THERMAL MODEL CALCULATIONS FOR 1.3 GHZ TTF ACCELERATOR CAVITIES

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Abstract

One main limiting mechanism of superconducting accelerator cavities is the thermal breakdown caused by either normalconducting or weak superconducting local defects at the inner (rf) surface of the niobium wall. The breakdown field is determined by the properties of the defect, especially size and surface resistance, as well as by the parameters of the surrounding niobium like thermal conductivity, wall thickness, Kapitza resistance, etc.. This paper describes the results of numerical model calculations investigating the influence of these parameters on the breakdown field and the rf losses. The behaviour of superconducting defects, e.g. tantalum, are studied. Calculated and experimental field dependances of the surface resistance are compared for 1.3 GHz nine-cell structures used at the TESLA Test Facility.

Introduction

Superconducting accelerator cavities machined of niobium are generally limited by anomalous loss mechanisms [1]. One limitation is the thermal breakdown of superconductivity usually called “quench“. Mainly it is caused by an either normalconducting or weak superconducting, local defect with increased power losses compared to the surrounding s.c. niobium. Also it is well-known, that fieldemission induced electrons impinging on the wall can result in an “electronic“ quench. Very few experiments [2, 3] on single-cell cavities show up field values of above 180 mT without fieldemission. Taking into account the temperature dependance of the critical magnetic field and the RF losses due to BCS-resistance, these experiments are most probable limited by global heating of the cavity surface (global thermal breakdown).

For the calculations a finite element code developed at the University of Wuppertal is used [4, 5, 6]. It solves the heat flow equation on a two-dimensional lattice for the stationary case, assuming a rotational symmetry around the defect. For the defect-free case the problem reduces to one dimension. The code calculates the temperature distribution over the lattice taking into account the thermal conductivity $\lambda(T)$ of the niobium and the Kapitza resistance $\Re_K(T)$ of the niobium/helium interface. The bath

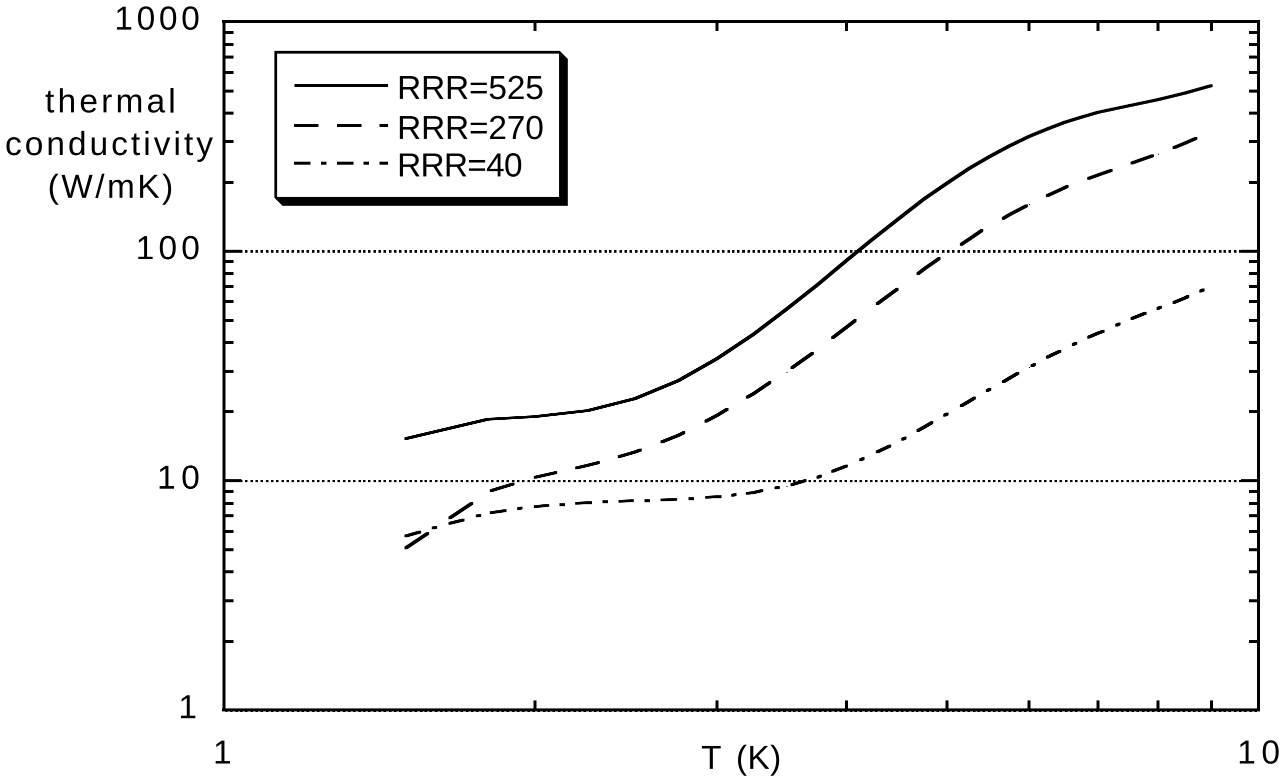

Fig.1: Thermal conductivity fits used for the calculations

temperature is taken as constant. The thermal conductivity of the bulk niobium is temperature dependant according to experimental results.

General Parameters

All calculations are performed for the TESLA-frequency of 1,3 GHz. For niobium and for a superconducting, tantalum-like defect the critical field is chosen as $B_c(0) = 200$ mT and $B_c(0) = 83,1$ mT, respectively. The temperature variation is given by $B_c(T) = B_c(0) \cdot \left(1 - (T/T_c)^2\right)$; the reduction of the critical temperature with increasing field is given by the reverse function e.g. $T_c(100\text{mT}) = 6,5$ K. The accelerating field is $\mu_o H_p / E_{acc} = 4,2\text{mT}/(\text{MV/m})$. The thermal conductivity is taken homogeneous over the disk according to measurements at Saclay [7], Wuppertal [5] and DESY [8] (Fig.1). The Saclay data are taken on RRR 270 Wah Chang niobium without any heat treatment. A RRR of 525 is measured on Heraeus material used for the cavity production after a double sided titanisation. For the comparison with older calculations several runs are performed for RRR 40. The surface resistance of the niobium is given by the temperature dependant BCS-term $R_{s,BCS}(T)$. In general, no homogeneous residual resistance is added in the present calculations. The normalconducting surface resistance of the defect R_{def} is assumed without any temperature dependance. For weak s.c. defects the surface resistance is calculated using a code developed by Halbritter [9]. Neither for the defect nor for the niobium any field dependance of the surface resistance is assumed. The Kapitza resistance $\Re_K(T)$ is taken from a measurement of Mittag [10], which fit well to new experiments at Orsay [11]. To study the influence of a bad niobium/helium interface [12], one set of calculations is done using $\Re_K(T)$-values increased by factor of 10. In general, the bath temperature is set to T_B = 1,8 K.

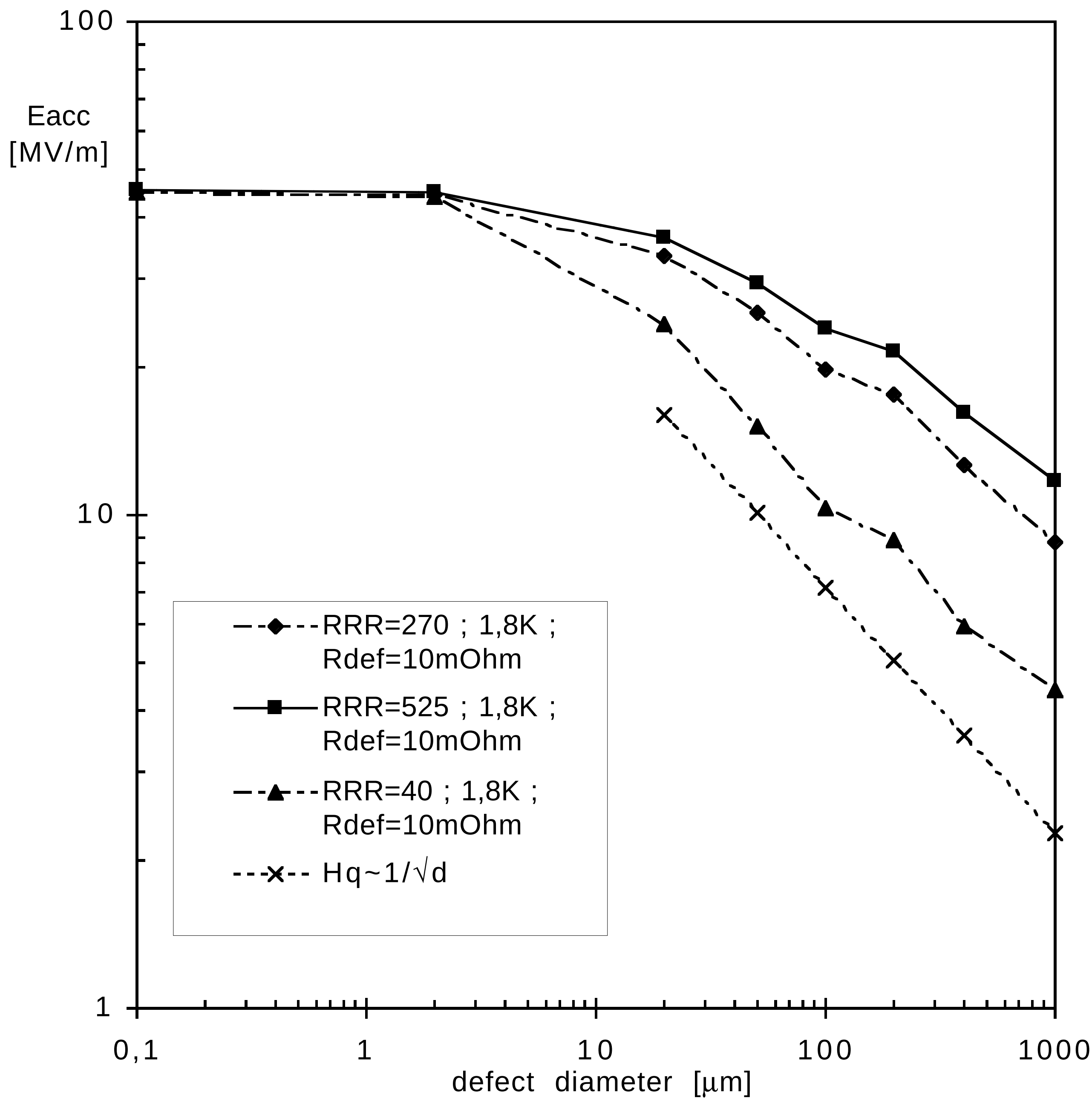

Fig.2: Calculated breakdown field for RRR=525, RRR=270 and RRR=40. The analytical Hq~1/√d is shown as comparison.

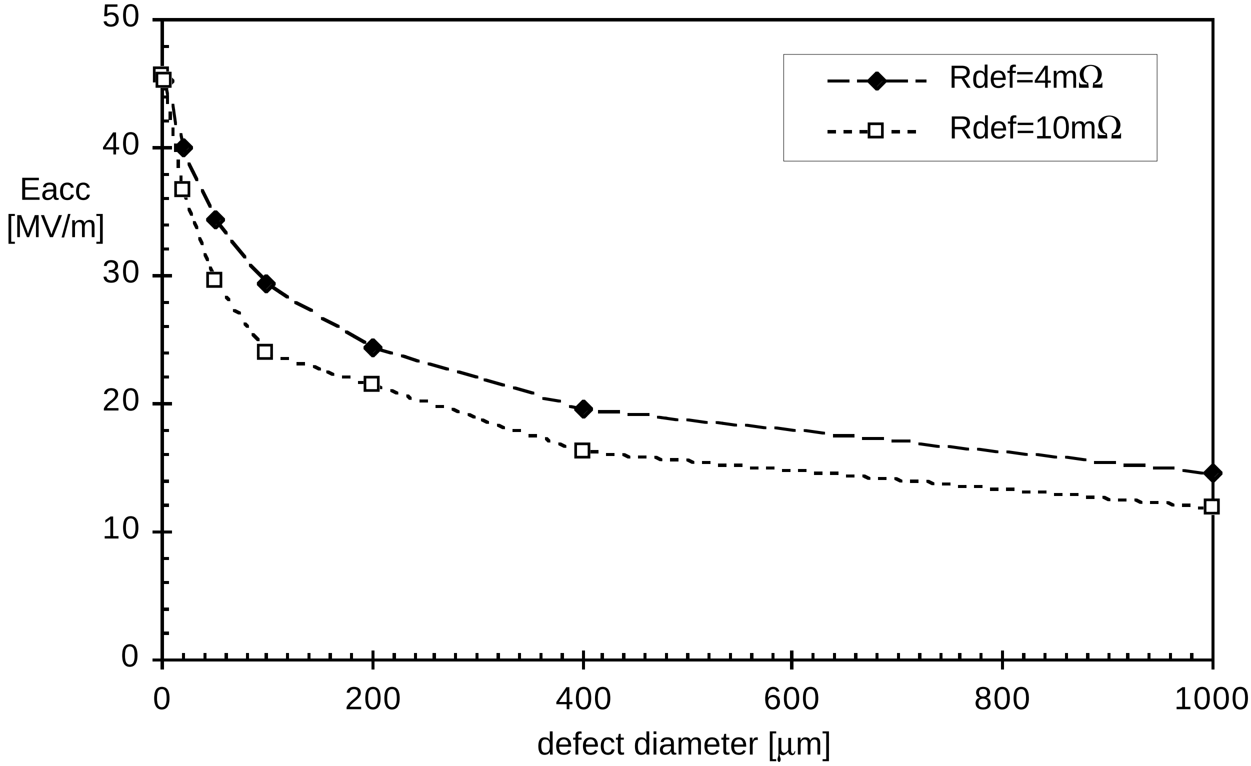

Fig.3: Calculated breakdown limit for different surface resistances Rdef of the defect (RRR=525 ; T=1,8K)

The condition for a quench is achieved, if no stable temperature distribution is possible in the lattice for a given magnetic field. Only a quench condition independent of the temperature of the defect or its neighbours allows the formation of normalconducting rings around the defect and - as a result - Q-switches. The used lattice - with the defect of diameter d at its vicinity - consists of concentric ring segments with growing width and thickness. Varying the lattice - especially close to the defect - gives deviations of the quench field up to 10 %.

Thermal breakdown fields vers. RRR, d and R_{def}

Fig.2 summarizes the dependance of the thermal breakdown field of the defect diameter with R_{def} = 10 mΩ. For gradients above 30 MV/m no normalconducting defects larger than 50 µm are tolerable, even in postpurified high RRR material.

For the defect-free case and very small defects the quench field is nearly independent of λ(T). It is emphazised, that this statement holds only for the chosen conditions with f_0 = 1,3 GHz and no residual resistance. At higher frequencies the increased BCS-surface resistance results in a reduction of the global breakdown limit [5]. For a

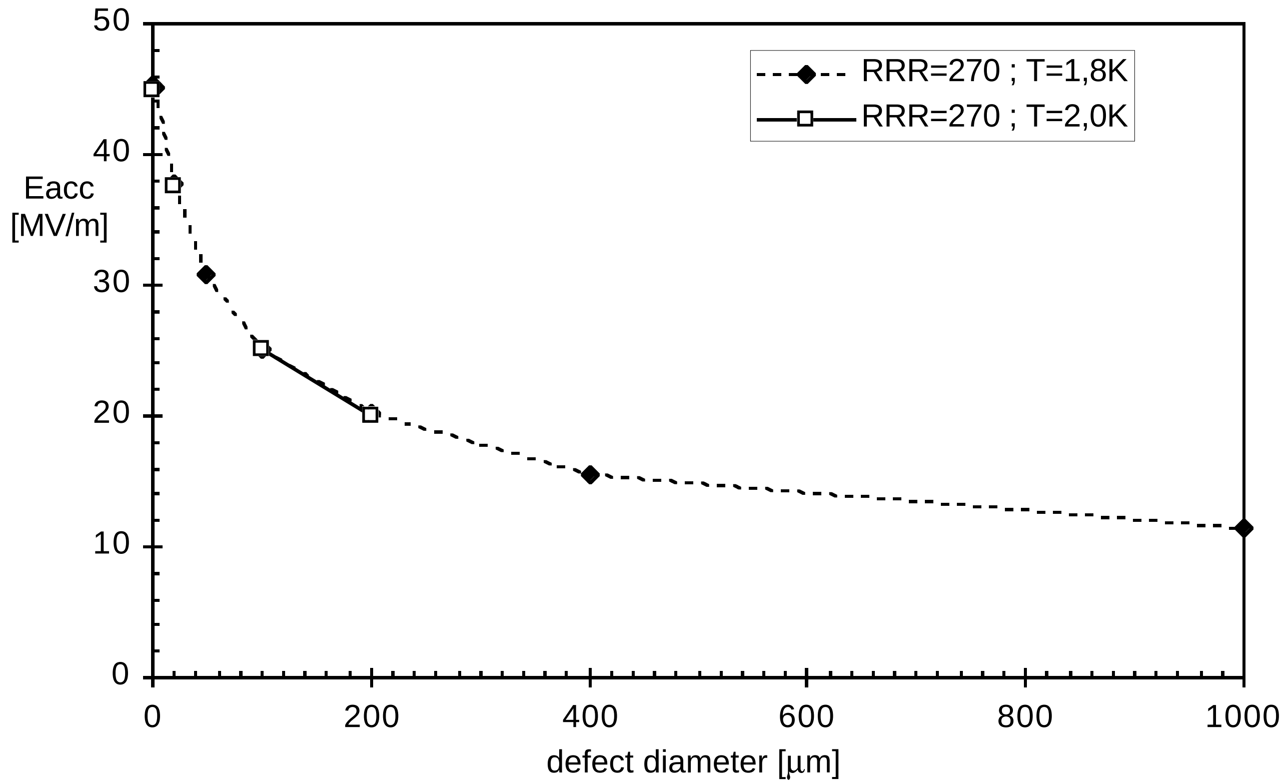

Fig.4: Comparison of breakdown limits for He bath temperature of T=1,8K and T=2,0K (RRR=270, Rdef=4mΩ)

homogeneous residual resistance R_{res} the quench field is slightly reduced, e.g. for RRR 270 a R_{res} of 100 nΩ reduces the quench field by 10 mT.

For larger defects a higher thermal conductivity leads to increased quench fields. This is obviously due to the fact, that the critical parameter for the breakdown is the heat conduction close to the defect. Here R_{res} has nearly no influence, because the losses are dominated by the defect. The calculations are in good agreement with the analytical derived square-root dependance [5] $H_Q \propto \sqrt{RRR/(R_{def} \cdot d)}$ for large defects and neglected Kapitza resistance. In the defect-free case the maximum field is E_{acc} = 45 MV/m, which results from the assumption of a critical field of 200 mT. If the rf critical field is higher - values up to $B_c(0)$ = 240 mT are discussed -, obviously this would result in higher gradients.

Varying R_{def} a comparable set of curves can be derived. For RRR 525 the results are shown in Fig.3 for R_{def} = 4 mΩ, the R_s of copper, and a worse material with R_{def} = 10 mΩ. To study the influence of the bath temperature in the superfluid regime, it is changed to T_B = 2,0 K. No variation of the quench field is observed (Fig.4), because the thermal conductivity close to the defect, which is dominating the behaviour, varies only slowly with the temperature between 1,8 K and 2,1 K.

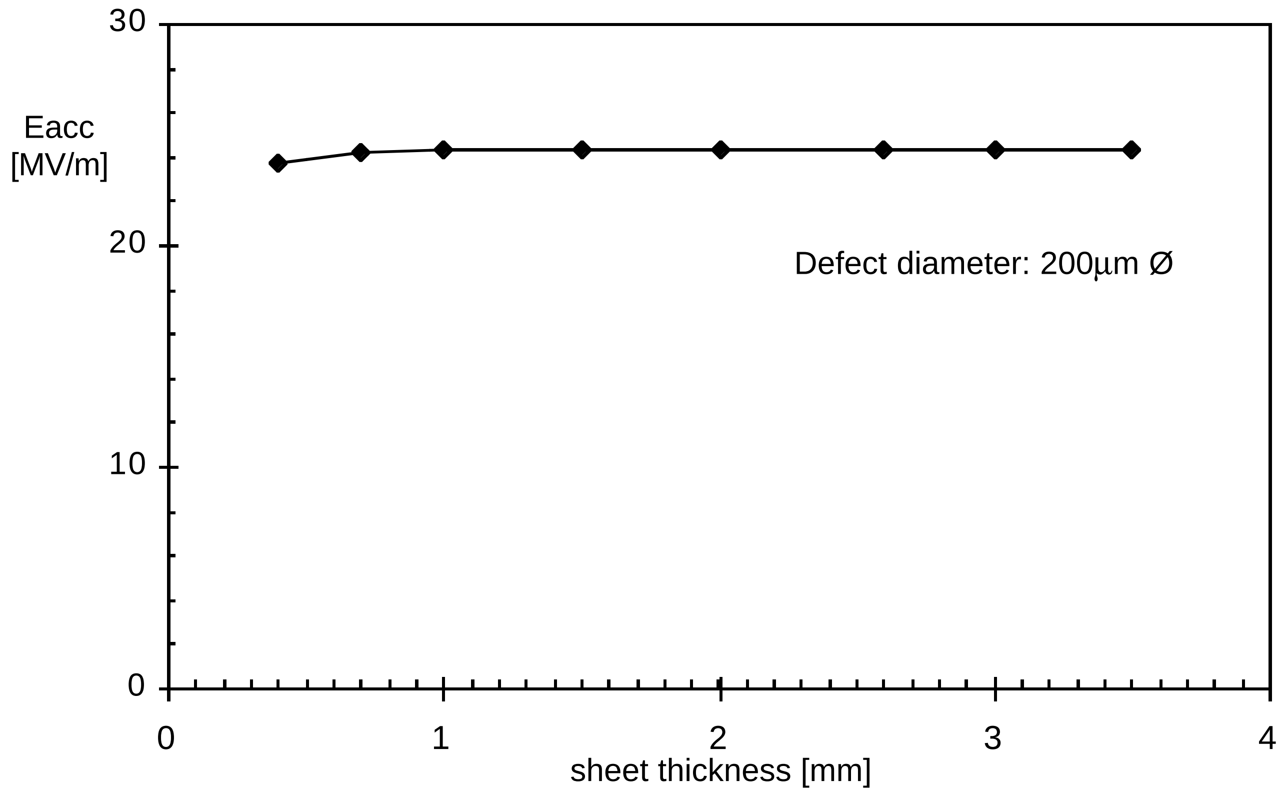

Fig.5: Quench limit as a function of the sheet thickness for a defect diameter of 200µm (RRR=525, T=1,8K)

Analytical considerations [5] predict the formation of stable normalconducting rings around the defect, if $R_{def} > 2R_{s,nl}$(Nb). Even for very high RRR the anomalous skin effect gives a lower limit of $R_{s,nl}$(Nb) around 2 mΩ. The calculations show such rings for R_{def} = 10 mΩ, but not for R_{def} = 4 mΩ. Typically, they occur at 90% of the quench field. For further investigations, especially the detailed consequences on the $Q_0(E_{acc})$-curves, calculations with a very fine mesh are foreseen.

Dependance on Wall Thickness

In general, the computations are performed for a wall thickness of 2,6 mm like presently valid for the TTF cavities. For a defect diameter of 200 µm, a defect surface resistance R_{def} = 4 mΩ and sheet thicknesses between 0,4 mm and 3,5 mm only a very weak dependance is obtained (Fig.5). This finding is in agreement with other numerical calculations [13], but in contradiction to an analytical approach [14, where the temperature dependance of the thermal conductivity is neglected. Analysing the radial temperature profiles below the quench at the He- and rf-side, the temperature increase at the rf-side of the sheet is nearly independent of its thickness (Fig.6 + 7). Again the breakdown occurs, if the niobium surrounding the defect exeeds T_c(H).

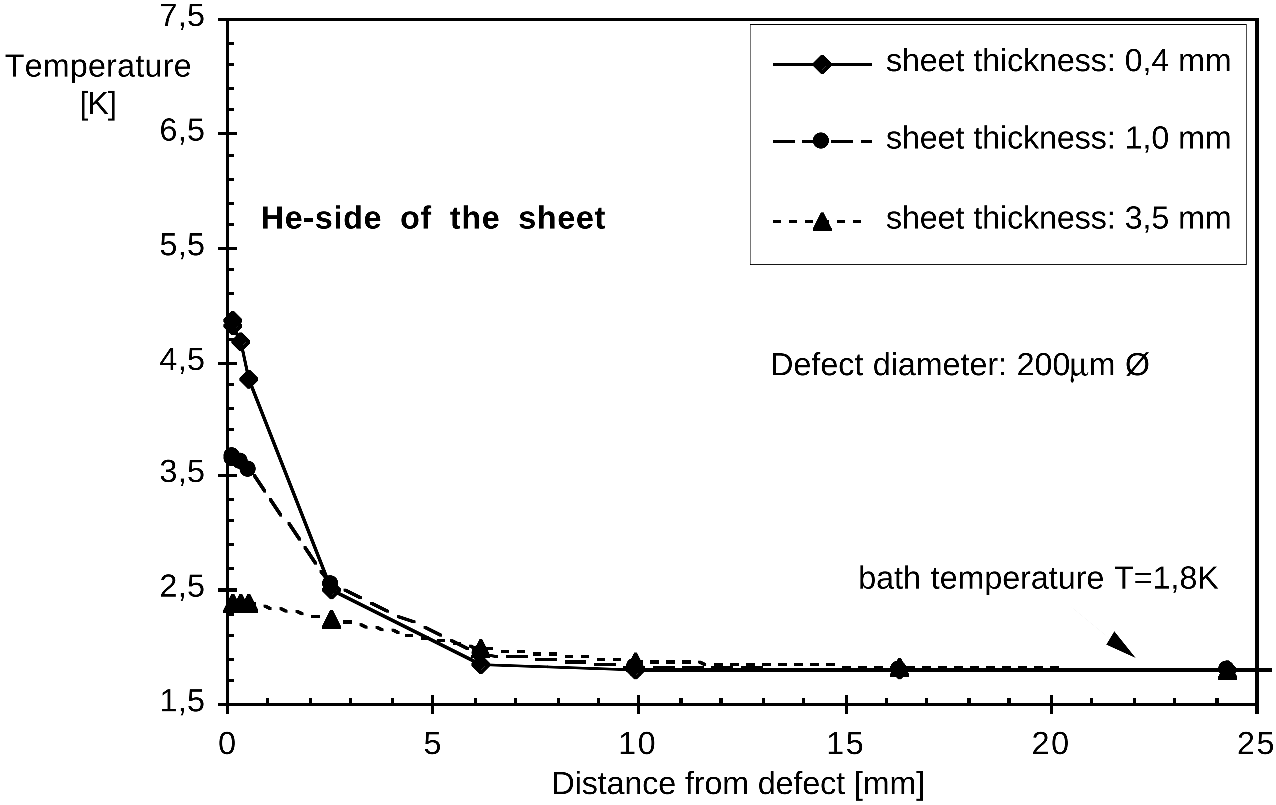

Fig.6: Radial temperature profile at Eacc=20MV/m for different sheet thickness (T=1,8K, RRR=525)

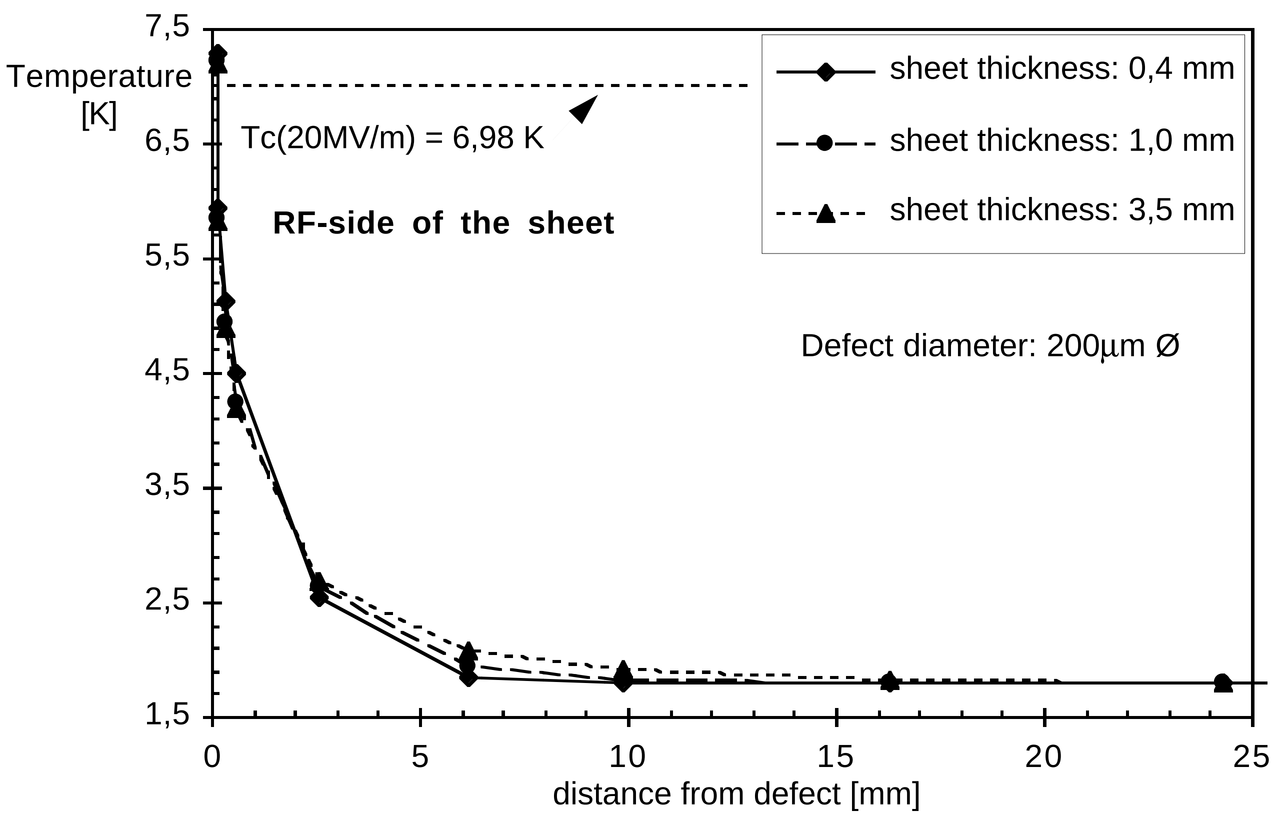

Fig.7: Radial temperature profile at Eacc=20MV/m for different sheet thickness (T=1,8K, RRR=525)

Increased Kapitza Resistance

One of the unsolved questions concerning s.c. cavities is the source of the often observed drop of the Q_0 with increasing field. Plotted linear as surface resistance versus field, the increase follows $R_s \propto E_{acc}^n$ with n = (1-2). Following an idea of E.Kako, the consequences of a factor 10 increased Kapitza resistance are studied. For the defect-free case and small defects the breakdown field decreases from 45 MV/m to 39 MV/m (Fig.8), which is a consequence of the limitation of the heat flux at the niobium/helium boundary. For large defects the quench field keeps nearly unchanged, reflecting the limitation due to the heat conduction close to the defect.

Assuming a TTF nine-cell cavity with RRR 525 and five defects of d = 200 µm, the $Q_0(E_{acc})$-behaviour is calculated for 'usual' and factor 10 increased Kapitza resistance (Fig.9, 10). Compared to experimental data (Fig.11, 12), the calculated quench as well as the amount of Q_0-drop are comparable. However, the calculated field dependance seems to be stronger than the measured $R_s \propto E_{acc}^2$. In addition, the comparison of the calculated and measured temperature increase at the He-side aren't in agreement. Typically, temperature mapping on a defect gives $\Delta T \propto E_{acc}^n$ with n = (2 - 7) [15]. Both, the calculations with and without increased Kapitza resistance result in n ≈ 2. This discrepancy is not understood, yet, but it is a hint that - though an increased Kapitza resistance might take part - the Q_0-drop is mainly due to another mechanism.

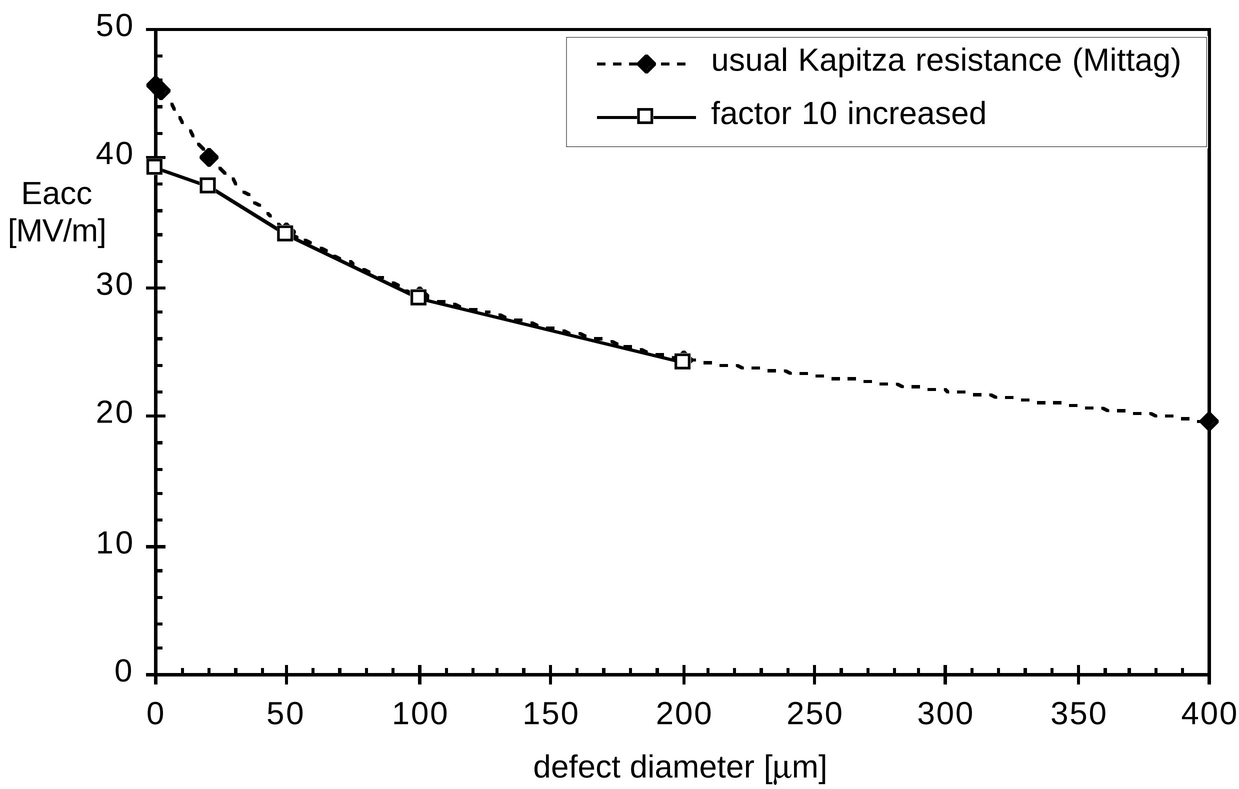

Fig.8: Comparison of breakdown limits for a factor 10 increased Kapitza resistance (RRR=525,T=1,8K, Rdef=4mΩ)

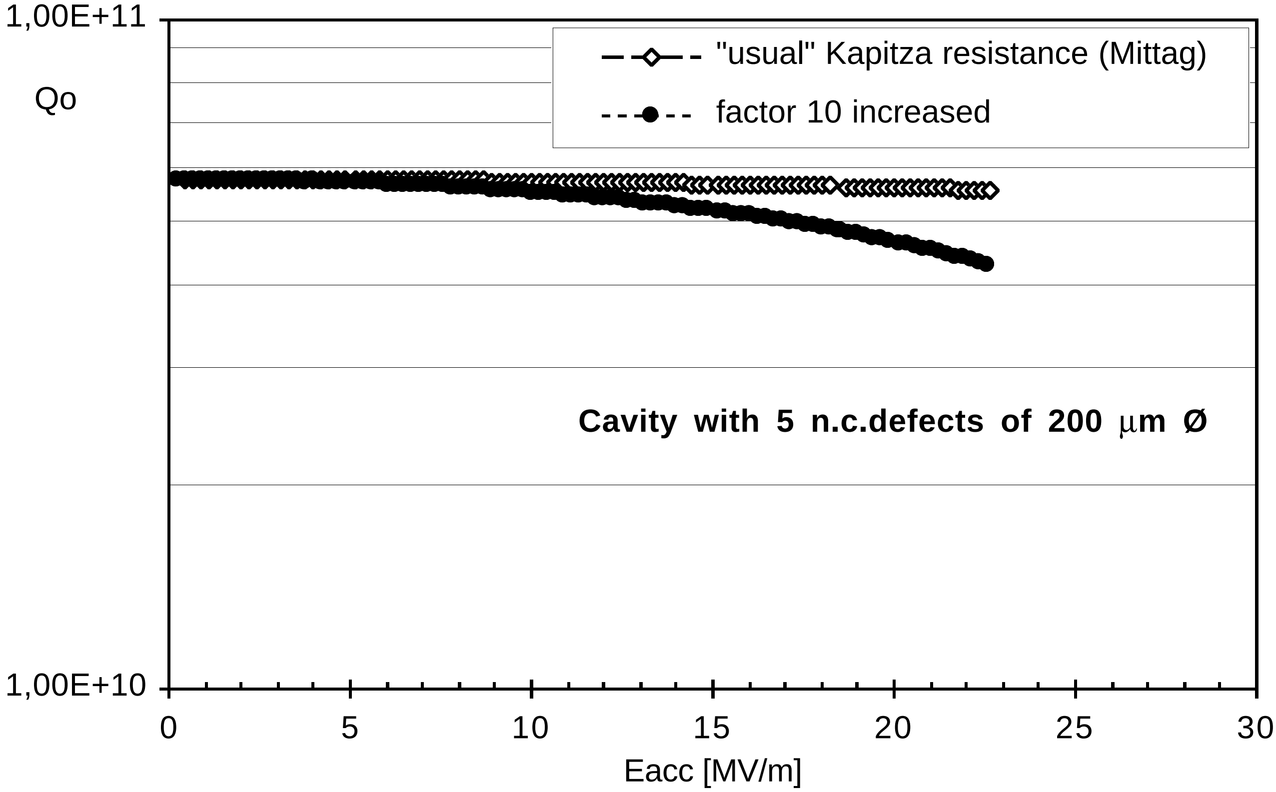

Fig.9: Comparison of Qo(Eacc)-dependance for a factor 10 increased Kapitza resistance (RRR=525, T=1,8K)

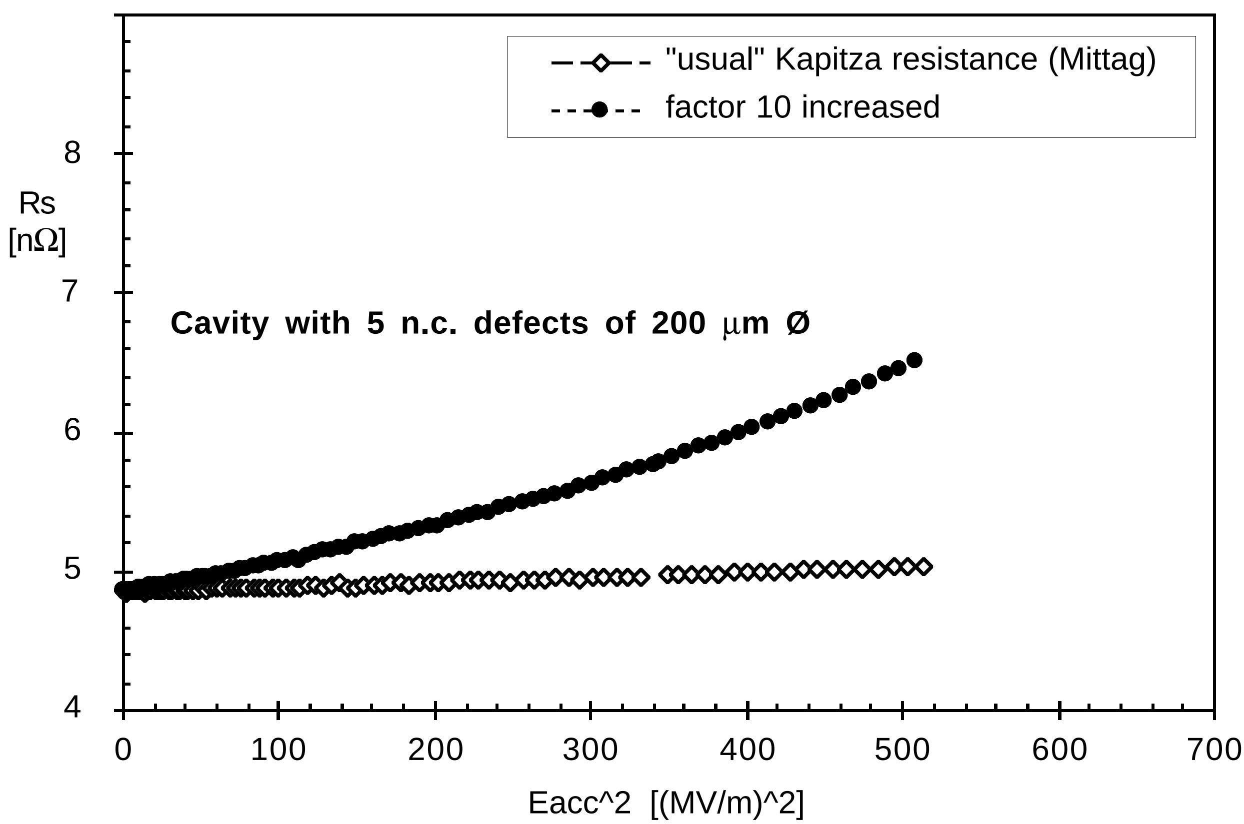

Fig.10: Calculated increase of the surface resistance versus the squared accelerating field (RRR=525, T=1,8K)

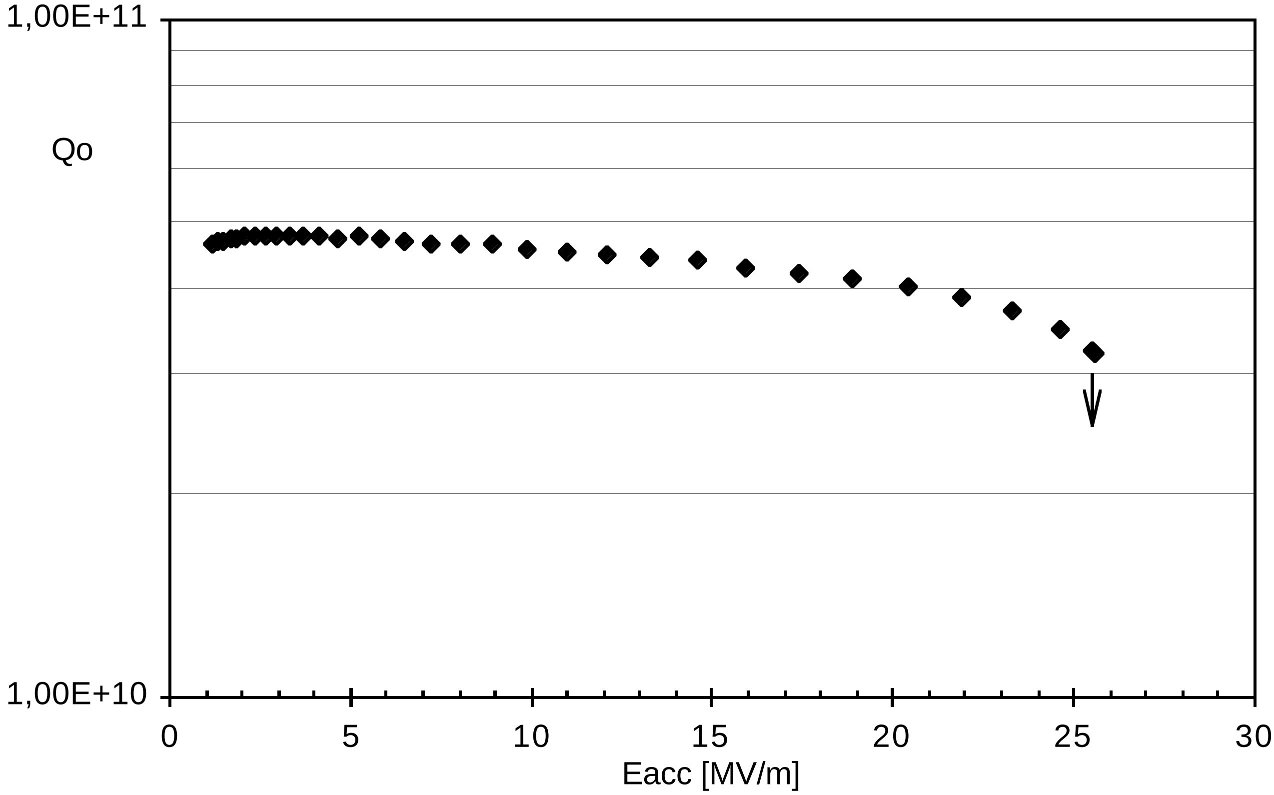

Fig.11: Measured Qo(Eacc)-performance of cavity D3
(limited by quench ; RRR≈525 ; T=1,8K)

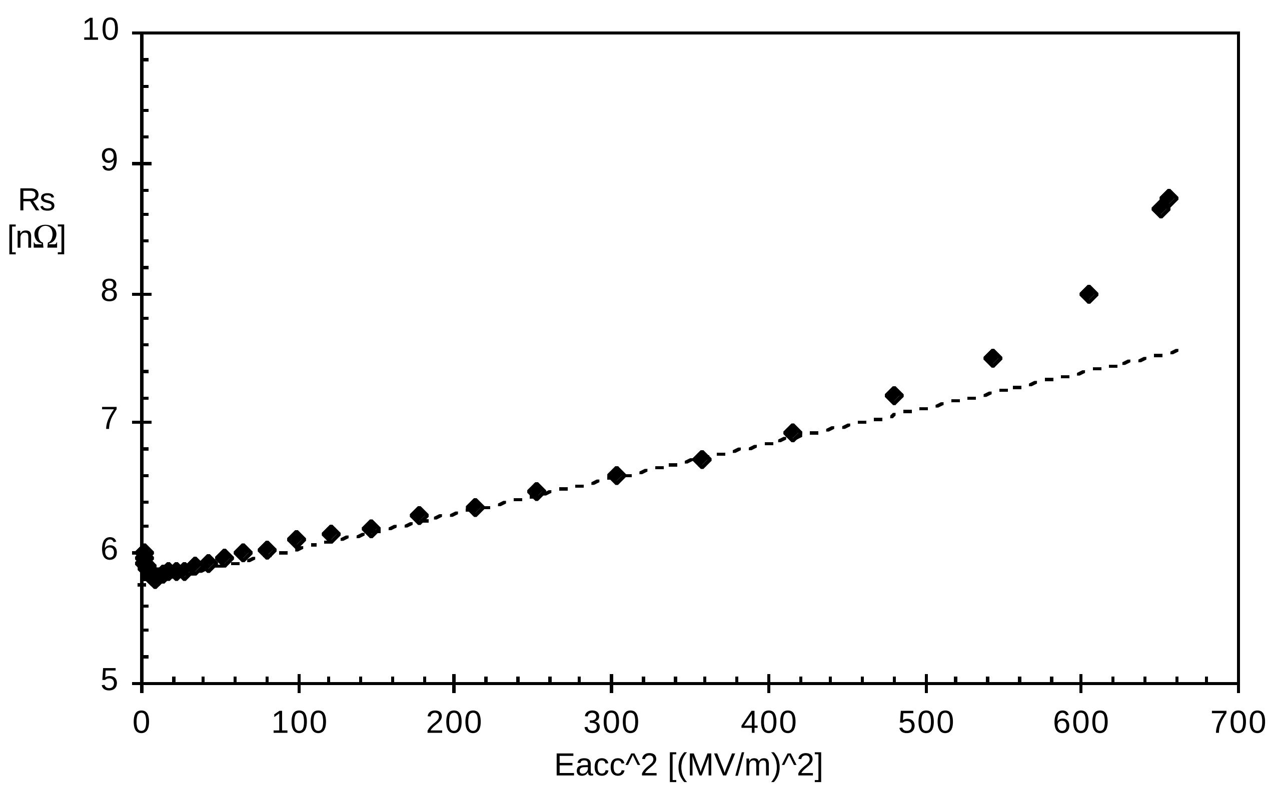

Fig.12: Quadratic increase of the surface resistance at the same test

Superconducting Defects

By cutting and elemental analysis, the early limiting quench defect of one nine-cell cavity is identified as a tantalum inclusion with an area of 0,5 mm^2. Tantalum is a superconducting material with T_c = 4,4 K and H_c = 83,1 mT. At 2 K it becomes normalconducting at $E_{acc} \approx$ 16 MV/m, which - for such a large defect - gives the upper limit of the quench field of the cavity. The experimental $Q_0(E_{acc})$-performance of this cavity starts with a flat Q_0 up to 8,5 MV/m ($\cong$ 36 mT). At this level a Q-switch occured and the Q_0 starts to drop fast until the quench at 12 MV/m and 10^{10}.

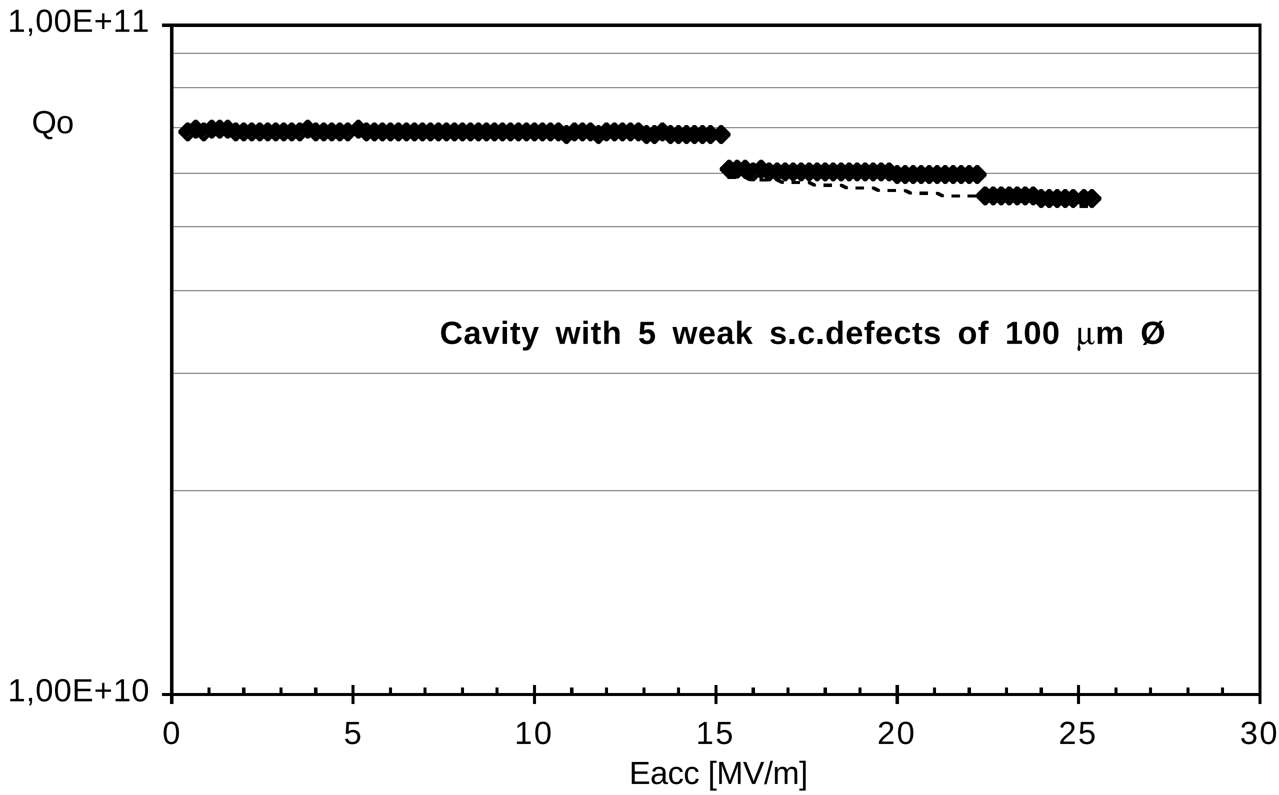

Fig.13: Calculated Qo(Eacc) of a cavity with 5 weak superconducting defects of 100µm Ø (RRR=525 ; T=1,8K ; Rdef(T>Tc)=10mΩ)

For a realistic modeling of the situation, weak s.c. rings around the defect with properties changing slowly from tantalum to niobium are assumed requiring a mesh of high density. Only first results of the ongoing work on this topic are available. The weak s.c. area becomes normalconducting due to the T_c(H)-decrease with increasing field. The temperature increase of the defect area itself- even though the s.c. surface resistance is much larger compared to the surrounding niobium - is less then 100 mK. If the defect becomes normalconducting, a Q-switch occurs due to the sudden increase of the losses (Fig.13). Rising the field more “Q-switches“ occur reflecting the discret structure of the mesh: More and more rings around the defect become normalconducting, which experimentally is observed as a continous Q-drop.

Nevertheless, there is no quantitative analysis possible, but the up to now results together with further improvements of the model are promising for the future.

Conclusion

Even in postpurified niobium of high thermal conductivity normalconducting defects of 50 µm or larger cannot be tolerated for gradients above 30 MV/m. In the defect-free case and assuming the critical magnetic field for rf applications $B_c \geq 200$ mT, gradients up to 45 MV/m can be reached in principle. A drastical increased Kapitza resistance reduces the defect-free quench limit significantly, where as the limitation for defect limited cavities keeps unchanged. The wall thickness has no influence on the quench limit in the practical important range between 1 mm and 3,5 mm. Experimentally observed Q-switches can be explained and qualitatively simulated as a weak superconducting defect becoming normalconducting. Quantitative analysis requires a refined model and last but not least plenty of calculation time.

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