ION MOTION IN THE VICINITY OF MICROPROTRUSIONS IN ACCELERATING STRUCTURES

D. Kashyn, G. S. Nusinovich, T. M. Antonsen and I. Haber, IREAP, University of Maryland, U.S.A.

Abstract

It is known that newly fabricated accelerating structures have almost ideally smooth surface. However, 'post mortem' examination of these structures reveals that their surface can be significantly modified after high-gradient operation. This surface modification can be caused by the appearance of microscopic protrusions. One of the factors leading to heating, melting and evaporation of these protrusions (factors resulting in the RF breakdown) is ion bombardment. In our study we analyse ion motion in the vicinity of micro-protrusion both analytically and numerically. First, we study the ion motion in the RF electric field magnified by the protrusion in the absence of electron field emitted current and show that most of the ions do not reach the structure surface. Then we add into consideration the interaction of ions with Fowler-Nordheim current emitted from the tip of the protrusion (dark current). First, we develop a model describing this interaction and then we supplement it with numerical results using PIC code WARP. We show that the ions move towards the area occupied by the dark current, but this does not increase the bombardment of micro-protrusions.

INTRODUCTION

The surface of almost ideally smooth High Gradient (HG) accelerating structures are damaged during RF operation. These surface modification and appearance of the microscopic protrusions are caused by RF breakdown. RF-breakdown severely limits the operation of the HG accelerating structures. Despite the long history of studies there is no general agreement on how exactly the process happens. The fact that most of the accelerating structures are not accessible during the experimental testing makes numerical and theoretical studies very important. In this paper we are focusing our attention on the process of so called ion bombardment. Some authors believe that this process might be a triggering mechanism of the RF breakdown [1]. We will discuss this phenomenon presenting both theoretical results as well as corresponding numerical simulations.

ION BOMBARDMENT

We first present some theoretical models of ion motion and the subsequent results of the analysis of those models.

Kapitsa's Method

According to this method [2] we separate the motion of the ions in the RF field into two parts. The first part is a slow motion caused by the ponderomotive force averaged over the RF oscillations, and the rest are fast but small RF oscillations. In the region close to the spherical apex of the protrusion, the electric field can be given by $E = E_0 \left(r_0 / r\right)^2 \sin \omega t$, where E_0 is the amplitude of the field magnified by the presence protrusion, r_0 is the radius of the protrusion apex, and r is the radial spherical coordinate of an ion reference frame with an origin in the apex. The ion motion in such a field is governed by the following equation:

$$\frac{d^2 r}{dt^2} = \frac{q_i E_0}{m_i} \frac{r_0^2}{r^2} \sin \omega t \qquad (1)$$

If we separate the coordinates according to the described method, i.e. write $r = R + \tilde{r}$ and average over the period we are able to write the equation for the slow motion as:

$$d^2 \rho / d\tau^2 = 1/\rho^5 \qquad (2)$$

with the boundary conditions $\rho(0) = 1$ and $\rho'(0) = \rho_0'$. Here $\rho = R / R_0$ is the radial coordinate normalized to its initial value, $\tau = \left(q_i E_0 / m_i c\omega\right)\left(r_0 / R_0\right)^2 \left(ct / R_0\right)$ is normalized time and ω is the frequency of the RF field. From the equation (2) we see that ions can only reach the protrusion if their initial velocity is large enough and oriented towards the centre of the protrusion. This critical value of velocity, normalized to the speed of light and denoted as $\beta_{i,cr}$ is equal to:

$$\beta_{i,cr} = \left(q_i E_0 / m_i c\omega\right)\left(r_0 / R_0\right)^2 / \sqrt{2} \qquad (3)$$

Figure 1 (a) illustrate the dependence of the critical value of normalized electric field $\alpha_{cr} = \left(q_i E_0 / m_i c\omega\right)$ on the normalized radial coordinate for the values of normalized velocity $\beta_{i,cr}$ equal to 10^{-3} and 10^{-4}. This normalized amplitude can be converted into a real field for a chosen type of ions. In figure 1 (b) the dependence of this electric field amplitude is shown as a function of the normalized radial coordinate for oxygen and copper.

Direct Calculations

The prediction made by the Kapitsa's method can be verified by direct calculations. If we introduce into equation (1) the normalize time $\tau = \omega t$, normalized coordinate $\nu = r / R_0$ and the normalized field amplitude $K^2 = \left(q_i E_0 / m_i c\omega\right)\left(c\omega / R_0\right)\left(r_0^2 / R_0^2\right)$ we can rewrite the equation of motion as:

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$$v^2 \frac{d^2 v}{d\tau^2} = K^2 \sin\tau \qquad (4)$$

with initial conditions $v(\tau = \tau_0) = 1$ and $v'(\tau_0)$. Parameter τ_0 was chosen to be *0* but in principle it is distributed from *0* to *2π*. The next set of figures shows the results of the solution of the equation (4). Figure 2(a) shows the temporal evolution of the normalized radial coordinate for different values of the normalized derivative, while figure 2(b) shows the minimal radial distance as a function of the absolute value of the derivative for several values of the constant K.

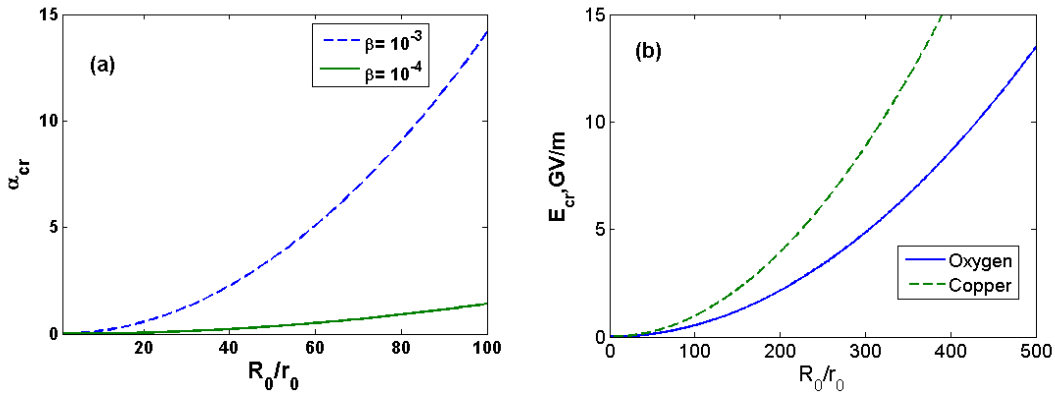

Figure 1: (a) Critical RF field normalized amplitude as the function of normalized radial coordinate for two values of critical initial ion velocity normalized to the speed of light; (b) Critical RF electric field in the vicinity of the apex as the function normalized radial coordinate for oxygen and copper ions with initial energy 10 eV.

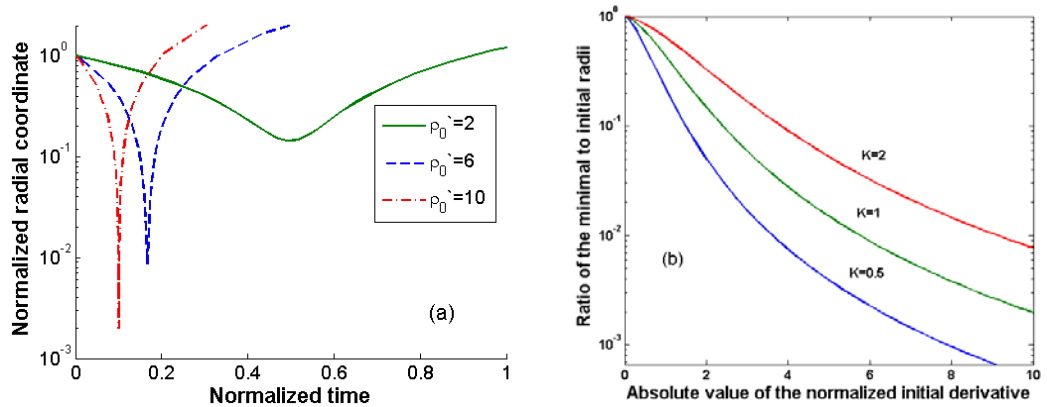

Figure 2: (a) Time evolution of the ion motion for several values of initial normalized derivative. (b) The ratio of the minimal distance of the ion to the protrusion to radius of the protrusion apex as a function of the absolute value of the initial derivative for several values of the normalized RF field amplitude. Parameter τ_0 is equal to zero.

In the figure 2 the normalized derivative is equal to $\rho_0' = (c/\omega R_0)\beta_0$. Initial velocity is normalized to the speed of light and can be written as $\beta_0 \approx 2\cdot 10^{-3}\sqrt{W_0(eV)(m_e/m_i)}$. This expression means that if the copper ion has energy of 10 eV then β_0 is equal to $2\cdot 10^{-5}$. We also note that in order for an ion to get close to the apex we need initial distances R_0 to be of the order of 30 nm for 10eV ions, or initial energies of the ions should be more than 10keV, if R_0 is of the order of micron.

WARP Simulation

We verified the results of our analysis using the time dependent plasma PIC code WARP [3]. The code itself is 3D code that combines the features of the accelerator code and PIC plasma simulations, and uses leapfrog algorithm to advance the time step. Using this code we simulated the box of 40 microns in size with 100x100x 100 grid in it. We populated the box with 10^6 ions of copper and choose the frequency of the RF field to be 11.42 GHz. Simulation spanned 20 RF periods, 25 time steps per each period. For our purpose the most important result is the speed of the departure of the ions from the tip of the protrusion. From the simulations we can estimate this speed to be $2.5\cdot 10^4 m/s$ which is consistent with the estimates based on (3).

INTERACTION WITH ELECTRONS

The next step is to add the interaction with the electron beam. Electric field in the vicinity of the sharp edges of the conductor is magnified by some amplification factor

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called p. If this factor is large enough, field emission will occur. The emitted current density is described by the Fowler-Nordheim formula [4]:

$$j_{FN} = \left(a_{FN} F_0^2 / \Phi\right) \exp\left(-b_{FN} \Phi^{3/2} \nu / F_0\right) \quad (5)$$

where a_{FN}, b_{FN} are some numerical constants, Φ is the work function (eV range) and $F_0 = epE_0$ is the product of the electron charge, the background field and the amplification factor. If the cross-sectional area of the emission site is A_0 then the averaged current over the period (half of the RF period the field is reversed and no current is emitted) is:

$$\langle I \rangle = \frac{A_0}{T} \int_0^{T/2} j(t)dt = \frac{A_0}{\pi} \int_0^{\pi} j(\omega t)d\omega t \quad (6)$$

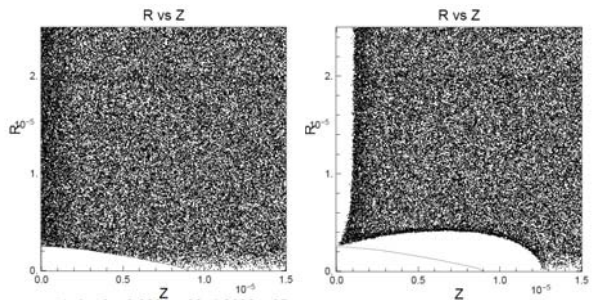

Figure 3: Time evolution of the ion population. Left picture is the initial setup and the right one corresponds to the beginning of the 3rd RF period. The protrusion shape is given by unpopulated area on the left figure.

Using the equation (6), the magnitude of the electric field at the distance *r*, and hence the force that the beam exerts on the charged particles can be written as:

$$F_e = q_i E = \frac{q_i I}{2\pi c \cdot r\varepsilon_0} \quad (7)$$

We compare this force with the ponderomotive force in the vicinity of the protrusion to obtain the following value for the critical distance, at which those two forces are equal:

$$r_{cr} = \frac{mc^2}{\Phi} \frac{ea_{FN}}{c\varepsilon_0} C_{\text{int}} \frac{R^5}{\lambda^2} \left(\frac{p}{r_0}\right)^2 = \frac{mc^2}{\Phi} \frac{ea_{FN}}{c\varepsilon_0} C_{\text{int}} \frac{R^5}{\lambda^2} \frac{1}{\theta^2} \quad (7)$$

the constant $C_{\text{int}} = \int_0^{\pi} \sin^2 \omega t \cdot \exp\left(-\frac{b_{FN} \Phi^{3/2} \nu}{\beta E_0 \sin \omega t}\right) d\omega t$ and we also introduced the parameter $\theta = \left(r_0 / p\right)$, which is the ratio of protrusion radius and the amplification factor. The dependence of the C_{int} on the amplification factor is weak, and in the range of interest, i.e. p from 20 to 60, is practically constant. For the other terms in (7) mc^2/Φ is the ratio of 511keV to several eV and the term $ea_{FN}/c\varepsilon_0$ is equal to $5.6 \cdot 10^{-4} m^{-1}$. Figure 4 shows the critical distance plotted as a function of initial distance from the apex for the several values of parameter θ.

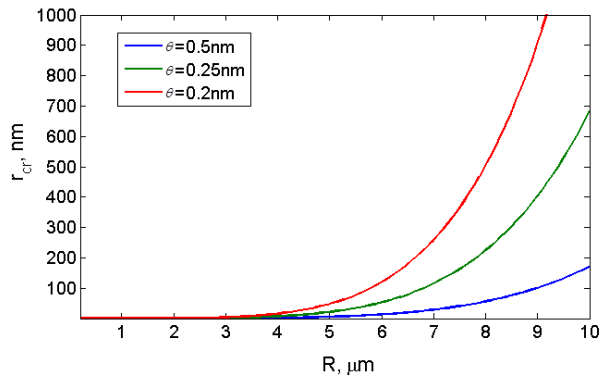

Figure 4: Critical distance as a function of the initial distance from the tip apex.

Calculations done for the averaged force shows that only ions that are closer to the protrusion than the critical radius will impinge on it. However our simulations with WARP show that some ions located further than the critical radius can still reach the surface of the protrusion during the first RF cycle providing they are inserted at the proper RF phase.

CONCLUSIONS

We presented our work on some theoretical estimates of the ion motion in the electric fields in accelerating structures magnified by the presence of the microscopic protrusions. We concluded that only a few ions can reach the protrusion. The only ions that may hit the protrusion are those that are either close to the asperity or very energetic. The presence of the electrons emitted from the tip may lead to increase of the bombardment rate but this effect does not increase the bombardment rate significantly.

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