Pulsed Electron-Beam Facility with Improved Purity of the Treatment Process

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Abstract – The facility providing effective and stable production of low-energy (10–30 keV), high-current electron beams has been created and successfully tested at conditions of oil-free vacuum. Facility is based on an electron gun with explosive-emission cathode and plasma anode placed into guide magnetic field. The report presents facility description and experience of its operation. The methods of decrease of the erosion products flux from the walls of vacuum chamber onto the treated target are proposed and realized. The facility is intended for the treatment of materials requiring the improved purity of the treatment process.

1. Introduction

Low-energy (10–30 keV), high-current (10–30 kA) electron beams (LEHCEBs) find more and more applications for material surface treatment. The base of the facilities producing wide-aperture (beam diameter up to 10 cm) LEHCEBs is an electron gun with explosive-emission cathode and plasma anode. [1]. High energy density (up to 20 J/cm^2) and short pulse duration (2–4 μs) allow one to concentrate the beam energy in a thin (1–10 μm) near-surface layer of the irradiated material providing its melting and even partial evaporation. Pulsed melting in vacuum essentially decreases the surface roughness simultaneously with a deep (up to 20 μm) cleaning of the layer from the contaminations presenting in the original material. Smoothing and cleaning the electrodes surface results in, for instance, enhancement of the electric strength of vacuum insulation which is very important for different high voltage facilities as well as high power microwave devices [2].

Fulfillment of such tasks as enhancement of the electric strength of vacuum insulation or treatment of the medicine parts requires an improved purity of the treatment process itself. Hence, it is necessary to use oil-free pumping and working gases of high purity as well as to perform a number of measures on decreasing of the amount of erosion products depositing onto the irradiated target. It should be noted that the uniform and stable excitation of explosive electron emission meets with big difficulties at conditions of oil-free vacuum, moreover at relatively low acceleration voltages. It is well known that explosive emission centers appearance becomes essentially easier under the presence of dielectric inclusions, oil films and other contaminations on the cathode surface [3]. Thus, the elucidation the possibility of the reliable operation of the explosive-emission cathode was one of the main tasks of the present work.

2. Facility Description

The block-diagram of the facility is given in Fig. 1.

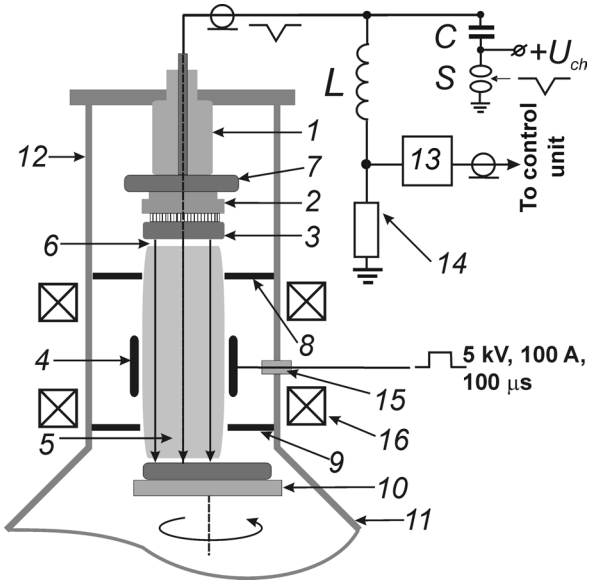


Fig. 1. *1* – Insulator; *2* – cathode; *3* – cathode plasma; *4* – anode; *5* – anode plasma; *6* – double layer; *7* – screen; *8* – diaphragm № 1; *9* – diaphragm № 2; *10* – collector; *11* – working chamber; *12* – electron gun body; *13* – restrictor of the signal amplitude; *14* – current sensor; *15* – anode input; *16* – solenoid. *C* – capacitor IK-50/3; *S* – high voltage thyratron TDI-50k/50, *L* – inductance coil

Plasma anode ($n_p \approx 5\times1012$ cm^{-3}) is formed with the help of high current (100–400 A) reflected (Penning) discharge in argon (in some experiments, hydrogen was used as a working gas) filling the chamber in a steady mode. Before filling the gas, the chamber was evacuated with turbo-molecular pump up to pressure of $(5–7)\cdot10^{-7}$ Torr. Beam collector and explosive-emission cathode are the cathodes of reflected discharge. Capacitor, high-voltage thyratron and inductance coil *L* compose the high voltage pulsed generator (HVPG). The inductance coil *L* provides also the closing of the part of discharge current through the cathode circuit. The emissive part of the cathode is made of copper wire network placed into stainless steel holder.

It is clear, that together with Penning discharge region, there is a region of coaxial magnetron discharge between the anode *4* and body of electron gun *12*. Our probe measurements have shown that plasma density in magnetron region is 3–5 times lower than in Penning one only. However, the portion of discharge current accounts for magnetron region is rather significant (up to 50%) due to the large surface area of the wall. And what is the most important, this magnetron plasma causes big losses of current in radial direction, which lead to breakdown and decreasing the transmission of stored energy into beam energy. Photo with the breakdown tracks on the inner surface of the electron gun wall is shown in Fig. 2. Under this breakdown, a significant amount of erosion products contaminating the treated target appears. Actually, these products contain big amount of oxides appearing under the interaction of the hot vapors of the target material with adsorbed water and residual oxygen.

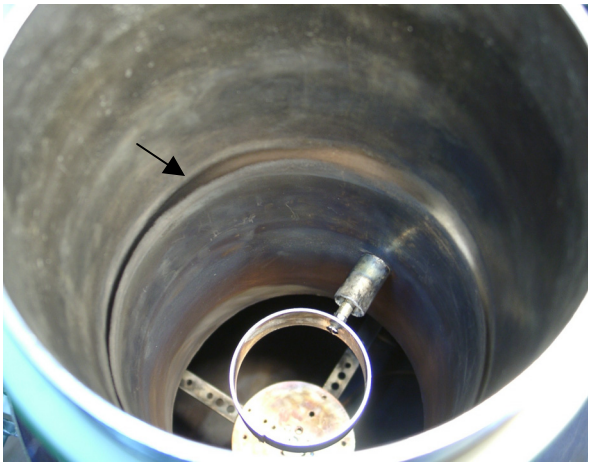


Fig. 2. Photo of the breakdown trace (melted shoulder marked by arrow) from the cathode to the wall of electron gun (after 300 shots). Diaphragms № 1 and № 2 were absent

To prevent this radial breakdown, we have installed the grounded diaphragm № 1 with diameter of 5–10 mm lesser than the cathode diameter. This diaphragm does not allow magnetron plasma to penetrate into the space between the cathode and wall. It should be noted at once, that such an improvement is not evident indeed. The fact is that this diaphragm may intercept the portion of discharge current accounts for explosive-emission cathode. This intercept results in a sharp decreasing of the anode plasma density in near-cathode region and, hence, to failure of the beam formation. Besides, we were afraid of beam pulse shortening because of the breakdown onto diaphragm, which run along the magnetic field lines.

However, experiments have shown that these apprehensions were groundless. For the cathode-diaphragm № 1 distance of 4–6 cm, beam pulse duration was even larger by 15–20% in comparison with the case of diaphragm absence. Total beam energy increased correspondingly [5].

It should be noted that the diaphragm edge is partially evaporated under the beam bombardment, however, these vapors move, evidently, to the cathode not to the target. They may reach the target during next shots owing to cathode erosion but the rate of cathode erosion is rather small (about 10–5 g/C). Moreover, choosing the diaphragm material one may provide an innocence of these vapors for the final goal.

Together with screen *7* placed on the cathode holder (see Fig. 1), the diaphragm № 1 forms a labyrinth protecting the insulator surface from the contaminations from the collector. This fact positively influences on the stability of the electron gun operation.

Diaphragm № 2 fulfills the following functions. It protects the anode input from the deposition of target vapors and thus increases its operation lifetime. Besides, diaphragm № 2 prevents the cathode spots appearance on the walls of working chamber during low-voltage stage of the store capacitor of high voltage pulsed generator. It means an additional decreasing the amount of erosion products contaminating the treated target.

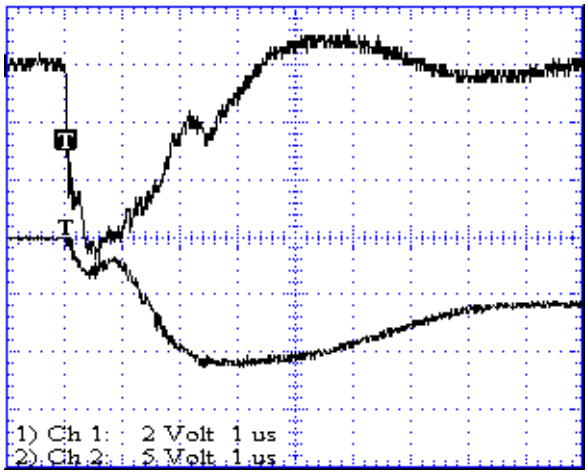
The insulator of electron gun is manufactured of the porcelain (facility described in [4] used a polyamid insulator, i.e. organic). Its surface is protected from the direct fluxes of anode plasma with the cathode holder itself.

We have also modified the starting circuit of the HVPG by installing of the current sensor in series with inductance coil *L* (Fig. 1). At normal operation of the reflected discharge, the portion of discharge current running through the explosive-emission cathode is monitored with this sensor. Sensor signal is applied to the input of control unit, which forms the triggering pulse of HVPG. In contrast to the previous scheme, where the total discharge current pulse was used, the new one practically excludes the idling mode in electron gun, which may occur in the case of discharge current running mainly in magnetron region.

3. Results of Facility Testing

Figure 3 presents typical waveforms of the acceleration voltage and beam current pulses illustrating the increasing of pulse duration at the presence of the diaphragm № 1.

It should be noted that presence of this diaphragm causes distortions in the measurements of beam current because the return current of plasma electrons gets the outlet channel to “ground”. Hence, the measured current becomes lesser by the value of return current. Since anode plasma is collisionless, so the return current does not damp in it. However, to choose the mode of treatment it is enough to use the data of calorimetrical measurements together with acceleration voltage waveforms. Thus, measurements of beam current do not represent principal interest from this point of view.



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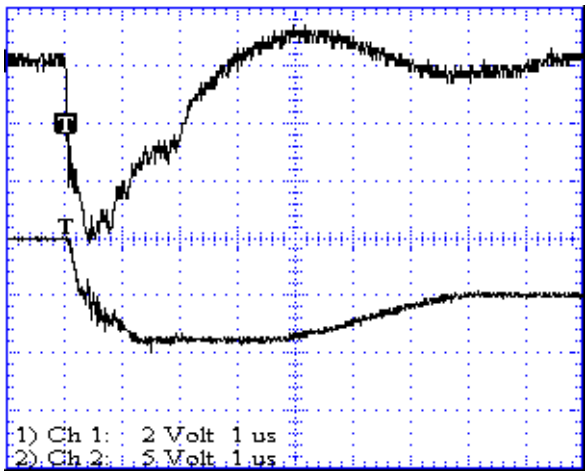


b

Fig. 3. Typical waveforms of acceleration voltage (upper traces, 8 kV/div) and beam current onto collector (lower traces, 6 kA/div) for the case presence (a) and absence (b) of the diaphragm № 1. The distance cathode-diaphragm is 4 cm. Argon pressure – 0.4 mTorr, U_{ch} = 25 kV, H = 1 kOe

During the irradiation process (irradiation cycle may take up tens or even hundred shots), vapors of diaphragm № 1 and target are deposited on the explosive-emission cathode. This deposition may influence on its emissive properties. We have carried out several experiments on clarification of diaphragm material affect on the cathode operation lifetime.

Stainless steel 12X18H10T (Russian standard), vacuum melted copper, and vacuum melted molybdenum, were used as diaphragm material. Electrodes of diameter 12 cm made of stainless steels 304L и 316L (US standard) were the targets. Beam energy density was 8–10 J/cm^2. The results of experiments are as follows:

1. In the case of stainless steel diaphragm, we observed the decreasing of beam current after 200–300 shots; idlings appeared after 300–500 shots, and full degradation (more than 70% idlings of total number of shots) of the cathode emissive ability came. Cathode surface was practically fully covered with stainless steel. This fact was the reason of cathode degradation because stainless steel has bad emissive properties.

2. The further replacement of the stainless steel by copper has led to recovery of the cathode emissive ability. Up to present moment, more than 5000 shots were done without any changes in cathode operation.

3. In the case of molybdenum diaphragm, the cathode operates rather good – rare idlings appeared after 2500 shots but the essential degradation of the cathode emission is not observed yet.

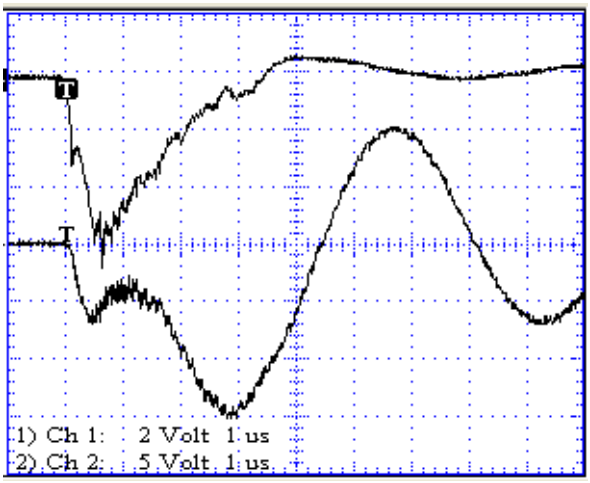
Using hydrogen as a working gas, we observed the essential increasing of the pressure threshold, at which reflected discharge transits into high-current mode. In the case of argon, this value was approximately 0.15 mTorr, and for hydrogen – 0.75–0.8 mTorr.

Comparison of the waveforms of acceleration voltage and cathode current for the cases of argon and hydrogen shows that it is needed to have hydrogen pressure larger by factor of 20–30 times to obtain the same values of current. However, at that, beam pulse duration decreases and beam energy becomes 1.5 times lower according to calorimetrical measurements. Experimentally observed difference in the current density in the cases of argon and hydrogen can not be explained in the frames of stationary double layer model. Actually, the relation between electron and ion current densities in such a layer are defined by Langmuir expression:

$$J_e = J_i\,(M/m)^{1/2},$$

where $J_i = 0.4en_p\,(2kT_e/M)^{1/2} + en_pv_d$, M и m are ion and electron mass, correspondingly, v_d is velocity of mutual motion of the cathode and anode plasmas, n_p и T_e are anode plasma density and its electron temperature, correspondingly, k is Boltzmann constant, e is electron charge. Assuming that $v_d = 2\times10^6$ cm/s [3], one can estimate that in the case of argon, the value J_e should be approximately 4 times greater (for the same value of plasma density), not 20–30 times. However, taking into account a non-stationary behavior of the double layer at the initial stage of beam pulse according to method [6], one can find that this contradiction may be eliminated. The other possible explanation concludes in difference of the ionization degree of argon and hydrogen.

Finally, the undertaken measures (oil-free pumping, porcelain insulator, installing of diaphragms and some others) allows us to increase the electric strength of first breakdown from 0.6 MV/cm for untreated electrodes to 1 MV/cm for electron-beam treated electrodes at the area of electrode surface about 100 cm^2 [7]. Electrodes were manufactured of stainless steel. Amplitude of the test pulse in [7] was 200 kV, and pulse duration was 50 ns. These results have been obtained at irradiation in argon; in the case of hydrogen, pulsed electric strength was approximately 30% lower. This decreasing is evidently caused by frailness of the cathode emitting wires under the action of hydrogen and further transfer of the micro-debris onto the treated target [7].



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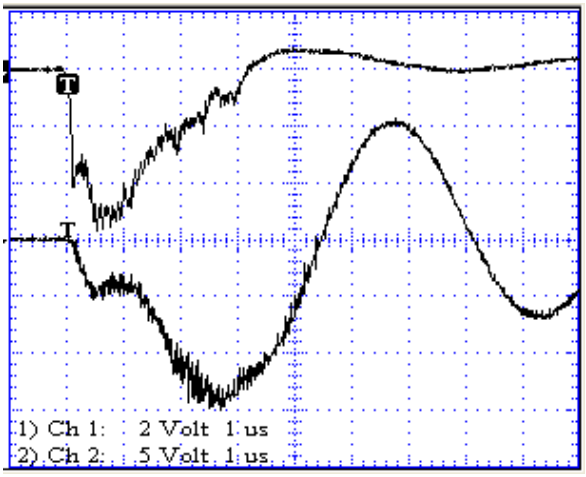

b

Fig. 4. Typical waveforms of acceleration voltage (upper traces, 10.34 kV/div) and total cathode current (lower traces, 14.35 kA/div) for different gases: (a) – argon at pressure 0.32 mTorr, (b) – hydrogen at pressure 7.2 mTorr. U_{ch} = 30 kV, H = 1 kOe

4. Conclusion

The facility providing pulsed electron-beam treatment of the samples and different products in oil-free vacuum has been created and successfully tested. Space localization of the reflected discharge with the use of diaphragms allows one to improve additionally the purity of the treatment process due to suppressing of the cathode spots on the walls of operating chamber and body of electron gun.

For manufacturing the diaphragms, it is preferable to use vacuum melted materials with low rate of evaporation.

The operation lifetime of the cathode is already quite enough. The achieved cathode lifetime in conjunction with the simplicity and low cost of its manufacturing allows one to use the facility both for research and technology purposes.

Acknowledgments

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References

[1] D.S. Nazarov, G.E. Ozur, and D.I. Proskurovsky, *in: Proc. 11th IEEE Int. Pulsed Power Conference.* Baltimore, USA **2**, pp. 1335–1340 (1997).

[2] A.V. Batrakov, A.B. Markov, G.E. Ozur, D.I. Proskurovsky, and V.P. Rotshtein, IEEE Trans. on Dielectrics. and Electric Insul. **2**, 237 (1995).

[3] G.A. Mesyats, and D.I. Proskurovsky, *Pulsed electrical discharge in vacuum,* Berlin, Heidelberg, Springer-Verlag, 1989, pp. 172–175.

[4] G.E. Ozur, D.I. Proskurovsky, and K.V. Karlik, *in: Proc. 5th Conf. on Modification of Materials with Particle Beams and Plasma Flows*, pp. 139–142, Tomsk, Russia, 2000.

[5] G.E. Ozur, D.I. Proskurovsky, and K.V. Karlik, *High-current electron gun.* Positive decision No. 01 И3-2003 of April 12, 2004 on the Russian patent invention (No. 2003108235 of March 24, 2003).

[6] M.Yu. Kreidel', E.A. Litvinov, G.E. Ozur, D.I. Proskurovsky, Fizika Plasmy (Sov.) **17**, 12, 1425–1439 (1991).

[7] A.V. Batrakov, D.J. Johnson, S.A. Onishchenko, and D.I. Proskurovsky, *in: Proc. 21th Int. Symp. on Discharges and Electr. Insul. in Vacuum (ISDEIV-21).* Yalta, Ukraine, Sept 27–Oct 1, 2004 (to be published).