Registration of over-accelerated electrons in a high-current picoseconds accelerator

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Abstract. A high-voltage ($U=280$ keV) high-current ($I=5$ kA) electron accelerator with a beam duration of 200 ps was investigated. The luminescent method showed that the beam diameter in the uniform pinching mode is about a micrometer, therewith the beam contains electrons with an energy exceeding 400 keV.

1. Introduction

Beams of high-energy electrons of subnanosecond duration are widely used for various applications. In particular, they are used to generate picosecond X-ray pulses, broadband optical pulses, powerful microwave and ultra-wideband radio-frequency signals, and supersonic pulses to study crystalline media [1-6]. In recent years, interest has also arisen in the use of ultrashort electron beams for pulsed radiolysis of short-lived radicals [7]. Finally, such beams of sufficiently large energy are used in problems of nuclear physics [8].

For a number of problems, the beams should be sufficiently intense and at the same time have a small diameter and an angular spread (i.e. small emittance). These requirements are contradictory, because a large space charge density leads to an expansion of the beam due to the action of the Coulomb forces. Earlier, the authors studied the parameters of an electron beam emitted by a high-current accelerator with an extremely high current and power rise rates [9, 10]. It was shown that at the beam duration of 200 ps the current was 5 kA, so that its rise rate reached $5 \times 10^{13}$ A/s. The electron energy in the mode of free expansion of the beam into the interelectrode gap was measured over the thickness of the stably colored layer of the LiF crystal [11] and was 280 keV, which coincided with the voltage across the accelerating gap.

By optimization the geometry of the electrode system and its matching with the parameters of the high-voltage generator, it was possible to achieve the effect of uniform pinching of the electron beam. The beam is extracted by a pulsed electric field from a flame of hot plasma, which is formed in the vicinity of the cathode tip due to the high rate of energy input into the discharge [10]. The upper estimate of the diameter of the pinched beam was obtained from the size of the erosion crater formed after a series of shots on the surface of the irradiated quartz crystal, and was less than 40 μm [12]. Therewith, substructures with a diameter on the order of a micrometer were observed in the crater. This indicates that the actual diameter of the pinched beam may be close to this value.

In these experiments, the phenomenon of capture and subsequent collective acceleration of multi charged ions of the cathode material by the electric field of the space charge of the pinched electron...
beam was also observed. The captured Tin+ ions of the cathode material were accelerated to an energy of ~ 10 MeV with a fluence at a pulse of 10^{17} ion/cm^2. This energy is approximately 30 times greater than the energy of electrons in the mode of free expansion of the beam, so that when the sapphire crystal (Al_2O_3) was irradiated, the Tin+ ions were effectively inserted into the lattice sites by impact, forming luminescent layers of Ti^{3+} of micron scale [12].

In this paper, estimates of the transverse size, as well as the electron energy during the operation of the accelerator in the mode of free expansion of the beam and in the mode of the pinched beam, were obtained using independent diagnostic methods.

2. Experimental details
The experiments are performed in a small-size electron accelerator [12], which is an essentially modified version of the previously used in [9, 10] (figure 1). The pulse of the high-voltage generator is applied to the needle cathode of a vacuum diode with an apex angle of about 1°. The cathode is made of a titanium rod with a diameter of 1.5 mm. As the anode, Ti foil 4 μm thick was used, which is part of an aluminum coaxial low-inductance vacuum chamber. At a distance \( d = 4 \) mm from the cathode tip, a sample is placed in vacuum chamber just in front of the anode foil. The residual pressure in the vacuum chamber is maintained at about 10^{-4} Torr. The increase in pressure to large values of the order of 10^{-3} Torr does not affect the experimental values.

The accelerator operating at a pulse repetition rate of 1–6 Hz is constructed on the basis of a hybrid sub-nanosecond high-voltage generator, which is designed according to the Tesla resonant generator circuit, where the output circuit capacitor is divided into two equal components C1 and C2, which are parts of a two-stage Marx generator. After the switching on of corresponding spark gaps, the low-inductance capacitors C1 and C2 form the shock capacitor, which loads the vacuum diode through the forming line. An effective power supply of the generator to the vacuum accelerating diode is achieved using special argon-hydrogen high-pressure (40 atm) spark gaps. Capacitors C1 and C2 are charged in parallel by the impulse voltage in a time of ~1 μs that increases the electrical strength of the insulating elements of the generator and spark gaps. This allows us to sharply reduce the overall dimensions of the generator (diameter 120 mm, length 350 mm), which led to a decrease in energy losses in both the skin layer, parasitic inductances and capacitances, and in the dynamic resistance of the discharge gaps. Due to this, it is possible to reduce the pulse length and, consequently, to increase the rate of current rise in the pulse. The impedance of the generator is about 30 Ohms.

Because of the extremely high energy density of the pinched electron beam, in this experiment ultrapure crystals of sapphire with an impurity concentration of ~10^{-7} wt%, possessing the relevant radiation resistance, are used to study the beam parameters. Spectral-optical measurements are performed with samples in the form plates (5×5×2 mm^3), cut from crystals.

The pulsed current of the electron beam is measured using a low-inductance Faraday cap. The synchronizing pulse is formed by means of a capacitive divider built into the vacuum diode chamber. The pulse energy of the electron beam is recorded by the calorimetric method. The pulse duration of the beam is measured by the duration of the cathodoluminescence pulse of the sapphire sample. A low-inertia (\( \tau < 10 \) ps) broad band (190-1100 nm) luminescence is recorded with a resolution of \( \leq 100 \) ps with a high-speed photocell FEK-15KM and a Tektronix TDS-6604B oscilloscope, the measured pulse duration is about 200 ps.

The transverse structure of the beam is determined from the structure of the photoluminescence (PL) area of the sapphire crystal irradiated by the beam. The luminescence is excited by the emission of a semiconductor laser with a wavelength of 450 nm and is observed with a binocular microscope, one eyepiece of which is conjugated to a color Levenhuk C1400 NJ14M CCD camera with a spatial resolution of 0.35 μm. The optical focusing system with precision piezoelectric drive allows scanning the luminescence area in depth with a resolution of about 0.5 μm.

The photoluminescence spectra are recorded with an ASP-100M 170-1100 nm fiber spectrometer (spectral resolution 1 nm). To study the kinetics of PL spectra, a spectral complex is used, in the excitation channel of which the second harmonic (440 nm) of a tunable femtosecond TIF-50 laser is
used. The luminescence spectrum at the output of the MDR-23 monochromator is recorded using a 31ELU-FM photomultiplier and a Tektronix TDS3032B oscilloscope with a spectral resolution of 0.05 nm and a time resolution of 1 ns.

Figure 1. Schematic diagram of the electron accelerator. (1) high-voltage power supply, (2) microcontroller, (3) picosecond high-voltage generator of the Marx-Tesla type, (4) cryostat with the sample. The insert shows the design of the accelerating diode: (5) titanium cathode, (6) anode, (7) sapphire substrate.

Figure 2a shows a photomicrograph of the surface of a sapphire crystal after irradiation with electron-ion beams in a series of 300 pulses with a repetition frequency of 1 Hz. It can be seen from the figure that luminescence, mainly in the red range of the optical spectrum, is recorded from an annular structure with a diameter of about 30 μm. At the same time, from figure 1b, where the cross-section along the depth of the irradiated region is depicted, it follows that as a result of irradiation an erosion crater with a depth of several tens of micrometers is formed on the crystal surface. The edge of the crater radiates in the red range of the spectrum, forming the above-mentioned ring structure, the central area of the crater radiates in the blue range of the spectrum, and in the center of the crater there is a channel with a diameter of the order of a micrometer, which luminesces in the green range of the spectrum.

To quantitatively analyze the results obtained, the spectrum of this radiation is measured. A broad photoluminescence (PL) band with a maximum at 780 nm, characteristic of Ti3+ ions embedded in the lattice sites of Al2O3 [13], is observed in the spectrum shown in figure 3. A blue line with a wavelength of 450 nm corresponds to the scattered laser radiation. The PL band at 560 nm in the green
spectral range is identified as the emission of defects (color centers) in sapphire, which are created by a beam with an electron energy of more than 400 keV [14].

The obtained results indicate that the diameter of the pinched beam does not exceed 1 μm. Taking into account that the electron charge in a beam is $10^{-6}$ C, and the beam length is ~ 5 cm, it is possible to estimate the electron density in the beam which exceeds $10^{19}$ cm$^{-3}$. We also emphasize that these results show the presence in the beam of electrons with energies exceeding 400 keV at an accelerating voltage of 280 kV.

![Figure 3](image-url)

**Figure 3.** Spatial structure of the luminescent area of a sapphire crystal after treatment with a high-energy electron-ion (Ti$^{n+}$) beam.

3. Discussion

Thus, using a sensitive optic diagnostic techniques, it is established that a significant fraction of electrons with an energy appreciably higher than the voltage across the discharge gap is present in a high-current picosecond electron-ion bunch being in a pinched mode. To explain this effect, we can assume the following scenario. The pinched electron beam is extracted from the hot titanium plasma flame localized near the cathode tip and accelerated by the cathode-anode electric field. Therewith, the electrons of the head part of the beam jointly accelerate the titanium ions due to the Coulomb interaction.

The subsequent electrons of the bunch are accelerated both by the electric field across the cathode-anode gap and by the field of accelerated ions flying in the front of the bunch. Such a hypothetical mutual acceleration of the plasma components in a dense electron-ion bunch through an ambipolar electric field is analogous to the mechanism of the wakefield acceleration, being widely studied in recent decades (see, for example, [15]). However, in order to elucidate a more detailed scenario of this “overacceleration,” further research is needed.

4. Conclusion

Thus, in this paper it is established that:

1. A picosecond electron accelerator emits a high-current electron-ion bunch, which in the pinched mode has a diameter on the order of a micrometer and a small angular spread (i.e., low emittance), the electron density in the beam exceeds $10^{19}$ cm$^{-3}$.

2. The energy of a significant part of the beam electrons in this mode is much higher than the voltage across the discharge gap, which indicates the presence of an effective additional accelerating mechanism.
Acknowledgments
This work was supported by the Russian Foundation for Basic Research (grant #17-02-00572).

References
[1] Mesyats G A and Yalandin M I 2005 Phys. Usp. 48 211
[2] Cook A M, Tikhoplov R, Tochitsky S Y, Travish G, Williams O B, and Rosenzweig J B 2009 Phys. Rev. Lett. 103 095003
[3] Adamo G, MacDonald K, FuY, Wang C-M, Tsai D, García F, deAbajo and Zheludev N 2009 Phys. Rev. Lett. 103 113901
[4] Bakunov M I, Tsarev M V, and Hangyo M Opt. Express 2009 17 9323
[5] Baryshnikov V I, Kolesnikova T A and Dorokhov S V 1997 Phys. Solid State 39 250
[6] Baryshnikov V I and Shipaev I V 2015 Bull. Russ. Acad. Sci. Phys. 79 198
[7] Bourdon J C, Garvey T, Le Duff J and Gaillard M 1998 Proc. 19th Int. Linear Accelerator Conf., Chicago 645
[8] ILC Technical Design Report, http://linearcollider.org.
[9] Baryshnikov V I and Paperny V L. 1995 Russ. Phys. Tech. Phys. Lett. 21 40
[10] Baryshnikov V I and Paperny V L 1995 J. Phys. D: Appl. Phys. 28 2519
[11] Martynovich E F, Baryshnikov V I and Grigorov V A 1985 Sov. Phys. Tech. Phys. Lett. 11 875
[12] Baryshnikov V I, Paperny V L and Shipaev I V 2017 J. Phys. D: Appl. Phys. 50 425206
[13] Pells G P and Phillips D C 1979 Radiation Journal of Nuclear Materials 80 207
[14] Baryshnikov V I and Kolesnikova T A 2005 Phys. Solid State 47 1847
[15] Rosenzweig J B, Cline D B, Cole B, Figueroa H, Gai W, Konecny R, Norem J, Schoessow P, and Simpson 1988 Phys. Rev. Lett. 61 98