Topic number 3

Ecton processes in the generation of picosecond runaway electron beams

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The mechanism of the generation of runaway electrons and of the cutoff of their current in a gas discharge is considered. It is shown that the field emission current from the cathode microprotrusions in the discharge is enhanced due to ionization processes occurring in the cathode region. This hastens explosive electron emission, which lasts tens of picoseconds. Thus, the runaway electrons current pulse is similar in nature to the ecton process in a vacuum discharge.

It is well known from the physics of nanosecond pulsed electrical discharges in gases that if the energy acquired by electrons in the electric field is greater than the energy lost by them in collisions, the electrons become running away. In this case, the generation of runaway electrons (REs) is a pulsed process. However, the nature of these RE pulses still remains obscure [1–5].

As shown experimentally, the duration of the RE current pulse in a discharge between stainless steel electrodes in atmospheric air is $2.4\cdot10^{-11}$ s. A nearly triangular voltage pulse of rise time $t_0 = 1.5\cdot10^{-10}$ s and amplitude 160 kV was used. The RE current was equal to several amperes. The leading and trailing edges of the RE pulse, each lasting no more than $2\cdot10^{-11}$ s, are of different nature. We believe that the leading edge is due to the field emission (FE) current from cathode microprotrusions (CMPs) [6]. This current is enhanced due to ionization of the gas until explosive electron emission is initiated as a result of the Joule heating of CMPs during a time determined by the relation $j^2\, t_1 = h$, where h is the specific current action for an electrical explosion of the cathode metal and j is the density of the electron current from the CMPs. For copper we have $\bar{h}=4.1\cdot10^9$ (A·s) /cm^4 [7]; hence, using the Fowler–Nordheim formula, we estimate the FE current density at $t_1=2\cdot10^{-11}$ s as $j=1.4\cdot10^{10}$ A/cm^2. This corresponds to the electric field at the tip of an CMP $E=1.5\cdot10^8$ V/cm. Note that in Ref. 6, the time t_1 is estimated as $t_1=0.11t_0=1.6\cdot10^{-11}$ s. In vacuum, these extreme values of the parameters t_1, j, and E cannot be attained because of the electronic space charge effect [8]. In gases, this effect is not essential or even absent due to that the space charge is neutralized by the gas ions.

The electron emission mechanism changes after EEE: a cathode spot (CS) arises, and the intensity of electron emission from the spot quickly decreases as a result of energy loss. Assuming that a CS cools only due to heat conduction, we have $t_2=i^2/64\pi^2a^2h$, where a is the thermal diffusivity of the cathode metal [7]. For copper we have $a\approx1.2$ cm^2/s; thus, for the RE current i=1A, we obtain $t_2=1.8\cdot10^{-11}$ s.

The formation of RE pulses is similar to the formation of an electron butch (ecton) during a cycle of the CS operation in a vacuum arc [9]. The ecton processes in a vacuum arc take 10^{-9}–10^{-8} s.

Note that in our experiment, we have obtained historically high rates of rise of the electric field at CMPs: ~10^{19} V/(cm·s). Previously, it was supposed that the mechanism of the RE current cutoff is related to the plasma processes occurring in the electrode gap [3, 10]. In our opinion, this mechanism is governed by the emission processes taking place at the cathode. This concept seems to be more realistic in view of the very short times of the generation of runaway electrons and of the cutoff of their current.

1. References

[1] G.A. Mesyats, Yu.I. Bychkov, and V.V. Kremnev, Sov. Fiz. Usp. **15** (1972) 282.

[2] L.P. Babich, T.V. Loiko, and V.A. Tsukerman, Sov. Fiz. Usp. **33** (1990) 521.

[3] V.F. Tarasenko and S.I. Yakovlenko, Phys. Usp. **47** (2004) 887.

[4] G.A. Mesyats, M.I. Yalandin, A.G. Reutova, et al., Plasma Physics Reports **38** (2012) 29.

[5] S. Yatom, A. Shlapakovski, L. Beilin, et al., Plasma Sources Sci. Technol. **25** (2016) 064001.

[6] G.A. Mesyats, JETP Letters **85** (2007) 109.

[7] G.A. Mesyats, Pulsed Power, Kluwer/Plenum (2004).

[8] J.P. Barbour, W.W. Dolan, J.K. Trolan, et al., Phys. Rev. **92** (1953) 45.

[9] G.A. Mesyats, Phys. Usp. **38** (1995) 567.

[10] S.Y. Belomyttsev, I.V. Romanchenko, V.V. Ryzhov, and V.A. Shklyaev, Technical Physics Letters **34** (2008) 367.