

Production of Low-Energy, High-Intensive Pulsed Electron Beams in a Channel Spark

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Abstract - The process of the formation of a dense, low-energy (5-10 keV) pulsed (~ 100 ns) electron beam in a gun of "channel spark" type has been studied. It has been experimentally shown that intensive pre-ionization of the drift channel in combination with pulsed voltage supply of the cathode allows one to produce electron beams with current rise-rate more than 10^{11} A/s, current density more than 10 kA/cm², and beam current exceeding Alfvén current value by a factor of 1.5-2.

1. Introduction

Electron-beam ablation (super-fast evaporation of solids for high-quality thin film deposition) is one of the promising applications of high-intensive (more than 10 kA/cm²), low-energy (5-10 keV) pulsed (~ 100 ns) electron beams of small diameter (several millimeters). Electron-beam ablation is considered as one of alternatives to pulsed laser ablation which is more advanced at the moment. Electron-beam ablation possesses a number of important advantages: low-cost equipment (5-10% of the laser systems), big efficiency, possibility of ablation of optically transparent targets and some others [1, 2].

For the improvement of deposited film quality and decreasing the energy losses caused by the heat conductivity into the depth of target, it follows to short beam pulse duration that means the necessity of current rise-rate increasing. This makes corresponding requirements both to high-voltage pulse generator supplying the electron gun and to the speed rate of the cathode emitting surface formation as well as the speed rate of plasma anode formation serving also as transportation channel.

In electron guns [1, 2] called by authors as Channel Spark, a hollow cathode is supplied by low-inductance capacitor, one of the plates of which has dc negative potential. Working gas pressure makes up 1-3 Pa. Beam start is performed by triggering of an auxiliary pulsed low-current gas discharge. Discharge plasma penetrates through the backside hole in the hollow cathode and excites its emission. The channel made of glass or ceramic tube provides a narrow directivity of the beam, electrical insulation and protection of the cathode from deposition of the target erosion products. As plasma density in the channel grows, a double layer operating as an acceleration gap

moves toward output edge of the tube with the velocity of about 10^6 m/s [1].

Since the filling of the hollow cathode with plasma is a relatively slow process, this scheme can not provide the high rise rate of beam current, and, hence, high rate of energy input into the target. The other reason limiting rise-rate of beam current is concluded in beam losses upon plasma channel formation because the characteristic ionization time $t_i = (n_0 \sigma_i u)^{-1}$ is matched with beam pulse duration (n_0 is density of neutrals, σ_i is an ionization cross section by electron impact, u is a velocity of beam electrons). The rise rate values of beam current obtained in [1, 2] did not exceed 10^{10} A/s, beam current amplitude was lower than 1.5 kA.

To increase the rise rate of beam current and to decrease beam losses at initial stage of the pulse, we propose the preliminary (before the applying the acceleration voltage pulse to the cathode) formation of the plasma channel between the cathode and collector. Besides, plasma density should be approximately of the same value as expected beam electrons density that is needed for beam space charge neutralization.

2. Experimental technique

The design of electron gun used in our experiments (Fig. 1) is analogous to one described in [1, 2]. A short piece of copper tube with inner diameter of 4 mm represented as an explosive emission cathode. The inner diameter of ceramic tube made up also 4 mm and its length was 96 mm. Plasma column between the cathode and collector was created with the help of high-current (up to 1 kA) direct discharge in argon initiating in our case by Penning discharge. Working gas filled the channel in steady mode using a standard device PPT-10. Before the gas flooding, the vacuum chamber was evacuated to pressure up to 0.01 Pa. Working gas pressure was regulated by changing its flow and/or speed of pumping.

An acceleration voltage pulse of amplitude up to 25 kV was formed while discharge of low-inductance capacitor HCEI-40-0.05 (40 kV, 50 nF, 4 nH) [3] of our own production through the pseudo-spark switch TDI1-50k/50 [4]. Total inductance of the discharge circuit was 130 nH.

Voltage and current pulses were monitored with the help of standard electrotechnical gages which sig-

cient for full charge neutralization quantity and as a result pinch effect arises in beam.

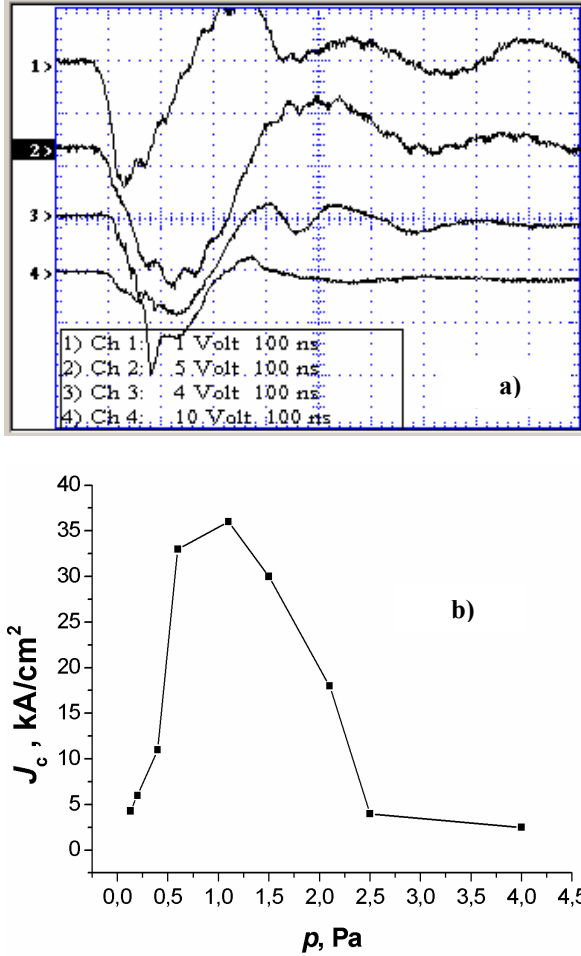


Fig. 3:

(a) – typical waveforms of pulses: acceleration voltage at the cathode (1; 6 kV/div), total current of pulsed generator (2; 3.5 kA/div), beam current onto the collector (3; 4 kA/div), and current density on beam axis (4, 18 kA/cm²*div). Argon pressure 1 Pa.

(b) – beam current density dependence on working gas pressure.

Charge voltage – 20 kV; time delay between start of discharge and voltage applying to the cathode – 10 μ s; distance between the ceramic tube edge and collector - 32 mm, diameter of the diaphragm hole – 1.2 mm

We believe that the following scheme is optimal from the point of view of beam focusing. Since the high rate of magnetic neutralization is difficult to achieve in the case of low-energy beams because of impossibility of separation of the acceleration gap and the drift channel with foil, so the beam pinching should be balanced by Coulomb repulsion. Estimations show that at high rate of electron current density

and relatively low density of plasma electrons (e.g. low gas pressure) a strong radial electric field tightening ions to the axis arises in the beam. This field is amplified due to pinching of electrons because a part of ions find themselves outside of the beam space. Then under the action of radial electric field, ions will move to the axis tending to recover the charge neutralization but injection of a new portion of electrons together with pinching will destroy it and so on. At such a dynamics, the axial electron velocity will not essentially fall as in the case of beam pinching and the current density will gradually rise during the pulse due to accumulation of ions in near-axis region. From our point of view, such a mechanism of beam focusing was realized in the case of average energy of electrons (60-80 keV), and also beam current achieved (3-4) I_A [6].

The proposed focusing mechanism corresponds to the results of theoretical paper [7] which considered in hydrodynamic approximation the equilibrium of relativistic electron beam in plasma taking in account the field caused by the separation of charges, e.g. without an artificial assuming the constancy of the charge neutralization degree (Lawson's model). In particular, it was shown that a dense beam achieves greater current (moreover greater than Alfvén current) even at the condition of magnetic neutralization absence, and it is better focused in rare plasma than in a dense one.

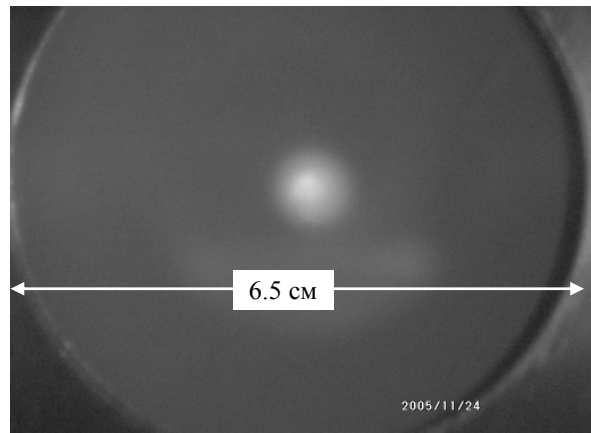


Fig. 4. Luminescence glow under the action of X-rays, caused by beam braking in tantalum target. Charge voltage – 20 kV, argon pressure 0.7 Pa, one shot. Distance between tube edge and target – 22 mm

Results of the X-ray observing principally prove the behavior of the beam current density dependence on pressure of working gas (Fig. 4). At capacitor charge voltage 20 kV, luminophore glow was observed up to pressures of 1.6 Pa and disappeared upon further pressure rising because of decreasing of the voltage drop in double layer being an accelerating gap for electrons and due to the axial electron velocity

falling caused by beam pinching. Increasing the charge voltage to 25 kV was not accompanied with luminescence at high gas pressures.

Beam energy was measured by calorimeter and, at optimal pressures, made up 3.7 ± 0.45 J at stored energy 10 J. The energy distribution character was estimated with the help of beam autographs on different targets: copper, tungsten and stainless steel made. At pressures 0.4-1 Pa, a zone of intensive melting and partial evaporation of characteristic diameter 3-6 mm surrounded by halo (cleaned surface without melting) of 30-40 mm in diameter (Fig. 5). In opposite, at high (> 2 Pa) pressures of argon, beam autographs look “weakly” – initial melting traces are observed in the case of stainless steel only. Such a behavior of beam autographs has a good agreement with the results of X-ray observations.

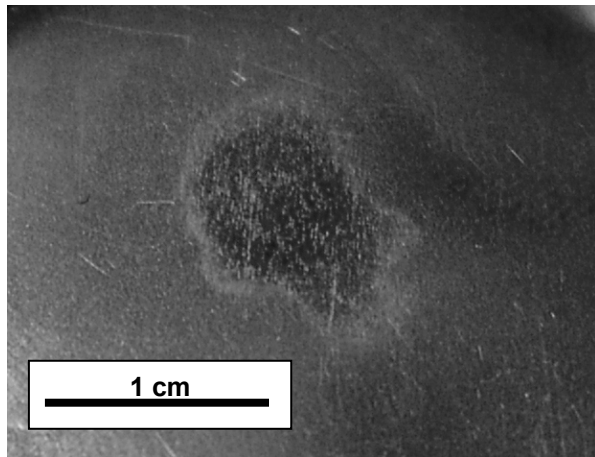


Fig. 5. Photo of beam autograph on stainless steel. Charge voltage – 20 kV, argon pressure 0.7 Pa, one shot. Distance between the tube output edge and the target – 20 mm

4. Conclusion

Thus in electron gun based on Channel Spark, a low-energy (5-10 keV) beam with current approximately 1.5-2 times exceeding the Alfvén one, current rise rate over than 10^{11} A/c and current density over tens of

kA/cm² has been firstly obtained. Such a result is achieved due to intensive pre-ionization of the beam drift channel providing its good charge neutralization.

It should be noted, that pulsed applying of the acceleration voltage in combination with pre-ionization has been already used in paper [8], but unsuccessful design of electron gun and low pre-pulse current did not allow authors to receive the beam with enough density.

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References

- [1] G. Muller, C. Schulteiss, *Proc. 10th Int. Conf. on High Power Particle Beams (BEAMS-94)*, 1994. pp. 833-836.
- [2] W. Frey, C. Schulteiss, H. Bluhm, *Proc. 14th Int. Conf. on High Power Particle Beams (BEAMS-2002)*, 2002. pp. 87-90.
- [3] A.V. Saushkin, N.A. Ratakhin, V.F. Fedushchak, and N.V. Zharova, *Proc. 13th Int. Symp. on High-Current Electronics*, 2004. pp. 195-197.
- [4] V.D. Bochkov, V.M. Dyagilev, Yu.D. Korolev, V.G. Ushich, *Rus. Instruments and Experimental Technique*, No. 5, 91, (1998).
- [5] D.A. Hammer, N. Rostoker, *Phys. Fluids*. **13**, No. 7. p. 1831, (1970).
- [6] D.V. Iremashvili, P.I. Kuznetsov, T.A. Osepashvili, A.P. Timoshenko, *Sov. Journal Tech. Phys.*, **49**, No. 7. 1485 (1979).
- [7] L.M. Anosova, L.M. Gorbunov, *Sov. Journal Tech. Phys.*, **47**, No. 6, 1150 (1977).
- [8] D.D. Hinshelwood, D.B. Chrisey, G. Cooperstein et al., *Proc. of 11th IEEE International Pulsed Power Conf.*, 1997. pp. 1042-1047.