Anomalous Energy Electrons of a Nanosecond e-Beam

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Performance of a sealed-off vacuum diode IMA3-150E, connected to a RADAN-220 generator of nanosecond pulses was investigated. Electrons with abnormal-high energies, exceeding the gap voltage, were registered in e-beam after a foil. It is shown that such anomalous energy electrons occur at the current pulse front, and beam current duration of such electrons is 200–450 ps at a half–height.

1. Introduction

The existence of the electrons with abnormal-high energies (above the gap voltage) in an electron beam formed in a vacuum diode has long been known [1]. The studies made before do not allow an uniquely interpretation of occurrence mechanism of such electrons (anomalous energy electrons) possessing the energies greater than they could possess due to the voltage applied to a vacuum diode. Many proposals were made with respect to the physical mechanism of this phenomenon. One of the first papers devoted to anomalous energy electrons recording [i] reports on an opportunity that electrons may acquire abnormal-high energies, being accelerated in electric fields. Such fields appeared at current redistribution in the process of pinching of vacuum discharge plasma filament, or in local electric fields occurred due to plasma filaments instabilities (constrictions or breaks). As a possible cause of high electric fields occurrence the internal instability of vacuum arcs, determined by cathode spot instabilities on metals was also named. In [2] the high voltages leading to appearance of anomalous energy electrons are related to the high values of *dI/dt* on total current interruption on unstable current pick-off.

In [3] anomalous energy electrons were recorded in a mode of unstable current pick-off. It was concluded that the limiting energy of anomalous energy electrons E_{lim} does not depend on voltage time (10^{-8}-10^{-7} s) and interelectrode spacing value (d=4-32 mm), being determined by the maximal energies of electrons in a beam (E_{max}=150-300 keV): for a multi-point cathode it is $E_{lim} \approx 3\ E_{max}$, and for a point cathode it is $E_{lim} \approx 2\ E_{max}$. In this paper it was also supposed that anomalous energy electrons might occur due to stochastic acceleration of electrons in cathode flare plasma in Langmuir turbulence stimulated by electron-drift instability.

In [4] anomalous energy electrons appeared on transportation of a subnanosecond e-beam in a drift chamber. Occurrence of such electrons is explained by self-acceleration of a part of electrons in the wave field of a volume charge, excited in a dense electron flow.

The majority of papers, discussing the issues related to anomalous energy electrons, were published several decades of years ago. Now available modern equipment makes it possible to do the more exact measurements with necessary subnanosecond resolution.

This work aims were to investigate performance of a sealed off vacuum diode IMA3-150E, and to record the time of appearance in e-beam of the electrons with anomalous energies. The parameters of an electron beam formed in IMA3-150E electron tube, connected to a nanosecond pulsed generator RADAN-220 were investigated before elsewhere [5, 6].

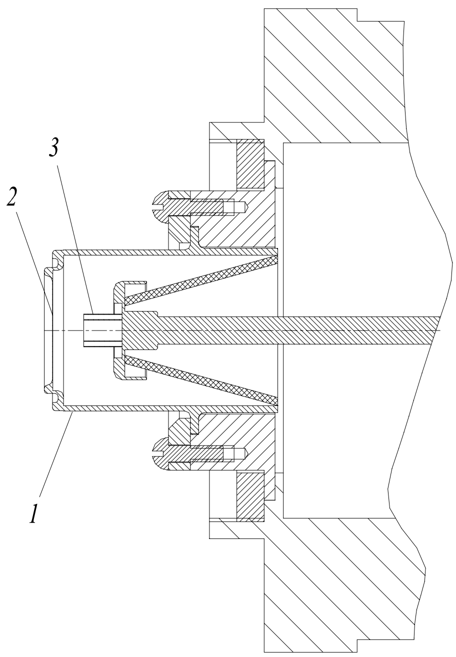

Fig. 1. Front view of RADAN-220 generator. *1* – electron tube IMA3-150E, *2* – Be window, *3* – cathode.

The current of an electron beam was measured by using current sensors. We used a 38-mm diameter disk electrode, connected to a low-resistance shunt (0.1 Ohm) and a 20-mm diameter collector loaded to 50-

Ohm cable. On the surface facing the foil the both sensors had triangular cuttings of ~1 mm in depth. Time resolution of the first sensor was no less than 0.2 ns, and that of the second sensor was 0.1 ns. A Tektronix TDS6604 oscilloscope with a 6-MHz passband was used to register the beam current.

The energy spectrum of an electron beam was defined through beam current reduction after passing through thin filters made of Al foils of different thickness.

3. Experimental results

The current waveform of an electron beam extracted from a vacuum diode through a Be-foil is shown in Fig. 2. It is seen that the beam current pulse consists from two pulses, and it is possible to distinguish in the first pulse two small peaks with different amplitudes. Since the first pulse had one order greater amplitude and energy of electrons, so, the data of investigation of this pulse are presented below. Second pulse occurs due to voltage pulse reflection from the vacuum diode, and further from the opposite end of generator [8, 9].

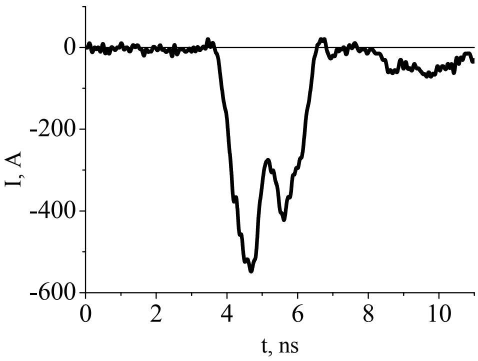

Fig. 2. The waveform for e-beam current.

In these experiments the maximal amplitude of the beam current was ~ 550 A, that is close to current amplitudes in [vii]. Earlier it was reported in [v, vi] that for these experimental conditions the beam current amplitude could be 0.8 and 0.9 kA, respectively. The difference in current amplitudes might be explained by the use of different assembles of RADAN-220 generators, different vacuum diodes IMA3-150E, as well as different collectors and registration methods.

The waveforms of e-beam current passed through a 3-mm diameter diaphragm, placed in the center of a

2. Experimental setup

As a source of a nanosecond e-beam we used in our experiments a small-sized high-current electron accelerator RADAN-220 [vi], which included IMA3-150E [7]. Figure 1 shows the front panel of the accelerator with an electron tube beam (thick line) and 4.5 mm distant from the center (thin line) are shown in Fig. 3. One can see from waveforms behavior that the beam current density redistributes with time. At the beam periphery the current amplitude decreases, and it increases somehow in its central part. It can occur as the effect of the cathode plasma expanding in vacuum diode anode direction.

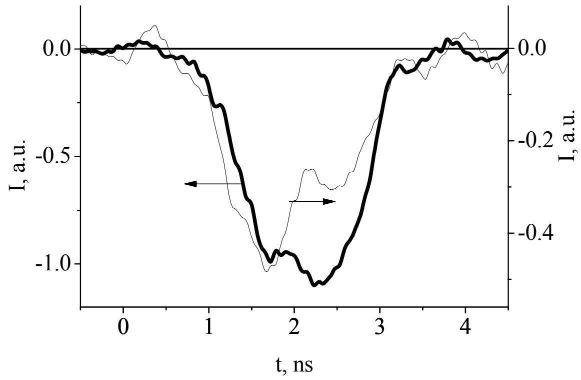

Fig. 3. Current waveforms of an electron beam passed through a 3-mm diameter diaphragm placed in the beam center (thick line) and 4.5 mm distant from the center (thin line).

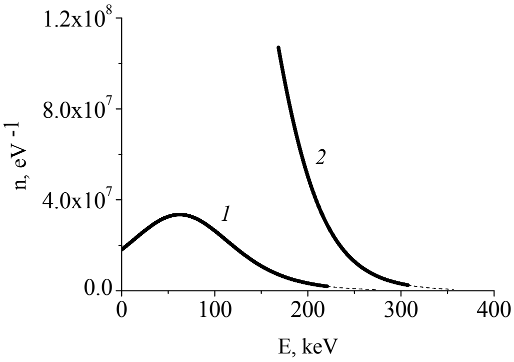

Fig. 4. E-beam energy spectrum. *1* – spectrum of e-beam extracted from a vacuum diode; *2* – spectrum of e-beam, taking into account that the beam passes 200 μm of Be-foil. Dashed line shows a part of spectrum for the electrons having the maximal energies in this area.

During these experiments, a spectrum of electrons passing through a Be-foil of a vacuum diode was measured. The experimental results are shown in Fig. 4. A spectrum, corresponding to the curve 1 in Fig. 4, represents by itself a spectrum of an electron beam extracted from a vacuum diode. It is seen that this spectrum has a maximum corresponding to the electron energy of ~ 63 keV. The spectrum, corresponding to the curve 2 in Fig. 4 was built taking into account that an electron beam is passing through a 200-μm Be-foil before it comes out from the diode. Absence of a maximum on the curve 2 is due to the great thickness of the diode Be-foil and its low transparency for the electrons having the energies below 250 keV [vi].

It should be noted that behind Al-foils of major thickness (>225 μm) the beam amplitude was instable from pulse to pulse, and in a number of cases the current was not recorded at all. That is why, on graphing distribution of electron energies, instead of the mean values of transmitted electric charge, we took its values for the current pulses with maximal amplitudes. The points corresponding to the major thickness of Al-foil are depicted on the curves of Fig. 4 as dashed lines.

It is known from [vi] that voltage applied to an electron tube is ~220 kV. That is why the electrons with the energies above 220 keV are considered to be the electrons with anomalously high energies (see Fig. 4, curve 2).

Distribution of the electron energy was also measured for the maximal amplitudes of beam current in the first and second parts of the pulse of beam current, see Figs. 2 and 3. Such spectra are depicted in Fig. 5 for the first (thick line) and the second (thin line) small peaks of a current pulse, as well as their summarized spectrum (dashed line). The spectrum of the second small peak disappears abruptly at electron energy value of ~105 keV, because with the high energy values, which require on taking a spectrum that e-beam shoot through Al-foils of major thickness, the second small peak disappeared. A maximum of the summarized spectrum corresponds to electron energy of ~ 68 keV, being almost identical to a maximum in Fig. 4, curve 1.

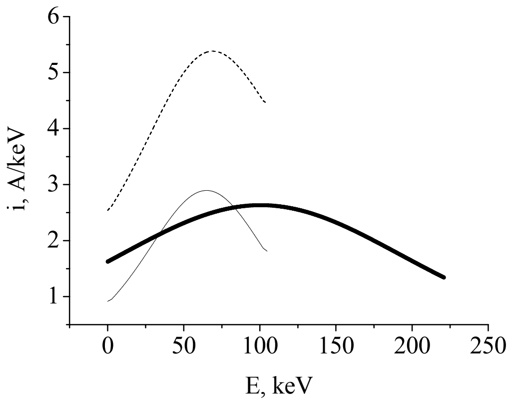

Fig. 5. Spectra for the first (thick line) and the second (thin line) small peaks of a current pulse, and their summarized spectrum (dashed line).

Figure 6 presents a current wave form for a beam, passed through a 320 μm thickness Al-filter, that corresponds to electron energy of ~ 260 keV.

In order to know a point of time when electrons with anomalously high energies (greater than the energies of the electrons, accelerated at the maximal voltage applied) are generated, an electron beam was extracted through a 100-μm thickness copper foil and the similar foil but with a hole of 3 mm in diameter made at the beam center. On passing through a solid copper foil the beam current was identical in its form to the current presented in Fig. 6. The current after passage through a copper foil with a hole is shown in Fig. 7, representing by itself current superposition, passed through a hole (see Fig. 3), and current of anomalous energy electrons, passed through the copper foil (see Fig. 6). It is seen that the electrons with anomalous energies occur at the front of a beam current pulse. Duration of anomalous energy electrons beam decreased from ~ 450 ps to ~200 ps (FWHM) with increasing of electrons energies. Remember that at the initial time there was no any small peak of current on waveforms of the beam current passed through a diaphragm of 3 mm in diameter, see Fig. 3.

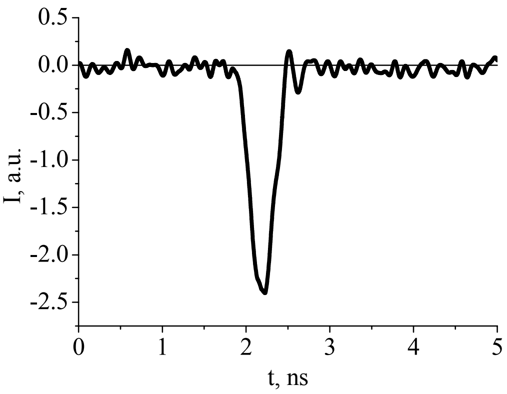

Fig. 6. The waveform of beam current, passed through Al-filter of 320 μm in thickness.

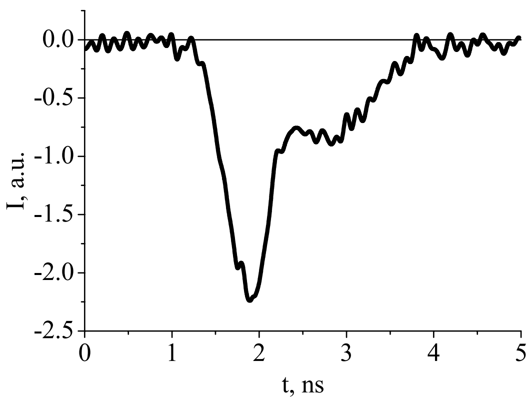

Fig. 7. E-beam current after it passed through a copper foil with a hole.

4. Conclusion

In this paper it is confirmed that except normal beam electrons a RADAN-220 generator with an electron tube IMA3-150E generates also the electrons with anomalously high energies. It is shown that anomalous energy electrons occur at the front of a beam current pulse, with pulse duration of 200-450 ps FWHM. Density of e-beam current is redistributed within a current pulse, decreasing more rapidly at the beam periphery than in the central part. The experimental data obtained during IMA3-150E performance might be useful in a number of applications, for example, at gas media excitation by an electron beam to get spontaneous and stimulated radiation [v, 10].

To clear up the cause of occurrence of anomalous energy electrons requires more additional studies, both experimental and theoretical ones. And, in our opinion, one should not relate appearance of electrons with anomalous energies to gap voltage increasing, for example, due to charging small capacity of interelectrode spacing. It is well known that an increase in voltage in a vacuum diode causes proportional increasing of the beam current amplitude. In these experiments duration of the current pulse of anomalous energy electrons was 200-450 ps FWHM (dependent on their energies), being negligibly changed from pulse to pulse. In compliance with that a peak of a voltage pulse might have almost identical duration leading to the essential increasing of amplitude of the beam current. However, the total beam current amplitude was almost unchanged, and amplitude of the beam current of anomalous energy electrons and their occurrence stability were different at different energies of electrons. With a foil thickness of ~ 250 μm, electrons with anomalous energies were recorded almost in every current pulse. With the foil thickness of ~ 320 μm, anomalous energy electrons were recorded on average one in ten of current pulses.

Apparently, additional acceleration of a small number of electrons up to the energies, above the gap voltage, is caused by the negative charge effect by the moving electron cloud. The similar mechanism of vacuum diode performance was reported in [iv], and that for gas diodes in [11, 12].

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