R&D in Progress to Overcome Field Emission in Superconducting Accelerator Cavities*

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Abstract

Systematic studies are in progress for understanding, controlling and eliminating field emission(FE) in superconducting cavities so that higher gradients can be achieved for application of superconducting cavities to future linear colliders. In exploration of potential cures, we have applied UHV heating above 1100 C as the final surface treatment on 1-cell, 1.5 GHz cavities. A new technique has been developed to extend temperatures to 1350 ^{o}C and heating times to 4 hours without degrading the purity of the wall. The average accelerating fields increased by 80% in comparison with similar chemically prepared cavities. The best cavity reached surface electric (magnetic) fields of 53 MV/m (1350 Oe). The influence of various treatments on the properties of 50 emitters analysed are presented. In other studies, we find that effectiveness of He processing continues as higher RF power levels are used. Systematic exposure studies show that the predominant source of emitters is not the dust-free air (Class 100) used for drying cavities, nor the pure methanol used for final rinsing. On the other hand we have shown that gases condensed on the cavity cold wall can drastically increase emission at pre-existing sites.

Introduction

Large scale application of superconducting RF cavities to electron accelerators is in progress at many laboratories around the world. Niobium is the superconductor of choice. If its performance can be further improved, new applications will be opened for the next generation of accelerators that can explore at the TeV energy frontier[1].

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 vicinity of 100 MV/m, well above the present capabilities of Nb cavities; thus there is much room for improvement. Our efforts to increase the field capabilities of Nb cavities using furnace treatment in the final stages of surface preparation have been fruitful. Eleven such tests on 1.5 GHz cavities averaged surface electric fields of 40 MV/m, with 53 MV/m as the new record. This is a substantial step towards making the superconducting cavity approach an attractive choice for a future TeV collider.

Influence of Heat Treatment on Field Emission

Final Preparation. All 1.5 GHz single cell cavities were fabricated from commercial high RRR Nb and further purified by solid state gettering[2]. After solvent degreasing, the standard chemical treatment procedure used for all cavities was as follows: (1) 1 - 3 minutes etch in buffered chemical polish (8 -10 minutes for a newly fabricated cavity) (2) rinse with Class I water, at least 3 times, (3) ultrasonic agitation in 5%H_2O_2 for 30- 45 minutes (4) ultrasonic agitation in Class I water for 30 - 45 minutes (4) rinse at least 2 times with Class I water before transporting to Class 100 clean area (5) rinse at least 2 times with high purity methanol in the dust-free area (6) dry in dust-free area in the horizontal position to minimize residue collection at high electric field regions of cavity (7) seal ends, bag cavity, and transport to RF test stand or to furnace area (8) attach to RF Test stand or install in furnace in front of Class 100 Laminar flow unit. In the subsequent text, CT refers to surface preparation without furnace, and HT with furnace treatment.

Heat treatment temperatures and times for all experiments are listed in Table 1. The vacuum in the furnace above the heat shields was a few x10^{-7} torr. One of the problems we faced with earlier HTs was 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 for the first 9 cases. Final bulk RRR values for HT cavities fell between 130 and 260. In the last two HT tests, a new procedure (discussed in more detail below) was developed to allow a temperature increase to 1350C and time to 4 hours without dropping the RRR. After withdrawal from the furnace, the cavities were sealed with clean polyethelene caps and transported to a class 100 clean room, where end pieces with an RF coupler were assembled to the cavity with indium joints. A problem observed from the earlier tests 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 began to rinse cavities with methanol after HT and noticed substantially less FE and higher final fields. Subsequently we routinely rinsed and dried all cavities. More recently we added ultrasonic agitation to the final rinse.

In all cases but one, FE was still observed to be present after HT. The onset of FE was at a higher field for HT cavities than with CT cavities. In previous reports we showed several temperature map comparisons between HT and CT tests indicating that HT significantly reduces the number and intensity of emitters present at the same field level[3][4].

Both RF and He processing were used to reach the highest possible fields with the available RF power (< 200 watts). Fig 1a is a statistical comparison between fired cavities and chemically treated cavities. The highest field reached in each test is shown after the RF processing approach was exhausted. With RF processing alone it was possible to reach, on the average 31 MV/m, with 47 MV/m as the best value. As well known, He processing was more effective. Fig. 1b is a similar comparison between HT and CT after He processing was exhausted. On the average it was possible to reach 40 MV/m, with 53 MV/m as the best value. After completion of He processing, Table 1 gives the Q values at the final field as well as the Q values before the remaining emission became significant.

TABLE 1

A Summary of the Performance of Heat Treated Cavities

No.	HT Condition T(^{o}C)	t(hrs)	Maximum E_{pk}	Q	Flat Region E_{pk}	Q	Estimated RRR	O P ick up (ppm) From Sample	Methanol Rinse After HT	Limited By
1	1100	2	34				-	-	N	FE
2	1200	2	38	3×10^{9}	29	1×10^{10}	-	-	Y	FE
3	1250	2.5	36	4×10^{9}	25	8×10^{9}	-	-	Y	FE
4	1350	0.25	33	6.4×10^{9}	16	1×10^{10}	260	6.7	N	FE
5	1250	2.5	46	1×10^{9}	35	5×10^{9}	177	15.7	Y	Defect
6	1250	5	50	9×10^{8}	32	1.5×10^{10}	230	19.3	Y	FE + Defect
7	1250	2	40	1×10^{9}	30	1×10^{10}	129	24.0	Y	FE + Defect
8	1350	0.25	43	2×10^{9}	36.6	1×10^{10}	132	17.5	Y	FE
9	1250	2	33	9×10^{9}	33	9×10^{9}	-	-	Y+US^{+}	Defect
10	1350*	4	43	1.7×10^{9}	32	7×10^{9}	400^{++}	-5.5	Y	FE
11	1350*	4	49	2×10^{9}	36	4×10^{9}	470^{++}	-5.5	Y+US^{+}	FE
12**	CT Outside to Remove Ti		53	2×10^{9}	45	5.5×10^{9}			Y+US^{+}	FE

* With Ti box protection
** Same cavity as 11 and no additional HT after
+ US = With Ultrasonic for one hr.
++ same as initial RRR

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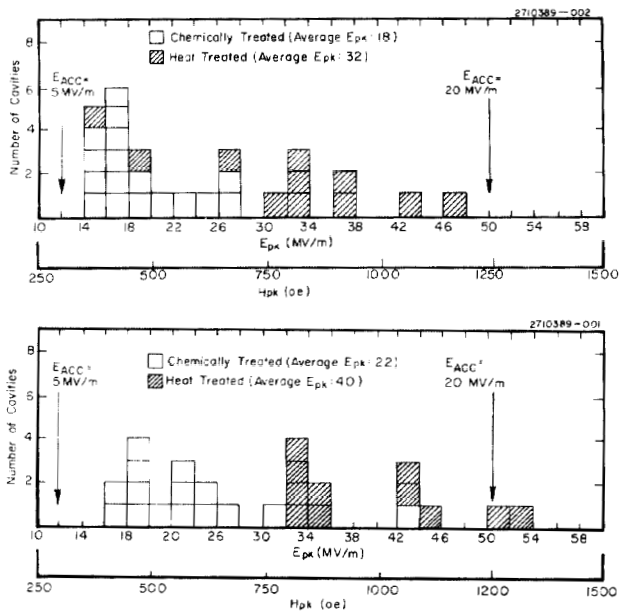

Fig.1 A statistical comparison between heat treated and chemically treated cavities for the maximum surface electric field achievable with (a)RF processing only (b) with He processing.

HT Without RRR Drop

As mentioned earlier, the RRR of Nb drops during the heat treatment due to pick-up of residual gases, typically oxygen, from the furnace vaccum. This RRR drop increases the probability of thermal breakdown. In order to investigate if higher temperatures and longer times during HT would further reduce FE and lead to higher fields, a protection technique was developed and applied at 1350C for 4 hours.

The procedure is shown in Fig. 2. A Nb box completely surrounds the cavity cell and short segments of the beam tube at both ends. On the inside, the box is lined with Ti sheets. During heat treatment, the outer wall of the cavity is coated by evaporation with Ti. The coating prevents O from striking the Nb cavity wall from the outside. Oxygen diffusing into the cavity wall from the inside (RF) surface is removed by solid state gettering at the Nb-Ti interface[5]. In our furnace the vaccum is sufficiently good that the net effect is oxygen loss from the cavity wall. The RRR of cavity improves if it is limited by bulk oxygen and stays constant if the cavity has already been completely depleted of oxygen by previous solid state gettering cycles. The vapor pressure of Ti at 1350 C is $2x10^{-5}$ torr. Most of the Ti vapour is contained within the Nb box, which is fabricated from overlapping Nb sheets. The small cracks due to imperfect fit-up between the sheets allow pumping of the Ti box volume. The Nb box protects the interior of the cavity and the furnace wall from being coated with Ti.

Two prelimnary trials and two complete cavity tests with RF measurements have been conducted with this procedure.

In the first trial, a 7.5 cm diameter Nb tube with RRR=250 was used to simulate a cavity. The tube was surrounded with a Ti band at the midsection and heated to 1350 C for 4 hours in a diffusion pumped furnace. In the region protected by Ti, the RRR remained constant, whereas in the uncovered region the RRR dropped to 40. We did not observe any Ti contamination on the inner surface to the sensitivity limit (0.2%) of our SEM/EDX system. At the outside surface, the concentration of the Ti was measured to be 45% dropping to zero in about 25 μm. The Ti rich layer could be completely dissolved with the standard buffered chemical solution in 6 minutes. In the second test, we fired a dispensable 1.5 GHz single cell cavity in our UHV furnace using the Ti lined Nb box at 1350 C for 4 hours. Samples cut from the cavity wall showed that the RRR of the cavity improved from 35 to 80, corresponding to an oxygen drop of 90 ppm. In this case the final RRR=80 is most likely limited by residual N and C content, typical of standard reactor grade material from which the cavity was fabricated. In the same test, a monitor specimen with RRR=250 (without solid state gettering) was positioned contiguous to one of the Nb walls. Like the cavity, only one side was coated with Ti. The RRR of this specimen improved to 360 after HT. Both results confirmed that substantial oxygen removal is possible by a one side Ti coating in a good vacuum furnace.

Finally two cavities were treated at 1350 C for 4 hours. In the first cavity (LE1-23)the low field Q was $1.2x10^{10}$, confirming previous evidence that Ti vapor did not reach the RF surface during furnace treatment. Observable FE started above 25 MV/m. With RF processing alone 41 MV/m was reached at a Q of $2x10^{9}$, and 43 MV/m at the same Q after He processing. The final Q vs E behavior is shown in Fig. 3d. A new problem encountered in this test was the presence of large temperature signals in many places over the equatorial region where the magnetic field is highest. Also the He processing stage was accompanied by an unusual frequency of breakdowns. We suspect that both unusual effects are attributable to the Ti-rich outer layer.

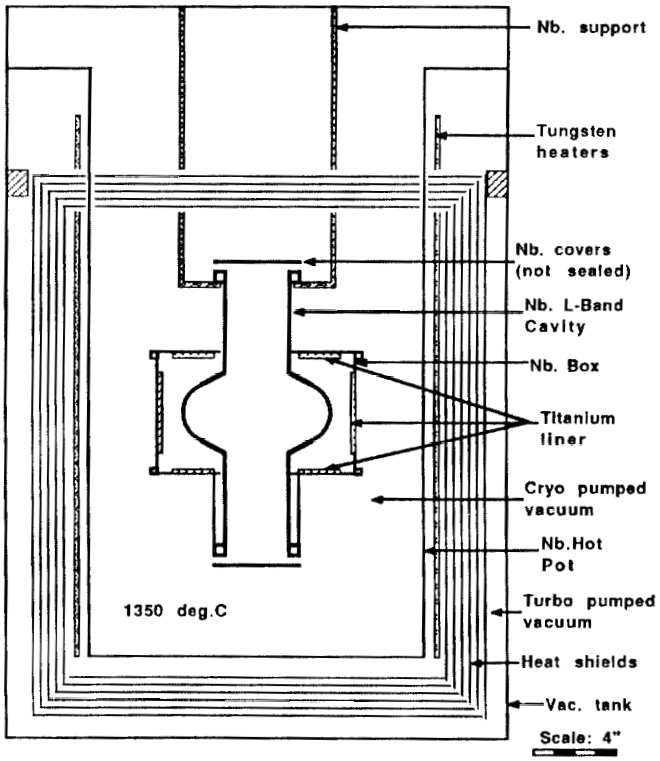

Fig. 2 Schematic of furnace treatment with Ti box protection to avoid RRR loss

For the second cavity(LE1-CSI) the low power Q was $6x10^{9}$. Significant emission started at 18 MV/m. With RF processing alone it was possible to reach 46 MV/m at a Q of $1x10^{9}$, and 49 MV/m at a Q of $2x10^{9}$ after He processing. Again we saw unusually high temperature signals at the equator and frequent breakdowns during processsing.

Suspecting that the Ti-rich layer on the outer wall of the cavity was impeding heat flow, we chemically etched the outside of the cavity for 7 minutes while keeping the inside surface sealed and filled with class 100 air. After the outside chemistry, we rinsed the RF surface with methanol and ultrasound agitaiton for one hour to make sure that any accidental dust was removed before re-attaching to the RF test set-up. In the subsequent test, the excess heating at the equator had substantially subsided, and so did the breakdown frequency. With RF processing alone we reached E= 52 MV/m at a Q of $1x10^{9}$, and with He processing we reached 53 MV/m at a Q of $2x10^{9}$. The final Q vs E beahvior is shown Fig. 3d. Part a of the same figure shows the behavior of this cavity in several tests with standard chemical treatment. Part b and c show results with this cavity from two previous HT cycles. Note that by the second HT, the RRR had dropped to 130, so that thermal breakdown took over as the limitation around 40 MV/m. The final HT at 1350 C (part d) cures this problem as it restores the starting RRR ~ 400.

Among the series of heat treated cavities, the last two tests show increased relief from field emission with higher temperature and longer times. As we bring field emission under control, surface magnetic fields between 1000 - 1350 Oersted are reached. At these levels, the highest possible bulk Nb RRR is essential to avoid thermal breakdown at imperfections. Thermal model calculations indicate that a 20 micron diameter defect (eg. normal conducting material) will be thermally unstable at 1350 Oersted, corresponding to the record performance we reached.

An interesting side effect was that after 1350 C HT with Ti box protection, the Q of both cavities at 4.2 K increased to $4.5x10^{8}$. This increase is consistent with a surface RRR of ~30, as expected since the inside surface was not protected from diffusion of O. We do not know exactly how deep the low RRR layer extends, but the high field results show that it is not deep enough to cause thermal stability problems. In later tests, we plan to determine the thickness by chemical etching of the RF surface.

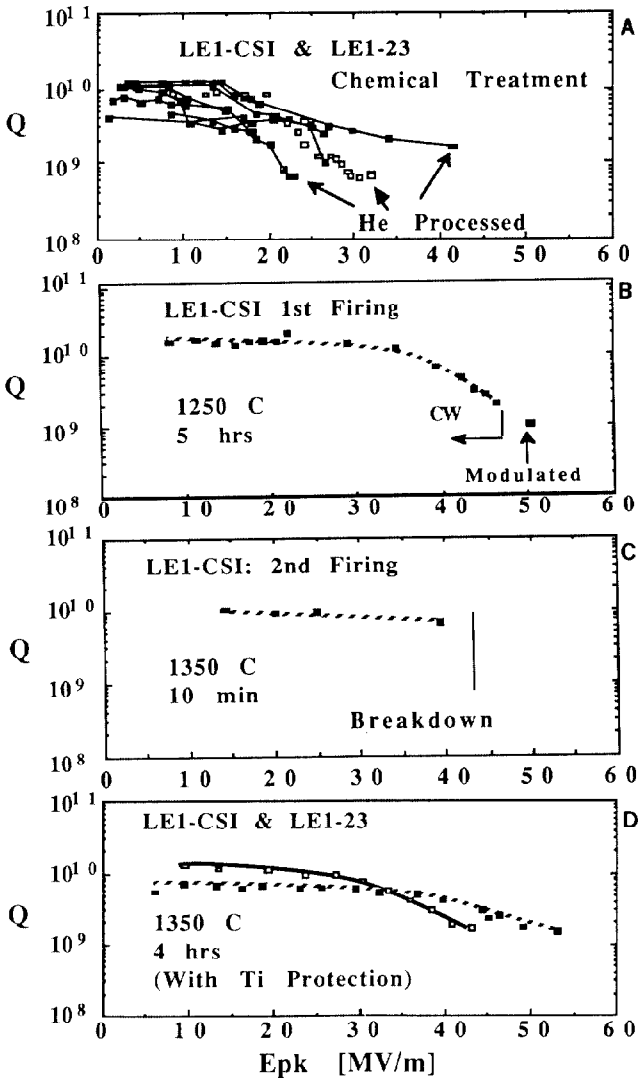

Fig.3 History of performance for two cavities: LE1-CSI and LE1-23. (a) Several tests after chemical treatment (b) 1st firing for LE1-CSI, RRR dropped from 400 to 230 (c) 2nd firing of LE1-CSI, RRR dropped further to 130 (d) firing of both cavities with new procedure, RRR = 400. (b),(c), and (d) are all after He processing.

Emitter Properties

Temperature maps we have accumulated to date from 1.5 Ghz cavity tests contain a rich body of information on emitters and other loss mechanisms in superconducting cavities. One type of heat source is rf dissipation at localized surface imperfections for which heating is observed proportional to E^2. Dissipation from impact of field emitted electrons is non-linear in E^2. With our rapid mapping system, we track emission heating (ΔT) from individual emitters over several increasing field levels(E). This heating is observed to follow a Fowler Nordheim (FN) behavior, i.e. a plot of $\ln(\Delta T/E^2)$ vs. 1/E is linear. Two properties by which postulated emitters are usually characterized are the Fowler Nordheim (FN) field enhancement factor (β) and the emissive area S. Together they describe the emission current as:

$$I = (AS\beta^2E^2/\phi)x\ \exp[-B\phi^{3/2}/\beta E]$$

Here I is the current in A/cm^2, E is in V/cm, ϕ is the work function (4 ev for Nb), A and B are constants.

In numerical simulations, we have calculated the trajectories followed by field emitted electrons in our cavity and the deposited power density distribution from the emission current. By smearing the power deposited on the inner wall to simulate the heat flow through the Nb wall, we also calculated the expected shapes for temperature maps. The shapes agree well with observed maps and confirm that the peak ΔT due to emisison current from a postulated emitter follows a FN behavior, with a slope that is correlated with the starting β value for the emitter[6][7]. Using the experimental calibration of the thermometer response, the simulations also yield a correlation between the intercept of the FN plot and the emissive area of the emitter. The calculated correlations take into account the effect of trajectory dynamics and are used in turn to obtain the β and S from the slope and intercept of experimental FN plots of $\ln\Delta T/E^2$ vs. 1/E.

At very low fields, where emission heating should be insignificant, we still observe a linear behavior of ΔT in E^2. We attribute this to local sources of resistive or dielectric loss. This loss component of heating is subtracted out in the analysis for emitter properties.

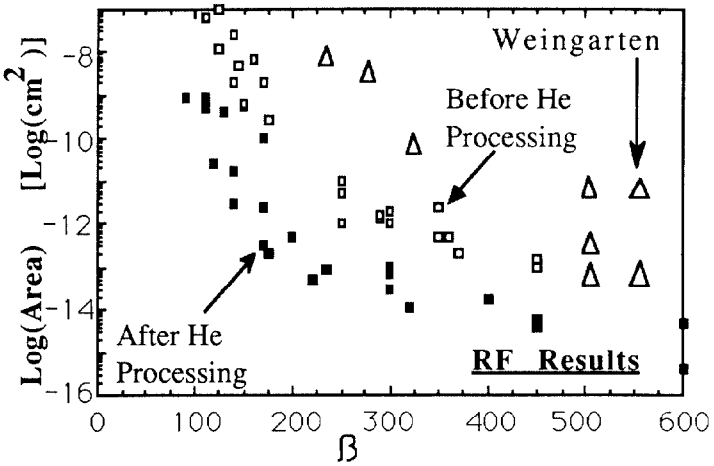

Fig. 4 Fowler Nordheim properties β and area for collection of emitters studied with the fast temperature mapping system from many tests.

Fig 4. summarizes the properties of ~50 emitters we have analyzed by the method described. A correlation between β and S is visible as first observed in refs.[8] (These data points are superposed). A reasonable distinction is observed between the emitters encountered after He processing and those before any He processing is applied. We are still in the process of classifying emitter properties with respect to their frequency of occurrence vs. field level and for various surface treatments used such as CT, or HT or rinsing with various agents.

Summary of Other FE Studies

For lack of space, we only summarize the results of other work in progress. In an attempt to search for the source of emitters that contaminate RF cavities, we have exposed RF surfaces which can sustain high electric fields (30 - 50 MV/m) to various mediums with which a cavity comes into contact in the course of surface preparation. We find that exposure to dust-free (Class 100) air does not destroy the surface with an abundance of new emitters[6][7]. Similarly we have eliminated the high purity methanol we use as the abundant source of emitters. Remarkably we have been able to reach the record 53 MV/m both after exposure to clean air followed by rinsing with clean methanol. Tests on water exposure have started and these show stronger degradation from increased emission, but more exposure tests are necessary to be conclusive. Tentatively we hypothesize that either chemical or water residues are responsible, and these are effectively cleansed by evaporation or dissolution during furnace treatment.

We have established the presence of dormant emission sites that can be activated by condensed gases even from the vacuum system of the test set-up[9]. Such sites appear to be present independent of specific surface treatment. It is not clear whether all active sites are inherently dormant. Perhaps condensed gas is the active culprit in all sites. We plan to conduct further tests on this question by improving the vacuum of the test set-up before cool-down to reduce the probability of condensed gases. Unfortunately the presence of dormant sites implies that RF or He processing has to be repeated to some degree each time a cavity is cycled to room temperature. Till now we have always been able to re-establish maximum fields after cycling to room temperature by additional RF or He processing.

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