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Formation of a picoseconds self-constricted beam of accelerated electrons in a high-current vacuum diode

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Abstract. A small-sized high-current electron beam accelerator with extremely short pulse duration has been developed. Correlation measurements showed that in the case of a needle cathode, the duration of the beam is ~1 ps. In this case, the diode emits a thin (≤2 μm) self-constricted electron beam with a current density of about 10^{12} A/cm^2. The electron energy is measured by the thickness of the colored layer in the irradiated LiF crystal and is more than 500 keV,

Keywords: high-current electron beam, extremely short pulse duration, self-constricted electron beam

1. Introduction

A very urgent task of modern accelerator physics is the creation of sources of electron beams of extremely short duration, of the order of a picoseconds and less than a picosecond. These radiation sources make it possible to obtain qualitatively new results in such areas as obtaining images of biological objects, developing new systems for diagnostics and radiation therapy of malignant tumors, precision study of the structure of substances and materials, and X-ray lithography. In addition, the development of technology for generating an electron beam of extremely short duration opens up wide opportunities in the development of new physical methods for accelerating charged particles, for example, under the influence of wake fields.

Currently, extensive researches are being carried out on sources of the electron bunches of picosecond and sub-picosecond duration based on modern installations of the “mega-science” type, for instance, the Novosibirsk Free Electron Laser, the linear accelerator LINAC-200 (JINR, Dubna), etc.

One of the most promising sources of ultrashort electron bunches is considered to be photoelectron sources, where the bunch is emitted by a photocathode as a result of irradiation with a relevant laser pulse [1].

However, such sources emit beams of electrons with a current of a few amperes. At the same time, some physical effects can manifest themselves only at a sufficiently high current of the electron beam, for example, the pinch effect, leading to the formation of an extremely high current density in the bunch and to a respectively high localization of the region of interaction of the beam with the target, which makes it possible to estimate transverse dimensions of the beam.

Thus, to develop relevant diagnostic techniques, it is necessary to elaborate small-sized sources of such beams. In addition, such sources are of specified interest, allowing in the laboratory to study the parameters of plasma bunches with extreme parameters (current density, particle concentration, etc.)

In the present work, we describe the design and principal parameters of a high-current source of an electron bunch with a duration close to a picosrcond and a current of the order of 10^2 of kiloamps.

2. Results and Discussion

A picosecond electron beam is originated by a two-stage electron accelerator [2]. The first stage is a nanosecond pulse voltage generator (PVG), based on a Tesla-Fitch hybrid circuit. In this circuit, the shock capacitor of the output circuit of the Tesla generator is divided into two identical components, which are charged in parallel to 140 kV in the first quarter of the oscillation period.

When the self-breakdown voltage of the single spark gap is reached, the oscillatory circuit of the Fitch generator is turned on. When the polarity of oscillations at the output of the PVG inverts, the voltage reaches 280 kV.

The second stage of the accelerator, which generates a picosecond discharge pulse, consists of a low-inductance coaxial capacitor, the inner plate which is a central copper internal electrode (6) in Fig. 1 mounted on a charging resistor R_p, and the outer plate is a coaxial housing of the discharge chamber. The cavity between the capacitor plates is filled with nitrogen at a pressure of 40 atm. The output electrode of the spark gap, which is also the cathode of the discharge gap, is vacuum-sealed in the separating isolator. A slicer with precisely adjustable gap formed by the central electrode of the coaxial capacitor (6) and an annular movable protrusion on the discharge chamber.

The discharge chamber is evacuated with a vacuum pump to a residual pressure of ~10^{-4} Torr and this accelerator could operate at a frequency of 12 Hz.

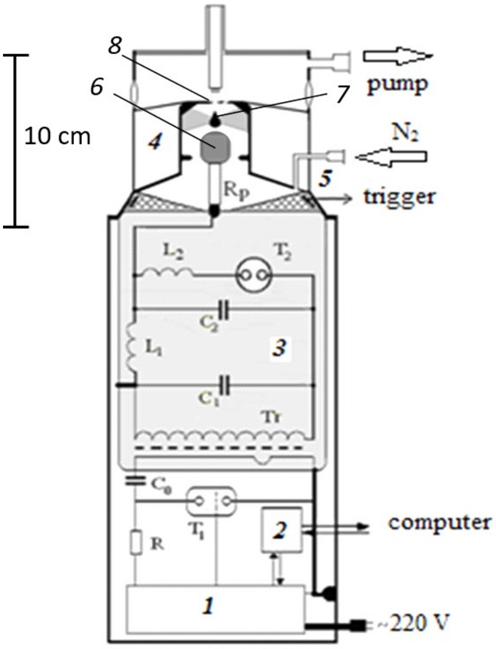

Fig. 1. Scheme of a picosecond electron accelerator: *1* – high-voltage power supply, *2* – microcontroller, *3* – nanosecond Tesla-Fitch pulser, *4* – picosecond pulser with an accelerating diode, *5* – first stage of a high voltage attenuator, *6* – inner plate of the coaxial capacitor, *7* – needle cathode, *8* – grid anode.

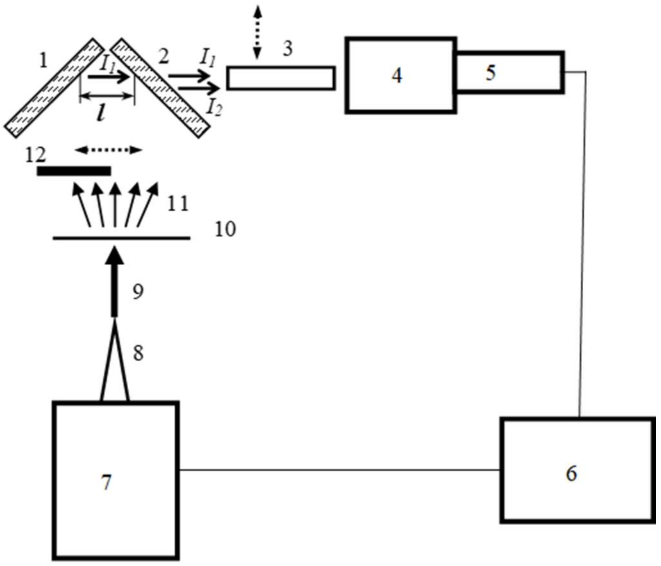

Fig. 2. Scheme of correlation measurements for estimating the electron beam duration: 1 – crystal-radiation source, 2 – crystal-source-gate of radiation, 3 – movable collimating tube, 4 – monochromator, 5 – photomultiplier tube, 6 – oscilloscope, 7 – electron accelerator, 8 – needle cathode, 9 – constricted electron beam, 10 – dissipative Al foil, 11 – scattered electron beam, 12 – movable lead shutter.

The capacitor of the picosecond pulser (6) is charged to a voltage of 280 kV. At this voltage, a sharpening spark gap breaks through to the cathode (7) of the accelerating diode, and after an adjustable time, a slicer spark gap breaks through. Thus, a picosecond pulse with a voltage of 280 kV is applied to the discharge gap, which forms an electron beam through this gap.

In this design of the accelerating diode, a needle-shaped Ti cathode with a sharpening angle of 8^0 was used. The use of such a cathode in a similar accelerator with the (sub)nanosecond duration of the electron beam showed that the cathode emitted an electron beam, which, under the action of the Ampere force, was compressed into a jet with a diameter of the order of a micrometer [3].

To avoid difficulties in the direct recording of the picosecond pulse of the discharge current *J*, we measured it in two stages. First, we measured the full charge of the electron beam per pulse $2\cdot10^{-7}$ C by a Faraday cup, which was placed behind the anode grid.

Then, the duration of the electron pulse τ was estimated by the correlation method by measuring the duration of the broadband 2p-valence cathode-luminescence (BCL) of a high-purity Al_2O_3 crystal excited by an electron beam. This method is based on the effect of electron beam-induced short-term self-absorption of a light pulse in an Al_2O_3 crystal [4].

In the optical scheme (Fig. 2), two identical Al_2O_3 crystals were used, the first one being used only as a BCL source with intensity I_1, and the second served as both a BCL source with intensity I_2 and a gate to cut off the radiation of the first crystal. To measure the radiation intensity of each crystal, they were irradiated in turn with an electron beam, while the other crystal was covered with a moveable lead shutter (12) in Fig. 2.

To measure the pulse duration, a wide beam is required that irradiates both crystals 1 and 2 simultaneously, so the emitted self-constricted electron beam was preliminarily scattered with an Al foil 100 µm thick (11).The light beams emitted by the crystals during their simultaneous irradiation with a scattered electron beam entered the detector with a delay $T = l/c$, (c is the speed of light) determined by the light beam path length l, which the beam emitted by crystal 1 passes between crystals 1 and 2. This length is specified by a position of the movable thin collimator tube (3). At a large length, when $T > \tau$, the detector recorded the full signal $I = I_1+I_2$. As the collimator is shifted upward in Fig.2, the path length l and, respectively, the delay between registered signals decreases. When the delay becomes less than the pulse duration, the pulses overlap, a part of the signal I_1 is absorbed by the gate, so that the amplitude of the recorded full signal I decreases. The minimum amplitude of the full signal corresponds to the complete overlap of light pulses emitted with both crystals.

In contrast to the previously used optical scheme [2], the disposition of Al_2O_3 crystals shown in Fig. 2. made it possible to reduce the length l to ~0.1 mm, which corresponds to the minimum recorded delay of signals from crystals 1 and 2 to 0.3 ps.

The measurements showed that, as l decreases to 3 mm, i.e. T was decreased to 10 ps, the signal I remained virtually unchanged; with T decreases to 2 ps, the signal decreased by a factor of 1.4; and when l decreases to 0.3 mm, i.e. T decrease to 1 ps, the signal decreased by 8 times (Fig.3). This means that, at $T \sim 1$ ps, the pulses of the emitter and the gate significantly overlapped, and this value can be considered as estimate of the electron beam duration τ, since the radiative time of 2p-valence luminescence in Al_2O_3 is less than 1 ps [5]. Thus, we can estimate the current of the emitted electron beam to be ~ 10^5 A.

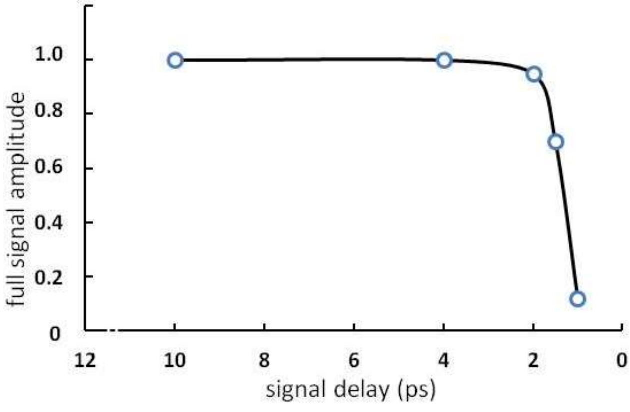

Fig. 3. Dependence of the full emission signal of crystals 1 and 2 (Fig. 2), normalized to the maximum value, on the delay between these signals.

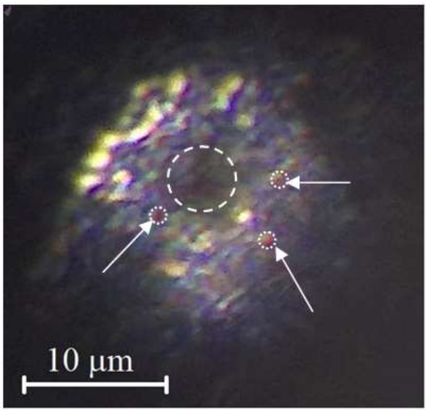

Fig. 4. Microphoto of the surface of a Al_2O_3 crystal, irradiated with 10 accelerator shots.

To establish the parameters of the emitted beam, the structure of the surface of an Al_2O_3 crystal irradiated with 10 shots was studied. Figure 4 shows a microphoto in the visible range of the irradiated region obtained during the irradiation process. Note that the observed pattern is due to the luminescence of the sample under the impact of a pulse of soft X-ray radiation (with energy <1 keV) from the micropinch plasma, previously observed under these experimental conditions [2].

The figure shows a central dark area with a diameter of about 4 μm, highlighted by a large dotted circle. This area of the most significant erosion of the sample surface under the impact of direct bombardment with an electron beam is similar to the corresponding area earlier observed under similar experimental conditions with an electron beam of longer duration [3]. There, an estimate of the diameter of the self-constricted electron beam was obtained ~1 μm based on the observed minimum size of the crater formed by the electron beam. This estimate does not contradict the picture shown in Fig. 4.

Moreover, in Fig. 4, red points indicated by arrows are also observed. These points correspond to luminescent Ti^{3+} ions, embedded in the Al_2O_3 matrix. These ions are ejected from the cathode, captured by the electric field of the space charge of the electron beam and accelerated to a sufficiently high energy.

Note that sapphire crystals are resistant to radiation with a threshold energy of defect formation in the cation subsystem of 380 keV for electron beams [6]. In our case, the expected maximum electron energy in the beam (280 keV) is below the threshold value. However, the energy of Ti^{n+} ions can substantially exceed the threshold energy of defect formation in the cation subsystem of the sapphire as a result of collective acceleration in the electric field of a constricted electron beam. In this case, titanium ions upon impact can replace regular Al^{3+} cations, as a result of which doping of the sapphire crystal with Ti^{3+} ions occurs.

Thus, in this experiment we observe an electron beam containing also ions of the cathode material, captured by the beam's space charge field and accelerated to energies significantly exceeding the voltage across the discharge gap. Wherein, ions moving outside the beam are recorded. A similar effect was previously observed by us under similar experimental conditions and was presumably associated with the Larmor rotation of ions in the intrinsic magnetic field of the beam current due to the presence of some ion radial velocity.

To quantitatively consider this effect, let us estimate the Larmor radius of ions r_L under these experimental conditions. Taking for a rough estimate the longitudinal velocity of ions corresponding to an energy of 400 keV and the magnetic field of the beam current $4 \cdot 10^3$ T at a radius of 5 μm, we obtain $r_L \sim 10^2$ μm. However, assuming the ion beam is sufficiently collimated, so that ion transverse velocity, at least an order of magnitude smaller than the longitudinal one, we obtain the estimate $r_L \sim 10$ μm, which is in reasonable agreement with the observed distance of the luminescent ions from the beam axis

Additional measurements of the energy of the electron beam emitted by the discharge over the thickness of the LiF crystal layer colored by the beam showed that the energy was ≤500 keV.

3. Conclusions

So, this paper describes the original method for estimating the pulse duration of an electron beam emitted by a small-sized electron accelerator. It is shown that the pulse duration is about 1 ps, the beam current reaches 10^5 A, and its diameter is about 1 μm. Measurements of the beam energy give a value of about 500 keV.

Ions of the cathode material Ti^{3+} were discovered moving outside the electron beam with an energy exceeding 380 keV. Estimates of the magnetic field of the beam suggest that the observed effect may be due to the Larmor rotation of ions of the cathode material, captured by the electric field of the space charge of the beam, in this magnetic field.

4. References

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