SIMULATION STUDY OF DIRECT CURRENT VACUUM BREAKDOWN AND ITS APPLICATION TO HIGH-GRADIENT ACCELERATING STRUCTURES

by

Marija D. RADMILOVIĆ-RADJENOVIĆ* * *and Branislav M. RADJENOVIĆ

Institute of Physics, University of Belgrade, Belgrade, Serbia

Scientific paper
https://doi.org/10.2298/NTRP2001030R

It is well known that radio frequency breakdown is one of the main limitations in high frequency accelerators. Similarities have been detected between breakdowns in direct current vacuum gaps and those in superconducting radio frequency cavities. Therefore, cavity breakdowns due to electric field phenomena can be understood by studying direct current vacuum breakdowns. Significant irregularity of a surface and a variety of involved processes objectively stipulate a number of factors which may lead to a breakdown. In this paper, the effects of surface conditions, accelerator gradient, pulse length, and operating frequency on the breakdown have been studied by using COMSOL simulation package. It was found that the dependence of breakdown rate on accelerating gradient and pulse length follows scaling laws. Based on the time evolutions of electron density and the potential in cone-cylinder electrode configuration at the pressure of 0.1 Pa, the time scale of a vacuum breakdown has been established. It was also confirmed that the emission from an electrode surface can be regarded as a major factor leading to electrical breakdown in vacuum. The obtained results could be very useful in high-gradient accelerating structures.

Key words: accelerator, cavity, breakdown, COMSOL

INTRODUCTION

Electrical breakdown is a serious constraint in many technologies related to strong electric fields. In radio-frequency (RF) linear accelerators and microwave cavities RF breakdown causes limitations of the maximum achievable gradient and the reliability of such devices [1-8]. Breakdowns primarily occur in areas of high electric field, but an electric field is far from being the only parameter that might affect breakdown rate (BDR). Better understanding of breakdowns could particularly be beneficial for particle accelerators which require the highest attainable electric fields in microwave resonators that accelerate particles. Despite some differences, breakdown voltage in microwave resonators shares some features with breakdowns in direct current (DC) vacuum gaps [9].

Although breakdowns in radio frequency cavities have been studied for a long time and are related to DC vacuum breakdowns, which have been studied for an even longer time, there is no standard model or a mechanism or a model which explains the data. An electrical breakdown always starts with the multiplication of some primary electrons accelerated by the electric field. In the case of sufficiently low pressures the mean free path of the electrons is long and the initial avalanche proceeds until plasma is generated in the entire discharge gap [6, 10, 11] Under very low pressures, the breakdown mechanism is usually called the *vacuum breakdown*. A vacuum breakdown is dominated mostly by electrodes and not affected by gas since the mean free path is of the order of few meters, so an electron crosses the gap without any collisions [12]. Consequently, current growth prior to breakdown cannot occur due to formation of electron avalanches. As it can clearly be recognized from fig. 1, a vacuum breakdown occurs at very low pressure, while a gas breakdown takes place at pressure higher than 0.1 Pa. In the transition zone (between 0.1 and 1 Pa) both types of discharge can be presented. In the range of vacuum discharge, breakdown voltages are dispersed due to surface conditioning effects and are independent of gas type presenting a clear difference between the two kinds of discharges.

In this study, we applied the COMSOL simulation package [13] in order to investigate the DC breakdown at the pressure of around 0.01 Pa which belongs to the vacuum zone according to fig. 1. Since DC

* Corresponding author; e-mail: marija@ipb.ac.rs

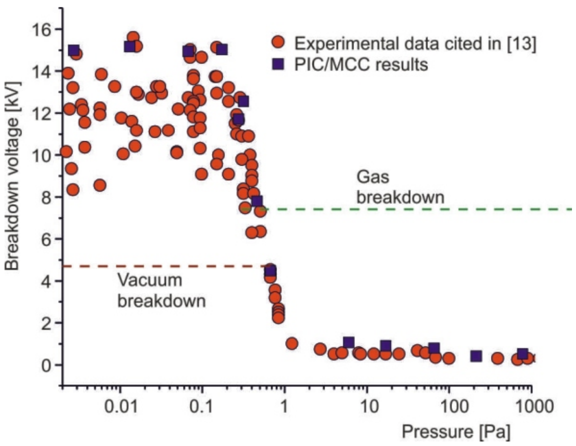

Figure 1. Breakdown voltage as the function of pressure; experimental data [12] are represented by circles, while squares correspond to simulation results

breakdowns are simpler it is useful to study them as a necessary starting point for future understanding of an RF breakdown. In DC spark systems it is also possible to separately test the effects that variously affect the breakdown. Although breakdowns primarily occur in areas of high electric field, electric field is far from being the only parameter which affects BDR. Here, the effect of the electric field and the pulse length on the BDR was considered. In addition, the time evolutions of the electron density and the potential in cone-cylinder electrode configuration at the pressure of 0.1 Pa have been analyzed in order to reveal the time scale of a breakdown in vacuum. The results are discussed with application to the suppression of vacuum breakdown in high-gradient accelerating structures.

VACUUM BREAKDOWN

A vacuum electrical breakdown can be referred to as a sudden, catastrophic exchange of the charge between two electrodes with a potential difference which, prior to breakdown, were separated by vacuum. By definition, there is an absence of a significant number of charge carriers in vacuum. A vacuum breakdown is usually a cathode dominated process with the anode acting only as a passive collector of electrons. For a breakdown to occur there must be a potential difference between electrodes. A metal surface exposed to a large enough positive electric field, will emit electrons [14]. This process is known as field emission and the emitted electrons as field emitted electrons.

The probability of an electron escaping from the surface of a metal depends on the properties of the metal, on the kinetic energy of the electron perpendicular to the surface as well as on the electric field at the metal surface. The emission current density can be expressed as follows [15]

$$j_{\mathrm{e}} \quad e \overset{\inf}{\underset{eV\ \min}{}} N(W_{\mathrm{z}},T)D(W_{\mathrm{z}},E)\mathrm{d}W_{\mathrm{z}} \tag{1}$$

where W_z is the kinetic energy of the electrons considering only the velocity of the electrons in the direction perpendicular to the surface, T and E are the temperature and the electric field at the surface, respectively, $N(W_z, T)$ – the number of electrons at energy W_z per unit area when the cathode is at temperature T, and $D(W_z, E)$ – the probability the electrons shall tunnel through the potential barrier.

In accelerating cavities, field emission current is often referred to as the *dark current* since it occurs without intense flash. Actually, breakdowns have a tendency to occur on areas of a cathode which exhibit enhanced levels of field emission. At low temperatures the expression for the electron current j_{FE} takes the form of the Fowler-Nordheim equation [16]

$$j_{\mathrm{FE}} \quad \frac{1.54\beta^2 E^2}{\phi} \mathrm{e}^{10.41\phi^{1/2}} \mathrm{e}^{[6.53\phi^{3/2}/(\beta E)]} \tag{2}$$

where E is the electric field and ϕ is the material work function (expressed in eV). The enhancement factor β is introduced because of surface irregularities and it is defined in terms of the local field divided by the average surface field. Its numerical value for a particular surface can be estimated from the slope of the so-called Fowler-Nordheim plot [16]

$$\frac{d\left(\dfrac{\log_{10} I_{FE}}{E^{2.5}}\right)}{d\left(\dfrac{1}{E}\right)} \qquad \frac{2.84\ 10^9 \phi^{1.5}}{\beta} \tag{3}$$

Establishing and understanding empirical scaling laws related to a breakdown provide the information necessary to design accelerating structures with higher performance. It was shown that BDR scales with pulse length τ was in accordance with the following law

$$BDR \quad E^{30}\tau^5 \tag{4}$$

where E was the accelerating gradient. It was shown that E^{30}/BDR = const at a fixed pulse length τ. On the other hand, the dependence of gradient on pulse length at a fixed BDR follows a well established scaling law [17]

$$E\tau^{1/6} \quad \mathrm{const} \tag{5}$$

that has been confirmed in many experiments (see for example [17]).

SIMULATION TECHNIQUE

Nowadays computer simulation has become an essential part of science and engineering [18, 19]. For this study, the DC vacuum breakdown was analyzed by applying COMSOL software package to solve the continuity and transport equations by using the finite element method [13]. The electron density and mean electron energy were computed by solving the following pair of drift-diffusion eqs. [13]

$$\frac{\partial}{\partial t}(n_e) + \nabla \cdot [-n_e(\mu_e \cdot \mathbf{E}) - \mathbf{D}_e \cdot \nabla n_e] = R_e \quad (6)$$

$$\frac{\partial}{\partial t}(n_\varepsilon) + \nabla \cdot [-n_\varepsilon(\mu_\varepsilon \cdot \mathbf{E}) - \mathbf{D}_\varepsilon \cdot \nabla n_\varepsilon] + \mathbf{E}\cdot\Gamma_e = R_\varepsilon \quad (7)$$

with $\Gamma_e = -(\mu \cdot \mathbf{E})n_e - \mathbf{D}_e \cdot \nabla n_e$ and $\mathbf{D}_e = \mu_e T_e, \mu_\varepsilon = (5/3)\mu_e$ and $\mathbf{D}_\varepsilon = \mu_\varepsilon T_e$ In DC discharges, Townsend coefficients are usually used instead of rate coefficients, so the electron source term and the electron energy loss are expressed as [15]

$$R_e = \sum_{j=1}^{M} x_j \alpha_j N_n |\Gamma_e| \text{ and } R_\varepsilon = \sum_{j=1}^{P} x_j \alpha_j N_n |\Gamma_e| \Delta\varepsilon_j \quad (8)$$

where α_j is the Townsend coefficient for reaction j and Γ_e – the electron flux.

One of the crucial steps in finite element calculations is meshing. Since meshing means surface separation into a number of smaller elements, computation time increases with the number of mesh elements. Therefore, meshing should be fine enough to get accurate results, convergence and stability, and coarse enough to avoid long calculation time.

Commercial simulation tool COMSOL is also capable of modeling some of the relevant electromechanical effects in the cavity. As an illustration, fig. 2 shows the accelerating component of the electric field of the 1.3 GHz π mode along the cavity axis including field vectors calculated by applying COMSOL package. Since the maximum values of the field are around the cavity irises, in these areas field emission effect is most probable. When the electric field reaches the threshold value, field emission becomes important since it affects the characteristic of the cavity. Since small imperfections on the cavity surface act as field emitters, the perfect cleaning, for example by high pressure water rinsing, is the most effective remedy against field emission.

RESULTS

Figure 3(a) shows that the breakdown voltage increases with successive flashovers, until a constant value is achieved. After that, the electrodes are assumed to be conditioned. This increase in voltage is attributed to the burning off by sparking of microscopic irregularities or impurities which may exist on the electrodes. Unconditioned electrodes may have breakdown values lower by around 50 % of the values recorded for the breakdown voltage with conditioned electrodes. The effect of electrode degradation after several breakdowns can be seen from SEM pictures shown in fig. 3(b) [11].

Figure 4 shows the electric field at various gap sizes based on current-voltage characteristics and corresponding Fowler-Norheim (F-N) plot recorded with pressure around 0.01 Pa [20]. The current starts at around 0.5 μA and then increases rapidly due to field emission effect. As can be seen from fig. 4(a), a shorter gap leads to the formation of stronger electric field and enhanced field emission. When the electric field becomes sufficiently strong, the electrons are liberated from the surface by quantum mechanical tunneling that leads to a breakdown. The current generating mechanism before breakdown is field emission, as confirmed by a linear F-N plot [20] with a negative slope shown in fig. 4(b).

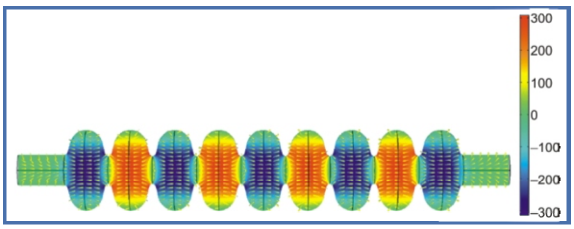

Figure 2. Component of the electric field along the 9-cells TESLA cavity operation on 1.3 GHz π-mode

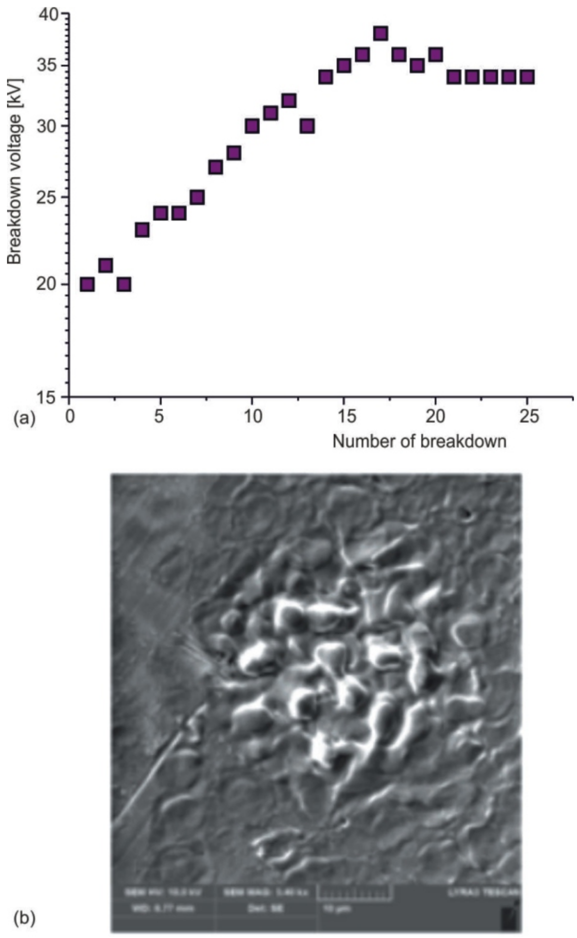

Figure 3. The dependence of breakdown voltage on the number of breakdowns (a) and SEM micrographs of the electrode surface after several breakdowns (b) [11]

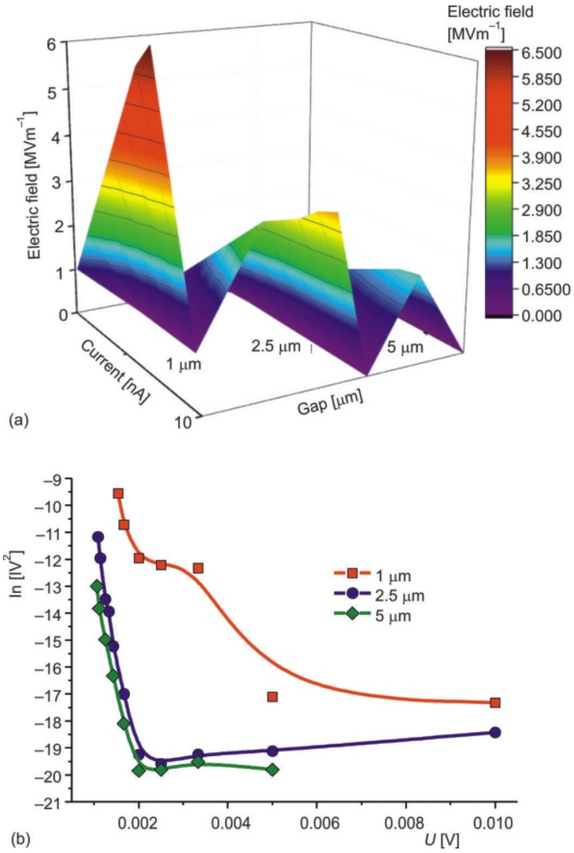

Figure 4. The electric field against the current (a) and corresponding F-N plots for the pressure of around 0.01 Pa (b); lines show fit to the experimental data (symbols) [20]

A breakdown in a cavity is almost always associated with some of cavity walls being heated until it vaporizes and the gas is then ionized by field emission. When this takes place all the incoming RF is reflected back up the coupler which is the major limitation to gradient in most pulsed RF cavities that can permanently cause damage of the structure. Although the exact mechanisms are still not well understood, Kilpatrick summarizes several data and theories according to a simple empirical criterion [21] drawn in fig. 5 where the white region corresponds to the region without sparks. All the limiting factors scale differently with frequency (*i. e.*, wavelength) and vary with pulse length.

In a typical high gradient experiment, the BDR expressed in "breakdown per pulse" (bpp) is usually measured at a fixed value of accelerating gradient and pulse length. However, it is most convenient to compare performance in terms of achieved gradient at a given value of pulse length and BDR by scaling the measured data. This has to be done in two steps: first, by scaling the gradient *vs*. BDR and then by scaling the gradient *vs*. pulse length as shown in fig. 6 which shows the dependence of BDR on electric field and on pulse length. The results of the fit shown in fig. 6 clearly demonstrate that expressions (4) and (5) describe well all the available experimental data [22] in a wide range of gradients and pulse length, respectively.

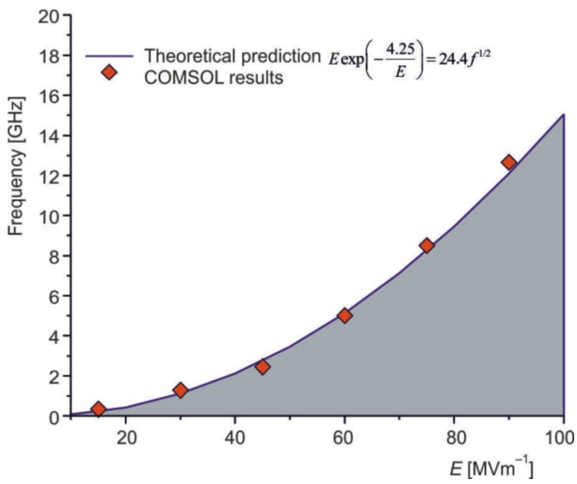

Figure 5. The dependence of frequency on electric field; theoretical prediction [21] and simulation results are presented by solid line and symbols, respectively

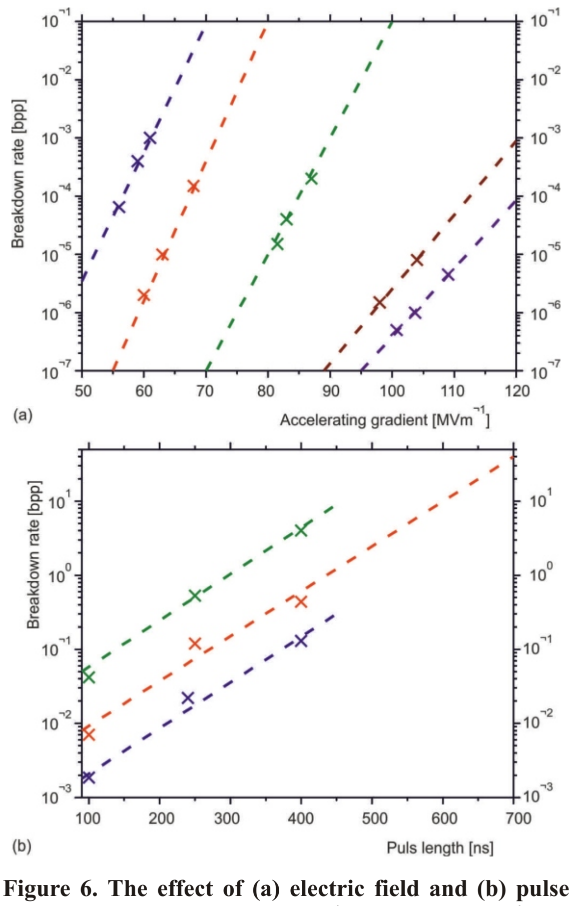

Figure 6. The effect of (a) electric field and (b) pulse length on the BDR measured in the compact linear collider accelerating structures (symbols) [22]; the line is the fit of the experimental data

Breakdowns in accelerating structures usually occur in high field regions of the iris. As can be observed from fig. 7(a), the main trend is that the accelerating gradient decreases when the iris aperture is increased. The maximum surface gradient which is on the iris tips, is a factor 2.1 higher for these structures. The maximum gradient corresponding to the onset of the saturtion in conditioning process, while the lower gra-

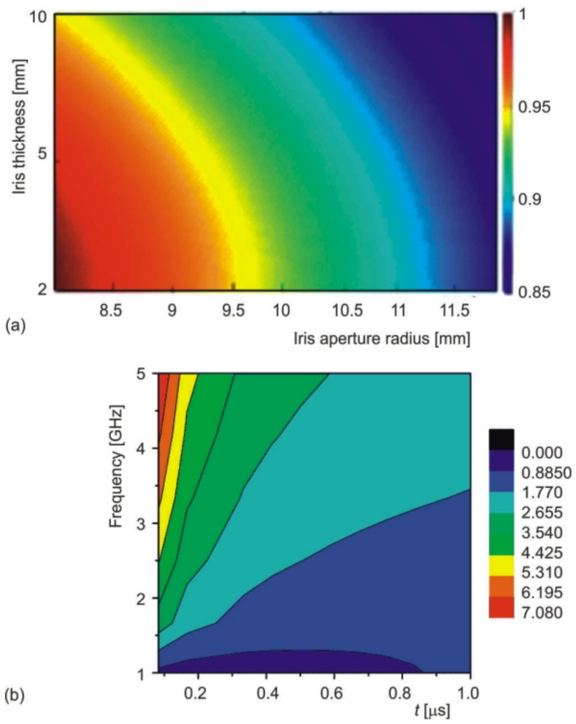

Figure 7. Accelerating gradient as the function of iris radius and thickness (a) and frequency and pulse length (b)

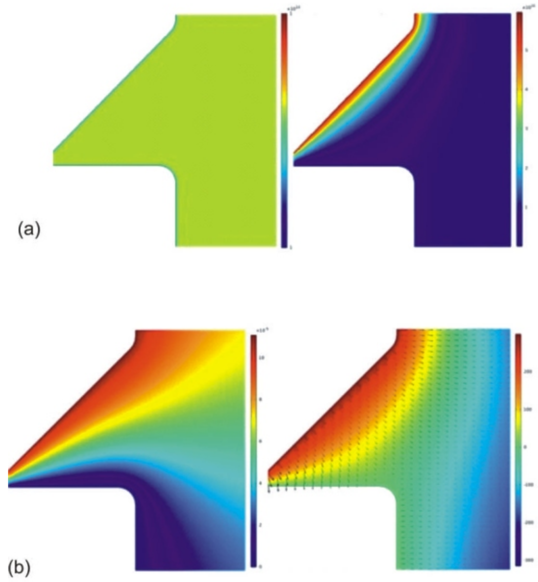

Figure 8. Electron density (a) and electric potential including electric field arrows at the initial time (t = 0) when breakdown occurs for cone-cylinder electrodes at pressure of 0.1 Pa (b)

dients correspond to the structure where BDR is 0.1 per hour.. On the other hand, the accelerating gradient is higher as the pulse length is shorter and frequency is higher as displayed in fig. 7(b).

Figure 8 contains simulation results for (a) electron density and (b) electric potential including electric field arrows for the cone-cylinder electrode arrangements at very low pressure of around 0.1 Pa. The presented results confirm that a vacuum electrical breakdown is a sudden exchange of charge between two electrodes dominated by surface processes. Since the electric field is very high, the field emission effect enhances secondary emission from the surface and breakdown occurs [23].

CONCLUSIONS

This paper focuses on studying the parameters that affect the BDR in the low BDR regime. For that reason COMSOL simulation package has been used in order to determine the influence of electric field, frequency and pulse length on the breakdown. All the limiting factors scale differently with frequency (*i. e.*, wavelength) and vary with pulse length, although they tend to be different from cavity to cavity. The accelerating gradient is higher as pulse length is shorter and frequency is higher. However, it was shown that for frequencies above 1 GHz and for very short pulses the Kilpatrick limit has basically lost its importance because the maximum achievable fields are governed by different phenomena. The fitting of the measured data taken from references reveals that the dependence of BDR on gradient and on pulse length follows established scaling laws which has been observed in many experiments. Time evolutions of electron density and the potential of the cone-cylinder electrode configuration at pressure of around 0.1 Pa allow us to establish the time scale of a vacuum breakdown. It is also confirmed that breakdown in vacuum is dominated by surface processes. More precisely, out-gassing from an electrode surface is regarded as a crucial factor leading to electrical breakdowns in vacuum.

ACKNOWLEDGMENT

The authors acknowledge funding provided by the Institute of Physics Belgrade, through the grant by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

AUTHORS' CONTRIBUTIONS

M. D. Radmilović-Radjenović and B. M. Radjenović performed simulations, prepared figures and wrote the manuscript.

REFERENCES

[1] Tan, J., *et al.*, Radiofrequency Field-Emission Studies. I: Design of a Microwave Cavity, *J. Phys. D: Appl. Phys., 27* (1994), 12, pp. 2644-2653
[2] Padamsee, H., RF Super Conductivity: Science, Technology and Applications, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2009
[3] Holzer, B. J., Introduction to Particle Accelerators and their Limitations, CAS – CERN Accelerator

School: Plasma Wake Acceleration, CERN, Geneva, Switzerland, 2014, pp. 29-50
[4] Nassiri, A., *et al*., History and Technology Developments of Radio Frequency (RF) Systems for Particle Accelerators, *IEEE Transactions on Nuclear Science 63* (2016), 2, pp. 707-750
[5] Padamsee, P., 50 Years of Success for SRF Accelerators-A Review, *Supercond. Sci. Technol., 30* (2017), 5, 053003
[6] Liarte, D. B., *et al*., Theoretical Estimates of Maximum Fields in Superconducting Resonant Radio Frequency Cavities: Stability Theory, Disorder, and Laminates, *Supercond. Sci. Technol., 30* (2017), 3, p. 033002
[7] Radjenović, B., *et al*., Study of Multipactor Effect with Applications to Superconductive Radiofrequency Cavities, *Nucl Technol Radiat, 32* (2017), 2, pp. 115-119
[8] Radmilović-Radjenović, M., *et al*., The Effect of Enhanced Field Emission on Characteristics of Supeconducting Radio Frequency Cavities, *Nucl Technol Radiat, 33* (2018), 4, pp. 341-346
[9] Alpert, D., *et al*., Initiation of Electrical Breakdown in Vacuum, *Journal of Vacuum Science and Technology, 1* (1964), 35, pp. 35-50
[10] Schnyder, R., *et al*., Direct Current Breakdown in Gases for Complex Geometries from High Vacuum to Atmospheric Pressure, *Journal of Physics D Applied Physics, 46* (2013), 28, 285205
[11] Klas, M., *et al*., The Breakdown Voltage Characteristics of Compressed Ambient Air Microdischarges from Direct Current to 10.2 MHz, *Plasma Sources Sci. Technol., 26* (2017), 5, 055023
[12] Radmilović-Radjenović, M., *et al*., The Breakdown Mechanism in Electrical Discharges: the Role of the Field Emission Effect in Direct Current Discharges in Microgaps, *Acta Physica Slovaca, 63* (2013), 3, pp. 105-205
[13] ***, COMSOL Multiphysics, available at https://www.comsol.com/
[14] Yamano, Y., *et al*., Dependence of Vacuum Electrical Breakdown Field and Field Enhancement Factor on the Number of Apertures Drilled in Small Electrodes, *Electrical Engineering in Japan, 196* (2016), 3, pp. 3-12
[15] Anders, A., *Cathodic Arcs– From Fractal Spots to Energetic Condensation*, Springer Science and Business Media, 2008
[16] Forbes, R. G., Field Emission: New Theory for the Derivation of Emission Area from a Fowler-Nordheim Plot, *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena, 17* (1999), 2, pp. 526-533
[17] Klas, M., *et al*., Breakdown Mechanism in Hydrogen Microdischarges from Direct-Current to 13.56 MHz, *J. Phys. D: Appl. Phys., 48* (2015), 40, 405204
[18] Verboncoeur, J. P., Particle Simulation of Plasmas: Review and Advances, *Plasma Physics and Controlled Fusion, 47* (2005), 5A, pp. A231-A260
[19] Kim, H., *et al*., Modeling RF Window Breakdown: from Vacuum Multipactor to RF Plasma, *IEEE Trans. Dielectr. Electr. Insul. 14* (2007), 4, pp. 766-773
[20] Radmilović-Radjenović, M., *et al*., The Role of the Field Emission Effect in Direct-Current Argon Discharges for the Gaps Ranging from 1 to 100 m, *J. Phys. D: Appl. Phys., 46* (2013), 1, 015302
[21] Kilpatrick, W. D., Criterion for Vacuum Sparking Designed to Include Both RF and DC, *Rev. Sci. Inst., 28* (1957), 10, pp. 824-826
[22] Calatroni, S., *et al*., New Local Field Quantty Describing the High Gradient Limit of Accelerating Structures, *Phys. Review Special Topics-Accelerators and Beams, 12* (2009), Oct., 102001
[23] Ito, Y., *et al*., Vacuum Electrical Breakdown Characteristics and Surface Condition of Ti Electrodes with Oxidation Conditions, *IEEE Transactions on Dielectrics and Electrical Insulation, 13* (2006), 1, pp. 98-104

Received on November 21, 2019
Accepted on May 18, 2020

Марија Д. РАДМИЛОВИЋ-РАЂЕНОВИЋ, Бранислав М. РАЂЕНОВИЋ

СИМУЛАЦИЈА КАРАКТЕРИСТИКА ПРОБОЈА У ВАКУУМУ И ЊИХОВА ПРИМЕНА НА АКЦЕЛЕРАТОРСКЕ СТРУКТУРЕ ВИСОКИХ ГРАДИЈЕНАТА

Познато је да механизам радио-фрекфентног пробоја представља један од значајнијих ограничавајућих фактора у високо фрекфентним акцелераторима. Уочене су сличности између пробоја (услед једносмерне струје) у вакуум и пробоја у суперпроводним радио-фрекфентним шупљинама. Зато се пробој у шупљинама, услед јаког поља, може разумети и проучавањем пробоја у вакууму. У овом раду, зависност пробојног напона од градијента поља, дужине импулса и фрекфенције је проучавана коришћењем одговарајућег софтверског пакета базираног на методу коначних елемената. Уочена је да зависност пробоја од градијента поља и дужине импулса подлеже законима скалирања. Добијени резултати могу се користити приликом конструкције високоградијентних акцелераторских структура.

Кључне речи: акцелератор, шупљина, пробој, COMSOL