FIELD EMISSION IN RF CAVITIES

B. Bonin
Commissariat à l'Energie Atomique, DSM/DAPNIA, France

Abstract
Electron field emission limits the accelerating gradient in superconducting cavities. The present paper shows how and why it is an important problem. The phenomenology of field emission is then described, both in DC and RF regimes. In a third part, the merits of a few plausible "remedies" to field emission are discussed.

1. WHY IS IT A PROBLEM ?

When exposed to an intense, properly oriented electric field, a conducting surface can emit electrons. In the case of an accelerating cavity, these electrons are accelerated by the RF field in the cavity. In normal conducting cavities, "field emission" must be avoided because it is a precursor to vacuum breakdown and is likely to cause dark current. Superconducting cavities are even more sensitive to field emission: in a superconducting cavity, even the small additional dissipation of RF power due to the electron loading of the cavity may correspond to a significant and undesirable degradation of the cavity Q-value, and an increase of the cavity cryogenic consumption (Fig. 1).

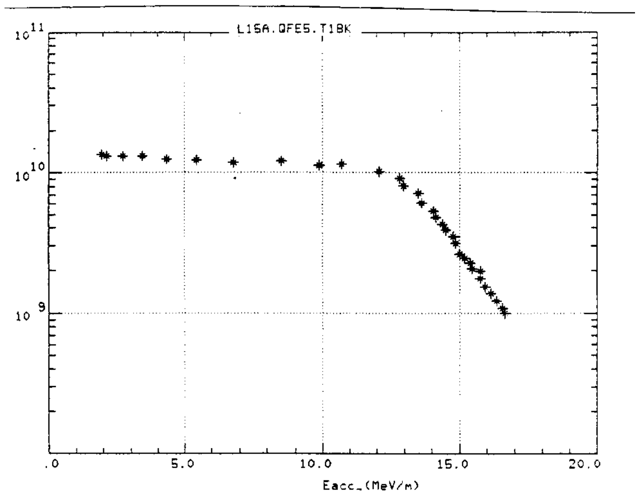

Fig. 1 Q-value vs accelerating gradient for a typical superconducting cavity. In this example, Q-degradation beyond E_{acc} = 12 MV/m is due to electron loading.

Furthermore, the emitted electrons follow complicated trajectories inside the cavity (Fig. 2). If the cavity is excited on the TM010 mode, the electron trajectories remain in the same meridian as their starting point. The electrons ultimately land on the cavity wall with an energy roughly proportional to the accelerating gradient (typically a few hundreds of keV for an accelerating gradient of 10 MV/m in a 1.5-GHz single-cell cavity). The corresponding energy deposit is usually rather local. It creates a hot zone on the superconducting surface, which can be identified in the temperature maps of the cavity as a ridge parallel to a cavity meridian (Fig. 3). This energy deposit is liable to hamper the thermal stability of the cavity, thereby limiting the accelerating gradient. The heating is also accompanied by copious X-ray emission originating from the electron landing point.

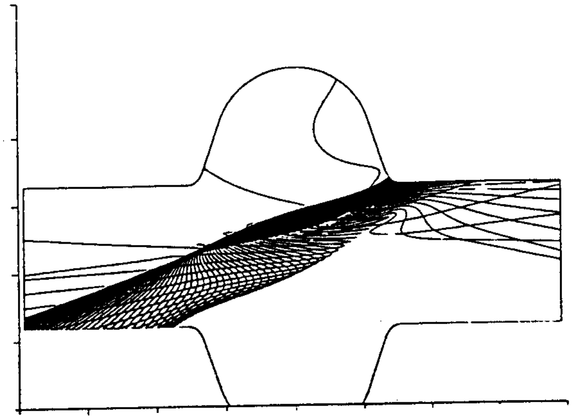

Fig. 2 Trajectories of electrons emitted inside the cavity

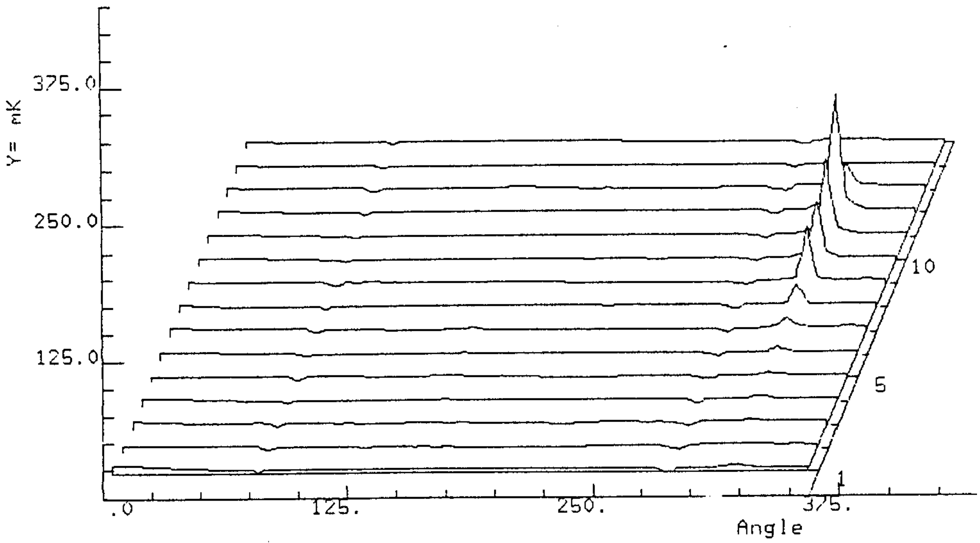

Fig. 3 Temperature map of a superconducting cavity plagued by field emission

The order of magnitude of the field emission current able to limit superconducting cavity performance is around a few μA. The field emission "disease" is very common indeed: for example, 60% of the CEBAF superconducting cavities are limited in gradient by field emission. This alone would justify the research efforts from many laboratories, aiming at a better understanding of the phenomenon, and at finding ways to avoid or to cure it. However, field emission is not always considered as a harmful phenomenon. It is exploited in vacuum electronics to produce cold electron sources. Here, the efforts go in the opposite direction, aiming at finding ways to enhance and to stabilize the emission. The author found it especially useful to compare the results from both communities, ie those who promote and those who fight against field emission.

2. PHENOMENOLOGY OF FIELD EMISSION

Fowler-Nordheim theory

In a metal, electrons are usually prevented from escaping by a potential barrier separating the Fermi level in the metal and the vacuum level. When an electric field is applied, the vacuum level takes a slope, and the barrier becomes triangular (Fig. 4). The width of the barrier decreases with increasing field. When it becomes thin enough, the probability for electrons to tunnel through the barrier becomes non negligible, and a field emission current arises. The height of the barrier is known as the metal work function, and amounts to 4–5 eV, according to the nature of the metal. Given this height, Fowler and Nordheim [1] calculated the tunnel probability through the barrier and derived the following relationship between the current density j and the the electric field E, for a perfect metal with a Fermi-Dirac electron density at 0 K:

$$j = \frac{A.E^2}{\Phi} \exp(-B\frac{\Phi^{3/2}}{E}) \tag{1}$$

If j is expressed in $A.m^{-2}$, E in $V.m^{-1}$, and Φ in eV, the constants A and B are respectively:

$$A = 1.54.10^{-6}$$
$$B = 6.83.10^{9}.$$

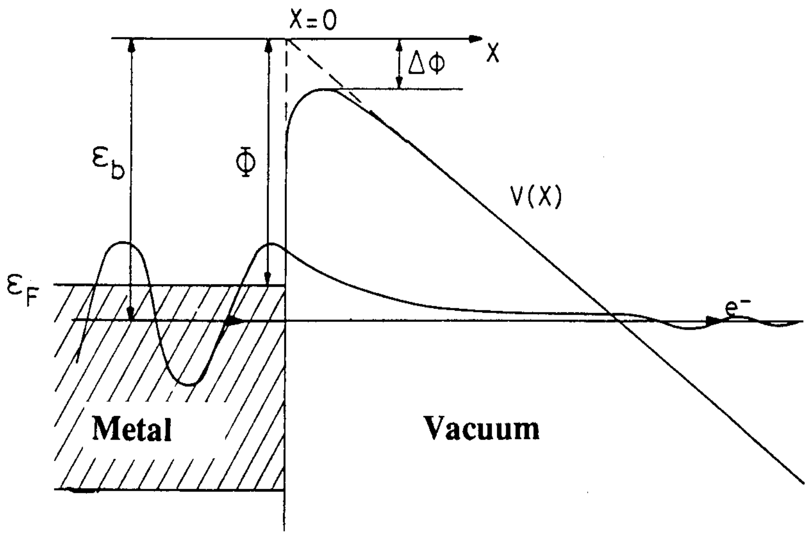

Fig. 4 Energy diagram of a metal-vacuum interface. The electrons fill the energy levels of the conduction band, up to the Fermi level. If an electric field is applied to the surface, the potential barrier seen by the electrons becomes triangular.

This law predicts a negligible current for fields below a few GV/m, and a very steep rise of the current above this limit. For very clean metal surfaces of restricted area (the tip of a sharp needle), the F-N law has been verified in a large domain of current densities, despite some difficulties to evaluate properly the magnitude of the local electric field in the metal vicinity. For current densities larger than $j \approx 10^{12}$ A/m^2, the agreement between theory and experiment apparently breaks down [2], probably because space charge phenomena arise, and because tip breaking due to the Joule effect tends to modifiy the surface morphology.

If the field emitted current density is maintained well below 10^{12} A/m^2, emission appears to be stable in time if the tip is maintained in ultra high vacuum. In vacua less than 10^{-8} mbar, species adsorbed on the tip can modify the shape of the potential barrier seen by the electrons, and the current density fluctuates [3].

Enhanced field emission (EFE)

For large area electrodes with a less well characterized surface, the phenomenology appears to be entirely different [4]. A significant current can arise for electric fields as low as a few MV/m. Many studies have shown that the emission is localized on microscopic emitting sites [5]. Each site seems to obey a phenomenological F-N law, with effective parameters: there is still a linear relationship between Log(I/E^2) and $1/E$ (Fig. 5), but if one assumes an unchanged value for the work function Φ of the emitting site, the local electric field seems to be enhanced by a factor β of the order of 100, and the effective emission is restricted to small, but very variable areas S [6]. The current I emitted by one site is then given by:

$$I = S.\frac{A.\beta^2.E^2}{\Phi}\exp(-B\frac{\Phi^{3/2}}{\beta.E}) \tag{2}$$

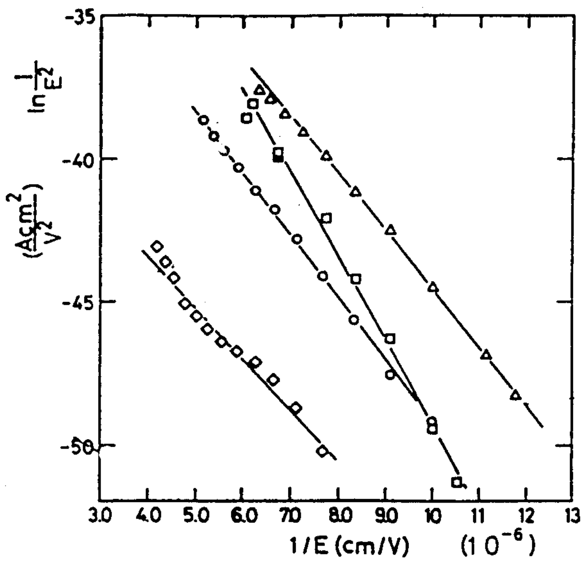

Fig. 5 Field emission characteristics of four emitting sites (from P. Niedermann, Ref. [7])

Recent investigations have correlated these emitting sites with surface defects, identifiable by electron microscopy [7]. (More precisely, not all the surface defects behave as emitters, but all emitters could be identified as previously existing surface defects.)

It was proved that particulate contaminants were powerful field emitters, with somewhat unstable field emission characteristics. Irregularly shaped conducting particles seem to emit much more than smooth ones [8]. Scratches, or other geometrical defects of the surface also behave as field emitters, with a more stable emission.

On a given surface, there is a considerable scatter in emitter characteristics. This results in a widely spread hierarchy of emitters. Consequently, even on surfaces of very large area, there is only one or a few emitter(s) whose current dominates over all the other ones.

Microscopic investigation of emitting sites reveals thermal effects associated with field emission. After exposure to electric field and emission of 1-100 μA, emission of some sites is often observed to drop.abruptly. This change appears to be associated with the sudden melting of the emitter (Fig. 6). Frequently, this melting takes place at the sharpest protrusion on the surface, thus suggesting that the previous active emitter was located there. Craters of molten material are also frequently observed [9], and seem to be correlated with a micro breakdown, and with the death of an emitting site. New emitters are often formed on the crater rim.

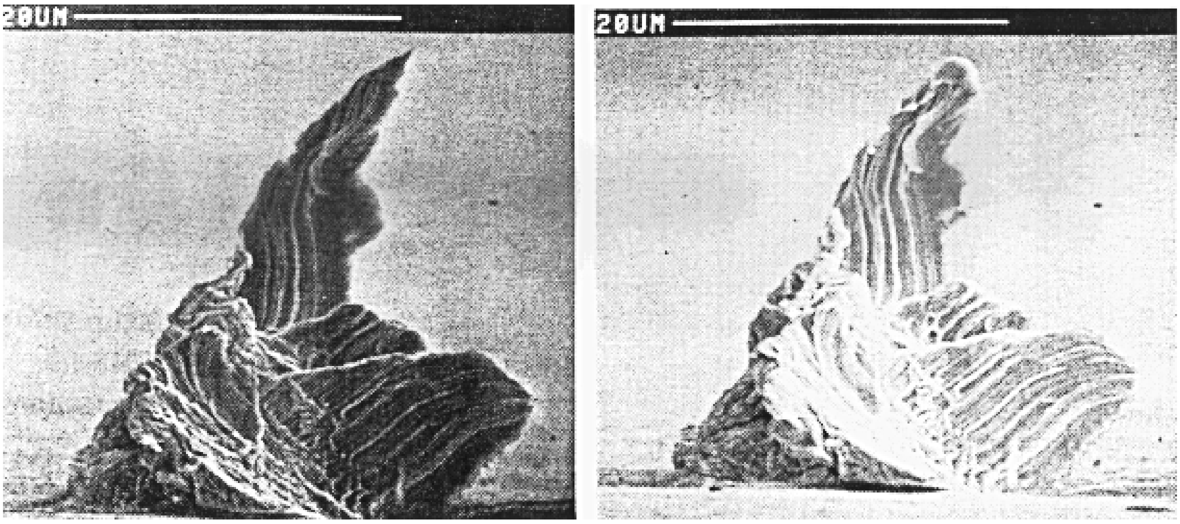

Fig. 6 Microphotograph of an emitting site: a) before emission; b) after emission. Note the apex melting.

Enhanced field emission in RF regime

Enhanced field emission has been extensively studied in DC regime, but has received much less attention in RF regime. So far, we have no indication that EFE should obey a different mechanism in DC and RF regimes. The typical tunneling time through a barrier of height $\hbar$ can be estimated via the uncertainty principle:

$$\tau \approx \frac{\hbar}{\Phi} \approx 2.10^{-16} \text{ s.}$$

This time is short compared with the RF period, it is thus legitimate to assume that the field emission process is instantaneous and occurs in a “quasi static” electric field. With this approximation, the average current emitted in RF regime can be calculated, using Eq. (2):

$$\begin{aligned} &< I > \approx S.\frac{C.\beta^{2.5}.E_{peak}{}^{2.5}}{\Phi} \exp(-B\frac{\Phi^{3/2}}{\beta.E_{peak}}) \\ &C = \frac{2.\sqrt{2}}{3.\pi}.\frac{A}{\sqrt{B.\Phi^{3/2}}}. \end{aligned} \tag{3}$$

Note that the law obtained analytically is very similar to the F-N law, except the 2.5 exponent in the prefactor. This law is in excellent agreement with experiment [10], with effective parameters β and S quite similar to the ones.extracted from DC measurements. This certainly adds credit to the conjecture that EFE obeys the same basic mechanism in DC and RF regimes.

The geometrical model

Many explanations of EFE have been proposed [11]. In this course, presentation of the simplest one is probably sufficient. Many geometrical defects such as scratches or conducting particles have been shown to emit mainly because there is a geometrical enhancement of the electric field at the apex of a protrusion of microscopic or even nanometric scale [8].

The degree of generality of this mechanism is still under discussion. It does not account for the role of adsorbates, which are noted for their capability to modify field emission, not for the odd energy spectra which were observed by Latham on some emitters [12]. However, there is no doubt that at least a large fraction of the emitting sites obey this simple mechanism.

Field emission from superconductors

Is field emission the same for normal metals and for superconductors? The gap brought by superconductivity in the electronic density of states is too narrow to have a significant consequence on the field-emitted current. Experimentally, no difference of field emission from a niobium tip was noted at the superconducting transition [13].

3. HOW TO AVOID FIELD EMISSION

Instabilities

EFE is a rather unstable phenomenon: emitters are known to switch “on” and “off”, and the field-emitted current often fluctuates. It is interesting to analyze these instabilities, because there is some hope to use them to destroy emitters.

Firstly, one can expect mechanical instabilities of the emitters. Because of the large field enhancement at the emitter apex, the electrostatic pressure

$$p = \varepsilon_0 . E^2_{microscopic}$$

gets close to the yield stress of usual metals. Necking or even breaking of the apex can thus occur, and the subsequent modification of the surface geometry results in changes in its field emission characteristics [14]. If the emitting site is a particle sitting on the surface, the same electromagnetic pressure can overcome adherence forces. Larger particles are loosened at lower electric fields. Note that the force exerted by the substrate on the particle is always repulsive, independent of the sign of the electric field, so that this “cleaning” mechanism is effective in RF as well as in DC regime [15]

The second kind of instability is of thermal origin. Several mechanisms can affect the emitter temperature [16]. Joule heating due to the field emitted current through the very narrow emitter apex does not make a significant contribution to the elevation of the apex temperature, unless the current density exceeds 10^{12} A/m^2. In RF regime, Joule heating due to the current induced through the emitter can contribute significantly to increasing the temperature of the emitter. Ion bombardment can also heat up the emitter. The process may be initiated by ionization of species desorbing from the surface. Ions accelerated by the field can deposit their kinetic energy on the metal surface at the end of their flight. This heating then promotes further desorption and ion bombardment. Further heating may cause vaporization of the metal itself, accompanied by a considerable enhancement of the vapor and ion density in the vicinity of the emitting site. This process is believed to lead to explosive phenomena and vacuum breakdown [17]. It leads generally to the destruction of the original emitting site, and to the formation of craters (Fig. 7). All these heating mechanisms are more effective if emitters are particulate contaminants in poor thermal contact with the substrate.

The emitters are thus mechanically and thermally fragile. This has been a matter of concern for the designers of electron sources based on field emission, but serves also as a guideline to find effective processing recipes to minimize field emission in RF cavities.

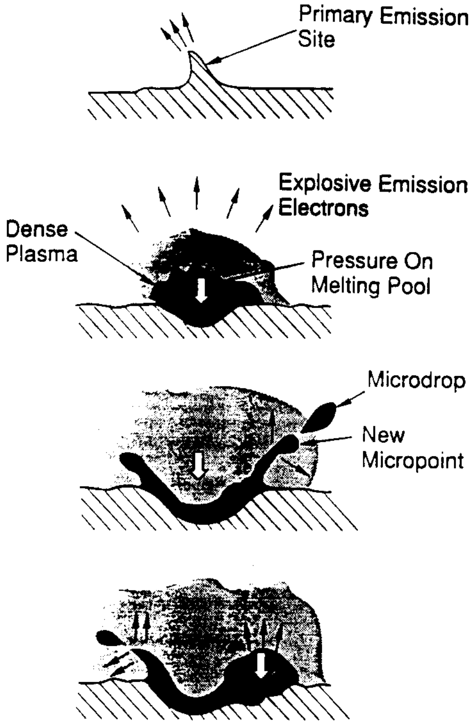

Fig. 7 Formation of a microbreakdown (from Ref. [17])

Helium processing

It can be envisaged to modify the emitters by ion bombardment. This method is used with some success in superconducting cavities under the generic name of "Helium processing". Helium gas at low pressure (10^{-5} mbar) is introduced in the cavity and RF field is applied. A reduction of the field emission in the cavity is often observed [18], probably due to the bombardment of the emitting site by the helium ions. This bombardment may cause a gas desorption on the emitter, or a destruction of the emitter by sputtering. In spite of its effectiveness, helium processing has severe drawbacks, related to the risk of deposition of sputtered contaminants on the cavity surface. Degradation of the cavity Q-value has often been observed after helium processing.

RF processing

It has long been recognized that both field emission current and breakdown probability decrease by exposing a virgin surface to an intense electric field. This kind of processing is currently applied in DC regime to upgrade the breakdown threshold of metal surfaces in vacuum, and in RF regime on normal conducting cavities. In most of these cases, this processing is made “in situ”, i.e, the surface is not reexposed to atmosphere after the treatment. When it is reexposed, the benefits of the processing are partly lost.

High-field processing has also been applied to superconducting cavities. Here, specific problems arise. Despite the long cavity filling time, the surface must be exposed to intense electric fields in a short time, if cavity quench is to be avoided. This short pulse time, combined with a severe electron loading during the pulse, requires large RF peak powers and an adjustable RF coupling.

In a remarkable series of experiments, the Cornell laboratory has established high-peak-power processing (HPP) as a very effective curative treatment against field emission [19] (Fig. 8). The parameter which determines the degree of reduction of field emission is the maximum electric field reached during the HPP stage. For example, by using processing fields as high as 60 MV/m, it is possible to eliminate field emission for CW fields of the order of 30–40 MV/m. The effectiveness of HPP probably lies in its capacity to heat the emitters selectively, initiating breakdowns which ultimately burn the emitters. Craters are formed during the treatment [9]. It has been shown that these craters themselves may eventually emit, but these can be processed in turn in the same way. The efficiency of the treatment saturates when the emission from the new craters equals the emission of the formerly destroyed emitters.

Despite impressive laboratory results, the usefulness of HPP might be reduced if the processed surface has to be re-exposed to air, because of the risk of ulterior particulate contamination. If HPP is done in situ, i.e without any re-exposition to air, it remains to be seen to what extent this kind of processing is really useful on real accelerators, with limited RF power and fixed couplings.

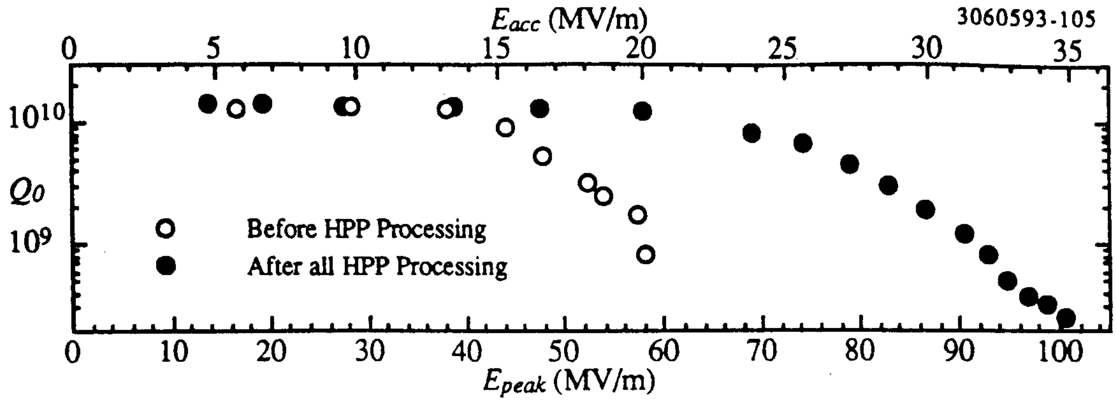

Fig. 8 High-peak-power processing can cure field emission in superconducting cavities (from Ref. [19]).

4. CONCLUSION

Clearly, the first cause of field emission in superconducting cavities is particulate contamination. Cleanliness is an indispensable prerequisite in avoiding enhanced field emission from extended surfaces. Effective removal of micron-sized particles is a rather difficult task, because the mechanical forces applied to the particle by the cleaning process decrease faster than the adherence forces when the particle size decreases. Advanced cleaning techniques like high-pressure rinsing [20] have been used to clean superconducting cavities, with a statistically significant reduction of field emission. The effectiveness of this treatment may be limited by eventual contaminations occurring later in the cavity history, but this kind of cleaning is probably one of the most precious preventive treatments available against enhanced field emission.

Systematic use of both preventive and curative remedies (i.e. ultra-clean treatments and high-voltage processing techniques) holds the promise of greatly improving the superconducting cavity performance level and reproducibility.

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