DOES UHV ANNEALING ABOVE 1100C AS A FINAL SURFACE TREATMENT REDUCE FIELD EMISSION LOADING IN SUPERCONDUCTING CAVITIES ?*

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Abstract
Research on advancing high field capability of Nb microwave cavities for application to future e+e- colliders is being conducted with 1-cell 1500 MHz elliptical cavities, equipped with a high speed temperature mapping diagnostic system. Above 10 MeV/m accelerating field, field emission severely loads cavity Q. One of the most interesting questions addressed regarding field emission (FE) in superconducting cavities is whether heat treatment (HT) reduces emission and permits higher fields, as suggested by dc FE experiments on Nb surfaces, conducted at the U. of Geneva. Comparison between heat treated and chemically treated cavities gives an encouraging picture for the benefits of HT. On the average, 75% higher fields are possible, and the best surface electric and magnetic fields reached were 1260 Oe and 50 MV/m.

Introduction

Having overcome a series of problems endemic to SRF cavities, such as thermal breakdown and multipacting, field emission (FE) is now recognized to be the dominant obstacle to reaching accelerating fields above 10 MV/m (peak surface fields E_{pk} above 20 MV/m). To approach a surface magnetic field at which superconductivity in Nb would breakdown, implies a surface electric field in the vicintiy of 100 MV/m, well above the present capabilities of Nb cavities; thus there is much room for improvement. The fact that for copper cavities pulsed with high power RF, surface fields of 400 MV/m have been achieved[1] gives hope that extensive research on Nb cavities will overcome field emission.

FE of electrons from ideal metal surfaces was first treated as a quantum mechanical tunneling phenomenon by Fowler and Nordheim (FN), who showed that an "FN plot" of $\ln(I/E^2)$ vs $1/E$ will result in a straight line (where I is the field emitted current). Surface fields on the order of 1000 MV/m should be required to get FN emission significant enough to be observable in RF cavities. However, SRF cavities in fact show emission currents at much lower fields, sometimes even below 10 MV/m. These currents typically give a straight-line FN plot if one assumes the local electric field to be enhanced by a factor of β; β values between 100 to 1000 are frequently extracted.[2]

Studies in which emission sites on Nb surfaces were located by a DC probe and subsequently examined by SEM have conclusively shown that the enhanced FE is associated with micron-size superficial particles or inclusions on the surface[3]. Substantial progress has been made on empirical characterization of DC field emitters on Nb surfaces. Typically half a dozen emission spots/cm^2 are seen at field levels up to 40 MV/m. Of these, more than 200 sites have been studied in detail over a surface area of 200 cm^2. The emitting particles have sizes ranging from 0.5 µm to 20 µm, with the most probable size between 0.5 and 1 µm. These particles were found to contain foreign elements such as S, C, Ag, W, Cu, Si, Cr and Mn.[3] Since the β's associated with these particles appear to be of the order of 10, mechanisms other than simple geometrical field enhancement seem to be at work. Studies of the emitted electron energy spectra suggest that the sites cannot be purely metallic in nature, and models based on semiconductors and insulators seem more consistent with the observed energy spectra.[4]

Substantial progress has been made in reducing the number of emitters present on a Nb surface using high temperature (HT) annealing in UHV. These results indicate that HT at T > 1200 C drastically reduced the density of emitters. Surfaces of ~1 cm^2 size which do not emit upto 100 MV/m have been repeatedly obtained by HT above 1400 C. This treatment makes both particles and emission disappear[3].

Encouraged by these results, we have begun to explore the effects of Ultra High Vacuum (UHV) annealing at temperatures above 1100 C as a final surface treatment in comparison with chemical treatment (CT). We have carried out 8 separate heat treatments on 1-cell, 1500 MHz high purity Nb cavities. These cavities were made from commercially available high purity Niobium, further purified by solid state gettering[5] to reach RRR values of 350 to 400. Model calculations[6] have shown that RRR values of 300 - 400 are needed to avoid thermal breakdown from 0.1 mm diameter "normal conducting" type defects. As another benefit, high RRR also improves the ability of a cavity to withstand, without thermal breakdown, the large power deposited on the walls by the impact of FE electrons. Thus the effectiveness of processing a cavity to overcome FE and reach higher fields improves with RRR.

We have used a high speed, superfluid He, thermometer based diagnostic system for characterization of emitter densities and behavior. In this system, 684 carbon resistor thermometers are affixed to the cavity so that each resistor is in thermal contact with the outer wall of the cavity. The thermometers are mounted on 36 boards (19 per board) which are spaced 10 degrees apart. Each board covers a fixed meridian. Thus, using a large number of fixed thermometers allows us to measure the temperature distribution faster than the older technique of mechanically moving a smaller array over the cavity surface. This system can scan the entire surface of the cavity in 15 seconds, as opposed to the older scanning system which takes 30 minutes. The high speed makes it possible to study in detail local heating as a function of field level and time. The high heat transfer coefficient of superfluid He as well as the absence of BCS losses at the low operating temperature(1.4 - 1.5 K) increases the temperature stability of the RF surface at high RF field. The temperature mapping system is described in detail elsewhere.[7] Temperature maps acquired during the tests harbor a wealth of information on detail properties of emitters and other lossy areas. Only representative temperature maps will be given here to correlate with the beneficial effects of HT.

In the past, heat treatment up to 1800 C was used as the final surface treatment for Nb cavities[8], but it was not possible to clearly study how effective this treatment was for reducing FE and for allowing higher fields because of the following reasons.

- -Many tests were limited not by FE but by the more frequently occurring phenomena of multipacting and thermal breakdown. The spherical (elliptical) shape cure for multipacting and the high thermal conductivity cure for thermal breakdown were not yet discovered. As a result, at ~ 1.5 GHz, field values reached were usually more than a factor of 2 lower than those reported here with heat treated cavities.
- -Temperature mapping techniques to observe emitters and their densities were not yet developed.

Experimental Details

After chemical polishing and cleaning with standard procedures, the cavities were heat treated in a UHV furnace. The furnace maintained a vacuum of a few x 10^{-7} torr at about 1200 C by a cryopump system. One of the problems we faced with HT is that the RRR of high purity Nb drops due to absorption of oxygen into the bulk from the resdual gases in the furnace. To minimize this effect, we restricted the time and treatment temperatures. Final bulk RRR values for HT cavities fell between 120 and 240.

Another problem was the introduction of dust into the cavity during insertion and removal from the furnace as well as from the furnace itself. To minimise this effect we took several steps :

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- Locate the furnace inside a Class 100 clean room
- Place debris baffles (Nb foil shields) at the beam tube openings when the cavity was in the furnace.
- Among the first five tests, three cavities were rinsed with dust-free high purity methanol after HT. We noticed substantially less FE and higher final fields. Subsequently we routinely rinsed all cavities to remove possible particulate contaminants that could be introduced while opening the furnace and removing the cavity.

After withdrawal from the furnace, the cavities were sealed with clean polyethelene caps and transported to a class 10 clean room, where they were rinsed and dried. End pieces with an RF coupler and pumping holes were assembled to the cavity with indium joints. The final attachment to the RF test set-up was carried out in front of a Class 100 portable laminar flow unit.

Field Emission Behavior of HT Cavities

In all cases, but one, FE loading was still observed to be present after HT, including the phenomena of emitter switching to a high emissive state. In the exceptional case, no FE loading was detected upto 32 MV/m, when defect induced thermal breakdown was reached.

During RF tests on HT cavities, both RF processing and He processing were used in an attempt to reach the highest possible fields with the available RF power. It is well known that He processing is more effective in reducing FE emission in cavities[8].

The comparisons we make below are an attempt to ascertain whether heat treatment alone is responsible for any improvement in FE loading.

The maximum E_{pk} reached before He processing for the fired cavities ranged from 16 MV/m to 36 MV/m; among these the better cavities had been rinsed with methanol after HT. A statistical comparison of all fired cavities with eighteen chemically prepared cavities is shown in Fig. 1.

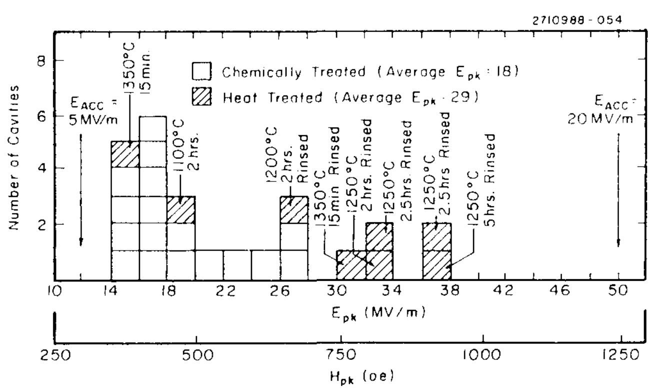

Fig. 1 A statistical comparison between the maximum E_{pk} reached by heat treated cavities and by chemically prepared cavities, without the use of He processing.

The maximium field reached for all 8 tests ranged between 32 and 50 MV/m, with the best results for the cavities rinsed after HT. An overall statistical comparison between HT and CT cavities after He processing is given in Fig.2

From the Q vs E behavior we observed that with CT, all the cavities used in this study showed significant FE loading above 15 MV/m before He processing. T-maps showed the responsible emitters. On the other hand, temperature maps for the same cavities at 16 Mv/m after HT showed hardly any emitters, and of course very little Q drop with field. Fig. 3 gives a representative comparison at 16 MV/m.

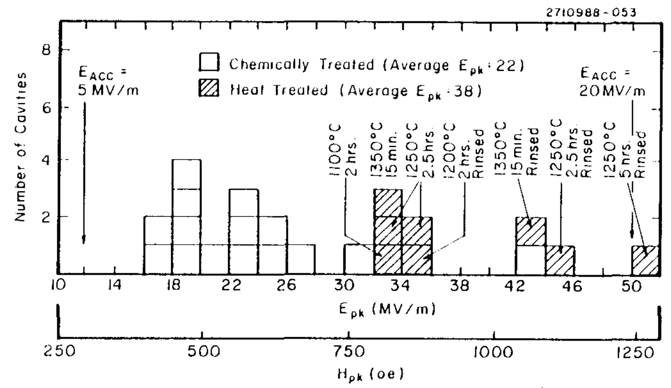

Fig. 2 A statistical comparison between the maximum E_{pk} reached by fired cavities and by chemically prepared cavities, both after He processing.

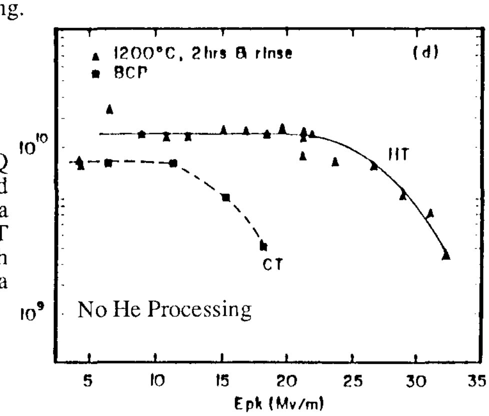

Fig. 3a. Decrease of Q with field emission for a cavity with CT compared with emission for a cavity with HT

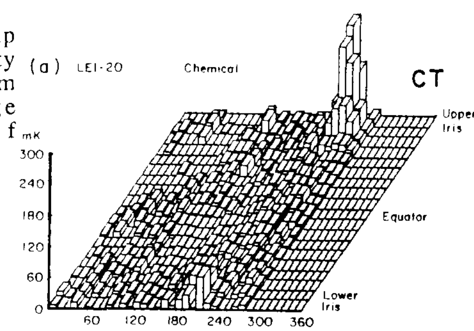

Fig. 3b. T-map for the CT cavity at 16 MV/m showing large number of emitters

No He Processing

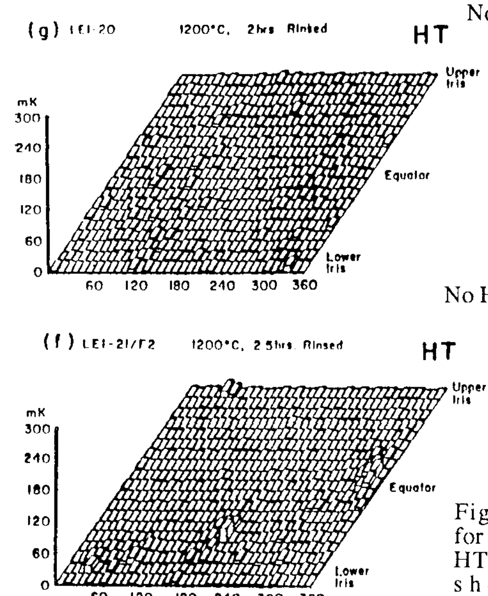

Fig. 3c. T-maps for 2 cavities with HT at 16 MV/m, showing the absence of emitters.

At a higher field of ~24 MV/m, T-map comparisons are shown in Fig. 4. Most HT cavities did not show significant emitters, and did not need He processing to reach this field. However, most CT cavities needed He processing, and showed many emitters.

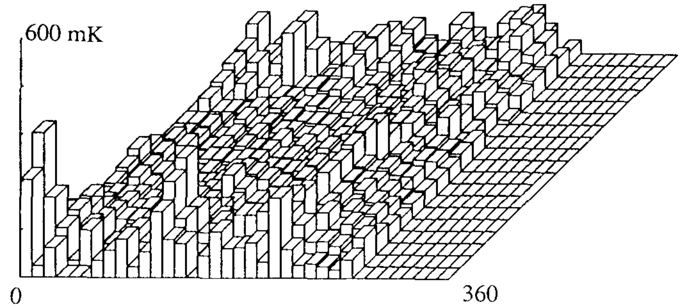

Fig. 4a T-map at a field of 24 MV/m reached after He processing with a CT cavity, showing large number of emitters.

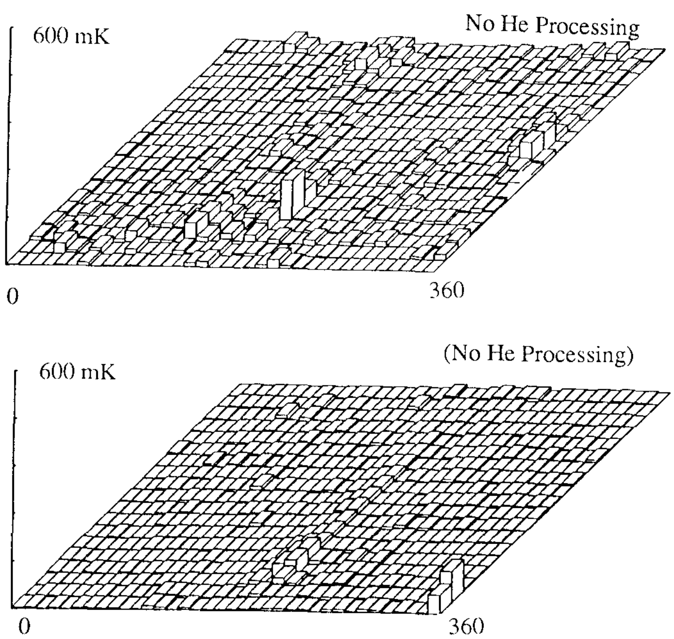

Fig. 4b T-maps of two HT cavities at 24 MV/m for comparison with Fig. 4a.

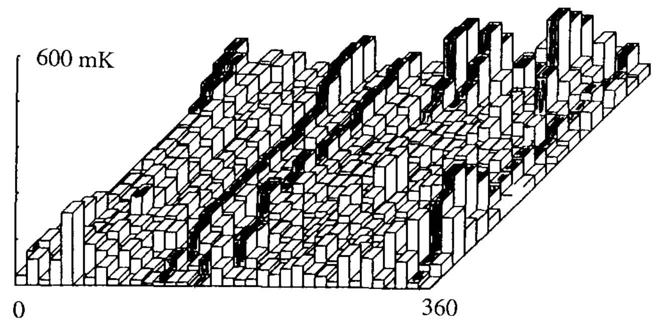

Fig. 5a The highest field T-map ever recorded. Here Epk was 46 MV/m and Hpk was 1150 Oe. The emission heating areas are shaded. FE is still the dominant problem at this field level, reached after He processing.

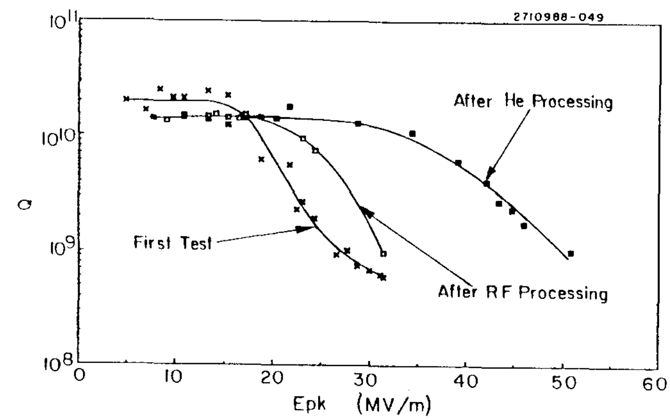

Fig. 5b. Q vs. Epk for three stages of processing the best cavity. The T-map shown in Fig. 5a was taken at the next to the maximum field level of 50.5 MV/m

One of the highest field temperature maps we have ever recorded is shown in Fig.5, along with the behavior of Q at increasing field before the field level at which this map was taken. We note from the large number of emitters that FE is still the dominant problem.

Conclusion

We focussed this study on one of the most interesting questions regarding FE in rf cavities: does heat treatment reduce emission and permit higher fields, as suggested by the U. of Geneva DC FE experiments? We confirm that the beneficial effects of heat treatment observed in DC FE studies do indeed translate to a reduction in FE for RF cavities. However, emission is not eliminated. In most cases maximum fields were still limited by heavy FE after switching, followed by frequent trips of our radiation monitoring system.

On the average 75% higher fields could be reached with HT. Best results were obtained by HT between 1200 to 1250 C for ~ 2 hours, followed by rinsing with methanol. Comparison of the emission landscapes revealed by the high speed thermometry diagnostic system showed that emitter density is substantially reduced after heat treatment.

To consistently reach surface fields higher than 24 MV/m with heat treated cavities, He processing continued to prove effective. In 8 consecutive fired cavity tests, surface electric (magnetic) field values between 32 - 50.5 Mv/m (775 - 1260 Oe) could be reached. For a multi-cell accelerating structure with the same cell geometry, E_{pk}/E_{acc} = 2.5 and H_{pk}/E_{acc} = 47 Oe/MV/m[14] , so that the surface electric (magnetic) fields reached in the tests discussed here would allow accelerating fields of 13 to 20 (17 to 27 MeV/m).

To make further progress, higher annealing temperatures or longer annealing periods may be necessary, but it will first be important to improve the vacuum in the furnace hot zone to maintain a high RRR.

References

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