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**Activities on superconductivity cavities
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SOMMAIRE

Study of luminous spots observed on metallic surfaces subjected to high

RF fields (page 5)

(Presented at the 1995 Particle Accelerator Conference, Dallas, USA, May 1 - 5, 1995)

T. Junquera, S. Maïssa, M. Fouaidy, A. Le Goff, (IPN - CNRS/IN2P3, Orsay)

B. Bonin, M. Luong, H. Safa, J. Tan, (CEA - DAPNIA/SEA, Gif-sur-Yvette)

Surface scanning thermometers for diagnosing the Tesla SRF cavities (page 9)

(Presented at the 1995 Particle Accelerator Conference, Dallas, USA, May 1 - 5, 1995)

T. Junquera, A. Caruette, M. Fouaidy, (IPN - CNRS/IN2P3, Orsay)

Q. S. Shu (DESY, Hamburg)

Progress in the study and construction of the Tesla Test Facility injector (page 13)

(Presented at the 1995 Particle Accelerator Conference, Dallas, USA, May 1 - 5, 1995)

R. Chehab, M. Bernard, J.C. Bourdon, T. Garvey, B. Jacquemard, M. Mencick, B. Mouton, M. Omeich, J. Rodier, P. Roudier, J.L. Saury, M. Taurigna-Quere, Y. Thiery (LAL - CNRS/IN2P3, Orsay)

B. Aune, M. Desmons, J. Fusellier, F. Gougnaud, J.F. Gournay, M. Jablonka, J.M. Joly, M. Juillard, Y. Lussignol, A. Mosnier, B. Phung, (CEA - DSM/DAPNIA, Gif-sur-Yvette)

S. Bühler, T. Junquera, (IPN - CNRS/IN2P3, Orsay)

Status report of the TTF capture cavity cryostat (page 17)

(Presented at the CEC/ICMC Conference, Columbus, Ohio USA, July 17 - 21, 1995)

S. Bühler, P. Blache, R. Chevrollier, T. Junquera, (IPN - CNRS/IN2P3, Orsay)

N. Colombel, R. Panvier, (LAL - CNRS/IN2P3, Orsay)

J. Gastebois, (CEA - DAPNIA/SEA, Gif-sur-Yvette)

A novel rotating temperature and radiation mapping system in superfluid He & its successful diagnostics (page 23)

(Presented at the CEC/ICMC Conference, Columbus, Ohio USA, July 17 - 21, 1995)

Q. S. Shu, G. Deppe, W. D. Moeller, M. Pekeler, D. Proch, D. Renken, C. Stolzenburg, (DESY, Hamburg)

T. Junquera, A. Caruette, M. Fouaidy, (IPN - CNRS/IN2P3, Orsay)

Study of luminous phenomena observed on contaminated metallic surfaces submitted to high RF fields (page 31)

(Presented at the International Field Emission Society Meeting, IFES 95, Madison, Wis. USA, August 7 - 11, 1995)

S. Maïssa, T. Junquera, M. Fouaidy, A. Le Goff, (IPN - CNRS/IN2P3, Orsay)

B. Bonin, M. Luong, H. Safa, J. Tan, (CEA - DAPNIA/SEA, Gif-sur-Yvette)

STUDY OF LUMINOUS PHENOMENA OBSERVED ON CONTAMINATED METALLIC SURFACES SUBMITTED TO HIGH RF FIELDS

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ABSTRACT

The primary limitation to the increase of the attainable accelerating gradient in superconducting cavities is the strong field emission (FE) of electrons from the RF surface.

Many studies devoted to the DC field emission have shown that the electron emission on a broad metallic surface stems from a few very localized sources, called emitters. Superficial dust particles (metallic or dielectric) or semiconducting impurities embedded in the surface can originate the emission. Different experimental results have led to several theoretical models explaining the physical mechanisms of the field emission.

We have investigated the RF field emission from a sample subjected to high RF fields ($E_{\text{peak}} > 40$ MV/m) in a copper cavity. Our study is focused on the luminous emissions occurring on the RF surface simultaneously with the electron emission. The optical apparatus attached to the cavity permits to observe the evolution of the emitters and the direct effects of the surface conditioning. Also, the parameters of the emitted radiation (intensity, glowing duration, spectral distribution) may provide additional informations on the field emission phenomena. This paper relates some results concerning samples intentionally contaminated with particles (metallic or dielectric).

INTRODUCTION

Nowadays the availability of higher energy particle beams for linear electron-positron colliders, depends on the accelerating gradient capability of superconducting radiofrequency (SRF) cavities beyond the 5-10 MV/m level presently available [1].

The primary limitation to the increase of the accelerating gradient is the field emission of electrons out of the cavity surface in the presence of high surface electric fields. The emitted electrons are accelerated in the electromagnetic field of the cavity and, when hitting the wall, give off their kinetic energy as heat and partially as bremsstrahlung x-rays. The deposited power can lead to the heating of the cavity walls and when the emission is sufficiently intense, thermal breakdown occurs. The main effect of this phenomenon is a drastic lowering of the cavity quality factor and consequently a severe reduction of the cavity performances.

These last years, an intense work has been performed in order to understand and to fight against this field limitation. Different diagnostic techniques were employed: thermometry, X-rays detectors, etc. and the result was a clear evidence of the localized nature of the emitter sites [2].

Based on previous work [3,4] in DC experiments, our idea was to study the luminous effects observed in metallic surfaces subjected to high electric fields and to apply this method for diagnostic purpose. The luminous effects, which seem clear in DC experiments, led the authors to propose a model of FE based on the electroluminescence originating from the electron emission sites.

The goal of the present study is the observation and the analysis of the luminous features in the surface of a RF cavity, using an advanced optical device. The experimental program using this technique is mostly driven by the interest of measuring the influence of the particle contamination of the cavity surface.

M. Jimenez [5] have shown a positive correlation between the electrical conductivity of the microparticles and their emissive capability. This work in DC reveals that metallic particles are intense electron emitters even at moderate electric fields (< 20 MV/m), while the dielectric particles start to emit at very high fields (100 MV/m).

Intensive work with prototype cavities [1] have shown that even with a careful preparation of the cavities (chemical polishing, ultra high purity water rinsing, clean room mounting, etc.), the emission takes place at surface fields starting at 10-15 MV/m. Using thermometers and X-rays detectors, the emission sites positions were localized and different methods of surface analysis (EDX, Auger, etc.) have proven the presence of contaminants (metals, etc.) in the region close to the emitter site.

More recently, a new conditioning technique (High Peak Power Processing conditioning) [1,6] allows to reach higher surface fields (~ 40 MV/m) without FE for important surfaces (> 100 cm²). At higher fields, new emitters appear or are activated avoiding to reach the theoretical limits of the superconducting cavities (electric fields close to 100 MV/m). During the conditioning experiments, the explosive behavior of conditioned emission sites have shown a close similitude to observations realised in DC experiments. The optical device presented in this paper could be also an interesting tool to study the conditioning of cavity surfaces.

EXPERIMENTAL SET UP

a) Cavity

A reentrant $\lambda/4$ cavity has been designed by the Saclay Group [7,8] for studying the RF field emission on removable samples. It has been shown [9] that FE at room temperature and at superconducting temperatures have practically the

same behavior. Hence the cavity used is a copper one, operating at room temperature, offering a fast and easy turn around and low operating costs. The cavity is powered by a 5 kW klystron operating in pulsed mode: frequency close to 1 Hz and pulse width limited in the range 1 ms to 5 ms, to avoid the walls heating. Its removable bottom supports a screwed sample, whose top is located on the maximum surface electric field area of the cavity. In that way, we ensure that emission comes preferentially from the sample. A hollow electrode measures the electron current emanating from the sample. It faces the sample and is positioned to allow only the electrons from emitter sites lying on the sample top to be collected.

Two types of samples with different diameter dimension and tip shape were used in the present study. Type #1 is 3 mm diameter cylindrical sample with a flat top and rounded edges. Type #2 is 2 mm diameter cylindrical sample ended by a conical tip. This second geometry offers the advantage of a higher maximum electric field ($E_{\max}$) in comparison with the first one and for a given input power, but it shows a smaller investigation surface. For a copper sample and 5 kW input power, type #1 geometry gives only $E_{\max} = 60$ MV/m, whereas 100 MV/m are reached with the type #2 geometry. If the sample is a niobium one, type #1 gives $E_{\max} = 50$ MV/m and type #2 gives 83 MV/m (for 5 kW input power).

b) Optical system

Straight up from the cavity, a mirror reflects the sample image to an intensified camera, through an optical system (Fig. 1), detailed in Ref [10,11]. The camera has a sensitivity of 5×10^{-4} lux in the wavelength range of 400-650 nm (at 40 % of the maximum relative response). Its spatial resolution is about $6 \mu\text{m}$ on the sample surface. The spectral analysis system consists of a pair of crossed slits ($50 \mu\text{m}$) remotely controlled to select the light emanating from just one spot. A prism is then positioned on the optical path and the dispersed light analyzed by a cooled CCD multichannel sensor (Hamamatsu C5809 model with 64 vertical pixels x 512 horizontal pixels and a spectral response in the range of 400-1000 nm, at 10 % of the maximum relative response)

An associated readout circuitry restores a video signal which is digitized by an oscilloscope and then processed by a PC computer program in its final form: radiation power versus wavelength.

The CCD sensitivity measurement was performed with different near-monochromatic light sources (laser diode, LED, narrow band filters) and the obtained results were within $\sim 7\%$ of the manufacturer's values. A spot with luminous intensity of 10^{-14} W is detectable by this way. Due to the wavelength dependence of the refractive index of the prism, the spectral precision varies: its value is 1 nm at 400 nm and 10 nm at 1000 nm.

c) Data acquisition

The klystron and the luminous sensors are triggered by the same pulse, in that way the camera restores a sample image synchronized to the RF pulse and the CCD detector delivers a spectrum at each RF pulse. The last improvement is the acquisition of the transmitted RF power value and the measured current via the Labview software and its associated analogous board. Complementary the camera images are simultaneously recorded during the experiment.

d) Experimental protocol

Particles are deposited by sprinkling on the top of a clean sample placed over the cold vapors of an LN_2 bath. The particles stick to the moistened surface and after drying remain well adhered, even during sample mounting in the cavity and even with the application of electrostatic fields. The samples are mounted in the cavity on a laminar flow bench. The prepared cavity is then evacuated and the experiment starts when the pressure reaches the range of 10^{-7} mbar. We usually examine the sample with a Scanning Electronic Microscope (SEM) before putting it in the RF cavity and after the RF test.

Fig. 1 : optical system for light spots observation and spectral analysis in RF cavities

EXPERIMENTAL RESULTS

a) Iron particles

A niobium sample (type # 2) was contaminated with about a hundred of iron particles (size $\sim 50 \mu\text{m}$) (Fig.2).

Fig. 2 : the Fe particles of the Nb sample before the RF tests

The first RF test, described in table 1, started with the progressive increase of the electric field in the cavity. At each plateau, the field was kept constant for several minutes in order to reduce the strong instabilities of gas desorption phenomena. A clear conditioning effect was observed throughout the experiment, as curve 1 of Fig.3 shows. From the field value of 7.5 MV/m , particles started to displace: some were ejected out of the sample surface, others lined up or piled up along the electric field direction, perpendicular to the surface (Fig.4). Particles movements were initiated during field increasing phases, none was observed at constant field. Jointly to these events, luminous flashes occurred around the moving particles and lasted one RF pulse. The RF power was turned off and the cavity vacuum allowed to recover.

	1st RF test	2nd RF test
RF pulse	4 ms / 1.25 Hz	0.5ms / 2.5 Hz
Vacuum pressure	$\sim 10^{-6}$ mbar	$\sim 10^{-6}$ mbar
Electric field threshold for the particles movement	7.5 MV/m / NO FE	NO PARTICLES MOVEMENT OBSERVED
Field emission threshold	10 MV/m / $600 \mu\text{A}$	51 MV/m / $6 \mu\text{A}$
Highest Electric field	58 MV/m / $46 \mu\text{A}$	69 MV/m / $41 \mu\text{A}$
Strongest current event	37 MV/m / $650 \mu\text{A}$	66 MV/m / $50 \mu\text{A}$

Table 1 : summary of the first RF test of the Nb sample, contaminated with Fe particles

Curve 2 of Fig. 3 describes the second RF test (RF pulse 0.5 ms / 2.5 Hz). After a fast field increasing phase, the highest power level was maintained for ~ 15 minutes, before the

decreasing phase. No particles movement and no luminescence were observed. Afterwards the SEM examination showed numerous stacks of 3-4 particles piled up and individual lined up particles (Fig. 4). The iron particles had melted and welded on the substrate, allowing a good electrical contact with it. Identically, a welding contact joined two particles of a stack and small craters ($\varnothing < 1 \mu\text{m}$) were visible at the contact vicinity.

Fig. 3 : electron current versus electric field during the RF tests of the Nb sample, contaminated with Fe particles

Fig. 4 : the Fe particles of the Nb sample after the RF tests

b) Alumina particles

Small size particles

A clean niobium sample (type #2) was tested in the cavity (RF pulse 2 ms / 1.2 Hz). At the highest field value of 86 MV/m , an electron emission of $2 \mu\text{A}$ was measured. Then the sample was taken out of the cavity and sprinkled with alumina particles of $\sim 1 \mu\text{m}$ size. After a forming period, an electron current of $7 \mu\text{A}$ was measured at the maximum field value. From 6 MV/m field value, few brief spots glowed for one or few RF pulses, giving a weak luminous intensity compared to the luminescence of the next alumina experiments. A multitude of few μm size craters were located on the substrate surface, no trace of the initial alumina

particles was observed. The short life and instability of the light spots made the spectral measurement very difficult in this experiment.

Large size particles

Two copper samples (#A and #B) of type # 1 were contaminated with alumina particles of 20-50 μm size. Submitted to RF field, they show a very impressive luminous activity. At low fields ($<10\text{ MV/m}$), few stable spots started to glow and their intensity was estimated at few 10^{-13} W (Fig.5).

Fig. 5: large alumina particles at E = 8 MV/m

The increase of the field in the cavity led firstly to a higher spots density with higher intensity saturating the intensified camera. Then, at higher power, the luminous spots originated surface explosions, followed by tracks with curved or straight trajectories (Fig.7). These strong events are accompanied by strong electron emission. After several RF pulses, the current and the luminous activity stabilized, but each RF power level increase triggers a new spectacular pattern of light tracks and explosions.

Fig. 6 : electron current versus electric field during the RF tests of the Cu sample #A, contaminated with Al_2O_3 particles

For the sample #A, the main experimental results are summarized on the table 2 and its current behaviour is detailed on the Fig.6.

	RF test 1	RF test 2
RF pulse	4 ms / 1.25 Hz	4 ms / 1.25 Hz
Vacuum pressure	$\sim 10^{-6}$ mbar	$\sim 10^{-6}$ mbar
Electric field threshold for stable luminescence	5 MV/m NO FE	20 MV/m NO FE
Spot intensity	few 10^{-13} W	few 10^{-13} W
Electric field threshold for unstable luminescence	9.5 MV/m 150 nA	19 MV/m 400 μA
Strongest current event	15 MV/m 1 mA	19 MV/m 400 μA
Electric field threshold for FE	7 MV/m < 0.5 nA	
Electron current at the maximum field	37 MV/m 30 μA	37 MV/m 150 μA

Table 2 : summary of the RF tests of the Cu sample #A, contaminated with $\text{Al}_2\text{O}_3 \sim 50\text{ }\mu\text{m}$ particles

Fig. 7 : large alumina particles at E = 20 MV/m

Several individual spots were measured with the spectral analysis system. Each spot exhibited the same type of spectrum, with different spectral density peak value and wavelength ranging from 600 nm to 800 nm (Fig.8).

Fig. 8 : three different light spots (sample #A)

The study of one spot in the electric field range of 30 to 40 MV/m has revealed that the peak wavelength was not modified despite the field increase (Fig.9).

Fig. 9 : optical spectra of the same spot at different electric fields (sample #A)

Melted alumina particles and overlapped craters were observed on the SEM examination, following the RF tests. These features reveal an intense heating during the test. The surface of the sample, exhibit small clusters of alumina particles (< 5 μm in diameter), resulting from explosive processes.

A sample #B was tested: a spectral analysis of stable spots initiated on the clean sample has shown spectra of the same previous form, with a peak centered in the wavelength range of 800-900 nm. Then, it was contaminated with alumina particles of size $\sim 20 \mu\text{m}$. A similar strong luminous activity was rapidly triggered with strong electron and ionic currents. One of the spots was analysed at different RF pulse lengths: the spectra obtained have maximum intensity wavelength varied in the range of 600-800 nm, keeping constant the spectrum shape.

DISCUSSION

The experimental luminous features could be analyzed by considering two different physical processes: electroluminescence and thermal radiation.

The electroluminescent mechanism, occurring in the dielectric particle, consists of a high field ionization of bound electrons

generating charge carriers, an acceleration of free carriers in the electric field, then collisions and excitation of luminescent centres by the high energy carriers. Large number of papers reports an associated electron emission [12]. Some of the main features of electroluminescence were observed in our experiments: electric field levels of 5-10 MV/m are required to trigger the luminescent spots, the luminosity increases sharply with the electric field increase, and a good fit with the electroluminescent experimental Alfrey Taylor law, relating the brightness and the inverse root of the electric field [13] (Fig.10).

Fig. 10 : luminous power versus the square root of the electric field, in a copper sample RF test

Some DC experiments [3] reveal spectra whose maximum intensity wavelength does not depends on the electric field level and observation of explosions and tracks seen to originate from the spots. These effects have been observed in our experiments. But the main disagreement concerns the luminous spectra measured. We have reported a bell or gaussian shape for all the observed spots, with a maximum intensity wavelength variable in the range of 600-900 nm. There is no evidence of spectra with a sharp peak as mentioned in [3] and other numerous papers dedicated to the electroluminescence in alumina.

The thermal radiation mechanism results from the heating of dielectric particles by the RF electric field. The power density absorbed by a dielectric is given by $P(\text{W/m}^3) = 1/2 \epsilon_0 \epsilon_r \omega E^2 \tan\delta/2$. Asserting that a spherical particle of alumina ($\sim 10 \mu\text{m}$ of radius), in poor thermal contact with the substrat, evacuates the heating by conduction to the substrat and by thermal radiation, its equilibrium temperature is estimated as a function of the electric field. The alumina emissivity were found in [14] and the thermal resistance recently measured by [15] ($R_{th} \sim 10^7 \text{ K/W}$). The 2300 K melting temperature of alumina is reached for an electric field of 45 MV/m. With these ingredients, the thermal radiation exhibits broad spectra, centered on the wavelength range of 600-900 nm, for temperatures close to the melting temperature of alumina ($\sim 2300 \text{ K}$) (Fig.11).

Fig. 11 : thermal radiation calculated spectra for an alumina particle of $\sim 10 \mu\text{m}$ radius and at two temperatures: $T = 2000 \text{ K}$ ($E = 40 \text{ MV/m}$) and $T = 2500 \text{ K}$ ($E = 50 \text{ MV/m}$)

Fig. 12 : thermal radiation calculated power for an alumina particle of $\sim 10 \mu\text{m}$ radius versus the square root of the electric field

Fig. 12 shows the estimation of the total radiated power versus the electric field, emitted by the spherical particle, then intercepted through the experimental optical solid angle by the detector.

In spite of the quite accurate measurements of the spectra main characteristics (shape, maximum intensity, wavelength, wavelength width, total luminous power) no correlation was evidenced between these parameters. Only two correlations can be stated: for a given spot, the dependence of its brightness with the electric field [13] and the influence of the RF pulse length (ΔT) on the displacement of the maximum wavelength to shorter wavelengths ($\lambda_{\text{max}} \sim 600 \text{ nm}$ obtained for $\Delta T \sim 0.5 \text{ ms}$ as compared with $\lambda_{\text{max}} \sim 800 \text{ nm}$ for $\Delta T \sim 2 \text{ ms}$). The large dispersion of these parameters could be interpreted asserting the shape, the emissivity and the thermal contact of each considered particle, determines its spectrum. If the mechanism of the luminous emission is dominated by thermal radiation, it is difficult to understand the maximum wavelength independence from the electric field. It is expected to vary with the electric field for a given spot.

One clear observation for alumina particles seems to be the possibility to condition the samples and the important

reduction of the electron current after very intense luminous and current activity. In the case of the metallic particles, some stable spots have been observed (stable spots were also observed on apparently clean samples [10]), but their number and intensity were far less than the case of alumina contamination. No intense light activity was detected during the conditioning period.

Some events could correspond to an electroluminescent behavior, but much of the experimental observations with contaminants could be interpreted by both electroluminescence and thermal radiation. For the moment, it is difficult to propose a clear mechanism occurring not only in the contaminants (here particles) but also on the surface itself (grain boundaries, foreign metal inclusions, etc.).

The next work concerns the confirmation of a correlation between light emission spots and electron emission, and a systematic test of different samples in order to find correlations between the luminous features, mainly the spectral ones.

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