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Effect of the geometry of cathode microprotrusions on the parameters of the explosive emission processes

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This report presents results of a numerical simulation of the electrical explosion of a cathode microprotrusion initiated by explosive emission current. The microexplosion parameters (the pre-explosion time and the specific current action integral) have been estimated in relation to the geometry (current density) of the microprotrusion and the type (direct-current and high-frequency) voltage across the diode. The variations in the main parameters of the cathode material (temperature and density) during such a microexplosion are investigated for tungsten and copper cathodes.

Introduction

Explosive electron emission (EEE) from a cathode occurs when intense energy fluxes and high electric fields act on the cathode, resulting in the transition of the cathode material from a condensed to a plasma state. The high-density plasma (cathode flare) propagates with high velocity through the electrode gap, and the diode current increases sharply. The emission of electrons from the boundary of the cathode flare is compensated by the electron emission from the metal-plasma contact. Despite the quite long history of the study of explosive electron emission, the main approaches used in analyzing this phenomenon are approximate and require more rigorous justification and refinement. One of these approaches uses the similarity of the phenomenon to the electrical explosion of conductors [1]. The use of the conductor explosion analogy to study microexplosion processes on a cathode in a vacuum breakdown is quite justified, as these phenomena rely on the same mechanism, namely, on the resistive heating of a metal by high-density electric current. However, this analogy is evidently weak in that EEE may occur from exploding cathode microprotrusions of varied geometry, and their heating is substantially affected by the heat transfer to the bulk cathode.

Introduction

Explosive electron emission in a diode is accompanied not only by an increase in diode current and formation of plasma jets, but also by splashing of molten metal from the cathode and formation of microcraters on the cathode surface. These processes are extremely undesirable, in particular, for future fusion devices, in which the initiation of explosive electron emission leads to unipolar arcing at surfaces exposed to the reactor plasma [2, 3]. Explosive emission processes also underlie the radio frequency vacuum breakdowns that may occur at the walls of accelerating structures in linear electron-positron colliders [4-7].

We have investigated the parameters of microexplosion processes for tungsten, as a candidate for the diverter material in future fusion devices, and copper, which will be used for the accelerating structure of the Compact Linear Collider (CLIC) being developed at CERN [8]. The microexplosion parameters (the pre-explosion time and the specific current action integral) have been estimated in relation to the geometry (current density) of the microprotrusion and the type (direct-current and high-frequency) voltage across the diode.

Description of the Model

The study presented here used the JULIA magnetohydrodynamic (MHD) code [5, 6]. The system of MHD equations, which was solved using this code, consisted of hydrodynamic equations describing the laws of conservation of mass, momentum, and energy:

$$\frac{\partial \rho}{\partial t} + \nabla(\delta \mathbf{v}) = 0, \tag{1}$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \nabla \mathbf{v} = -\nabla p + \frac{1}{c} \mathbf{j} \times \mathbf{H}, \tag{2}$$

$$\frac{\partial \delta \varepsilon}{\partial t} + \nabla(\rho \varepsilon \mathbf{v}) = -p \nabla \mathbf{v} + \frac{\mathbf{j}^2}{\sigma} + \nabla(\lambda \nabla T); \tag{3}$$

Maxwell's equations written in a quasi-stationary approximation (excluding displacement currents)

$$\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t} = -\nabla \times \mathbf{E}, \qquad \nabla \times \mathbf{H} = \frac{4\pi}{c} \mathbf{j}, \tag{4}$$

and Ohm's law

$$\mathbf{j} = \sigma\left(\mathbf{E} - \frac{1}{c} \mathbf{v} \times \mathbf{H}\right), \tag{5}$$

where ρ is the density of the material and **v** is its velocity; p, ε, and T are the material pressure, internal energy, and temperature; **H** is the magnetic field strength; **E** is the electric field strength in a fixed coordinate system; **j** is the current density; $\boldsymbol{\lambda}$ is the thermal conductivity, and σ is the electrical conductivity.

Description of the Model

The system of equations (1)–(5) was solved in cylindrical coordinates using wide-range equations of state [9] for the electrode material taking into account its transitions between solid, liquid, and vapor states. To calculate the electrical characteristics of the microprotrusion and its thermal conductivity, tabulated data on the conductivity of copper and tungsten were used [10]. In the calculations, it was supposed that the emission center has already been initiated and the explosive emission current is determined by the parameters of the external circuit with the external resistance $R = 1000$ Ω and voltage $U_0 = 3200$ V. For the rf voltage circuit, the voltage across the diode was specified as sinusoidal oscillations of frequency 12 GHz and amplitude $U_0 = 3200$ V. In both cases, the current increased to 3.2 A (the current through an explosive emission cell of a cathode spot estimated in terms of the ecton model for copper and tungsten cathodes [1]) within 1 ns. The method of solving the system of equations (1)–(5) is described in detail in [5, 6]. It was assumed that the microprotrusion had the shape of a cylinder and was located on the surface of a plane copper or tungsten cathode. The cylinder height was set equal to 1.5 μm and its radius was varied from 0.2 to 0.4 μm.

Simulation Results

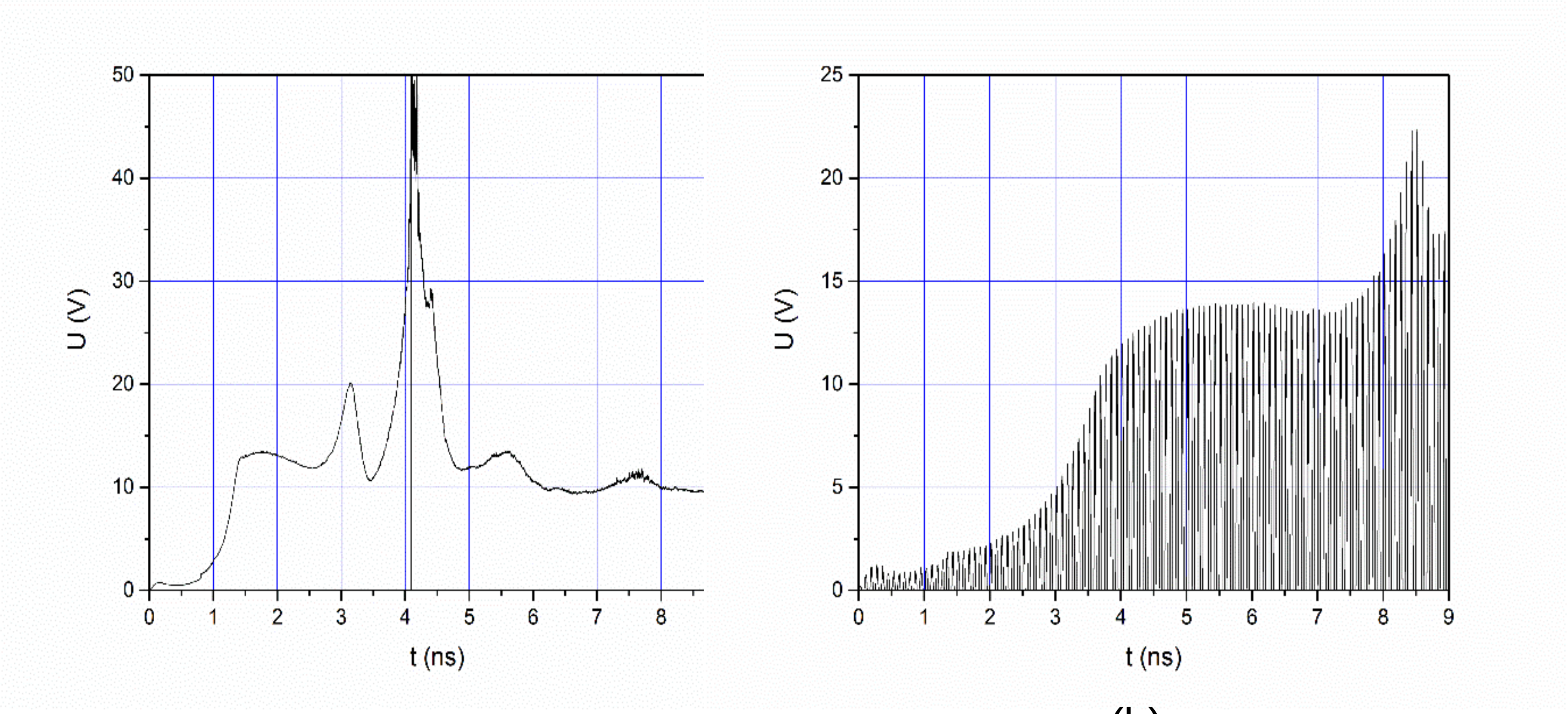
An important characteristic of a wire explosion is the specific current action integral:

$$\bar{h} = \int_0^{\tau_0} j^2 dt \qquad (6)$$

With this integral, based on the analogy between the explosion of wires and that of cathode microprotrusions, governing parameters were obtained for the processes that occur at the cathode of a vacuum arc during explosive electron emission and operation of a cell of the arc cathode spot (an ecton) [1].

The results of the numerical simulation performed using the system of equations (1)–(5) for copper and tungsten microprotrusions of radius 0.2 μm, the specific action integral equals 3.1 and $2{\cdot}10^9$ $A^2{\bullet}s/cm^4$, respectively, and it is the same for a dc and a rf circuit voltage. A different situation is observed when the microprotrusion radius is increased to 0.4 μm. In this case, the value of the specific action integral decreases and this decrease is more significant for a rf circuit voltage. Let us consider this effect for a tungsten microprotrusion, for which it is more pronounced, as an example.

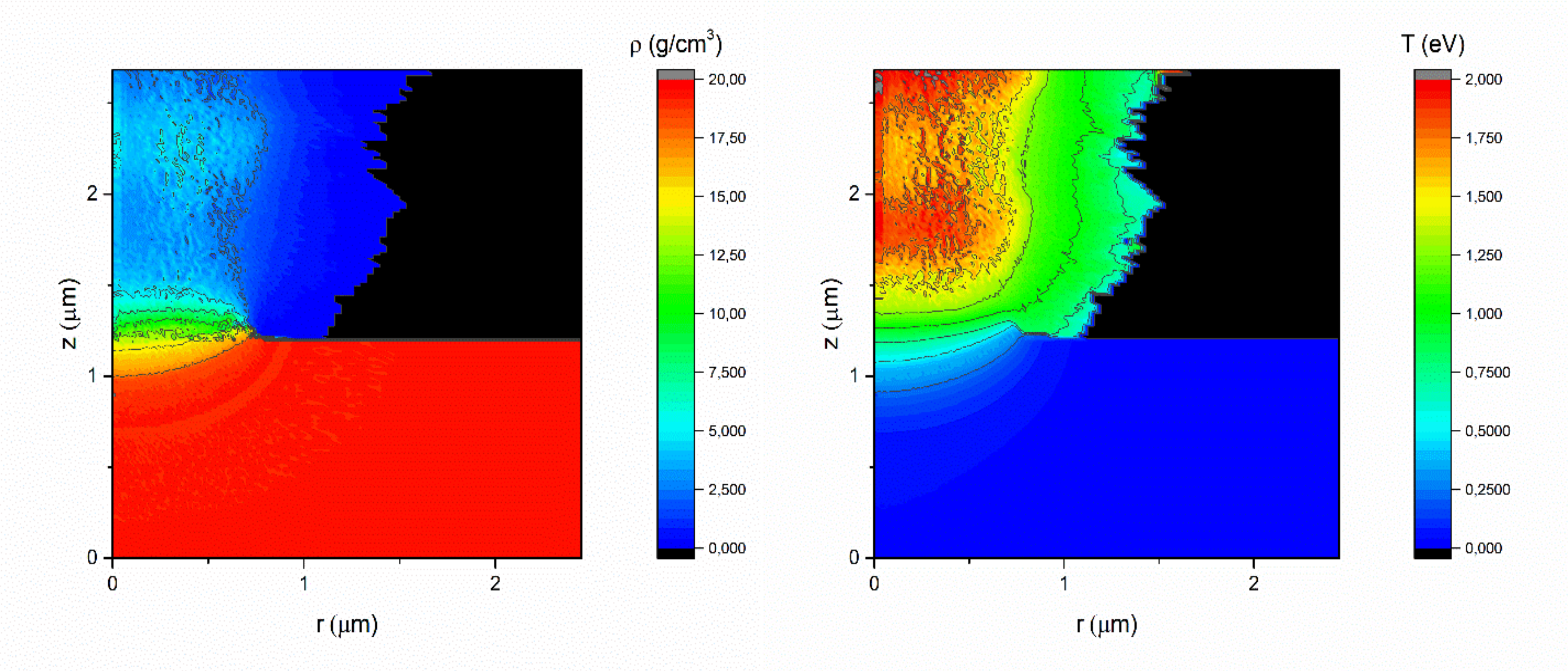
Simulation Results



(a) (b)

Fig. 1. Gap voltage during the explosion of a tungsten cathode microprotrusion of the radius of 0.4 μm vs time for a dc (a) and a rf circuit voltage (2).

Simulation Results

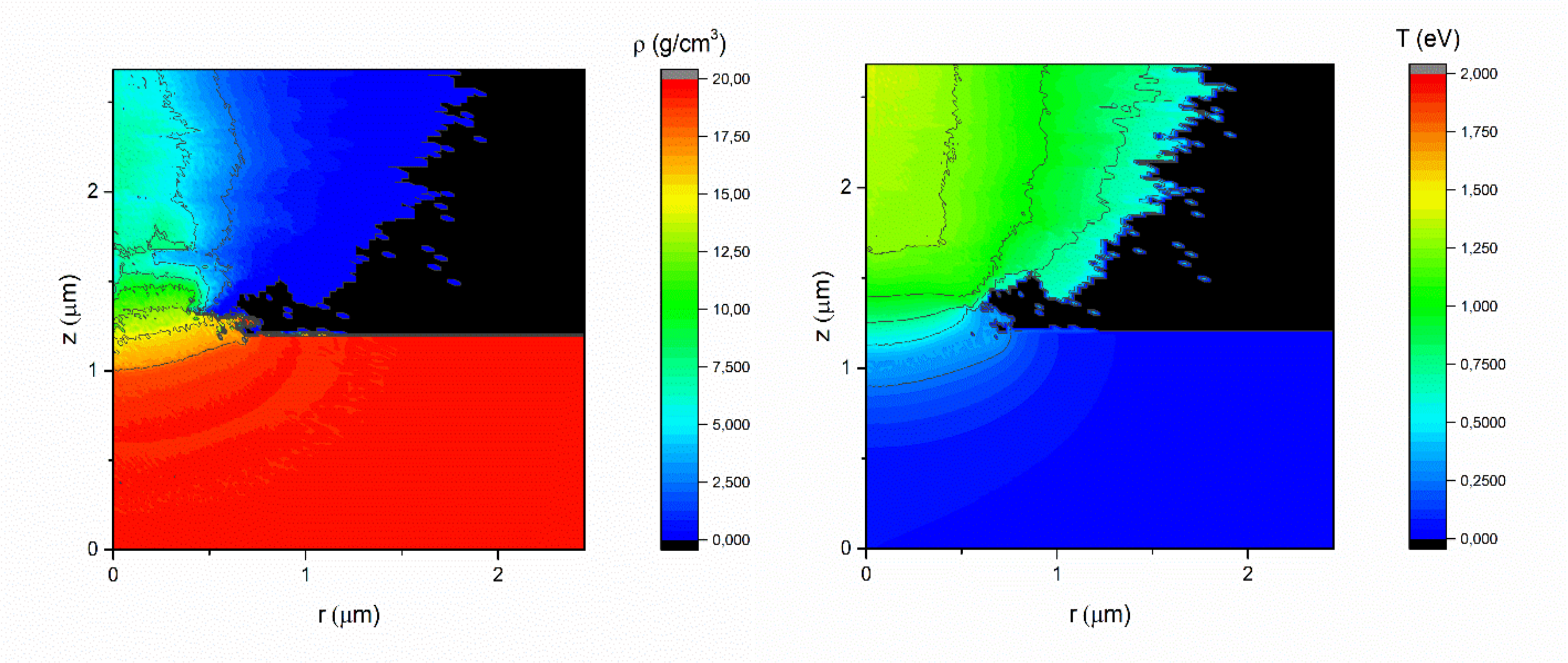


(a)

(b)

Fig. 2. Density (a) and temperature (b) distribution in an exploding tungsten cathode microprotrusion of the radius of 0.4 μm at a dc circuit voltage (*t* = 3 ns).

Simulation Results



(a) (b)

Fig. 3. Density (a) and temperature (b) distribution in an exploding tungsten cathode microprotrusion of the radius of 0.4 μm at a rf circuit voltage (t = 8 ns).

Conclusion

Figure 1 shows the electrode gap voltage waveforms for a dc (Fig. 1*a*) and an rf circuit voltage (Fig. 1*b*). The peaks in the voltage waveforms correspond to microprotrusion explosions. The specific action integrals estimated from the data given in Fig. 1 are $1.4 \cdot 10^9$ and $0.95 \cdot 10^9$ $A^2 \cdot s/cm^4$ for the dc and the rf circuit voltage, respectively. Thus, as the current density was decreased from $2.55 \cdot 10^9$ to $6.3 \cdot 10^8$ A/cm^2 (at a current of 3.2 A), $\bar{h}$ decreased by 30% at the dc circuit voltage and more than halved at the rf circuit voltage.

Obviously, the decrease in $\bar{h}$ upon going from dc to high-frequency rf circuit voltage is not related to the processes occurring in the bulk cathode. However, the heat removal from the cathode surface to the bulk should result in an increase in $\bar{h}$. Therefore, it can be supposed that this behavior of the specific action integral is due to the fact that a decrease in current density results in a decrease in the energy input to the microprotrusion. The validity of this supposition is clearly illustrated by Figs. 2 and 3, which present the microprotrusion material density and temperature immediately before the explosion. These parameters were calculated for the times 4 ns (dc circuit voltage) and 8 ns (rf circuit voltage) at which the gap voltage began to sharply increase (see Fig. 1).

CONCLUSION

As can be seen from Figs. 2 and 3, the material temperature is about 2 and 1.5 eV for the dc and the rf circuit voltage, respectively. This difference is due to the fact that the heating rate decreases with a decrease in current density. For the rf circuit voltage, the average current density over a period is 1.5 10^8 A/cm^2, whereas for the dc circuit voltage the current density is 6.3 10^8 A/cm^2. A similar effect was observed in our previous study of the explosion of micrometer-sized conductors [11] in which the energy deposited in a conductor before its explosion was shown to decrease with a decrease in current density. Thus, we have obtained one more proof that the processes occurring in an electrical explosion of a micrometer-sized conductor and those occurring in explosive electron emission from a cathode microprotrusion follow the same scenario.

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