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Annular electron beam with virtual cathode in a coaxial diode with magnetic insulation

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Abstract. Accumulation of electrons in course of transportation of tubular high-current electron beam in a coaxial diode with magnetic insulation was studied in the situation of counterstream electron motion occurring due to the formation of a virtual cathode. Accumulation of electrons in these flows is accompanied by gradual increase in their relative energy spread and simultaneous decrease in the maximum kinetic energy. The process is described analytically and confirmed in numerical modeling. The theory is an extension of the known theory of coaxial magnetically insulated diode (based on the conservation of axial component of the generalized momentum) taking into account the spread of electron energies. The numerical modeling employed the KARAT electromagnetic PiC-code. Experiments were performed using high-current electron accelerator SINUS-7 (pulsewidth 50 ns) in the range of diode voltages 350—800 kV, magnetic fields 8—24 kOe, electron beam currents 2—12 kA. A gradual increase of potential of the electron beam between the explosive-emission cathode and the virtual cathode was observed, which accompanies accumulation of circulating electrons as predicted in theory.

1. Introduction

Coaxial magnetically insulated diodes (CMIDs) with edge-type explosive-emission cathodes are used for production of tubular high current electron beams. Such diodes, immersed in strong magnetic field, produce electron beams with high enough density, stability and uniformity; they are applied in high power microwave tubes, electron beam ion sources/traps and other devices of electrophysics. Since the electron beam in a CMID is thin-walled, it possesses very low spread of particle kinetic energy.

The theory of coaxial magnetically insulated diode is well-studied and proven in numerous computer simulations and experiments. To date, the following problems have been solved: the limiting current of electron beam in a cylindrical channel [1], eventual states of electron beam [2], electron beam current in a CMID [3, 4]. Some approaches to description of electron beam states with longitudinal nonuniformities in such systems have been developed [5, 6]. Numerical modeling based on Particle-in-Cell (PiC) method enabled studying non-stationary states of electron beams with a virtual cathode (VC) [7]. A state of electron beam where the relativistic factor of electrons is lower than that for the limiting current (the compressed state) was demonstrated in axisymmetric and 3D simulations. At that time, this state was predicted in theory, but it was not experimentally investigated [8—11]. Success of numerical modeling stimulated certain improvements of analytical models of beams with a virtual cathode [15-17] and their experimental verification [18, 19]. It was the time-dependent PiC-modeling that allowed demonstration of situations where a spread of kinetic energy develops and grows in an initially monoenergetic electron beam. For the first time this was apparently observed in [7] and later similar effects were reported in [8, 17, 18]. The emergence of the energy spread, significantly affecting the observed phenomena, and accumulation of additional charge have been observed experimentally in the study of motion of the VC in sectioned channels [15].

The purpose of the present study was to demonstrate experimentally the accumulation of charge in an electron beam with a virtual cathode in a coaxial diode with magnetic insulation, and compare the parameters of the observed effect with the theory and numerical modeling. The modeling was made in 2D and 3D using KARAT electromagnetic PiC code [19]. The experimental setup was based on SINUS-7 high-current electron accelerator [20].

2. Theory and numerical modeling

In this section, let us consider a situation leading to development of kinetic energy spread in an initially monoenergetic hollow electron beam produced in a CMID comprising a virtual cathode.

Let the diode is extended with a channel having a step-wise widening sufficient to formation of VC, causing reflection of certain fraction of electrons (figure 1). Such a beam transport system is typical to many pulsed power applications. It is known that variation of current incident on VC causes corresponding changes in the current reflected from VC, while the transit current remains nearly equal to the limiting current for the wide section [2]. The wider this section the lower the transit current behind the VC. This is the way how a VC "stabilizes" the transit current in a CMID. Another essential issue is oscillations in the reflected and transit currents. These oscillations cause certain spread in the kinetic energy of electrons in both the reflected and transit electron flows. The amplitude of the oscillation is maximum if the beam incident on the VC is monoenergetic, and it reduces greatly when the energy spread exceeds a definite level. In the latter case the phase trajectories of electrons form a wide strip and the VC works as separator passing electrons with higher kinetic energies and reflecting electrons of lower energies with no considerable oscillations in the reflected and transit currents.

Let us consider evolution of the system assuming that the voltage applied to the diode is constant. At zero moment of time, electron emission from the cathode edge starts with the current limited by electron space charge. The emitted particles accelerated to the energy $\gamma = \gamma_F$ (which corresponds to Fedosov's current [3]) fill the transport channel up to the wider section where the VC is formed. The beam reflected from the VC gains some energy spread and runs back to the cathode edge where its most part is reflected forward. At the cathode, its potential barrier works similar to the VC separating the electrons by their reflection point according to their kinetic energy. The particles with the energy higher than the cathode potential hit the cathode and are absorbed here. Electrons reflected from the cathode (accompanied by newly emitted ones) reach the VC where they are separated into reflected and transit ones, and so on. The multiply repeated process results in accumulation of electrons between the cathode and the VC while the potential of the electron flow in this section gradually increases in time and the relative energy spread rises. Figure 2 illustrates the evolution of the system phase plots obtained from KARAT modeling. In the simulation, the cathode radius was 1.6 cm, the narrow section radius was 2 cm and the wide section radius was 4 cm. The lengths of the sections were 15 cm and 25 cm, respectively. The axial magnetic fields strength was 10 T. The diode was fed with a TEM wave adjustable amplitude so that the diode voltage was held near 500 kV. In this simulation, it took about 200 ns for the kinetic energy of the beam to reduce to about 50 kV.

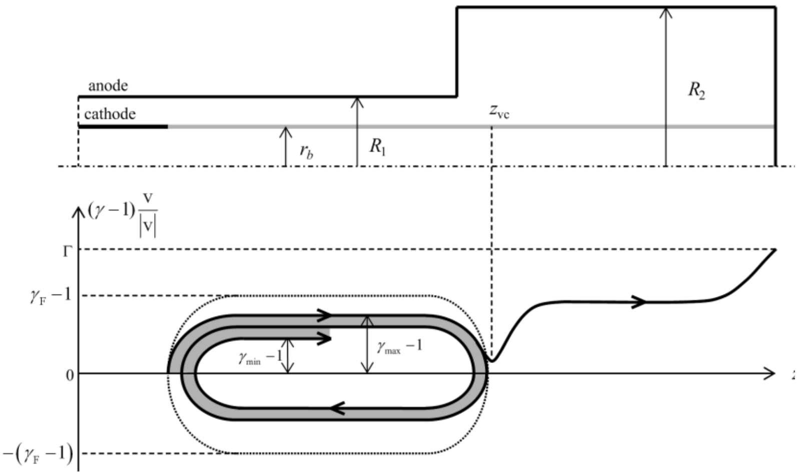

Figure 1. Schematic layout and phase diagram illustrating the analytical model.

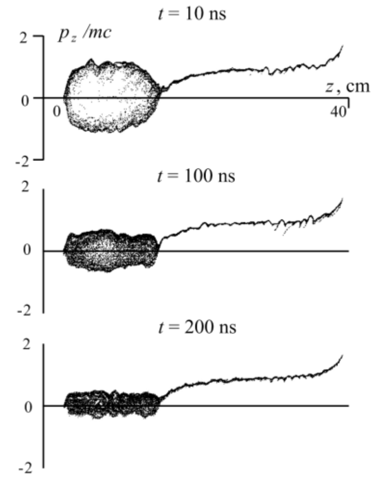

Figure 2. Evolution of the system phase plots (axisymmetric modeling using KARAT code).

Another series of numerical modeling was carried out to determine a feasible minimum for kinetic energy of electrons in a CMID with defined voltage level. It was demonstrated in a simulation involving a "counter-cathode" for particle reflection that the maximum energy of electrons could drop to as low as 1 keV while the diode voltage was sustained at about 500 kV [21]. The time for transition to this state was over 150 ns for the transport channel length 20 cm.

The theory considers a stationary tubular electron beam of radius r_b and infinitely thin wall guided by strong axial magnetic field in a uniform channel of radius R. The channel wall is at ground potential. The beam electrons can move in both positive and negative directions along z axis. The relativistic factor γ of electrons in the flow is assumed to be uniformly distributed from γ_{min} to γ_{max}. Using conservation of energy and conservation of the generalized (particle and field) momentum the following expression for the electron current was obtained:

$$I = \frac{I_0}{2\ln R/r_b}\cdot\frac{\Gamma-\gamma_{max}}{\gamma_{max}-\gamma_{min}}\left[\sqrt{\gamma_{max}^2-1}-\sqrt{\gamma_{min}^2-1}-\operatorname{arctg}\sqrt{\gamma_{max}^2-1}+\operatorname{arctg}\sqrt{\gamma_{min}^2-1}\right],$$

$$(\Gamma-1)^2 = (\Gamma-\gamma_{max})^2 + 2\cdot(\Gamma-\gamma_{max})\left\{\frac{\gamma_{max}+\gamma_{min}}{2}-\frac{\ln\gamma_{max}/\gamma_{min}}{\gamma_{max}-\gamma_{min}}\right\},$$

here Γ is the relativistic factor corresponding to the diode voltage, and $I_0 = mc^3/e \approx 17$ kA.

The equations determine the feasible range for the value of energy spread $\Delta\gamma/(\Gamma\text{-}1)$ in the transported beam. This range is rather narrow: from zero to nearly 0.25 in the non-relativistic case, and it contracts as Γ rises. It is important that with any preset value of $\Delta\gamma/(\Gamma\text{-}1)$ within this range, the beam can exist in two states with different relative energy spreads and maximum kinetic energies. The exception is the "boundary" state with maximum value of $\Delta\gamma/(\Gamma\text{-}1)$, which is instable with the respect to small variation of this value. It means that near this "boundary" regime, any small longitudinal disturbances in the electron beam will result in coexistence of segments with slower and faster particle motion, as it was observed, for example, in [7, 17, 22].

Some more details of the above theory are given in [21]. Of course, the theory can describe a sequence of some steady states, but it is unable to describe any oscillations (e.g. produced by virtual cathode), which determine the real rate of the system evolution process.

3. Experiment

The experiment employed a high current electron accelerator SINUS-7 equipped with a coaxial magnetically insulated diode. The experimental arrangement is depicted in figure 3. The electron beam was transported in the area with nearly uniform magnetic field. The lengths of the narrow and wide channel sections were L_1 = 150 mm and L_2 = 300 mm, with the radii of R_1 = 24 mm and R_2 = 41 mm, respectively. The diode current was varied by adjusting the distance L_{AC} between the anode and the cathode from 80 mm to -20 mm. It is negative when the cathode penetrates the channel narrowing. The electrostatic potential of the electron beam in the narrow section was measured with a capacitive voltage divider situated at the middle of the section.

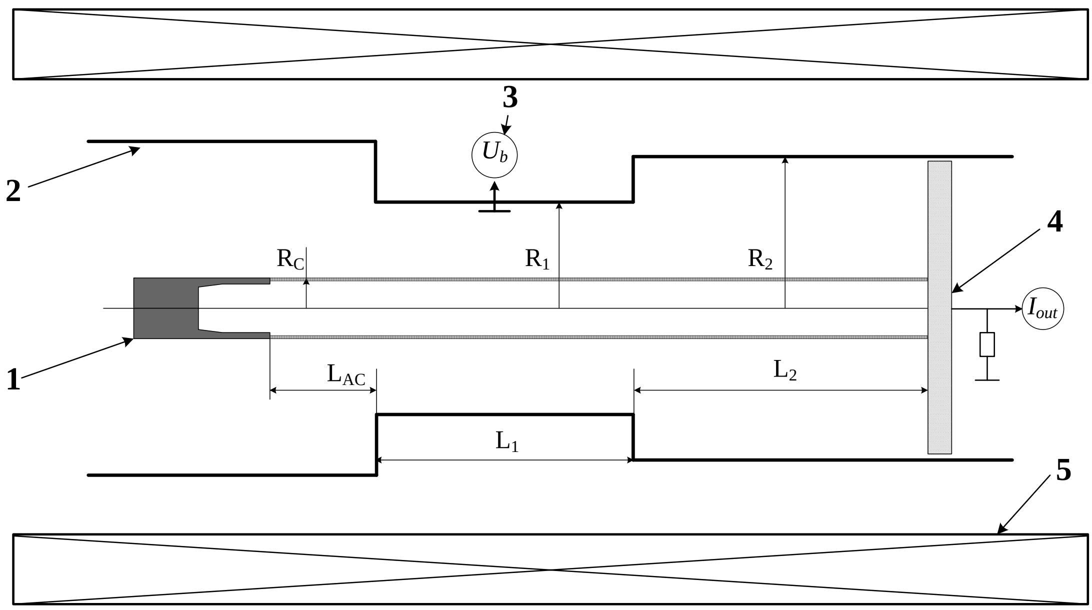

Figure 3. Experimental arrangement: 1 – cathode, 2 – anode, 3 – capacitive voltage divider, 4 – electron beam collector, 5 – magnetic coil.

The experimental parameters were varied over a wide range: cathode voltage 350—800 kV, magnetic field 8—24 kOe, and the diode current 2.0—12 kA. The voltage pulse duration was 50 ns (FWHM). The vacuum diode voltage and current were measured by means of capacitive voltage divider and low-inductance shunt, respectively. Both these sensors were situated in the oil-filled transmission line immediately near the vacuum diode. The diode current was also measured using a Rogowski coil mounted in the flange of the magnetic coil. The current of electrons at the collector was measured using a low-inductance, low-resistance shunt included in the collector circuit.

Electrons were emitted from an explosive-emission edge-type cylindrical graphite cathode with edge thickness 0.5 mm. Three cathodes with the radii of 20, 32, and 40 mm were tested. No assured indication to charge accumulation was obtained using a 20-mm cathode. For the 40-mm cathode, certain leakage of electron current to the walls of the transportation channel has been observed in lower magnetic fields.

Clear signs of charge accumulation with no radial current leakage were obtained with the use of the 32-mm cathode. The typical waveforms of diode voltage U_d, total diode current I_d, electron beam current I_b and electron beam potential (signal from capacitive divider, U_b) are in figure 4. Noticeable oscillations of the beam potential taking place near the pulse maximum are probably produced by the “strata” with lower and higher electron energies moving back and forth along the beam, as it was predicted by the theory and demonstrated in simulations [7, 17, 21, 22].

Knowing the waveform of the diode voltage U_d enables calculation of the beam potential, as though the beam is monoenergetic and there is no charge accumulation in the system. Some increase in the beam radius caused by expansion of the cathode plasma with typical rate $2 \cdot 10^6$ cm/s was taken into account. Comparing this calculated potential with the measured potential and with the simulated one allowed a conclusion whether there is a charge accumulation and how intense it is.

The waveforms of the potentials are presented in comparison in figure 5. The difference between the potential calculated under monoenergetic approximation and the measured potential is increasing with time making about 40% at the front of the pulse and exceeding 60% by the beginning of the fall.

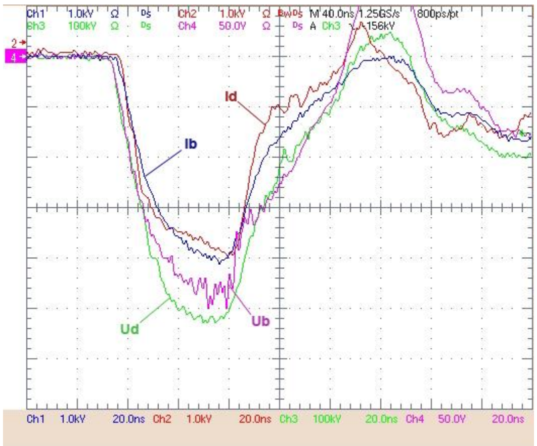

Figure 4. Waveforms of beam current I_b (Ch1), diode total current I_d (Ch2), diode voltage U_d (Ch3) and the beam potential U_b (Ch4).

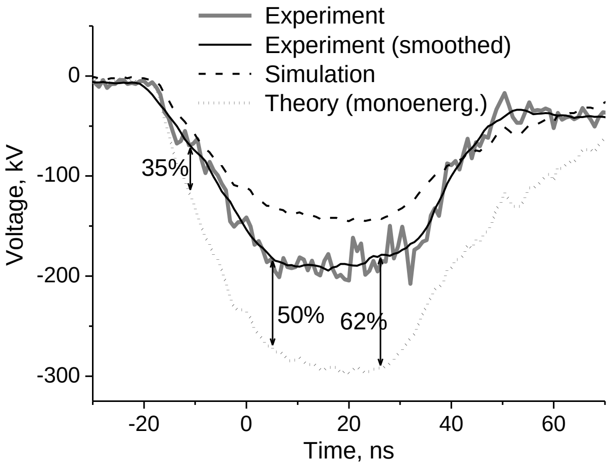

Figure 5. Waveforms of the beam potential with respect to the channel wall: experimental (original and smoothed), simulated with axisymmetric version of KARAT code, and calculated in the case of no energy spread of electrons

The increase in the beam potential within the pulse width is still notably less than the value predicted in theory for the case when the electron charge is completely accumulated. It is seen that the electron charge still continues accumulating at the end of the pulse. Note that in axisymmetric modeling the time for full accumulation was about 100 ns. Therefore, the width of the accelerator pulse is insufficient for observation of the complete process. Another factor that slows down the charge accumulation and the clearness of the final state of the beam is the three-dimensional instability of the beam leading to its filamentation. This effect is visual in simulation using 3D Cartesian version of KARAT code.

4. Conclusion

Thus, the process of electron charge accumulation in a coaxial magnetically insulated diode with virtual cathode was confirmed in experiment. The developing process is clearly visual even with relatively short pulse duration of the electron accelerator (50 ns). The result obtained is potentially important is such areas as generation of high-power microwaves in vircators, collective acceleration of ions by moving virtual cathodes, and operation of electron beam based ion traps.

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