PERFORMANCE OF 1300 MHz KEK–TYPE SINGLE CELL NIOBIUM CAVITIES

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Abstract

Four single cell niobium cavities fabricated from Tokyo–Denkai material of RRR = 200 have been tested repeatedly with the purpose to evaluate different fabrication and processing techniques used at KEK and Jefferson Lab, respectively. Two cavities– K–15 and K–16 –have been manufactured completely at KEK prior to shipment to CEBAF. In addition, K–16 had received a barrel polishing treatment at KEK, resulting in the removal of 40 μm of material from the surface.

Cavity K–17 was electron–beam welded at Jefferson Lab; the deep drawing of the half cells and the trimming of the cups for electron–beam welding were done at KEK, however. Cavity JL–1 was completely fabricated at Jefferson Lab. Often, some processing field levels related to electronic activity in the cavities, possibly multipacting, have been seen at KEK and the purpose of this investigation is a verification of such observations. In addition, a comparison of different fabrication procedures and surface treatments are of interest for optimizing cost and performance for larger scale application.

In several cavities accelerating gradients between 20MV/m$\leq E_{acc} \leq$27 MV/m have been measured with only little field emission loading. In one of the cavities resonant electron loading was "provoked" by rinsing it with oil contaminated acetone. The observed multipacting levels at E_{acc}=13 MV/m and 25 MV/m could be identified with the help of simulation calculations as 1–point and 2–point multipacting across the equator of the cavity. There is–as previously reported–a rather strong dependence of the quench field levels on the amount of material removed from the surface, confirming a picture of a surface damage layer, which becomes depleted of defects as more and more of it is removed.

Introduction

At KEK very high accelerating gradients have been achieved reproducibly in single cell 1300 MHz cavities[1] by applying barrel polishing, electropolishing and heat treatment to the niobium. However, very often processing levels between 15MV/m≤E_{acc}≤22MV/m were encountered when measuring the performance limits of these cavities. These levels do not depend on the final surface treatment prior to the test. It is therefore of great interest to find out whether these processing levels are inherent to the cavity shape or if they are caused by some problems in the surface cleaning procedure or by contamination in the test system. Performing a series of tests with cavities of the same shape from the same material but in a different laboratory setting with different surface treatment procedures should shed some light into the origins of these processing levels. As a second objective a comparison of different fabrication procedures, e.g. electron–beam welding and surface treatments are of interest in optimizing cost and performance for larger scale application. Especially a comparison of cavity performance levels based on electropolishing/heat treatment and buffered chemical polishing, which is exclusively used at JLab for surface treatment of niobium, should result from this test series.

Results and Discussion

I). Cavity Performance Tests

In the following the results of the performance tests on each of these four cavities will be discussed as obtained prior to this workshop. Some cavities will need additional tests after the workshop in order to fully explore the performance limitations. All cavities received a standard surface treatment prior to the cryogenic test: degreasing in a detergent with ultrasonic agitation, water rinsing, buffered chemical polishing in a 1:1:1 solution of $HF/HN_3/H_3PO_4$, high pressure ultrapure water rinsing for ≤ 60 min, threefold rinsing with reagent grade methanol in a class 100 clean room and assembly of coupling and pumping ports. Subsequently the cavity is attached to the test stand, pre-evacuated by a turbomolecular pump for ≤ 30 min and then the cavity is permanently pumped by a 20 l ion pump even at helium temperature. Usually the cavities are cooled down to 4.2 K within 30 min and most of the performance tests (Q_0 vs E_{acc}) is done at 2 K.

Cavity K - 15

For the first test of this cavity a surface layer of 150 μm was immediately removed. The cavity quenched at a gradient of E_{acc}=9.5MV/m. Subsequently the equatorial weld was mechanically ground and the cavity was tumbled for 48 hrs, followed by a chemical removal of 60 μm of material prior to test #2. In this test a severe barrier between 8 MV/m ≤ E_{acc} ≤ 9 MV/m with the signature of a thermal limitation was encountered (see figure 1). An inspection of the cavity interior after warm-up revealed a 3 mm long crack near the equatorial weld. After grinding this defect and an additional chemical material removal of 50 μm of niobium the cavity quenched at E_{acc}=13.5MV/m in the subsequent experiment. Obviously this cavity is a candidate for further investigations of the electron beam weld and application of further treatments such as barrel polishing to find the final performance limitations.

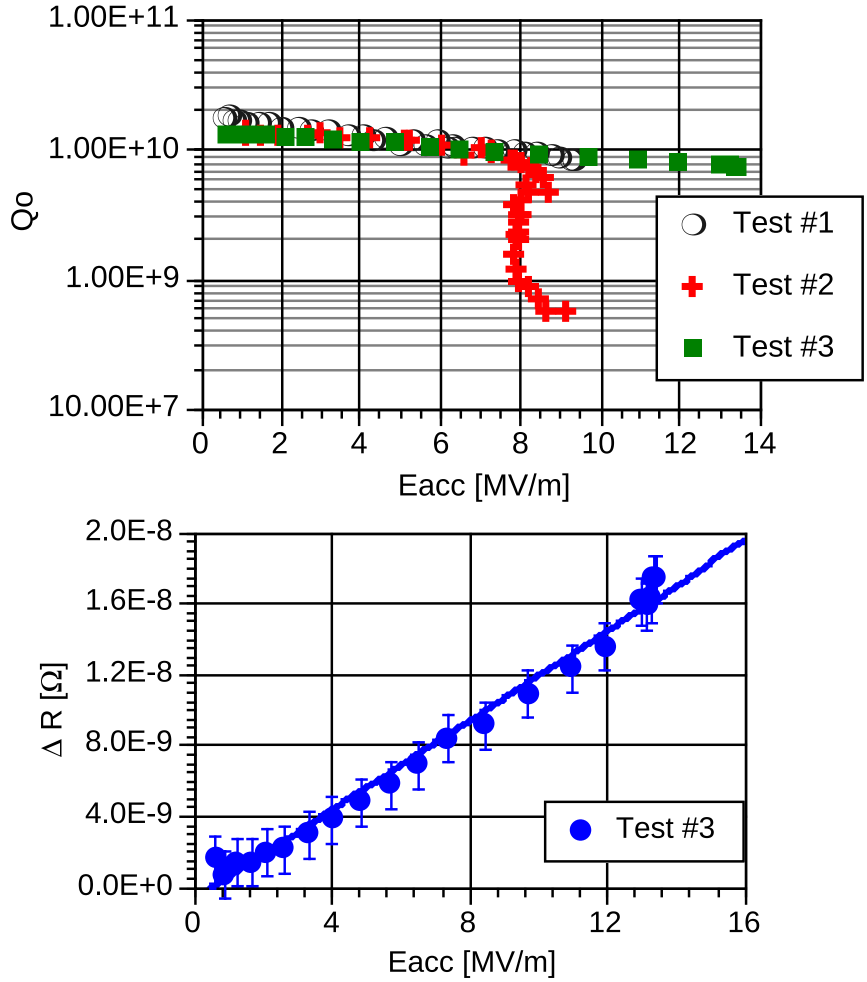

Figure 1: Performance of cavity K–15; the slope in Q_0 vs E_{acc} in test #3 is caused by an additional resistance ~E_{acc}.

Cavity K - 16

This cavity received a barrel polishing treatment[2] at KEK resulting in a material removal of 40 µm. No heat treatment followed prior to the first cryogenic test at JLab. This cavity suffered from extreme Q - disease after a chemical polishing of ≈ 130 µm even with a fast cooldown through the dangerous temperature region of 70K≤T≤130 K for hydrogen precipitation (see figure 2)[3]. A possible cause for the obvious large amounts of hydrogen pick-up by the niobium could be the continuous destruction of the protective natural oxide layer against hydrogen diffusion during the barrel polishing process. One could also speculate that the niobium surface gets highly sensitized during the barrel polishing process and during the subsequent chemical polishing large amounts of hydrogen are dissolved in the material.

After a hydrogen degassing at 900°C the Q-degradation was eliminated. From the measured temperature dependence of the Q–value a residual surface resistance of R_{res}=2.2 nΩ was deduced and an accelerating gradient of E_{acc}=25MV/m was measured at 2 K, limited by field emission, which started around E_{acc}=20MV/m.

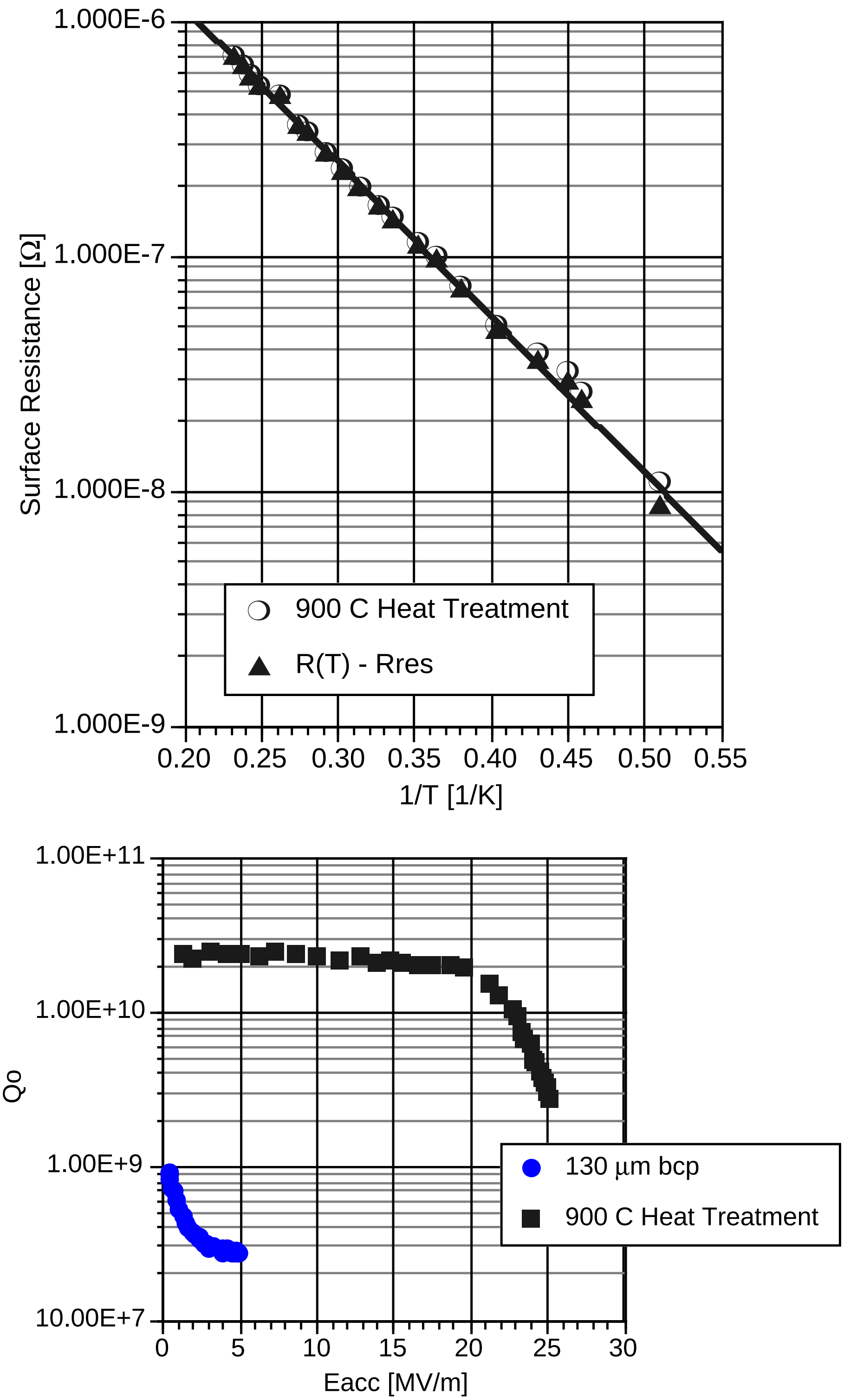

Figure 2: Performance of cavity K–16 . Strong Q-disease was seen immediately after barrel polishing and chemical treatment. After hydrogen degassing at 900° C a residual resistance of R_{res}=2.2 nΩ was achieved and gradients up to E_{acc}=25MV/m were measured.

Cavity K-17

This cavity was used to reconfirm the rather significant dependence of achievable gradients on the amount of material removal as has been seen previously[4]. In a series of six successive tests material up to 180 µm was sequentially removed in small amounts and the cavity performance was measured as shown in figure 3. This experiment again showed the benefit of “deeper chemistry” and confirms a picture of a surface damage layer, which becomes depleted of defects as more and more of it is removed. Obviously the quality of the electron beam weld has to be excellent and the weld has to be free of “flaws”.

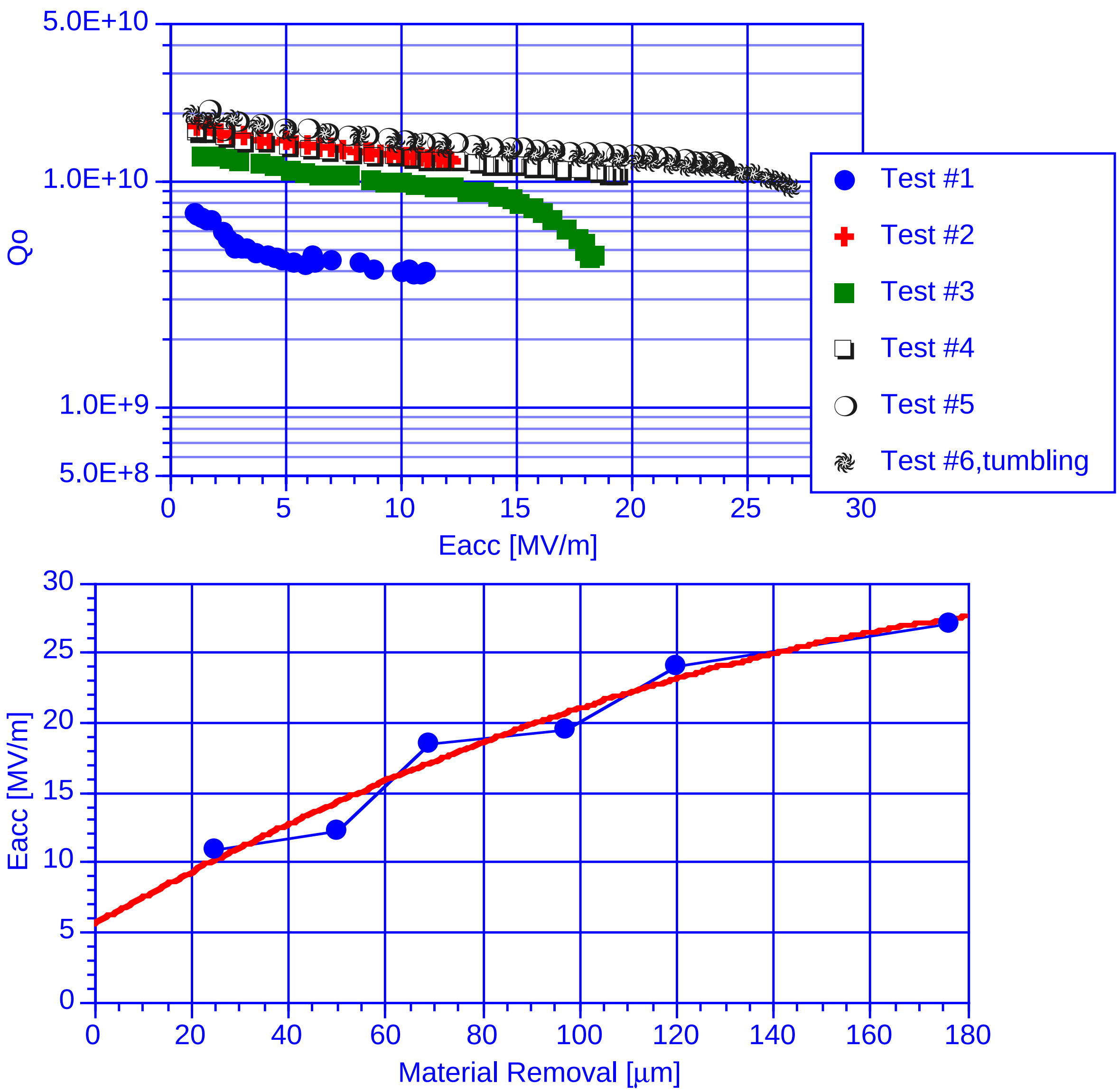

Figure 3: Dependence of achievable gradient on amount of material removal, measured on cavity K–17.

Cavity JL-1

This cavity had shown excellent results as reported previously[4], but after subsequent chemical treatment had degraded in performance. A further removal of ≈ 30 µm of material did not improve the cavity quench field of E_{acc}=27MV/m. There was no electron loading, however the Q-value degraded above E_{acc}>25MV/m as shown in figure 4. Similar observations were reported in[5,6], but the reasons for the degradation is not yet known. To further investigate the quench limitation, Q_0 vs E_{acc} was measured at different temperatures and the slope in $Q_0(E_{acc})$ was analyzed in terms of an additional resistance $\Delta R = R(H=0)[1 + \Upsilon^*(H/H_c)^2]$ with a critical field $H_c \approx$ 2200 Oe for niobium and Υ^* being a measure of the heat transfer from the niobium surface to the helium bath[7]. As can be seen in figure 4 there is a strong increase in Υ^* just above T_λ (from $\Upsilon^* \approx 2.5$ to 12) pointing towards a heat transfer difficulty of the defect responsible for the quench[7]. Further investigations including the use of temperature mapping are needed to understand the performance degradation of this cavity.

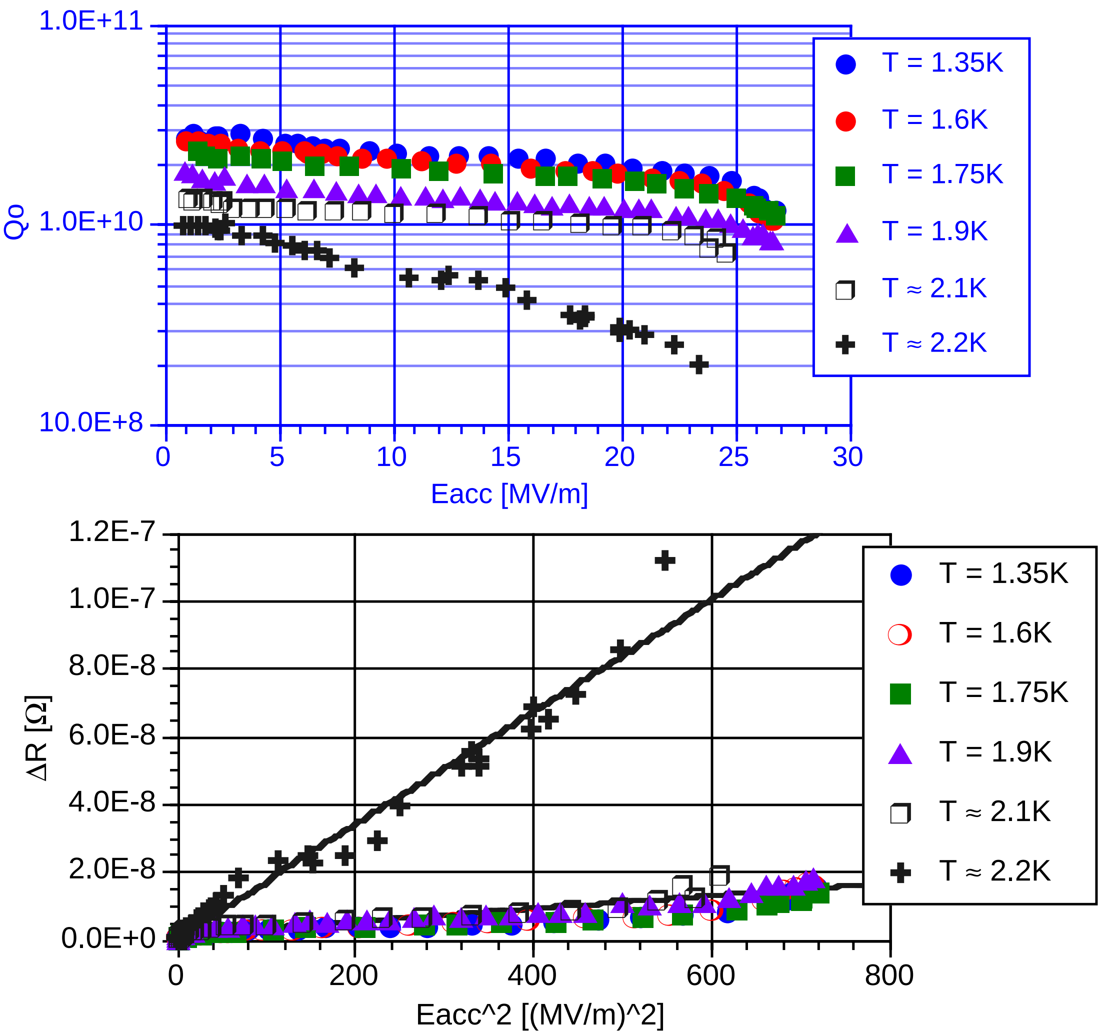

Figure 4: Results from tests on cavity JL–1. The slope in Q_0 vs E_{acc} is caused by an additional resistance $\Delta R \sim E_{acc}^2$. The change in slope around T_λ points to a heat transfer problem at the defect.

II). Electron Loading

During the tests discussed above in a few occasions very "transient" electron loading was seen when increasing the field levels in the cavities. In preparation for test #7 with cavity K–17 the interior was rinsed with oil contaminated acetone in order to enhance the secondary electron emission coefficient of the surface and to provoke multipacting. The results of this experiment are as following: with a sensitive detector transient radiation was detected at field levels around $E_{acc} \approx 13$ MV/m, 17 MV/m and 25 MV/m; no significant "barriers" were seen however, which would show up as a degradation in Q_0 (E_{acc}). Some small deviations could be detected in the dissipated power as a function of E_{acc}^2.

Computer simulation calculations have subsequently been carried out at INFN Genoa by one of us (R. Parodi). The calculations are based on a "crude" model for the kinematic conditions for resonant electron trajectories at the cavity equator ("2-point magnetic multipacting")[8]. This model roughly predicts 2-point multipacting at the highest gradient, at which loading was seen experimentally ($E_{acc} \approx 25$ MV/m). A secondary electron yield as shown in figure 5 was used for the simulations applying the INFN "in-house" TWTRAJ–code.

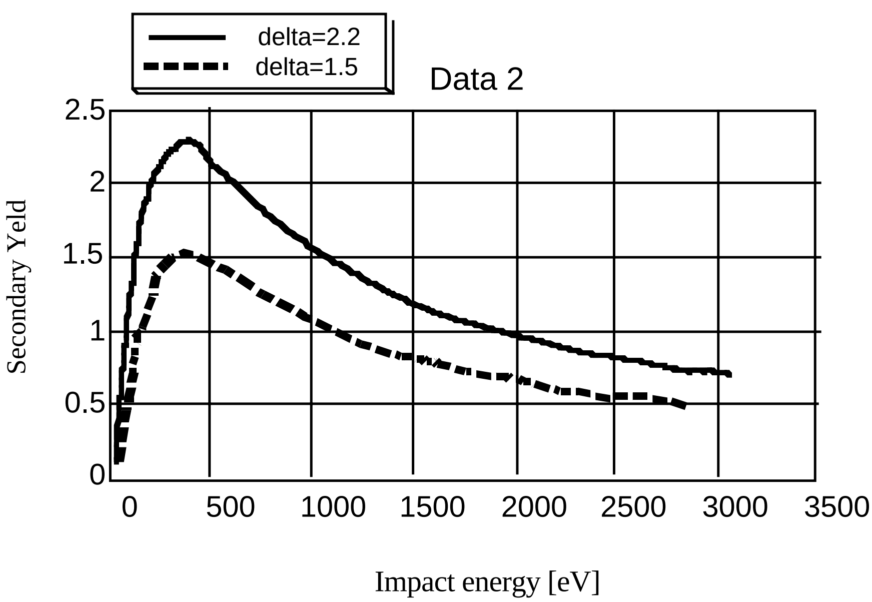

Figure 5: Secondary electron yield vs electron impact energy[9] used for the simulation calculations.

Electrons starting near the equator with a starting energy of 2 eV are confined in this region at a field of 1100 Gauss–corresponding to accelerating gradients ≈ 25 MV/m–and return back to the surface after a mean flight time of half an rf period with strong multiplication–the footprint of multipacting. The impact energies of the returning electrons are always < 300 eV, at which value the secondary electron yield δ has its maximum. Because of the steep decrease in δ for $E_{imp} \leq E_{max}$, the process is very sensitive to the surface conditions. The results of a simulation, which took into account only the true secondary electrons, is shown in figure 6.

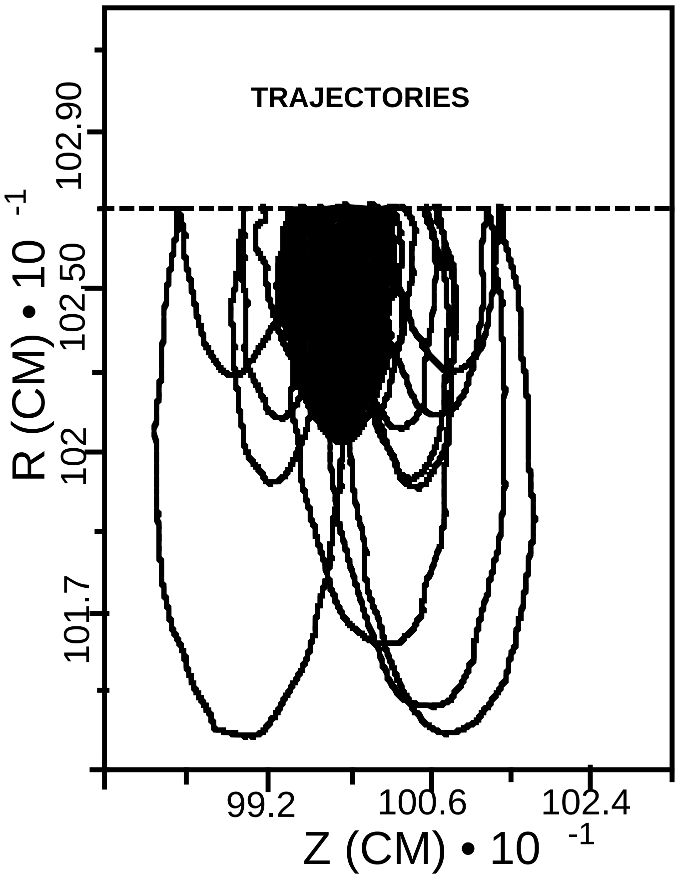

Figure 6: 2–point multipacting at E_{acc}≈25MV/m, corresponding to a peak magnetic field of H_{peak}≈1100 Gauss at the equator of the cavity.

A more realistic simulation using an angular distribution of secondary electrons and re–emissions of backscattered and elastically scattered electrons suppressed the electron multiplication process somewhat, but the effect of the magnetic field is strong enough to focus the electrons at the equator with sufficient multiplication to sustain multipacting even when the fields are swept between 1000 Gauss and 1200 Gauss. For the observed multipacting level at E_{acc}≈ 13 MV/m the kinematic conditions for 1–point multipacting at the equator are satisfied. Even though the rounded cross section of the cavity should prevent this type of loading[10], the electrons still gain enough energy (100 – 200 eV) to generate secondaries (δ >1) to sustain a multiplication process. However, the process is very sensitive to the secondary electron yield and the re-emission energy and angular distribution of the secondaries. The multipacting level seen at E_{acc}≈17MV/m in the oil–contamination experiment has not yet been explained by trajectory simulations and further calculations are needed.

Summary

In three of the four cavities made from Tokyo–Denkai RRR = 200 niobium gradients E_{acc}>25MV/m have been measured. Cavity K–15 apparently has a problem in the electron beam weld and quenched at lower fields.

Barrel polishing needs to be followed by a hydrogen degassing heat treatment in order to eliminate Q–disease–this was initially seen in cavity K–16. Barrel polishing is a very useful surface preparation process for eliminating some possible problems in electron–beam welds; the electron–beam welding procedures used at JLab are quite successful in this respect.

The processing levels often seen at KEK could be provoked in an experiment, where the secondary electron yield of the niobium surface was intentionally increased by oil contamination. Trajectory calculations identified the experimentally observed levels at $E_{acc} \approx 13$ MV/m and 25 MV/m as 1–point and 2–point multipacting, respectively, taking place in the equator region of the cavity. Both levels are very sensitive to the surface conditions.

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