OVERVIEW OF ADVANCES IN THE BASIC UNDERSTANDING OF DARK CURRENT AND BREAKDOWN IN RF CAVITIES

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Abstract

In the last decade there have been substantial advances in understanding the nature of field emission through DC high voltage studies that locate emission sites, followed by electron microscopy studies to examine the sites. Emission sites have also been located in superconducting RF (SRF) cavities by temperature mapping. The sites found were also examined in an electron microscope after dissecting the cavities. In many RF tests, the emission current from individual sites was tracked with increasing field until a voltage breakdown occurred. The breakdown event was generally followed by decreased field emission. The RF test was stopped, the cavity dissected and the breakdown site analyzed by microscopy. Scanning electron microscopy, energy dispersive x-ray analysis, and Auger studies were used to obtain topographical and elemental information about the emission and breakdown sites. Although these studies were primarily motivated by the desire to reduce field emission in superconducting niobium cavities, the lessons learnt, and the models that have emerged, apply to all field emitting surfaces.

1 INTRODUCTION

The superconducting approach to the next linear collider aims for surface fields E_{pk} >50 MV/m in ten thousand cavities. At these electric fields, an important limitation to the performance of superconducting cavities arises from the emission of electrons from high electric field regions. Power is absorbed by the electrons and deposited as heat when electrons impact the cavity walls. If the emission grows intense, it can even initiate thermal breakdown of superconductivity. In the normal conducting, high frequency approach to linear colliders the goal is to operate ten thousand copper structures at E_{pk} between 100–200 MV/m with klystrons that will supply 50–100 MW of power. Field emission (dark current) is a major concern for the accelerating structures as well as for the output cavities of klystrons, which must operate at comparably high electric fields. Field emission electrons can be captured and accelerated along the structure. A high dark current in the structure may cause transverse wakefields, and spoil the emittance of the beam. It can present problems to various diagnostic equipment in the accelerator.

One of the consequences of high field emission is electrical breakdown, or sparking. Voltage breakdown is found to be beneficial to rf cavities. In a process referred to as conditioning, after several breakdown events, the dark current decreases, and the field in a structure can be raised. However, excessive breakdown events can physically damage a klystron output cavity, changing its resonant frequency and destroying the klystron. There is a need to understand how field emission leads to breakdown and processing, so that the important parameters for conditioning can be identified, for e.g., power level, field level, pulse length.

To address these issues, there have been extensive studies about the nature of field emission sites and the development of voltage breakdown. Based on the results from DC and RF studies, as well as from extensive DC breakdown studies in the literature, models have emerged that elucidate the nature of field emission as well as the nature of breakdown. These studies have stimulated the invention of techniques to avoid emission sites and to destroy them.

2 DC STUDIES OF EMISSION SITES

Using needle-shaped tungsten electrodes, cm^2 surface area samples were scanned for emission sites. Niobium, copper and gold cathodes were studied at Geneva[1], Saclay[2] and Wuppertal[3]. The number of sites observed increased rapidly with increasing field. Artificial emission sites were also introduced and studied.

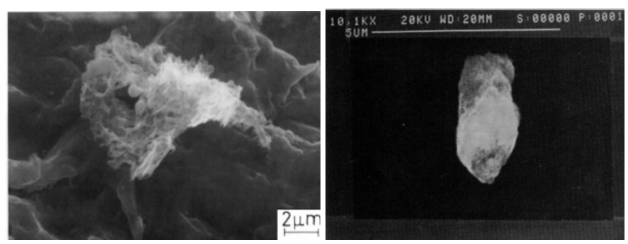

Figure 1. Microparticle field emitters. Foreign elements found were (left, scale bar = 2 µm) C (right, scale bar = 5 µm) Si and O (Geneva and Saclay)

Once individual sites were identified, they were examined by surface analytical instruments. In general no whiskers were found. However, if the surface was scratched, the projections at the edge of the scratch were strong field emitters. But scratches are rare on well prepared surfaces. Instead, the predominant emitters found were "metallic" microparticle contaminants. Fig. 1 shows electron microsocpe pictures of field emission sites found

† Supported by the National Science Foundation.

in DC studies at Geneva and Saclay. The foreign elements found in these emitters are listed in the captions. After extensive studies, the following list of elements have been found in particulate emitters: Ag, Al, C, Ca, Cl, Cr, Cu, Cs, F, Fe, K, Mg, Mn, Na, Ni, O, S, Si, Ti, W, and Zn.

3 EMISSION SITES IN CAVITIES

Individual field emission sites were located in single cell niobium superconducting cavities by temperature mapping. The heat deposited by the impacting electrons is detected by an array of thermometers placed on the outer wall of the cavity. The heating profile can be unfolded with the help of the calculated electron trajectories to yield the FN properties and the location of the emitting site to within a few mm. Occasionally it was even possible to detect the RF heating due to the emission site.

By many tests on several cavities at CERN[4] and Cornell[5], the density of emission sites found in RF cavities is compared in Fig. 2 with the density of sites observed in DC studies. Note that the Geneva DC samples were exposed to ordinary room air and show a larger density of sites as compared to the Wuppertal samples which were prepared in a class 100 clean room. For emitters found in SRF cavities, the Fowler Nordheim (FN) β values were between 100–700, and the emissive area values were between 10^{-9} to 10^{-19} m^2, in rough agreement with the range of FN emitter properties found in DC studies.

Some of the emission sites found in the SRF cavities were subsequently examined in an electron microscope after dissecting the cavities. Fig. 3 shows two such emitting areas; one site consists of stainless steel particles[6], and the other site is an indium particle[7]. Note that there are small regions where the particles are melted. It is likely that the melting occurred due to the joule heating from the high field emission current density which, according to the measured β values was estimated to be 10^{11} to 10^{12} A/m^2.

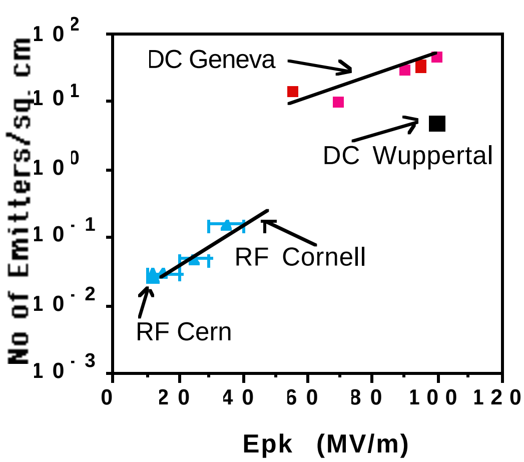

Figure 2. Density of field emission sites in DC and RF studies

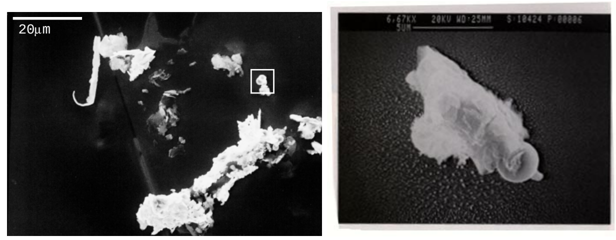

Figure 3. SEM micrograph of (left, scale bar = 20 mm) stainless steel particles found to be emitting and (right, scale bar = 5 mm) an indium metal flake field emitter. Small melted regions can be recognized by their spherical shape.

So far, the range of FN properties, the typical morphology and the elemental composition of emitters in RF and DC studies are very similar. To test the exact same emitter under RF and DC conditions, iron particles were placed on a cathode and studied in a DC field emission microscope at Saclay[9]. Subsequently, the cathode (and the particles) were transferred into a copper RF cavity. In both DC and RF fields, the FN properties were found to be nearly the same.

The only known difference between DC and RF field emission is the behavior of insulating particles. At Geneva[1], insulating particles, identified by their tendency to charge up during SEM examination, were found not to emit. In artificial contaminant studies at Saclay[9], insulating particles, such as A_2O_3 and SiO_2, when placed on a niobium or gold surface, did not emit in a DC field, but were found to emit when placed in a copper RF cavity. One possible explanation for the difference is that the theramally isolated and insulating particles heat up to high temperatures in RF fields, and become more conducting, due to excitation of electrons across the insulating band gap. Thus even insulating particles could behave "metallic" in RF fields.

It is often found that emission switches on at a certain field level, and remains on when the field is lowered. Recent thermometry studies[10] with a niobium cavity showed that the switch-on is associated with the arrival of a particle, detected by the increased RF heating at the emission site. DC studies have also shown that particles in high electric field regions can tear away from the surface, thereby producing a mechanism for emitter switch-off[9].

4 NATURE OF FIELD EMITTERS

A remarkable finding from DC studies is that only 5–10% of the total number of foreign particles are emitters. What makes a micron-size particle into a field emitter?

As already mentioned, if it is insulating it is not an emitter in a DC field. Another important distinguishing aspect between emitting and non-emitting particles is the jagged structure of emitting particles. In DC field emission studies conducted at Saclay[11] with artificially introduced particles, it was found that smooth, spherical iron or nickel particles do not emit, but jagged particles emit strongly. In a simple geometrical interpretation, the particle as a whole enhances the field and smaller protrusions on the particle further enhance the field, so that the combined enhancement is sufficient to explain large β values.

This simple geometric explanation can only be part of the story, however. Not all irregular shape artificially introduced “metallic” particles of MoS_2 were found to emit[1]. Results from DC field emission studies at Wuppertal[3] suggest that the interface between the particle and the substrate plays an important role. As shown in Fig. 5, heating a Nb surface and its emitting particles to 1400 C renders the surface emission free. Many emitting particles disappear with the heat treatment, but not all. One may argue that at 1400 C the jagged residual particles became smooth. However, as Fig. 5 also shows, re-heating a 1400 C heat-treated, emission-free Nb surface to 200 C converts residual non-emitting particles into emitters. It is unlikely that heating to 200 C will make a smooth particle into a jagged one. One possibility is that the interface between the particle and the underlying surface plays an important role, and is responsible for the changes in emission with heat treatment.

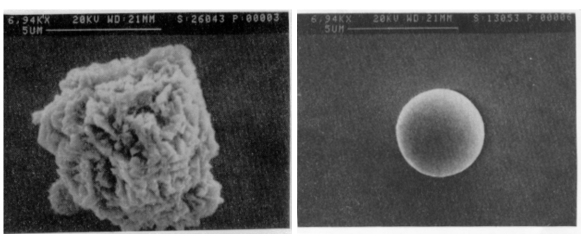

Figure 4. SEM micrographs of nickel, (left) the jagged particle is emitting (right) the smooth particle is non-emitting up to 100 MV/m (Saclay)

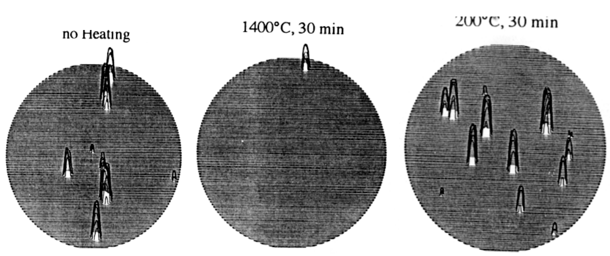

Figure 5. DC field emission show peak areas of high emission. (left) Without heat treatment. (middle) An emission-free niobium surface obtained by heating to 1400°C. (right) Reheating a 1400°C treated field emission-free surface to 200°C creates new emitters. (Wuppertal).

Based on studies of emitted electron energy spectra, the Aston group[12] has proposed a Metal-Insulator-Metal model which involves an insulating interface between the emitter and the base metal. In the presence of a local field enhancement due to the metal particle, electrons tunnel into the insulator from the metal substrate. Here they acquire kinetic energy from the penetrating electric field and are "heated". The electron population at high energy is similar to that of a metal surface at a high temperature. Those electrons with enough energy to pass over the surface potential barrier are emitted into the vacuum as in a standard thermionic emission process. The detail nature of the insulating interface determines the surface potential barrier and therefore the magnitude of the emission current. Emitter switch-on mechanisms are also proposed based on the formation of conducting channels in the insulating interface.

Another important factor that plays a role in whether a particle is a field emitter or not is the influence of condensed gas. There is substantial evidence to show that condensed gas can start field emission[13]. The emission landscape observed by temperature maps was found to change on warming a cavity to room temperature and re-cooling. New emission sites were activated when He and O_2 were admitted into a cold cavity. These sites became dormant when the cavity was warmed up to room temperature. Re-admission of gas was found to activate the exact same sites. A theoretical model of resonant tunelling due to adsorbed atom states was proposed a long time ago[14]. Adsorption of hydrocarbons, on the other hand, was found to decrease emission, by raising the work function[15].

5 VOLTAGE BREAKDOWN

In many instances, during tests[7,10] on 1-cell 1.5 GHz and 3 GHz niobium cavities, increasing field emission current from individual sites was tracked with increasing field using temperature maps, until a processing event occurred. This event was recognized by decreased emission. After the event, the RF test was stopped, the cavity dissected and the breakdown site analyzed by electron microscopy. Sites such as those shown in Figs. 6 were found at the processed emitter locations. They have a starburst shape with molten, crater-like core regions. In most cases the craters were molten niobium. Micron size molten particulate debris near the molten craters were analyzed by EDX to reveal contaminants, such as copper, indium, iron and titanium. Thin layers of foreign metals coating the craters were analyzed by the more surface sensitive Auger method to reveal foreign elements[16].

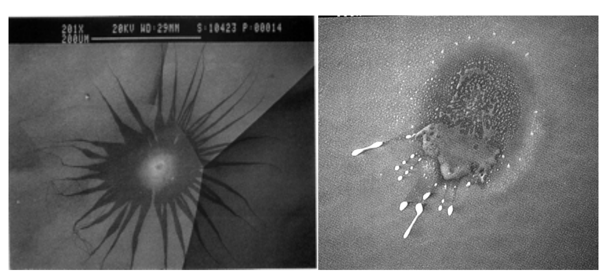

Figure 6. SEM pictures of a processed site found at the (left) Low magnification shows a starburst believed to be caused by a plasma. (right) High magnification SEM picture shows a central crater region within the starbursts, e.g. molten indium particles in a splash pattern.

After analysis of nearly 100 processed sites, the list of foreign elements found near exploded emitter craters is C, Ca, Cr, Cu, F, Fe, In, Mn, Ni, O, Si, Ti. This list has a substantial overlap with the list from DC studies.

Studies of cathode spots from DC arcs[17] reveal many similarities to the results discussed here. Photographs show 100 µm luminous spots (plasma), and post-mortem pictures show molten crater areas. As in the cavities, individual craters found have a characteristic size on the order of microns. But the starburst features found in Nb cavities were never reported in DC studies. Pursuing these close similarities, experiments were carried out to look for the starbursts by initiating a spark with high DC voltage across a small gap between two Nb electrodes in UHV[18]. The Nb surface was prepared by the same treatment as cavity surfaces. SEM studies of the Nb cathode in the sparked area showed a starburst with molten cores. (Fig. 7), similar to those found in Nb cavities. It is therefore plausible to conclude that starbursts found in RF cavities also take place during a spark or discharge.

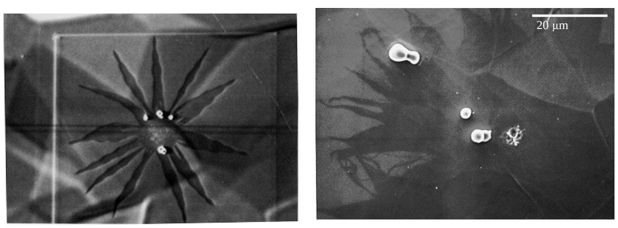

Figure 7 (left) SEM micrograph of a starburst and central molten crater found on a Nb surface at the location of a DC spark at 100 MV/m. (right) Large molten iron drops found at the periphery of a starburst show high temperatures reached inside a starburst region.

Further surface studies of starburst regions reveal much about the activities within the plasma. Auger studies[16] have shown that the surface within the dark starburst region is cleaner, i.e an absence of foreign elements. Occasionally (Fig. 7) large molten particles are found at the outer periphery of a starbusts, suggesting that the temperature of the starburst region exceeds 1000 C.

Extensive tests have been carried out at SLAC [19] on 3 GHz and 11.4 GHz copper cavities using high power (50–100 MW) pulsed RF (µsec). Surface fields between 200–600 MV/m were reached after many hours of spark conditioning which reduced the dark current by orders of magnitude. During the sparks the emitted current increased by a factor of 20–30 and the vacuum degraded from 10^{-8} to 10^{-7} torr. The pressure bursts suggest gas evolution during sparks. Subsequent visual inspection of high field regions show numerous crater areas, with many overlapping craters. After processing to very high fields the entire iris is pock marked by overlapping craters. It would be interesting to conduct Auger studies of craters in copper cavities to reveal the foreign elements responsible.

That the presence of gas is important to initiate a breakdown event was confirmed by a He processing experiment on a Nb cavity[6]. Temperature maps showed that at the maximum field level and available RF power a field emission site did not yield to RF processing. However, when He gas was admitted, the site processed immediately. After dissection, SEM pictures at the site showed the explosive event of Fig. 8.

Recent DC high voltage studies show gas desorption plays an important role in the onset of voltage breakdown[15].

6 A MODEL FOR BREAKDOWN AND PROCESSING

We have seen in Fig. 3 that field emission is accompanied by partial melting of the site even before the site is processed and, from the He processing event, that the presence of gas is important for the breakdown event. The gas for the discharge could come from the metal vapors issuing from the molten regions, or from the evolution of surface-adsorbed gases. Additional heating due to ion bombardment may be responsible for further melting and gas evolution. The field emitted electrons ionize the gas forming a plasma. The activity in the plasma region leaves a clean starburst as a physical trace on the Nb surface or appears as a luminous spot reported in DC studies.

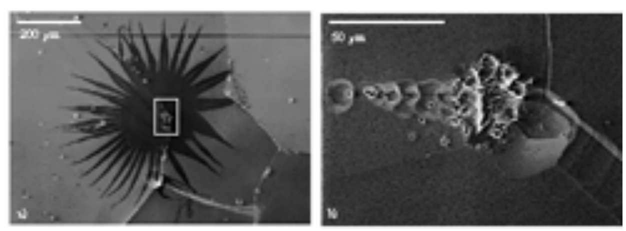

Figure 8. (Left, scale = 200 µm) SEM picture of the helium-processed site showing (a) a starburst and (right, scale = 50 µm) molten craters in an expanded view. Note that (right) is rotated by about 60 degrees relative to (left).

Recently, MASK simulations[10] have been carried out to study how the field emission current ionizes gases present in the vicinity of the emitter. These studies show that, since the ions move slowly relative to the electrons, a significant number of ions accumulate near the emitter, and lead to a substantial electric field enhancement. The ion enhanced fields can become very large. For example, if the peak RF applied field is 30 MV/m at an emitter with $\beta = 250$ and area of 3×10^{-14} m^2, the ion enhanced field is 100 MV/m at 1 µm from the original emission site, 200 MV/m at 0.5 µm and higher still closer to the emitter. When the field emission current starts to increase unstably, the simulation is stopped. We deduce that a discharge follows when the large number of ions produced nearby the site cause an instability in the field emission current. At the core of the spark the avalanche heating must be sufficiently intense to cause the melting and explosive cratering found. Unlike the original particle, which has jagged features, the crater and other melted particles do not emit because they are smooth particles. Foreign elements from the original emission site are left behind after the explosion as debris, or as a thin film over the melted region. Both types of debris have been identified. The enhanced fields from the slowly spreading ion cloud may also initiate multiple arcs between the ion cloud and the surface, resulting in multiple craters from an individual emission site. It is plausible that the ion enhanced fields stimulate emission from regions of the surface that have lower β values.

According to the MASK simulation, the number of ions produced and the associated field enhancement depends on the total current from the emitter. Previous estimates based on processed emitter data[7] have also indicated that it is necessary for the total current to approach a threshold level ($\approx$ mA) in order for an emitter to process.

7 IMPLICATIONS & CONCLUSIONS

The DC and RF studies show that most emitters are micron-size contaminants that come from surface preparation, cavity assembly procedures and the vacuum apparatus. To minimize such contaminants it is important to assemble cavities in class 100, dust free clean rooms. However, even though clean room assembly is necessary, it is not enough to give field emission free cavities for $E_{pk} > 20$ MV/m. Additional cleaning measures, or emitter destruction measures, are needed. High pressure (80–100 bar) water rinsing of the cavity surface has been found to provide field-emission-free surfaces to $E_{pk} = 60$ MV/m in superconducting cavities[20].

We have seen that individual emitters can be exploded during breakdown event. The model of breakdown suggests ways to improve processing of emission sites. For a site with a particular value of β and A_e, the field must be increased to reach a βE value corresponding to an emission current density of $> 10^{11}$ A/m^2 to approach heating and melting at the site so that a sufficient gas density is created. But to process a site the total current must be increased to a threshold value approaching $\approx$ mA. To reach the necessary field level, high RF power is required. Short pulses are sufficient, because the emitter explosion takes place very fast (< µsec) when the conditions are ripe. MASK simulations and DC field emission studies using very short pulses show that spark formation times are between nsec to µsec[21].

From systematic pulsed power conditioning experiments carried out[7,22] with 1-cell, 2-cell and 9-cell niobium cavities at 1.3 and 3 Ghz using pulsed power levels between 50 kW and 1 MW, and pulse length between 5 µsec and 0.5 msec, we find that the most important parameter for successful processing is the value of the surface field reached**.** To obtain *field emission free* behavior at a certain operating field level, experiments show that it is necessary to condition cavities to approximately twice the operating field. Conditioning for longer times at the same field level, or with longer pulses at the same field level did not help to reduce the dark current or to reach higher fields.

REFERENCES

[1] Ph. Niedermann, PhD Thesis No. 2197, Univ. of Geneva (1986).

[2] C. Chianelli, Proc. of the 5th Workshop on RF Superconductivity, DESY, ed. D Proch, p. 700, DESY-M-92-01 (1991).

[3] N. Pupeter et al, Proc. of the 7th Workshop on RF Superconductivity, ed., B. Bonin CEA/Saclay 96 080/1, p. 67 (1995) & E. Mahner, Proc. of the 6th Workshop on RF Superconductivity, CEBAF, Ed. R. M. Sundelin, p. 252 (1994).

[4] W. Weingarten, Proc. of the 2nd Workshop on RF Superconductivity, CERN, ed. H. Lengeler, CERN , p. 551 (1984).

[5] H. Padamsee, Proc. of the 4th Workshop on RF Superconductivity, KEK, ed. Y. Kojima, Rep. 89-21, p. 207(1990).

[6] J. Knobloch et al, Proc. of the 1995 Part. Acc. Conf., Dallas, p. 1623 (1995).

[7] J. Graber, Nucl. Inst. and Meth. in Phys. Res. A 350, p. 572 & p. 582 (1994).

[8] B. Bonin et al, Proc. of the 6th Workshop on RF Superconductivity, CEBAF ed. R. Sundelin, p. 1033 (1993).

[9] J.Tan Proc. of the 7th Workshop on RF Superconductivity, ed., B. Bonin CEA/Saclay 96 080/1, p. 105 (1995).

[10] J. Knobloch, PhD Thesis, Cornell University.

[11] M. Jimenez et al, J. Phys.D, Appl. Phys. 27, 1038 (1994).

[12] N.S. Xu, High Voltage Vacuum Insulation, Ed. R.V. Latham, Academic Press, p. 115 (1995).

[13] Q.S.Shu et al, IEEE Trans. Mag-25, 1868 (1989).

[14] C.B. Duke and M.E. Alferieff, J. Chem. Phys. 46, 923 (1967).

[15] W.T. Diamond, Chalk River Internal Report Nos. TASCC-P-97-4&5.

[16] T. Hays in refs [8] p. 750 (1994).

[17] Pulsed Electrical Discharge in Vacuum, G.A. Mesyats and D.I. Proskurovsky, Springer Verlag (1988).

[18] D. Moffat et al. Part. Accel. 40, 85 (1992).

[19] J.W. Wang and G.A. Loew, Proc of the 1989 Particle Acc. Conf. IEEE Catalog No. 89CH2669-0, 1137 (1989).

[20] P. Kneisel and B. Lewis, in refs [9] p.311 (1995).

[21] G. A. Mesyats, IEEE Trans. Electrical Insulation, EI-18,(3). 218 (1983). & B. Juttner, IEEE Trans. Plasma Science, PS-15(5),474 (1987).

[22] C Crawford et al, Particle Acc. 49, 1 (1995).