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DYNAMICS OF THE Z PINCH WITH A LIGHT LINER. II. SINGLE-ENVELOPE LINERS AND THE ANOMALIES OF THE CUMULATION STAGE

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The results of calculations of the compression of single-envelope liners toward the axis in the one-dimensional magnetic radiative gas dynamics approximation are considered. A refinement is proposed for the method of calculating the cumulation stage, making it possible to obtain better agreement with experimental data.

As shown by experiments [1-3], a cylindrical liner accelerated by the magnetic pressure of the intrinsic current to velocities of 200-400 km/sec can be an effective means of increasing the power. The power increases as a result of a substantial shortening of the plasma retardation time at the symmetry axis in comparison with the linear acceleration time. In real systems relativistic-electron-beam generators are used as energy sources giving a current pulse of several megamperes with a rise time of less than 100 nsec and the energy is delivered to the liner by magnetically insulated vacuum lines, i.e., the power supply is a system with distributed parameters and the equation for long lines must be used to describe this system. In order to solve such equations one must know the electrical engineering parameters of the line (per unit length), which cannot be reproduced from the published data. With acceptable accuracy for practical purposes one can use an ordinary RLC circuit (a system with concentrated parameters), choosing its parameters so that the dependence of the current on time would correspond sufficiently well to the experimental data until the maximum current is attained. This is how we conduct the calculation here, as described earlier [4]. After the current reaches maximum, a crowbar-breaker is tripped and we then calculate a close inductance-liner circuit, while the processes in the disconnected part of the circuit, capacitance-external resistance, are not considered in this case. We note that the approximation in which the dependence of the current on time is prescribed beforehand is unsatisfactory for reasons discussed below. The method of calculating the system of magnetic radiative gasdynamic (MRGD) equations is described in the first part of this communication [4]. Since the calculation of the ionization component of the plasma from the system of nonstationary equations of charge kinetics is fairly long, however, in this part of the study the composition of the plasma is found from the stationary equations, i.e., we set $dN_2/dt = 0$. As shown by comparison of the calculations of liner compression with steady-state and transient kinetics, the results differ little and the calculation time increases by an order of magnitude. This is because all the plasma properties according to the steady-state kinetics can be calculated beforehand and the ready tables can be used in the MRGD calculations.

Let us consider the results of calculations of the following variants of compression of single-envelope liners (Sections 1, 2 – see [4]).

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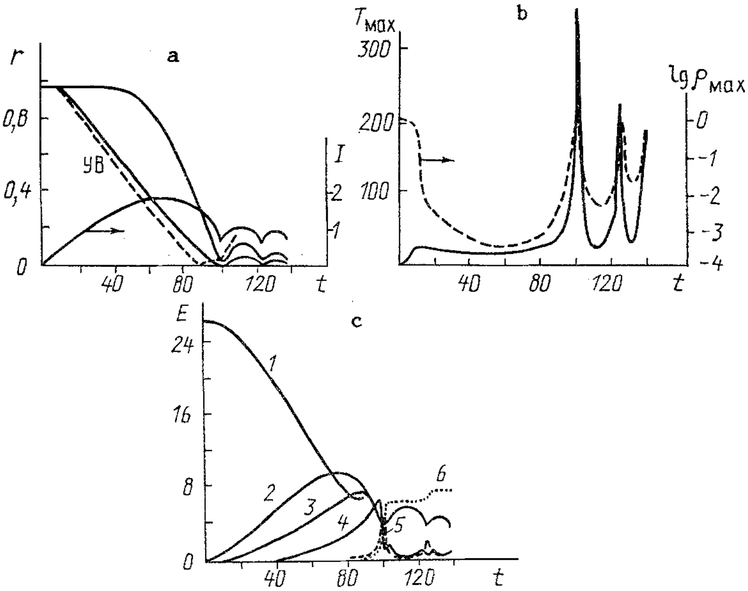

Fig. 1. Time dependence of the current and radii of the contact boundaries (a), the maximum temperature and density (b), and the components of the energy (c) in variant 3. Energy components: 1) capacitance, 2) inductance and magnetic field, 3) external resistance, 4) kinetic, 5) internal, 6) radiation, 1, MA, r, cm; t, nsec; ρ, g/cm^3; T, eV; E, kJ.

3. Plastic liner (composition $CgO_{10}N_2$), r_0 = 0.95 cm, 1 = 1 cm, M = 110 μg, C = 0.985 μF, L = 2 nH, R = 0.04 Ω, U_0 = 231 kV, r_* = 3.6 cm, t_* = 85 nsec, ambient — air, (78% nitrogen, 21% oxygen, 1% argon) with density $2 \cdot 10^{-6}$ g/cm^3, and E_0 = 26 kJ.

4. As in Sec. 3, except that r_0 = 1.25 cm.

Because of the skin effect the gas adjacent to the inner side of the liner (we are considering variant 3) heats up to 25 eV in 10 nsec. The radiation from this region evaporates the envelope, whieh begins to expand intensively, and a shock wave moving toward the symmetry axis is formed in the ambient air. The outer boundary of the envelope is restrained by the magnetic pressure and virtually does not move for 40 nsec. The inner boundary of the liner is accelerated toward the symmetry axis and moves with a velocity ≈ 105 km/sec and the shock wave moves ahead of it with a velocity of ≈125 km/sec (Fig. 1a). The current increases, reaches a maximum of 1.9 MA in 70 nsec, and then gradually decreases (Fig. 1a). The increase causes the magnetic pressure to rise and, starting from 40 nsec, the outer boundary of the liner also tends to the axis, gradually increasing its velocity and catching up to the inner boundary. The radiation equalizes the temperature over the thickness of the liner and in this stage of compression to the axis it is 8-10 eV with a small maximum of ≈15 eV on the leading edge of the shock wave (Fig. 1b). The density of the evaporated liner in this interval of time is roughly 10^{-4}-10^{-3} g/cm^3 (Fig. 1b).

At 85 nsec the crowbar-breaker disconnects the capacitance and the external resistance from the circuit. By that time 9.0 kJ had been transferred to the energy of the inductance (of the magnetic field) and 3 kJ to the kinetic energy. Part of the energy is lost: 7.2 kJ was released in the external resistance and 6.7 kJ remained in the capacitance (Fig. 1c). At 86 nsec the shock wave reaches the axis, is reflected and raises the temperature and density, travels along the oncoming material of the liner, and emerges outside at 100 nsec. By 101 nsec the linear has been compressed to the axis. The temperature and density increase to 354 eV and 3.1 g/cm^3, respectively. With the compression the resistance of the plasma grows, causing the current to decrease to a minimum of 0.65 MA. The gas pressure then exceeds the magnetic pressure and the liner plasma expand after reflection from the axis. In this case the resistance decreases, the current again increases 10 1.15 MA (112 nsec), and the maximum temperature and density decrease. The following changes in the energy characteristics correspond to these processes. The kinetic energy rapidly decreases and the internal energy reaches a maximum at 3.7 kJ, after which it decreases while the radiation loss rapidly increases to 6 kJ. Expansion of the compressed plasma causes the

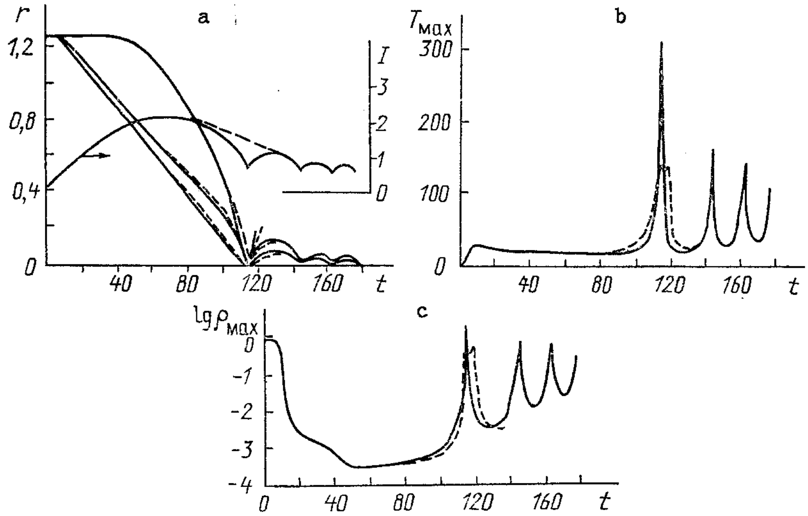

Fig. 2. Time dependence of the current and radii of the contact bounderies (a), the maximum temperature (b), and density (c) for variant 4. The dashed lines represent calculation with allowance for the rarefied gas in the interelectrode space.

kinetic energy to rise to 1.8 kJ. As a result of dispersion the gas pressure of the plasma decreases, after some time the magnetic pressure begins to exceed it and the dispersion of the plasma is slowed down, the plasma stops at a radius of 0.13 cm, and then again is compressed toward the axis (125 nsec). A second temperature peak (230 eV) and a second density peak (1.5 g/cm^3) are formed. The energy characteristics and the current vary in much the same way as in the first compression. The radiated energy increases to 7.4 kJ. Compression is subsequently repeated once more at 140 nsec. In this case the density rises to 0.7 g/cm^3 and the temperature, to 150 eV.

We note the characteristic behavior of the current at the time of compression of the plasma at the axis, viz., it drops to a minimum and then increases. This is due to an increase in the resistance of the plasma column during compression, despite the increase in electrical conductivity as a result of the rise in temperature.

Although such behavior was not detected (for the reasons, see below) in the studies [1-3] which we considered, in experiments [5, 6] with gas liners, obtained by pulsed admission of gas, the current varies under compression in just this way. Clearly, if in the calculations we prescribe the time dependence I(t) of the current instead of calculating it, the gasdynamics of the cumulation and the resulting parameters may be completely distorted. This will be due to the fact that the increase in the plasma resistance (which should entail a drop in current) is in no way associated with the change in current, i.e., the magnetic pressure will be inaccurate (since the value of the current is incorrect) and the compression dynamics will be changed greatly. Thus, if in the prescribed dependence I(t) the time at which the current passes through the minimum (and especially if there is no minimum) is slightly "shifted" relative to the calculated cumulation time, the resulting parameters are incorrect.

The dynamics of liner compression obtained in variant 4 (solid lines in Fig. 2) is qualitatively similar to that considered above for variant 3 and, therefore, we shall not discuss it in detail. The energy characteristics for this variant are shown in Fig. 3a.

In the calculation at the time of cumulation the full width at half-height τ of the radiation pulse (and the peak of the maximum temperature) is roughly 2 nsec, while the experimental value is ~10 nsec. To explain this discrepancy reference is often made to the formation of instabilities and a transition to two-dimensional MRGD calculation is recommended [7], which is more involved and requires considerably more computer time. At the same time, this discrepancy can be explained as follows. As the liner converges onto the axis its resistance decreases rapidly since the cross section decreases more rapidly than the electrical conductivity grows as the temperature rises. Indeed, we assume that the outer radius of the liner depends on time as

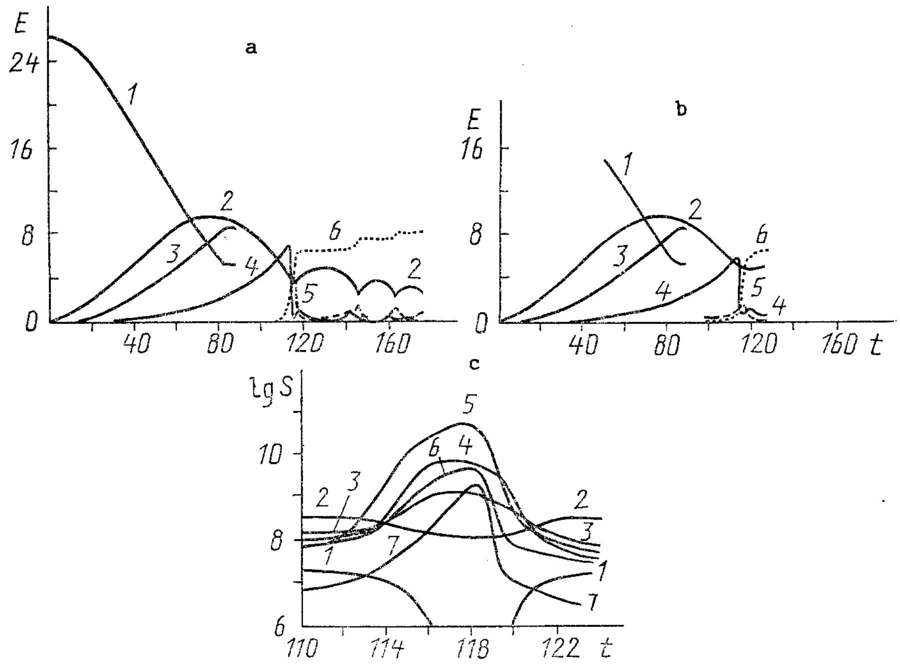

Fig. 3. Time dependence of the energy in different elements of the electric circuit (a, b) notation as in Fig. 1c) and the emergent radiation fluxes [c) the numbers denote the number of the group] for variant 4; a) usual calculation, b) calculation with allowance for the rarefied gas in the interelectrode space 5, W/cm^2.

$$R = c\,|t - t_c|^{\alpha},$$

where t_c is the cumulation time and c and α are constants. The rate at which the liner converges then is

$$v = dR/dt = \alpha R/|t - t_c|.$$

From the law of conservation of energy we have

$$M\,\frac{v_0^2}{2} = M\,\frac{v^2}{2} + N\,\frac{3}{2}\,kT, \quad N = M/m,$$

where v_0 is the liner velocity at some time t_0, when the temperature is still low; M is the liner mass; m is the atomic mass; and T is an average temperature (as shown by calculation, after the shock wave reaches the axis the temperature from the axis to the outer boundary of the liner is almost constant, because of radiation energy transfer). It thus follows that

$$T = \frac{mv_0^2}{3k}\left[1 - \left|\frac{t - t_c}{t_0 - t_c}\right|^{2(\alpha-1)}\right].$$

Let us consider the dependence of the liner resistance R_1 on time: $R_1 = \ell/(\sigma S)$, where ℓ is the liner length, S is the cross-sectional area, and σ is the electrical conductivity. Since it is determined by the Slitzer formula at high temperatures, the electrical conductivity virtually does not depend the density (through the Coulomb logarithm) and is proportional to the three-halves power of the temperature, i.e., $\sigma \sim T^{3/2}$. Then

$$\frac{R_1}{l} \sim (\sigma S)^{-1} \sim (\sigma R^2)^{-1} \sim T^{-3/2} R^{-2} \sim$$
$$\sim \left[1 - \left|\frac{t - t_c}{t_0 - t_c}\right|^{2(\alpha-1)}\right]^{-3/2} |t - t_c|^{-2\alpha}.$$

As a result the resistance increases at $t \to t_c$: $\frac{R_1}{l} \sim |t - t_c|^{3-5\alpha} \to \infty$ for $3/5 < \alpha < 1$ and $R_1/l \sim |t - t_c|^{-2\alpha} \to \infty$ for $1 < \alpha$.

The fact that part of the energy can be carried off by radiation does not change this result, although the electrical conductivity will increase more slowly (because the rate of temperature growth decreases). When the envelope is compressed, low-density gas flows in from the outside and radiation from the compressing liner heats this gas to 8-10 eV. Starting from a certain time the resistance of this rarefied gas in the interelectrode gas becomes smaller than that of the internal dense gas (or the liner itself). As a result of this a large part of the current flows through this rarefied region and a low current flows in the dense core; the ponderomotive force in this region will be small and the material of the liner begins to compress by inertia. Because of this the outer boundary cannot catch up to the inner boundary; the liner is rather "thick" upon arrival at the axis. As a result, the radiation pulse "stretches" in time. The rarefied gas through which the main current flows will be acted on by a large ponderomotive force and it will be "pushed" toward the outer boundary of the liner.

A calculated half-width of the radiation pulse that is substantially smaller than the experimental value is a characteristic feature of one-dimensional calculations. This is because practically all of the published studies on liner modeling in the one-dimensional MRGD approximation use a Lagrangian net, moving together with the material. In this case Maxwell's equations are solved for cells of the net that correspond initially to the radii from the symmetry axis $r_0 = 0$ to the edge of the electrodes $r_1(t)$. In view of this, the entire current should flow in the space from r_0 to r_1. With compression of the liner $r_1(t)$ moves away from the edge of the electrodes toward the symmetry axis. As a result the region from r_1 to the edge of the electrodes is not taken into account in the calculation, and a large part of the current passes precisely in this region upon compression, as explained previously. This is why calculation differs from experiment as to the width of the radiation pulse. Calculations of liners in the two-dimensional formulation are usually carried out in Euler coordinates, i.e., a net is prescribed in space (constant in time) as material flows through it. In this case the rarefied envelope on the outside of the liner in the interelectrode space is automatically taken into account and, therefore, the agreement with experiment in regard to the radiation pulse is much better [7]. Another difficulty arises in Euler coordinates, i.e., a rather fine net near the symmetry axis is required if the cumulation stage is to be calculated correctly and this may substantially affect the calculation time.

The laser shadow photographs given in [1] suggest that an envelope of rarefied gas is formed on the outside of the liner. The problem of the origin of this envelope is fairly complicated. This may be gas that flows in behind the liner into the interelectrode space and is then "pushed" by ponderomotive forces. It may also be that instabilities develop on the outer boundary of the liner as it converges to the axis and as a result part of the mass of the liner remains outside of the main mass (this occurs after the elapse of some

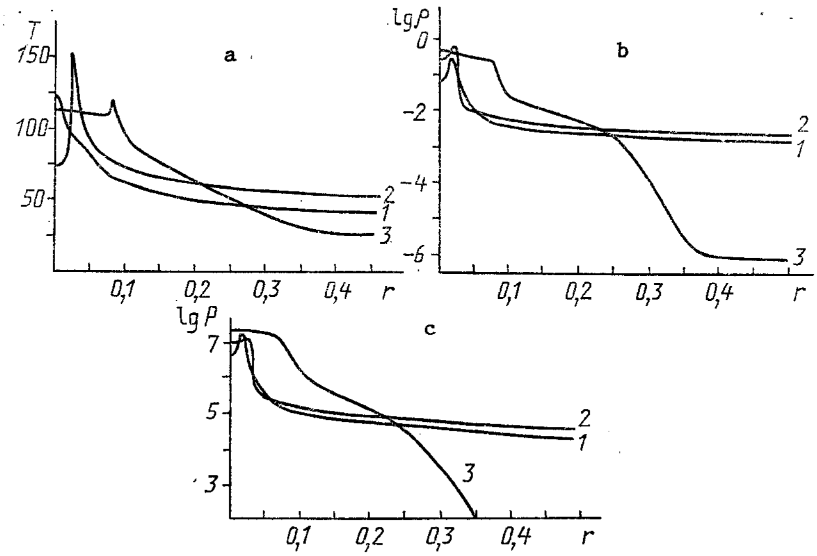

Fig. 4. Distribution of the temperature (a), density (b), and pressure (c) along the radius in variant 4 of the calculation for several times: 1) 114.23 nsec; 2) 114.68 nsec; 3) 118 nsec, T, eV; ρ, g/cm³, P, atm.

characteristic time of instability development). The second of these possibilities cannot be taken into account in a one-dimensional calculation. At the same time, the first can be incorporated rather simply into a one-dimensional calculation. To do this we need the outer boundary $r_1(t)$, for which Maxwell's equations (and the MHD motion) are calculated, with a continuous shift with respect to mass so that it would stay in the neighborhood of the edge of the electrodes. Such calculation (variant 4) with allowance for the flow of current in the rarefied envelope (dashed lines in Fig. 2) shows that the full-width at half maximum of the radiation pulse (and temperature) in this case is roughly 10 nsec. The plasma parameters decrease appreciably at the time of cumulation (T_{max} = 154 eV, ρ_{max} = 0.48 g/cm³), which is in better agreement with the experimental results (T_{max} = 130-180 eV). The velocity of the outer boundary of the liner just before reflection is 280 km/sec and its thickness is ≈0.1 cm. The energy characteristics also change (Fig. 3b). In particular, the radiated energy by 130 nsec is 6 kJ, which is less than without allowance for this effect (6.6 kJ). The calculated time dependence of the fluxes of the emergent radiation for 1-7 spectral groups is shown in Fig. 3c. We note that the optical thickness of the plasma (for the same spectral group, where the flux of the emergent radiation is maximum) is 0.3-3. The profiles of the temperature, density, and pressure along the radius at several times near cumulation are shown in Fig. 4.

Modeling of the compression of liners in the MRGD approximation makes it possible to study the physics of the processes occurring here as well as their sequence and interrelationship. Our study here of the dynamics of single-envelope liners reveals an interesting distinctive feature, i.e., multiple compression at the axis with a gradual drop in the plasma parameters at the time of cumulation. We have demonstrated that the presence of rarefied gas in the interelectrode space, flowing in behind the liner and "pushed" by the magnetic field, changes the compression dynamics and the plasma parameters at the cumulation time. Inclusion of this effect makes it possible to improve the agreement between calculation and experiment within the framework of the one-dimensional method. Of course, numerous calculations are required to ascertain the effect of instabilities on the final stage of the compression and inhomogeneities along the liner.

NOTATION

Here r denotes the radius; t is the time; v is the velocity; m is the atomic mass; M is the liner mass; T is the temperature; k is Boltzmann's constant; and σ is the electrical conductivity.

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