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Statistical model for field emitter activation on metallic surfaces used in high-gradient accelerating structures

S. Lagotzky *, G. Müller

University of Wuppertal, School of Mathematics and Natural Sciences, 42119 Wuppertal, Germany

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ABSTRACT

Both super- and normal-conducting high-gradient linear accelerators are limited by enhanced field emission (EFE) in the accelerating structures, e.g. due to power loss or ignition of discharges. We discuss the dependence of the number density of typical emitters, i.e. particulates and surface defects, on the electric field level at which they are activated for naturally oxidized metallic surfaces. This activation is explained by the transition of a metal–insulator interface into geometric features that enhance the EFE process. A statistical model is successfully compared to systematic studies of niobium and copper relevant for recent and future linear accelerators. Our results show that the achievable surface quality of Nb might be sufficient for the suppression of EFE in the superconducting accelerating structures for the actual European XFEL but not for the planned International Linear Collider. Moreover, some effort will be required to reduce EFE and thus the breakdown rate of the normal conducting Cu structures for the Compact Linear Collider.

1. Introduction

Enhanced field emission (EFE) of electrons often limits the achievable gradients of accelerating structures, both superconducting [1] (e.g. for the European X-Ray Free-Electron Laser, EXFEL, and the International Linear Collider, ILC) and normal conducting ones [2] (e.g. for the Compact Linear Collider, CLIC). Experience with the cavity mass production for the EXFEL has shown that at least 20% of the fabricated nine-cell Nb cavities need to be retreated mainly because of the occurrence of EFE during the vertical test [3] to achieve the required specifications. In case of the actual multi-cell Cu structures for CLIC, EFE is considered as major origin of the electron loading and breakdown events, which may lead to severe damage of the cavity surface [4].

EFE investigations of different metallic surfaces with artificially produced emission sites have shown that especially conducting particulates with irregular shapes and regions of mechanical damage are strong geometric field emitters [5], while regular and insulating particulates do not show EFE [6]. Moreover, only 5% of the protrusions identified by scanning electron microscope (SEM) emit at fields below 100 MV m^{-1} [7]. Field emission scanning microscopy (FESM) and correlated SEM measurements with energy-dispersive X-ray spectroscopy (EDX) of Nb and Cu samples relevant for recent accelerating structures confirmed particulates and surface defects as main origin of EFE with field enhancement factors $\beta = 10-120$ and typical emission areas $S = 10^{-4}-10^{4}$ μm^2 [8–10]. Although the emitter number density N can be significantly reduced by high pressure rinsing [11,12] and dry ice cleaning [13,14], N increases strongly even on cleaned surfaces with the applied macroscopic electric surface field E_s. It is remarkable, that field emitters on Nb usually become activated at a certain field level $E_s = E_{act}$, which is usually much higher than the final macroscopic onset field E_{on}, both defined for a current of 1 nA. FESM measurements on polycrystalline Nb suggested an exponential rise of $N(E_{act})$ [15].

Systematic EFE measurements, however, are usually performed on small samples within typical areas of about 1 cm^2 or less, which are much smaller than the high electric field area in accelerating structures. Therefore a scaling law for $N(E_{act})$ is needed to estimate the number of active field emitters in accelerating structures by EFE measurements on small samples at rather high electric field levels. Padamsee et al. [16] introduced and further improved [17] the first statistical model to simulate the electron loading induced by EFE in single and multicell superconducting cavities (1.5 GHz) based on empirical distribution functions for β and S, i.e. an exponential $N(\beta)$ and a Gaussian $N(\log S)$. For a constant total N and randomly placed field emitters on the inner surface of a cavity, electron trajectories as well as the deposited power on the walls were calculated for a given accelerating gradient. This model, however, did neither include the EFE activation correlated with switches of the quality factor Q_0 [18] nor predict $N(E_{act})$ required for comparison with sample measurements.

* Corresponding author. Tel.: +49 202 439 3492; fax: +49 202 439 2811.
E-mail address: s.lagotzky@uni-wuppertal.de (S. Lagotzky).

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Therefore, we have set up here a new statistical model for the activation of EFE on metallic surfaces. A simple exponential dependence of $N(E_{act})$ [9], however, can be excluded since it would lead to a finite $N(E_{act}=0)$ which is unreasonable. In order to consider the influence of different surface preparation techniques, different $N(\beta)$ are derived for the activation of surface features and particulates by taking into account the actual sample roughness and cleanliness. Finally, the resulting scaling law $N(E_{act})$ is calculated and compared to recent EFE results on Nb and Cu samples.

2. Statistical model

The activation of field emitters can be explained by the presence of an insulating oxide layer with a thickness d_{ox} ($\sim$ few nm) on top of the metallic bulk [9]. Accordingly, surface defects initially form a metal–insulator–vacuum (MIV) [19,20] and particulates a metal–insulator–metal (MIM) [21,22] emission regime. Then the field enhancement is given by $\beta^{act}_{MIV} \approx h_s/r_s$ and $\beta^{act}_{MIM} \approx h_p/d_{ox}$ (see Fig. 1) which gives reasonable values above 1 for typical field emitting surface defects and particulates on metallic surfaces with $h_s > r_s$ and $h_p > d_{ox}$ [23]. Such emitters provide no significant EFE current ($I < 0.1$ nA) at surface fields $E_s < E_{act}$. However, the applied field is able to penetrate into the insulating oxide, and if $\beta^{act} \cdot E_s/\varepsilon_r$ is high enough ($10-100$ MV m^{-1}, ε_r: relative permittivity) electrons are injected from the metallic bulk into the oxide by electron hopping through trap levels caused by impurities. Further increase of the field narrows the potential barrier at the metal-oxide interface, so that electrons can tunnel into the oxide (e.g. $j \sim 1$ pA μm^2 at $\beta^{act} \cdot E_s/\varepsilon_r \approx 100$ MV m^{-1} for a barrier height $\varphi_0 = 1$ eV [24]). These electrons are accelerated towards the insulator–vacuum (MIV) or insulator–metal interface (MIM) and transfer energy to the ionic lattice [25]. Typically such currents are too low to cause a significant temperature rise within the oxide layer. In case of sufficient electron energy gain for the reduction of the oxide ($\sim$1–3 eV), however, a metallic conducting channel forms [26]. Accordingly, a significant EFE current is measured at the emission sites by geometric field enhancement, i.e. at a modified $\beta^{on}_s \approx (h_s/r_s)\cdot(h_c/r_c)$ and $\beta^{on}_p \approx h_p/r_p$ (both >1 as argued above) for surface defects and particulates, respectively (see Fig. 1). This

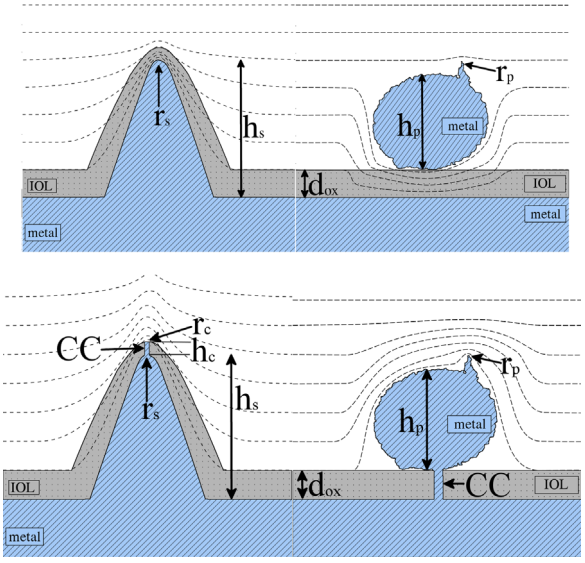

Fig. 1. Equipotential lines for a surface protrusion of height h_s with apex radius r_s (left) and for a rough particulate of height h_p with apex radius r_p (right) before (top) and after (bottom) creation of a conducting channel of height h_c with apex radius r_c into the insulating oxide layer. Please note that h_c might be smaller than the thickness d_{ox} of the oxide.

EFE current is described by the modified Fowler–Nordheim equation [27]

$$I = a\frac{S\cdot E^2}{\varphi t^2(y)}\cdot\exp\left(-b\frac{\varphi^{3/2}v(y)}{E}\right) \tag{1}$$

where S is the emitting area in m^2, $E=\beta^{on}\cdot E_s$ the locally enhanced field in V m^{-1}, φ the work function in eV, $a = 1.541484\cdot10^{-6}$ A eV V^{-2}, $b = 6.830888\cdot10^{9}$ eV$^{-3/2}$ V m^{-1}, and $t(y)$ as well as $v(y)$ are tabulated functions [28] that depend on the relative reduction of the work function $y=\Delta\varphi/\varphi$ induced by the image charge.

It is remarkable that the transition from β^{act} to β^{on} is a transient event, so it is impossible to measure β^{act} of single emitters directly, while β^{on} can be easily determined by analyzing the $I(E)$-dependence of single emission sites. For accelerating structures, it is most important to know at which field levels and how many emitters are activated, and how strong the emission is after their activation. For both types of emitters, EFE finally occurs if the locally enhanced field is above a material-specific field limit E_{lim}

$$\beta^{act}\cdot E_{act} \geq E_{lim} \tag{2}$$

at which the conducting channel is finally formed in the oxide layer as described above. Primarily $E_{lim} \approx 100$ MV m^{-1} – 1 GV m^{-1} depends on the dielectric breakdown of the insulating oxide in dc measurements and probably on the local microwave losses in RF cavities, too.

In order to calculate N at a given E_{act}, all activated emitters that fulfill (2) must be integrated for a given distribution function $N\left(\beta^{act}\right)$

$$N(E_{act}) = \int_{E_{lim}/E_{act}}^{\infty} N(\beta^{act})\mathrm{d}\beta^{act}. \tag{3}$$

The distribution of $N\left(\beta^{act}\right)$ for real surface defects and particulates is not known yet, but it is reasonable to consider two independent functions $N\left(\beta^{act}_{MIV}\right)$ and $N\left(\beta^{act}_{MIM}\right)$. Obviously it is impossible to determine the relevant dimensions of the defects and particulates (h_s, r_s, h_p and d_{ox}) for the surface of interest. The distribution functions, however, can be estimated from the actual surface roughness and cleanliness.

The power spectral density (PSD) is a reasonable way to describe the distribution of surface features at different lateral scales depending on their spatial frequency f_x [29,30]. The PSD can be separated into a fractal, K correlation and shift Gaussian component, of which the fractal one dominates for sharp features ($r_s < 10$ μm) [31]. Assuming the correlation $r_s^{-1} \sim f_x$ and a constant h_s for a polished surface results in

$$N\left(\beta^{act}_{MIV}\right) \sim \mathrm{PSD}_{fractal}\left(r_s^{-1}\right) = N_s^{tot}\cdot\frac{K}{\left(\beta^{act}_{MIV}\right)^n} \tag{4}$$

where the parameters K and n depend on the roughness and N_s^{tot} is a normalization constant.

The expected distribution of the height of particulates $f_p(h_p)$ results from the air condition during surface preparation. Usually it can be described by a log-normal distribution [32]. Assuming a constant d_{ox} and replacing $h_p = \beta^{act}_{MIM}\cdot d_{ox}$ leads to

$$N(\beta^{act}_{MIM}) \sim f_p(h_p) = \frac{N_p^{tot}}{\sqrt{2\pi}\sigma_p\cdot\beta^{act}_{MIM}\cdot d_{ox}}\exp\left(-\frac{\left(\ln(\beta^{act}_{MIM}\cdot d_{ox})-\mu_p\right)^2}{2\sigma_p^2}\right) \tag{5}$$

where the parameters μ_p and σ_p depend on the surface cleanliness and N_p^{tot} is a normalization constant.

As long as surface defects and particulates are the main types of emitters, it is reasonable to take the sum of (4) and (5) with equal weights as shown in Fig. 2 for the integration of (3), which can be