Results from a nearly "Defect - free" Niobium Cavity

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Abstract

In collaboration with KEK a 1300 MHz single cell niobium cavity was built at CEBAF from niobium of RRR ≥ 200 supplied by Tokyo - Denkai with standard fabrication processes such as deep drawing and electron beam welding. Several chemical surface treatments were applied to the niobium surface with subsequent measurements of the Q vs. E_{acc} behavior of the cavity at or below 2K. After a layer of approximately 150 µm had been removed from the niobium surface, the cavity exhibited an extremely good performance both in Q - value and accelerating gradient: at 1.3K a Q - value of 1 x 10^{11} was measured at a low rf - field corresponding to a residual resistance of $R_{res} \approx 2.6$ nΩ and the peak surface electric field could be raised to $E_{peak} \approx 75$ MV/m without field emission loading. This value corresponds to an accelerating gradient $E_{acc} \approx 42$ MV/m. Thermal model calculations performed at the University of Wuppertal indicate that the cavity exhibited a nearly " defect - free " surface during this test. The cavity seemed to be limited by a global heating as deduced from an oscillatory field behavior at the highest achieved field level.

Introduction

Even though over the last few years steady progress has been made in improving the performance of superconducting accelerating cavities, the main limitations at higher gradients remain still field emission loading and thermal magnetic breakdown.
Advanced surface preparation techniques such as UHV - annealing [1] or high pressure ultrapure water rinsing [2, 3, 4] in connection with improved assembly and handling procedures shifted the onset fields for field emission loading in cavities towards gradients >15 MV/m, at least in a laboratory environment. The development and exploitation of high peak power rf processing [5, 6] resulted in additional " in-situ " improvements of cavity performance and gradients above E_{acc} = 20 MV/m are reported more frequently even for multi-cell structures. However, often enough are high gradient niobium cavities nowadays limited by thermal magnetic breakdown at field levels below the fundamental limitations given by the critical magnetic field of the niobium. Thermal model calculations [7, 8, 9] and experimental verifications have shown that local surface defects or field emitted electron currents can lead to a thermally induced breakdown of the superconducting state . Improvements can be gained by increasing the thermal conductivity of the cavity material; this is often accomplished by solid state gettering in UHV in the presence of Ti at elevated temperatures [10].
This paper reports about a series of tests, which have been performed on a niobium cavity fabricated from niobium with a rather moderate RRR - value; nevertheless in the course of these experiments the cavity exhibited an extremely good performance , qualifying it as a nearly "defect - free" cavity based on thermal model calculations.

Cavity Fabrication and Surface Preparation

The cavity shape was adopted from an optimized design by KEK [11] for a linear collider cavity. The cavity parameters are : f = 1296 MHz, geometry factor G = 274 Ω, shunt impedance R/Q = 102 Ω, $E_{peak}/E_{acc} = 1.78$ and $H_{peak}/E_{acc} = 43.8$ Oe/MV/m (E_{peak} and H_{peak} are the peak surface electric field and peak surface magnetic field, respectively).

The cavity was fabricated from high purity niobium of RRR ≥ 200 provided by Tokyo - Denkai and standard fabrication techniques as listed below were applied:

Step 1: Deep drawing of half cells with Al 7071 dies at 100 tons; coining of the beam pipe extrusions at 25 tons and restamping of the half cell at 100 tons

Step 2: Machining of welding steps on half cells with proper dimensioning of half cells

Step 3: Degreasing, removal of approximately 10 µm from the surface by buffered chemical polishing (bcp) and electron - beam welding of the beam - pipe / flange subassembly to the half cells

Step 4: Careful visual inspection and mechanical removal of all visible surface defects

Step 5: Slight bcp (≤ 5 µm), electron - beam welding of equator weld with a defocussed beam, resulting in a smooth and flat underbead

Step 6: Standard chemical surface treatment :

● degreasing in detergent with ultrasonic agitation ● rinsing with ultrapure water ● buffered chemical polishing, inside only ● rinsing with ultrapure water ● High pressure ultrapure water rinsing for ≥ 20 min at 80 bar ● 3 x rinsing with reagent grade methanol in clean room and assembly of rf - probes ● attachment to cryogenic test set - up and evacuation ●

Experimental Results and Discussion

For the first test the standard amount (for CEBAF' s production cavities this is approximately 65 µm) of material was removed prior to the cold test . A Q_o - value of $Q_o = 1.6 \times 10^{10}$ at 2K was measured and the field in the cavity could be raised to $E_{peak} = 26$ MV/m. At this level the rf- signal showed the signature of multipacting , and no attempt of processing this barrier was made. For the subsequent test an additional 50 µm were removed ; this time the Q_o improved to $Q_o = 2.5 \times 10^{10}$ corresponding to a residual resistance of $R_{res} = 2.7$ nΩ and a field of $E_{peak} \approx 37$ MV/m was measured. This time instabilities in the rf - system prevented further increases of the power level. However , after the test at 2K the cavity was warmed up to 100K and kept at this temperature for ≥ 24 hours. After cooldown no degradation of the cavity performance was seen.

After an additional removal of 50 µm the cavity exhibited an extraordinary good performance, which is shown in figures 1 and 2: not only was the low residual surface resistance of the previous test maintained, but the cavity fields could also be raised to very high gradients in the absence of field emission loading.

Fig.1 shows the temperature dependence of the surface resistance during this test . By fitting the experimental data to the BCS theory as supplied by J. Halbritter's surface resistance program [12, 13], a residual resistance of R_{res} = 2.6 nΩ and the material parameters as listed below were obtained.

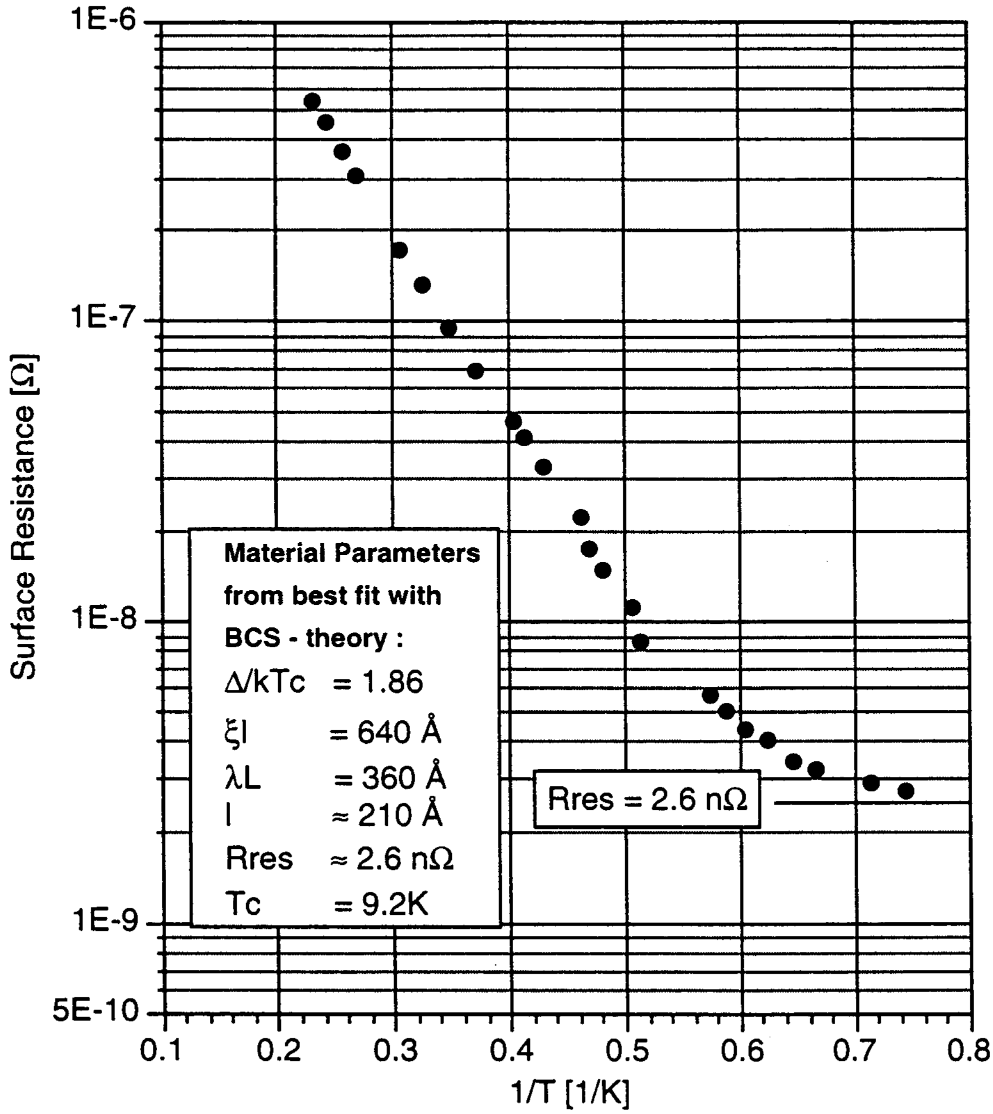

Fig. 1: Temperature dependence of the surface resistance .

The dependence of the Q - value on the peak surface electric field at 3 different temperatures is plotted in figure 2 . Since the coupling probe for the forward rf - power was fixed during the experiment and the cavity was undercoupled at 2K and 1.8K , the reached fields of E_{peak} ≈ 52 MV/m at 2K and E_{peak} ≈ 68 MV/m at 1.8K were limited by the available rf - power . At 1.6K the cavity was nearly critically coupled and there was sufficient rf - power available to reach the field limit. At the highest fields the cavity exhibited an oscillatory reduction of the field, which recovered after a few seconds, indicated that possibly a global warming of the cavity surface was taking place.

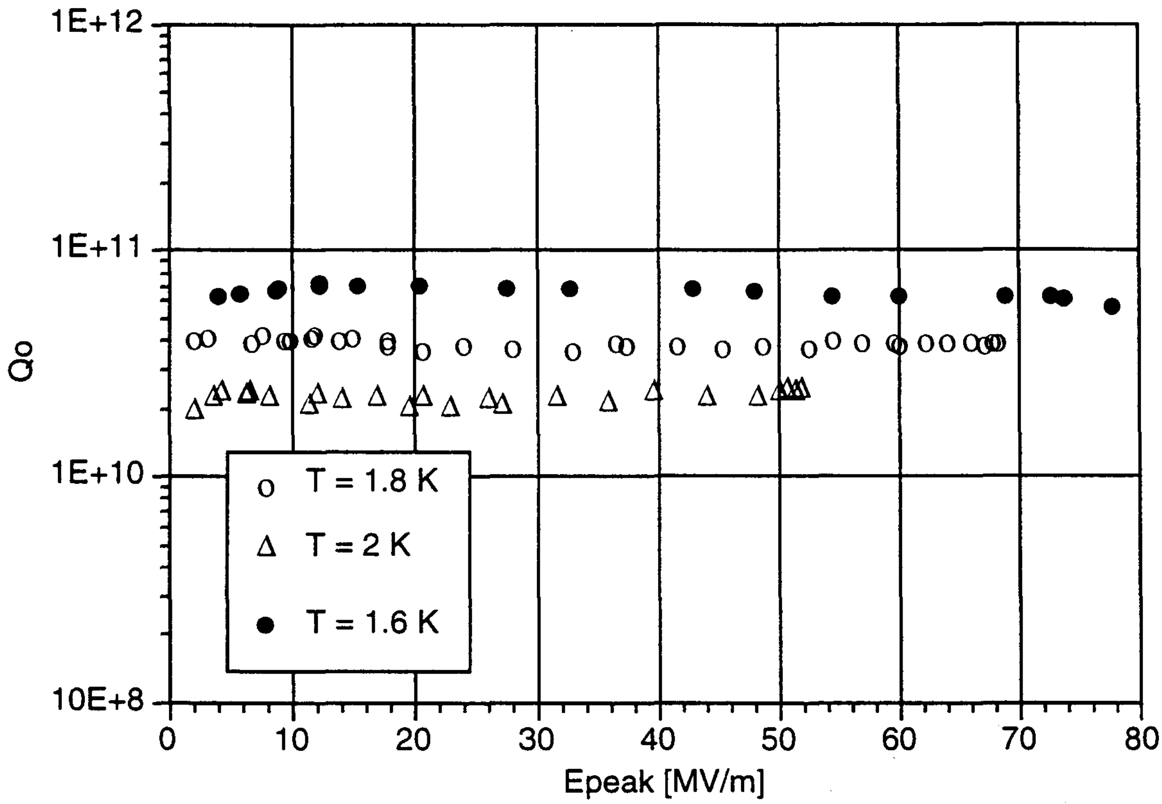

Fig. 2: Q_o vs. E_{peak} at 3 different temperatures for a nearly "defect - free" niobium cavity

These experimental results were compared to thermal model calculations, which predict the threshold field H_q for thermal instabilities in a superconducting cavity caused by defects of radius r_D and a resistance R_D in a material with the thermal conductivity $\lambda(T)$ [7]. The computer simulation code used for these calculations was developed at the University of Wuppertal. It solves the heat flow equation on a two-dimensional lattice, assuming a rotational symmetric temperature distribution in the vicinity of local defects [9]. The temperature dependence of the BCS - part of the surface R_{BCS} (T), the thermal conductivity $\lambda(T)$ of the niobium, the Kapitza-resistance R_K (T) at the niobium/helium interface, the inner and outer temperature of the wall material of thickness d and the helium bath temperature are taken into account under the assumption of a homogeneous residual surface resistance R_{res} . The surface resistance R_S (T) is the sum of the BCS - part the residual resistance and the resistance of the defect : $R_S (T) = R_{BCS} (T) + R_{res} + R_D$. Both R_{res} and R_D are assumed to be field and temperature independent.
More details of the model calculations can be found in [9] and in ref. [14] a large set of model calculation for a frequency of 3 GHz are discussed. Some of the uncertainties in the simulation calculations comparing them to a particular measurement arise from the assumed temperature dependence of the thermal conductivity of the cavity material, the Kapitza-resistance [15] and the defect resistance. However, there is nearly no dependence of the thermal stability on frequency and the S - band simulation calculations reported in [14] are quite valid for a comparison to the experimental results. These calculations indicate that niobium cavities in the most ideal situation of very high thermal

conductivity and exhibiting no defects become thermally unstable at rf magnetic surface fields between 1800 to 2000 Oe. For the particular set of parameters derived from the measurements presented in figures 1 and 2 a quench field of approximately 1800 Oe was calculated for the defect-free case. This simulation is very close to the observed behavior of this cavity and indicates that in this particular test the rare case of a nearly "defect-free" niobium surface was encountered. On the other hand, cavities fabricated from the same material and tested at KEK have shown very similar performance [16]

Conclusion

The comparison between the best experimental results on this cavity with the thermal model calculations indicates that in this particular test the performance of a nearly "defect - free" niobium surface was measured. Even though this was a singular event and obviously a variety of lucky circumstances must have come together such as the absence of field emission loading or foreign material inclusions , surface scratches or chemical residue this result demonstrates that theoretical predictions and experimental achievements are not contradictory. The major challenge for the SRF - community is to further improve fabrication and handling procedures so that more frequently the limits given by the material parameters can be reached.

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