

Research of Energy Equilibrium of Planar Diode with Explosive Emission Cathode

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Abstract - The results of experimental tests of operating mode and energy equilibrium of planar diode with graphite explosive emission cathode during the generation of electron beam are presented. It was shown that at the diode impedance matching to output resistance of nanosecond generator the volt-ampere diode characteristics are determined by the Child-Langmuir's law at the 70-80% distance of voltage pulse duration applied to the diode. The research of energy equilibrium showed that the principal reasons of energy losses during the electron beam formation are electron scattering in the anode-cathode gap. The energy loss value does not exceed 10% of the input energy while operating in the matching mode and becomes 30% higher with the increase of the anode-cathode gap.

1. Introduction

The reliability and resource of high-current electron accelerator operation are determined by its efficiency. Any unproductive energy losses lead to the heat and preliminary destruction of the accelerator construction units. It is known that the diode is the most energy intensive unit of the accelerator. In order to increase the effectiveness of energy transfer stored in the double forming line (DFL) of the high-current electron accelerator the matching transformer placed between the double forming line and diode unit was offered to use [1]. The transformer core saturation during the DFL charging allowed to significantly reduce the pre-pulse amplitude and its influence on the diode operation without the picking discharger application [2, 3]. The research performed showed that in case of forced demagnetization of matching transformer core the voltage pulse shape applied to the cathode is close to optimal and takes into consideration the decrease of anode-cathode gap impedance due to the explosive emission plasma scattering [4]. This allows matching the diode to the generator during all the pulse of electron beam generation. The use of transformer in the developed electron accelerator allowed significantly increasing the operation effectiveness of nanosecond generator and the accelerator as a whole [5, 6].

The researches showed that further decrease of energy losses and accelerator efficiency increase are possible at the optimization of diode unit of the elec-

tron beam. In the presented work the research results of energy losses in the accelerator diode unit are presented.

2. Experimental Set-up

The experiments were performed at the pulse electron accelerator TEU-500 [2, 3] with the accelerating voltage of 350-450 kV, pulse duration at the half-height of 60 ns, total energy of electrons per pulse up to 250 J. The pulse frequency rate in the experiments was 0.5-1 Hz. Figure 1 shows the accelerator diode unit and the position of voltage and current sensors.

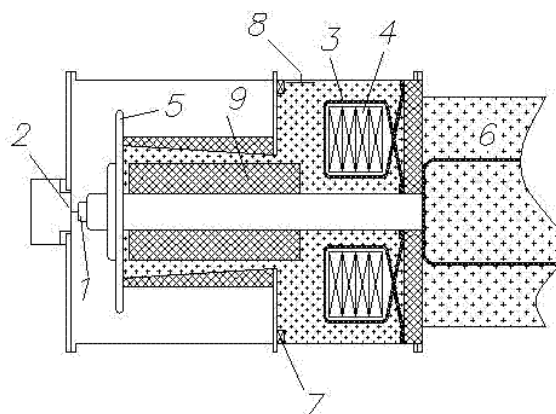


Fig. 1. Diode unit of pulsed electron accelerator: 1 – cathode; 2 – anode mesh; 3 – winding of matching transformer; 4 – autotransformer core; 5 – potential disk of cathode-holder; 6 forming line of accelerator; 7 – Rogowsky coil; 8 – capacitor divider; 9 – frame of demagnetization inductance

In order to measure current going in the load of the nanosecond generator the Rogowsky coil (RC) with a reverse turn was used. For voltage measuring the capacitor divider placed in the oil-filled chamber was used. The total current of electron beam was measured by the Faraday cup (FC). The distance between anode mesh and FC collector was 5 mm. FC was pumped out together with the diode chamber up to the pressure not more than 0.05 Pa.

The registration of electric signals coming from the sensors was performed by the oscillograph Tektronix 3052B which has 500 MHz pass band. The inaccuracy of electric signal synchronization did not exceed 0.5 ns. The obtained accuracy of voltage measurement by

the capacitor divider, current in the load by Rogowsky coil, total current of electron beam by Faraday cup and their frequency characteristics allow calculating the energy equilibrium with the accuracy of 10%. The researches were performed for the planar diode configuration. The flat diode 45 mm in diameter, a flat mesh made of stainless steel with 70% transparency was used as an anode.

3. Research of Operation Mode of Planar Diode

It is known that the diode electron current with explosive emission cathode can be limited by the emission ability of cathode and by the volume charge in the anode-cathode gap. At the infinite emission ability of the cathode the volt-ampere characteristic of the diode is determined by the Child-Langmuir correlation [7].

Figure 2 represents oscillograms of voltage applied to the diode and oscillograms of electron beam current measured by FC.

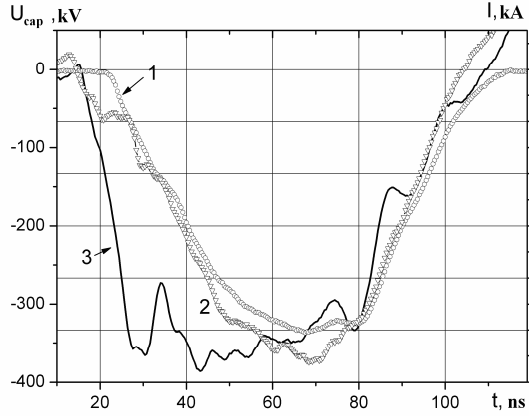


Fig. 2. Oscillograms of electron beam current I_e (1), total current of diode I_{RC} (2) and voltage U_{cap} (3). Cathode made of graphite, 45 mm in diameter. Gap is 10 mm

Oscillograms are averaged according to last 10 consequent pulses going with 0.5 Hz frequency.

The planar diode with the cathode 45 mm in diameter and 10 mm anode-cathode gap has the impedance close to the output impedance of nanosecond generator (30 Ohm). This provides the matching mode. Figure 3 shows the diode impedance values as experimental (from oscillograms of diode total current and voltage U_{cap} , Fig. 2) so calculated ones according to the Child-Langmuir correlation.

The experimental values of diode impedance were calculated according to the correlation

$$Z_{exp} = \frac{U_{cap} - L \cdot \frac{dI_{RC}}{dt}}{I_{RC}},$$

where L is inductance of diode equal 160 nHz.

The impedance calculation is performed under the condition that the diode current is limited by the volume charge, the value of the anode-cathode gap decreases and the area of emission surface increases due to the explosive emission plasma scattering at a constant speed. As it will be discussed below the anode plasma influence can be neglected in our case.

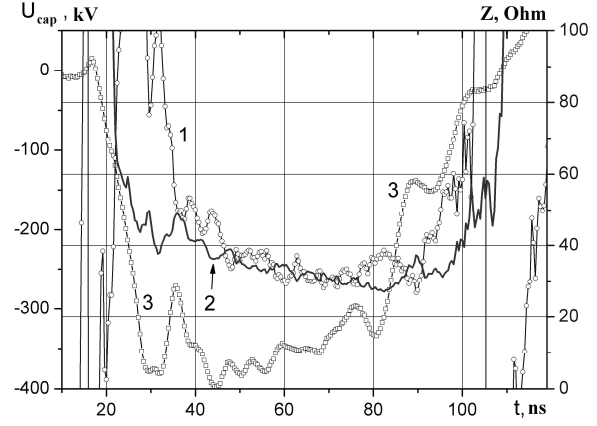


Fig. 3. Change of experimental (1) and calculated (2) values of planar diode impedance during electron beam generation. Curve 3 is voltage pulse

The calculations are done according to

$$Z = \frac{(d_0 - v \cdot t)^2}{2.33 \cdot 10^{-6} \cdot \pi (r_0 + v \cdot t)^2 \cdot \sqrt{U_k}},$$

where U_k is voltage applied to the diode, v is velocity of explosive emission plasma scattering ($2.5 \cdot 10^6$ cm/s), r_0 is cathode radius, d_0 is initial anode-cathode gap.

During first 10 ns after the application of voltage to the diode the electron current is low (see Fig. 2). This can be explained by the delay of plasma formation at the surface of graphite cathode. During 20 ns since the voltage pulse beginning the experimental values of diode impedance is much higher than calculated ones. This is caused by the process of plasma surface formation. During this time the current is limited by the emission ability of the cathode. The satisfactory coincidence of experimental and calculated values of the diode impedance in 20-25 ns after the voltage application shows that during this time the current of planar diode with graphite cathode is limited by the volume charge in the gap.

While calculating according to the Child-Langmuir correlation it is supposed that cathode and anode are flat. But at the beam extraction from the diode unit a metal mesh is used as anode. The mesh does not have uniform surface. Moreover, in the paper [8] it is shown that the formation of the anode flame leads to a partial compensation of the volume charge (due to the oncoming current of ions from the anode plasma) and to a decrease of impedance lower than theoretical value. In order to estimate the discontinuity

influence of the anode surface and anode flame on the planar diode operation mode the measurements of diode current were performed using a flat metal plate and mesh with cuts 6 mm in width (70% transparency) as anode. Figure 4 presents oscillograms of current measured by RC for these two modes of diode operation.

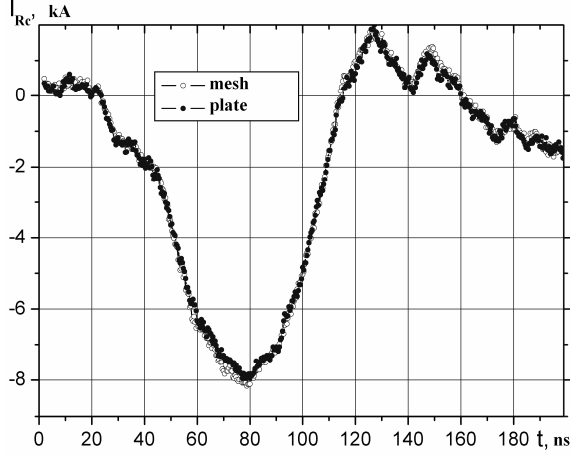


Fig. 4. Oscillograms of total current consumed by diode while using a solid metal plate and metal mesh as anode. Cathode made of graphite, 45 mm in diameter. Gap is 12 mm

The researches showed the absence of total current consumed by the planar diode at the switch of anode mesh to the solid metal plate for the anode-cathode gaps from 10 up to 17 mm in length. This indicates a weak influence of anode plasma on the compensation of volume charge in the anode-cathode gap under our experimental conditions. The presence of sharp edges on the anode mesh surface does not also significantly influence the planar diode operation providing the storage of diode configuration simpler for mathematical description.

4. Research of Energy Equilibrium of Planar Diode

The change of total energy going to the diode unit from the nanosecond generator during the formation of voltage pulse can be written in the form of

$$E(t_1) = \int_0^{t_1} I_{RC} \cdot U_{cap} \cdot dt,$$

where I_{RC} is current measured by RC, U_{cap} is voltage measured by capacitor divider.

The energy of electron beam at the moment t_1 is determined by the correlation

$$E_e(t_1) = \int_0^{t_1} I_e \cdot (U_{cap} - U_{ind}) \cdot dt,$$

where I_e is current of electron beam, U_{ind} is voltage fall at the inductance of the diode unit which is

$$U_{ind} = L \cdot \frac{dI_{RC}}{dt}.$$

While calculating the energy of electron beam the current value measured by FC was corrected to the optical transparency of the anode mesh (70%).

Figure 5 shows the change of energy supplied from the nanosecond generator to the diode and the change of energy of electron beam during the generation of beam current pulse.

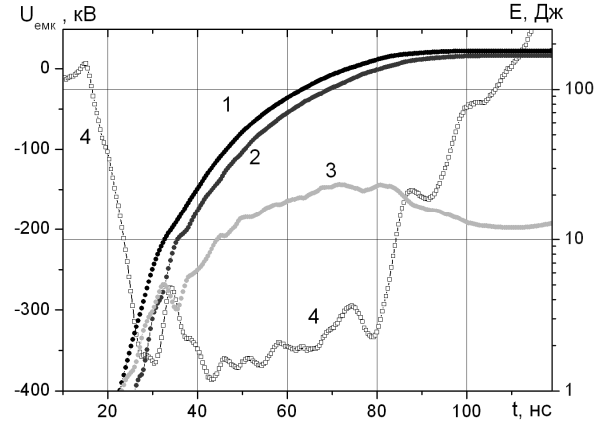


Fig. 5. Energy equilibrium in diode unit during beam current pulse generation: 1 – energy from generator; 2 – electron beam energy, 3 – energy losses; 4 – voltage pulse. Cathode made of graphite, 45 mm in diameter. Gap is 10 mm

The energy losses in the diode unit take place during all the period of electron beam generation. They can be associated with the formation of explosive emission plasma on the cathode surface or with the scattering of beam electrons on the way from cathode to Faraday cup collector. Figure 6 shows the dependence of energy losses from the value of anode cathode gap.

The results of the diode with cathode 45 mm in diameter is presented in the figure. The cathode is made of graphite or carbon fabric. The general performance of the dependence for various cathodes shows that the energy losses in the diode are not caused by the process of explosive emission plasma formation but by the process of beam electron transportation.

The researches of energy density distribution in the cross section by the dosimetric film showed [9] that an average energy density of electron beam at the output of planar diode (behind the anode mesh) is constant along the cross-section. We assume that the energy density of electron beam is equal along all the area of cross-section of the beam and the angle β of scattering does not change on the way of electron from the emission surface to the FC collector. In this case the decrease of electron energy got into the FC

collector with the increase of distance of cathode-collector FC is proportional to the increase of cross section of electron beam at the expansion for the β scattering angle. The energy losses in this case will be

$$\Delta E = j \cdot \Delta S = j \cdot \pi \cdot (r_0 + \Delta r)^2 - j \cdot \pi \cdot r_0^2,$$

where j is an average density of electron beam energy in the cross-section, r_0 is cathode radius, Δr is the increase of electron beam radius.

At the electron scattering for β angle the beam radius increases for $\Delta r = d \cdot \tan \beta$ value while going d distance. If the increase of beam radius is less than cathode diameter the energy losses will be proportional to the anode-cathode gap due to the electron scattering:

$$\Delta E = 2 \cdot j \cdot \pi \cdot r_0 \cdot \tan \beta \cdot d = K \cdot d$$

where K is constant.

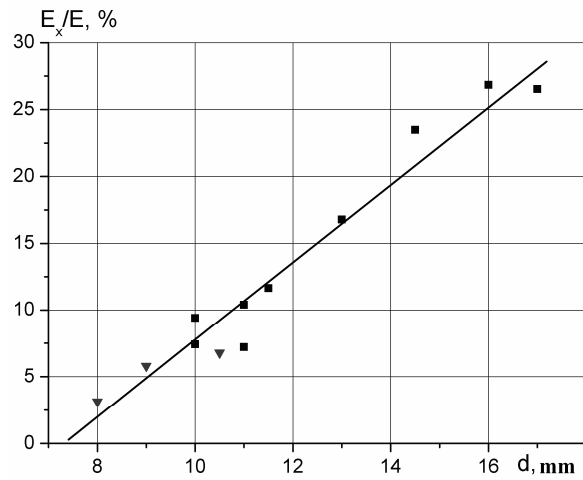


Fig. 6. Dependence of energy losses in diode unit standardized for total energy supplied to diode from anode-cathode gap: \blacktriangledown is cathode made of carbon fabric, \blacksquare is cathode made of graphite

The extrapolation of the straight line in Fig. 6 shows that at the 7 mm anode-cathode gap the energy losses in the diode unit are absent. With the diameter of the transparency area of the anode mesh of 70 mm this corresponds to the electron scattering of the fringe region of the beam for 60° angles. The distance of high-current pulsed electrons in the anode-cathode gap is also noted in the paper [8] where the scattering angle is 44.5° .

Conclusion

The performed research of the operation of planar diode with explosion emission cathode made of graphite showed that at the matching of diode impedance to the output resistance of nanosecond generator the electron beam current is limited by the volume charge in the anode-cathode gap. The total current of the electron beam is described by the Child-Langmuir correlation along the principal part of voltage pulse taking into consideration the explosion emission plasma scattering with constant velocity. The energy losses in the diode unit are caused by the scattering of beam electrons of fringe region on the way from the emission surface to the FC collector and while operating in the matching mode do not exceed 10 % of the supplied energy.

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