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Transport of an electron beam generated in a Plyutto—Luce diode through a vacuum channel

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The article discusses the results of an experimental study on the transport of a high-current electron beam generated in the Plyutto—Luce diode (27 kA, 270 kV, 90 ns) and transported via a 90 mm diameter vacuum channel at the pressure of $2 \cdot 10^{-4}$ Torr. The electron beam current was recorded at different distances (20–150 cm) from the diode system. There were detected a delay in the electron beam arrival, which depended on the distance to the diode, and a smooth decrease in the total charge transferred by the beam, which correlated with the delay time. The beam propagated over a distance of up to 150 cm; the beam with current significantly exceeding the limiting current in vacuum propagated over 55 cm.

Keywords: high-current electron beam, Plyutto—Luce diode, beam transport, limiting vacuum current, space charge compensation.

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A nanosecond-duration electron beam penetrating a local plasma structure is used for collective acceleration of ions. Such a system was for the first time used in the works of Plutto et al. [1]. Later the idea was developed in the studies of Luce et al. [2] where the plasma cloud was formed by using either a breakdown along the surface of the anode dielectric insert or gas injection [3]. A review of more recent studies may be found in [4]. The magnitude of electron current propagating in the vacuum chamber is limited by the electron-beam space charge [5] with formation of a virtual cathode localized near the diode system. At the same time, a number of experimental studies [3,5–9] have shown that, if the beam charge is properly compensated by ions, the electron beam propagates over a significant distance provided its current exceeds the limiting vacuum current (I_{lim}) in the working chamber. The space charge is compensated mainly by accelerated ions from the anode plasma and by residual gas ionization. Ionization is initiated both by the beam electrons slowing down in the virtual cathode field or oscillating between the virtual and real cathodes, and also by accelerated ions themselves. This compensation leads to the limiting current increase in the intermediate region and, hence, to virtual cathode displacement and electron beam propagation over a greater distance. At the same time, collective acceleration of ions by the virtual-cathode moving electric field is observed [7]. What is important is to establish linear losses of the electron beam charge during such a beam propagation in vacuum drift channels, since this determines collective ion acceleration in the Plutto—Luce diode. These are the issues this study was devoted to.

The experiments were conducted on accelerator TEMP-4 in the operating mode with an electronic diode similar to

that described in [8,9]. In the considered experiments with a pointed cathode and anode dielectric insert, accelerating voltage was 270 kV, half-height duration was 90 ns, and amplitude of the total diode current was 27 kA.

The beam diagnostic system consisted of two Rogowski coils, liquid voltage divider, and collector with cutting off low-energy electrons. The first of the coils was located in the diode space and measured total diode current (I_{diode}), the other was located on the side of vacuum chamber and measured the current injected into the chamber (I_{inj}). To cut off low-energy plasma electrons, aluminum foil $10 \mu\text{m}$ thick was placed in front of the collector.

Pay attention (Fig. 1) to the voltage spike at the leading edge of the accelerating voltage oscillogram and relatively high voltage rise rate approximately equal to $3.4 \cdot 10^{13}$ V/s. This is caused by that the generator works with the diode system in almost idle mode implying charging of the dielectric insert by beam electrons and actual cutoff of the diode. When the generator worked with a planar diode free of dielectric insert, this value was $0.5 \cdot 10^{13}$ V/s.

Later (in approximately 20–30 ns) there take place a surface breakdown of the dielectric insert, plasma bunch generation, and formation of electron beam now injected into the working chamber. The diode current increases at the rate of $\sim 5 \cdot 10^{12}$ A/s. The diode current generation delay relative to voltage is about 25 ns. Fig. 1 also presents oscillograms of the electron beam current measured by the collector at the distance of 40 cm from the anode, as well as the injected electron beam current. In this case, the vacuum channel diameter was 90 mm, residual gas pressure in both the diode and working chamber was $2 \cdot 10^{-4}$ Torr. This pressure was optimal for collective ion acceleration in this configuration of diode system [7].

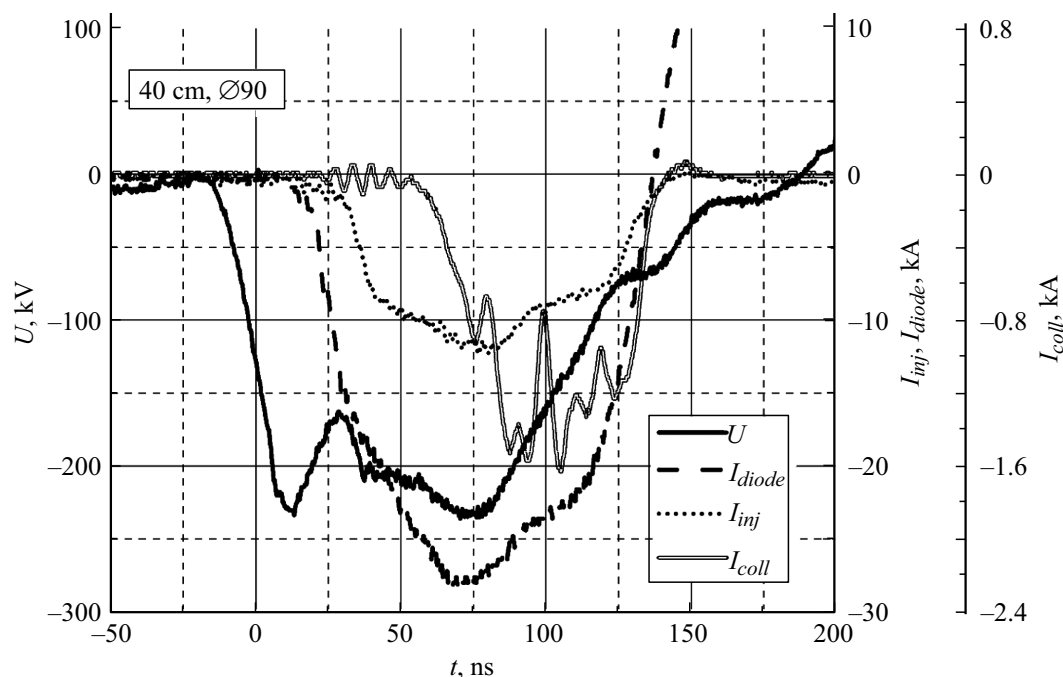


Figure 1. Oscillograms of accelerating voltage (U), diode current (I_{diode}), drift-tube inlet current (I_{inj}), and collector current (I_{coll}) at 40 cm from the anode plane.

When distance from the anode increases, a delay of the collector beam current and decrease in its amplitude are observed (Figs. 1 and 2). This may be explained by formation of a virtual cathode in the direction of electron beam propagation. Accelerated ions from anode plasma ionize the residual gas. An additional contribution to ionization is made by the oscillating beam electrons that slow down in the virtual cathode region thus increasing the ionization capacity of residual gas. As a result, a shift of the virtual cathode localized part and acceleration of ions in the moving electric field take place. Displacement of the virtual cathode along the electron beam propagation was previously revealed by installing magnetic field loops [5], transverse current collectors [7]. Further we have conducted experiments on the electron beam propagation in an elongated drift chamber 90 cm in diameter and up to 150 cm in length using the Plutto–Luce diode.

Fig. 2 presents the dependence of the collector electron beam current and total beam charge on the electron beam propagation distance (up to 150 cm). Each point is averaged over five dimensions. Efficiency of the beam charge propagation was estimated as a ratio of the detected collector charge to total charge of the beam injected into the vacuum chamber.

Fig. 2 shows that, at the distance of 150 cm from the Plutto–Luce diode, electron current $I_{coll} \approx 2.5$ A was detected, which corresponds to a charge equal to $2.5 \cdot 10^{-3}$ % of the injected charge.

The beam current and charge decrease monotonically with increasing distance according to the exponential law; at short distances, the collector current and charge decrease

at the same rates. However, at distances over 60 cm, the charge detected by the collector decreases faster than current, which indicates a reduction in the electron bunch length. This effect may be caused by the fact that at such distances the beam is more strongly affected by defocusing and absence of the decayed virtual cathode. The bunch loses density and has time to get conditionally divided into less extended groups of different-energy electrons. After that, only longitudinally short bunches having sufficient energy pass through the foil installed on the collector. Therefore, the charge is to be calculated as a current integral over a shorter time than in the case of less distances. It is important to note that the collector's readings and rate of their variation depend mainly on three factors: (i) time of bunch propagation that determines the current amplitude; (ii) Coulomb scattering of the beam with insufficient space-charge compensation; (iii) beam focusing. The rate of the electron beam current reduction is higher than that of the charge density determined by the electron beam divergence (Fig. 2).

We have confirmed the possibility of transferring current above 100 A for a distance of up to 150 cm and current exceeding the maximum vacuum current (570 A in the given vacuum channel geometry) for 55 cm. At all the distances, the electron beam was accompanied by an ion bunch, which was confirmed by detecting prompt gamma photons from the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction on a fluorine target. This fact confirms the interrelationship between the electron beam and ion bunch compensating it during their propagation over considerable distances.

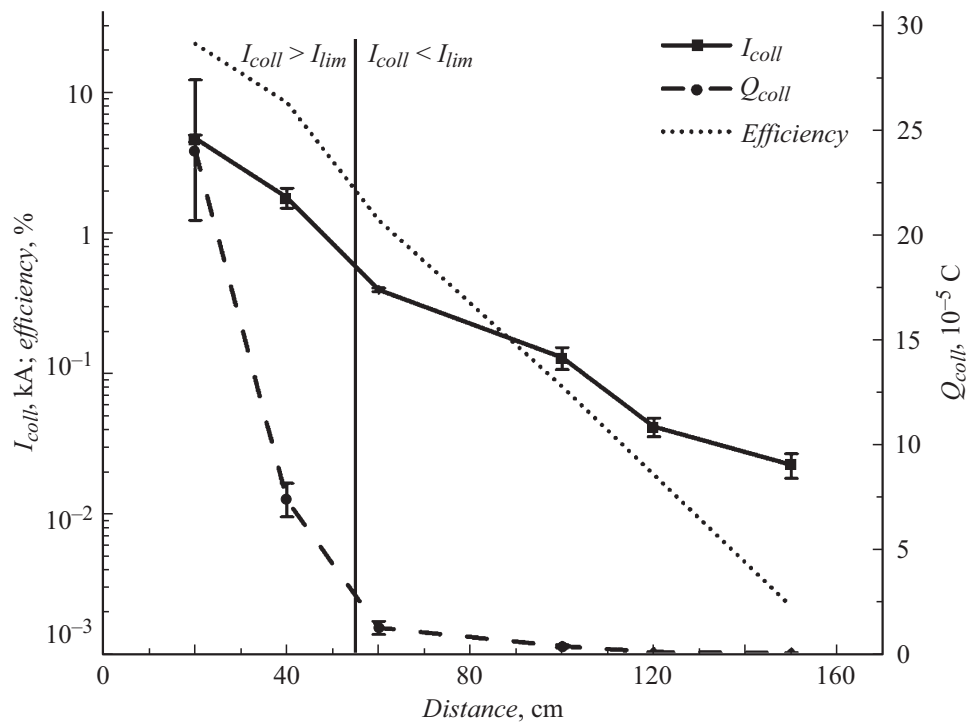


Figure 2. Distance dependences of collector current (I_{coll}), charge transferred by the beam (Q_{coll}) and transfer efficiency ($Efficiency$). The vertical axis separates the regions of transferring beams with above-limit current ($I_{coll} > I_{lim}$) and below-limit current ($I_{coll} < I_{lim}$).

The results of this study may be further used for the fundamental description and examination of dynamics of the virtual cathode and compensation of space charge of high-power pulsed beams. They may also be applied in practical tasks requiring reduction of target ablation by using diode plasma or supplying the target with high pulsed power. Examples of such tasks are elemental activation analysis of the sample surface or pumping other setups with high pulsed power.

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Conflict of interests

The authors declare that they have no conflict of interests.

References

- [1] A.A. Plyutto, K.V. Suladze, S.M. Temchin, E.D. Korop, *Sov. Atom. Energy*, **27** (5), 1197 (1969). DOI: 10.1007/BF01164972
- [2] J.S. Luce, H. Sahlin, N.R. Crites, *IEEE Trans. Nucl. Sci.*, **20**, 336 (1973). DOI: 10.1109/TNS.1973.4327115
- [3] W.W. Destler, P.G. O'Shea, Z. Segalov, *IEEE Trans. Nucl. Sci.*, **32** (5), 3481 (1985). DOI: 10.1109/TNS.1985.4334402
- [4] A.E. Dubinov, I.Yu. Kornilova, V.D. Selemir, *UFN*, **172** (11), 1225 (2002). (in Russian) DOI: 10.3367/UFNr.0172.200211a.1225 [A.E. Dubinov, I.Yu. Kornilova, V.D. Selemir, *Phys. Usp.*, **45** (11), 1109 (2002). DOI: 10.1070/PU2002v045n11ABEH001255].
- [5] C.N. Boyer, W.W. Destler, H. Kim, *IEEE Trans. Nucl. Sci.*, **24** (3), 1625 (1977). DOI: 10.1109/TNS.1977.4329031
- [6] A.L. Ipatov, G.P. Mkheidze, A.A. Savin, *Pis'ma v ZhTF*, **10** (11), 681 (1984). (in Russian)
- [7] V.A. Ryzhkov, I.N. Pyatkov, G.E. Remnev, *Nucl. Instrum. Meth. Phys. Res. A*, **1042**, 167436 (2022). DOI: 10.1016/j.nima.2022.167436
- [8] V.A. Ryzhkov, G.E. Remnev, I.N. Pyatkov, M.V. Zhuravlev, *Tech. Phys. Lett.*, **46** (4), 361 (2020). DOI: 10.1134/s1063785020040252
- [9] V.A. Ryzhkov, M.V. Zhuravlev, P. Glumac, G.E. Remnev, *Nucl. Instrum. Meth. Phys. Res. A*, **1080**, 170821 (2025). DOI: 10.1016/j.nima.2025.170821

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