

REDUCING FIELD EMISSION IN SUPERCONDUCTING RF CAVITIES FOR THE NEXT GENERATION OF PARTICLE ACCELERATORS

Q. S. Shu, W. Hartung, A. Leibovich, J. Kirchgessner,
D. Moffat, R. Noer*, H. Padamsee, D. Rubin, J. Sears**
Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853

Abstract

Currently field emission is the most serious obstacle to reaching the higher fields called for in future applications of superconducting radio frequency cavities to particle accelerators. We have used heat treatment up to 1500°C in an ultra-high vacuum furnace, along with processing of cavities and temperature mapping, to suppress field emission and analyze emitter properties. In 27 tests of 1-cell 1500MHz fired accelerating cavities, on the average the accelerating field E_{acc} increased to 24 MV/m ($H_{pk} = 1250$ Oe) from 13 MV/m with chemical treatment alone; the highest E_{acc} reached was 30.5 MV/m. Emitter properties, efficiency of He processing, and results of exposure of well processed rf surfaces to various media are also discussed. The effort has been made to transfer to real accelerating structures our success in achieving high gradients in single cell test cavities.

INTRODUCTION

As a result of their great advantages over conventional structures, superconducting cavities have been widely and rapidly applied in beam acceleration systems around the world [1]. Presentday superconducting radio-frequency cavity structures used in particle accelerators provide accelerating fields E_{acc} up to 10 MV/m. However, for many reasons future large scale applications need higher fields - e.g., 30 MV/m for TeV e^+e^- linear colliders [2].

The theoretical limit of E_{acc} for Nb (the material of choice for these applications) is as high as 50 MV/m, set by the critical magnetic field $H_{rf} = 2000$ Oe. The corresponding E_{pk} in accelerating cavities, where $E_{pk}/E_{acc}=2$, is 100 MV/m. Over the past years lesser limitations have been overcome – multipacting through the use of spherical or elliptical cavity shapes, and thermal breakdown through the use of high purity (high RRR) Nb material. Present performance is limited by field emission (FE). In order to control FE and thus approach the theoretical limit, our strategy has centered on the use of high temperature heat treatments (HTs) with various firing parameters, along with diagnostic tools to achieve better understanding. A Ti box protection technique, furnace performance, and assembly procedures have been continuously improved so we are now able to fire cavities at 1500°C for 16 hrs without dropping the RRR (purity) of the cavity wall. This allows us to get the maximum benefits from HT without being stopped by low-RRR induced thermal breakdown.

We have also carried out systematic experiments to study emitter sources. Around 2000 temperature maps of cavity surfaces were taken during rf tests and analysed in detail. He processing has also been carried out in more than 50 tests.

THE HISTORY OF A REPRESENTATIVE FIRED CAVITY

We have made 27 cavity firings. The history of a representative cavity is presented here to show the benefits of HT and the progress made in the continuous improvement of the HT technique. The cavity was made from commercial Nb with RRR equals to 200 and improved by solid state gettering to RRR equals to 400[3]. Before firing, it was tested after each of 5 chemical treatments (CTs). Its overall rf performance is shown in Fig. 1. The average E_{pk} is less than 30 MV/m with Q less than 1×10^9 . The best field was 42 MV/m. Then the cavity was fired in the furnace (Fig. 2) at 1350°C for 5 hrs, but no Ti box was used. FE was greatly reduced, and an E_{pk} of 47 MV/m was reached with cw rf power (increasing to 50 MV/m with modulated rf). However, a monitor sample,

* Permanent address: Carleton College, Northfield, MN 55057.

** Work supported by the National Science Foundation, with supplementary support from the US-Japan collaboration.

*** Manuscript received September 24, 1990. IEEE Transactions On Magnetics, Vol. 27, No.2, March 1991

placed with the cavity during firing, showed a RRR drop from 300 to 146, corresponding to an oxygen pickup of 19.3 wppm from the residual gases of the furnace vacuum. If we assume that the cavity also picked up the same O concentration, its RRR will drop to about 230. Such a RRR drop increases the probability of thermal breakdown. In order to further verify the influence of HT on the cavity performance, we next fired at a higher temperature of 1500°C. Considering the probable RRR drop, the firing time was reduced to 15 minutes. As shown in Fig. 1, FE was further reduced, resulting in a Q flat to 40 MV/m with a value of about 1×10^{10} . However, the cavity broke down at 40 MV/m. The RRR sample showed an O pickup of 17.5 wppm, implying that the cavity wall RRR was around 132.

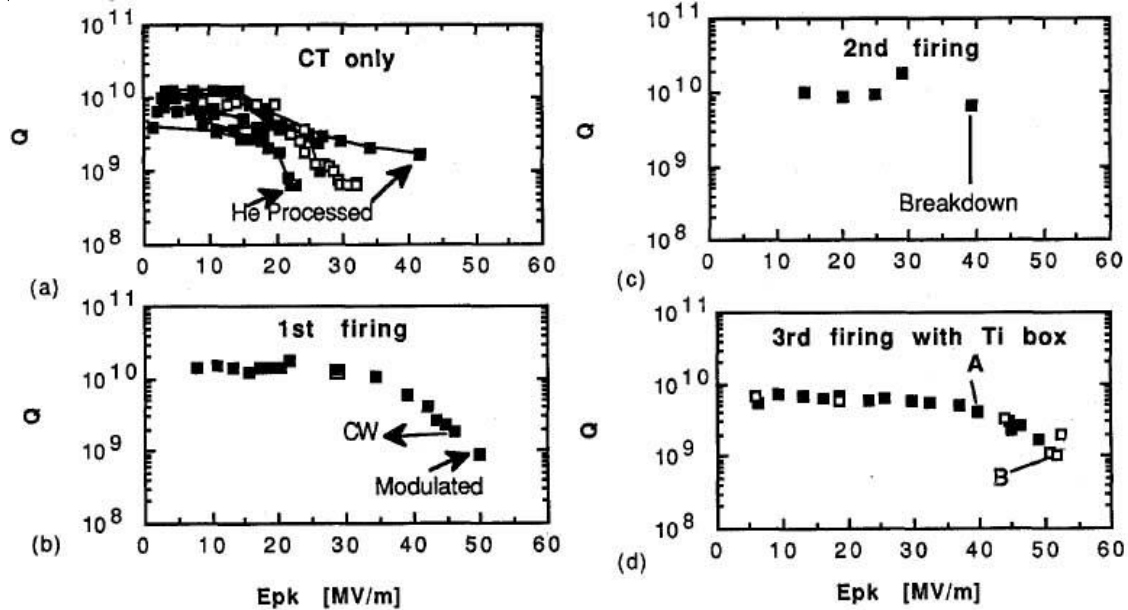


Figure 1. History of cavity LE1-CSI. (a) After chemical treatments. (b) After 5-hr 1350°C firing. (c) After 15-min 1500°C firing. (d) After 4-hr 1500°C firing with Ti box.

In order to solve this RRR problem, we developed the "Ti box" protection technique[3,4] 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 high furnace temperatures ensure that a coating of Ti is evaporated onto the outer wall of the cavity. (The vapor pressure of Ti at 1350°C is a few $\times 10^{-4}$ torr.) Oxygen diffusing into the cavity wall from the residual gas is removed by solid state gettering at the Nb-Ti interface [4]. In our furnace the vacuum is sufficiently good that the net effect is oxygen loss from the cavity wall. The RRR of the cavity increases if its pre-HT performance was limited by bulk oxygen and stays constant if the cavity was already completely depleted of oxygen by previous solidstate gettering cycles.

Using the Ti box, the cavity was fired at 1500°C for 4 hrs. The highest E_{pk} reached following the firing was 49 MV/m with a Q of 2×10^9 . A RRR monitor sample, which was placed in the furnace so that only one side was contact with Ti, showed an increase from 295 to 420 after firing, corresponding to an O loss of -5.5 wppm and implying an increase in the cavity bulk RRR from 132 to 400. However, during the rf tests unusually large temperature increases were observed on the cavity equator and elsewhere, suggesting a high thermal resistance layer (perhaps a Ti coating) on the outer cavity surface. A special device was designed to allow a chemical polish (BCP) of this surface while the inner surface remained sealed with class-10 clean air. After 7 minutes of outside BCP the inner rf surface was rinsed with methanol and ultrasound agitation for one hour to remove any accidental dust. The cavity was then retested, reaching 53 MV/m with a Q of 3×10^9 ; the large equator temperature rises were found to have vanished. It was also observed that the low power Q at 4.2K of a fired cavity is higher than that for CT only, implying that the RRR of a fired cavity rf surface is lower than the dc bulk RRR. This phenomenon will be discussed in separate paper.

This cavity preparation procedure has been adopted: fire with Ti box, BCP outer surface only, rinse inner surface with methanol, and then install in test cryostat.

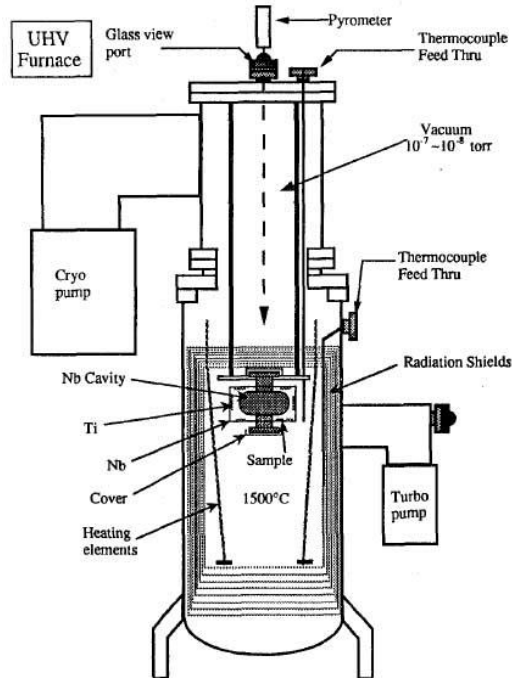


Figure 2. Heat treatment furnace. Nb cavity is shown in place for firing with Ti box.

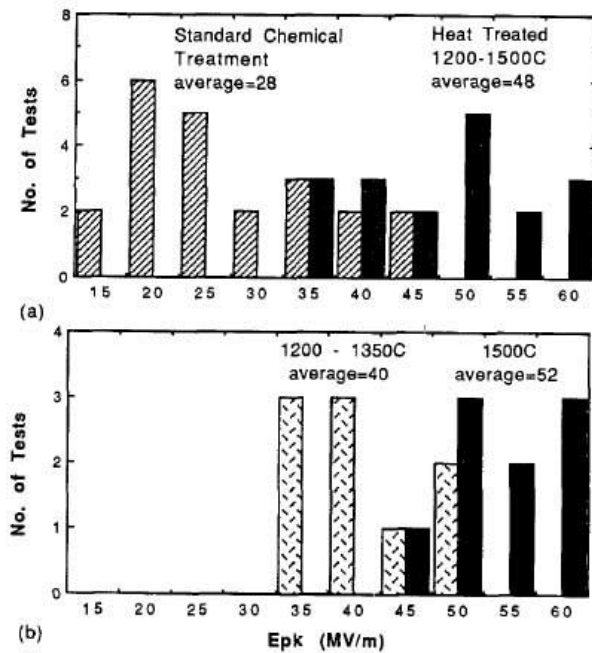


Figure 3. Maximum E_{pk} reached in cavity tests. (a) Chemically treated cavities compared with all heat treated cavities. (b) Intermediate- temperature HT compared with high-temperature HT.

RESULTS OF HT CAVITIES

Overall RF Performance

Substantial progress was made by heat treatment of cavities at 1200-1500°C in a UHV furnace for 2-8 hrs[5,6]. As shown in Fig. 3(a) the average E_{pk} reached in these cavities increased to 48 MV/m from the 28 MV/m reached in chemically treated cavities.

The HTs are classified in two categories: (1) IHT-intermediate temperature (1200-1350°C) heat treatment without Ti box, and (2) HHT-high temperature (1500°C) heat treatment with Ti box. As shown in Fig. 3(b) for IHT cavities, the average E_{pk} reached is 40 MV/m. For HHT cavities with rf processing alone it was possible to reach an average E_{pk} of 48 MV/m on the average, with 61 MV/m as the best value. He processing raised the average to 52 MV/m.

As another comparison, Fig. 4 shows that chemically treated cavities often have Q lower than 1×10^9 before reaching 20-40 MV/m, while most of the HT cavities exceed even 50 MV/m while maintaining Q greater than 1×10^9 .

Comparison of Field Emission

Our temperature-mapping diagnostic system [6,7] allows us to examine the detailed effects of HT on field emission. Figure 5 shows temperature maps for a representative cavity taken before and after HT, each at a field of 30 MV/m. The post-HT map shows drastically reduced emission.

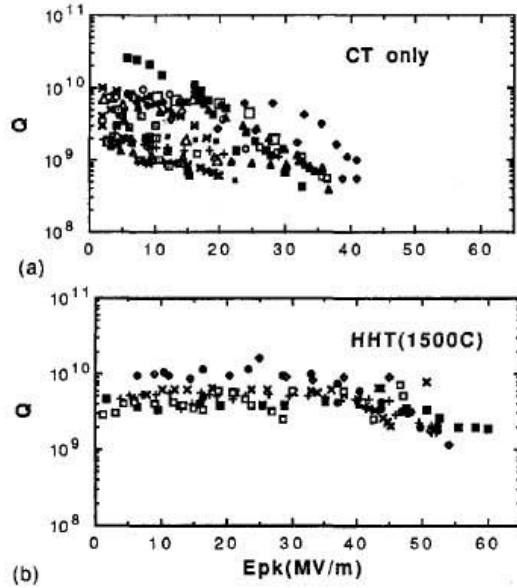


Figure 4. Q vs E_{pk} for (a) chemically treated cavities, 21, and (b) heat treated cavities
bottom: after subsequent

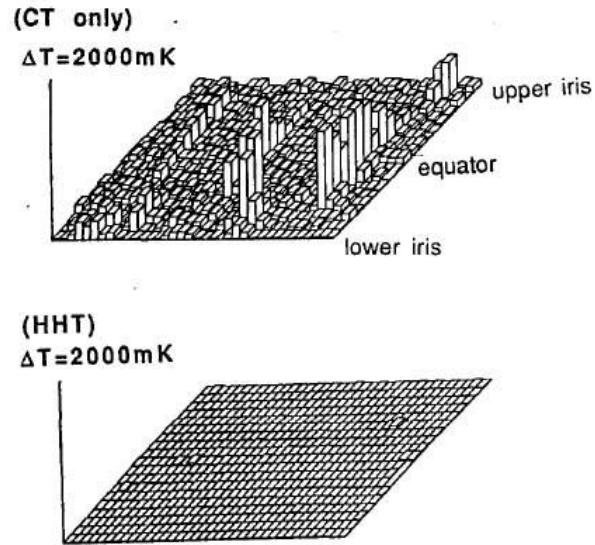


Figure 5. Temperature maps at 30 MV/m for cavity LE1-21.
Top: after chemical treatment;
heat treatment.

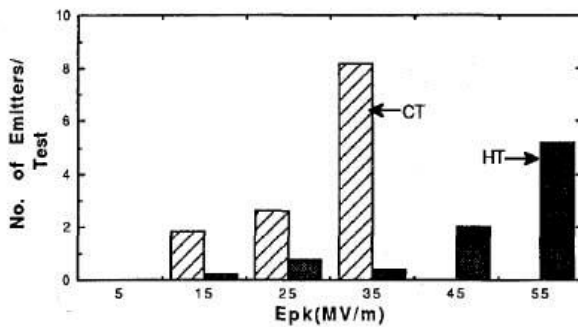


Figure 6. Number of emitters apparent in temperature field maps as a function of maximum E_{pk} reached, for chemically treated and treated and heat treated cavities.

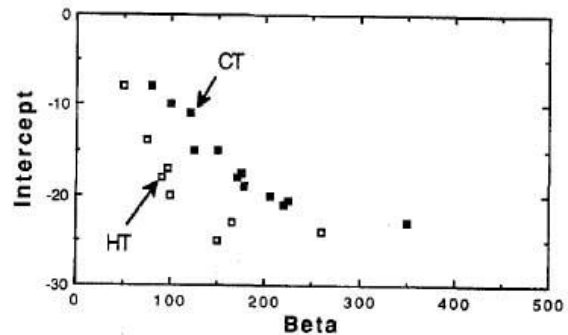


Figure 7. Fowler-Nordheim plot intercept vs enhancement factor, for chemically heat mated cavities.

Figure 6 shows a comparison of the emitter densities [8] for CT and HT cavity surfaces. It is evident that at the same field level CT cavities have much higher emitter densities than HT cavities.

We can also examine the properties of individual emitters in CT and HT cavities [3,8,9]. As is well known, an emitter may be characterized by two properties: the field enhancement factor β and the equivalent emitter area A . For this discussion we use the intercept of the Fowler-Nordheim plot in place of A , since this intercept is proportional to A and can be directly found from the plot. Figure 7 plots this intercept vs β showing that the distribution for CT cavities lies in the upper right (higher emission) region, while that for HT cavities lies toward the lower left. The stronger emitters were processed out first in both CT and HT cavities.

COATING MATERIAL CHOICE AND TEMPERATURE CALIBRATION

Which material is chosen to prevent a RRR drop during HT depends on the vapor pressure of the material and the results of solid state gettering, which removes O from Nb. Table 1 shows the vapor pressure vs. temperature for several possible materials.

Table 1. Vapor pressure (in torr) vs temperature					
Material	1300°C	1400°C	1500°C	1600°C	Melting
Y	4E-5	3E-4	2E-3		1520°C
Ti	4E-6	3E-5	3E-4	1E-3	1660°C
Zr	1E-11	4E-10	3E-9	4E-8	1850°C
Nb-Ti(46 w%)					1800°C

Several observations are in order: 1) Y is used to purify the Nb sheet from which the cavities are manufactured[3]. However it is not good for HT at 1500°C, since its vapor pressure is too high. 2) Ti is good for HT at 1400-1500°C, but not at 1600°C. 3) Zr is not effective at $\leq 1650^\circ\text{C}$, as verified by our tests. However it may be useful at $\geq 1750^\circ\text{C}$. 4) Nb-Ti is able to hold the RRR at 1500°C which is better than Zr.

In employing the above processes, it is important that the furnace temperature be known to good accuracy. Ours is read with an optical pyrometer through a small hole in the heat shields, using an emissivity correction. The calibration and correction were checked with the aid of a Ti foil (melting point 1660°C) sealed in a Nb tube with an electron beam weld. Heated in separate runs to nominal temperatures of 1651 and 1670°C, the foil was found respectively to have remained solid and melted, showing that our nominal temperatures are correct to better than 20°C.

RECENT STUDY OF BENEFITS FROM HE PROCESSING

It is well known that He processing plays a role in reducing FE, and therefore raises the E_{pk} in rf cavities. More than 50 tested cavities were He processed, with temperature maps systematically taken before, during, and after He processing. In particular, we have investigated whether there is any relation between cavity treatment and the effectiveness of He processing.

Fig. 8(a) indicates such a relation between E_{pk} reached before He processing and benefits from He processing. The fractional increase in E_{pk} , due to He processing, is plotted against the maximum E_{pk} reached before processing. It is apparent that, in general, the higher the field a cavity reaches before processing, the smaller the benefit achieved by processing.

Fig. 8(b) and 8(c) were taken in the same test, and show the time dependence of He processing effects. Clearly the significant gains in both Q and E_{pk} were completed during the first 20 minutes of processing.

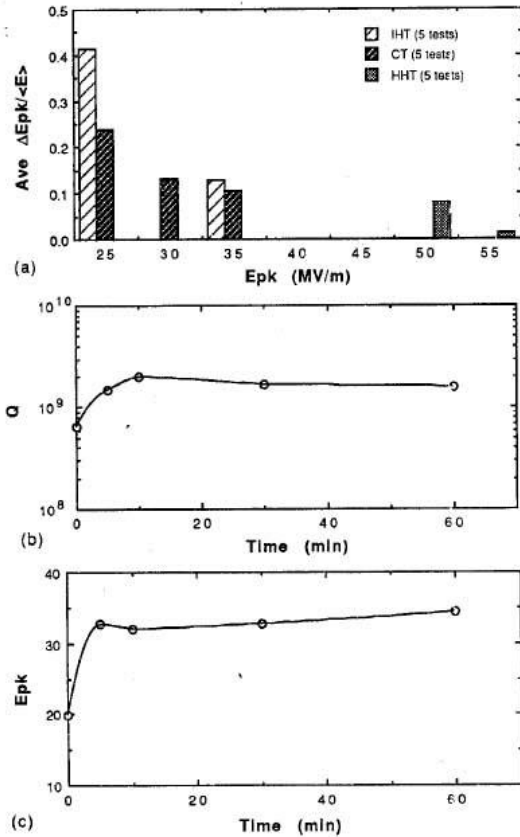


Figure 8. Helium processing: (a) fractional increase in maximum E_{pk} vs maximum E_{pk} , for chemically treated and intermediate- and high-temperature heat treated cavities, (b) and (c) time dependence of He processing effects.

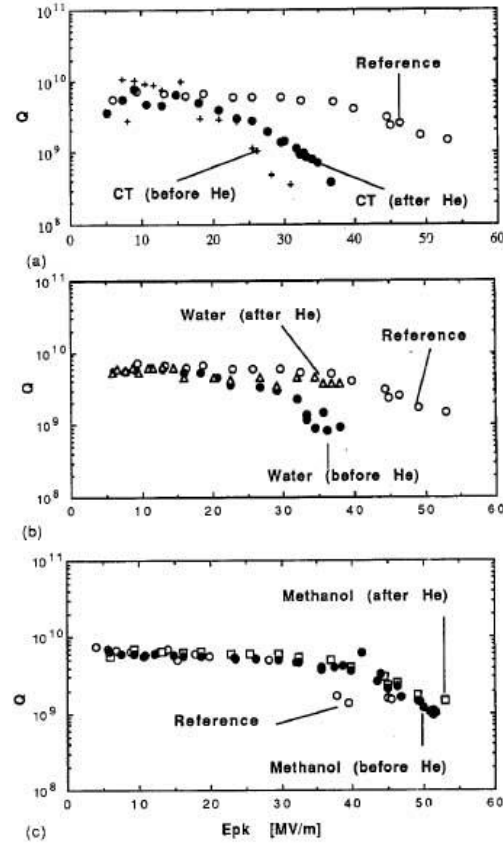


Figure 9. Cavity performance before (Reference) and after exposure to various media: (a) rinsing water, (b) methanol, and (c) chemical treatment.

EXPERIMENTS TO IDENTIFY EMITTER SOURCES

After we found that condensed gases activate potential emission site[9], a systematic study was conducted to try to identify the way in which our emitters are introduced into the cavities. Such knowledge would make treatment and processing more effective. Strategy has been to intentionally expose well processed and characterized rf cavity "reference" surface to various media used in cavity surface preparation[10]. After exposure tests, we carefully study both the new emitters and the resulting rf performance degradation. These tests have indicated (see Fig.9) that:

1. Clean air and clean methanol do not introduce new emitters onto a surface.
2. Water may degrade a surface, but performance can usually be recovered by He processing. More tests are needed to verify this.
3. Chemical etching agents are a problem, reducing the Q and E_{pk} .

SUMMARY OF OTHER EFFORTS

Specially designed non-accelerating "mushroom" cavities [11] have been developed to investigate how high an rf electric field a Nb surface can support. The cavity has very high E_{pk} over only a small area at the center of the dimple. In addition, the H_{pk}/E_{pk} is much less than in normal cavities. This design makes it possible to attain a very high E_{pk} without reaching an H_{pk} limitation and with a low probability of activating FE. The highest surface electric field we have reached is 145 MV/m with $Q = 3 \times 10^9$ at 1.5K.

We are also investigating high power rf processing. The benefits of rf processing at a fixed power level

diminish after a short period, but further gains are possible as the rf power increases. To this end a 3-GHz pulsed high power facility has been installed, with a peak power of 200 kW, a maximum pulse width of 2.5 ms, and a repetition rate of 1Hz. Preliminary results show a reduction of field emission after high peak power processing [12,13].

One of our major goals is to transfer to real accelerating structures our success in achieving high accelerating gradients in test cavities. In view of the limited size of our UHV furnace, the first multicell cavity we have constructed for HT [14] has 6 cells. Its E_{pk}/E_{acc} is 2.1. This cavity has been chemically treated and rf tested. The E_{acc} reached in the first test was 17 MV/m with $Q = 4 \times 10^9$ at 1.5K. It will be heat treated in our UHV furnace soon.

ACKNOWLEDGEMENTS

Sincere thanks are given to the Cornell technicians and machine shop personnel for their indispensable support. F. Barnes made a great contribution to the preparation of the tests and D. Chandler made a significant contribution to preparation of this paper.

REFERENCES

- [1] *Proc. 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, Aug. 14-18, 1989.
- [2] D. Rubin, "Superconducting RF Linear Collider." *Proc. 1989 Particle Accelerator Conference*, Chicago IL.
- [3] H. Padamsee, "A New Purification Technique for Improving The Thermal Conductivity of Nb Microwave Cavities." *IEEE Trans. Mag. Vol. Mag-21, No., 1007-1011, (1985)*.
- [4] P. Kneisel, "Use of Ti Solid State Gettering Process for Improvement of Performance of Superconducting RF Cavities." *J. Less Common Metals* 139, 179-188 (1988).
Q. S. Shu et al., "R & D in Progress to Overcome Field Emission in Superconducting Accelerator Cavities." *Proc. 1989 Particle Accelerator Conference*, Chicago IL.
- [5] H. Padamsee, "Does UHV Annealing above 1100°C as Final Surface Treatment Reduce Field Emission Loading in Superconducting Cavities?" *Proc. 1988 Linac Conference*, Williamsburg VA.
- [6] Q. S. Shu et al., "A Study of Influence of Heat Treatment on Field Emission in Superconducting RF Cavities." *NUC. Instr. and Methods in Phys.* A278, 329-338 (1989).
- [7] H. Padamsee et al., "RF Field Emission in Superconducting Cavities." *Proc. 3rd Workshop on RF Superconductivity*, Argonne IL, 251-273 (1987).
- [8] H. Padamsee et al., "New Results on RF and DC Field Emission." *Proc. 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, 207-248 (1989).
- [9] Q. S. Shu et al., "Influence of Condensed Gases on Field Emission and Performance of Superconducting RF Cavities." *IEEE Trans. Mag.* 25, 1868-1872 (1989).
- [10] Q. S. Shu et al., "The Effects of Exposing Well Processed RF Surfaces of Superconducting Cavities to Various Media." *Proc. 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, 539-569 (1989).
- [11] D. Moffat et al., "Superconducting Niobium RF Cavities Designed to Attain High Surface Electric Field." *Proc. 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, 445-466 (1989).
- [12] J. Kirchgessner et al., "Superconducting RF Activities at Cornell University." *Proc. 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, 37-52 (1989).
- [13] J. Graber et al., "High Peak Power Processing of Superconducting Cavities". *Proc. 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, 529-538 (1989).
- [14] H. Padamsee et al., "A New Shape Candidate for a Multi-Cell Superconducting Cavity for TESLA." CLNS: 90/985, Cornell University (1990).