Research of Anode Foil Stability of High-Current Electron Accelerator

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Abstract – The results of experimental study of the mechanisms of the damaged anode foil when outputting a powerful pulsed electron beam from the high current diode with an explosion-emission cathode into the atmosphere are given in the paper. The experiments were performed at the accelerator TIA-500 with the following parameters: accelerating voltage is up to 500 kV, beam current is up to 10 kA, half-height pulse duration is 60 ns, repetition frequency is up to 3 Hz.

The influence of the material and explosion-emission cathode surface and distribution of cross-section electron beam on the anode foil resistance was investigated.

It was found that the main reason limiting the lifetime of the anode foil is the occurrence of arc discharges between the cathode and the anode foil at the pulses following the main negative pulse of accelerating voltage (post-pulses). Injection of the vacuum discharger-crowbar into the construction of the high current diode allows to exclude the damage of the anode foil by arc discharges.

1. Introduction

Using a high current electron beam in radiation technologies is results in the necessity to create the system of the electron beam output directly into the atmosphere or another gas-phase environment. The construction of the anode is usually used, which consists of the support grid and a thin foil from metal with a low atomic number. Pulsed electron beam generation in the diode with an explosion-emission cathode takes place at the initial stage of the vacuum breakdown of a discharge gap formed by the diode cathode and anode. When applying the voltage pulse, “explosion-emission plasma” is formed on the cathode, the latter being the source of electrons and it fills the diode with the rate (2–3)·10⁶ cm/s. The density of electron current being high, the plasma is formed on the anode as well, which is expanded to the cathode with the rate similar to the cathode’s one. Having overlapped the diode gap by cathode or anode plasma the arc phase of the vacuum breakdown is formed [1].

Safety of the anode foil when outputting the beam from the vacuum diode is one of the key parameters of practical application of pulsed electron accelerators. For continuous and pulsed electron accelerators of millisecond and submillisecond duration the main mechanism of the damage of the foil is a heat one associated with the losses of part of beam energy while passing through the foil. Overheating of the foil limits the acceptable energy flux density at the level ~ 0.1 kW/cm² [2, 3]. The processes associated with the specific operation of high current diodes with explosion emission cathodes and generators providing the formation of pulses of accelerating voltage make a significant impact on the resistance of the foil in the sources of powerful pulsed beams. In particular, at high currents in the diode a local overheating of the foil is possible as a result of pinching of the beam under its own magnetic field [2, 3]. The destruction of the foil may also occur as a result of the formation of the arc in the diode [4].

For the nanosecond generator generating pulses of accelerating voltage the high-current diode with explosion emission plasma cathode is essentially the load with the impedance varying with time. At the same time, in high-current accelerators with generators performed on the segments of transmission lines in the form of single (SFL) or double (DFL) forming lines, the occurrence of the reflected waves is inevitable at a discharge of the forming line [5]. Significant reduction of voltage pulses on the diode during charging the forming line (pre-pulses) has been solved by us in [6] by the matching autotransformer between the double forming line and the diode. The autotransformer also provided higher output impedance of the water by a double forming line. Spurious pulses on the diode complicate the nature of the processes and their influence on the stability of the foil requires further research.

In the given work we represented the results of research directed to detecting the main mechanism of the anode foil destruction in high current diode and the data on the modernization of the diode node ensuring the increase in its lifetime at currents in the diode less than 20 kA and accelerating voltage up to 500 kV, when influence of own magnetic field to the distribution of beam current density in cross-section can be neglected.

2. Experimental procedure

The experiments were carried out at the high current electron accelerator TIA-500 with the following parameters: the amplitude of accelerating voltage pulses is up to 500 kV, that of beam current is up to 10 kA,
half-height pulse duration is 60 ns, repetition frequency is up to 2 Hz. The system of forming accelerating voltage pulses includes the primary accumulator – Marx generator for voltage 250 kV, double forming line (DFL) and with deionized water as a dielectric and matching single-turn autotransformer doubling the amplitude of of the accelerating voltage pulse on the diode [6]. Output impedance of the accelerator is 40 Ohm.

The construction of the diode used in the given experiments is represented in Fig. 1. The diode provides production of continuous cross-section electron beam with diameter up to 70 mm with distribution of current close to homogeneous. The diameter of the cathode 6 was 60 mm, anode-cathode gap $d_1$ was regulated in the range of 12–18 mm. The pulses of accelerating voltage on the diode, diode total current and electron beam current were recorded during the experiments. To measure electron current in the diode gap instead of the anode foil collector 4 of a low resistance (0.05 Ohm) reverse current shunt is settled (Fig. 1).

The collector surface (Al) was polished for identification of a print of a beam and arch influence. The vacuum discharger – crowbar has been organized by introduction of an additional path formed by electrode 5 and the cathode of the accelerator 6. Pressure of residual gas in the diode was $(5-8) \times 10^{-5}$ Torr.

Experiments with a extraction of a beam from the diode through a foil have shown, that fast destruction of a foil is correlate with the appearance of current impulses in the diode with enough big amplitude after the finish of the basic voltage impulse.

Principal cause of occurrence post-impulses is the problem in the matching of an impedance of the diode with explosive-emission cathode and a output impedance of a forming line. Incomplete allocation of energy of a forming line in the diode for duration of the basic impulse results to formation post-impulses and to increase in probability of occurrence of the centers of explosive emission at a foil at change of voltage polarity. Such effect is characteristic for cathodes with the increased delay of the beginning of explosive emission, in particular, is long time working (number of impulses $\geq 10^6$) [4]. Besides, formation of the explosive-emission centres on a foil is promoted by subsidence on its surface some particles of a cathode material, formed in the course of explosive emission. Therefore the choice of a material and cathode type can make appreciable impact on foil service life with other things being equal.

For the purpose of check of these assumptions comparative measurements for cathodes of two types – flat graphite and multispike cathode from a graphite fabric have been spent. It is known, that multispike cathodes have smaller delay time of explosive emission concerning the beginning of voltage growth on the diode [4]. In Fig. 2 dependences of a diode impedance on time with cathodes from graphite and a graphite fabric are resulted. Faster formation “explosive emission” plasmas at use multispike cathode from a graphite fabric leads to the best matching of the diode with a forming line. It explains the big duration of a flat part of the diode impedance curve within of the basic impulse.

![Fig. 1. Experiment scheme: 1 – flange of output windows; 2 – case of the vacuum chamber; 3 – vacuum seal; 4 – collector of the shunt of a return current; 5 – electrode of crowbar; 6 – explosive-emission cathode (Ø60 mm); 7 – cathode holder; $d_1$ – distance between the cathode and shunt collector; $d_2$ – distance between cathode and crowbar electrode](image1)

![Fig. 2. Change of a diode impedance during an impulse of accelerating voltage: 1 – multispike cathode from a graphite fabric; 2 – flat cathode from graphite](image2)
occurrence of mechanical stress, cracks and, finally, its destruction. The emergence of through holes with subsequent leaking of the diode in the derivation of the beam in the atmosphere or drift chamber with high pressure, occurs in this mode for 10 to 100 pulses.

In the first case erosion tracks density is significantly higher. Oscillograms reveal it obvious that more frequent occurrence of current pulses during the positive after-pulses with the following quick fall of the diode impedance.

Though the use of the carbon cloth cathode allows to reduce energy of the arc discharge in after-pulses, in the final analysis even relatively small erosion of the anode do not allow to reach guaranteed resistance of the anode foil within $10^3$–$10^4$ pulses. Therefore to reduce the influence of after-pulses on the destruction of the anode foil in the diode gap the additional electrode was injected in the shape of the thin conical ring from the stainless steel covering the exhaust window with the foil (pos. 5 in Fig. 1). This electrode together with the peripheral part of the cathode forms the protective diode gap parallel to the main one. During the pulse of the accelerating voltage on the ring falls the part of the electron flux emitted with the cathode periphery. Maximum electron current density is achieved on the thin edge directed to the cathode, where within the main pulse the anode plasma is formed. Within the after-pulses current in the diode flows only in the crowbar, at first in the form of the electron flux emitted from plasma formed on the edge, and then in plasma at its overlapping the gap. The shunt current flowing in the crowbar reduces the possibility of forming the cathode spots and arc discharges between the cathode and the anode foil. Fig. 5 represents the photos of the reverse current shunt collector surface before and after setting the protective electrode. The graphite cathode with the diameter of 60 mm was used, the gap from the electrode edge to the cathode ($d_2$, Fig. 1) was equal to the gap from the cathode to the collector ($d_1$, Fig. 1) and was 18 mm.

When substituting the graphite cathode with carbon cloth cathode, the lifetime of the anode foil under other similar conditions increased ten times and was $\sim 10^3$ pulses. Nevertheless, on the surface of the anode typical erosion tracks were recorded inherent in quickly moving vacuum arc cathode spots.

In Fig. 4 the photos of the erosion tracks are given on the anode using graphite as a cathode (Fig. 4, a) and the cloth from graphite threads (Fig. 4, b) made after 50 sequential pulses with frequency 1 Hz and for every case.

With the protective electrode, the anode foil sustained $10^5$ pulses without destruction and visible erosion tracks of its surface at frequency rate being 2 Hz.

Despite the other well-known solutions, such as setting the nets or grids in the form of extensive cells in front of the foil on the way of the beam, injecting the additional ring electrode impacts little the energy of the accelerating beam and do not bear hard on the
distribution of current density in cross-section. It is important to note that as a result of vacuum and plasma arc discharges in the crowbar there is no destruction of the working part of the cathode, because these processes cover only peripheral parts (edge and the lateral surface) of the cathode. This fact can be of crucial importance to provide the long steady operation of the installation without changing the cathode.

Conclusion
The research carried out shows that the main reason limiting the lifetime of the anode foil is formation of the cathode spots on it and the flow of current in the diode during the after-pulses of positive polarity following the main negative pulse of the accelerating voltage. Improvement of matching the diode with the forming line of the accelerator due to the use of the cathode with lesser time delay of explosive emission decreases energy in after-pulses and results in increasing the lifetime of the foil, but does not exclude its damage. Insertion of the additional anode electrode forming the second diode gap with the peripheral regions of the cathode, which is parallel to the main one, almost exclude the destruction of the anode foil and increases the resource of its operation up to $10^3$ pulses, and the losses of electron beam do not exceed 20%. In its essence it is the protective vacuum discharger-crowbar, where the flow of current reduces sharply the possibility of forming the cathode spots and plasma arc discharges between the cathode and anode foil.

References