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QUEST FOR HIGH GRADIENTS

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This paper gives an overview of recent investigations on performance limitations of superconducting cavities. Great progress has been made in inventing cures by better cavity materials and handling processes. The newest and most important processing tools and recent cavity results are described and discussed.

Keywords: Superconducting cavities

1 INTRODUCTION

Superconducting cavities are used in many accelerator machines like storage rings at CERN,[1] DESY[2] and KEK[3] and at electron linacs at HEPL,[4] Frascati,[5] Darmstadt[6] and CEBAF.[7] The operating experience with hundreds of multicell structures has proved that the sc cavity technology is reliable. The benefits like less power consumption, higher gradients and less beam-cavity-interaction are demonstrated. The actual operating gradients are still far from the thermo-dynamic limit. In light of the great progress made in the last years this technology is promising for future applications.

Especially for the Te V Superconducting Linear Accelerator TESLA[8] project there is a demand for high gradient multicell cavities. The accelerating gradient achieved in accelerators today of E_{acc} = 5 to 10 MV/m has to be improved to E_{acc} = 15 MV/m for the Tesla Test Facility TTF[9] and to E_{acc} = 25 MV/m for TESLA. Several very good reviews about the physics and technology of sc cavities have been published in the last years.[10–16] Therefore I will concentrate here only on the latest and promising investigations, developments and test results. In particular I will describe the newest methods to fight the main limitations of the accelerating gradient of sc cavities as thermal breakdown (quench) and field emission (FE).

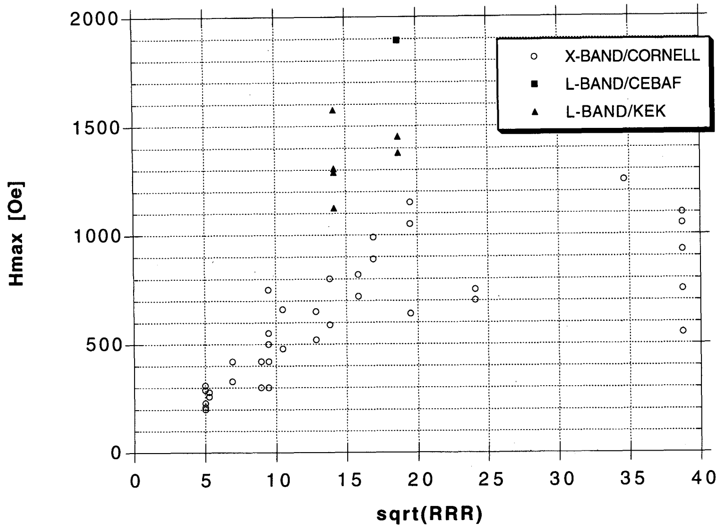

FIGURE 1 The achieved magnetic field plotted as function of the square root of RRR. Measurements on 1-cell X-band cavities from Cornell (1985) are compared with recent 1-cell L-band cavity results from KEK and CEBAF. A description of this figure is given in the text.

2 LIMITATIONS

2.1 Quench

In order to stabilise a thermal breakdown (which is caused by heating of a local defect above the critical temperature due to RF power dissipation) the thermal conductivity of the niobium material was improved over the last years. The purity of niobium sheet material (as measured by the Residual Resistivity Ratio RRR) available from industry increased from RRR = 50 fifteen years ago to better than RRR = 300 today. Further improvement of the RRR by a factor of 2 can be done by solid state gettering (for instance Ti heat treatment). Measurements at different laboratories gave clear evidence that an improved RRR leads to higher quench fields. Figure 1 shows measurements on X-band cavities done in 1985 at Cornell.[17] The maximum magnetic field (H_{max}) established in the cavity has a linear dependence on the square root of the RRR. Above RRR of approx. 400 the H_{max} seems to be independent from RRR. The benefit of Ti heat treatment (HT) has been demonstrated several times: Cornell,[17] Saclay[18] and CEBAF.[19] Two examples are shown in Figures 2 and 3. On the contrary newer test results from KEK[20]

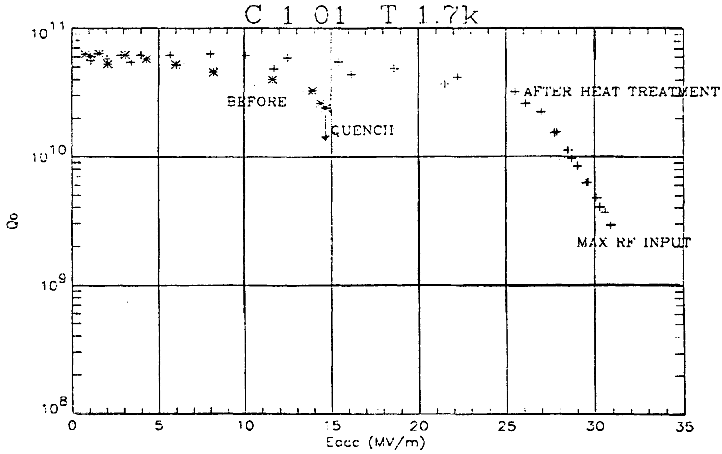

FIGURE 2 Q vs. E_{acc} performance of a 1-cell cavity from Saclay before and after Ti heat treatment at 1400°C. The RRR is improved from 250 to about 1000. The quench before HT was a defect on the equator weld. It was cured by HT.

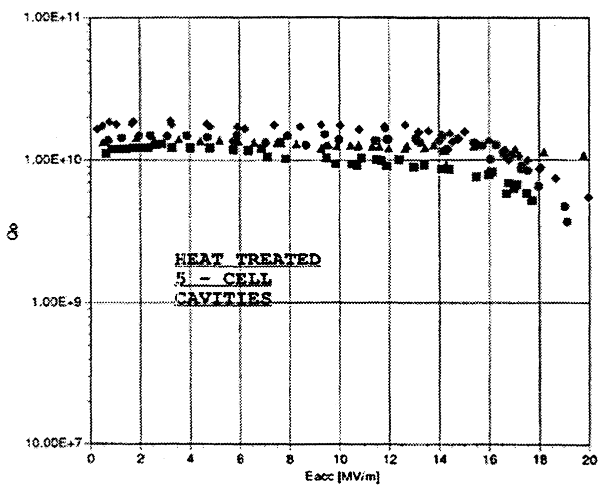

FIGURE 3 Q vs. E plots of CEBAF 5-cell cavities after HT (1400°C), with Ti (inside and outside of the cavity) and HPWR. All cavities are limited by quench. The CEBAF average quench performance of 336 cavities is 15 MV/m without heat treatment.[30]

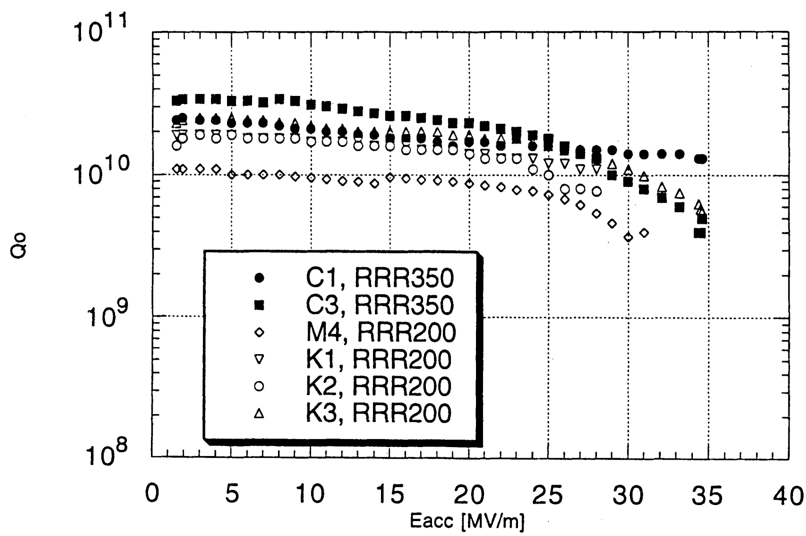

FIGURE 4 Q vs. E_{acc} plots of 6 single cell cavities from KEK made out of RRR 200 and RRR 350 niobium. C3, M4, K2 and K3 were heated at 760°C for hydrogen outgasing. C1 and K1 were heated at 1400°C with Ti from outside without improvement of RRR. All cavities were HPW rinsed. The fields were limited by quench.

demonstrate high gradients of E_{acc} = 25 to 35 MV/m for material of RRR 200 and 350 (see Figure 4). The best value of E_{acc} = 43 MV/m could be reached with a single cell cavity made from RRR 200 material (see Figure 5).[21] Furthermore, latest measurements of RRR 1000 cavities showed not very high quench thresholds: E_{acc} = 18 MV/m and 25 MV/m.[22]

2.2 Field Emission

Physic's nature of field emission (FE) is described for example in Ref. 11. The most important information from all FE studies of the last years is that field emission is most likely caused by particles on the surface, especially from those of conducting surfaces. Geometric irregularities like scratches and holes are also possible field emitters. It is most important for the FE behaviour that the material surface has to be clean and defect free. The effort of clean surface preparation by using class 10 clean rooms and ultra pure water led to a substantial gain in FE suppression.

In order to gain a field level above 20 MV/m three new methods have been developed:

1. Heat Treatment (HT) at 1400°C can render a FE free surface.[23,24]
2. High Pressure Water Rinse (HPWR) is a very promising technique to get a clean surface. Recent test results on 1-cell structures show no FE up to the quench limit at $E_{acc} > 30$ MV/m (see Figures 4 and 5).
3. High Power Processing (HPP)[25] raises the electric field at a possible emitter and melts or evaporates it by the high FE current. The pulse must be short enough to prevent a quench at the cavity. Afterwards 50% of the pulsed HPP field level can be excited under cw conditions without FE loading.[26] Figure 6 shows a curve before and after HPP.

The conditions for HPP at Cornell and DESY for example are: power = 100 kW ... 2 MW, pulse length = 10 μs to 2 ms, the Q_{ext} must be low ($\sim 10^6$) to allow a fast field raise in the cavity. Sometimes the improvement of FE behaviour is accompanied by a reduction of the low field Q_0. After a warm up — cool down cycle the Q_0 usually recovers (Figure 6). At Saclay it could be shown on samples that the electric field can overcome the adherence force and push the emitting particle away. The aim is to establish high electric fields in a very short time (less or equal 10 μsec). Under those conditions much less craters or melting points are developed.[18]

3 NB$_3$SN

Several years ago there were already attempts to use Nb$_3$SN cavities because of the great potential of the theoretical field limit of $E_{acc} = 88$ MV/m. The improved thermal conductivity of niobium as well as the better understanding of the surface deposition techniques induced Wuppertal University and CEBAF[27] to start a new R & D programme. Two single cell cavities have been Nb$_3$SN coated and show very promising results (see Figure 7). The CEBAF design values could be reached with Nb$_3$SN cavities at a cooling temperature of 4.5 K (CEBAF operates at 2 K).

4 FIRST MEASUREMENT RESULTS FROM THE TTF CAVITIES

In order to demonstrate the feasibility of a linear collider the TESLA collaboration started to build the TTF at DESY, using 9-cell SRF cavities

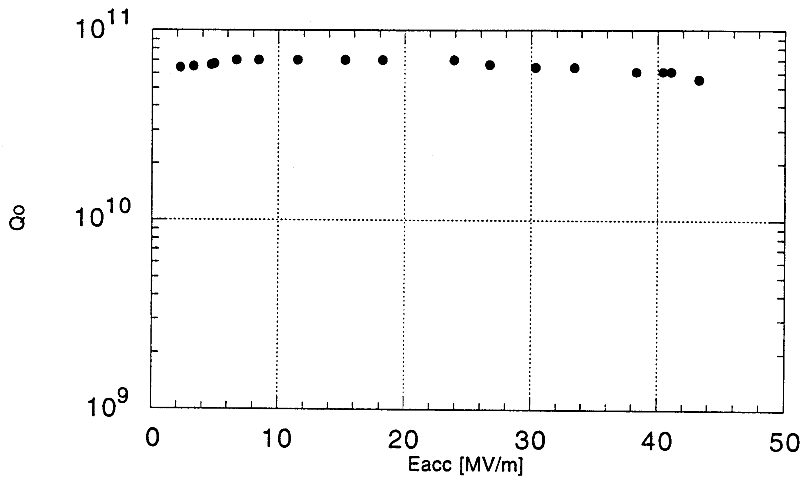

FIGURE 5 World record for E_{acc} (limited by quench), measured at a 1-cell cavity after HPWR (RRR = 200, 1.3 GHz, 1.6 K, CEBAF-KEK collaboration).

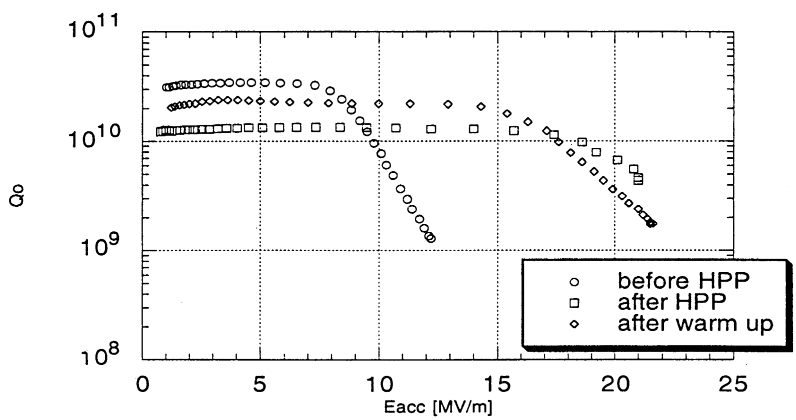

FIGURE 6 TTF type 9-cell cavity without HOM couplers before and after HPP. The Q_0 recovered partially after warm up to room temperature.

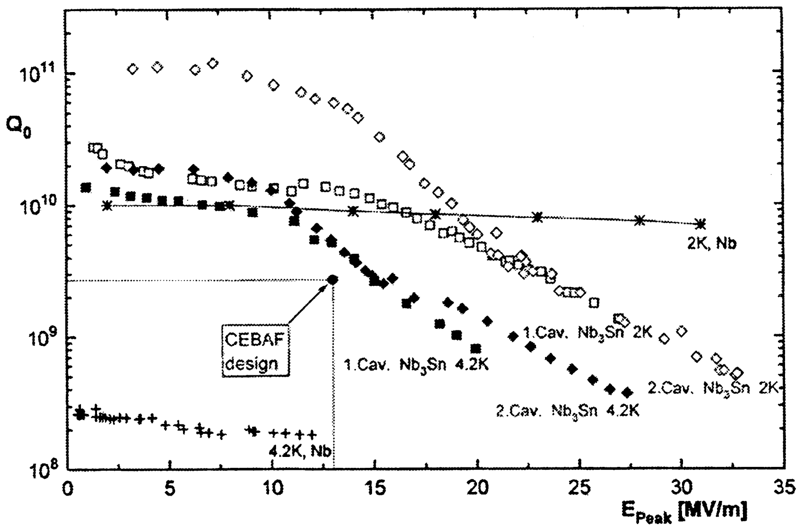

FIGURE 7 Q vs. E_{peak} of the first two Nb3SN-coated 1.5 GHz single-cell cavites in comparison to pure Nb at 4.2 K and 2 K from CEBAF.

at a frequency of 1.3 GHz manufactured out of RRR 300 Nb material. The most advanced methods are chosen to prepare the cavities for high gradients: The class 100 cleanroom is equipped with a closed loop, automatic chemistry, a HPWR (100 bar) and a furnace for Ti heat treatment up to 1400°C. There are class 10 areas for cavity assembling. A high power klystron (5 MW, 10 ... 2000 μs pulse length) and test stands with high power couplers are available for HPP. Figure 8 shows the Q vs. E curve for the first production cavity with HOM couplers assembled in the vertical test. Since the operation in the linac is pulsed the cavity is also measured under pulse conditions. In Figure 9 an oscilloscope trace of the field monitor probe and the power delivered to the cavity is shown. After a rise time of 500 μs the cavity field reaches 26 MV/m ($Q_{ext} = 3 \times 10^6$, as planned for TESLA), then the forwarded power is lowered to 25% in order to simulate the beam load. For the 800 μs designed for TESLA operation the field stays at 26 MV/m. During this measurement the amplitude control was not active. A horizontal test of the capture cavity equipped with the Ti vessel, HOM couplers and the tuning mechanism has been done.[28] For this application only 12 MV/m

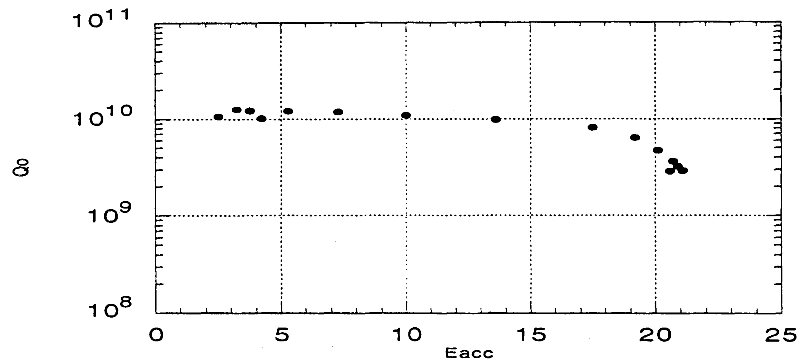

FIGURE 8 First production cavity (D2) for TTF with HOM coupler measured in the vertical cryostat (9-cell, 1.3 GHz, RRR = 500). The field is limited by a quench.

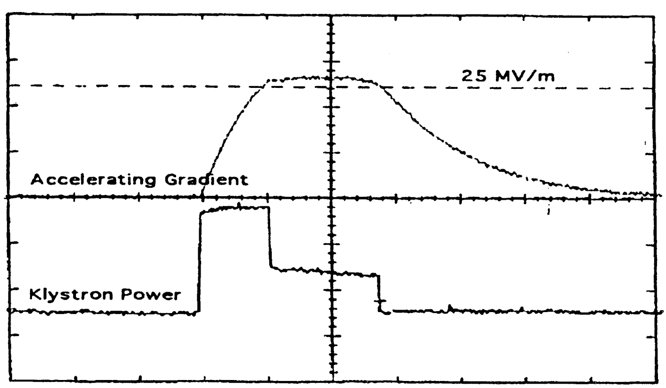

FIGURE 9 Oscilloscope traces taken during the pulse operation of TTF cavity D2. The upper trace shows the voltage of the cavity. During 800 μsec it is 26 MV/m. The lower trace is the klystron forwarded power. Further description of this figure is given in the text.

are necessary. Up to 18.5 MV/m no field emission occurs, then a quench limits the field (Figure 10). The Lorentz force detuning was also measured at the same cavity. A detuning coefficient of $K = -0.98$ Hz/(MV/m)^2 was measured. It is very close to the designed value of $K = -1$ Hz/(MV/m)^2 and thus demonstrates the effectiveness of the mechanic stabilisation by stiffening rings near the iris.

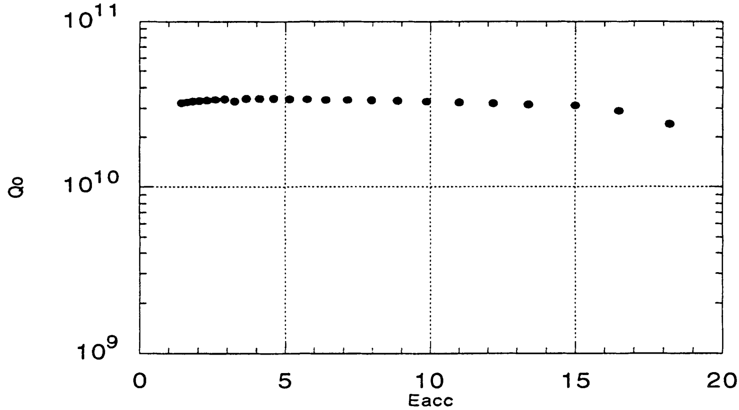

FIGURE 10 Q vs. E_{acc} plot showing the performance of TTF capture cavity during horizontal test. Both HOM couplers and tuning system are installed. The field is limited by a quench.

5 DISCUSSION

Field emission in SRF cavities has been measured in many laboratories. The experimental data were analysed with the Fouler & Nordheim theory. The resulting field enhancement factor β shows values around or above 100. These values could not be identified with field enhancement at a simple protrusion. Recent pictures of field emitters led to the conclusion that a "tip on a tip" model can explain the discrepancy: the multiplication of two field enhancement factors results in a possible value of 100.[29]

However, it is still not understood why only a small amount of all particles on the RF surface emit and why heat treatment at 1400°C can switch off field emitters in cavities. Even more puzzling is the observation that a moderate heat treatment of around 600°C switches field emitters on again.

Cleanliness is the most important factor for suppressing FE. After HPWR the cavity has the "cleanest" performance. Therefore all following activities should be carried out in such a way that no dust contamination of any kind can effect the RF surface. In fact, it would be the best to make the HPWR after the assembling of the main- and HOM-coupler and to clean these parts at the same time. This possibility has to be taken into account already when designing the coupler.

After ultra clean processing, handling and assembling there is still a great chance that some field emitter sides remain on the surface. This is especially true for multicell structures with large surfaces and the complicated couplers' geometries. HPP can be done after the cavity has been assembled.

Because of the availability of high power couplers and klystrons at the operating accelerator it is in principle possible to perform HPP *in situ*. A moderate HPP on installed cavities has been done at CERN and CEBAF.

After the great effort over the last years to increase the RRR to the range of 200 to 300 followed by a quench field improvement from 5 to 15 MV/m there is now some evidence that further increase of RRR not necessarily leads to higher quench fields. L-band results from the last years show that much higher fields can be achieved already with RRR 200 to 300 (see Figure 1).

Figure 1 shows a collection of measured cavity data vs. the square root of RRR. In the range of $25 \ll \mathrm{RRR} \ll 300$ the X-band data for H_{max} scale with $(\mathrm{RRR})^{\frac{1}{2}}$. This agrees with model calculations of a thermal breakdown by local defects.[17] In this model the Kapitza resistance is neglected and the thermal gradient is established only across the Nb cavity wall. Recent measurements of the Kapitza resistance, however, showed that the contribution equals the thermal resistance of a RRR 300 Nb material of 3 mm thickness. Therefore a further increase of RRR (= reduction of thermal resistance of Nb) will not result in the same increase of H_{max} because of the constant contribution of the Kapitza resistance. This might explain the saturation of H_{max} for RRR > 300 of the X-band measurements. The recent L-band data of Figure 1 show a higher H_{max} for RRR $\sim$ 300 as compared to the X-band result. This can be explained by improved preparation and cleaning techniques which avoid large sized defects. But it also demonstrates that the RRR value alone is not enough to characterize a "good" cavity material.

In Figure 2 a dramatic improvement of the quench field is gained after Ti heat treatment. The RRR is improved from 250 to about 1000. With the above mentioned contribution of the Kapitza resistance this gain of more than a factor of 2 cannot be explained by the simulation. As a matter of fact the original quench of this cavity (actually 4 cavities showed a similar behaviour) was localised at the end of the equator weld. There is the suspicion that "dirt" from insufficient cleaning before welding resulted in a contamination cluster at the end of the weld. It is most likely that a heat treatment at 1400° dissolves such clusters by diffusion and thus eliminates the quench. It cannot be excluded that the "as is" Nb material contains such clusters, too. Therefore the benefit of a heat treatment might result from a homogenisation process rather than from improvement of the RRR.

A negative side effect of solid state gettering is the lowered yield strength $\sigma_{0.2}$ from typically 40 N/mm to less than 10 N/mm. The reduced mechanical strength has to be compensated for during handling by a stabilising mechanical support.

It is worth mentioning that the developments on the cavity geometry improved the ratio of E_{peak}/E_{acc} for the up-to-date cavities (For example the multicell cavities for HERA (1982): E_{peak}/E_{acc} = 2.5 and TESLA (1992): E_{peak}/E_{acc} = 2.0). This also helped to increase the accelerating field.

6 CONCLUSION

The most promising tools developed in the last years are

- High Power Processing as a possibility to fight field emission even *in situ* and
- High Pressure Water Rinse which is (here I would like to quote Peter Kneisel) "the most reproducible tool in my 28 years of experience with sc cavities".

The significant improvement of the thermal conductivity of niobium raises new questions on the material properties. It is shown that gradients without field emission up to $E_{acc} > 30$ MV/m for single cells and $E_{acc} > 25$ MV/m for multicells are possible.

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