THE EFFECT OF ENHANCED FIELD EMISSION ON CHARACTERISTICS OF SUPERCONDUCTING RADIO FREQUENCY CAVITIES

by

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Electron field emission limiting the accelerating gradient in superconducting cavities remains the dominant setback in cavity production. The need to understand and control the field emission has become increasingly important because of the prospect of using high-gradient structures in linear colliders. Since building an accelerator structure is a complicated and costly process, elimination of unnecessary steps has priority. In this paper an analysis of the influence of the enhanced field emission in superconducting radio frequency cavity together with modal field calculations by using COMSOL finite elements package has been presented. The obtained results reveal that the electric field required for the field emission is generated in the cavity irises. The imperfection of the cavity surface leading to very high fields is modelled by a simple cone. The estimated value of the enhancement factor for the cone tip of around 4 is in a good agreement with the data found in the literature. In addition, from the slopes and the intercepts of the Fowler-Nordheim plots, a dependence of the enhancement factor and the effective area on the work function has been estimated.

Key words: superconducting cavity, Tesla cavity, field emission, enhancement factor

INTRODUCTION

Superconducting radio frequency (SRF) science and technology deal with the application of superconducting materials to radio frequency (RF) devices with the most common application to the particle accelerators [1-8]. The main advantage in the use of SRF cavities is the reduced dissipation due to wall losses [9-13]. The wall loss power dissipation is proportional to the surface resistance, which is reduced by a factor of one million in superconducting cavities. Unfortunately, the exponentially increasing power dissipation due to field emission quickly consumes all available power so it can be concluded that the performance of SRF cavities is limited by field emission [14, 15].

The surface of an accelerating structure such as SRF cavity contains a number of imperfections caused by grain boundaries, scratches, bumps, *etc*. The electric fields at these small imperfections can be greatly enhanced and, in some cases, the field can be increased by a factor of several hundred. Enhanced field emission (EFE) is regarded as a fundamental limitation in a wide range of high-voltage vacuum devices, for instance, X-ray tubes, electron microscopes, power vacuum switches, klystrons, and SRF resonators for particle accelerators [16]. Actually, EFE is considered as the main impediment to higher acceleration gradients in superconducting niobium (Nb) radiofrequency cavities [17]. The strength, number and sources of EFE sites strongly depend on surface preparation and handling.

Field emission (FE) of electrons from sharp tips represents the most severe constraint in high-gradient superconducting cavities [18]. Small particles on the cavity surface operate as field emitters causing the exponential drop of the quality factor above a certain threshold. Superconducting cavities are even more sensitive to field emission since even small additional dissipation of RF power due to the electron loading of the cavity may correspond to a significant and undesirable quality factor degradation of the cavity [19]. Emitted electrons impact elsewhere on the cavity surface, heating the surface and therefore increasing the surface resistance and power dissipation of the cavity. In extreme cases, FE heating of the cavity walls can lead to the thermal breakdown. Acceleration of emit-

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ted electrons absorbs power out of the electromagnetic fields which would otherwise be available for acceleration of the particle beam. Eventually, as fields are raised, the power dissipation into FE related processes limits the attainable fields in the cavity. For all of these reasons, understanding the origins of field emission and avoiding field emission in cavities have attracted significant attention.

In this paper the effect of the enhanced field emission on the properties of the SRF cavities has been systematically studied. In addition, three-dimensional (3-D) calculations of the π-mode field for 9-cells TESLA cavity operated on 1.3 GHz has been performed by using COMSOL package [20, 21]. The local field enhancement factor beta is introduced in the Fowler-Nordheim (F-N) equation in order to explain field emission current densities due to geometric features. Local variation of enhancement factor that determines the local dependence of the emitted current have been analyzed based on the F-N theory. The negative slopes of the so-called F-N plots confirm the presence of field emission leading to an exponential drop of the Q_0 factor (defined as the ratio of the geometry factor to the microwave surface resistance). From the slopes and the intercepts of the F-N plots, the dependence of the enhancement factor and the effective area on the work function has been established.

THEORETICAL BACKGROUND

As already emphasized, one of the effects that limit the high-field performance of superconducting cavities is electron FE [22]. The high electric field generated in the cavity leads to the electrons quantum tunnelling out of the structure creating a field emitted current. Generally speaking, FE represents the extraction of electrons from a solid by tunneling through the surface potential barrier under the influence of a strong electric field. Emitted electrons are then accelerated by the cavity fields and upon striking the cavity walls their kinetic energy is converted to heat and X-rays. At high fields, once emitted a field emitted current can interact with the cavity fields and affect the properties of the cavities. [23]. When the electric field becomes sufficiently large, the electron loading absorbs energy from the RF field leading to the exponential drop of factor Q_0 as illustrated in fig. 1.

A high electric field lowers the potential barrier and makes it sufficiently penetrable allowing tunnelling of electrons through a potential barrier, rather than escaping over it. During FE, an electron tunnels out of a material primarily due to the electric field. The field emission current density j_{FE} is determined by the transmission coefficient D of the barrier [25]

$$j_{\mathrm{FE}} \quad e \int_{0}^{\infty} n(\delta) D(\delta, E) \mathrm{d}\delta \tag{1}$$

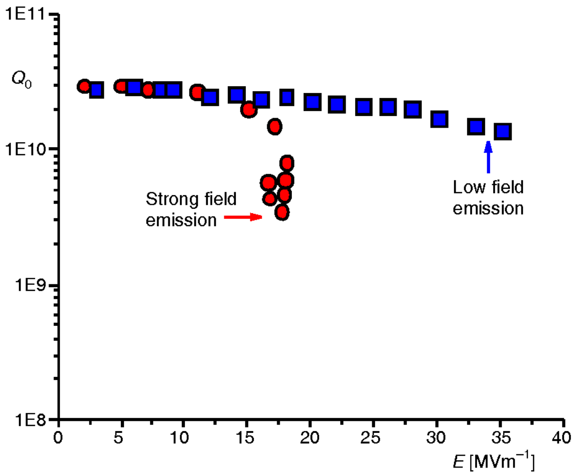


Figure 1. The effect of the field emission on the Q_0 factor of the superconducting cavity [24]

with δ as the fraction of the electron's energy that is associated with the component of momentum normal to the surface of the conductor and E as the electric field strength at the surface, while e is the electron charge. The field emission rms current for RF fields is given by the F-N eq. [25]

$$\overline{I_{FE}^{RF}} \quad \frac{5.79\ 10^{12} \exp(9.35\varphi^{0.5})(\beta E)^{2.5} A_{\Xi}}{\varphi^{1.75}} \exp \frac{6.53\ 10^{9}\varphi^{1.5}}{\beta E} \tag{2}$$

assuming that the emitter has an effective area A_{Ξ}, while ϕ represents the work function (expressed in eV) of the material of the cavity, and β is the enhancement factor defined as the ratio of the local emitter field over the applied field.

Originally, the F-N equation has been established for cold flat surfaces. The local field enhancement factor β is often introduced in the F-N equation to represent the geometrical effects at the surface since the high localized field also enhances field emissions. Sharp and jagged features on the surface can be present at scratches or metal particles. The "macroscopic" geometry of particles that have been found at field emitter sites cannot explain the full enhancement factors of up to several 100 that are observed [26, 27]. The numerical value of β for a particular surface can be obtained by plotting $I_{\mathrm{FE}}/\mathrm{E}^{2.5}$ *vs*. 1/E on semi-log paper, which is called a F-N plot given by the relation [28]

$$\frac{\mathrm{d}(\log_{10} I / E^{2.5})}{\mathrm{d}(1/E)} \quad \frac{2.84\ 10^{9}\varphi^{1.5}}{\beta} \tag{3}$$

This is attributed to field gradient enhancements resulting from microscopic surface irregularities. In practice, F-N plots which yield the values of β are probably determined by a single or few emitters in a surface. The point at which the F-N line intercepts the

y-axis is proportional to the emitting area *i. e.* the intercept of the line with the $\log_{10}$ (I_{FE} /E$^{2.5}$) axis [29]

$$\log_{10}\frac{I_{FE}}{E^{2.5}}\ {}_{E\ \infty}\qquad \log_{10}\frac{5.79\ 10\ ^{12}\exp(9.35\varphi\ ^{0.5})(\beta E)^{2.5}A_{\Xi}}{\varphi^{1.75}} \tag{4}$$

provides the value of A_{Ξ}.

RESULTS

Field calculation of the 9-cells TESLA cavity operated on 1.3 GHz has been performed by using COMSOL simulation package [20] with the simulation conditions based on details and parameter given in ref. [30]. Accelerating component of the electric field of the 1.3 GHz π-mode along the cavity axis and field vectors are presented in fig. 2. Since eigen solver provides eigen values, an electric field is expressed in arbitrary units. Actual values can be obtained by applying real excitation source working on 1.3 GHz adjusted to produce accelerating field of around 25 MV/m. The areas of the strong fields are clearly resolved. Strong electric field and irregularities on the cavity surface enhance electron emission. The most illustrative is fig. 3 which shows the distribution of the electric field on the cavity surface operated on 1.3 GHz π-mode. Since the maximum values of the field are around the cavity irises, in these areas field emission effect is most probable, which was confirmed both from the literature and our calculations, as shown in fig. 3. When the electric field reaches the threshold value, field emission becomes important affecting the characteristic of the cavity. Removing irregularities from the surface and thereby enhancement of the field will diminish the effect of the field emission.

It is well known that the largest enhancements of the field originate from sharply peaked imperfections, so here we use a cone tip as a model of imperfection that deteriorates the system characteristics. The component of the electric field on the conical conductor is given by the expression [29, 30]

$$E\qquad \frac{\partial \Phi}{\partial r}\qquad vAr^{v\ \ 1}P_v(\cos\theta) \tag{5}$$

where P is the Legendre function [31, 32]. For a sharp cone tip, β and

$$v\qquad 2\ln\frac{2}{\pi\quad\beta} \tag{6}$$

where β is the tip angle. In that case, the field singularity is of the order of $(1/r)$. We have calculated the changes of the π-mode field near the cone tip (of 500 m height, as a reasonable estimation of imperfection geometry) located at the iris, where the electric field reaches its maximum value on regular geometry, as shown in fig. 4. In contrast to the analytical expres-

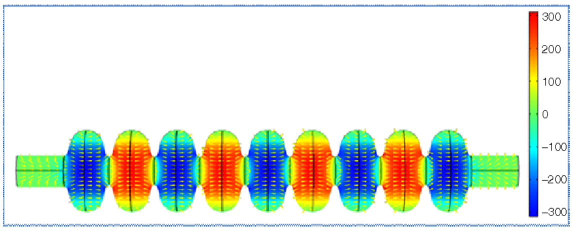


Figure 2. Component of the electric field along the cavity axis. Electric field lines of the 1.3 GHz – mode

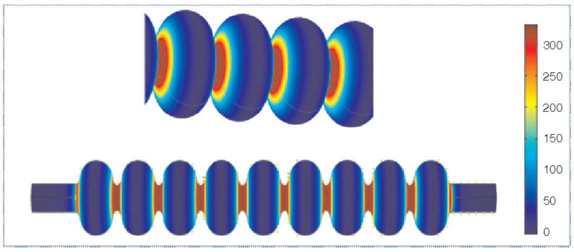
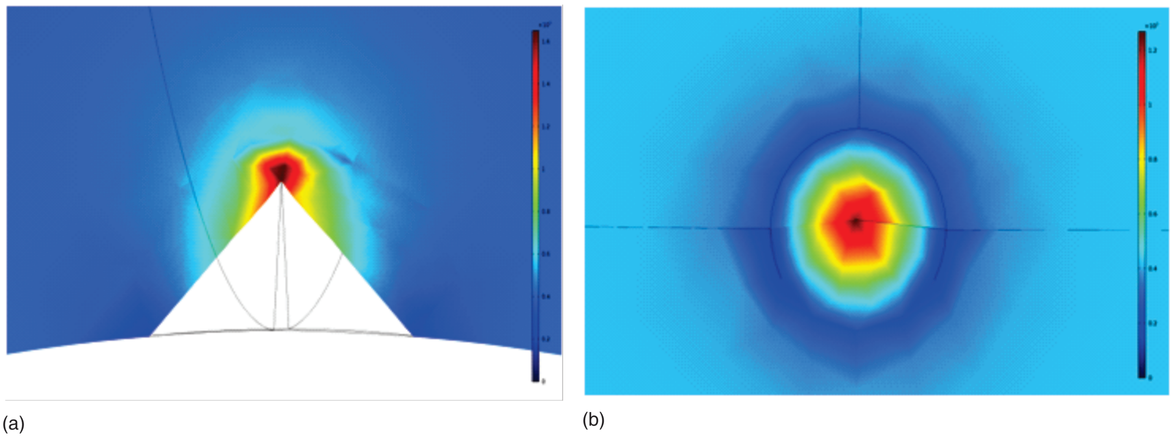


Figure 3. Electric field on the surface of 9-cells TESLA cavity operation on 1.3 GHz – mode



(a) (b)

Figure 4. Model field near the conical tip (white) located tangentially to the iris: (a) front view – perpendicular to the viewing plane shown in fig. 3, and (b) bottom view – along the cone axis from the above. The field is given in arbitrary units. The solid grey lines in the middle are artifacts of the mesh generating process, having no physical meaning

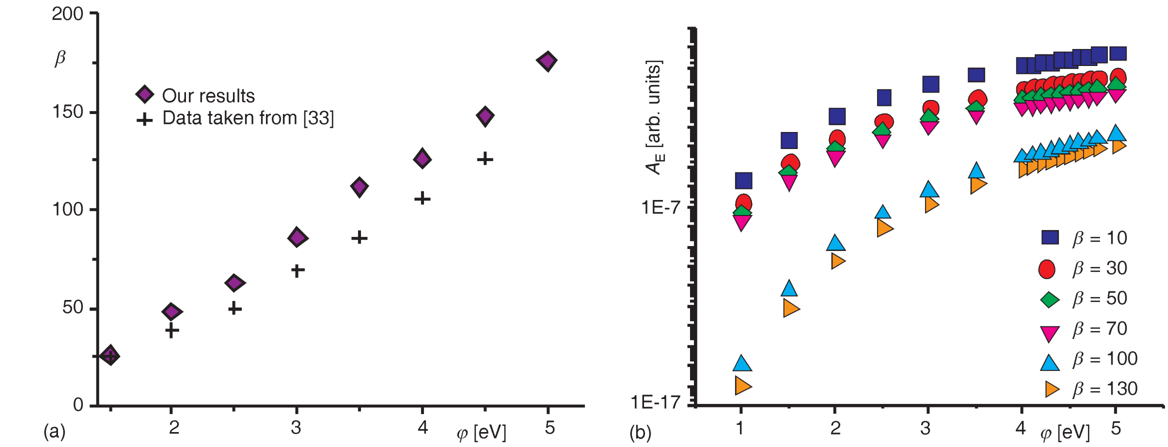


Figure 5. The dependence of: (a) the enhancement factor and (b) the effective area A_E on the work function, with enhancement factor β as a parameter. Crosses correspond to the experimental data taken from [33]

sion that has singularity on the tip, calculated values of the field have no singularity, but a drastic increase of the field on the tip is reproduced. From the ratio of the highest and lowest values of the electric field we estimated the enhancement factor for the cone tip to be around 4 which is in accordance with the calculated value found in the literature [27].

Figure 5 shows the dependence of the: a) enhancement factor and b) effective emitting area on the work function. Although, the effective area decreases with increasing enhancement factor both, the enhancement factor and effective area increase with increasing the work function. The calculated values for the enhancement factor (violet diamonds) agree well with the data estimated from the measurements (crosses) [33].

CONCLUSIONS

This paper is devoted to the main limiting process related to the high surface electric fields which means the liberation of electrons from the metal surface by the high electric field. Actually, the SRF community has devoted considerable resources to understanding the origins of field emission and paid a great deal of attention to avoiding field emission and dealing with residual emission. At the onset of field emission, the factor Q_0 of the cavity typically starts to fall steeply because of exponentially increasing electron currents emerging from the surface. Even when there is no field emission the Q_0 starts to drop above accelerating fields of 20 $\mathrm{MVm^{-1}}$. In this paper, the effect of the enhanced field emission on properties of the SRF cavities has been theoretically studied together with model field calculations by using COMSOL simulation package. Simulations conditions for the 1.3 GHz -mode were based on the parameters and details of real 9-cells TESLA cavity. The obtained results reveal that enhanced field emission takes place in the irises. The cone tip, that models the surface imperfection that deteriorates the system characteristics, may act as an emitter leading to the high electric field and thereby the enhanced field emission. From our calculations we estimated the enhancement factor for the cone tip of around 4 which agree well with the calculated values from the literature [27]. The F-N expression (2) indicates that the exponential dependence of the field emission on the electric field strength pins the electric field to the value for field emission. The F-N currents and plots strongly depend on the enhancement factor and work function. It was shown that the enhancement factor and the effective area increase with increasing the work function. Since particulate contaminations and imperfections cause the enhanced field emission in superconducting cavities, the results presented here are useful for designing of superconducting cavities, showing that cleanliness and polishing of the surfaces are indispensable prerequisites in avoiding enhanced field emission from extended surfaces.

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AUTHORS' CONTRIBUTIONS

The manuscript was written by M. D. Radmilović-Radjenović, B. M. Radjenović, and P. D. Beličev. Simulations were done by M. Radmilović-Radjenović, B. M. Radjenović, and P. D. Beličev. The figures were prepared by M. Radmilović-Radjenović.

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УТИЦАЈ ЕМИСИЈЕ УСЛЕД ЈАКОГ ПОЉА НА КАРАКТЕРИСТИКЕ СУПЕРПРОВОДНИХ РАДИО-ФРЕКВЕНТНИХ ШУПЉИНА

Емисија услед јаког поља ограничава градијент убрзања у суперпроводним шупљинама представљајућу, тако, доминантни недостатак у њиховој производњи. Потреба за разумевањем и контролом емисије услед јаког поља постала је веома важна управо због могућности коришћења структура високих градијентитета у линеарним колајдерима. С обзиром на то да је изградња таквих структура веома компликован и скуп процес, елиминација непотребних корака има приорите. У овом раду представљена је анализа утицаја емисије услед јаког поља у суперпроводној радиофреквентној шупљини заједно са прорачунима поља добијеним коришћењем одговарајућег софтверског пакета базираног на методи коначних елемената. Добијени резултати показују да јако електрично поље, које доводи до појачане емисије, настаје на отворима (ирисима). Несавршеност површине која доводи до ефеката јаког поља моделована је на примеру конуса. Процењена вредност тзв. фактора побољшања код конусног облика је око 4, што је у доброј сагласности са подацима пронађеним у литератури. Поред тога, процењена је зависност фактора побољшања и ефективне површине од тзв. функције рада која је карактеристична за сваки материјал.

Кључне речи: суперпроводна шупљина, Тесла шупљина, емисија услед јаког поља, фактор појачања