BCS-part of the surface resistance ($R_s(T) = R_{BCS}(T) + R_{res}^{hom} + R_D$), the thermal conductivity $\lambda(T)$, and the Kapitza-resistance $\mathcal{R}_K(T)$ at the Nb/He-interface are taken into account. Data about the most important quantity, $\lambda(T)$, have been measured at Wuppertal and Saclay on samples of different purity. $\mathcal{R}_K$ was taken from the literature [7]. The homogeneous part of the residual resistance (R_{res}^{hom}) and the resistance of local defects (R_D) were assumed to show neither field nor temperature dependence.

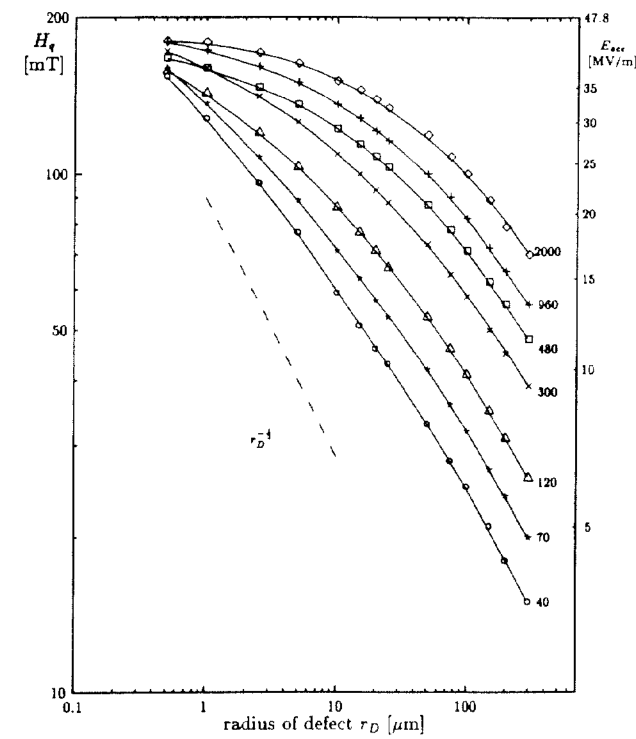

Figure 1: Expected breakdown limit for different defect sizes. The parameter is the RRR (see Fig.3). $\frac{H_q}{E_{acc}} = 4.18\,\frac{\mathrm{mT}}{\mathrm{MV/m}}$ corresponds to the S-band S-DALINAC cavities [3]. ($T_B < 2.1\,\mathrm{K}$, $f = 3\,\mathrm{GHz}$, $R_D = 8\,\mathrm{m}\Omega$, $R_{res}^{hom} = 0\,\Omega$, $D = 2\,\mathrm{mm}$).

In addition to the calculation of the quench limit, the program determines the temperature distribution inside the Nb sheet. Thus, it can be checked, if thermometry in superfluid helium is still useful. Another feature is to calculate the optimum operation temperature for the cavity. Finally, the field dependence of the $\Delta T(r) = T_{Nb}(r) - T_B$ and the Q_0 can be simulated.

2 THERMAL STABILITY OF LOCAL DEFECTS

Assuming one local, normal conducting defect of radius r_D and surface resistance $R_D = 8\,\mathrm{m}\Omega$ (corresponding to Nb at 10 K and 3 GHz), Fig.1 presents the surface field strength, where the thermal breakdown is expected to occur. For these calculations, the thickness of the Nb sheet

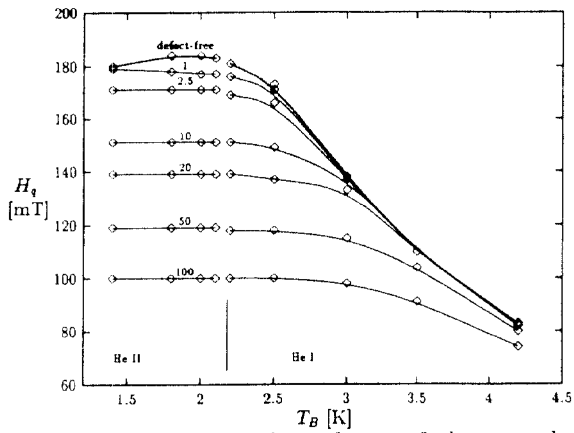

Figure 2: Temperature dependence of the quench field strength ($RRR \approx 2000$, $R_D = 8\,\mathrm{m}\Omega$, $D = 2\,\mathrm{mm}$, $R_{res}^{hom} = 0\,\Omega$, $f = 3\,\mathrm{GHz}$)

was set to $D = 2\,\mathrm{mm}$; a homogeneous part of the residual resistance was neglected. The bath temperature has no significant effect on the quench limit H_q as long as the cavity is cooled with superfluid helium (e.g. Fig.2 for $RRR \approx 2000$). Today, the best S-band single-cell cavities with $RRR \approx 300 - 500$ reach quench limits of $H_q = 135\,\mathrm{mT}$ [8], corresponding to a local defect of less than $5\,\mu\mathrm{m}$ in radius (Fig.1). Even for such a small defect, the quench field strength would improve by $\approx 20\%$, if the cavities were built from the new $RRR \approx 2000$ material. Taking $\frac{H_q}{E_{acc}} = 4.18\,\frac{\mathrm{mT}}{\mathrm{MV/m}}$ (corresponding to the S-band S-DALINAC cavities [3]) $E_{acc} = 38\,\mathrm{MV/m}$ is within reach. Thus, the new material is very attractive for applications, needing high field strengths.

3 TEMPERATURE DISTRIBUTION AT LOCAL DEFECTS

In case of a temperature-independent thermal conductivity, the isotherms around a small defect form half-spheres and the temperature decreases proportional to $1/r$ – just like the electrical field around a point charge in a homogeneous dielectric. However, the thermal conductivity of niobium changes significantly with temperature (Fig.3). Fig.4 gives an example of the resulting $\Delta T(r) = T_{Nb}(r) - T_B$ dependence around a defect with $R_D = 8\,\mathrm{m}\Omega$ and $r_D = 10\,\mu\mathrm{m}$ at $H = 58\,\mathrm{mT}$ for $RRR \approx 40$ and $RRR \approx 2000$, respectively. In the reactor grade niobium ($RRR \approx 40$), $\lambda(T)$ stays more or less constant at low temperatures $T < 3.5\,\mathrm{K}$. Thus, the temperature decays proportional to $1/r$ along the whole sheet thickness except the first $20\,\mu\mathrm{m}$ close to the defect (Fig.4). There, the slope reduces, as $\lambda(T)$ increases with T. In the high purity Nb ($RRR \approx 2000$) $\lambda(T)$ increases more steeply and monotonously with T. Thus, $\Delta T(r)$ decays slower, approaching the $1/r$ dependence close to the Nb/He interface, where T and $\lambda(T)$ are quasi constant. Starting from a much lower ΔT at the defect, the ΔT-signal at the LHe side is higher than in reactor grade niobium.

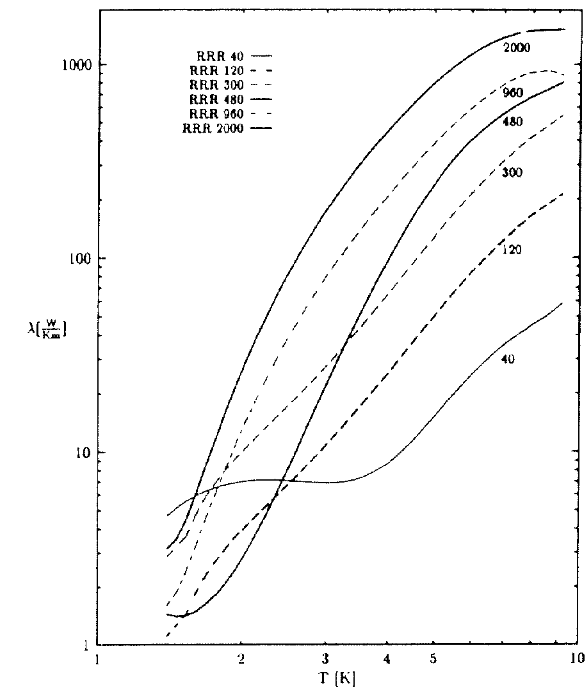

Figure 3: Thermal conductivity of Nb samples. RRR 40: annealed; 120, 300, 480, 960: as received; 2000: RRR 480 postpurified at 1350°C. The relation $RRR \approx 4 \cdot \lambda(4.2\,\mathrm{K})$ is still valid at $RRR \approx 2000$.

Fig.5 presents the field dependence of ΔT for Nb of different purity. Close to the defect the temperature increases less, the larger the RRR value is, reflecting the $\lambda(T)$ dependence. At the Nb/He-interface $\Delta T = \mathcal{R}_K \cdot (\frac{dP}{dA})_B$ increases nearly proportional to H^2 in all cases because $(\frac{dP}{dA})_B = c(\lambda) \cdot (\frac{dP}{dA})_{RF}$ and $(\frac{dP}{dA})_{RF} \propto H^2$. The individual slope $c(\lambda)$ is a direct response to the $\lambda(T)$ dependence (see Fig.2). The detectable signal amplitude for thermometry in superfluid helium is not governed by the $RRR (\propto \lambda(4.2\,\mathrm{K}))$ but by the $\lambda(T)$ at lower temperatures.

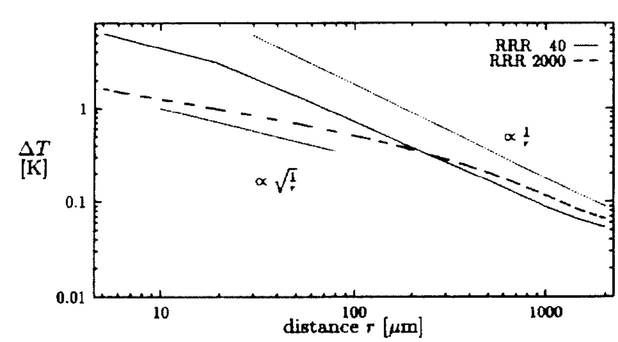

Figure 4: Temperature decrease around a local defect ($r_D = 10\,\mu\mathrm{m}$, $R_D = 8\,\mathrm{m}\Omega$, $T_B = 1.4\,\mathrm{K}$, $H = 58\,\mathrm{mT}$).

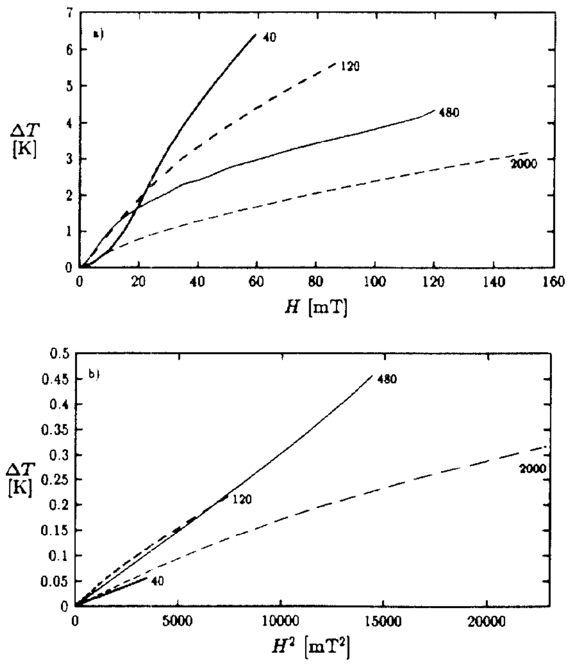

Figure 5: Field dependence of the temperature increase a) at the local defect b) at the Nb/He-interface opposing the defect ($R_D = 8\,\mathrm{m}\Omega$, $r_D = 10\,\mu\mathrm{m}$, $T_B = 1.4\,\mathrm{K}$). The parameter is the RRR.

4 COMPARISON WITH EXPERIMENTAL DATA

As expected from Fig.5b, thermometry in sf helium should detect $\Delta T \propto H^2$. However, experiments show ΔT increasing exponentially with the local rf surface field – at least close to local defects [4]. This behaviour cannot be simulated using a field- and temperature-independent residual resistance ($R_{res}^{hom} + R_D$). In addition, $R_s = \frac{G}{Q_0}$ is observed to increase proportional to H^2 in many experiments [4], though the bath temperature is constant within 3 mK and no field emission is present. Checking all reasonable combinations of (r_D, R_D, R_{res}^{hom}), our simulation runs showed that the experimentally observed Q-degradation and quench limit H_q cannot be explained with the assumtion of a few localized defects ($R_D \neq f(T,H)$) (Fig.6). Thus, the effect might be due to a large number of small defects (adsorbed gases, oxides, hydrides,...), causing small Q-switches that cannot be detected individually. This idea is supported by our investigations of small pillbox cavities ($\approx 20\,\mathrm{GHz}$), where such Q-switches could be detected one by one [9].

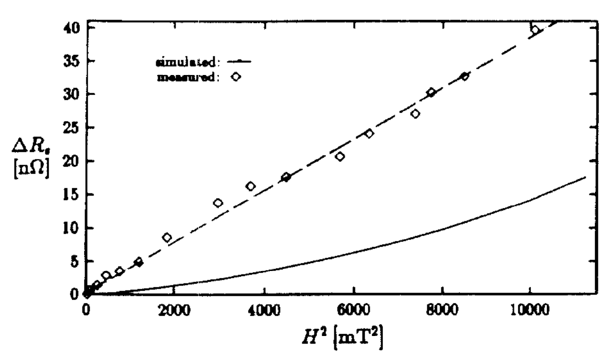

Figure 6: Field dependence of $R_s = \frac{G}{Q_0}$ at $T_B = 1.5\,\mathrm{K}$. Simulation was calculated assuming $r_D = 1.3\,\mathrm{mm}$, $R_D = 90\,\mu\Omega$. Other values yield even smaller ΔR_s and/or H_q.

5 CONCLUSIONS

For accelerators needing high gradients and Q_0 values (e.g. linear colliders like TESLA) the new niobium with $RRR \approx 2000$ is very attractive. Thermometry in sf helium will still be a useful tool to localize and characterize anomalous losses. Thermal model calculations show that the often observed $Q_0(E)$ decrease with increasing field strength cannot be explained by a few local defects. The effect must be due to a very large number of small bad spots or even homogeneously distributed losses, showing the correct field dependence. Thus, it can be expected, that the slope of the $Q_0(E)$-curve reduces as the purity of the niobium increases.

6 ACKNOWLEDGEMENT

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