Electrodynamic contraction of multiwire liners

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Results of experiments and theoretical calculations of electrodynamic contraction of multiwire liners are reported. It is shown that collapse of a multiwire array produces on its axis a high-temperature radiating plasma pinch. Wire liners permit adequate matching to a high-power electric-pulse generator; an appreciable fraction (up to 25%) of the electric energy fed to the liner (up to 100 kJ per pulse) is converted into radiation. Experiments and a theoretical analysis have shown, however, that the contraction dynamics of such liners does not ensure a compact collapse of the arrays to the axis; the soft x-ray flashes generated by the axial-pinch plasma are therefore not shorter than 30 ns. An important feature of such systems is the jetlike flow, due to the action of MHD tidal forces, of plasma from the wires to the liner axis.

1. INTRODUCTION

Advances in the technology of high-current terawatt electric generators have made it possible to start, in a number of countries, experimental research into the contraction of thin cylindrical shells (liners) of milligram mass per unit length.[1–3] A current of the order of several megaamperes passing through such a liner will cause the liner material to flow towards the axis at a velocity $\approx 5\cdot 10^7$ cm/s. As a result, the kinetic energy of the collapsing liner is transformed into internal energy of an axial plasma formation of temperature $T_e \leqslant 1$ keV and density $n_e \sim 10^{20}$ cm^{-3}. The radiation energy of such a plasma is ≈ 100 kJ (a radiation yield ≈ 40 kJ is reached[4] in *K*-liners of elements having $Z \sim 10$) and can be used to compress thermonuclear targets in inertial controlled fusion.[5,6] Obviously, the efficiency of generator-energy conversion into linear kinetic energy, and also the plasma-radiation intensity and its spectral characteristics, depend substantially on the shell dynamics and on the distribution of its velocities and density. Unfortunately, since the diagnostics of such an object is difficult, practically no systematic investigations of its dynamics have been carried out to date.

One fast-liner variant comprises a set of thin (5–30 μm in diameter) wires uniformly arranged on a cylindrical shell. Such assemblies, hereafter called arbitrarily wire liners, are widely used in experimental research, since they are simple to construct and their initial parameters are easily variable.

Current flowing from a generator through an individual wire heats it and leads to formation of an expanding plasma column. In a number of investigations (e.g., Refs. 7 and 8) it has been shown that the bulk of the current flows in this case in the low-density corona of the wire. Under these conditions, as was qualitatively shown in Refs. 9 and 10, the corona can be accelerated towards the axis more rapidly than the main mass of the wire, affecting adversely the compactness of the collapse and increasing accordingly the duration of the soft-x-ray pulse. We have undertaken in the present study a detailed experimental and theoretical investigation of the dynamics of a wire liner, with an aim at elucidating the main factors that influence the compactness of the collapse. Measurements using a combination of laser and electron-optical methods of plasma diagnostics have made it possible to obtain, simultaneously with an overall picture of the collapse, information on the density distributions at various instants of time, and construct on this basis a theoretical model of the plasma flow.

2. EXPERIMENTAL SETUP AND DIAGNOSTIC APPARATUS

Experiments on multiwire assemblies were carried out with the "Angara-5-1" facility,[11] comprising an eight-module generator of high-power pulses of 90 ns duration at half-maximum. The modules fed a common load placed in a vacuum chamber. The generator voltage at the entrance to the energy-concentration system reached 1.2 MV at a total current 4 MA from all the modules to the load.

We used in the experiments liners 3 cm high, made of aluminum, copper, and tungsten wires having a total mass 0.2–1.0 mg. The wires were strung along a cylinder 15–30 mm in diameter and their number ranged from 6 to 24. The diameter of the array of the current-return leads was as a rule 10 mm larger than the liner diameter.

The setup used to sound the liner plasma was similar to that in Ref. 12, and generated a radiation pulse of 2 ns duration and 0.2 J energy. The optical system for shadow photography of the liner is shown in Fig. 1. A delay line made up of mirrors 4–6, 20, and 21 permitted variation of the interval between the pulses in the range 5–50 ns. Laser beams passed through the plasma and were incident on various sections of a "Mikrat-300" photographic film placed behind a remotely controlled electromechanical shutter 17. The wedges 7–9, 11, and 12 served to produce a convenient layout of the frames on the recording film. Light filters 18 were used to equalize the light-flux intensities in the individual channels and to suppress the intrinsic plasma radiation.

It should be noted that the total number of frames was limited to three, in view of the complex experimental conditions. The optical system had to be assembled on a large base (for example, the distance from laser 2 to mirror 3 was of the order of 20 m). The structural features of the target unit of the "Angara-5-1" facility did not make it possible to record laser radiation refracted in the liner plasma by an angle $\geqslant 2°$ in each channel. It was necessary to ensure a field of view ≈ 30 mm in diameter and spatially separate images from the various channels.

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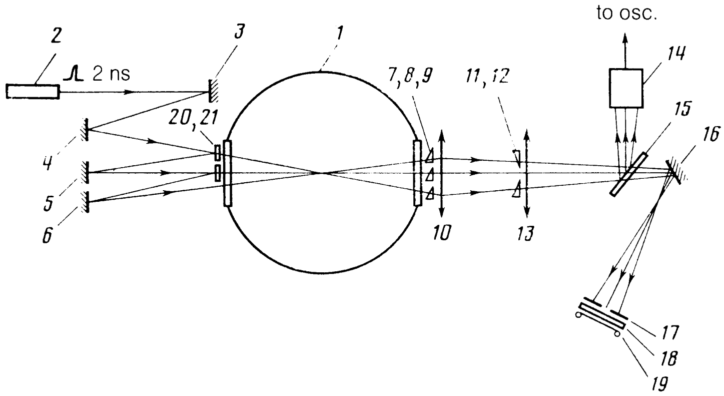

FIG. 1. System for laser sounding of a plasma: 1—vacuum chamber; 2—laser; 3—6, 16—mirrors; 15, 20, 21—semitransparent mirrors; 7–9, 11, 12—optical wedges; 10, 13—objectives; 14—coaxial photocell; 17—light filters; 18—mechanical shutter; 19—photographic film.

The laser setup was synchronized with the current pulse on the load to within ± 5 ns. This synchronization accuracy was achieved by using a specially developed discharge unit with ultraviolet illumination of the interelectrode gaps.[13]

Simultaneously with the laser sounding, we investigated in the experiments the shape and dynamics of the plasma formation in its own optical radiation, using electron-optical methods. We used both slit scanning and frame-by-frame photography. The plasma was photographed in a framing regime, with a frame exposure time ≈ 5 ns, by a recording system[14] consisting of two functional parts: a cable-coupled generator shaping a rectangular electric pulse of 5–10 kV amplitude, and small two-electrode electron-optical converters pulse-fed by the cable-coupled generator.

The requirements imposed on the electron-optical recording system were good triggering stability, short operating time, high degree of immunity to electromagnetic noise, sound technical assembly, and reliability. These requirements were met by using in the cable-coupled generator an ROU-5 sealed gas-filled discharger.[15] A check on the switching properties of such discharges has shown that their operating time at a triggering pulse ≈ 10 kV and a charging voltage 15–20 kV is $\leqslant 10$ ns.

The image converters used electrostatic focusing and fiber washers on the cathode and on the screen. A specially designed cassette clamped RF-3 photographic film to the exit washer of the converter. The use of washers at the entrance and exit made it possible, when necessary, to increase the gain by connecting modules in tandem.

To record the image in the slit-scanning regime we used an SFÉR-2 image converter with a multislit photocathode measuring 3×15 mm (Ref. 16). The apparatus scanning duration was adjustable from 5 to 750 ns on 21 mm of the screen at an operating time not longer than 10 ns. The optical gain was 10^3, and the spatial resolution was not worse than 10 pairs of lines/mm.

The image-converter triggering pulse was produced by the high-voltage synchronization system of the "Angara-5-1" modules. Owing to the high level of electromagnetic noise, the electron-optical apparatus was placed in a shielded room. The line noise was suppressed with commercial RC filters of type FP-30 and with voltage stabilizers.

3. INVESTIGATION OF ELECTRIC EXPLOSION OF SINGLE WIRES

To understand the physical processes observed in contraction of multiwire systems it is necessary to study beforehand the plasma produced by the flow of currents on the order of hundreds of kiloamperes through a single wire. Such a study, using the described procedures, was carried out with a high-power generator at currents up to 0.5 MA in the wire. The current rise time was about 90 nm.[12]

Figure 2 shows laser shadow photographs of a caprone (nylon-6) filament of 80 μm diameter and 50 mm length, obtained in successive instants of time. Their analysis shows that the plasma column expands to a diameter 1–2 mm within the first 40–50 ns. Inhomogeneities with characteristic scale ≈ 1 mm are simultaneously produced at a rate $(1-4)\cdot 10^7$ cm/s.

The density distribution pattern was obtained by interferometry methods. It follows from the interference patterns (Fig. 3) that a plasma region opaque to the probing radiation is present along the axis. The diameter of this dense core is much smaller than the plasma-formation diameter. Estimates show that $\approx 70\%$ of the total wire mass is concen-

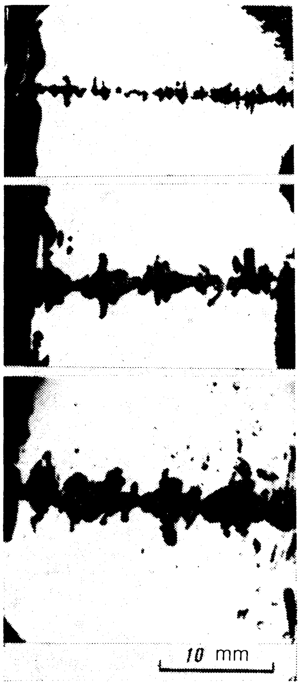

FIG. 2. Laser shadow photographs of a nylon-6 filament, obtained successively at 90, 115, and 135 ns after the start of a current pulse.

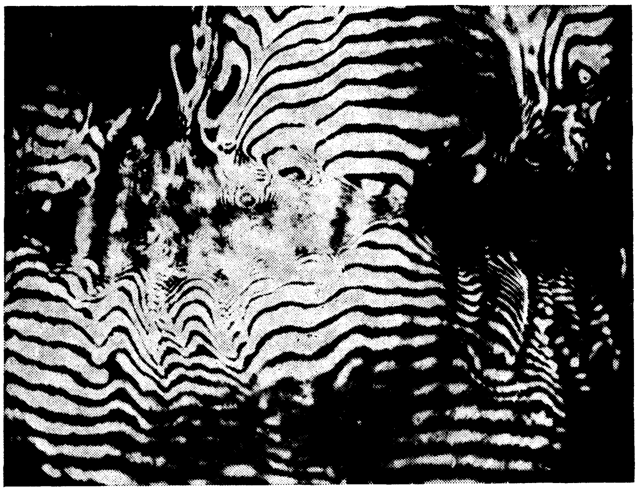

FIG. 3. Interference pattern of exploding nylon-6 filament, 105 ns after the start of the current pulse.

trated in this region at the current maximum (440 kA). The blurring of the fringes on the interference patterns in the constriction regions permits the radial velocity to be estimated at $\sim 10^7$ cm/s, much lower than the Alfvén velocity.

The plasma temperature can be determined from the Bennett condition by assuming that all the current flows through the constriction. In this case, taking into account the experimental electron density $n_e \approx 10^{18}$ cm^{-3}, we obtain $T \approx 2$ keV.

The main features of the dynamics of electric explosion of single conductors are preserved when wires of other materials are used. Figure 4 shows a typical schlieren photograph of an exploding copper wire 20 μm in diameter and 4 cm long. It can be seen that the characteristic scale of the inhomogeneities and of the broadening rate are approximately the same as for a nylon-6 filament.

Analysis of the laser-photography results (shadow and schlieren photographs, interference patterns) leads to the following picture of the plasma dynamics of an electrically exploding wire. An inhomogeneous plasma corona is produced along the entire wire in the very first few nanoseconds of current flow. The corona has a relatively low density

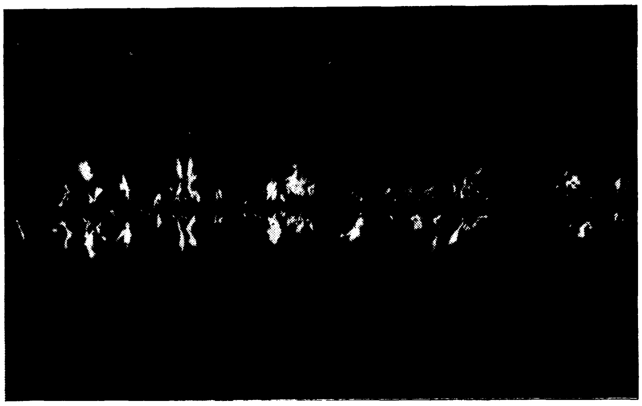

FIG. 4. Schlieren photograph of exploding copper wire of 20 μm diameter, 40 ns after the start of the current pulse.

($n_e \sim 10^{17}$–10^{18} cm^{-3}) with an inhomogeneity scale 0.3–0.5 mm. These inhomogeneities exist during the entire time of current flow through the wire. Axial perturbations also develop during the first few dozen nanoseconds in the wire region opaque to the laser radiation. They have a characteristic length l that increases with increase of the current and a plasma-column opaque-zone transverse dimension d. It should be noted that $l \sim d$ at each instant of time. The maximum radial velocity of the transverse plasma spikes of density $n_e \sim 10^{17}$–10^{18} cm^{-3} increases with the current and reaches $(0.5–1)\cdot 10^8$ cm/s at a current $I \approx 500$ kA, close to the Alfvén velocity V_A for these parameters. The transverse dimension d of the opaque region (density level $n_e \geqslant 10^{19}$ cm^{-3}) decreases as the current is increased, at an average rate $(0.5–1)\cdot 10^7$ cm/s.

The experiments on the dynamics of electric explosion of thin filaments show the following: 1) the transverse dimension d of the plasma column increases monotonically with time at a rate $\sim 10^7$ cm/s; 2) column inhomogeneities, of characteristic scale $l \sim d$, exist in the plasma during the entire current-flow time.

4. EXPERIMENTAL RESULTS ON THE DYNAMICS OF MULTIWIRE LINERS

In accordance with zero-dimensional calculations of the motion of a cylindrical liner, the maximum kinetic energy of the shell is obtained when the relation between the parameters is

$$\alpha = \tau_0^2 I^2 / M_0 R_0^2 \approx 10^3,$$

where M_0 in g/cm is the liner mass per unit length, R_0 its initial radius in centimeters, I the current amplitude in amperes, and τ_0 the collapse time in seconds. In our experiments $\tau_0 \approx 10^{-7}$ s.

The liner experiments were aimed at investigating the dynamics of their contraction. The first experiments were performed with a high-current generator of line-current amplitude ≈ 1 MA. We used a rather heavy liner of 2 cm diameter, consisting of eight tungsten wires with total mass 120 μg/cm per unit length. In this case $\alpha \approx 10^2$.

The laser shadow photographs (Fig. 5) show that the first state consists of an electric explosion of the wire and an expansion of the plasma columns to a diameter 1–2 mm. As the current through the liner increases, plasma streams develop and propagate from the wires towards the liner axis. Density-distribution inhomogeneities appear along the axes of the individual wires, with characteristic scale ≈ 1 mm. These inhomogeneities persist to the end of the contraction, and their characteristic axial dimensions remain practically constant. The average velocity of the plasma streams is estimated from the successive framing shadow photographs to be of the order of $3\cdot 10^7$ cm/s. The ratio of the radial plasma velocities in the stream to the rate of its transverse expansion is ~ 10. The transport of matter by the plasma stream leads, at the 270th nanosecond, to formation on the axis of a dense pinch that remains stable for 100 ns. The minimum radius of the plasma column is ≈ 1.5 mm. The high density of the current through the disk electrodes feeding the liner, and the high-power radiation from the plasma, cause intense evaporation of the electrode material and expansion of the near-electrode plasma which fills at 400 ns practically the entire gap between the supply electrodes.

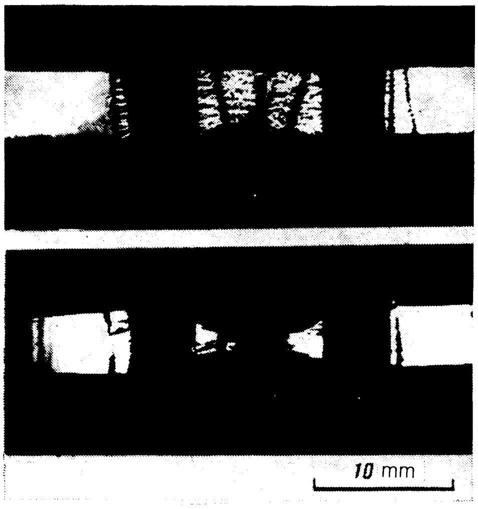

FIG. 5. Shadow photographs of wire liner, obtained with an "Angara-5-1" module successively at 210 and 290 ns after the start of the current pulse.

It should be noted that the wires themselves do not move during the entire process, and their matter is "transported" to the liner axis by the plasma streams. The average particle density in these streams can be estimated by assuming that the material is uniformly transported in a time $\tau \approx 300$ ns. The ratio of the mass of one wire to the mass of particles in the volume of a plasma stream of velocity V_r is $V_r\ \tau/R_0$. At a liner mass 120 μg we obtain for $V_r = 3\cdot 10^7$ cm/s an ion density $n_i \approx 10^{17}$ cm^{-3}, which agrees with the experimental estimate of the ion density[12] if a fivefold ionization is assumed.

Laser probing of a wire-liner plasma has shown thus that at $\alpha \approx 10^2$ the wires themselves do not move, but their mass flows over to the liner axis, in the form of plasma streams having an ion density $n_i \approx 10^{17}$ cm^{-3}, to produce a pinch of radius ≈ 1.5 mm.

The experiments on the contraction of multiwire liners at a parameter $\alpha \approx 10^3$ were performed with an eight-module "Angara-5-1" facility. Frame photography of the liner emission in the optical band has shown that the wires remain in their initial position during the greater part of the time prior the instant of collapse. Their transverse dimension reaches 1–1.5 mm. Next, in less than 25 ns, a pinch several millimeters in diameter is formed on the axis. The corresponding photographs are shown in Fig. 6. Plasma jets from the periphery to the liner axis are sometimes seen after the pinch formation. The shape of the pinch attests to the presence instabilities with mode $m = 1$, and the mode $m = 0$ appears sometimes.

The gradual flow of the wire material over the liner axis is particularly clearly seen on the plasma-emission slit scan shown in Fig. 7. A liner of eight tungsten wires and 15 mm diameter was used. The liner mass was 100 μg/cm per unit length. It can be seen that the time for the material to flow over to the axis is approximately 30 ns.

One more slit-scan photograph of the emission of an aluminum liner is shown in Fig. 8. In this case the observation direction was such that the radial and azimuthal motions of the wires could be seen simultaneously. This scan shows that supersonic plasma flows are produced by the wire motion towards the system axis. The ratio of the radial and

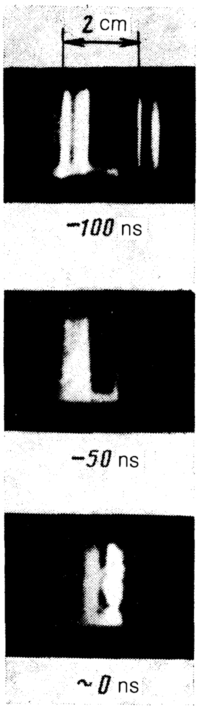

FIG. 6. Framing image-converter photographs of the emission of an aluminum liner. The forward (dark, on the right) and return (light, left) current leads are shown. The instant $T = 0$ corresponds to the minimum of the soft x-ray pulse.

azimuthal stream dimensions reaches in this case ≈ 10. The supersonic stream velocities indicate that the acceleration is electrodynamic, i.e., the plasma flowing to the axis carries a current. Figure 9 shows laser shadow photographs obtained during various collapse stages of an aluminum liner of diameter 15 mm and mass 150 μg/cm per unit length. On each edge of the first two frames are seen two return current leads (their projections are superimposed on the second frame) and four cylindrical plasma formations, which are superimposed projections of pairs of exploding wires. The plasma jets directed from the wires to the liner axis can be clearly distinguished.

The timing of these frames relative to the load-voltage pulse is shown in the same figure. In this case the instant $t = 0$ corresponds to the maximum of the soft x rays from the plasma liner. It can be seen that approximately 30 ns prior to this instant there is formed on the liner axis a pre-plasma

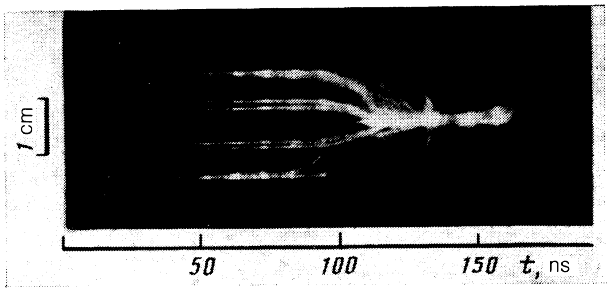

FIG. 7. Slit scan of the emission of a tungsten liner of 15 mm diameter and 150 μg/cm mass.

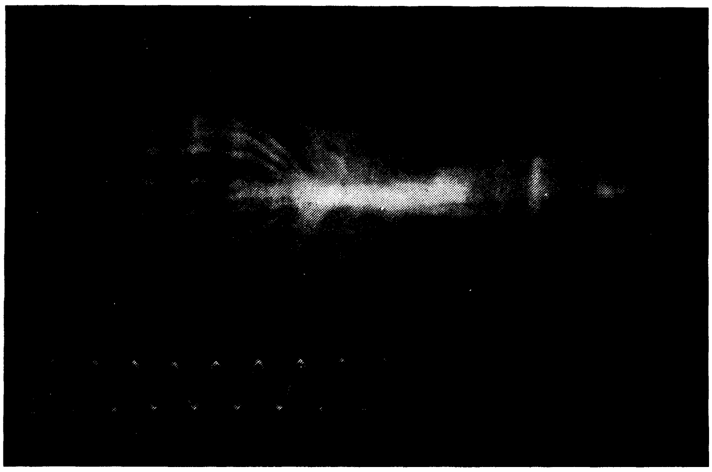

FIG. 8. Slit scan of the cross section of an aluminum liner of 15 mm diameter and 150 μg/cm mass. The period of the timing sinusoid is 10 ns.

channel having a helical structure with pitch ≈ 1 mm. Closer attention reveals a slight taper of the channel, due apparently to the influx of plasma from the target-unit cathode.

The formation of a pre-plasma channel on the liner axis is confirmed also by a slit scan shown in Fig. 10. In this case the observation direction was chosen such that the central part was not fenced-in by wires. The photograph shows clearly that a pinch was already produced on the axis at 20–25 ns prior to the arrival there of the wires.

Let us estimate the electron density in the pre-plasma channel. The incomplete registration of the probing radiation (Fig. 9) may have two causes: refraction of the laser radiation, and absorption of the sounding radiation by the plasma.

Consider the first cause, i.e., the radiation recorded on the film was refracted through the angle $\beta \leqslant 2°$. Using the results of Ref. 18 we can conclude that the refracted radiation does not land on the entry aperture of the registration system at $n_e^0 \geqslant 10^{20}$ cm^{-3}. Taking into account the experimentally determined electron temperature $T_e \approx 300$ eV of the pinch formation,[10,19] we assume an average ion charge $\overline{Z}_{Al} = 8$. We have for the number of Al ions per unit pinch length at 30 ns prior to the liner collapse

$$N_i = n_e \pi d^2/4\overline{Z} = 5\cdot 10^{16} \text{cm}^{-1}.$$

A liner density 150 μg/cm per unit mass corresponds to $N_0 = 3\cdot 10^{18}$ Al atoms per centimeter of liner length. We obtain consequently for the relative fraction of the mass reaching the liner axis

$$M/M_0 = N_i/N_0 \geqslant 0{,}02.$$

If the incomplete registration of the probing radiation is due to light absorption in the plasma, the absorption length L is of the order of the characteristic dimension of the opaque region. Assuming $L \sim d = 2\cdot 10^{-2}$ cm and using the expression of Ref. 20 for the absorption length, we have

$$L = 10^{36} T_e^{3/2} n_e^{-2} \overline{Z}^{-1}. \tag{1}$$

For $T_e = 300$ eV and $\overline{Z} = 8$ we obtain $n_e \geqslant 10^{20}$ cm^{-3}, which yields for the ratio M/M_0 a lower bound 0.02.

It can thus be concluded that, regardless of the cause of the incomplete registration of the radiation probing the pre-plasma channel, more than 2% of the liner mass is located on its axis prior to its collapse.

The third frame of the shadow photograph of Fig. 10 pertains to the final collapse stage. On the edges of the photograph are seen the return current leads from the surface of which plasma jets are accelerated to the outside, while the center shows a completely opaque cylindrical formation approximately 6 mm in diameter.

Let us estimate the lower bound of the mass of matter in

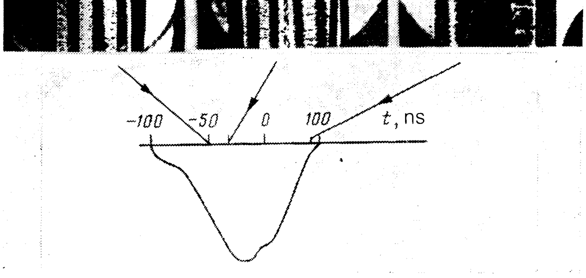

FIG. 9. Successive shadow photographs of an aluminum liner, and the voltage pulse on the liner, in the "Angara-5-1" facility. Liner mass 150 μg/cm.

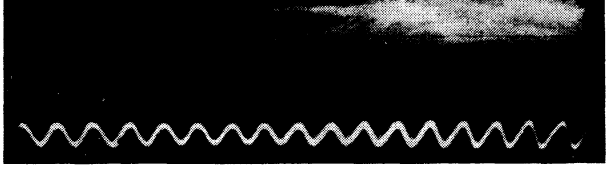

FIG. 10. Slit scan of the emission of an aluminum liner. Liner diameter 15 mm, mass 150 μg/cm. The orientation of the return current leads makes it possible to see the axial zone of the liner. The period of the timing sinusoid is 10 ns.

the pinch at that instant of time. If the laser beam is blocked by refraction, we obtain the estimate $N_i \approx 1.5 \cdot 10^{18}$ cm^{-3} and a lower-bound $N_i / N_0 \approx 0.5$.

If the pinch is made opaque by absorption of the probing radiation, we obtain, assuming an absorption length $L \approx 2$ mm and putting $T_e = 300$ eV in expression (1), $n_e = 4.5 \cdot 10^{19}$ cm^{-3} and $N_i = \pi d^2 n_e / 4\bar{Z} \approx 2 \cdot 10^{18}$ cm^{-1}. The relative fraction of ions on the liner axis is then not less than 0.6 of the total.

We find thus that during the final collapse stage an x-ray emitting pinch contains not less than 50% of the liner mass.

5. THEORETICAL MODEL

We consider a liner having N wires and a radius R_0, through which a total current I_Σ flows. A theoretical analysis of the collapse of multiwire liners carrying mega-ampere currents shows that a compact acceleration of individual plasma columns in the collective magnetic field is impossible. This was qualitatively considered in Refs. 21 and 22. A more rigorous analysis is based on the magnetohydrodynamic equations of a plasma having a finite conductivity $\sigma(T)$, in which we take account of the loss to radiation in the form $W = W_0 N_i^k T^n$ and the loss to ionization $\varepsilon = 3bT/2$, where W_0, b, k, and n are constants. The system of equations is then

$$m_i N_i d\mathbf{V}/dt + m_i N_i \mathbf{a} = -\nabla p + [\mathbf{j} \operatorname{rot} \mathbf{A}]/c, \tag{2}$$

$$\partial N_i/\partial t + \nabla(N_i \mathbf{V}) = 0, \tag{3}$$

$$\tfrac{3}{2}(\bar{Z}+1+b) N_i dT/dt + p \nabla \mathbf{V} = j^2/\sigma - W, \tag{4}$$

$$p = (\bar{Z}+1) N_i T, \tag{5}$$

$$c^{-1}\partial \mathbf{A}/\partial t - [\mathbf{V} \operatorname{rot} \mathbf{A}]/c = -\mathbf{j}/\sigma, \tag{6}$$

$$-\Delta \mathbf{A} = 4\pi \mathbf{j}/c. \tag{7}$$

The equations here are written in the coordinate frame of the mass center of wires moving with acceleration $\mathbf{a}$, and $\mathbf{A}$ is the electromagnetic-field vector potential. Let a current $\mathbf{j}$ flow along the z axis, let $\mathbf{A}$ have only one component A_z, and let the x axis be directed along $\mathbf{a}$. We consider a stationary solution of the system (2)–(7). From the equation of motion (2) and from the equations of state (4) and (5) it follows that inside the region $-Y(x) \leqslant y \leqslant Y(x)$ occupied by the plasma (it is natural to consider solutions that are symmetric with respect to x) the quantities N_i, T, j_z, and A_z can depend only on the argument x, i.e., the magnetic-field component $B_x = \partial A_z / \partial y$ is zero in the plasma. Matching on the surface $y = Y(x)$ the solutions of Eq. (6) in the plasma and in the vacuum, we arrive at the necessary condition for the existence of a stationary solution of the system (2)–(7):

$$\int j(x') \ln \left\{ \frac{(x-x')^2 + [Y(x) + Y(x')]^2}{(x-x')^2 + [Y(x) - Y(x')]^2} \right\} dx' = 0, \tag{8}$$

which corresponds to $B_x |_{y = Y(x)} = 0$. The condition (8) can be met for arbitrary x only in the case of a plane layer of infinite length along y (the analog of a solid liner). The acceleration of such a layer was considered in Ref. 23, in which case the motion remains asymptotically nonstationary, but the deviation from compact acceleration is small. For plasma regions that are bounded in the xy plane, however, i.e., for finite $Y(x)$ distributions (the case of a wire liner), the conditions (8) are not met; the integral (8) remains finite. There can therefore likewise be no quasistationary solution of the problem (2)–(7), i.e., there can be no compact acceleration of the liner wires. The plasma of the wires is strongly stretched towards the liner axis by the MHD tidal forces $\mathbf{j} \times \mathbf{B}/c$.

Three characteristic regions can be distinguished in the multiwire-liner matter distribution; a) near the center of the wire, where the intrinsic pressure causes thermal expansion of the plasma into the separatrix region; b) region of radial streams towards the liner axis; c) region in the vicinity of the liner axis, to which the plasma streams from the wires converge and where the kinetic energy of the plasma streams is converted into thermal energy of the plasma.

Consider the region a). The constant outflow of plasma from the outer layers of the exploded wire establishes near the separatrix a plasma flow from the central zone of the wire to its periphery. In the quasistationary state, at a sufficiently large distance, this plasma motion is nearly axisymmetric and the plasma pressure exceeds the magnetic pressure. In a cylindrical coordinate frame with center on the wire axis, the stationary solution of Eqs. (2)–(7) consists of the following: the plasma-ion density

$$N_i = \tfrac{1}{2}\lambda^{1/2} S_0 [1 + (r/r_1)^{2p}]^{1/2} (r/r_1)^{-p}, \tag{9}$$

the electron temperature

$$T_e = 2p_0 (r/r_1)^p / (\bar{Z}+1) S_0 \lambda^{1/2} [1 + (r/r_1)^{2p}]^{1/2}, \tag{10}$$

the magnetic field

$$B_\theta = 2I_0 [1 + (r/r_1)^{2p}]^{1/p} / cr, \tag{11}$$

and the plasma expansion rate

$$V_r = \{4 (r/r_1)^{2p} / \lambda r^2 [1 + (r/r_1)^{2p}]\}^{1/2}. \tag{12}$$

Here

$$\lambda = 8\pi \sigma_0 p_0 / c^2 (\bar{Z}+1) S_0, \quad p = 4/(3-n+k),$$

$$r_1 = \{[p_0/(\bar{Z}+1) S_0]^{n-1} W_0 S_0^k c^4 2^{n-k-5} \lambda^{2/p} / I_0^2 \sigma_0\}^{-1/4}, \tag{13}$$

the conductivity of the plasma being ionized is assumed to be $\sigma(T) = \sigma_0 T$; the constant p_0 is determined by the pressure of the magnetic field near the separatrix ($r \approx r_0$), i.e., $p_0 \approx (I_1 / c r_0)^2 / 2\pi$; I_0 is an integration constant having the meaning of the current along the wire axis. It should be noted that the drift of the current by the expanding plasma is compensated by the current diffusion. The solution (9)–(13) is valid only outside the central region of the wire, where the plasma density is much lower than that of the solid. The plasma flux S_0 is due to its detachment by the forces $\mathbf{j} \times \mathbf{B}/c$ from the periphery of the plasma core, where the wire's magnetic self-field becomes equal to the collective field. The magnetic field should therefore reach a minimum at $r \approx r_0$. This condition leads to the relation $I_1 \approx 1.4\, I_0$ between the constant I_0 and the current I_1 through an individual wire ($k = 1$ and $n \approx 2$ for a plasma of a wire made of a material with $Z \gg 1$ in a state close to local thermal equilibrium). Using the values of the current I_1 and of the plasma parameters, we can estimate the flux S_0 at

$$S_0 \approx (W_0^2 / \sigma_0 r_0^2 c^4)^{1/3} I_1^2 \bar{Z}^{-5/3}. \tag{14}$$

The above expressions determine uniquely the distributions of the plasma and of the magnetic field in the vicinity of the dense core of the wire.

The solution above is valid so long as the flux (14) does not carry away the greater part of the wire mass. It should be noted that for substances with large Z the plasma flux increases because the emissivity increases (for a given current).

On the peripheries of the wires the plasma is accelerated to the liner axis, in the form of plane supersonic jets, by the Ampere forces in the collective magnetic field. The steady-state flow of the plasma jets in region b) can be treated in the framework of the stationary solution of the problem (2)–(7) with a flux (14).

If the transverse dimension of the jet is smaller than the liner radius R, i.e., the characteristic angular dimension of the jet is $\varphi \ll 1$, the equations of motion have a self-similar solution. The self-similar variable is the dimensionless parameter

$$\xi = 4\pi\sigma R\varphi^2 c_s/c^2, \tag{15}$$

where c_s is the speed of sound. Self-similar separation of the variables leads to the following relations for the physical parameters of the plasma and of the magnetic field:

$$N_i = N(\xi)\varphi, \quad A_z = A(\xi)/\varphi^{1/2}, \quad V_R = V_R(\xi), \quad V_\varphi = \varphi V(\xi).$$

(We consider here the case $\varphi \geqslant 0$.) The plasma-temperature variation is neglected. Even the very fact of self-similar separation yields important information on the structure of the flow. The ion density varies along the level lines $\xi = \text{const}$ in proportion to $R^{-1/2}$, the electromagnetic potential $A_z \propto R^{1/4}$, and the plasma-velocity component V_R is constant. Analysis of the ordinary differential equations obtained from the system (2)–(7) after substitution of the self-similar separation (15) leads to the conclusion that the current in the supersonic stream is concentrated mainly in a narrow central region of thickness $\delta \approx (c_s/V_R)(Rc^2/4\pi\sigma c_s)^{1/2}$ with a current distribution $J(R) = J_0(R_0/R)^{1/4}$, where J_0 is the current density per unit length of the jet near the core of the wire at $R = R_0$, and the current in the jet is $I_s = 4J_0R_0/3$. This current produces a magnetic field having the following components outside the layer δ (accurate to the leading terms of the expansion)

$$\begin{gathered} B_R = (2\pi J_0/c)(R_0/R)^{1/4}, \\ B_\varphi = -3\pi J_0\varphi(R_0/R)^{1/4}/2c - 2\gamma I_\Sigma(R_0/R)^{1/4}/cR_0 \end{gathered} \tag{16}$$

($\gamma \sim 1$ is a geometric factor).

Matching the magnetic field on the conditional boundary between the wire core and the jet flow makes it possible to determine the ratio of the currents in the core and jet and to relate them to the total current:

$$I_s \approx R_0 I_1/Nr_0 \;\text{и}\; I_1 \approx I_\Sigma r_0/(R_0 + Nr_0). \tag{17}$$

The final current ratio depends on the ratio r_0/R_0, which can be determined only by an evolutional solution that takes the initial phase of the process into account. During the start of current flow the wires can be regarded as insulated up to the instant of the plasma-jet detachment. In this case $r_0 \approx R_0/N$. According to this estimate, the currents in the wire and in the jet are approximately equal.

Calculating from the equation of motion and work needed to accelerate the plasma in the jet at a given plasma flux S_0, we can estimate the plasma velocity in the jet:

$$V_R \approx I_s I_\Sigma (R_0 - R)/\pi c^2 R_0 S_0 m_i r_0, \tag{18}$$

and the ratio of the kinetic and magnetic energy densities:

$$\chi = 4\pi\rho V_R^2/B^2 \approx (R_0/R)^{1/2}(R_0 - R)(I_s/I_\Sigma)(\pi/r_0), \tag{19}$$

where ρ is the plasma density.

Plasma acceleration in the jet is accompanied by its contraction, but the angular dimension φ of the jet increases in proportion to $R^{-1/2}$ and the jets from neighboring wires coalesce at $\varphi \approx \pi/N$. In this region, the flow is no longer jetlike. The radius at which the coalescence takes place is equal to $R_* \approx R_0(Nr_0/\pi R_0)^2$.

In the vicinity of the liner axis the plasma stops and its kinetic energy goes over into the energy of the clamped magnetic field and into the thermal energy of the plasma.

The ions and electrons are not equally heated behind the front of the flow-deceleration wave. The electrons acquire energy via Joule heating by the current at the magnetic-field discontinuity, and a fraction of the energy is transferred to the electrons from the ion component through collisions. In addition, the plasma column stopped on the liner axis is itself further heated, owing to its conductivity, by the current. The energy input to the plasma via Joule heating is comparable with the kinetic energy of the liner. The combination of these mechanisms determines the plasma-column radiation intensity.

6. DISCUSSION OF RESULTS

Our physical picture of electrodynamic acceleration and contraction of multiwire liners has a number of interesting plasma-dynamics features. The experimental results and the theoretical analysis show that the contraction of wire liners constitutes plasma-jet flow from the individual wires to the system axis. The picture of formation and evolution of the plasma jet flow is the following.

During the initial current-flow phase the wires are exploded and expand at acoustic velocities. The plasma flow moves the current towards the periphery. A significant role in the crowding out of the current to the surfaces of the plasma columns of the individual wires is played by the overheating of the external tenuous plasma layers. After reaching the separatrix of the common magnetic field, the plasma begins to be accelerated by $\mathbf{j}\times\mathbf{B}/c$ forces towards the liner axis, where a thin pinch is produced. During the initial instants the plasma in the jets is tenuous and cannot yet be recorded by laser and optical methods, whereas the pinch produced is distinctly visible (Fig. 9). The density of the plasma in the streams increases with increase of the current.

If the wire material has high emissivity, the plasma temperature is relatively low, so that the jets are plane, i.e., the flow has a large Mach number (≈ 10). Estimates show that at equal currents the plasma flow depends on the emissivity of the wire material ($S_0 \propto W_0^{2/3}$). For aluminum, the time of establishment of jet flow is shorter than the time in which the current becomes nearly constant. A quasistationary flow of plasma is thus established from the wires to the system axis, whereas the wires themselves hardly move. This flow can be described within the framework of a stationary self-similar solution, a procedure valid so long as the wire can be regarded as slowly moving, i.e., until the remaining wire mass becomes comparable with the mass of the plasma in the jets, after which almost all the wire material contracts to a pinch.

From the foregoing experimental results and analytic solution we obtain the estimates $V_R \approx 3 \cdot 10^7$ cm/s for the average flow velocity and $N_i \approx 10^{17}$ cm^{-3} for the plasma density in the jets. The characteristic angular dimension φ of the jet increases like $\varphi \propto R^{-1/2}$ as the system axis is approached. At a radius $R_* \approx 0.1\ R_0$ the jets coalesce and form an axial pinch that can be distinctly recorded by all diagnostic methods with spatial resolution (laser probing, pinhole photographs, slit scanning). The kinetic energy of the plasma jets becomes thermalized when they coalesce. The energy radiated in this case is concentrated in the hardest part of the recorded spectrum.

Owing to the higher emissivity, the plasma flux from tungsten wires is much larger than that of an aluminum plasma. The plasma mass becomes comparable with the wire mass already during the stage when the flow sets in. There is therefore no quasistationary flow stage for tungsten wires. Their motion is more compact (Figs. 7 and 8). Owing to the higher emissivity of tungsten, the radius and temperature of the pinch produced after the collapse of the wire material are smaller than for an aluminum pinch. Indeed, if the Bennett conditions are met, if radiation equilibrium obtains, and if the currents are equal, then the ratios of the radii and temperatures in the pinches are inversely proportional to the respective emissivities:

$$R_{\rm Al}/R_{\rm W} \approx (T_{\rm Al}/T_{\rm W})^{5/4} \approx (W_{0\rm W}/W_{0\rm Al})^{1/2}.$$

This is the cause of the softer emission spectrum from a tungsten liner. Notice must also be taken of one more feature of the dynamics of wire liners. Laser shadow photographs reveal plasma inhomogeneities along the axis; they are the results of inhomogeneities in the expanding plasma of the exploded wires, and are not amplified when the jets coalesce.

An important consequence of the experimental and theoretical results is the weak dependence of the qualitative flow picture on the number of wires in liners of the same mass. A theoretical model shows that the wire-mass fraction trapped in the jet stream decreases like $N^{-1/3}$ with increase of the number of wires. Experiments revealed no substantial differences for N ranging from 6 to 24. The contraction of the wire liners seemed in all cases to constitute a gradual conversion of their material into an axial pinch. It should be noted that the presence of plasma streams from the wires seems to suppress the onset of $m = 0$ instabilities. Arguments concerning the stability of a pinch with a peripheral plasma to formation of contrictions were advanced in Refs. 24 and 25.

7. CONCLUSION

Summarizing the experimental and theoretical investigation of the dynamics of a multiwire liner, we can draw the following conclusion: Collapse of a multiwire liner produces a high-temperature strongly radiating plasma pinch on the liner axis. Wire liners can be well matched to high-power electric-pulse generators. An appreciable fraction (up to 25%) of the generator energy can be converted into radiation. The dynamics of the collapse of such liners, however, prevents emission of soft x-ray pulses shorter than 30 ns. An important feature of the considered system is the jetlike character of the plasma flow from the wires to the liner axis, which is due to the action of MHD tidal forces. It appears that a more compact contraction and accordingly a steeper radiation pulse can be obtained by using continuous, especially gaseous, liners.

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