EXPERIMENTAL STUDY ON THE LUMINOUS RADIATION ASSOCIATED TO THE FIELD EMISSION OF SAMPLES SUBMITTED TO HIGH RF FIELDS

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ABSTRACT

Nowadays the accelerating gradient of the RF cavities is limited by the strong field emission (FE) of electrons stemming from the metallic walls.

Previous experiments evidenced luminous radiations associated with electron emission on cathodes subjected to intense DC electric field. These observations led these authors to propose new theoretical models of the field emission phenomenon.

Our experimental study extends these previous DC works to the RF case. We have developed a special copper RF cavity equipped with an optical window and a removable sample. It has been designed for measuring both electron current and luminous radiation emitted by the sample, subjected to maximum RF electric field. The optical apparatus attached to the cavity permits to characterize the radiation in terms of intensity, glowing duration and spectral distribution.

This paper summarizes the results concerning different niobium or copper samples, whom top was either scratched or intentionally contaminated with metallic or dielectric particles.

INTRODUCTION

Field emission phenomenon is the ultimate limitation of the accelerating gradient of the RF cavities in the linear colliders. These superconducting (SC) RF devices suffer from the occurrence of enhanced field emission (EFE) at surface electric fields typically higher than 10 MV/m, i.e. much below the Fowler-Nordheim (FN) limit for ideal metallic surfaces (> 2 GV/m). For many years, this local field enhancement was attributed to metallic microprotrusions or whiskers on the emissive surfaces. But such surfaces topography studies failed to reveal any protruding microstructure consistent with measured field enhancements. Besides, an increasing body of evidence indicated various kinds of emitting features leading to the conclusion that the electrons emission can stem from a "non-metallic" emission mechanism. New theoretical models emerged but hitherto the mechanism(s) explaining thoroughly EFE is (are) not elicited. One of these original observations is the luminescence of cathodes under the influence of intense electric fields. Studies [1-2] of the conducting surfaces exposed to high electric fields (5 - 40 MV/m) in vacuum have shown luminescence occurring from discrete regions on the cathode. Electron emission accompanied the luminescence, and in his additional investigation [2] Hurley could conclude that the electron emission originates from precisely the same sites as the light sites. The spectral distribution of the spots were found comparable to electroluminescent spectra and the luminous intensity was found to obey the law of the electroluminescence. Since electroluminescence is a "non-metallic" phenomenon, these authors concluded to the existence of an emission mechanism involving inclusions of semiconductor type.

Luminous radiation observations have also been reported in the RF cavities : at CERN [3], a photomultiplier measured luminous intensity in a monocell superconducting cavity equipped with a view port. The measured spectra suggested a thermal behavior due to the heating of the electromagnetic fields on an insulated particle of the metallic wall.

Guided by these original results, we developed a new tool, offering the possibility to study simultaneously the RF field emission on a very confined surface and its associated luminous emission.

EXPERIMENTAL SET UP

The investigated surface is the top of a sample (in copper or niobium), located on the maximum surface electric field (E_{max}) area of a copper reentrant $\lambda/4$ (1.5 GHz) RF cavity. A klystron fed the resonant device each second during pulses of 1 to 5 ms, with an available maximum RF peak power of 5 kW.

At the upper part of the resonator, a hollow electrode collects the electrons emitted by the sample tip, simultaneously the light stemming from this surface is reflected through an optical system to a luminous detector (Fig. 1) (The experimental apparatus is detailed in previous papers [4 - 5]). A sensitive camera (sensitivity of 10^{-15} W) localizes the luminous events on the sample surface with a theoretical resolution better than 10 μm on the sample surface. A morphologic detail of the surface (currently a scratch) is taken as reference for the localization of luminous points. But this mark is spotted with an uncertainty, lowering the effective resolution of the localization to ~ 100 μm.

A discrete event is isolated by the interposition of a square diaphragm forming by crossing a pair of slits (width of 50 μm) remotely controlled. The transient behavior of the radiation in comparison with the RF pulse is measured when the selected sensor is a photomultiplier (sensitivity of 10^{-15} W). A prism is positioned on the optical path and disperses the luminous beam to a cooled linear CCD multichannel sensor (sensitivity of 10^{-14} W). Its video output, digitized by an oscilloscope, is processed by a Labview software. Finally, the spectral distribution of the radiation is drawn out with a resolution better than 10 nm.

The spectral bandwidth of the sensors extends from the visible wavelengths to the near infra-red ones. The spectral

ranges at 40 % of maximum relative response are equal to : 400 - 650 nm for the intensified camera, 160 - 750 nm for the photomultiplier and 500 - 950 nm for the CCD sensor.

In addition, the pulses of RF transmitted power from the cavity are continually recorded by a data acquisition board, jointly to the measured current. The transmitted power value allows to deduce the E_{max} value, so by this way precise investigation of the influence of the electric field intensity on the current is achieved, simultaneously to the luminous investigation. All the video images are recorded by a video tape recorder.

Two types of sample are tested, they differ in their diameter and tip shape. Type #1 geometry (3 mm diameter cylindrical stick with a flat sample and rounded edges) offers a maximum value of E_{max} of 50 MV/m, whereas 90 MV/m are reached with the type #2 (2 mm diameter cylindrical stick ended by a conical tip). These values are obtained for the maximum input RF power of 5 kW.

After the RF tests, the sample is removed from the cavity and observed on a scanning electronic microscope (SEM).
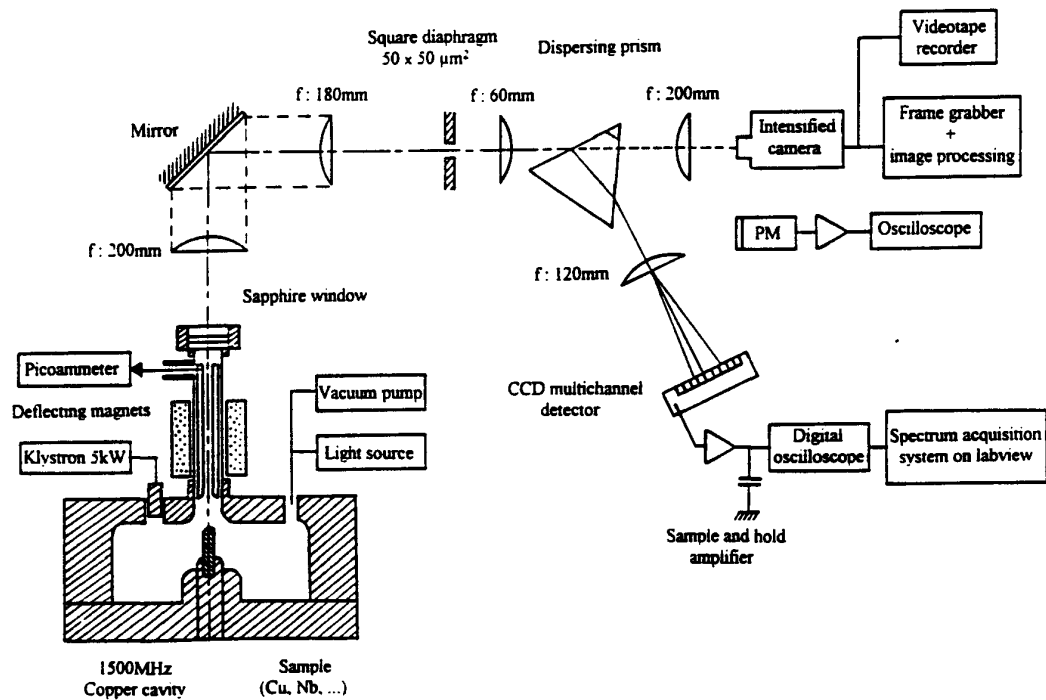

Figure 1 : The experimental set up

FIELD ELECTRON EMITTERS

The early studies established that the electron emission occurs on discrete micron-sized regions of broad-area high voltage electrodes, called electron emitters. Recent analytical techniques have the ability to obtain high-resolution spatial and material composition where exactly electrons are emitted in relation to the microstructure of the cathode surface [6]. Field emission sites investigations in SC RF cavities confirm similar features for the RF field emitters [7]. Broadly speaking, the electron emitters can be categorized as follows :

1/ **Surface irregularities** consisted of geometrical deformations of the surface, without external element present, these defects can result from accidental mechanical contacts or chemical etching.

2/ **Foreign elements** such as superficial particles resting or embedded in the surface substrate, whom size varies from 0.1 to 10 μm. The material composition of such particles is apparently independent of the surface and can be very varied : electric conductors or insulators were found.

These results led us to test "natural" samples, i.e. polished then chemically treated and rinsed. In order to examine specific emitters types, we intentionally "contaminated" samples : their top was scratched with a tungsten or diamond point or sprinkled with specific and calibrated particles (iron and alumina particles).

LUMINOUS EVENTS OBSERVED ON THE DIFFERENT SAMPLES

We present on the following paragraph the different light phenomena observed on different samples.

A/ The luminous spots from "natural" samples and scratched samples

There are threshold fields E_{th} which activate very localized light emissions on the RF surface of both "natural" and scratched samples. These discrete events will be referred to as luminous spots or sites. The value of the "activator" field varies with the considered site, with the sample material and obviously depends on the sensitivity of the sensor.

Because different behaviors were encountered, we will not draw a distinct and clear mechanism describing the initiation and the development of a site under the influence of the electric field. Some spots started shining at E_{th}, then

intensified their luminous activity as the field increased or the pulse was lengthened and finally disappeared at higher field. Their luminous activity was reproducible in a well-delimited field range of about 10 - 20 MV/m. On the contrary, other ones experienced a kind of conditioning, they "switched on" at E_{th} and persisted at higher fields, then after a field decrease below E_{th}, they got the ability to shine. For copper samples, we encountered sites which sparkled on a sufficient broad field range to evaluate their radiated power as a function of the electric field. The measurement was consistent to the electroluminescent law, relating the brightness of the light to the inverse root of the electric field [8].

Two kinds of sites can be distinguished taking their "optical life" as criterion. When they glow during one or two RF fields, we refer them to as "unstable" sites whereas the "stable" sites reach currently durations of few RF minutes.

Their apparent diameter on the sample was typically evaluated to few tens of micometers. Most frequently, the spots appeared on the sample edge where the field was found highest in the Urmel calculations of the resonator, but some were also to be seen on the flat part of the sample. The sites were located on the sample surface and retrieved in a square of ~ 100 μm edge under a SEM after the RF test. In very few cases, a melted particle or crater was found close to the site locations, but mostly no striking morphologic feature was found at their location. Concerning the scratched samples, no luminous sites were detected directly in the scratch. The number of sites per sample was typically less than a ten.

We observed different transient effects, measured by the output current of a photomultiplier. Sometimes light is emitted in synchronism with the RF power, while in other cases, it is emitted with a delay of 1 to 2 ms, which was seen decreased during the test.

The spectra obtained on "stable" sites show broad gaussian shapes centred on the range of 700 - 800 nm wavelengths.

"Stable" spots have been observed simultaneously during the conditioning period of the sample, i.e. during strong variations of measured current or even stable ionic currents. After these instabilities period, "stable" spots were detected at low field levels, at which no emission electron stemmed from the sample top. At higher fields, such "stable" spots were currently active jointly to a stable electron field emission. It is interesting to notice that no luminescence was observed on one niobium sample, in spite of an stable electron emission (of 2 μA at 86 MV/m).

The following table gives few orders of magnitude of results :

Sample type	Cu (Ø 3 mm)	Nb (Ø 2 mm)	Cu (Ø 3 mm)	Nb (Ø 2 mm)
Contamination	scratch	scratch	Alumina (50 μm)	Alumina (1 μm)
E_{th}	25 MV/m	10 MV/m	5 MV/m	20 MV/m
Sites intensity	10^{-13} W - 10^{-12} W	few 10^{-13} W	> 10^{-13} W	10^{-13} W - 10^{-12} W
Sites type	stable (not correlated with the contamination)	unstable (not correlated with the contamination)	stable and unstable, with flares and luminous tracks	unstable
Spectra	broad shape (measured with filters)	no measured	broad gaussian shape (measured with the CCD sensor)	no measured

B/ The luminous spots and the explosive events on samples contaminated with alumina particles

1/ Contamination with small alumina particles (diameter ≤ 1 μm)

A clean niobium sample exhibited in the cavity a field emission of ~ 2 μA at the maximum field. Contaminated with small particles of alumina, during its conditioning period few "unstable" spots at "low" field level (~ 6 MV/m) and very unstable currents where jointly observed. Then, no light activity was detected until a field of ~ 80 MV/m was reached. At this level, unstable spots glowed simultaneously to strong vacuum perturbations. After this regime of instability, a more stable phase was recovered and an electron emission was detected at 52 MV/m leading to a current of ~ 7 μA at the maximum field level. But no more spots were visible during the emission. The SEM examination revealed a large number of small craters (diameter of ~ 1 - 2 μm) in the area where appeared the spots and maybe where were deposited the alumina particles. Let's notify that no trace of initial particles was found over the sample surface.

2/ Contamination with "large" alumina particles (≥ 20 μm)

Stable spots were initiated at low field (~ 5 MV/m). During the pulses concomitant to these luminous events, the electrode signal exhibited a strong increase of positive or negative current, mostly triggered at the end of the RF pulse and which is extended beyond the RF duration. The intensity and the number of spots increase with the electric level. Then, at about 8 MV/m, unstable and intense spots occurred, correlated with strong increases of the electrode current. For higher fields (> 10 MV/m), explosions were triggered during 1 or 2 RF pulses and appeared irregularly, typically

during the power increases. Generally a strong spot shined, succeeded by a very intense flare (Fig. 2) saturating the camera and was accompanied by a multitude of adjacent activated sites on the top surface. This flare initiated sometimes intense luminous tracks with curve or straight trajectories. Simultaneously, strong perturbations were detected on the vacuum gauge, revealing strong gas desorptions or residual gas ionizations. A second RF test was performed, the intense luminous activity started at higher field level of ~ 19 MV/m and a more stable electron current was detected with a maximum value of 120 µA at 38 MV/m.

The spectral analyses of the first low field stable spots reveal broad gaussian shape spectra, centred on a specific wavelength λc. At given field level, different spots brighted on the surface and showed different central wavelength, ranging from 600 to 800 nm (Fig. 3). It is of some interest to emphasize the independance of λc in respect to the electric value : for a given spot, the increase of the electric field does not alter the spectral distribution of the emitted light : the peak at λc is maintained, only its luminous intensity is increased.

After the RF test, small melted clusters of alumina particles and few overlapped craters were seen on the surface.
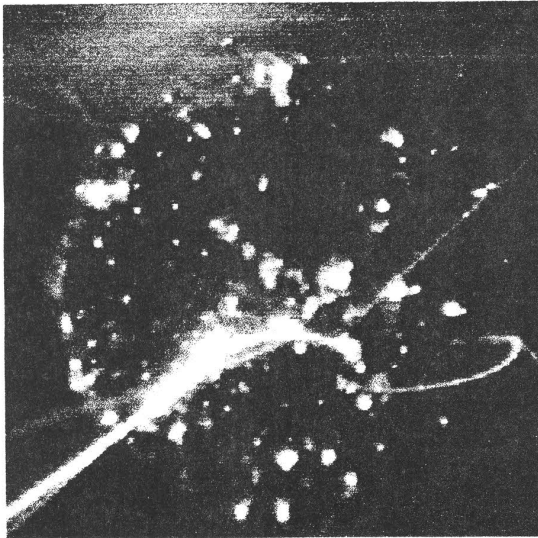

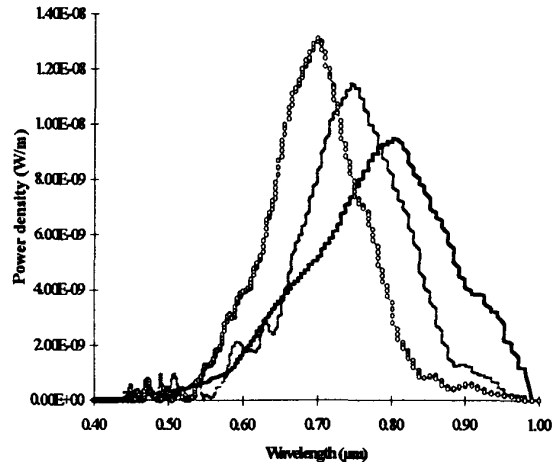Fig. 2 : luminous activity at E = 20 MV/m on a copper sample (Ø 3 mm) contaminated with ~ 20 µm alumina particles

Fig. 3 : three different light spots on a copper sample (Ø 3 mm) contaminated with ~ 20 µm alumina particles

C/ The microdischarges on samples contaminated with iron particles (diameter of ~50 µm)

No spots as described above were detected on a sample contaminated with iron dusts. But we observed clearly the effect of the electric field on the metallic contaminants ; it provoked particles motions, initiated at low field level (8 MV/m). The particles were ejected out of the surface, lined up and piled up along the electric lines perpendicular to the surface (Fig 4). These displacements occurred at the field increases, none was observed at constant field. They were accompanied by luminous flashes, sparkling around the moving particles for one RF pulse. All these phenomena were observed during the conditioning period, when strong instabilities on the vacuum gauge and on the current were measured, revealing gas desorptions. Then a second RF test was performed : the faster field increase phase showed neither particles movement neither luminescence, but a stable field emission (50 µA at the maximum field level of 70 MV/m).

Afterwards, the SEM investigation showed numerous stacks of 3 - 4 particles piled up and individual lined up particles. The iron particles had melted and welded on the substrate, resulting in a good electrical contact with it. Identically, a welded contact joined two particles of a stack and small craters (diameter < 1 µm) were visible at the contact vicinity.

DISCUSSION

The luminescence in such experiments can stem from two physical processes:

1/ Electroluminescence: this optical emission occurs in a dielectric medium under the influence of high electric field. High energy carriers are released due to a high field ionization, they collide

Fig. 4 : The iron particles lined up on a niobium sample

luminescent centres and excitate them. These activators return to lower energy level emitting optical photons. In [2], Hurley evidenced a definite relationship existing between electron-emission and light-emission processes at discrete
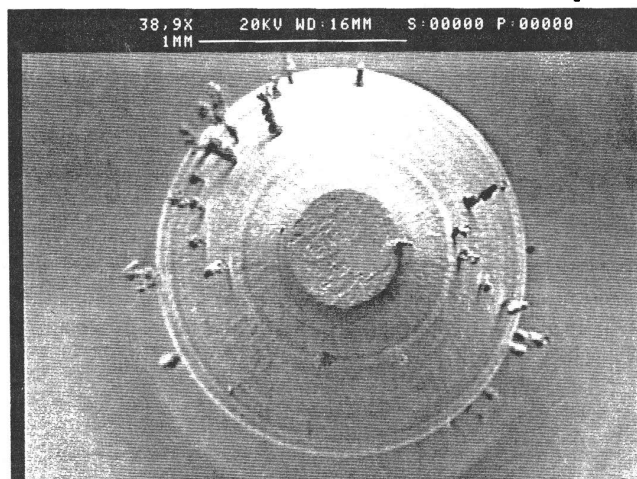
points, associated with oxide type impurities. Electron emission is thought to occur by a Fowler-Nordheim process at the vacuum-oxide surface interface where the field is locally intensified, then conducting filaments are electroformed through the impurities. On this model, electron scattering from weak point in the filaments produces electroluminescence in the surrounding oxide.

2/ Thermal radiation : the thermal emission occurs for a dielectric particle in bad thermal contact with the cavity wall. The RF power is absorbed in this dielectric volume in the form of heating, which is evacuated by radiation and by conduction to the substrate. A consequence of this intense heating is a possible thermoionic emission occurring simultaneously to the radiation.

At the moment, our experimental reults do not evidence an explanation rather the other one. Indeed, the experimental relationship between the light intensity and the electric field verifies the electroluminescent law but this argument in favour to the first phenomenon is counteracted by the spectral distributions. The electroluminescent spectra exhibit defined peaks, identifying the types of luminescent impurity involved. Such sharp structures have never been observed in our case. On the contrary, the broad shapes spectra measured could be close to radiation spectra, attenuated by the specific material emissivity. However, because the RF heating is directly dependent on the electric field by the relationship $P(W/m^3) = 1/2 \, \varepsilon_0 \, \varepsilon_r \, \omega \, \mathrm{tg}\delta \, E^2$, the reached temperature should vary with the field. Therefore, for a given luminous spot, the peak wavelength of its spectrum is expected to shift with the field, what our results do not support.

These preliminary establishments require deeper interpretations based on simulations of the evoked physical processes and the estimation of their pertinent physical parameters. For instance, for the second thesis, some relevant parameters could be the field levels promoting the experimental luminous intensities, the reachable temperature, the time scales of such phenomena. In order to verify the orders of magnitude, a simple estimation has been already envisaged : the RF field heating of a spherical alumina particle in poor thermal contact with the substrate. Asserting this energy is evacuated by conduction and by radiation, we have evaluated the reached temperature as a function of the electric field. In these conditions, the particle reaches the 2300 K melting temperature of alumina for a electric field of 45 MV/m and radiates a luminous power of few 10^{-9} W through the experimental solid angle.

The experimental results on the alumina contamination are spectacular, they reveal the strong dependance of the optical behavior on the dielectric contaminants size. This impressive emission suggests that a plasma is developed when high field levels are reached resulting in the destruction of the alumina particles. These results have to be compared to the direct and post-mortem investigations of RF cavities which suffered from RF field emission. Microscopic features found at the processed emission sites after the occurrence of an RF spark (starbursts, molten craters ...) indicate that emitter extinction takes place by an explosive process [7]. Possibly the plasma cloud associated with the spark is responsible for the surface features. The most interesting aspect remains to elicit : the understanding of the origin of a such plasma.

Concerning the iron particles, the particles edifices are likely very nocive for the RF cavities; it is interesting to remark that effects like sparks or microdischarges are induced in the vicinity of the iron particles, carried by gas media, i.e. vapour resulting likely from an intense heat.

CONCLUSION

Few others contaminants should be tested soon in our experimental set-up. The adaptation of this apparatus to a special shaped SC cavity [9], called the "mushroom" cavity. Its buttom, consisted of a "dimple", permits to dispose of a small region exposed to very high RF electric fields. It is envisaged to contaminate this region and to investigate the expected optical emission.

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