Magnetic self-insulation of electron beams in vacuum lines

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Transport of relativistic electron beams along vacuum lines is studied under conditions of magnetic self-insulation. The establishment of a quasistationary regime of magnetic self-insulation in which the energy-transfer efficiency reaches 100% is studied experimentally. In the wave regime a steepening of the rise of the electromagnetic pulse and a slowing of its velocity are observed, the velocity being in good agreement with the calculated value. On decrease of the diameter of the inner electrode of the coaxial line at the end anode a current density in the focused beam up to 0.5 MA/cm^2 is obtained, which is explained by the presence of plasma accelerated from the inner electrode in the end cathode-anode gap.

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1. INTRODUCTION

For initiation of a thermonuclear reaction in shell targets containing a mixture of deuterium and tritium, in addition to laser radiation it is possible ot use pulsed high-current beams of relativistic electrons with a characteristic duration 100 nsec and a power[1] 10^{14}–10^{15} W. One of the most important problems arising here is transport of the beam to the surface of the external shell of the target. The characteristic transport length can be estimated by considering the multimodular accelerator Angara-5, which is intended for heating a target with radius $r_t \sim 1$ cm by electron beams with a total energy 5 MJ and power[2] 10^{14} W.

An individual element of the Angara-5 accelerator is a module which permits production of an electron beam with energy 2 MeV and current 1 MA with a pulse length at half-height 60 nsec. This module is a high-current dc accelerator in which the electrical generator producing the voltage pulse is separated from the evacuated beam-shaping region by a dielectric diaphragm.[3] Here the electric field strength at the vacuum surface of the diaphragm must not exceed a certain critical value E_{cr} at which electrical breakdown occurs. From this condition we can estimate the required diaphragm area S for specified values of energy flow $P=IU$, electric and magnetic fields in the diaphragm region, and location of the modules in space in accordance with the formula

$$P=\frac{c}{4\pi}\int \mathbf{E}\times\mathbf{H}\cdot d\mathbf{S}.$$

The transport length l to the target with a spherical arrangement of the modules is

$$l>(SN/4\pi)^{1/2},$$

where N is the number of modules of the accelerator. As can be seen from Eq. (A), for reduction of S it would be possible to increase the magnetic field strength. However, the value of H is limited since an increase of the magnetic-field energy in the vicinity of the diaphragm decreases the rate of rise of the energy flow as the result of the inductance. Assuming that the magnetic-field energy must be substantially less than half the energy of the pulse, we obtain

$$\frac{H^2}{8\pi}Sl<c\frac{EH}{4\pi}S\frac{\tau}{2} \quad \text{or} \quad \frac{H}{E}<\frac{c\tau}{l}.$$

Under realistic conditions ordinarily $H\lesssim 10E$ ($E_{cr}\sim 5\times10^4$ V/cm), which leads to $S\gtrsim 2\times10^4$ cm^2 and $l\gtrsim 4\times10^2$ cm. In a realistic design l increases to 6–7 m.

Beyond the diagram of an individual module an electromagnetic pulse is propagated, which is then converted with a high efficiency at the diode into a beam of relativistic electrons. If this conversion occurs at a sufficient distance from the target, the problem arises of further transport of the electron beam.[4] This problem can be solved by propagation of the beam in a plasma, but with the necessary current level ~10^7–10^8 A the transport and subsequent focusing is hindered as the result of the large angular divergence of the beams. Another approach to the problem of transport and focusing onto a target is the use of vacuum transmission lines connecting the generator with the diode, which is close to the target. Since at the target surface it is necessary to provide an energy flow density $PN/4\pi r_t^2 \lesssim 10^{14}$ W/cm^2, from Eq. (A) for the energy flow in a coaxial line P it is possible to evaluate the electric and magnetic field strengths at the end of the vacuum line. If an electromagnetic wave in which $E=H$ is propagated along the line, then it follows from (A) that $E\lesssim 10^6$ V/cm. However, already at an electric field strength $E\sim10^5$ V/cm explosive emission of electrons from the negative electrode arises as the result of appearance at its surface of a plasma of evaporated micropoints,[5] and electrons appear in the interelectrode gap. Thus, in this region of parameters the propagation of a vacuum electromagnetic wave is impossible and it is necessary to consider the problem of simultaneous propagation along the line of an electromagnetic pulse and a flux of electrons.

Here the following pattern of physical processes occurs in the line. In the leading edge of such a wave a vacuum precursor can exist—an ordinary electromagnetic wave arising as the result of delay of the explosive emission. Then follows the front of the nonlinear wave, where the circuit for the total current is completed in the wave propagation process both as

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the result of displacement current and as the result of outflow of electrons to the anode. Here, as we have shown elsewhere,[6] a wave with a steepened front is shaped, similar to a wave in a line with a magnetron effect.[7] It is important that behind the front of such a nonlinear wave there arises self-insulation of the electrons, which means that the electrons are turned around under the influence of the magnetic field of the wave and do not hit the anode. As a result there is formed in the interelectrode gap a layer (sheath) of relativistic electrons, and the electric field E and magnetic field H in the gap are rearranged, with establishment of a field configuration with $H>E$.

An important function of the magnetic field is the slowing down of the expansion of the near-electrode layers of plasma, which leads to a substantial increase in the time of operation of the line before it is shorted by the plasma. The disappearance of the outflow currents and the increase of the time before shorting of the line by the plasma increase its electrical strength. Comparatively recently this phenomenon has received the name magnetic insulation, although the study of the effect of a magnetic field on the insulation of vacuum gaps has a history of many years[8] and the first apparatus in which in effect magnetic insulation was used was the magnetron. Turning on an additional longitudinal magnetic field, generally speaking, facilitates insulation of the sheath of electrons and simultaneously slows down still more the expansion of the plasma in the line. However, this requires additional external sources of energy and makes the beam more rigid, which in a number of cases can hinder self-focusing of the beam in the diode at the end of the line. Transport of pulses along lines with magnetic insulation due to the currents themselves was first accomplished in the Aurora accelerator.[9] The one-dimensional theory of magnetic self-insulation in a coaxial diode was constructed in Refs. 10–14, and experimental studies of the quasistationary regime are to be found in Refs. 11, 12, and 15.

In the present work we present the results of theoretical and experimental studies of magnetic self-insulation of the line. In Section 2 the theory of magnetic self-insulation is set forth on the basis of a hydrodynamical description of electron flow. In Sections 3 and 4 we give a description of experiments with lines working in the quasistationary regime and of the focusing of the beam at the end of the line. The wave regime is the subject of Section 5.

2. THEORY OF MAGNETIC SELF-INSULATION IN THE HYDRODYNAMICAL APPROXIMATION

In this section we will derive the equations which describe the nonlinear TM wave in a coaxial transmission line in the presence of electrons which appear in the gap. Our basic equations will be the hydrodynamical equations of motion for cold electrons

$$\frac{\partial p_r}{\partial t}+v_r\frac{\partial p_r}{\partial r}+v_z\frac{\partial p_r}{\partial z}=-eE_r+\frac{e}{c}v_zH_\varphi, \tag{1}$$

$$\frac{\partial p_z}{\partial t}+v_r\frac{\partial p_z}{\partial r}+v_z\frac{\partial p_z}{\partial z}=-eE_z-\frac{e}{c}v_rH_\varphi, \tag{2}$$

where

$$p_r=\gamma mv_r,\quad p_z=\gamma mv_z,\quad \gamma=(1-v^2/c^2)^{-1/2}$$

and the Maxwell equations

$$-\frac{1}{c}\frac{\partial H_\varphi}{\partial t}=\frac{\partial E_r}{\partial z}-\frac{\partial E_z}{\partial r}, \tag{3}$$

$$4\pi en\frac{v_r}{c}=\frac{1}{c}\frac{\partial E_r}{\partial t}+\frac{\partial H_\varphi}{\partial z}, \tag{4}$$

$$4\pi en\frac{v_z}{c}=\frac{1}{c}\frac{\partial E_z}{\partial t}-\frac{1}{r}\frac{\partial}{\partial r}rH_\varphi, \tag{5}$$

$$\frac{1}{r}\frac{\partial}{\partial r}rE_r+\frac{\partial E_z}{\partial z}=-4\pi en. \tag{6}$$

Calculations show that the difference between the results obtained in the hydrodynamical approximation with zero temperature and in the kinetic approximation is not great at moderate potentials[16] ($\gamma\lesssim 10$). This can be shown also by direct calculation, using the results of kinetic theory.[10–14] We shall use the equation for the radial momentum $p=\rho mc$ in the "plane" case when $d\ll a$:

$$\rho^2\rho'^2=h^2(\rho)=g_0\rho(1+\rho^2)-h_0^2\rho^2, \tag{7}$$

where

$$g_0=8\pi e^2n_0/mc^2,\quad h_0=e|H_0|/mc^2,$$

n_0 is the characteristic electron density, H_0 is the magnetic field at the inner electrode with radius a, and the prime indicates differentiation with respect to $x=r-a$; d is the width of the coaxial gap.

Integrating Eq. (7) for $\rho^2<1$, we obtain the following expression for the height of the rise of electrons in the interelectrode gap for the case when the entire coaxial gap is filled by the electron flux:

$$d=g_0\pi/h_0^3=\rho_0\pi/h_0, \tag{8}$$

where ρ_0 is the maximum dimensionless transverse momentum in the layer. If we use now the expression for the parapotential current corresponding to filling of the entire gap[17]:

$$h_0d=\ln(\gamma+(\gamma^2-1)^{1/2}),$$

then it follows from the condition $\rho_0^2<1$ and from Eq. (8) that

$$\gamma<\operatorname{ch}\pi=11.6. \tag{9}$$

Thus, for moderate relativistic potentials in a coaxial line the hydrodynamical model with zero temperature is a sufficiently good approximation. Here it follows from the calculations that there actually is a limitation on the difference of potentials in the electron sheath. Since experimentally equilibrium is realized with incomplete filling of the coaxial gap, the realistic limitation on the potential in the coaxial line is weaker than Eq. (9).

Now differentiating Eq. (1) with respect to z and Eq. (2) with respect to r and subtracting the second from the first, we find that

$$\frac{\partial A}{\partial t}+\frac{\partial}{\partial r}v_rA+\frac{\partial}{\partial z}v_zA=0, \tag{10}$$

where

$$A=\frac{\partial p_r}{\partial z}-\frac{\partial p_z}{\partial r}-\frac{e}{c}H_\varphi.$$

It follows from Eq. (10) that, as in the stationary case, we can assume (see Ref. 18)

$$\partial p_r/\partial z-\partial p_z/\partial r=eH_\varphi/c. \tag{11}$$

Substituting the expressions for the velocities from Eqs. (4) and (5) into $1/\gamma^2=1-v^2/c^2$, we obtain the expression for the density n. It is then convenient to go over to quantities having the dimension of inverse length:

$$h=eH_\varphi/mc^2,\quad e_1=eE_r/mc^2,\quad e_2=eE_z/mc^2.$$

Here from Eqs. (1) to (6) we can obtain with respect to γ, h, and

$$a_1=\frac{1}{c}\frac{\partial e_1}{\partial t}+\frac{\partial h}{\partial z},\quad a_2=\frac{1}{c}\frac{\partial e_2}{\partial t}-\frac{1}{r}\frac{\partial}{\partial r}rh$$

the following four differential equations:

$$\Delta\gamma-\frac{\gamma}{(\gamma^2-1)^{1/2}}a_0+\frac{1}{c}\frac{\partial}{\partial t}\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r(\gamma^2-1)^{1/2}\frac{a_1}{a_0}\right)+\frac{\partial}{\partial z}\left((\gamma^2-1)^{1/2}\frac{a_2}{a_0}\right)\right\}=0, \tag{12}$$

$$\frac{1}{r}\frac{\partial}{\partial r}ra_1+\frac{\partial a_2}{\partial z}=-\frac{1}{c}\frac{\partial}{\partial t}\left(\frac{\gamma}{(\gamma^2-1)^{1/2}}a_0\right), \tag{13}$$

$$\tilde{\Delta}h-\frac{1}{c^2}\frac{\partial^2 h}{\partial t^2}=\frac{\partial a_1}{\partial z}-\frac{\partial a_2}{\partial r}, \tag{14}$$

$$\frac{\partial}{\partial z}\left((\gamma^2-1)^{1/2}\frac{a_1}{a_0}\right)-\frac{\partial}{\partial r}\left((\gamma^2-1)^{1/2}\frac{a_2}{a_0}\right)=h. \tag{15}$$

Here $a_0=(a_1^2+a_2^2)^{1/2}$ and

$$\Delta=\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2},\quad \tilde{\Delta}=\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}r+\frac{\partial^2}{\partial z^2}.$$

Considering Eqs. (12)–(15), it is easy to see that for a local equality $(\gamma^2-1)^{1/2}/a_0=\text{const}$, equations of the hyperbolic type are obtained for γ and h. Here the type of equation is retained also in the general case $(\gamma^2-1)^{1/2}/a_0\neq\text{const}$. In view of the hyperbolic nature of Eqs. (12)–(15) the quantities γ and h can be found for all lines from their values at the line input.

An additional relation for determination of the velocity of propagation of the electromagnetic pulse can be obtained from the equality $E_z=0$ at the surface of the coaxial electrodes. Combining Eqs. (12) to (15) and utilizing the fact that $E_z=0$ at the surface of the electrodes, we obtain

$$\frac{\partial}{\partial z}(\gamma-1)=\frac{1}{c}\frac{\partial}{\partial t}\int_a^b dr\left\{h-\frac{\partial}{\partial z}\left[(\gamma^2-1)^{1/2}\frac{a_1}{a_0}\right]\right\}. \tag{16}$$

Finally, using Eq. (4), we obtain an expression for the outflow current

$$I_{\text{out}}=2\pi b\int_{-\infty}^{+\infty}dz\,env_r\Big|_{r=b},$$

which is conveniently represented in the form

$$i_{\text{out}}=\frac{2eI_{\text{out}}}{mc^3}\ln\frac{b}{a}=b\int_{-\infty}^{+\infty}dz\,a_1\Big|_{r=b}\ln\frac{b}{a}, \tag{17}$$

where b is the radius of the outer electrode. Equations (12)–(15), (16), and (17) together with the boundary conditions and initial conditions completely determine the propagation of a wave of the *TM* type in the coaxial line.

Before analyzing the wave solutions of the system of equations, we note that for $\partial/\partial t=\partial/\partial z=0$ the equations have a stationary one-dimensional solution which describes the self-insulation of an electron beam in coaxial line for a definite relation between the current I and the potential U in the coaxial line (coax). If we assume that the electric field E_r at the negative electrode is zero, then inside the electron sheath (see Ref. 17)

$$\gamma(r)=\text{ch}\left(\alpha\ln\frac{r}{a}\right),\quad h(r)=-\frac{\alpha}{r}\text{ch}\left(\alpha\ln\frac{r}{a}\right). \tag{18}$$

Here the possible current I and potential U determine the parameters of the sheath in accordance with the formulas

$$\gamma=\text{ch}\,\psi+(s-1)\psi\,\text{sh}\,\psi, \tag{19}$$

$$i=s_0 s\psi\,\text{ch}\,\psi, \tag{20}$$

where

$$\alpha=s\psi/\ln\frac{b}{a},\quad s=\ln\frac{b}{r_1}\Big/\ln\frac{r_2}{r_1},\quad s_0=\ln\frac{b}{a}\Big/\ln\frac{b}{r_1}$$

$$\gamma=1+\frac{eU}{mc^2},\quad i=\frac{2eI}{mc^3}\ln\frac{b}{a},$$

and r_1 and r_2 are the boundaries of the electron sheath.

For $s_0=1$, $s=1$ corresponds to a parapotential current and $s=\cosh^2\psi$ corresponds to the minimum possible current in the coax for which insulation is retained.

For a given current and voltage it is possible to determine the current flowing along the negative electrode from the condition

$$\frac{2eI_c}{mc^3}\ln\frac{b}{a}=s_0 s\psi.$$

It should be noted that the parameter s_0 is related to the gap between the electron sheath and the cathode, which can arise as the result of inhomogeneities at the input to the coax or during the time evolution of the electron sheath. From the definition of s_0 it follows that $r_1=b(a/b)^{1/s_0}$.

Let us now consider the propagation in a coaxial transmission line of a nonlinear wave of magnetic self-insulation.[6,19] Here we shall assume that the wave in the coax is established and that all quantities in it depend only on $z-ut$ and r. In this case Eq. (16) can be written in the form

$$\frac{\partial}{\partial z}\left(\gamma-1+\frac{u}{c}\int_a^b h\,dr+\frac{\partial^2}{\partial z^2}L\right)=0, \tag{21}$$

where

$$L(z)=-\frac{u}{c}\int_{-\infty}^{z}dz\int_a^b dr\frac{(\gamma^2-1)^{1/2}}{a_0}\frac{\partial}{\partial z}\left(h-\frac{u}{c}e_1\right).$$

Obviously the functional $L(z)$ determines the structure of the wave front of the nonlinear electromagnetic wave. We shall assume that on both sides of the front of the wave $\partial/\partial z=0$ and shall integrate Eq. (21) over z over the region of the wave front. Here the functional L drops out and the following integral expression is obtained which relates the electrodynamical quantities on the two sides of the wave front:

$$\left\{\gamma-1+\frac{u}{c}\int_a^b h\,dr\right\}=0, \tag{22}$$

where $\{A\} \equiv A(z=+\infty) - A(z=-\infty)$. Similarly from Eq. (17) it follows that

$$i_{\text{out}} = b \ln \frac{b}{a} \left\{ h - \frac{u}{c} e_1 \right\}. \tag{23}$$

If there are no electromagnetic waves in front of the wave front, then outflow currents $i_{\text{out}} \neq 0$ arise at the wave front. For the case when the electron sheath is close to the cathode ($s_0 = 1$) and the amplitude of the vacuum precursor can be neglected, the following expressions are obtained from Eqs. (22) and (23) for the wave-front velocity u/c and the outflow currents i_{out} at the front:

$$u/c = (\gamma - 1) \operatorname{sh} \psi / (\gamma \operatorname{ch} \psi - 1), \tag{24}$$

$$i_{\text{out}} = s\psi(\gamma - \operatorname{ch} \psi + \operatorname{sh}^2 \psi) / (\gamma \operatorname{ch} \psi - 1). \tag{25}$$

Solving these equations together with Eqs. (19) and (20) for $s_0 = 1$, we can obtain expressions for u/c and i_{out} in form of functions of γ and i beyond the wave front. For a fixed potential difference on the coaxial line the values of u/c and i_{out} are completely determined by choice of the current i along the coax. In particular, this choice can be made from the condition of a minimum of the energy expended by the generator in producing the flow in the coax.

It should be noted that the energy of a unit length of the coax W, which is equal to the sum of the kinetic energy of the electrons in the coax and the energy of the electromagnetic field,

$$W = \frac{1}{2} \left(\frac{mc^2}{e} \right)^2 \left[\frac{1}{2} b^2 (h^2 - e_1^2) \ln \frac{b}{a} - (\gamma - 1) b e_1 \right]_{r=b}, \tag{26}$$

decreases as the coax is filled with electron flow. The expression for the coax energy Wl actually has the meaning of the thermodynamic internal energy of a system with a variable number of particles and is equal to the work expended by the generator in creation of the electron flow. For the minimal value of W at a fixed value of the potential on the coaxial line the value of the current i in the coax only slightly exceeds the minimum current in it[16,20]:

$$i_{\min} = s_0 \psi \operatorname{ch}^3 \psi, \quad \gamma = \operatorname{ch} \psi + \psi \operatorname{sh}^3 \psi. \tag{27}$$

This choice of the current in the coaxial line beyond the front of the nonlinear electromagnetic wave leads to values of $u(\gamma)/c$ and $i_{\text{out}}(\gamma)$ (see Fig. 1) which are in good agreement with the results of numerical calculations and the experimental measurements for an established value of the potential beyond the wave front.[21,22] The characteristic width Δ of the established nonlinear electromagnetic wave can be found from Eq. (21). Using the expression for L, we find that $\Delta \sim r_2 - r_1$.

To study the process of establishment of the wave and to find its structure, it is necessary to solve the complete system of equations (12)–(15) for a specified source at the input to the coax. In the general case as the result of the rise of the current pulse in the coax beyond the wave front there is established a flow whose parameters change, and the energy of a unit length of the coax W exceeds the minimum value. Here, of the two possible states with a specified current I and potential U, there is realized the state with maximum magnetic flux in the coaxial gap and correspondingly higher energy W. This corresponds to an electron sheath close to the cathode and is due to the appearance of inductive electric fields under the conditions of rise of the magnetic flux in the coax. Here the transition to the state with minimum energy is possible only in the dissipation time of the equivalent electrical circuit.

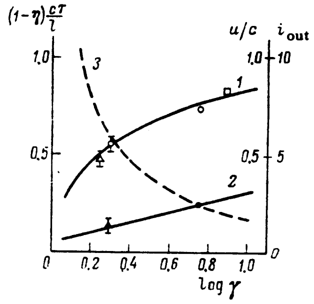

FIG. 1. Velocity of propagation of the nonlinear wave u/c (1), outflow current i_{out} at the front (2), and transport efficiency η for various values of the parameter $l/c\tau$ (3) as a function of the voltage at the input to the line U, $\gamma = 1 + eU/mc^2$; △ and ▲ are the experimentally measured velocities of the wave front and the outflow current at the front; ○ and ● are the results of calculations[22] of the velocity of the wave front and the outflow current; □ is the velocity of the wave front according to the measurements of Ref. 15.

It should be noted that the wave of magnetic self-insulation is evolutionary.[7] Considering small perturbations beyond the wave front, we can show that their velocity is greater than the velocity of the wave. On the other hand, if a perturbation appears in front of the wave of magnetic self-insulation, it increases the amplitude of the precursor, explosive emission occurs at the cathode, and the perturbation moderates its velocity. The latter is valid, of course, only in the case when the delay of the explosive emission is sufficiently small.

The magnetic self-insulation wave under discussion is not, strictly speaking, stationary, in view of constant losses at the front. If we assume that the values of the voltage U and current I beyond the wave front remain constant and the losses in the front lead to a shortening of the pulse, then we can determine the energy flow P_{loss} due to energy loss in the front.

Using Eqs. (1)–(6), we obtain the law of conservation of the energy of the electromagnetic field and the kinetic energy of the particles:

$$\frac{\partial}{\partial t} \left[\frac{\mathbf{H}^2 + \mathbf{E}^2}{8\pi} + (\gamma - 1) mc^2 n \right] + \operatorname{div} \left[\frac{c}{4\pi} \mathbf{E} \times \mathbf{H} + (\gamma - 1) nmc^2 \mathbf{v} \right] = 0. \tag{28}$$

Integrating this equation over the cross section of the coaxial gap, we obtain

$$\frac{\partial W}{\partial t} + \frac{\partial P}{\partial z} + 2\pi b (\gamma - 1) nmc^2 v_r \Big|_{r=b} = 0, \tag{29}$$

where W is the energy of the unit length of the coax and $P = IU$ is the energy flow in the coax with magnetic self-insulation.

Assuming in Eq. (29) that all quantities depend on $z - ut$ and carrying out integration with respect to z over the region of the wave front, we can obtain the power loss at the wave front

$$P_{\text{loss}} = \dot{P} - uW. \tag{30}$$

Taking into account that the wave front moves for a time l/u and assuming that the shape of the voltage and current in the wave is close to rectangular, we find the efficiency η of transport of energy in the line, determined from the ratio of the energy lost in the wave front to the total energy of a pulse of duration τ:

$$\eta = 1 - \frac{l}{c\tau}\left(\frac{c}{u} - \frac{c}{v}\right). \tag{31}$$

Here

$$\frac{v}{c} = \frac{P}{cW} = \frac{(\gamma-1)\operatorname{ch}\psi}{(\gamma-1)\operatorname{sh}\psi + s\psi/2}$$

is the velocity of propagation of energy in the stationary regime of magnetic self-insulation. In Fig. 1 we have shown the dependence of the transport efficiency η on γ for various $l/c\tau$.

3. QUASISTATIONARY REGIME

Experiments on magnetic insulation were carried out in the MS accelerator with an internal impedance of 10 ohms with a voltage at the line input of 200–500 kV and a current of 20–40 kA. The voltage-pulse duration at half-height was $\tau \approx 40$ nsec, and in the front—$\tau_f \approx 15$ nsec. In front of the diode of the accelerator was placed an auxiliary spark gap which decreased to 16 kV the voltage pulse on the diode arising in the course of the pulsed charging of the double shaping line of the accelerator.

Decreasing the voltage of the prepulse avoided premature appearance of plasma at the electrode surface and increased the reproducibility of the experimental results.

Study of the magnetic self-insulation regime was carried out in coaxial vacuum lines of length $l \leq 70$ cm. The parameter $l/c\tau$ did not exceed 6×10^{-2}, which assured quasistationary behavior. A vacuum coaxial line was connected to the output of the accelerator, as shown in Fig. 2. The characteristic impedances of the lines were chosen in the range from 20 to 100 ohms, and the radius of the inner electrode was from 0.36 to 12 mm. Variation of the interelectrode gap as the result of inaccuracy in installation of the inner electrode of the coax did not

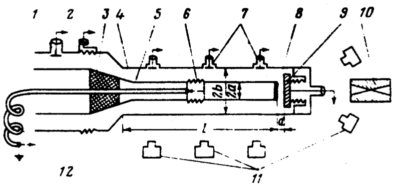

FIG. 2. Diagram of experiment: 1—capacitance divider, 2—shunt, 3—prepulse spark gap, 4—outer electrode of the line, 5—inner electrode of line, 6—cathode shunt, 7—Faraday cup, 8—cathode, 9—anode, 10—pinpoint camera, 11—x-ray detectors, 12—inductive coupling.

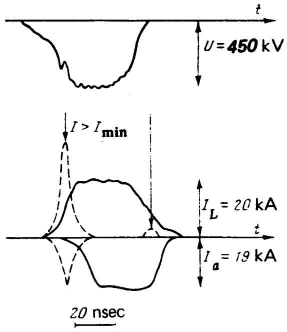

FIG. 3. Oscillogram of voltage U, current I_L at the line input and current I_a at the line output, and of the outflow currents (dashed curves) measured in the middle of the line of length 50 cm by two Faraday cups in the quasistationary regime.

exceed 10–30% and depended on the radius of the outer electrode. For small radii, conical transitions were used to increase the electric field strength at the input to the line adiabatically.

At the output of the vacuum line we placed a diode whose anode could be adjusted, permitting variation of the impedance of the diode. The diode was actually the load of the line, the impedance of which, as the result of the formation and motion of the plasma, depended on time and on the material of the cathode and anode. The experimental arrangement permitted the efficiency of coupling of the line and diode to be established.

The principal regularities of the magnetic self-insulation regime under study were obtained from measurements of the voltage and currents on the line.[11] The voltage at the input of the line was measured by a capacitance divider calibrated electrically, and by means of a magnetic analyzer. The energy of the electrons in the diode, determined from the penetrating power of the bremsstrahlung, corresponded to the readings of the capacitance divider. The current I_L at the input to the line and the current I_a in the end anode were measured by noninductive shunts.

In Fig. 3 we have shown typical oscillograms of the currents and voltages. The line current was delayed with respect to the voltage by 10–15 nsec, which were necessary for the appearance of intense explosive emission from the negative electrode.[23] The moment of appearance of the emission corresponded to the break in the voltage curve and to the appearance of x rays from the side walls of the outer tube of the coax. For the conditions indicated in Fig. 3, it corresponded to the rise of the electric field strength at the inner tube of the coax to 350 keV/cm in 20 nsec. The electron current to the anode was delayed by 5–10 nsec with respect to the line current. An additional time shift apparently arose as the result of the necessity of a longer time for development of emission from the cathode than from the side surface of the inner electrode, since the current density of the cathode is greater by $\sim 2l/a \approx 10^2$ times (l is the length of the line and a is the smaller radius). This delay depended on the cathode material. Thus, replacement of the stainless steel cathode by graphite reduced this time by 4–5 nsec, which corresponds to the

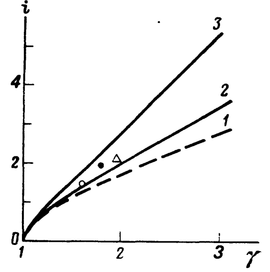

FIG. 4. Limiting currents $i=(2eI/mc^2)\ln(b/a)$ as a function of the voltage $\gamma=1+eU/mc^2$: 1—single-particle approximation, $i=(\gamma^2-1)^{1/2}$; 2—curve corresponding to minimum current $i_{\min}$; 3—curve corresponding to parapotential current $i_p=\gamma\ln(\gamma+(\gamma^2-1)^{1/2})$; ○, ●, △—experimental points corresponding to the respective ratios $b/a=1.6/1.1$, $2.6/1.3$, and $2.6/1.0$ obtained as the result of averaging over 6–10 shots.

conclusions of Ref. 23.

After completion of the processes of establishment of emission with sufficiently small cathode-anode gaps d the diode current coincided within 10% with the line current, which confirms the results of earlier experiments.[11,12] On increase of the cathode-anode gap the line current I_l dropped, and the voltage on the line increased, and with unlimited increase of d the voltage U on the line and the current in the line took on their limiting values. Here the outflow currents were closed in the end part of the section of coaxial line.

In Fig. 4 we have shown the experimental and theoretical dependences of the limiting currents of a cylindrical diode on the voltage, which had already been studied in Ref. 11. Later experiments[24] showed that the diode impedance does not depend on its length, and that the current is concentrated at the end of the line, which is confirmed by the destruction of the outer electrode of the coax. Establishment of this regime in the line should occur in coaxes whose length is greater than the transverse size, which is in agreement with the ideas of Creedon.[17]

In this section we investigate the dynamics of the establishment of magnetic self-insulation by detection of the outflow currents to the side surface of the line. These measurements were made by Faraday cups (see Fig. 2) mounted on the outer tubing of the coax. To remove the effect of displacement currents on the Faraday cup readings the collectors were screened with aluminum foil of thickness 10–12 μm. The outflow current signals, measured by two diametrically opposite probes in the middle of the line, are given in Fig. 3. The outflow currents appeared when the current I_L in the line was less than $I_{\min}$ and were decreased by an order of magnitude for $I_L > I_{\min}$. Here the magnetic self-insulation regime was established in the line. The outflow currents are maximal at the beginning of the pulse and then fall off more rapidly than the difference of the currents in the line and the anode. This indicates a shift of the outflow currents to the diode with increase of the current and magnetic field in the line.

The current values in the line, as was remarked above, approach their limiting values on unlimited increase of the gap d. Here it is possible to choose an accelerator gap d such that the diode current is practically identical to the limiting line current. Establishment of limiting values of the currents and voltages permits comparison of the experimental results with the conclusions of the theory of magnetic self-insulation. In Fig. 4 we have plotted the theoretical dependence of $I_{\min}$, the parapotential current I_p, and the current according to the single-particle model I_0 on the quantity $\gamma=1+eU/mc^2$ and the experimental points for lines with various characteristic impedances. It follows from the figure that the best correspondence with the limiting currents exists for $I_{\min}(\gamma)$.

The function $I_{\min}(\gamma)$ shown in Fig. 4 was obtained on the assumption that the electron sheath is close to the cathode. However, in Refs. 11 and 12 it was noted that as the result of inhomogeneity in z at the line input or as the result of the nonstationary nature of the pulse a removal of the flow from the cathode, accompanied by increase of $I_{\min}(\gamma)$, is possible. Comparison of the experimental data with a calculation according to the hydrodynamical model shows that the sheath can be assumed close to the cathode. The results of measurements for $\gamma \sim 7$, as was reported by Smith *et al.*,[15] also turned out to be close to the model of a close sheath. The position of the sheath can also be judged by comparing the recorded current along the cathode with the theoretical value, which depends on the configuration of the sheath. Measurements of the current were made by means of a shunt line installed in a gap in the negative electrode, the signal from which was taken off by inductive coupling. It turned out that after establishment of the insulation regime in the line the current along the negative electrode is closer to the theoretical values calculated for the model of a close sheath (see Fig. 5).

The experiments were carried out mainly in lines with a small diameter ratio ($b/a \lesssim 2$). Increase of the ratio to $b/a \gtrsim 5$ is accompanied by appearnace of outflow to the positive electrode even for currents which substantially exceed the minimum current. This change in

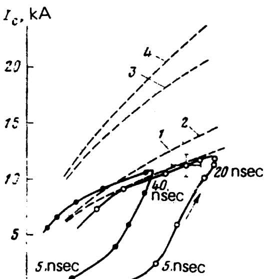

FIG. 5. Current along the inner electrode of the line I_c as a function of the voltage on the line U: 1, 2, 3, 4—theoretical curves; 1, 2 are for an electron sheath close to the inner electrode; 3, 4 are for an electron sheath pulled away from the inner electrode of the line by 0.5 cm; 1, 3—current along inner electrode for parapotential current in the line; 2, 4—for minimum line current; ●, ○—time dependences of the current measured in the inner electrode. The experimental points are given every 5 nsec.

the regime of operation of the line can be interpreted as a breaking away of the electron sheath from the cathode and its motion toward the anode.

As was shown in Sec. 2, for $I > I_{min}$ and for fixed I and and U the current configuration in the coax can have two equilibrium states which differ in the thickness of the electron sheath. In the experiments carried out, an attempt was made to determine approximately the location of the outer limit of the electron sheath in the gap. For this purpose we placed in the interelectrode gap a Faraday cup mounted on the outer electrode and recorded its reading as a function of its depth of penetration h into the interelectrode gap. The perturbations of the electric field arising from this should only increase the current to the Faraday cup. However, for currents exceeding I_{min} there was practically no outflow up to $h \lesssim (b-a)/3 = 5$ mm. For a line with $b/a = 2.6/1.0$ at $U = 500$ kV and $I_l = 20$ kA it follows from calculations carried out by means of Eqs. (19) and (20) that the gap between the outer boundary of the sheath and the surface of the positive electrode can take on two values: 0.34 and 1.28 cm, corresponding to different degrees of filling of the interelectrode gap by the electron flow. Thus, we can state that in the established regime the configuration with a thin sheath of electrons is realized. These same measurements in the front of the pulse showed that during the establishment of magnetic insulation the electrons fill the entire interelectrode gap.

It should be noted that for currents of the order of I_{min} an asymmetry of the outflow, which was preserved with time, was experimentally recorded (Fig. 3). This fact indicates formation of perturbations of the sheath drawn out along the line and apparently related to inhomogeneity of the emission of electrons in the gap.

The transport efficiency of pulses along the line in the established regime for $I > I_{min}$ is close to 100%. Under the experimental conditions in the MS accelerator, connection of the line segment between the accelerator tube and the diode decreased the beam energy. For a line length 0.7 m the loss was at least 10% and was due to outflow currents in the pulse fronts. Efficient transport was obtained for high electric fields in the coaxial gap. The maximum electric field strengths in the gap E_{max} for $b/a = 1.6/1.3$ and $b/a = 1.6/1.1$, calculated from Eqs. (18)–(20), with inclusion of the space charge of the electrons which had entered the interelectrode gap, for the case when the configuration with a close sheath is realized, are respectively 990 and 830 kV/cm.

To determine the highest achievable electric fields in the interelectric gap, we carried out experiments with coaxial lines of small diameter. Since the accelerator voltage was limited to a value ~500 keV, a high field strength could be reached by choosing small interelectric gaps or small radii of the inner tube. Measurements showed that for $a = 2$ mm and $b = 4$ mm the field strength without inclusion of space charge reaches 2.5 MV/cm, and in the line with $a = 0.36$ mm and $b = 4$ mm it reaches 5.6 MV/cm.

4. FOCUSING OF THE BEAM AT THE OUTPUT OF A LINE WITH MAGNETIC INSULATION

Transmission of energy from a line with magnetic insulation to a diode of small size was studied in thin coaxial lines of length ~10 cm, principal attention being devoted to focusing of the beam at the diode.[19] The radius of the inner electrode of the coax was varied from 0.36 to 2 mm, and the outer radius was usually 2–4 mm and was increased in some experiments to 25 mm. The line was mounted along the axis of a cylindrical drift chamber of diameter 50 mm with metallic walls. A plane anode covering the entire cross section of the line was moved along the axis. In lines with small interelectrode gaps the danger of premature filling of the line and the end anode with plasma produced by the prepulse is increased. Therefore in front of the input to the line we mounted an additional spark gap with surface breakdown of a dielectric, which did not transmit the prepulse voltage to the line.

For high inpedances of the end diode, such that the beam current practically did not reach the anode, an insulation regime with limiting current was established in the coaxial lines. In this regime the line impedance Z rapidly dropped and the line was shorted if the interelectric gap turned out to be less than 1.5–2 mm. On increasing the gap the value of Z remained almost constant with time. A feature of the lines with a gap $b-a > 1.5$–2 mm was their large diameter ratio (cylindricity): $b/a = 2$–11. Measurements showed that the limiting current in such lines no longer depended on the ratio of the electrode radii, and the impedance of the line was established at the level 20–25 ohms. The value of the limiting current exceeded by several times the minimum current calculated from Eq. (27) for a close electron sheath ($s_0 = 1$). This feature was preserved also for lines whose transverse dimensions were increased by a factor of eight. This shows that the increase of the minimum current in thin, highly cylindrical lines cannot be explained only by the rapid change of the interelectrode gap as the result of expansion of the plasma layers. It is possible that the increase of the minimum current of the line is due to the conditions of formation of the electron sheath at the input to the line and to its pulling away from the negative electrode (see Eq. (27)).

On approach of the anode to the end of the line, the diode current rose. Its behavior consisted in appearance of a time delay relative to the line current, which is illustrated by the oscillograms of Fig. 6. The delay time decreased linearly with decrease of the diode gap d from 20 to 3 mm, and the switching of the line current to the anode occurred more rapidly. Before appearance of an anode current I_a equal to the line current I_l, the main part of the difference current $I_l - I_a$ was completed in the form of an electron beam at the end of the line. This is confirmed by recording the space and time dependence of the bremsstrahlung from the side wall and its disappearance under the action of the beam. For $I_a \approx I_l$ the radiation dropped sharply. It is important to note that the measured impedance of the diode turned out to be 10–30 times less than that estimated from the Langmuir-Child law for a spherical

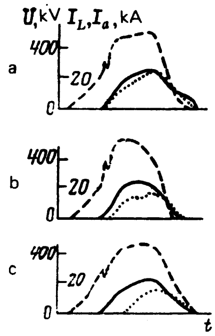

FIG. 6. Oscillograms of the current I_L (solid curve) and voltage U (dashed) of the line and the anode current I_a (dotted curve) for $b/a = 0.4/0.075$ mm, $d = 3$ mm (a), 5 mm (b) and 10 mm (c).

diode.

In these experiments a focusing of the beam in the anode plane was observed. The focusing was studied by two methods. The distribution of the current density at the anode, averaged over the pulse, was found from photographs in the x-ray beams by a pinpoint camera. The angle at the vertex of the two cones forming the chamber was 7°, and the diameter of the opening was 180 μm. We have shown the distribution of current density in Fig. 7a. The characteristic diameter of the focal spot under optimal conditions is 1 mm. The dynamics of the focusing was investigated by means of an x-ray detector with a time resolution 5 nsec. The bremsstrahlung was recorded by a detector through a lead collimator which distinguished a portion of the anode surface, the diameter of the collimator opening being varied. The high reproducibility of the position of the focus on the anode and the intensity of the bremsstrahlung permitted us to determine from comparison of signals that $\gtrsim 20\%$ of the current fell in the focal spot and the current density reached 0.5 MA/cm^2. In regimes with sharper focusing ($b/a = 0.4/0.036$) the time of the maximum focusing with increase of d is shifted to the end of the pulse (see Fig. 7b). The delay in appearance of the beam current at the anode and the time shift of the focusing increased linearly as d was changed from 3 to 20 mm. In contrast to experiments on focusing of a beam in diode with a pin cathode, in which an extraordinarily strong dependence of current density on d was observed,[25] in our experiments the maximum current density changed only weakly as d was changed from 3 to 6 mm.

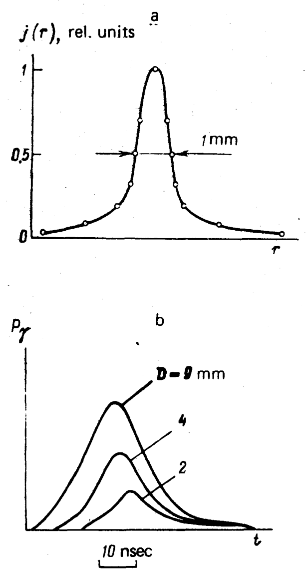

FIG. 7. a—Distribution of electron-beam current density $j(r)$; b—intensity of collimated x rays P_γ from the end of the line for various collimator diameters D.

The behavior of the diode impedance and the beam focusing can be explained by the appearance at the end of the negative electrode of the line of a plasma sheath and acceleration of this sheath to the anode. The motion of the plasma carries the effective emission boundary to the anode, decreasing the diode impedance, and leads to a switching of the line current to the anode. For a constant plasma velocity, the anode current delay should increase linearly with increase of the gap between the end of the line and anode, which is confirmed experimentally (Fig. 6). Simultaneously with decrease of the diode impedance, the beam current density at the anode should increase, and conditions arise for focusing of the beam as the result of filling of the diode with plasma. As follows from Fig. 6, the directional velocity of the plasma should be of the order $v_p \approx d/\tau_d = 5 \times 10^7$ cm/sec, which is 5–15 times greater than the values of v_p observed in plane diodes or in diodes with an isolated pin cathode. There are several mechanisms capable of explaining this velocity value. The most probable one is acceleration of the near-electrode plasma at the output of the line by radial outflow currents, much as occurs in coaxial plasma accelerators.[26] If the plasma acceleration time is less than the pulse duration, $\delta/v_z < \tau$ (δ is the length of the line section in which the principal outflow current $\sim I_{min}$ flows), then from the equation of motion of a plasma containing ions with mass M:

$$nM\frac{dv_z}{dt} = \frac{\partial}{\partial z}\frac{H_\varphi^2}{8\pi} \qquad (32)$$

we can estimate the possible plasma concentration m, substituting into Eq. (32) the experimentally determined plasma velocities and field values:

$$n = H_\varphi^2/4\pi M v_z^2 \approx 4\cdot 10^{16}/A, \qquad (33)$$

where A is the mass of the ion in atomic mass units.

In the experiments described by Orzechowski and Bekefi,[27] it was shown by means of spectroscopic measurements that the cathode plasma consists mainly of light ions. Transferring these conclusions to the conditions of our experiment, it can be found from Eq. (32) that the plasma concentration should be within the range 10^{15} to 10^{16} cm^{-3}. This concentration is sufficient to compensate the space charge of the beam and to decrease the diode impedance as the result of shortening of the effective length of the accelerating gap.

The model adopted for the appearance of plasma in the diode explains rather well the change in the focusing regime as the result of increase of the outer electrode radius in the transition to a diode with a pin cathode. Increase of the outer electrode diameter should be accompanied by a reduction of the velocity of the plasma jet, since at the same time the size of the outflow region ($\delta \sim b$) increases and the accelerating force

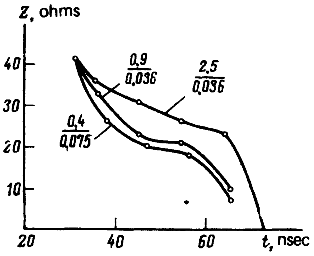

FIG. 8. Input impedance Z of a line of length 10 cm as a function of time for various ratios of the radii of the outer and inner electrodes of a coaxial line for $d=3$ mm. The beginning of the voltage is at $t=0$, and the beginning of the current is at $t=20$ nsec.

$$\frac{\partial}{\partial z}\frac{H_\varphi^2}{8\pi}$$

falls off. As a result the diode current delay increases and its impedance rises. In Fig. 8 we have shown measurements of the impedance of lines with various outer diameters, which confirm these conclusions.

As in the case of focusing in diodes with a pin cathode, in lines with large diameters the range of cathode-anode gaps optimal for focusing is reduced. In the focusing regime the electron energy corresponded within 20% with the voltage on the diode. This followed from determination of the bremsstrahlung penetration by the absorber method on the assumption of monoenergetic electrons. The absolute intensity of the bremsstrahlung from the anode also is satisfactorily explained by the bremsstrahlung of a monoenergetic beam.

Thus, these experiments show that as the result of loss of a portion of the beam energy it is possible to reduce the diode impedance by 20 to 30 times. The experimental results are satisfactorily explained if we assume shaping of the accelerated jet of cathode plasma, which provides focusing of the beam onto the anode. From the measurements it follows that the beam energy at the output of thin lines may amount to more than 70% of the pulse energy.

5. WAVE REGIME IN LINES WITH MAGNETIC SELF-INSULATION

In this section we describe an experimental study of the establishment of magnetic self-insulation in coaxial lines for a duration of the rise time of the electromagnetic pulse τ_f at the input less than or of the order of the propagation time of the pulse along the line $\tau_f \lesssim l/c$ (l is the length of the line). A number of conditions must be satisfied for the shaping of the wave front and its propagation. First, the line length must exceed by several times the dimension of the wave front, and the time of formation of the nonlinear wave must be no greater than the time of propagation of the wave along the line. A second necessary condition is the provision of sufficient electron emission at the wave front. Here we note that according to Sec. 2 for an established propagation regime it follows that the width of the front of the nonlinear electromagnetic wave is of the order of the interelectrode gap, and the first condition is satisfied with a large margin. However, as experiment shows, the real width of the front turns out to be substantially greater, which may be due both to a greater time of establishment of such a front or to inadequate emission from the cathode.

In the first experiments carried out in the MS accelerator, the line length was 3.5 m. Subsequently this length was increased to 4.5 m. For simplicity of installation of lines with such a length, they were mounted vertically at the accelerator output. The radius of the outer electrode of the coaxial line was 2.6 cm, and the inner electrode—1.0 cm. The line was supplied with the usual set of diagnostic probes: shunts for determination of the currents at the input and output, Faraday cups for measurement of the outflow currents to the sidewalls of the outer electrode, capacitance voltage dividers, and x-ray probes for measurement of the energy and current of the electrons.

On appearance of the pulse at the line input, intense explosive emission begins, the development time of which is determined by the time shift between the current at the line input and the outflow current measured by the Faraday cup at the beginning of the line (see Fig. 9). The outflow current appearing as the result of intense emission at this Faraday cup (see Fig. 2) arose 10 nsec after arrival of the pulse, allowing for the propagation time of the wave. The velocity of propagation of the signal in the coaxial line, determined from the delay in appearance of the maximum outflow currents at the Faraday cups located along the line, turned out to be substantially less than the velocity of light. The same velocity values were obtained from the delay in the signals of the x-ray detectors which recorded the radiation from the side surface of the line. Analysis of the outflow-current oscillograms and also of the current at the end of the line shows that along the line after appearance of explosive emission there is propagated a wave whose front is steepened. The dependence of the wave-front propagation velocity on the voltage and outflow current in the front, obtained by subtraction of the oscillograms for the current at the anode and the shunt current, is in good agreement with the theory developed on the assumption that the electron sheath is close to the inner electrode of the line. The experimental points and the theoretical curves plotted from Eqs. (24) and (25) with inclusion of Eqs. (19)–(20) are given in Fig.

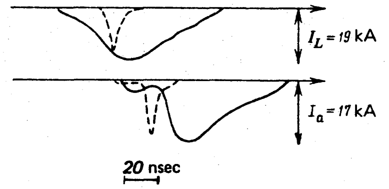

FIG. 9. Oscillograms of the voltage U, current I_L at the input, and current I_a at the output of the line, and also of the outflow currents (dashed curves) measured by two Faraday cups at the beginning and end of the line in the wave regime.

1. It can be seen that the results of experiments[11] carried out at voltages up to 3 MV also agree within experimental error with the theoretical results.

The width of the wave front calculated from the measured velocity and duration of the main outflow pulse is 1–1.5 m, which is 3–4 times shorter than the length of the line. An indication of the reliability of this estimate of the front duration is the fact that the measured outflow-current density ~(3–4) A/cm² agrees with the theoretical value determined from the outflow current in the main front and the surface of a section of the outer electrode equal to the length of the front: $j_{out} = I_{out}/2\pi b u \tau_f$, where u is the velocity of the wave. Beyond the wave front there is established in the line a current close to the minimum current for an electron sheath configuration close to the inner electrode of the line. This confirms the assumption made in plotting the curves in Fig. 1.

Before the wave front with magnetic self-insulation a vacuum precursor is propagated along the line—an ordinary electromagnetic wave. The amplitude of the precursor is limited by the appearance of emission from the negative electrode. If emission from the negative electrode is possible at any field strengths, the amplitude of the vacuum precursor will be vanishingly small as the result of high damping and transformation into the wave with magnetic self-insulation. For small amplitudes the velocity of this wave is low and it will be overtaken by the portions of the wave with higher field strength. This process leads to a steepening of the wave profile at the front and to formation of electromagnetic shock waves.[7] In a real line with a delay between the appearance of the electric field and the emission of electrons the amplitude of the precursor is determined by this delay t_d, which decreases with increase of the electric field strength E and can be determined from Ref. 23. To determine the shape of the precursor it is necessary to know the dependence of the emission-current density on the time and field.

At the front of the nonlinear electromagnetic wave there are outflow currents which decrease the efficiency of energy transmission in the wave regime of magnetic self-insulation. These outflow currents, reaching the anode, can in principle produce an anode plasma which should lead to the appearance of ion currents in the interelectrode gap and to additional energy loss. Therefore it is necessary to evaluate the possibility of such losses.

Using the relation obtained above for the power loss P_{loss} in the wave front, we can obtain the following expression for the energy contribution at the anode w in J/g as the result of electron outflow currents:

$$w = 5.3 P_{loss}\ (\mathrm{TW})/\lambda \frac{u}{c} b\ (\mathrm{cm}),$$

where λ is the product of the electron range in matter by the density in g/cm². Estimates with this formula show that for $U = 2$ MV the power is $P_{loss} \sim 2$ TW and $w \sim 1$ J/g, which is 10^2–10^3 times less than the energy contribution necessary for creation of ion currents from the anode.[28,29]

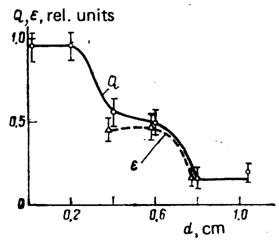

FIG. 10. Charge-transport efficiency Q and energy transport efficiency ε as a function of the cathode-anode gap d.

The efficiency of transmission of the wave energy along the line is shown in Fig. 10 as a function of the cathode-anode gap. In the optimal regime corresponding to a gap of 6 mm the efficiencies for transport of energy and charge coincide and amount to about 50%. We note that the transport efficiency η calculated theoretically from the power dissipated in the front exceeds the experimentally determined value and amounts to 70%.

6. CONCLUSION

Experiments with lines in the quasistationary and wave regimes indicate satisfactory agreement with the theory of magnetic self-insulation set forth in Sec. 2. The electric field strengths obtained in lines at a voltage level ~0.5 MV are close to the values required for transporting the beams of the Angara-5 installation. The results of experiments with coaxial lines[15] show that in the transition to voltages ≤3 MV no qualitatively new features of magnetic self-insulation are observed. Therefore the efficiency of beam-energy transport along uniform lines can be estimated from Eq. (31). For the practically important ranges of wavelength (≤10 m), voltage (2–3 MV), and pulse length (50–100 nsec), the efficiency is $\eta \gtrsim 0.8$.

An important result is the observed reduction of the impedance of the diode at the end of the line and the beam focusing, which were described in Sec. 4. In the process of switching the line current to the anode, as the result of appearance of near-electrode plasma sheaths at the line output, ion outflow currents can arise. Therefore it is necessary to investigate magnetic insulation with a transverse flow of ions, and also the dynamics of the plasma motion, in order to select optimal conditions for matching the line and the diode.

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