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FIELD EMISSION STUDIES ON TECHNICAL NIOBIUM SURFACES

by

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ABSTRACT

The performance of superconducting accelerating cavities are limited by the spurious field emission of electrons. Various vacuum surface treatments have been investigated in a UHV system to reduce this emission. On baked niobium samples, the application of an electrical field leads to a gradual decrease of the field emitted currents; after an argon glow-discharge, the currents are high and stable. An argon-oxygen discharge reduces markedly the field emitted currents and could be an interesting treatment for superconducting cavities.

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FIELD EMISSION STUDIES ON TECHNICAL NIOBIUM SURFACES

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Abstract. - The performance of superconducting accelerating cavities are limited by the spurious field emission of electrons. Various vacuum surface treatments have been investigated in a UHV system to reduce this emission. On baked niobium samples, the application of an electrical field leads to a gradual decrease of the field emitted currents; after an argon glow-discharge, the currents are high and stable. An argon-oxygen discharge reduces markedly the field emitted currents and could be an interesting treatment for superconducting cavities.

INTRODUCTION

The large amount of energy radiated as synchrotron light from high energy electron storage rings has to be fed back into the beams by powerful accelerating systems. In an attempt to limit the joule losses in these accelerating systems, superconducting niobium cavities (SCC) are being developed in several laboratories (1),(2),(3). However, the performance of SCC is limited by the spurious emission of electrons (4), which can originate either by electron bombardment of the cavity surface (secondary electron emission) or by field emission from the same surface. Whereas the detrimental effect of the first phenomenon can be circumvented by an appropriate geometrical design of the cavity (5),(6), and/or by special surface treatments (7),(8), field emission remains as the field limiting factor in most existing cavities. Since electron field emission is largely determined by the properties of the surface layers (9), the performance of SCC can be altered by an appropriate choice of surface treatments (e.g. baking, ion bombardment in a glow discharge (GD)). The effects on the field emission from niobium samples will be reported here.

EXPERIMENTAL SYSTEM AND MEASUREMENT PROCEDURE

Because field emission is strongly dependent on the surface properties, it is important to ensure a clean and well defined environment for this type of measurement. Measurements were made in an all metal system, baked to 300°C for 24 hours at a base pressure close to 10^{-8} Pa. During glow discharge

treatments, the gas was introduced at approximately 1 Pa and the sample negatively biased to approximately 1 kV to ignite the discharge; the ion dose reaching the sample during a glow discharge treatment was set to be 3×10^{22} ions/m². An Auger spectrometer and a residual gas analyser were used to characterize the sample and the experimental conditions.

Samples (20x20 mm² and 1.1 mm thick) were cut from 'reactor grade' niobium sheet (>99.9%) and prepared according to a general recipe involving surface etching as used in practice for niobium cavities (10). After a rinsing with demineralized water, the samples were dried using ethanol. Field emission measurements were made with an insulated stainless steel rod (5×10^{-3} m in diameter) at a known distance (typically 5×10^{-4} m) from the sample. The positive high voltage (typically ≤ 20 kV), applied to the rod was then stepwise increased and the field emitted current measured in the range 1×10^{-11} A - 1×10^{-6} A. These currents and corresponding voltages were then used in the usual Fowler-Nordheim (FN) coordinate system to yield the field enhancement factor β and the emitting area. The value (E_c) of the electric field necessary to extract a given current of 1×10^{-8} A (or sometimes 1×10^{-11} A) will be used to characterize and compare different surface treatments.

EXPERIMENTAL RESULTS

After a 300°C bakeout, the first measurements were rather irreproducible and the application of a high electric field for some hours led to a reduction of the field emitted currents as shown on figure 1 where the FN plots of 5 successive voltage increases from one sample are displayed. The corresponding E_c and β values are given in Table 1. Careful ramping of the electric field, avoiding any electrical discharge, led to an increase of E_c from 12 MV/m to 39 MV/m. There was a significant scatter of E_c values from one sample to another. The change in E_c in table 1 corresponds to a decrease of the field

Figure 1. - FN plots of a baked sample

TABLE 1

EXP.	E_c (MV/m) (1×10^{-8} A)	β
1	12	233
2	15.5	115
3	31.5	68
4	39	63

enhancement factor β from 230 to about 60. This decrease of β is not a monotonic process but is generally discontinuous as shown by the abrupt change of the FN curve 4 in figure 1.

In distinction to this behaviour of baked samples, an argon GD subsequent to a bakeout provides a stable Nb surface which shows little evolution of the FN curves. In figure 2 curves A and B show the first and last FN plots obtained from 6 consecutive field increases covering a period of 26 days. The curves are very linear over a large range (from 1×10^{-11} A to 1×10^{-6} A). The high current value (1×10^{-6} A) could be extracted without any sparking. The relatively good reproducibility obtained from such a surface is shown in Table 2. The field E_c increased by less than 10% compared with a factor of 3 on the baked sample, and the variation of β is insignificant. The field emitted currents following an argon GD are lower than those first emitted by a sample which has only been baked but, finally, significantly higher after such a sample has been cycled a few times (compare tables 1 and 2).

Several treatments by an argon 10% oxygen GD on

Figure 2. - FN plots after an argon GD (AB) and argon-oxygen GD (C)

TABLE 2

EXP.	E_c (MV/m) (1×10^{-8} A)	β
1	19.2	159
2	20	143
3	20.5	159
4	21	148
5	21	165
6	21	160

pre-baked samples have also been tested. These all resulted in a marked decrease of the field emitted current, as can be seen from figure 2 which shows typical FN plots of a sample before (e.g. A or B) and after (C) this treatment. After the argon-oxygen GD, the field emitted currents are very low and stable, but exceeding a certain critical electrical field results in a violent sparking, which completely destroys the beneficial effect of the treatment. This degradation is accompanied by drastic changes (pitting, ejected particles...) of the surface which are visible on electron microscope photographs of the breakdown zone. The reduction of the field emission current of a sample cycled from a pure argon GD to an argon-oxygen GD and back again is given in Table 3.

DISCUSSION

A general trend in the usually accepted models is the postulate of surface defects and/or micro-particle contamination, enhancing locally the field emission (11-14). GD treatments have in the

TABLE 3

E_c (MV/m) (1×10^{-11} A)		
EXP.	BEFORE G.D.	AFTER G.D.
1	18	43
2	20	44
3*	36*	78*

*These measurements were obtained at a distance of 0.2 mm between the sample and the probe. Other measurements were obtained at a distance of 0.5 mm.

past (15) proved to be an efficient method of treating large vacuum systems in order to reduce the gas desorption yields i.e. by sputtering, partially or completely, the surface layer. The increase of the field emitted current from the argon glow-discharged sample with respect to the initial value from a baked sample can be attributed to the removal of the protective oxide layer. It is known that oxide layers (16) reduce the field emission of niobium. The irreproducibility of the field emission characteristic of the baked sample is related to local modifications of the natural oxide, as can be deduced from the stable behaviour of the oxide free argon GD samples. The progressive decrease of the field emission from baked sample is finally limited by imperfections and impurities in the natural oxide layer. It is known from the work on Josephson junction that the characteristics of the niobium oxide layer can be influenced by its production method (17). In the present case the oxide layer after the argon-oxygen GD has been produced in a well defined and cleaner environment than the wet natural oxide which forms after a chemical polishing treatment, as can be checked on Auger spectra. This situation results in the observed increase in E_c which is more than doubled by the argon-oxygen GD. Nevertheless, exceeding a limiting field limit led to the rupture of this protective layer and to a strong increase of the field emitted currents.

CONCLUSIONS

Although the existence of preferential sites for field emission can put in question the validity of measurements made at an arbitrary place on a sample, several features shown in these measurements have been observed in large (several m^2 of surface) SCC. These are: the progressive decrease of the field emitted currents from a non glow-discharged surface exposed to a high electrical field (e.g. RF processing (4)), and the enhancement of the field

emitted currents subsequent to a pure argon GD (18). These similarities between our measurements and observations made during the operation of real cavities suggest that the effect of the argon-oxygen discharge could result in a beneficial reduction of field emission in superconducting cavities.

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