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Pulse current compression of high-current relativistic electron beam on a virtual cathode

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The limit transport current of a high-current relativistic electron beam (REB) in a strong magnetic field in a coaxial liner with the potential of the central electrode equal to the potential of the cathode forming the REB has been analytically calculated. The conditions for the virtual cathode formation in a coaxial diode with magnetic insulation and a double cathode, in which the diameter of the inner conductor changes along its length, have been found. The phenomenon of temporal compression of the REB current has been experimentally demonstrated. The current amplitude increase by 1.5–2 times with pulse duration decrease from 2.5 ns to ~1 ns is due to the appearance of the virtual cathode. The directions for further study of the REB dynamics, its temporal and energy parameters contributing to the virtual cathode formation and, as a result, temporal compression of the REB, have been outlined.

Keywords: Explosive emission cathode, high-current electron beam, virtual cathode, nanosecond pulse, magnetic field.

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Introduction

For the generation of high-current relativistic electron beams (REBs) in direct-action accelerators at electron energies on the order of 10^6 eV and beam currents of $\sim 10^3$ A and above, explosive-emission cathodes are used. The current magnitude in this case is limited not by the emission capability of the cathode, but by the REB potential, which is determined by the shape of the electrodes and the electron flow. At a fixed initial electron energy, as the current increases, the electron flow potential rises and, under certain conditions, reaches that of the cathode voltage, while the electron velocity drops practically to zero. Such an electron cloud with the cathode potential and zero particle velocity has been termed a virtual cathode (VC).

Virtual cathodes, which are of great interest for ion acceleration, the generation of strong electromagnetic waves (in particular, the vircator – a microwave radiation generator based on a VC), and for a number of other applications, have been studied for many years in various configurations. For many purposes, REBs are formed in a strong magnetic field as a tubular-shaped electron flow; therefore, a significant part of VC research has been conducted specifically in this configuration. In the present work, we will also restrict ourselves to the axially symmetric case of forming a tubular REB and transporting it in a strong solenoidal magnetic field within a circular cross-section vacuum chamber with conducting walls – in a hollow metal pipe.

It was shown in [1] that, for a fixed radius r_b of a thin-walled tubular REB propagating along

the axis of the chamber with radius R , its current cannot exceed the limiting value I_{lim} :

$$I_{lim} = I_0 \frac{\left(\Gamma^{2/3} - 1\right)^{3/2}}{2 \ln \frac{R}{r_b}}. \quad (1)$$

Here, the current is $I_0 = \frac{4\pi\epsilon_0 mc^3}{e} \approx 17 \text{ kA}$,

and the factor Γ is determined by the potential difference U in the accelerator diode:

$$\Gamma = 1 + \frac{eU}{mc^2}, \quad (2)$$

where the value is $\frac{mc^2}{e} \approx 511 \text{ kV}$.

The relativistic factor $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$,

which depends on the electron velocity v , for the current I_{lim} is equal to $\gamma = \Gamma^{1/3}$. The potential of the electron flow is determined by the difference between the total and kinetic energies:

$$\Phi = (\Gamma - \gamma) \frac{mc^2}{e} = U - (\gamma - 1) \frac{mc^2}{e}. \quad (3)$$

When attempting to inject a current exceeding the I_{lim} value, the electron beam transitions to an unstable “compressed” state [2], in which $\gamma < \Gamma^{1/3}$, and which rapidly collapses toward $\gamma \rightarrow 1$, turning into a VC. The current flowing from the VC remains equal to I_{lim} on average [3], but becomes non-stationary, and two main frequency groups prevail in the oscillation spectrum. The so-called “transit-time” frequencies are determined by the motion time of electrons trapped between two equipotential regions: the accelerator cathode and the VC. The second frequency group is the Langmuir frequencies of the electron cloud $\omega_{Le} = \sqrt{\frac{4\pi ne^2}{m}}$ with a concentration n that varies in time and space.

The most common method of creating a VC using a REB propagating in a strong magnetic field is its injection into a chamber with a variable

radius. It is seen from formula (1) that as the chamber diameter R increases, the limiting current I_{lim} decreases. Therefore, the REB is injected into a chamber with a small radius, where its current does not exceed the limiting value. Further, as the REB propagates in a uniform magnetic field, the chamber expands so that the I_{lim} value falls below the current value, and then a VC is formed in the transition region from the smaller to the larger radius.

The described configuration is not the only possible one for creating a VC. Our preliminary calculations [4] showed that, with a certain electrode configuration and a REB pulse duration of up to several nanoseconds, the forming VC first impedes the passage of electrons through it, and then rapidly releases the accumulated charge. Thereby, the REB current pulse duration decreases, while its amplitude increases.

The purpose of the present work was the experimental demonstration of the phenomenon of current increase in a nanosecond relativistic electron beam upon shortening of the REB pulse duration the REB pulse shortening, which can be called electron beam current pulse compression or, more concisely, temporal compression of an electron beam. In the present work, experimental studies of the transport of an REB formed in a strong magnetic field through a VC region in the previously proposed configuration [4] were carried out, as well as analytical estimations of the conditions required for this. The configuration [4] makes it easy to experimentally implement the variation of the limiting transport current I_{lim} while keeping the parameters of the REB formed at the cathode constant, as well as keeping the VC location in the same liner cross-section while maintaining the configuration of its outer walls unchanged.

Analytical calculations

The method of REB formation and virtual cathode generation is shown in Fig. 1. The entire structure possesses axial symmetry and is placed in a strong uniform magnetic field. In Fig. 1, a cathode **2** with infinite emission capability at its emitting edge with radius r_c is placed inside a cylindrical chamber **1** with radius R . A cylinder **4** with radius r is fixed on the cathode by means of

a holder rod **3** with radius r_s . Pipe **1**, which acts as the anode, is grounded, while cathode **2**, rod **3**, and cylinder **4** constitute a single conducting structure held at the same negative potential U . In a strong uniform magnetic field, the radius of the tubular relativistic electron beam **5** coincides with the radius of the cathode edge: $r_b = r_c$.

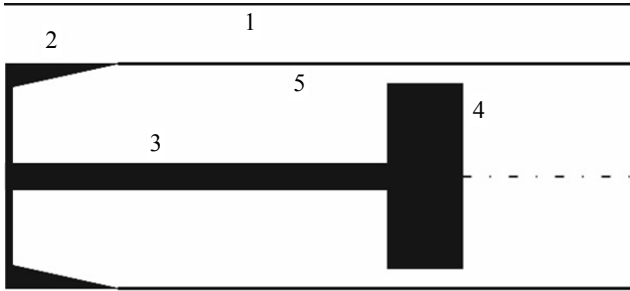


Fig. 1. Diode with a virtual cathode: 1 – cylindrical chamber (anode), 2 – explosive-emission cathode edge, 3 – rod, 4 – cylinder, 5 – REB trajectory

In [5], the current of an external cathode formed in a magnetically insulated coaxial diode with a double cathode, which corresponds to electrodes **2** and **3** in Fig. 1, was calculated. The current from cathode **2** in the presence of the long conducting rod **3**, which is equipotential to it, but without taking cylinder **4** into account, is equal to

$$I_N = \frac{I_0}{2 \ln \frac{R}{r_s}} \left[\frac{\Gamma - \gamma}{1 - \varkappa} - \frac{\gamma - 1}{\varkappa} \right] \sqrt{1 - \frac{1}{\gamma^2}}, \quad (4)$$

where

$$\gamma = \frac{3}{2} \sqrt{1 + \frac{8}{9} \varkappa (\Gamma - 1)} - \frac{1}{2}, \quad 0 < \varkappa = \frac{\ln \left(\frac{r_b}{r_s} \right)}{\ln \left(\frac{R}{r_s} \right)} < 1,$$

the index N indicates the first author of paper [5], and the beam potential is determined by formula (3).

For $r_s \rightarrow 0$ ($\varkappa \rightarrow 1$), the electron beam current according to formula (4) and the factor determining the potential Φ according to formula (3) take the corresponding values of the Fedosov current I_F [6] and the factor γ of a tubular REB formed by a magnetically insulated coaxial diode in a hollow circular waveguide:

$$I_F = I_0 \frac{1}{2 \ln \frac{R}{r_b}} \frac{(\Gamma - \gamma) \sqrt{\gamma^2 - 1}}{\gamma},$$

$$\text{where } \gamma = \sqrt{\frac{1}{4} + 2\Gamma} - \frac{1}{2}. \quad (5)$$

Cylinder **4** in Fig. 1 with radius $r > r_s$ and potential U can cause the formation of a virtual cathode. The current of the tubular REB behind the virtual cathode equals the limiting transport current of the electron beam [3]. Therefore, a virtual cathode is formed if the current from the cathode in the presence of the rod with radius r_s exceeds the limiting transport current of the electron beam in the region where cylinder **4** is located. The calculation of the current of an infinitely thin tubular REB in an infinitely strong magnetic field under the specified conditions presents no difficulties under the assumption that the longitudinal dimensions of the system substantially exceed the transverse ones.

By repeating procedures similar to those performed in [1, 5, 6], one can obtain the dependence of the limiting transport current of a tubular thin-walled electron beam in the coaxial configuration shown in Fig. 1 on the parameter γ :

$$I_{coax} = \frac{I_0}{2} \left[\frac{\Gamma - \gamma}{\ln \frac{R}{r_b}} - \frac{\gamma - 1}{\ln \frac{r_b}{r}} \right] \sqrt{1 - \frac{1}{\gamma^2}}. \quad (6)$$

The maximum of this function, i.e., the limiting transport current, is reached at:

$$\frac{dI_{coax}}{d\gamma} = 0, \quad \gamma = \sqrt[3]{\frac{\ln \frac{R}{r_b} + \Gamma \ln \frac{r_b}{r}}{\ln \frac{R}{r_b} + \ln \frac{r_b}{r}}}. \quad (7)$$

For $r \rightarrow 0$, the value $\gamma \rightarrow \Gamma^{1/3}$ and the current according to formula (1) takes the value of the limiting current [1] for the transport of a tubular REB in a hollow circular waveguide: I_{lim} .

Fig. 2 shows two current dependences on the radii. Note that the abscissa axis represents

the radius values of different electrodes, but such a comparison helps to better understand the features of the process. The upper curve 1 according to formulas (6, 7) shows the dependence of the limiting REB transport current I_{coax} on the cylinder radius r . In this case, $R = 24$ mm, $r_b = 10$ mm, and the parameter $\Gamma = 1.5$. At $r = 0$, i.e., in the absence of the cylinder, the current equals the limiting current [1] in a hollow waveguide: $I_{coax} = I_{lim}$.

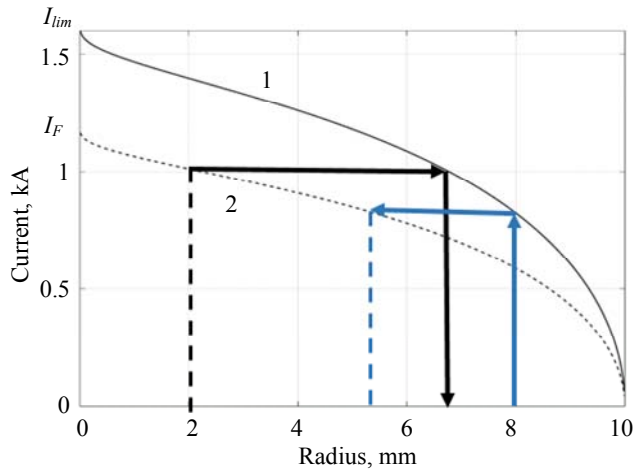


Fig. 2. Dependences of: 1 – the limiting REB transport current in the coaxial configuration $I_{coax}(r)$ according to formula (6); 2 – the current of the external electrode of the double cathode $I_N(r_s)$ according to formula (4)

The lower curve 2 according to formula (4) illustrates the dependence of the Nechaev current I_N [5] from the external electrode of the double cathode 2 in Fig. 1 on the rod radius r_s . As applied to Fig. 1, this is the current from cathode 2 as a function of the radius r_s of rod 3 in the absence of cylinder 4. At $r_s = 0$, i.e., in the absence of the internal electrode (rod), this current (5) coincides with the Fedosov current [6] from the cathode in a hollow waveguide: $I_N(r_s = 0) = I_F$. In both dependences $I_{coax}(r)$ and $I_N(r_s)$, as the radii of the internal electrodes r and r_s approach the radii of the cathode and the electron beam ($r_c = r_b$), the currents of the formed beam I_N and the transported beam I_{coax} tend to zero.

The dependence $I_{coax}(r)$ according to formula (6) does not involve the parameter r_s in any way, and conversely, $I_N(r_s)$ according to formula (4) lacks any dependence of the current on the radius r , which makes it possible to compare these dependences in Fig. 2, as well as to optimize the experiment on VC generation. By fixing the cylinder dimension r , one can select the required rod radius r_s , and vice versa. Examples of such a selection are shown in Fig. 2 by arrows. Curve 2 shows that for a rod radius $r_s = 2$ mm, the cathode current equals 1 kA. The horizontal line from it to the right and the vertical line from its intersection point with curve 1 indicate the cylinder radius $r \approx 6.7$ mm, above which the transported current becomes smaller than the cathode current. In other words, a VC is formed at $r_s = 2$ mm and $r > 6.7$ mm, i.e., at a distance from the REB to the cylinder $r_b - r < 3.3$ mm. In the opposite case, the vertical line from $r = 8$ mm to the intersection with curve 1 shows that a cylinder of such a radius does not transmit a current exceeding 0.8 kA. The horizontal line from this point to curve 2 determines the maximum rod radius for VC formation at fixed cylinder dimensions: at $r = 8$ mm, i.e., at $r_b - r = 2$ mm, the rod radius $r_s < 5.3$ mm.

The described scheme of VC generation provides simpler methods of varying the experimental parameters (changing the rod and the cylinder) compared to the traditional REB configuration in a tube with expanding walls. However, as will be shown below, the VC parameters can be optimized altogether within a single series of experiments without replacing parts or even changing their positions.

Experimental Setup

Fig. 3 shows the scheme of the axially symmetric experimental setup used in this work for VC investigation.

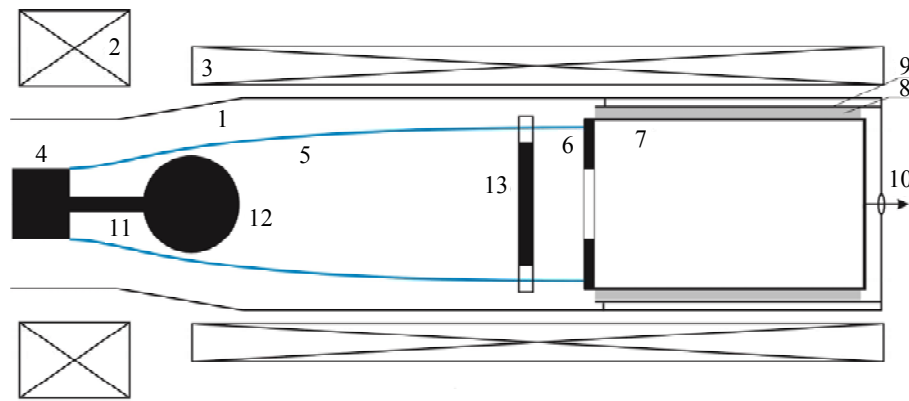


Fig. 3. Experimental setup for VC investigation: 1 – vacuum chamber; 2 – coil; 3 – solenoid; 4 – cathode; 5 – REB; 6 – collector; 7 – inner metal cylinder of the current meter; 8 – dielectric; 9 – outer metal cylinder of the current meter; 10 – coaxial vacuum-tight connector; 11 – threaded rod; 12 – spherical electrode; 13 – slit diaphragm

Vacuum chamber 1 with a vacuum pumping system ensures a pressure not exceeding 0.1 Pa. Coil 2 and solenoid 3 with independent power supplies create a quasi-stationary magnetic field: the coil – up to 3.5 T, the solenoid — up to 1 T. A graphite explosive-emission cathode 4 with a diameter of 20 mm is located in the region of the strong magnetic field of coil 2, and chamber 1 near the cathode has a diameter of 48 mm. A negative potential pulse is applied to the cathode from the Radan-303 high-voltage pulse generator [7] with an additional pulse-forming unit. After the pulse former, the generator pulses have a rise time of 0.3 ns and a plateau of 2 ns with an amplitude of 250 kV at a total FWHM duration of 2.5 ns (see Fig. 4). A calibrated capacitive voltage divider (not shown in the figure), which measures the pulsed voltage, is located in the oil-filled transmitting coaxial line with an impedance of 50 Ω at a distance of about ~60 cm from the cathode.

The cylindrical electron beam 5 propagates along the magnetic field lines from the region of coil 2 into the region of solenoid 3, gradually increasing in diameter from 20 to ~34 mm. The characteristic length of the magnetic field variation region is about ~15 cm. Vacuum chamber 1 also has a variable diameter that varies in accordance with the magnetic field lines and equals 60 mm in the region of solenoid 3. The electron beam 5 is collected on collector 6, which is simultaneously a part of the picosecond-duration high-current REB current meter described below [8].

A rod 11 with a diameter of 5 mm with a thread is fixed on cathode 4, onto which electrode 12 is screwed. This electrode has the shape of a sphere with a diameter of 30 mm, in contrast to its functionally analogous cylindrical electrode 4 in Fig. 1. The spherical shape of the electrode, which is at the cathode potential, and its polished surface prevent electron emission from it during the pulse, which has a duration of about ~2 ns.

It is clear from Fig. 2 that the onset of a VC in our case is actually determined by the distance from the REB trajectory to the sphere 12, which is equipotential to the cathode. Coarse adjustment of this distance in the experiment is performed by changing the position of the sphere along rod 11. With the change in the REB trajectory radius during the transition from the strong magnetic field region to the weak one by 7 mm over a characteristic length of 15 cm, such adjustment can be easily performed with an accuracy of at least 1 mm. In addition, the independent power supply systems of coil 2 and solenoid 3 provide additional possibilities for controlling the REB radius. If the position of sphere 12 and the beam current in solenoid 3 are fixed, then weakening the field of coil 2, i.e., the magnetic field at the cathode, leads to a decrease in the distance from the electron trajectories to the sphere. Moreover, this distance optimization can be carried out at different positions of the sphere (and the associated position of the VC) along the axis, thereby substantially changing the distance from it to the cathode.

The choice of the current measurement method was determined by the short REB pulse

duration, which makes the use of traditional shunts and Rogowski coils problematic. The current meter [8] shown on the right in Fig. 3 represents a long coaxial waveguide and consists of inner 7 and outer 9 metal cylinders separated by dielectric 8. The outer electrode of the waveguide is grounded to chamber 1, the inner electrode on the REB side is connected to collector 6, and on the opposite side – to the central conductor of the coaxial vacuum-tight SMA-type connector 10. The REB current with an amplitude of ~ 1 kA induces a voltage of about 1.5 kV on the measuring line with an input impedance of $\sim 1.5 \Omega$. To transmit the signal through SMA coaxial connectors and attenuators without the risk of breakdown, the measured current and the resulting voltage on the line were reduced in advance by more than an order of magnitude, for which purpose beam 5 passed onto collector 6 through a slit diaphragm 13. The 40 cm length of the current meter made it possible to reliably record signals before the appearance of re-reflections in the line after ~ 4 ns. The registration of cathode potential signals and currents was carried out using an oscilloscope with a sampling rate of 50 GSa/s and an operating frequency bandwidth of 10 GHz.

Experiment results and discussion

Fig. 4 shows the oscillograms of the cathode potential (*a*) and the currents: (*b*) – in the classical scheme without a VC, and (*c*) – upon VC formation. Preliminary precise synchronization of the potential and current pulses was hampered not only by the large distance of ~ 1 m between the sensors. Along this path, the signal velocity was determined by the propagation velocities of the wave in the transmitting coaxial line of the accelerator and the measuring coaxial line, as well as by the velocity of the electrons of the formed beam, which gradually changed from zero to the maximum value. However, the current signals – Fig. 4 (*b*) and (*c*) – were obtained from the same sensor; therefore, their mutual delay can be judged with confidence.

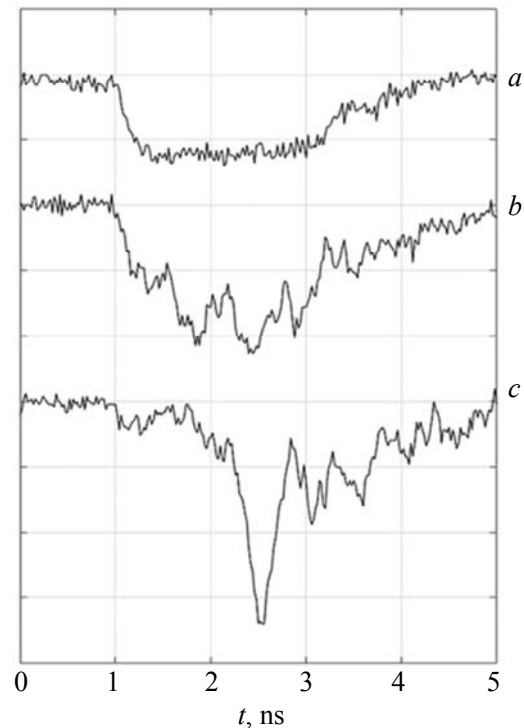


Fig. 4. Oscillograms: *a* – cathode potential; *b* – REB current in the absence of the rod and the spherical electrode on the cathode; *c* – REB current after the VC

In the absence of the rod and the spherical electrode on the cathode, i.e., when forming a REB in a classical magnetically insulated coaxial diode [6], the voltage (Fig. 4*a*) and current (Fig. 4*b*) pulses coincide in duration and are equal to approximately 2 ns from the beginning of the leading edge to the beginning of the pulse fall. The similarity of the shape of these pulses after 2 ns – a sharp drop to about half the amplitude over ~ 0.4 ns and a smoother decay thereafter – suggests that the voltage and current pulses begin simultaneously with an accuracy of up to 0.2 ns.

The current oscillations with a period of 0.6 ns, visible on the oscillograms, can have at least two possible origins. First, they may be a consequence of the explosive-emission cathode operation at the initial stage of electron emission development from emerging and disappearing cathode micro-flares. Second, the cause may be the use of a slit diaphragm that limits the total REB current. It is known that a convective diocotron instability develops in magnetized tubular REBs [9], which at the nonlinear stage of development manifests itself in the form of beam filamentation. The number of filaments (threads) is greater, the thinner the current tube. Under the conditions of the described experiment, with a

REB wall thickness of up to 1 mm after traversing a distance of ~ 0.5 m from the cathode to the current meter, the number of filaments amounted to several tens: the beam imprint on the target clearly demonstrated current inhomogeneities with a spacing of ~ 1 mm along the perimeter. Several such current filaments passed through the slit diaphragm. In crossed fields – the axial magnetic field and the radial electrostatic field of the electron flow space charge — the current filaments have the form of spirals whose twist angle depends linearly on the REB current. With small fluctuations of the cathode current, a different number of current filaments passes through the slit diaphragm; therefore, the recorded current after the diaphragm varies much more strongly. This pattern was previously observed by the authors of [8]; therefore, to register the total REB current without slit diaphragms, more complex methods of attenuating the electrical signal from the current meter directly in the vacuum chamber were employed.

When the propagation trajectory of beam electrons 5 and electrode 12 approached to a certain distance, a VC was formed. The signal from the current sensor (Fig. 4c) began with a delay of more than 1 ns compared to the case without a VC, but its amplitude exceeded that shown in Fig. 4b without a VC by a factor of ~ 1.5 . Approximately the same effect was observed in calculations using the CST code [4] in a diode configuration with a uniform magnetic field, as in Fig. 1, but with a spherical electrode, as in Fig. 3.

The following sequence of events can be assumed. Initially, the potential of the spherical electrode delays the passage of REB electrons for a certain time, and space charge accumulation occurs in the space between the cathode and the sphere. When the current is cut off, the cathode potential increases to higher values than in the absence of electrode 12, because the signal from the accelerator transmitting line with an impedance of $45\ \Omega$ encounters a load with a higher impedance. To a certain extent, this simple explanation agrees with the results of numerical simulation of the process under consideration [4].

Conclusion

The purpose of the present work was the experimental demonstration of the phenomenon of current increase in a nanosecond relativistic electron beam upon shortening of the REB pulse duration, which can be called the temporal compression of an electron beam. The design allows for the experimental implementation of the variation of the limiting transport current I_{lim} while keeping the parameters of the REB formed at the cathode constant. This feature distinguishes the work from previous ones – the VC can be either formed or not formed in the same liner cross-section while maintaining the configuration of its outer walls and the solenoids that create the magnetic field. In addition, methods for both coarse and fine adjustment to select the VC formation parameters have been proposed. Coarse adjustment was carried out by moving the central electrode by means of a threaded connection with the vacuum system vented, whereas fine adjustment was achieved by slightly changing the magnetic field profile by varying the current in one of the two solenoids during a single series of experiments.

The substantiation and consistent explanation of the physical processes occurring in the diode with the described electrode configuration require additional experiments and three-dimensional numerical simulation. In particular, first, it is necessary to obtain more reliable experimental results in which the influence of the slit diaphragm (and the diocotron instability of the REB) on the measurements of the total beam current will be excluded. Second, numerical simulation of the processes in the diode is required using parameters that not only reproduce the conditions of the conducted experiment, but also exploit the advantages of a numerical experiment, which is not limited by the framework of direct experimental realization.

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