INFLUENCE OF CONDENSED GASES ON FIELD EMISSION AND THE PERFORMANCE OF SUPERCONDUCTING RF CAVITIES

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Abstract

In a program to study the field emission (FE) and to improve the performance of 1-cell 1500-MHz superconducting Nb microwave particle accelerator cavities, we have recently achieved peak surface fields as high as 51 MV/m through the use of 1200℃ UHV annealing, methanol rinsing and high-power He processing. Performance is limited by excess FE from localized points on the cavity walls. Cycling of these cavities to room temperature and admission of He processing gas frequently produce large changes in Q correlating with the appearance or disappearance of the dominant field emitter, suggesting that condensed residual and impurity gases play a significant role in enhancing FE. By intentionally condensing O_2 into a cold cavity, we have produced similar effects, increasing the dissipated power and reducing Q each by an order of magnitude at the same field level. Preliminary tests have also been carried out with H_2 and water vapor. These results suggest that improvements in the outgassing and vacuum environment of these cavities may be important.

1. INTRODUCTION

One of the most important goals of current research on superconducting radio frequency (SRF) particle accelerator cavities is to reach the highest possible accelerating fields. 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).

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 $In(I/E^2)$ 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.[1] Since the β′s associated with the local geometry of the cavity surface appear to be of the order of 10, some other mechanism seems 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. [2]

At Cornell-LNS, we are carrying out systematic studies aimed at understanding, characterizing and controlling FE in SRF cavities. These efforts to achieve higher fields follow several lines:

1. Reducing the number of emitters by heat treatment (HT)
2. Extending the well known He and RF processing methods to suppress FE, by using higher RF power levels during processing.
3. Searching for emitter sources to find, e.g., at what stage of the surface preparation of cavities emitters are introduced onto the cavity surface.
4. Improving our understanding of FE from cold surfaces in RF fields by routinely utilizing a high-speed, superfluid-He,thermometer-based diagnostic system which provides detailed measurements of emitter densities and characteristics from temperature maps acquired at selected field levels. [4]

Recent progress in the use of heat treatment has been encouraging (see Fig. 1). Since we started HT, the average maximum E_{pk} achieved has increased by 75%, from 22 to 38.5 MV/m, and arecent test (involving HT, a methanol rinse, and He processing) resulted in a record of 50.5 MV/m. In all cases, however, it was FE loading-

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-typically from a single dominant emission site--that set the limitation.

In the course of our measurements, we have frequently noted effects which suggested that gases condensed on these dominant emitters may play a significant role in limiting cavity performance. In the following, we will discuss these effects (sections 2.1 and 2.2) and then report several experiments intended to further probe condensed gas effects (section 2.3).

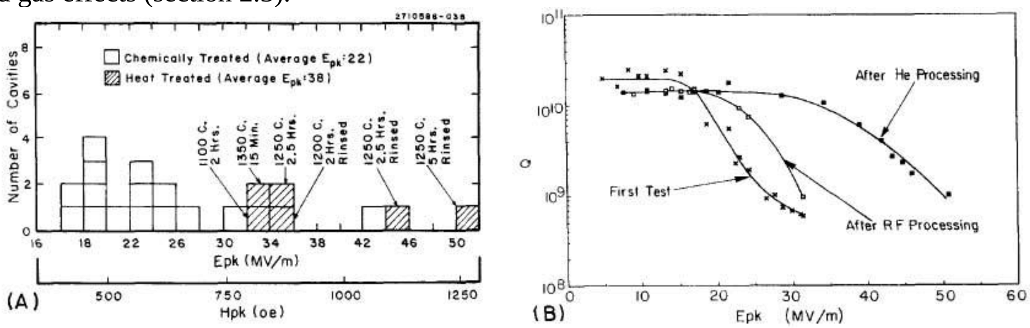


Figure 1. (a) A comparison of the maximum E_{pk} reached by fired cavities and by chemically prepared cavities. (b) Q vs E_{pk} for three stages of processing the best cavity of (a)

2. INFLUENCE OF CONDENSED GASES CASES

For each series of measurements reported-be1ow, we present the RF data as plots of dissipated power vs E_{pk}^2 or Q vs E_{pk}. Selected points along these curves are marked & accompanied by temperature maps. The maps were acquired from an array of 684 carbon resistor thermometers, carried on 36 boards (see Fig. 2). Each board carries 19 resistors and covers one longitudinal meridian. Trajectories of FE electrons accelerated by the cavity fields are such that the all the energy gained by these electrons is deposited along the same meridian as the emitter when they strike the cavity wall. The temperature mapping system has previously been described in detail.

2.1 Thermal Cycling

The first phenomenon suggesting the importance of condensed gases is the change in emission landscape often observed after cycling a cavity to room temperature. Figure 2 shows two examples. In Case I, map A was taken at E_{pk} = 38 Mv/m, the highest field attainable under those condition. After warming to room temperature and then cooling down without physically disturbing the test set-up, the dominant emitter was found to have disappeared, as shown in map B. Thermal cycling to room temperature does not always improve a cavity's emission characteristics; in some cases new emission sites appear, as shown in Case II.

Though one can imagine other mechanisms to explain these effects, the most likely seems to involve condensed gases. A site, caused to emit more strongly by an overlaying layer of gas, might be extinguished by the removal of the gas in warming up under vacuum; as the cavity cools again, residual gases may occasionally re-condense on a potential emission site, thereby activating it.

2.2 Influence of He Exposure

The second observation suggesting the importance of condensed gases comes from our experiences with He processing. The effectiveness of He processing in suppressing FE is well established. Fig. 3(a) shows an example, where the dominant emitter visible in map A at E_{pk} = 32 MV/m has been caused to disappear in map B. Expectedly, as the processing continues and higher fields are reached, new emitters appear as seen in maps C and D. (Only the dominant emitters have been shaded for clarity of presentation.)

Occasionally, however, admission of He into a cold cavity for processing is observed to activate emission. Fig. 3(b) shows an example, using the same cavity. After cycling to room temperature, maps E and F (42 and 46 MV/m) show that previously dominant emitters are now quiet (the behavior described in section 2.1). On re-admission of He, we note in map G that one of the old emitters visible in map D is now re-activated. This behavior can be explained by contaminants present in the He that recondense on an emission site which had been deactivated by room temperature cycling.

2.3 Influence of Condensed O_2

The phenomena just discussed suggest that condensed gases may be important in SRF FE processes.

Accordingly, we have carried out some experiments to check their influence more directly. First, we intentionally exposed a cold cavity to a large dose of clean oxygen gas. Fig. 4 shows the result. Map A (25.5 Mv/m) provides the baseline at the onset of FE and before admission of any gas. Map B is acquired after the spontaneous switch-on of an emission site and a correlated field decrease to 24.5 MV/m. At this stage, high purity O_2 was admitted continuously into the cavity, so that a constant pressure of -100 mTorr was maintained at the room temperature end of the cavity vacuum pipe. We suspect that most of the gas condensed along the cold pipe wall before even reaching the cavity, but a small fraction could condense on the cavity wall. Within a few minutes, the emission increased discontinuously, and E_{pk} fell to 19.7 Mv/m at about the same RF power dissipation level.

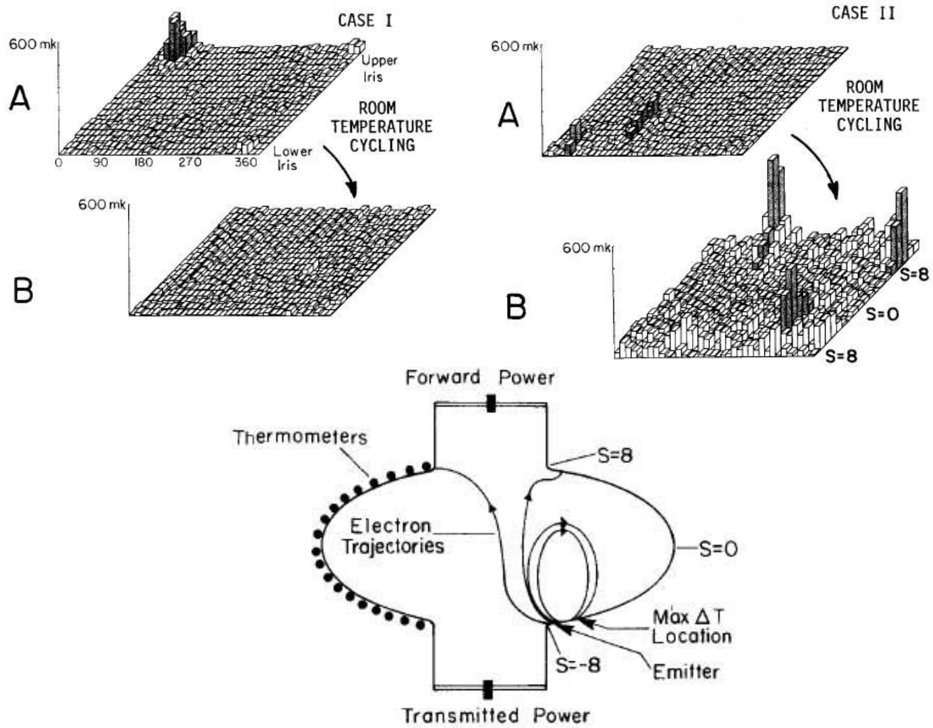
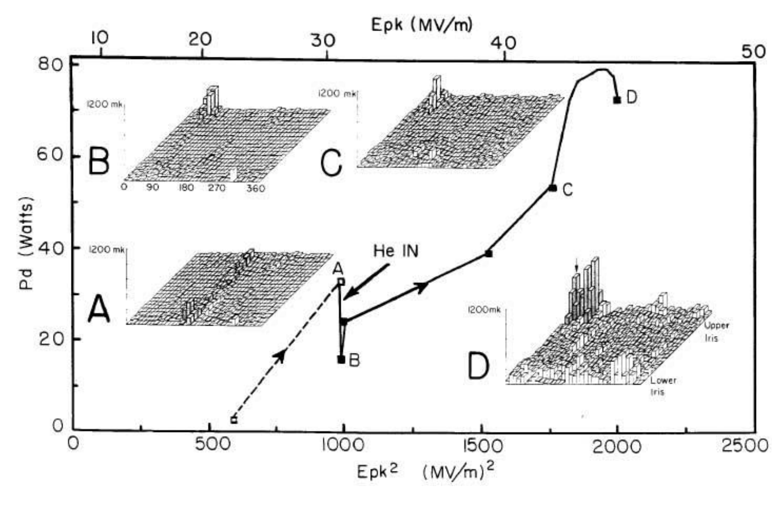


Figure 2. The influence of thermal cycling on FE. Maps show the temperature rise of each thermometer due to heating from cavity-accelerated FE electrons. Each map was taken at about E_{pk}=38 MV/m. Case I: Emitter disappears after cyclitg to room temperature. Case II: New emitters appear after cycling to room temperature. Bottom: Cavity cross-section, showing one board of thermometer resistors, four representative electron trajectories, and the coordinate system used to index emitter locations.



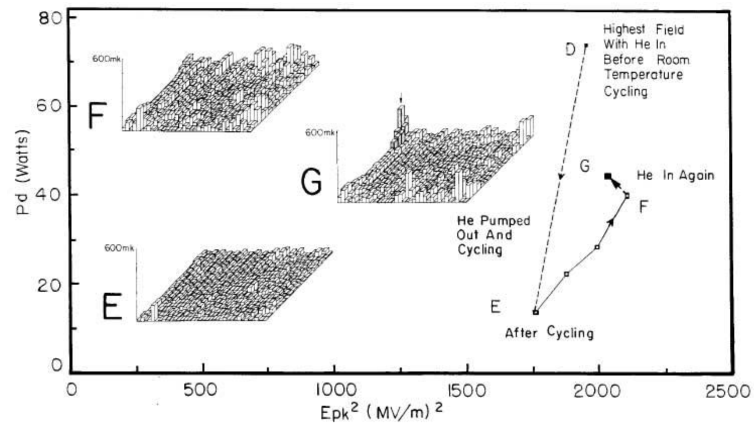


Figure 3. (a) He processing: an emitter disappears between A and B. (As the field level increases, effects of new emitters [shaded] dominate the landscape.) (b) Cycling to room temperature shows that the dominant emitters in (a) are quiet (maps E and F). Re-admission of He for further processing shows that He can re-activate an old FE site (map G).

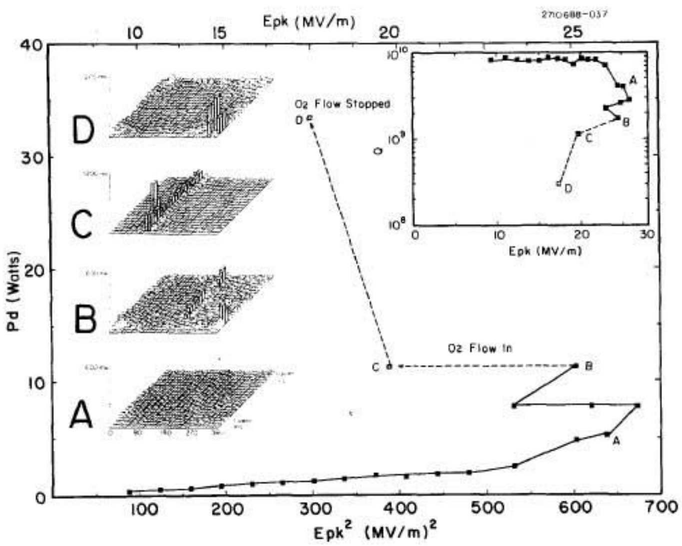


Figure 4. Dissipated power P_d vs E_{pk}^2 The dashed line represents data with O_2 flowing into the cavity. Maps A-D show the effects of new emitters that switch on due to the exposure of the cavity to O_2 The dominant emitter heating is shaded. The corresponding Q of the cavity as a function of E_{pk} is plotted at the upper right.

Map C shows the local heating due to the new emitter responsible for these effects. A computer simulation of the trajectories of emitted electrons and their energy deposit in the cavity walls shows that the observed heating profile can be produced by an emission site located at S=-7.3 cm (Fig. 2, bottom); if one arbitrarily assumes an emitter area of $1\times10^{-12}m^2$, the observed temperature distribution corresponds to $\beta = 240$.[5]

After another few minutes with continued O_2 flow, a second discontinuous field drop, to 17 MV/m, was observed. Increasing incident RF power did not appreciably raise the field level, as emission increased rapidly. Map D shows the dominant emitter (at 350°, with S=-7.4 cm and β= 265 calculated as above). At this point, dissipated poweris raised to 33 W from about 2 W, and the Q drops to about 3×10^8 from 10^{10} with the same field level.

Before concluding that only condensed gas could be responsible for these new sites, it was necessary to rule out other possibilities such as (a) bulk O_2 snow on the surface or (b) solid dust particles entrained into cavity with gas flow. To do this, the cavity was brought to room temperature without any mechanical disturbance, and the O_2 was pumped out for more than 24 hours. On re-cooling, map E in Fig. *5* was taken at E_{pk} = 23 MV/m. Here the dominant emitter previously present at 350° is absent. If the two incidents of emission increase with gas flow were caused by dust particles, it is difficult to see how they would be suppressed by the temperature cycling. Accordingly, we rule out dust.

At this stage, oxygen gas was again admitted to the cavity. However, this time we tried to reduce the gas exposure by introducing one charge (100 cm^3 at 100 mTorr) of a 50-50 mixture He and O_2 The emitter at 350° reappeared promptly as shown in Fig. 5, map F, and the field level fell to 17.9 MV/m, roughly as before. The $\triangle$T vs S profile and hence the β were essentially unchanged. It is highly unlikely that oxygen snow will land on the same spot each time; indeed, the amount of gas this time was too low to form snow. On this basis, we are left with only one remaining plausible explanation for the phenomena presented above: the emitters were activated by condensed gas.

(We note that after a few minutes with RF power, the reactivated emitter just discussed could be He processed with the He admitted in the same charge, and the field of 23 MV/m recovered with the disappearance of the emitter [map G])

3. RELATED EXPERIMENTS

The results of our experiments with oxygen suggest to us two conclusions:

(a) Other common constituents of vacuum systems such as water vapor and hydrogen may also increase FE.

(b) If condensed gases aggravate emission, it is clearly important to minimize their presence. Benefits may accrue by outgassing a cavity surface at the baking temperatures (200-400℃) used in outgassing vacuum systems. Improvements in the vacuum system connected to the cavity when cooling down may also be beneficial.

A few obvious experiments along these lines have been tried to look for gross beneficial or detrimental effects. These should by no means be treated as conclusive, but only as first simple efforts.

A cavity was baked at 275℃ for 6 hours in order to reduce the gases adsorbed on the cavity surface. Because of in vacuum seals at the ends of the cut-off tubes, only the cavity along with a short segment of each cut-off tube was heated, while the rest of the vacuum system remained at room temperature. The outer surface of the cavity was surrounded by flowing Ar to prevent oxidation. No significant improvement was observed from the baseline performance, where heavy FE was present above 22 MVIm.

Another test was made in which we tried to preferentially condense any residual gases on the field-free bottom plate of the cavity rather than on the high-field parts of the cavity surface. Thus the cavity was held at room temperature while its bottom plate was immersed in liquid nitrogen. In this condition the assembly was lowered into the pre-chilled (77K) test dewar. Liquid He was immediately added. Once again there was no improvement over the baseline performance, which showed heavy field emission above 38 MV/m.

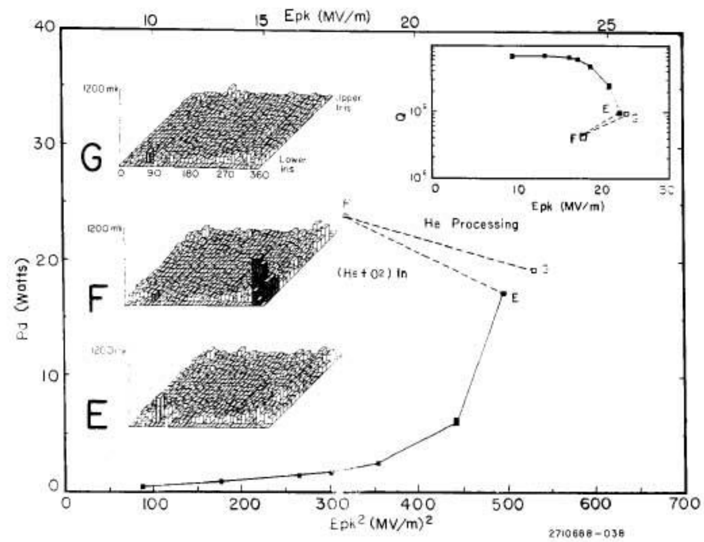


Figure 5. Performance of the same cavity as in Fig. 4 after cycling to room temperature. Map E shows the absence of the dominant emitter in Fig. 4 (map D); map F shows reactivation of the same emitter by re-exposure to O_2; map G confirms that He processing is efficient in suppressing condensed-gas-associated emission.

In another experiment we admitted several 100 mTorr of H_2 gas into the cavity and vacuum system at room temperature, and cooled down without further pumping. We estimated that about 10 monolayers of H_2 should condense on the cavity wall at liquid He temperature. Measurements showed significant alteration in the emission landscape, but little overall change in the cavity performance as measured by dissipated power and Q.

Finally, in another test, He gas was saturated with water vapor by bubbling it through water before introduction to a cold cavity for He processing. Again, no significant change over the baseline (heavy FE loading above 33 MV/m) was observed, though it is possible that all the water was condensed on other cold surfaces before reaching the cavity itself.

4. CONCLUSION

We have shown that the introduction of O_2 into a cold cavity seriously degrades its performance, reducing the Q and increasing the dissipated power by about a factor of 10. We assume that the condensation of the O_2 , onto quiescent sites stimulates them into emission, and that a similar process involving impurities present in He processing gas is responsible for the occasional appearance of new sites when He is admitted. Finally, the appearance and disappearance of emission sites on cycling to room temperature can be explained by the adsorption and desorption,of residual gas.

Though evidence for changes in FE due to condensed gases in RF cavities has been previously presented,[6] to the best of our knowledge this study provides the first direct evidence of their effects. A theoretical study has shown that it is possible for a resonant tunneling process through a thin overlying insulating layer on a field-emitting pure metal surface to increase emission.[7] While the basic emission process present in SRF cavities must be more complex, a similar resonant tunneling process can depresumably also enhance the emission in this case.

In light of the role of condensed gases in aggravating emission, it will be important to explore the possible benefits of cooling cavities in a better vacuum, as well as to attempt better outgassing of the RF surface before cool-down.

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