Investigation of the space-time stability of a large cross section electron beam generated by an accelerator with a grid plasma cathode

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Abstract. In an electron source with a grid plasma cathode on the basis of a low-pressure arc discharge, a study was made of the spatiotemporal stability of a pulsed-periodic beam of a large cross section (750×150) mm², outputted into the atmosphere through an outlet foil window. The research was carried out using an automated system that allows real-time measurements with the ability to visualize the data on the computer. This system allows to ensure the accuracy of measurements no worse than ±2% and differs from the known analogues in compactness, reliability and simplicity of design. The use of this system made it possible to investigate the distribution of the current density over the beam cross-section in a wide range of its parameters, such as beam energy, beam current, and beam current pulse duration. A satisfactory agreement between past and present experimental data is shown. The use of this system for measuring the current density distribution along the beam cross section makes it possible to substantially increase the accuracy of the design of the scientific experiment, and, consequently, the speed of debugging and the repeatability of the technological process.

1. Introduction
Accelerators that generate large-cross section electron beam (LCSEB) are oriented toward solving a wide range of problems [1-3]. Regardless of the principle of the electron source, there are a number of basic parameters of the LCSEB, including the inhomogeneity of the current density distribution over the beam cross section [1]. In each individual case, considerable effort must be made to reduce this parameter, since even small local inhomogeneities in the current density along the LCSEB in a number of applications can be unacceptable [4].

One way to estimate the distribution of the current density over the beam cross section is to analyze its autograph obtained on a polymer film [5]. However, the main disadvantage of this method of measurement is the impossibility of promptly obtaining quantitative data, since the transparency of the film after irradiation continues to change for tens of hours.

For the reduction of time to obtain quantitative data for example, in [6] a probe system consisting of 24 probes uniformly located over a collector area of 350 mm in diameter was used. Each of the probes, fixing part of the beam current, was electrically connected to the capacitor which were memory cells. Reading system was performed at the relay and the stepping switch which was connected to an alternately capacitor for measuring. The use of such a system has reduced the time of
the survey and data collection up to 1 min. At the same time, another technical solution was proposed [7], based on the use of electronic components in the design of the measurement system, where signals from 108 sensors were registered with an intermediate memory in 2.7 seconds. However, when it comes to measuring the parameters of the microsecond-submillisecond pulse-periodic LCSEB, the use of measurement systems with such a long time response is of little promise.

After several decades, the use of microprocessor technology allowed the creation of a system for measuring the distribution of current density in real time with a relative accuracy of measurements no worse than 2%, also based on a survey of sensors that are Faraday cylinders connected in series with capacitors [4]. This system allowed not only to survey 48 sensors during a time from 2.5 ms to 30 s, but also to transmit the received data to a personal computer via fiber-optic communication channels, and then present this data in the form of a digital table and graphic image (histogram on the monitor screen) changing in time. At that, only every fourth measurement of the distribution was viewed in real time. The disadvantages of such a system include the complexity of its creation and tuning, as well as the relatively low operation speed associated with the slow speed of data exchange with a personal computer (PC).

The most modern from the point of view of the element base is the measurement system [8] designed to measure the current density distribution of a completed pulse corona discharge. This system executed on a high-speed 32-bit microcontroller (MC) also allows visualizing the received data and surveying 64 sensors at the time of one channel survey not exceeding 1 μs. At the same time, for survey of all sensors it is required to introduce additional time delays related to the speed of analog multiplexers. Also, the system requires fine tuning of individual units during the setup stage of the device and has a rather complex scheme for switching the measurement modes, which can complicate its operation. Using appropriate sensors this system can be used to measure the current density distribution of LCSEB, however, no direct experiments in this direction have been carried out.

The task was set to develop and create a fast-acting system for measuring the current density distribution over LCSEB that was outputted into the atmosphere. To demonstrate the possibilities, their expansion, and adaptation of the developed measurement system to a specific electron accelerator, the accelerator [9] with a grid plasma cathode was chosen as the main object of research. The use of layer stabilization of the emission plasma boundary makes it possible to generate beams with parameters (electron energy, beam current in the accelerating gap, duration and repetition frequency of beam pulses), which have a weak dependence on each other over a relatively wide range [9-12]. To accomplish such a task, no special efforts were taken in the accelerator to reduce the beam inhomogeneity, although in a number of works [11-13] it was shown that when working with such electron accelerators there are several fairly simple methods for reducing the beam inhomogeneity.

2. Experimental procedure

Figure 1 shows a simplified schematic of the electron accelerator [9]. Plasma cathode 2 is a hollow semi-cylinder at the faces of which there are two cathode units. The inner surface of the semi-cylinder serves as hollow anode 7 common to two cathode units. Emission grid 5 has overall dimensions of 750×150 mm. It is covered with stainless steel mask 6 which breaks the emission surface into 344 meshes of diameter 12 mm as individual emission structures of the plasma cathode. For electron extraction through the grid meshes, a dc accelerating voltage of up to $U_0=200$ kV is applied between the cathode and an output foil window consisting of support grid 8 and output foil 9 (AMg-2n alloy) with a thickness of 30 µm. The support grid having a total geometric transparency of 56%, contains the same number of holes as in mask 6 but of larger diameter equal to 15 mm. Thus, the electron beam is the superposition of beams formed by individual emission structures whose plasma boundary is stabilized by a fine metal grid. The use of the multi-aperture two-electrode electron-optical system makes it possible to substantially increase the efficiency of the electron beam output from the vacuum to the atmosphere, and also to increase the stability of the electron accelerator [14], but the design of the support grid includes water-cooled sections that divide this LCSEB into 8 beams of a smaller area, which substantially worsens the beam distribution along its cross section.
Under each of the eight sectors of the output foil window, eight sensors of the measuring system were installed, which are collector plates $13$ of stainless steel with a size of $5 \times 5$ cm each, in the chain of which capacitors $15 \ C=2.2 \ \mu F \ (\pm 2\%)$ are installed. It is known [15] that in the energy range of the beam tens to hundreds of keV, the fraction of electrons reflected from the collector surface depends weak on the beam energy and is determined mainly by the atomic number of the material from which the collector is made. The reflection of electrons from the plates can be neglected for a relative measurement of the beam current density distribution because all the collector plates $13$ are made of the same material. It is important to note here that, since the electron beam is outputted in the ambient atmosphere, a plasma is generated in the air and the charge leaves the ground and such current leakage can also be effected through grounded collector plates, which can substantially distort measurement results. To reduce the probability of such leaks, all collector plates are placed behind a grounded metal shield $14$ (figure 1), in which $8$ holes of $4 \times 4$ cm, coaxial collector plates, are made. To fix the total current to the "ground" from all collector plates in the "earth" circuit, Rogowski's coil is installed, which allows to determine the total current $\Sigma I_N$ through all the measurement sensors. In addition, all the main components of the measurement system are also located in a grounded steel casing, which is necessary to reduce the influence of electrical interference on the operation of the device.

A block diagram of the developed measurement system is shown in figure 2. Such system can be conditionally divided into three blocks:

- measuring unit (MU) (set of collector plates-sensors), intended for fixing a part of the current of the LCSEB;
- primary data acquisition and processing unit (PDAPU), in which external synchronization of the start of the beam current pulse is made, coinciding with the ignition current pulse (initiation of the cathode spot), with the moment of starting the main program of the measurement system, where measuring capacitors and sending the received information to the PC via fiber optic communication channels;
- the PC required to visualize the real-time distribution of the current density of the LCSEB.

In the measuring channel of the system, the signal from the capacitor is fed to a resistive voltage divider made using a trimmer resistor $R=10 \ k\Omega$ (bourns 3266W-1-103LF), which lowers the signal level to the input level of the microcontroller's analog-to-digital converter (ADC). Also, using of a potentiometer allows to calibrate the measuring channel.

The system provides for the possibility of measuring signals of both positive and negative polarity. The measurement mode is changed by means of VT1 and VT2 transistors (IRF8313PbF). To measure
signals of positive polarity, for example, when studying the distribution of an ion beam (experimentally not tested, but incorporated into the design of the developed measurement system), between transistor current pulses, the VT2 transistor is in a closed state, which is necessary to discharge the measuring capacitor. The VT1 transistor in this case is in the open state. In the case of measurement of negative polarity signals, the measuring capacitor is charged through the VT1 transistor to a voltage of +15V before measuring current. To charge all capacitors, a common source of stabilized voltage (SSV) is used. In this case the VT2 transistor is in the open state. Switching modes is carried out by the program from the PC. When an external synchronization pulse appears, both transistors open before the end of the current pulse and the ADC conversion is completed.

Figure 2. Block diagram of the developed measurement system: MU – measuring unit; S – sensors; PDAPU – unit for the collection and processing of primary data; MCH – measuring channel; CB – control bus; MC – microcontroller; ADC – analog-to-digital converters; SU – synchronization unit; USART – universal asynchronous transceiver; SSV – source of stabilized voltage; OC – optical converter; PC – personal computer.

The signal from the output of the resistive divider of the measuring channel is fed to the input of the ADC of the microcontroller (ATXmega128a1u). The architecture of this MC includes two four-channel 12-bit ADCs, which allows to survey all 8 sensors for \( \approx 2 \mu s \) at a clock frequency of 32 MHz. 8 KBytes of SRAM and 128 KB of FLASH make it possible to operate the system both in single pulse mode and in pulse-frequency mode with the accumulation of measurements of the current density distribution of LCSEB. The presence of the direct memory access and system events allowed to carry out a simultaneous operation of both the ADC, set the delay time of the beginning of the transformation from the appearance of the synchronization pulse with an accuracy of 100 ns, the opening VT1 and VT2 transistors for a time not exceeding 100 ns and writing data to the memory of the MC without the participation of the central processor.

For communication with the PC and synchronization unit, optical converter boards were designed and manufactured. For synchronization, the receiver was connected to the input of the event system. When a synchronization pulse appeared, a timer was started, which provided a delay in starting the conversion of the ADC, which was triggered by the event generated by this timer. Communication with the synchronization source and the PC was carried out over the optical fiber. To transfer data from the side of the MC the USART was used in asynchronous mode. On the PC side the connection was made via a USB interface, via a USB-UART interface converter (SiLabs cp2102) with further conversion to an optical signal. The limiting bandwidth of this system is 1 Mbaud. Each ADC channel was calibrated using an external reference voltage source (REF192ESZ). The zero offset was calculated with the closed VT2 transistor, the maximum measured voltage with closed VT1 transistor.
A typical demonstration of the real-time visualization of the beam current density distribution along its long side is shown in figure 3.

![Diagram](image)

**Figure 3.** Demonstration of visualization in real time of the beam current density distribution along its long side (Q – charge, N – censor’s number).

### 3. Results and discussion

Using the developed measurement system, it was shown that the qualitative picture of the distribution of the current density over the LCSEB remains unchanged with increasing amplitude (figure 4a) or the beam current pulse duration (figure 4b), and its character repeats the results obtained in [9, 10, 14]. In spite of the fact that such a method of diagnostics of the plasma cathode operation is indirect, using the obtained data it is possible to assert the stability of arc discharge burning in the plasma cathode space during the beam pulse.

![Graph](image)

**Figure 4.** Distribution of the current density over the beam cross section at different currents in the accelerating gap (a) and for different pulse widths (b). $U_0=160$ kV.

From the distributions of the current density shown in figure 5a it can be seen that when the beam energy decreases the output of the beam current in the atmosphere decreases, which is associated with an increase in beam current losses in the output foil [16]; however, the qualitative picture of the distribution also remains unchanged, i.e. the nature of the change in the beam current density
distribution depends weakly on its energy. However, from the distributions in figure 5b can be seen that as the distance from the collector plates to the outlet foil window increases, the inhomogeneity of the current density distribution along the beam cross section decreases, which is most likely due to the interaction of the electron beam with atmospheric pressure air, which leads to a change in both the energy and angular distribution of the electrons [17, 18].

![Graph](image)

**Figure 5.** Distribution of the current density along the beam cross section as a function of the beam energy (a) and from the distance from the collector to the output foil window (b). $U_0=160$ kV.

The coincidence in the form of the current $\Sigma I_N$ and the current $I_0$, presented on the oscillogram (figure 6), confirms the absence of any non-self-sustaining discharge of the measuring capacitors, which indicates the reliability and correctness of the method used to measure the current density distribution over the LCSEB.

![Oscillogram](image)

**Figure 6.** Characteristic oscillogram of the current in the accelerating gap $I_0$ (20 A/cl.) and current $\Sigma I_N$ (0.25 A/cl.). Duration scan 25 $\mu$s/div.

4. Conclusion

The conducted studies of the distribution of current density over the LCSEB allowed us to conclude about the stability of the operation of a grid plasma cathode, consisting in the constancy of the spatial and temporal characteristics of the low-pressure arc discharge burning at pulse duration up to 100 $\mu$s.
The measurement system allows rapid diagnostics of beam current density distribution with high measurement accuracy (<2%), which is extremely important not only for scientific but also for technological purposes when installing an electron accelerator in a production line.

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References
[1] Bugaev S P, Kreindel Yu E and Schanin P M 1984 Large section electron beams (Moscow, EAI) 112 p (in Russian)
[2] Sokovnin S Yu 2007 Nanosecond electron accelerators and radiation technologies based on them (Yekaterinburg, UD RAS) 224 p (in Russian)
[3] Rostov V V, Alekseenko P I, Vygodtsiev P V, Shteinle A V, Mazin V I, et. al. 2012 Siberian medical journal 27 141
[4] Abroyan M A, Kosogorov S L, Nabokova I V, Uspenskii N A, Chemichev V A, Shapiro V B and Shvedyuk V Ya 2007 Instr. and Exper. Techn. 50 530
[5] Kondratyev E A, Pismennyy V D, Rahimov A G and Saenko V B 1979 Application of charged particles accelerators in the national economy: Proc. III All-Union Conference. Leningrad. 3 203 (in Russian)
[6] Koval N N and Ovysannikov V I 1977 Proc. of the regional scientific and practical conference "Young Scientists and Specialists - to the National Economy" Tomsk 32
[7] Kochenkov V A, Mikhaillov V I, Naek S V, Porkhun A I, Skorobogat S L and Silvko V N 1977 Prib. Tech. Exp. 2 139
[8] Ponomarev A V, Pedos M S, Mamontov U I, Gusev A I and Scherbinin S V 2015 Instr. and Exper. Techn. 58 499
[9] Vorobyov M S, Koval N N, and Sulakshin S A 2015 Instr. and Exper. Techn. 58 687
[10] Gielkens S W A, Peters P J M, Witteman W J, Borovikov P V, et. al. 1996 Rev. Sci. Instr. 67 2449
[11] Schanin P M, Koval N N, Tolkachev V S, Gushenets V I 2000 Russian Phys. J. 43 427
[12] Koval N N, Kreindel Yu E, Tolkachev V S and Schanin P M 1985 IEEE Trans. Electr. Insul. EI-20 735
[13] Vorobyev M S and Koval N N 2016 Tech. Phys. Let. 42 574
[14] Vorobyov M S, Koval N N, Sulakshin S A and Shugurov V V 2015 IOP J. of Phys.: Conf. Series. 652 012048
[15] Archard G D 1961 J. of Applied Phys. 32 1505
[16] Seltser S M and Berger M J 1974 Nucl. Instrum. and Methods. 119 157
[17] Grigoryev Yu V and Shanturin L P 1979 Prib. Tekh. Eksp. 4 194 (In Russian)
[18] Kozyrev A V, Kozhevnikov V Yu, Vorobyov M S, Bakshet E Kh, Burachenko A G, Koval N N and Tarasenko V F 2015 Las. & Part. Beams. 33 183