SOME ESTIMATIONS FOR CORRELATION BETWEEN THE RF CAVITY SURFACE TEMPERATURE AND ELECTRICAL BREAKDOWN POSSIBILITY

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Abstract

The electrical breakdown in accelerating cavities is the complicated phenomenon and depends on many parameters. Some reasons for breakdown can be avoided by appropriate vacuum system design and the cavity surface cleaning. This case for normal conducting accelerating cavities free electrons - the dark currents due to Fowler-Nordheim emission can be considered as the main reason of possible electrical breakdowns. It is known from the practice the combination of the high electric field at the cavity surface with high surface temperature is the subject for risk in the cavity operation. In this paper the dependence of the dark current density on the surface temperature is considered and effective electric field enhancement is discussed.

INTRODUCTION

As it is well understood now, the electron current, emitted from the rf cavity surface, is one reason for electrical breakdown. When the electron current reach some threshold value, the sparking and further breakdown take place.
The investigation of electron emission is a special branch of technical physics and a lot of researchers worked in this field. Extensive special bibliography exists related to the investigation of emitting surface parameters on the emitting current. The systematic review one can find in [2] with related references.
The purpose of this report is not to find new relationships - just, referring to the well known in the emission study effects, estimate the influence of the surface temperature in normal conducting cavities on the dark current emission.

ELECTRON EMISSION

The electron emission from metals is quantum tunneling effect through potential barrier. The probability of the electron tunneling depends on both the barrier parameters - width, height - and the electrons energy state. Several physical processes can change the electron energy state - the external electric field, the temperature of material, the external photons. The quantitative description of electron emission, taking unto account all processes, is very complicated and just under simplifications we can obtain some analytical conclusions.
The electron field emission has been explained in [1] for the limiting case $T_c = 0^o K$,

$$ j_0(E_s) = \frac{A(\beta E_s)^2}{\phi} exp(-\frac{B\phi^{3/2}}{\beta E_s}), \qquad (1) $$

where E_s is the surface electric field, in $\frac{MV}{m}$, ϕ is the work function of the material, in eV ($\phi = 4.47eV$ for copper), $A = 1.54 \cdot 10^6 \frac{eVA}{(MV)^2}$, $B = 6830\frac{MV}{m(eV)^{3/2}}$, β is the ratio of local field at the emitter to the average surface field E_s. For the case of very high electric fields it can be corrected [3] as:

$$ j_0(E_s) = \frac{A(\beta E_s)^2}{\phi} exp(-\frac{B\phi^{3/2}}{\beta E_s})(1 - \frac{5\beta E_s}{18B\phi^{(3/2)}}). \quad (2) $$

Anyhow, both (1) and (2) are obtained in the assumption of absolute zero material temperature. The estimations of the material temperature influence were done in [4] and extended in [5]. The parameter with temperature dimension is the inversion temperature T_i, K^o, related with the external field strength E_s as:

$$ T_i = \frac{0.567E_s}{\sqrt{\phi}}. \qquad (3) $$

Emitting electrons can either absorb the heat from thee emitter ($T_i > T_c$), or generate it, if ($T_i < T_c$) - Nottingham effect. The inversion temperature T_i is the linear function of the external electric field E_s and, to estimate values, $T_i = 134K^o$ for $E_s = 500\frac{MV}{m}$.
Analytical results in [4], [5] are obtained for the case of 'low temperature' and 'high electric field', when temperature addition can be considered as small. According [4], the current density j_{T_c}, emitted from the surface with the temperature T_c is:

$$ j_{T_c} = j_0 \frac{\frac{\pi T_c}{2T_i}}{sin(\frac{\pi T_c}{2T_i})}, \qquad (4) $$

for the temperature range $0 < T_c < 1.2T_i$. Extended temperature region $1.2T_i < T_c < 2.2T_i$ is considered in [5] and

$$ j_{T_c} = j_0 \cdot 1.16 \cdot exp(0.31\frac{T_c^3}{T_i^3}). \qquad (5) $$

The plot of the current ratio densities $\frac{j_{T_c}}{j_0}$ for temperature range $0 < T_c < 2.2T_i$ is shown in Fig. 1. The plot in Fig. 1 exhibits fast rise of the current density for $T_c > 1.5T_i$. Unfortunately, we can not extend the plot for higher ratio values $T_c > 2.2T_i$ - it is out of physical assumptions, done in the obtaining these analytical estimations.
The extension to higher temperatures requires numerical simulations. Such results are known, see, for example [6], and shows significant current density rise with the surface temperature increasing (up to order) for relatively low electric fields. For higher temperatures T_c the current density
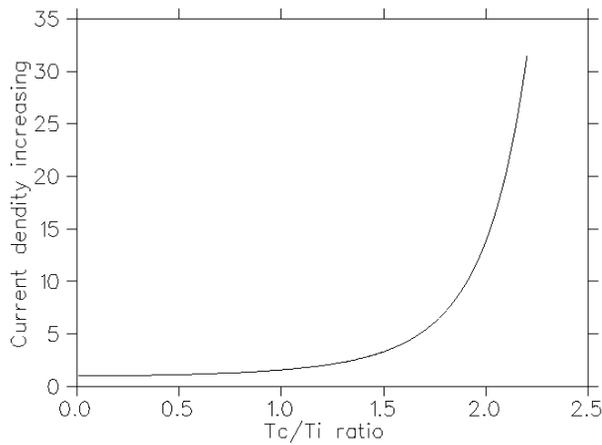
Theory, Codes, Simulations
RF Cavity Codes

Figure 1: The current density increasing with the surface temperature rise.

Figure 2: The current density increasing with the surface temperature rise for different E_s values. 1 - $E_s = 600\frac{MV}{m}$, 2 - $E_s = 800\frac{MV}{m}$, 3 - $E_s = 1000\frac{MV}{m}$.

increasing is not so large, as one can expect from continuation of the plot in Fig. 1, some saturation take place. Using in this paper the known analytical estimations, we can consider the results obtained for the emitted current increasing as the low estimations.

For normal conducting cavities we are interesting in the surface temperature $T_c \sim (293 \div 373)K^o$. We do not assume the higher temperatures, which can lead to high internal stresses and surface destruction.

According (1), the current density j_0 rises very fast with E_s and parts of surfaces with high electric field $E_s \geq 10^3\frac{MV}{m}$ provide the main contribution in the emitted current. But, such electric field leads (3) to high $T_i \geq 300K^o$ value and the effect of emitting current increasing for moderate cavity temperature $T_c \sim 300K^o$ is not important, according (4) for such parts.

The low inversion temperature $T_i \leq 100K^o$ corresponds to the surface field value $E_s \leq 380\frac{MV}{m}$. For such E_s values one can expect the large current increasing with surface temperature, but original current density j_0, according (1), is negligibly small.

In Fig. 2 the plots of the current density j_{T_c} increasing with the surface temperature T_c rise for different E_s values are shown. Significant increasing of the total emitted current we can expect at the part of the cavity surface with 'moderate' electric field $E_s \sim (500 \div 800)\frac{MV}{m}$. Normally, at the well treated cavity surface the electric field is much lower and only special surface imperfectness generate very high E_s value and serve as effective emitters.

EMITTERS MODEL

As it is known from practice, see, for example, [7] and related references, the field emission takes place at the average surface field values, much lower, than predicted by (1). It is explained now, and can be explained only by the existence at the regular cavity surface of point-like emitters with very high local electric field.
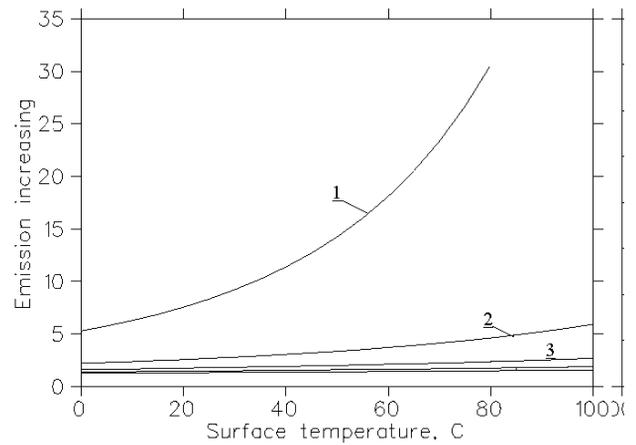
Regular Surface

To have the high quality value Q, close to the design one, the cavity surface should be treated with the surface roughness $R_a \leq 0.2\delta$, where δ is the skin depth at the operating frequency f_0. For $f_0 \sim 1000MHz, \delta \approx 2\mu km$ and should be surface roughness $R_a \leq 0.4\mu km$. It defines the average height of lugs and the deepness of growth at the cavity surface after mechanical treatment. Instead the lugs can be sharp with the high local field at the ends, there is the limitation [8] to the field emission possibility, which provide the relation between the minimal height of the lug h_{min} and the

$$E_{s_{min}} > \frac{4\phi}{eh_m}, \qquad (6)$$

where e is the electron charge. For a field emission the high field is necessary both on the emitter surface, and in the nearest finite vicinity. The small sharp emitters can result in high β value and high local field at the end, but the field decreases very fast with the distance from the emitter end and finally can not extract electron from the metal. For $h_{min} = R_a = 0.4\mu km, E_{s_{min}} > 50\frac{MV}{m}$. It is approximately two times higher as Kilpatrick limit at L-band frequency and normally exceed the maximal surface field in operating regime. The contribution of the well treated regular surface in the emitted field current should be small.

Single Emitters

At the cavity surface exist, see, for example [7], a lot of small (micron scale size) objects - hairlike strands, cone shaped bumps, shiny spheres, sphere on sphere - which can provide the field enhancement and serve as effective emitters. The real emitter shape is less important as compared to the produced β value. Let consider a single emitter as a half of ellipse with axis dimensions $a > b = c$ and axis a is directed perpendicular to the cavity surface. For such model the field distribution is known and the maximal elec-

tric field E_{sm} at the ellipse end is [8]:

$$E_{sm} = E_s \frac{x^3}{(\frac{1}{2}ln(\frac{1+x}{1-x} - x)(1 - x^2)}, \qquad (7)$$

where $x = \sqrt{\frac{a^2-b^2}{a^2}}$. The plot of field enhancement $\beta = \frac{E_{sm}}{E_s}$ is shown in Fig. 3. Along the ellipse envelope the field decreases as $E_{sm}cos(\Theta)$, where Θ is the angle between the normal vector to the ellipse surface and a-axis.

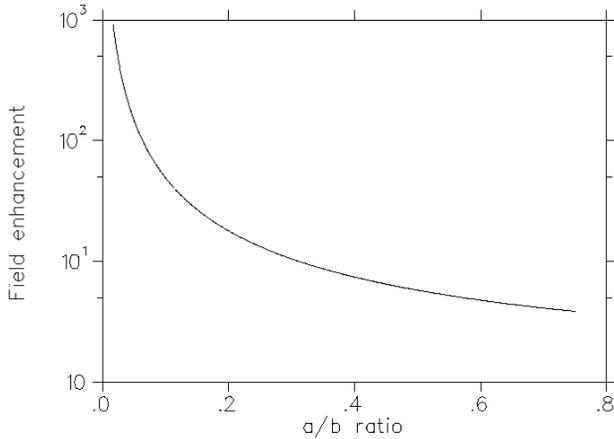For such emitter model we can calculate the emitted cur-

Figure 3: The field enhancement of the elliptical emitter as the function of $\frac{b}{a}$ ratio.

rent values for different $E_s, \frac{b}{a}, T_c$.

The primary effect on the field emission has the local electric field value, which can achieve $E_{sm} \sim 10\frac{GV}{m}$ at $E_s \approx 40\frac{MV}{m}$, corresponding to $\beta \approx 200$ [7]. The field emission is a strongly nonlinear process and the rapid rise of current with local field heavily weights result toward the effective emitters with highest fields, which provide the main part of the emitted current.

During cavity rf conditioning, the initial dark current value decreases at least in two orders. It can be explained either by the reduction of effective emitters number, or, by reduction of emitters efficiency due to emitters shape smoothing and local filed decreasing. To decrease the dark current intensity in two orders, it is required to remove emitters with $\beta > 150$.

Let consider a set of elliptical emitters with $10 \leq \beta \leq 150$ and calculate the ratio of the total emitted current I_0 assuming zero-temperature approximation (1) and I_t - assuming the temperature correction (4), (5). We neglect the emitter heating due to Joule losses - it is essential for effective emitters, which should be destroyed during rf conditioning. The plot of $\frac{I_t}{I_0}$ is shown in Fig. 4 for $E_s = (10 \div 60)\frac{MV}{m}$ and $T_c = (0 \div 100)C^o$.

As one can see from Fig. 4, significant value of the ratio is at low E_s values. As a rule, maximal electric field is at the restricted part of the cavity surface, at drift tubes, at the iris ends. The main part of the surface has a lowered (as compared to maximal) E_s value. Due to strong nonlinear-
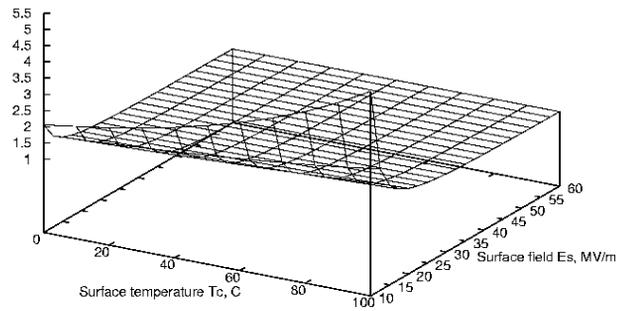

Figure 4: The ratio of total currents I_0 and I_t, emitted by the set of elliptical emitters for $E_s = (10 \div 60)\frac{MV}{m}, T_c = (0 \div 100)C^o$.

ity of the field emission, the unit area in such part provides a small contribution to the total dark current value, but total effect can be significant.

CONCLUSION

In this paper some estimations related to the cavity surface temperature influence on the field emitted (dark) current. For room temperature range the cavity surface temperature is not a primary effect in the dark current emission. The main effect is from enhanced electric field at the effective emitters. But increasing of surface temperature leads to the emission increasing from noneffective emitters, which can be widely distributed at the surface. Also it involves in the field emission the parts of the cavity surface with lowered, as compared to maximal value, surface field. As the result, the total dark current value increases, increasing the breakdowns possibility.

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