Electron Source for Producing Radial Converging Electron Beam

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Abstract – Electron beam is generated by cylindrical multipoint explosive emission cathode 28 cm in diameter and 35 cm in length. The source was made according to triode scheme. Electron kinetic energy is 120 keV, beam current 2 kA, pulse duration 30 μs. The source is applied for modification of the outer surface of fuel cladding elements. Temporal and spatial characteristics of an electron flow are presented.

1. Introduction

For improvement of corrosion resistance of structural and fuel claddings materials in Pb and Pb-Bi coolant it was suggested to apply the modification of material surface properties with the help of pulsed intense electron beams [1]. Practical realization of this technology needs in an electron source which is able to produce pulsed radially converging electron beam. Beam energy density on the target (fuel cladding) of 10 mm in diameter should exceed 30 J/cm^2. Kinetic energy of electrons is 120 keV. The description of the source and its operating characteristics are presented in the given paper.

2. Description of the Accelerator

Scheme of the source forming radial converging electron beam is given in Fig. 1. In Fig. 2 its general view is shown.

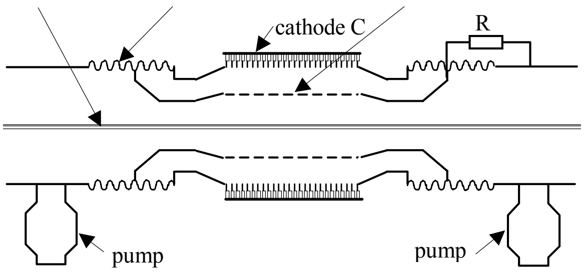

Fig. 1. Scheme of the electron source

As an electron emitter a multipoint explosive emission cathode is used. The source is of triode type. The radii of the cathode and controlling grid are 14 cm and 10 cm correspondingly. The target diameter in a majority of the measurements was equal to 10 mm (it corresponds to diameter of fuel element claddings). The length of the work part of the cathode 32 cm is restricted by the influence of the beam magnetic field on electron trajectories. In the given version of the source scheme the controlling grid is under floating potential which is determined by the magnitudes of the beam current and resistor *R* inserted in the circuit of the controlling grid. This allows to regulate the beam current value without changing of the resistance in the circuit of the controlling grid. Calculated parameters of the electron beam are the following: electron energy 120 keV, beam current 1400 A, longitudinal size of beam 32 cm, energy density on the target up to 40 J/cm^2, pulse duration up to 30 μs.

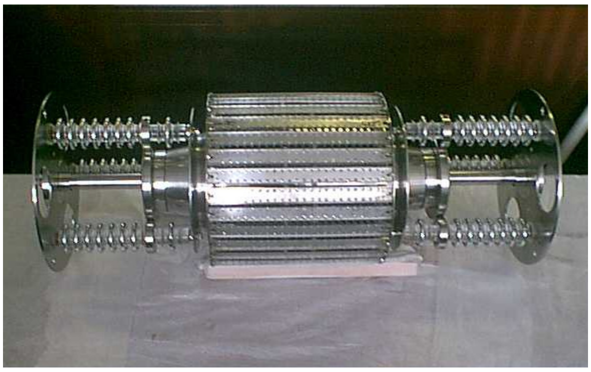

Fig. 2. Photo of the source

To obtain required beam parameters it is necessary to ensure an electrical strength of insulators and vacuum gaps, absence of an electron emission from the controlling grid, high efficiency of the electron flow focusing to the target. In order to solve these tasks the full-size model of the source was manufactured and tested. Numerical simulations of the electron beam formation were also performed. In Fig. 3 calculated magnitudes of the electric field strength on the grid surface from the cathode (E_1) and anode (E_2) sides versus value of the grid resistor are shown when in calculation a real grid geometry and beam space charge were took into account. From this figure one can see that electric field strength on the grid at the anode side is not great and in this case an electron emission from the controlling grid must be absence. If the grid resistor 1200 Ω, the electric field strengths E_1 and E_2 equal and it this case the grid does not influence on the electron trajectories. In Fig. 3 the calculated dependence of the beam energy density at the target on the grid resister value is also shown.

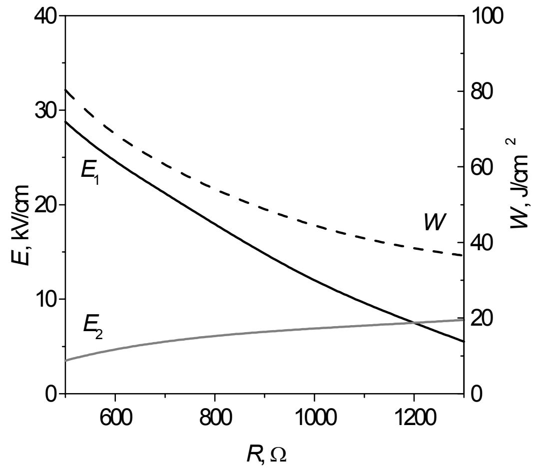

Fig. 3. Dependence of electric field strength on the controlling grid at the cathode side E_1, at the anode side E_2, and the beam energy density on the grid resistor value R

3. Results of the Measurements

For generation of high voltage pulses a Marx generator consisting of four stages was used. Each stage is 6th-cells artificial network. Experiments have shown that, if controlling grid potential is provided by high-ohmic divider, the pulse duration is less than one determined by capacity of the Marx generator. The stable operation of the source with the pulse duration determined by a capacity of the Marx generator can be achieved when controlling grid potential is provided by low-ohmic divider (~ 100 Ω) and does not exceed 70 kV. In Fig. 4 one can see oscillograms of the cathode potential, grid potential and beam current.

Source operation and efficiency of the electron beam focusing to the target depend on the target diameter. This is illustrated by Fig. 5 in which the dependence of the relation of the beam current on the target I_t to the total (cathode) current is shown. It is seen that the total cathode current I_c and target current I_t increase with increasing the target diameter up to 30 mm then they reach maximum values. Maximum values of the currents correspond very well to calculated ones.

Incomplete hitting the beam to the target of 10 mm in diameter is connected with an azimuth divergence of electrons. In order to get an information on the magnitude of an angular spread of electrons measurements of the beam current to target of different diameter were performed. Results are shown in Fig. 6.

Angular distribution function may be approximated by Gauss distribution

$$\frac{di}{d\alpha} = C\exp\left(-\frac{\sin^2\alpha}{\sin^2\alpha_0}\right), \quad (1)$$

where i – total current from single point, α – azimuth angle, α_0 – angle determined angular spread magnitude, C – const.

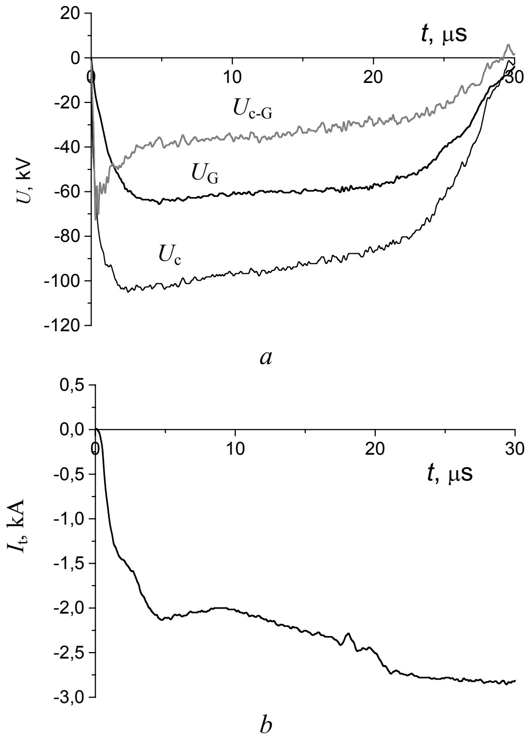

Fig. 4. Oscillograms of cathode potential U_c, grid potential U_G (a), and beam current I_t (b)

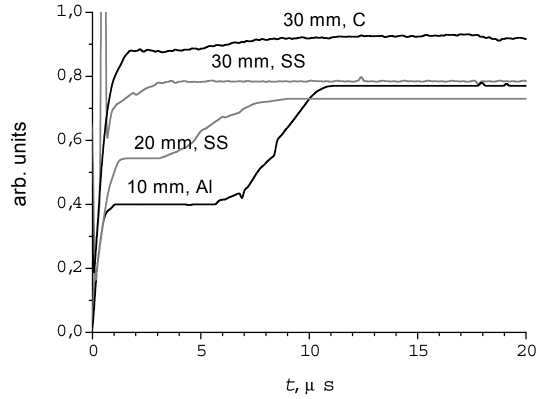

Fig. 5. Dependence of the current part hitting a specimen on time for different materials (C, SS, Al) and diameters of specimens

The total current from single point is

$$i = 2C\int_0^{\pi/2}\exp\left(-\frac{\sin^2\alpha}{\sin^2\alpha_0}\right)d\alpha\,. \quad (2)$$

The current part from single point hitting the target is determined by the expression

$$\frac{i}{i_0} = \Phi\left(\sqrt{2}\frac{\sin\alpha_{\lim}}{\sin\alpha_0}\right), \quad (3)$$

where $\Phi(x) = \frac{2}{\sqrt{2\pi}}\int_0^x \exp(-\frac{t^2}{2})dt$.

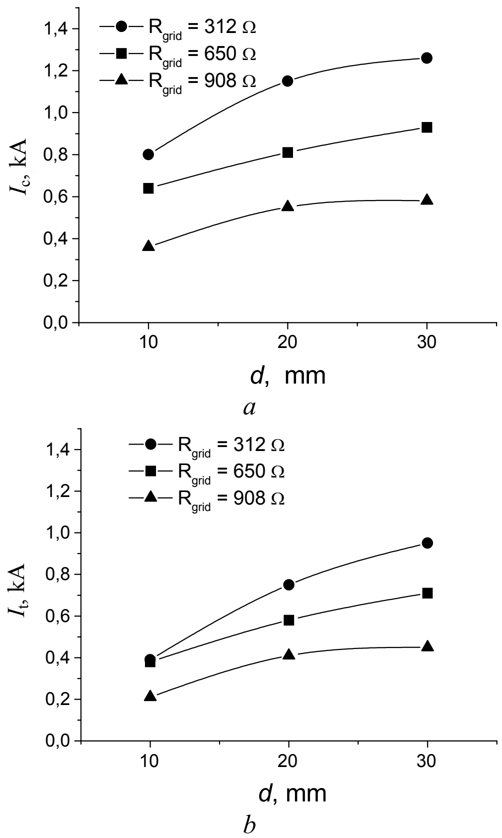

Fig. 6. Dependence of total cathode current I_c (*a*) and target current I_t (*b*) on target diameter *d*

The angle α_{lim} we may determine with the help of the numerical simulations. The current part hitting the target i/i_0 we may found from experimental data. For the target of 10 mm in diameter measured value i/i_0 equals ~ 0.5, calculated value α_{lim} equals 8°. Using obtained values α_{lim} and i/i_0 we may find α_0 with help of formula (3). Obtained by such way value α_0 at distance 1 cm from cathode equals ~ 20°. This value α_0 we used for calculation of the dependence of the current part hitting the target on target diameter. This dependence is shown in the Fig. 7. It is seen that calculating dependence corresponds to experimental data. It allows to conclude that a source of the divergence is a distortion of an electric field near the cathode points, therefore, for increasing the efficiency of the beam focusing to the target of ≤ 10 mm in diameter the improvement of the electric field distribution in the cathode region is necessary.

In Fig. 8 the temporal dependence of the beam energy density on the Al target of 10 mm in diameter is shown. It is seen that the energy density achieves 35 J/cm^2 that corresponds to minimum value required for modification of fuel claddings operating in Pb–Bi coolant.

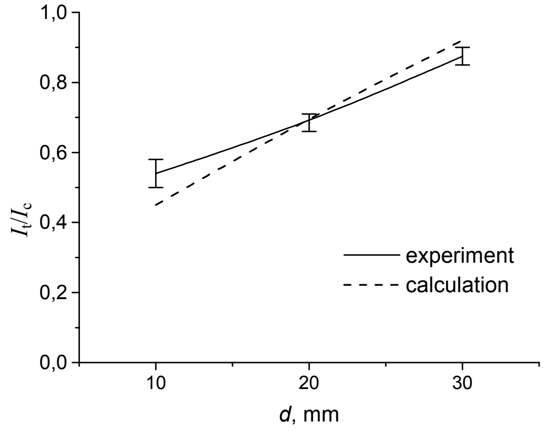

Fig. 7. Dependence of the current part hitting the target on target diameter

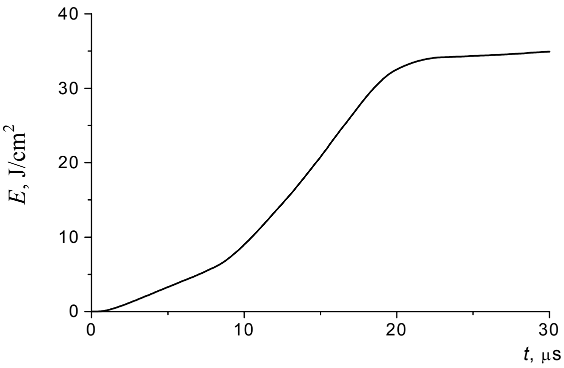

Fig. 8. Dependence of beam energy density on the irradiated specimen on time

4. Conclusion

The design of an electron source with radial converging electron beam was suggested, realized and studied. When the target diameter *d* exceeds 20 mm, the source operates in accordance with results of calculation. Under smaller diameters of a target the angular spread of beam electrons plays important role. Part of electrons oscillates in the source volume. This leads to decreasing the beam current and efficiency of its focusing to the target. The average energy density of the target of 10 mm in diameter is 35 J/cm^2 that corresponds to the minimum value required for improvement of corrosion resistance fuel cladding operating in Pb and Pb–Bi coolants.

5. Acknowledgment

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Reference

[1] G. Mueller, A. Heinzel, J. Konys et al., J. of Nuclear Materials **301(1)**, 40–46 (2002).