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The dust nature of micro field emitters in accelerators ☆

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ABSTRACT

Field emission currents emitted by micro-emitters are a limiting factor for the operational gradients of accelerating radio frequency (rf) cavities. Within the rf field emission theory the existence of needle like micro field emitters with very high length relative to the radius and corresponding high enhancement factor (β) is assumed. In this article the hypothesis that micro field emitters consists of long chains of conductive micro-particles is considered. Five different forces acting onto the particles in a high rf field are considered and the respective equations are derived. Some experimental observations and their explanation within this hypothesis are discussed.

1. Introduction

The electron field emission effect, i.e. the exponential growth of dark current at high rf field levels, has a large influence on the usable accelerating gradient of accelerators. The exponential growth of the dark current with increasing intensity of the electric field is described by the Fowler-Nordheim equation [1], which can be expressed by the simplified Fowler-Nordheim expression [2], widely used by experimenters:

$$I_{FN}(E) = \frac{A_{FN}A_e(\beta E)^2}{\varphi} exp\left(-\frac{B_{FN}.\varphi^{3/2}}{\beta E}\right), \tag{1}$$

where $A_{FN} = 1.54{\bullet}10^6$; $B_{FN} = 6.83{\bullet}10^3$; A_e is the effective emission area in m^2; E is the field gradient expressed in MV/m and φ is the work function of the emitter in eV.

The field emission theory does not exclude needle-like emitters as dark current sources on the inner cavity surface. The electric rf field can be hundreds times enhanced and is concentrated on the top of a needle-like micro-emitter where the field enhancement factor is equal to the ratio of the emitter height to its radius. Studies show that even with the up-to-date technology of processing of cavities, these emitters have extremely high enhancement factors of $50 \div 1000$ [3]. Field emission analysis based on bremsstrahlung radiation from cavities, which were prepared without cleaning technologies (only being processed) [4] show enhancement factors of up to $\sim$2000. This article discusses the hypothesis that forces acting onto long, conductive emitters lead to a straightening of the emitters. It is assumed that the conductive particles consist of carbon or graphite as these are among the most common materials in nature.

Another point of view is considered in [5] where photo emission and field emission in an RF gun were studied simultaneously. The authors of [5] propose small enhancement factors but very low work functions φ to explain the dark current; i.e. $\beta < 5$ and $\varphi < 0.5$ eV though the usual work function is on the order of 4–5 eV. The precisely polished copper back plane of the gun was used as photocathode with a surface-field of 50–75 MV/m. The field emission current together with the laser induced photo current were observed. Surprisingly, a Schottky-enabled photo effect from different sites of the laser spot is reported, which is only possible if the surface electric field at these sites is enlarged by 30-60 times as compared to the nominal field, i.e. $\beta > 30 \div 60$. The field emitted current is compatible with $\beta \sim 130$ and a work function of $\varphi \sim 4$ eV.

Air filters cannot prevent that small, conductive particles with a radius of 0.5–5 μm [6] enter cavities during assembly. Needle-like emitters with large enhancement factor can be formed out of these particles by forces appearing in a high electric field. These forces, which are larger than the gravitational force of the particles by some orders of magnitude, are described in this article. It would be impossible to see such needle-like emitters in a vented cavity because they are easily destroyed by air flow and contaminates from the flow.

This paper is based on the common hypothesis that the field enhancement factor can be as big as 1000. This explains rf processing effects and allows to find new processing technologies. Such a big enhancement factor is proved e.g. by experiments [7] where the trace of field emission electrons was observed by means of a YAG screen installed outside of the superconducting RF gun. The form of the observed traces is feasible only, if the top of the emitter is exposed to a large electric field which directs from the

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top to all directions of the 3D hemispherical space.

The second section concerns the mechanical forces acting onto particles and between conductive particles which form an emitter as a long chain of these particles. The program CLANS [8] is widely used in the calculations. In the third section the effects of light emission phenomena in rf cavities [9] and other effects are discussed to support this study.

2. Forces acting on conductive particles

Conductive particles and emitters in an rf field are influenced by five different forces. The magnitude of the forces is very high in comparison to the gravitational force of the particles. Their definitions are useful to study the behavior of the emitter model and compare it with experiments. SI units are used throughout the article.

2.1. Attractive particle-particle and particle-wall force

Two particles, as well as a particle and a nearby wall, are attracting each other by the force named in the following F^a, because the charges at the ends of particles or on a particle and its mirror image in the conductive wall have opposite signs. In Fig. 1b a particle is depicted above the cavity surface. The image charge is distributed such, that the added electric field lines end up perpendicular on the surface. The force has a dipole characteristic, so it rapidly decays when the particle moves away from the surface, or when two conductive particles move away from each other.

From the symmetry of the electric field lines of the mirror image charges in the cavity wall (see Fig. 1b) follows that the attractive force between the cavity wall and a particle is equal to that between two identical particles. To calculate this force, we calculate the variation of the total energy of the rf cavity field due to a displacement of the particle playing the role of a perturbing body, $\Delta U/2U=\frac{\Delta\omega}{\omega}$ [11], where U and ΔU are the total electromagnetic rf energy in the cavity and its variation due to the movement of the perturbing body by Δz, respectively. The force of the rf field F^a

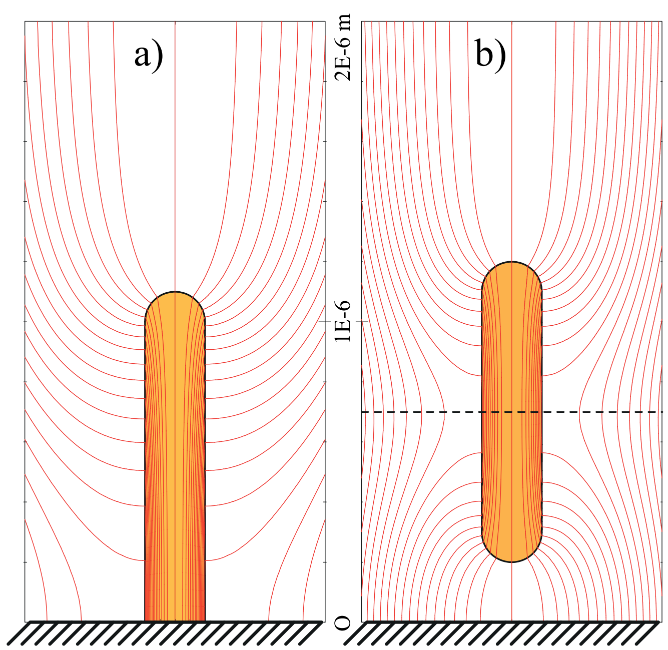

Fig. 1. Force lines of the electric field of an attached emitter with $\beta=10$ (a) and a flying particle with $\beta=5$ (b) (CLANS, data outlined in [10]). The electric field inside the particles is much smaller than the field in the cavity and precedes it by 90° in phase.

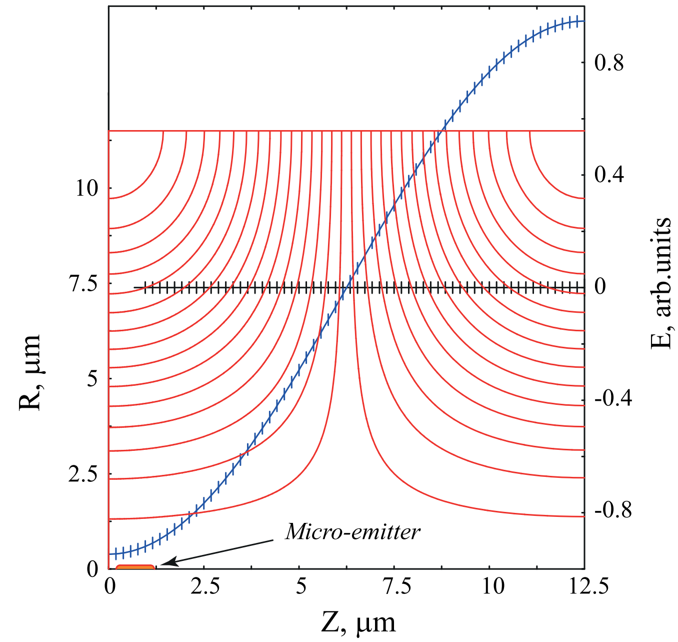

Fig. 2. Force lines of the E_{011} mode in the pillbox cavity and distribution of electric field strength along the axis.

acting on the perturbing body is determined by the law of conservation of energy

$$F^a\bullet\Delta z= -\,\Delta U=-U\bullet\Delta\omega/\omega. \quad (2)$$

In a series of SLANS computations of the resonance frequencies of a cylindrical (pillbox) cavity, a conductive particle with $\beta=5$ ($L/r=10$, where $L=1.0$ μm is the particle length, $r=0.1$ μm is the particle radius) was placed on the cavity axis at different distances from the wall. For the sake of better sensitivity of the method, the cavity dimensions were chosen rather small: a radius of 11.52 μm and a height of 12.52 μm. The resonant frequencies of the two lowest modes E_{010} and E_{011} are at 10^{13} and $1.56\bullet10^{13}$ Hz, respectively. The skin layer does not matter in this example, since the field within the conductive particles is negligible and cannot influence the energy variation in the cavity significantly [10]. Since the rf field for the E_{010} mode is uniform along the axis, the attractive force to the wall F^a is only studied for this field configuration. The field for the E_{011} mode changes with the local variation of the gradient (see Fig. 2), and thereby the gradient force F^g considered below is naturally present. Fig. 3 presents a graph of the variation of the resonant frequencies of the two modes when a

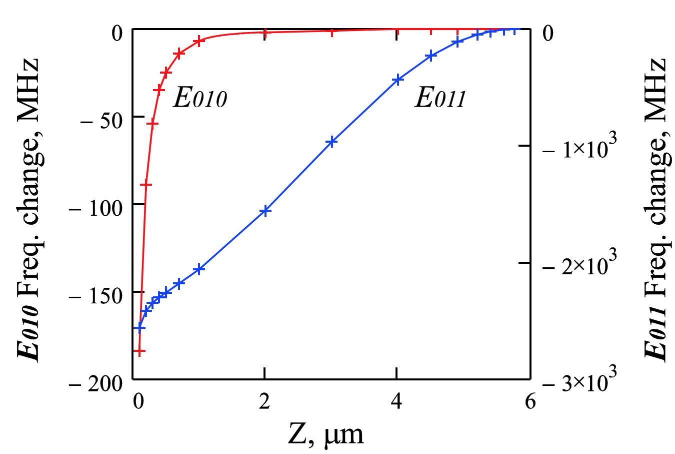

Fig. 3. Variation of the frequency of the E_{010} and the E_{011} mode due to an emitter positioned along the cavity axis.