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A SELECTION OF HIGHER GRADIENT CAVITY EXPERIMENTS

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Abstract

In the two years since the 7th SRF workshop, a variety of cavity tests have been carried out with the objective to reproducibly achieve surface electric rf fields above 40 MV/m with no or only very little electron loading. This paper reports about a collection of tests on single cell and multi-cell cavities, which received standard surface treatments such as buffered chemical polishing and high pressure ultrapure water rinsing, but no heat treatments. Often the cavities were limited by quenches, posting a limit of 700 to 1000 Oersted on achievable peak magnetic fields of high purity niobium of RRR values between 200 and 250. In a seamless single cell cavity fabricated by V. Palmieri of INFN Legnaro by spinning, a very promising gradient of $E_{acc} = 25$ MV/m was measured. In collaboration with CERN, several tests on sputtered niobium prepared at CERN were also carried out, and accelerating gradients up to 25 MV/m were achieved. A single cell cavity, electron beam welded after electrochemical buffing, showed only good performance–$E_p > 50$ MV/m–after the removal of more than 100 μm of material. However, this cavity showed rather heavy Q disease even when cooled down rapidly; the Q degradation could be partially reversed by diffusing the oxygen from an anodized Nb_2O_5 layer into the niobium by heating the cavity *in-situ* at $T = 250^\circ$ C.

Introduction

It is by now well established that advanced surface treatment techniques such as post purification in the presence of titanium at elevated temperatures[1-3] or high peak power processing[4] can significantly improve the performance of superconducting niobium cavities made from high purity material. In addition, diagnostic tools such as temperature mapping in superfluid[5] or subcooled helium are being used successfully in several laboratories to identify the causes of performance limitations in cavities and to establish procedures to prevent their occurrence. Because none of these techniques were available "in house", standard surface treatments as listed below have been applied in the niobium cavity tests reported in this contribution: ultrasonic degreasing with detergent, buffered chemical polishing in a 1:1:1 solution of $HF/HNO_3/H_3PO_4$, high pressure ultrapure water rinsing, clean room assembly after rinsing with reagent grade methanol and the use of "guided" repair and helium processing techniques.

Objectives

The objectives of our investigations reported here can be summarized as following:

a) Main emphasis was placed on reproducibly achieving higher gradients in any type of cavity (multi-cell cavities and single cell cavities of different shapes) by applying the treatments listed above.

b) The limitations of non heat-treated niobium of RRR values around 200 to 250 were explored ("quench" limits) by possibly eliminating electron loading up to these limits.

c) The usually observed slope in Q_0 vs E was analyzed with respect to its dependence on electric field in order to gain some understanding of the underlying physics causing these dependencies.

d) Different surface treatment methods such as electro-chemical buffing[6] or tumbling[7] were explored in collaboration with colleagues from other institutions.

e) Experiments on cavities made from niobium of different manufacturers as well as made from different materials (sputtered niobium, Nb_3Sn) have been carried out and the performance of a seamless cavity fabricated by spinning instead of the usual forming and electron beam welding has been explored.

Below, results from the following tests are reported :

1. Tests on five five-cell production cavities of RRR ≥ 250, which have been fabricated at JLab from spare parts remaining from the cavity production contract ("spare cavities").
2. Tests on single cavities of the Cornell/CEBAF shape (RRR ≥ 250) at 1497 MHz.
3. Tests on single cell cavities of the KEK shape at 1300 MHz made from material of RRR ≈ 200.
4. Tests on a seamless cavity of the CERN-shape manufactured at INFN Legnaro by V. Palmieri (f = 1498 MHz).
5. Tests on a sputtered niobium cavity prepared at CERN.
6. Tests on an Nb_3Sn single cell cavity prepared at the University of Wuppertal.

Experimental Results and Discussion

I). "Spare" five-cell Cavities

After completion of the cavity contract for the 360 production cavities, JLab received a number of spare parts as "leftovers" from the cavity manufacturer, such as coupler subassemblies, beam pipes and braces. From these spare parts and existing cavity half cells made from RRR ≥ 250 niobium, five additional—"spare"—cavities were built, serialized as IA 362, IA 363, IA 365, IA 366 and IA 367.

In order to reach the performance limits of these cavities, they were tested without peripheral parts such as rf windows, HOM couplers or gate valves.

The procedures described in the introduction were applied with some emphasis on deeper material removal, which had shown a beneficial effect on cavity performance in a previous investigation.[8] One of the cavities (IA 362) had been post purified in the UHV furnace at KFK at 1350° C.[9]

Except for this cavity, which was limited by the available rf power at E_{acc} = 19.6 MV/m, all other non heat treated cavities "quenched" at E_{acc} = 17.3 MV/m, 16.5 MV/m, 17.2 MV/m and 10.7 MV/m. The average "useable" gradient defined as the field value at which 1 W of power is dissipated in field emission loading was $E_{acc} \approx 15$ MV/m. All cavities with the exception of the heat treated cavity showed a slope in Q_0 vs E_{acc}. The additional resistance responsible for this slope could in most cases be fitted with a polynomial of 2nd order. It is not clear which mechanism causes this kind of field dependence, b~~ut there is~~ a suspicion that due to the "deeper chemistr~~y" hydrog~~en precipitation ("Q disease") might be involved. As an example, in figure 1 the performances of IA 363 is shown; this result was achieved in the first test after a removal of ≥ 120 μm of material from the surface; however, the final performance limits in the other cavities were reached after one or two additional tests.

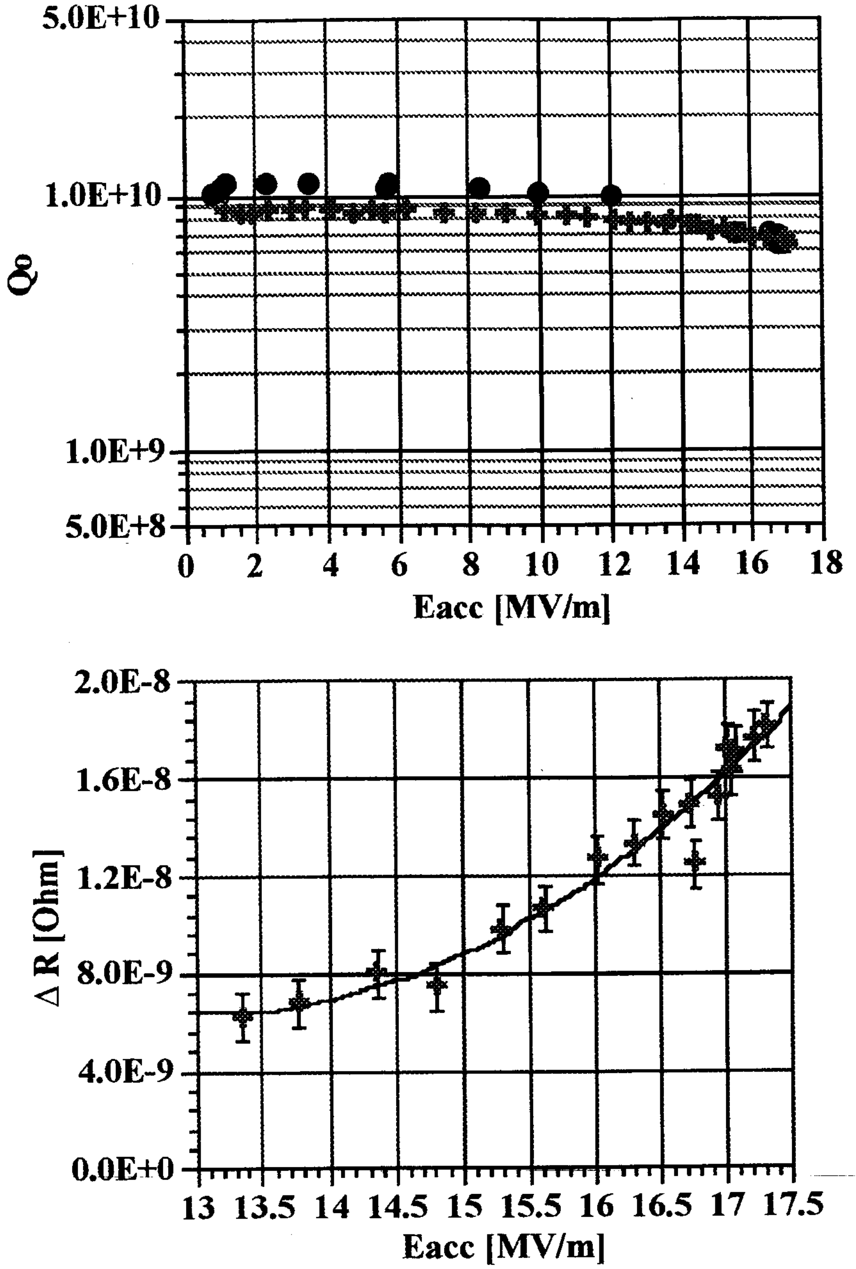


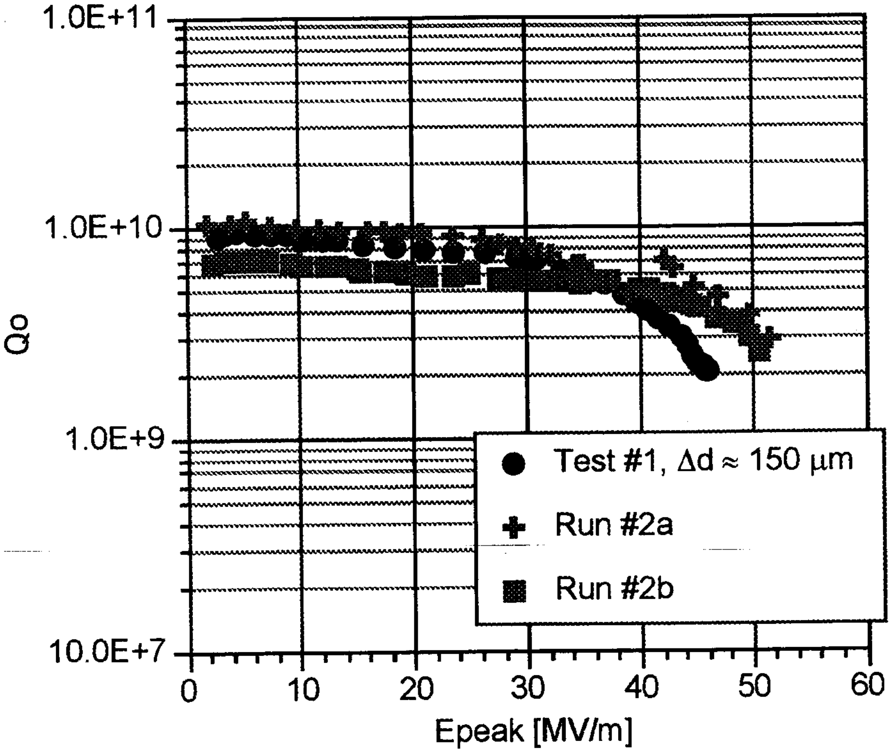
Figure 1 : Performance of "spare" cavity IA 363: Upper part shows Q_0 vs E_{acc} , lower part shows the dependence of Δ R on E_{acc} (polynomial fit of 2nd order)

II). Single Cell Cavity Tests

a) "TESLA Cavity"

Last year the TESLA project had some difficulties with the performance of several nine-cell cavities from one vendor[10]. These cavities exhibited a strong slope in Q_o vs. E_{acc} and quenches at field levels below the specifications.

It was not clear whether these limitations were caused by the material used for the manufacturing of these cavities or by some unexpected flaws during the manufacturing process. A single cell cavity from the same material ("TESLA - cavity") was fabricated at JLab applying standard fabrication and electron beam welding procedures, and several tests were performed with this cavity. Experimental results are shown in figure 2 for two subsequent tests after 150 μm and ≈ 170 μm, respectively, had been removed from the surface. In each test the cavity was limited by a quench. In a subsequent test strong Q degradation was observed after the cavity had been held at a temperature of ≈ 100 K for approximately 12 hours. The experimental results clearly showed that there was no problem with the material, but—as was confirmed by additional experiments at DESY—that poor beam electron welding was the cause of the substandard cavity performance.



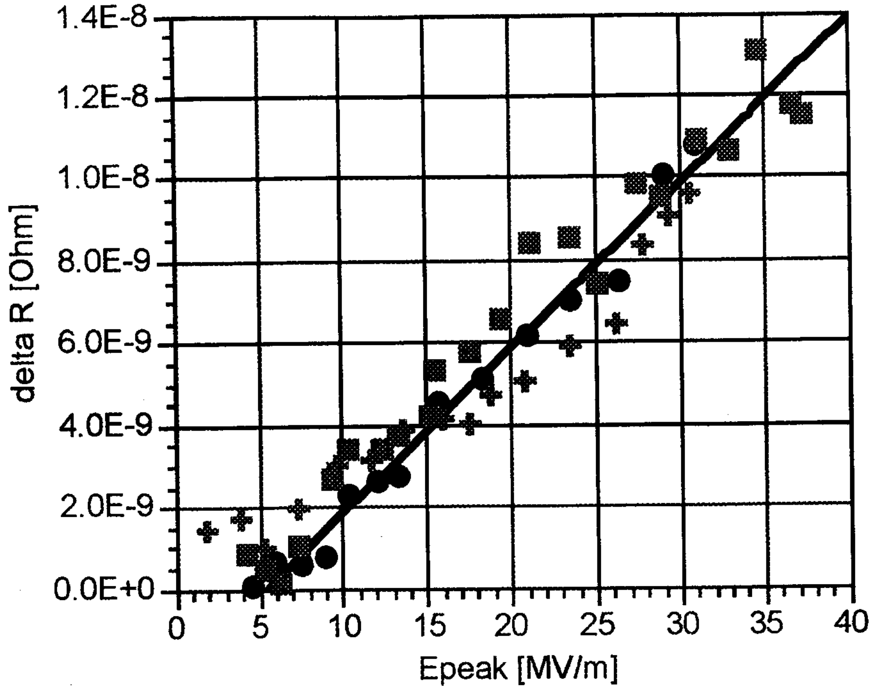


Figure 2: "TESLA Cavity" performance. In test #2a an emitter processed at $E_p \approx 40$ MV/m, lowering the Q value in run 2b. The additional resistance causing the slope in Q_0 vs E_{peak} is linear in E_{peak} as shown in the lower graph.

b) KEK-type Cavities

In collaboration with KEK several single cell 1300 MHz cavities of the KEK type were fabricated and tested. The results of this investigation are reported in a separate paper in these proceedings[11]. Shown in figure 3 as an example are the results of a test series on one of these cavities (K-17), where material was removed in small sequential steps and the change in cavity performance was measured. As has already been shown in a previous investigation, the removal of larger amounts of material from the surface resulted in an improvement of the quench field levels, confirming a picture of a surface damage layer, which becomes depleted of defects as more and more of it is removed.

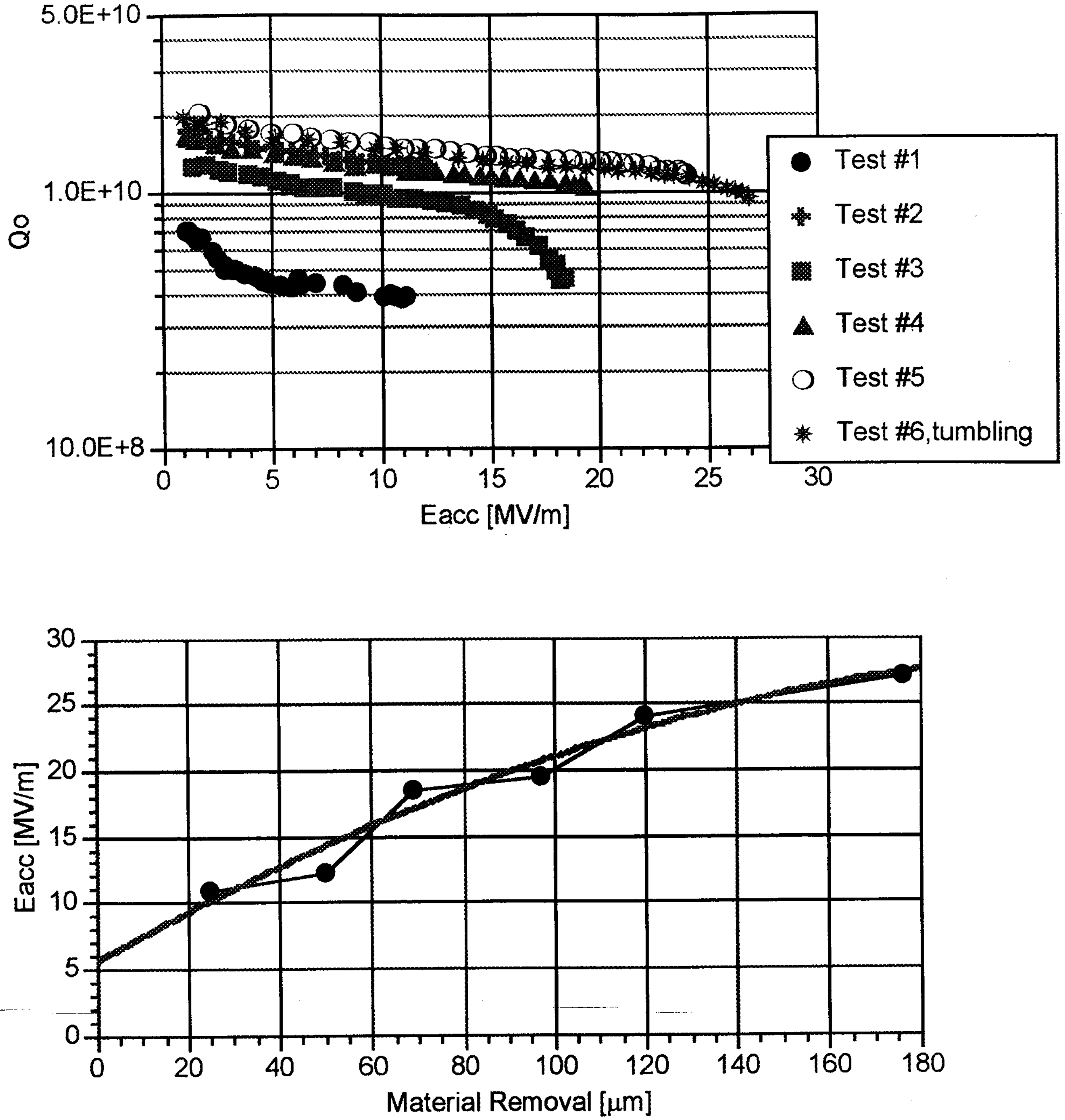
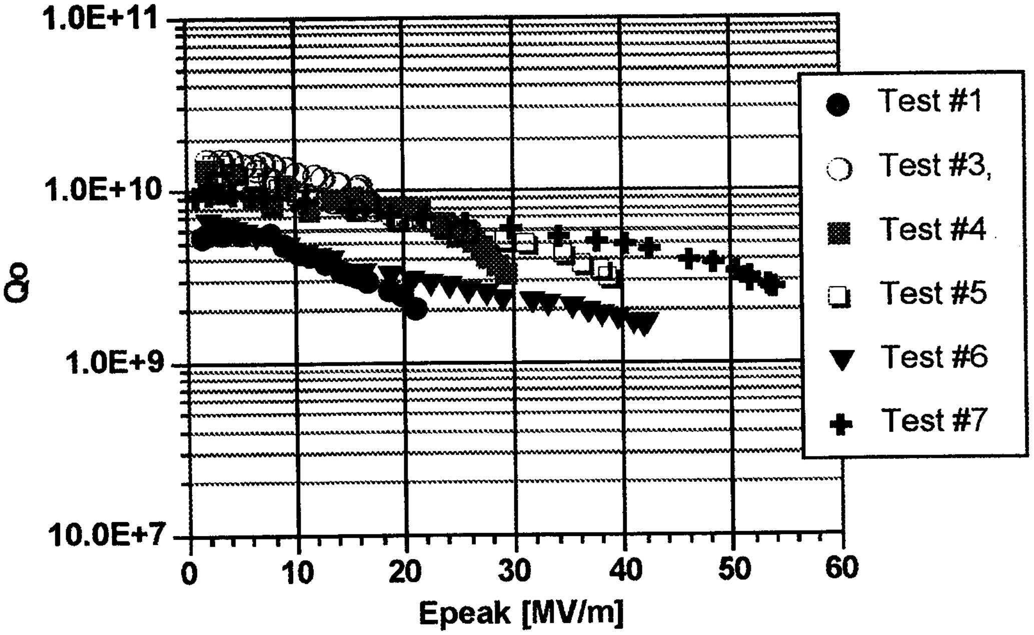


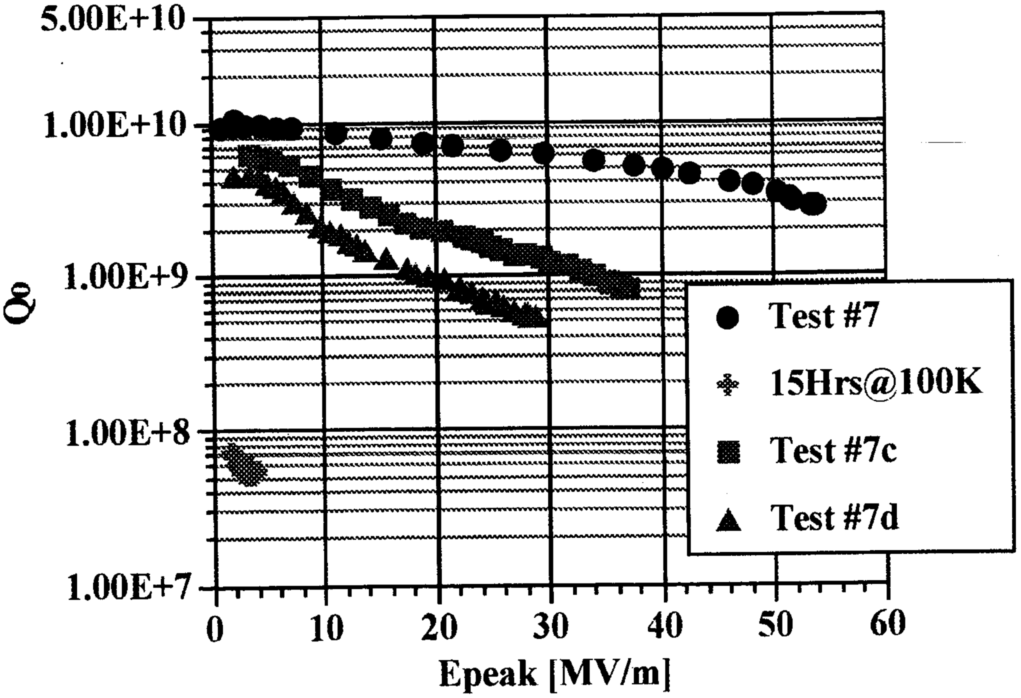
Figure 3: Performance of a 1300 MHz KEK-type single cell cavity (K-17) after subsequent amounts of material were removed from the surface as indicated in the lower graph. In test #6 the cavity was tumbled for 48 hrs prior to buffered chemical polishing.

d) Electro-chemical Buffing

In many cases the performance of superconducting niobium cavities is limited by the onset of non-resonant electron loading, and it has been well established that both artificial contamination and surface protrusions[12] are causes of enhanced field emission. Therefore it is rather trivial to attempt to reduce surface roughness, since a smoother surface seems to have fewer protrusions and in addition has a better chance of being cleaned more appropriately.

Electro-chemical buffing—a proprietary process, in which an abrasive material is simultaneously applied to a surface in an electropolishing setup—has shown excellent results on stainless steel surfaces. We applied this surface treatment method to the cavity half cells of a single cell cavity prior to electron beam welding. Even though the surfaces looked shiny, the cavity did not perform initially very well. Only after the removal of more than 300 μm of material did the quench field reach $E_{peak} \approx$ 54 MV/m (figure 4a). Of course then the effect of the surface smoothening was totally lost. Moreover, this treatment method showed an additional problem: the cavity showed severe Q disease when being held at 100 K for 15 hours as shown in figure 4b. The Q degradation was partially recovered, when an anodized Nb_2O_5 layer was diffused into the niobium *in situ* at 250° C (figure 4c).





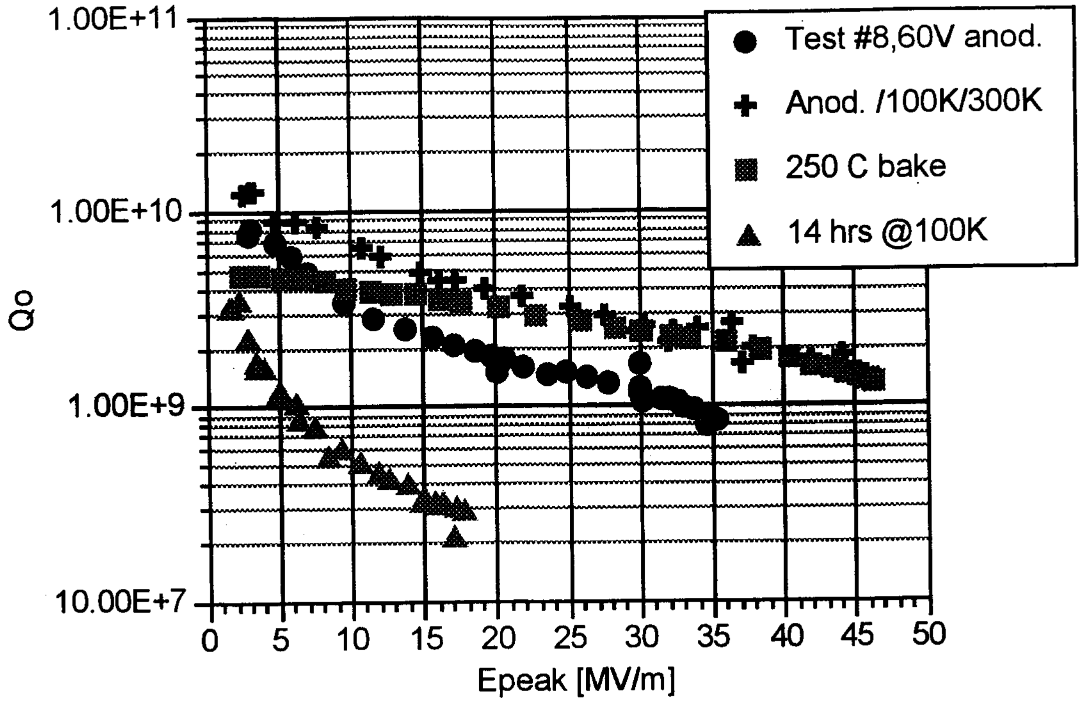


Figure 4: Results from the electro-chemical buffing surface treatment. Up to 300 μm were removed from the surface by buffered chemical polishing (total amounts removed: test #1 - 2μm, test #3 - 48μm, test #4 - 98μm, test #5 - 163 μm, test #6 - 204 μm, test #7 - 300 μm). Q disease is shown in figure 4b, which did not even recover after warm-up to 300 K (tests 7c,7d). Figure 4c indicates some improvements in Q degradation after diffusion of oxygen into the surface layer.

e). Seamless Cavity ("Palmieri - Cavity")

A seamless cavity of the CERN - shape , which was fabricated at INFN Legnaro by V. Palmieri by spinning, was received through CERN (I. Campisi) with a sputtered niobium layer on the surface. This cavity had been heat treated at CERN at ~1000° C[13]. Upon receipt the sputtered niobium layer was removed, approximately an additional 20 μm were chemically etched, and after high pressure rinsing the cavity was tested. It showed the remarkable performance as plotted in figure 5 with a quench field of E_{acc} = 22 MV/m. In a subsequent test, after some mechanical grinding of rough areas inside the cavity and an additional 40 μm of material removal, the gradient even improved to $E_{acc} \approx 25$ MV/m; no quench was observed because of a limit on the available rf power: the exponential (or E_{acc}^8) decrease in Q value without the presence of electron loading reduced the fixed coupling so much that much of the forward rf power was reflected at the cavity. The lower Q value in test #2 might be caused by insufficient removal of the damage layer introduced by the mechanical grinding.

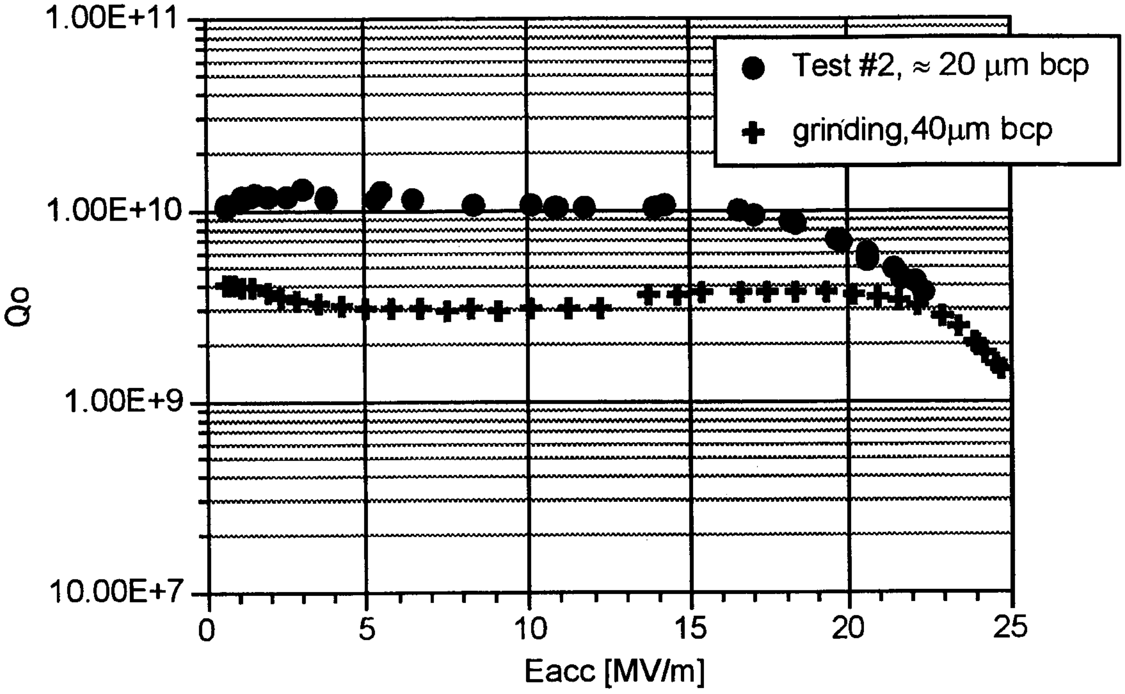


Figure 5: Performance of a seamless cavity fabricated by spinning, after heat treatment at 1000° C at CERN. The decrease in Q_0 at high gradients (without observation of electron loading) is not clear.

III). Sputtered Niobium

In collaboration with CERN a sputtered niobium cavity prepared at CERN[14] was tested several times at JLab after only high pressure ultrapure water rinsing at different pressures was applied. The best performances are shown in figure 6: a nearly field independent Q value up to $E_{acc} \geq 12$ MV/m both at 4.2 K and 2 K in the second cooldown after a 50 bar high pressure rinsing and a gradient of E_{acc} = 24 MV/m after a new cleaning at 80 bar. However, there is still a very strong slope in Q at gradients > 12 MV/m and the additional resistance is proportionally to approximately E_{acc}^4. Surprisingly, in several cases the cavity quenched; the quenches seemed to be triggered by processing events at higher fields. As a result the Q vs. E had degraded as shown in figure 6, but nearly recovered after warm-up to 100 K as indicated in run 3c. Most likely the quenches generated thermo-currents, which in turn led to trapping of magnetic flux and an additional loss associated with it.

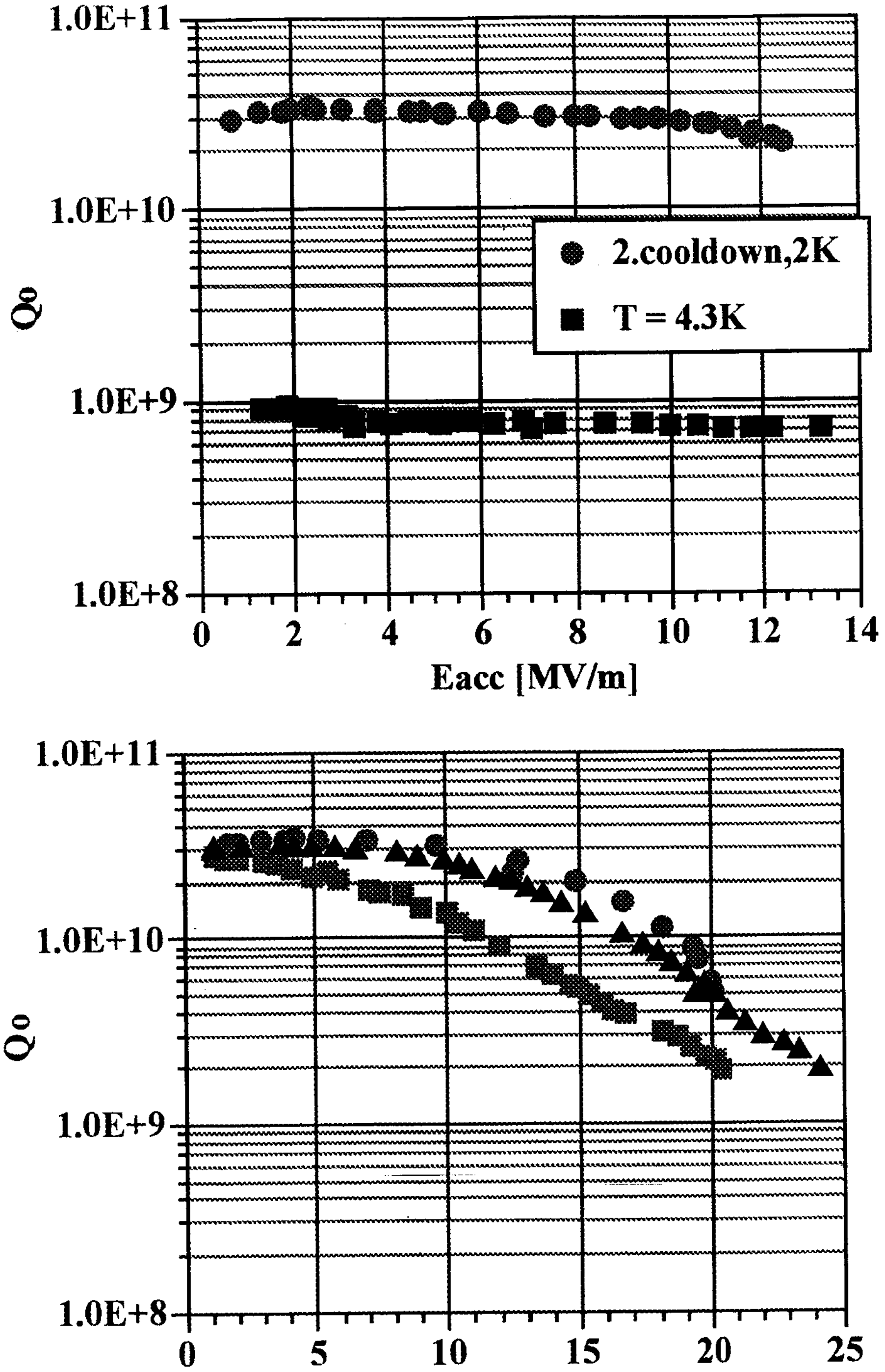


Figure 6: Performance of a sputtered niobium cavity prepared at CERN and tested at JLab after high pressure rinsing. Test 3b is after some quenches occurred in the cavity at higher gradients; test 3c was obtained after warm up to 100 K.

IV). Nb3Sn

Some experiments were conducted with Nb_3Sn cavities with the main purpose to learn through the use of temperature mapping in subcooled helium more about the Q_0 vs E dependence of this material. The results of these investigations are summarized in a separate paper in these proceedings[15]. In the course of this investigation a new cavity was prepared at the University of Wuppertal, which after several cleaning steps with high pressure water resulted in the performance shown in figure 7: at 4.2 K and at 2 K peak surface electric fields of $E_{peak} \approx 32$ MV/m with very little field emission were measured and the limitation was due to availability of more rf power. As in the case of sputtered niobium and to a lesser extent the seamless cavity performance a strong—exponential or E^n with $n > 4$—dependence of the additional resistance on electric field was found. One might speculate that these strong field dependences might be caused by a presently unknown fundamental loss mechanism common to these materials.

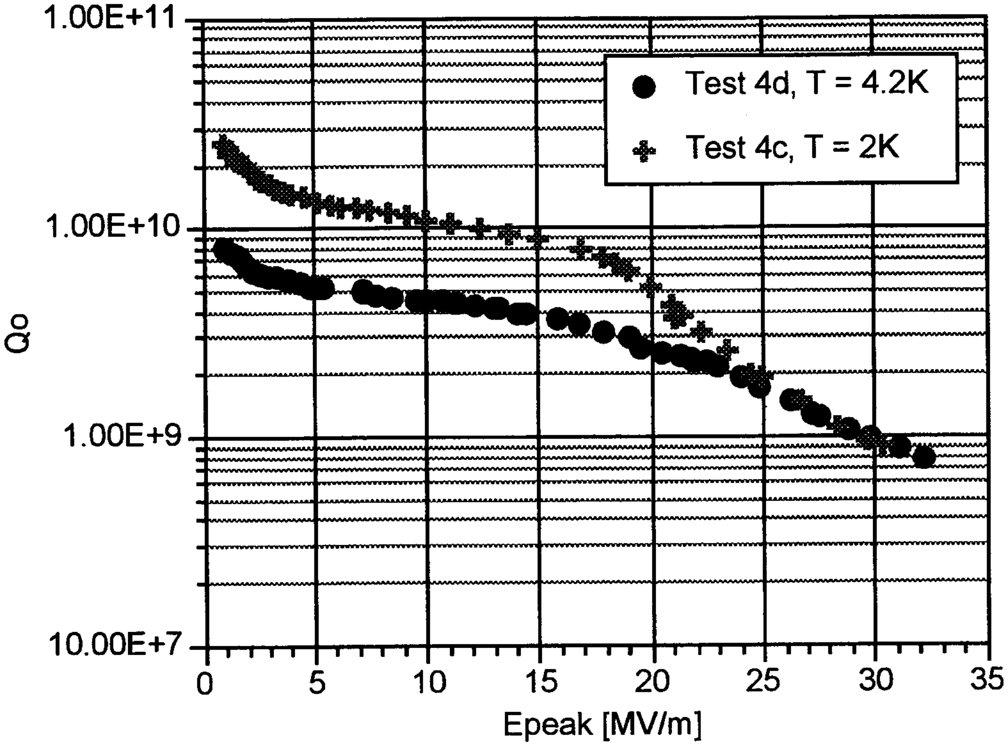


Figure 7: Q_0 vs E_{peak} for the best Nb_3Sn cavity prepared at the University of Wuppertal by the vapor diffusion process.

Observations

From the variety of the experiments conducted with the various types of cavities and different materials the observations can be summarized as following:

a) The application of standard treatment and fabrication methods resulted in reasonable reproducibility of cavity performance: in single cell cavities surface electric fields of $E_p \geq 40$ MV/m and in five-cell cavities $E_p \geq 35$ MV/m can often be achieved with no or only modest electron loading.

b) In non heat-treated cavities made from niobium of RRR values ≤ 250 magnetic breakdown often occurs at peak magnetic fields of 700 Oe ≤ Hp ≤ 1000 Oe. However, temperature mapping would be necessary to determine whether these quenches were caused by defects in the material or in electron beam welds.

c) Usually a slope in Q_0 vs E was observed, which often showed a linear dependence of the additional resistance on field. Such a dependence has also been seen in cavities with severe Q disease and was interpreted as the result of "weak links" in the Nb/NbH system. Therefore the slope in these tests might be an indication that even during fast cavity cooldown hydrogen precipitation is occurring.

d) The removal of >120 μm of material from the surface has a rather beneficial effect on cavity performance and higher gradients can be achieved compared to smaller amounts of material removal. However, there are some indications that too much material removal by bcp can degrade cavity performance, possibly due to grain boundary etching.

e) The seamless single cell cavity fabricated at INFN Legnaro by V. Palmieri by spinning showed a very encouraging gradient of $E_{acc} \approx 25$ MV/m, indicating that this fabrication method is highly desirable for inexpensive cavity fabrication. This cavity showed at high fields a non- understood Q degradation of an exponential (or E^8) nature without the observation of electron loading. More experiments are needed to understand this phenomenon and to establish the reproducibility of such high performing seamless cavities.

f) Much progress has been made at CERN in understanding and improving sputtered niobium layers. In the experiments with a Nb/Cu cavity prepared at CERN and tested at Jlab after high pressure rinsing, gradients up to $E_{acc} \approx 24$ MV/m have been measured. There is still a slope in Q_0 vs E_{acc} at higher gradients but a nearly field independent Q value up to $E_{acc} \approx 12$ MV/m was measured.

g) With Nb_3Sn layers high Q values can be obtained at 4.2 K; Q_0 shows a strong non-linear dependence on electric field, which at higher gradients limits the use of this material because of the high cryogenic losses. However, high electric field up to $E_p = 32$ MV/m have been obtained after high pressure water rinsing. For gradients $E_{acc} \leq 8$ MV/m ($E_p \leq 20$ MV/m) Nb_3Sn might very well be an alternative to niobium for operation at 4.2 K as opposed to 2 K, if the same performance levels as in single cell cavities can be reproduced in multi-cells.

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References

1. H. Safa; these proceedings
2. M. Pekeler; these proceedings
3. K. Saito; these proceedings
4. J. Graber et al.; Nucl. Instr. & Meth. A350, 572(1994)
5. J. Knobloch, Thesis Cornell University (1997)
6. Y. Baba, Ultra Finish Technology Comp., 4-1 Mizue-cho, Kawasaki-ku, Kanagawa Pref. 210, Japan,

   H. Kitamura, Y. Kojima et al.; these proceedings
7. T. Higuchi, K. Saito et al.; Proc. 7th Workshop on RF Supercond., p.723 Saclay 1995
8. P. Kneisel; Part. Acc. 53, p. 97 ff (1996)
9. Heat treatment was done by H. Baumgaertner, KFK Karlsruhe
10. M. Pekeler; Proc. 1997 Part. Acc. Conf. (Vancouver 1997), to be published
11. P.Kneisel, K.Saito, R.Parodi; these proceedings

12. T. Habermann; these proceedings
13. C. Benvenuti et al.; these proceedings
14. S. Caletroni; these proceedings
15. P. Boccard et al.; these proceedings