Prolonged Plasma Production at Current-Driven Implosion of Wire Arrays on Angara-5-1 Facility

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***Abstract*—Results of experimental investigation and modeling of prolonged plasma production during implosion of cylindrical wire arrays are presented. Results of the radiography of dense cores of imploding wire array and the measurements of internal azimuthal magnetic field in wire array give new experimental evidences of prolonged plasma production phenomenon. This phenomenon is important property of current-driven implosion of the wire arrays at current rise rates $\sim$(0.5–1) 10^{14} A/s. The prolonged plasma production can determine the current and the density profiles as before final stage of a Z pinch compression, so in the moment of Z pinch stagnation. From this point of view, the requirement that residual uncompressed plasma should not shunt the current at the discharge periphery becomes of the greater importance. The conditions exist when the prolonged plasma production isn't an obstacle for the achievement of high-power X-ray emission from Z pinch. Presented experimental results on multiwire array implosion can be explained on the basis of prolonged plasma production without referring to multiwire array azimuthal structure.**

***Index Terms*—Heterogeneous plasma producing matter, multiwire array implosion, prolonged plasma production, super terawatt Z pinch, X-ray radiation.**

I. Introduction

THE MULTIWIRE arrays are used for making fast super terawatt Z pinches as the high-power pulsed sources of a soft X-ray radiation [1]–[4]. An effective implosion of high current discharge through multiwire array depends strongly as on the plasma shell formation from multiwire array during current rise period, so on the residual plasma parameters in the array region during the stagnation of Z pinch and X-ray emission.

We elaborate the physical model of wire array plasma production and the current-driven implosion of plasma. We treat the wire array as a particular case of heterogeneous plasma producing medium. There are two factors, which can effect significantly on dynamics of Z pinch in this medium:

1) large distinction between the densities of condensed component of plasma producing medium (thin wires, solid particles, droplets of microns size), and plasma produced;
2) structure of the plasma producing medium (for example, the cylindrical wire array has a strong azimuthal structure, alternatively, the low density foam has chaotic structure).

In our early experiments [5] on implosion of the wire arrays with relatively small wire number, we discovered that the prolonged plasma production is important property of current-driven implosion of the wire array at the rates of current rise $\sim$(0.5–1) 10^{14} A/s. It was found there, that low-density coronal plasma had predominantly radial expansion with the axial inhomogeneity of 0.3–0.5 mm and the plasma precursor was recorded on the array axis. Direct measurements of the wire array resistance at the beginning of the current has shown that the plasma appearance at the wire surface takes place before the tungsten wire melting, after $\sim$5 ns from the current start [6]. After that event, the wire array transforms into heterogeneous composition of the low-density plasma and the cold dense frame. The discharge current flows through the plasma, the wires being heated by energy flux from the plasma by means of the thermal conductivity and the radiation transfer. The prolonged plasma production were found later in wire arrays with higher wire number and, as consequence, the thick plasma current shell [7].

We treat the prolonged plasma production as the particular case of the "cold start" effect in fast Z pinch. It is inherent feature of such heterogeneous plasma-producing medium, as the thin wires or the low-density foam [8], [9]. It was shown in experiments [7], [9] that the conditions can exist under which the plasma with developed MHD turbulence can be imploded in high-power pinch and can be heated, to effectively convert the generator energy into soft X-ray radiation. In spite of the prolonged plasma production, the a narrow temporal peak of X-ray radiation was emitted due to the final plasma implosion. The full-width at half-maximum (FWHM) of the X-ray pulse was about 6 ns and the X-ray emission power reached 5 TW.

We have proposed the theory of the prolonged plasma production in [10]. This theory is based on experimental witness of the early and simultaneous penetration of the coronal plasma and the azimuthal magnetic flux inside the wire array or the foam liner. The following relation for the plasma production rate was proposed in [10]:

$$\dot{m} = 0.2\left(\frac{I_{\mathrm{MA}}}{R_{\mathrm{cm}}}\right)^{1.8} \frac{\mu\mathrm{g}}{\mathrm{cm}^2 \cdot \mathrm{ns}}$$

where I_{MA} is the total current through the liner and R_{cm} is the initial liner radius. The agreement between the values of the time

Manuscript received August 28, 2001; revised December 25, 2001. This work was supported by the Russian Foundation for Basic Research under Grant 00-02-16177, Grant 99-02-16471, Grant 99-02-17952, Grant 01-02-17319, and Grant 01-02-17526, and by Sandia National Laboratory, Albuquerque, NM, under Contract BE6066.

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Publisher Item Identifier S 0093-3813(02)05332-8.

of the wires evaporation calculated on the basis of this formula and measured experimentally was presented in [11]. We assume as well in [10], that the prolonged plasma production has more significant effect on the multiwire array implosion dynamics than its azimuthal structure.

Detailed experimental investigations and the modeling of the implosion dynamics of wire array were done also by J. P. Chittenden, M. G. Haines, S. V. Lebedev *et al.* [12]. They develop the model of the prolonged plasma production assuming that the region around wires in the array where the current is concentrated is relatively small, and the plasma is leaving this region virtually without current.

In the present paper, we propose some new results on experimental investigation and modeling of the prolonged plasma production at current-driven implosion of wire arrays on "Angara-5-1" facility. The radiography of dense component of the wire array discovered that dense component has the fine structure and the azimuthal asymmetry in the near-wire region. The magnetic probe signal shows that the precursor plasma carrying the 3%–15% of the total current penetrates into the internal region of the array at early stage of the discharge. Only the part of total current penetrates into this region at the moment of maximum of the Z pinch X-ray radiation. We believe that the array mass is relatively high for this case. These results are in agreement with the data of the modeling presented in that paper.

II. Experimental Setup

A. The Experimental Installation and Diagnostics

The parameters of pulsed power generator of "Angar-5-1" facility are as follows: the maximum voltage on matched load of 1.5 MV; the pulse duration of voltage at a half-magnitude equals to 90 ns; the wave resistance of the generator is of 0.25 Ω; and the peak current through matched load is 5 MA.

The set of diagnostic techniques, used in the experiments, included: magnetic probes for total discharge current recording; miniature magnetic probes for driving current recording inside wire array during the plasma production and the implosion; visible and X-ray range frame MCP cameras; visible range streak camera; open vacuum photodiodes, and the X-ray backlighting of wire array by means of the pulsed X-ray radiation of additional X pinch (an idea of this method is similar to [13], [14]).

B. Design and Preparation of Wire Arrays

The cylindrical tungsten wire arrays were used. The parameters of wire array: initial diameter from 8 to 20 mm; diameter of the wires from 5 to 10 μm. The number of wires in the arrays changed to have an interwire gap from 100 μm and more. The electron microscopy with the diameter of probing electron beam ∼100 Å proved high quality of array wires. The cleaning of wire surface in array was executed by dc current heating of wires in vacuum. A reliable suppression of current prepulse action on wire array load was provided in experiments.

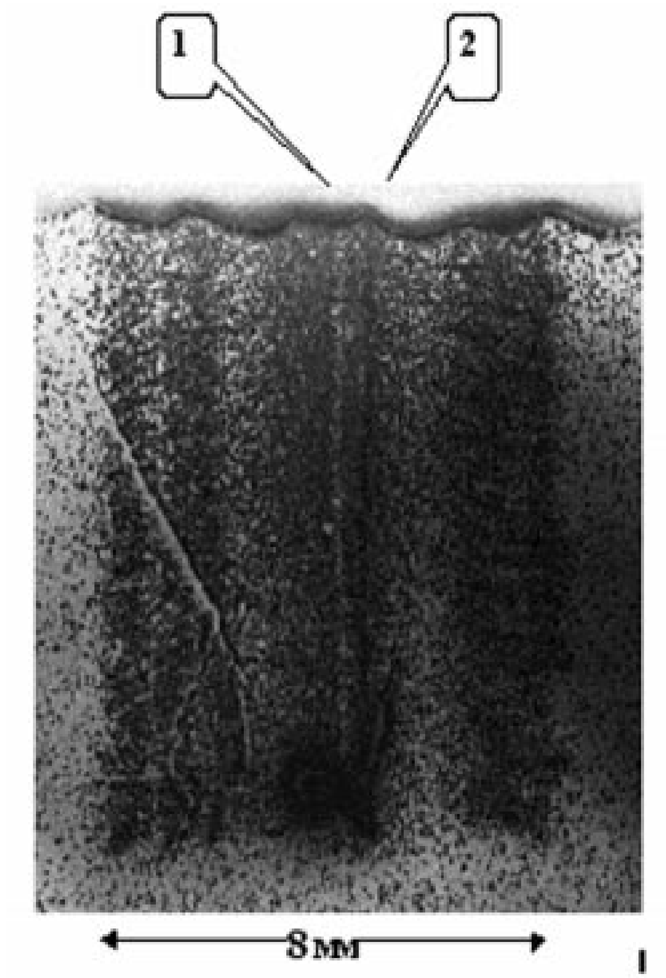

Fig. 1. An image of part of wire array in self X-ray radiation. 1) The glow of a wire located behind the plasma precursor, 2) the shadow of a wire located in front of the plasma precursor. Exposition is 3 ns.

III. Experimental Results

A. X-ray Backlighting Study of Dense Cores in Imploding Wire Array

The plasma precursor is formed on the array axis before the final pinch stagnation. Plasma precursor filling of internal volume of the array is the source of X-ray radiation. Dense parts of the wires produce shadows, which can be seen on a background of the radiating plasma. An instant (3 ns) X-ray frame of a small part of wire array is shown in Fig. 1. The following objects are distinctive on the given image: the glow of a wire 1) located behind the plasma precursor, and the shadow of a wire 2) located in front of the plasma precursor. Hence, a bright plasma-producing layer is located on internal surface of the wire and a plasma-producing region has no azimuthal symmetry near the wire. The wire matter is being spent in most extent from the wire side, looking to the array axis.

The structure of dense cores was obtained by X-ray backlighting of the array by radiation of additional X pinch. For this purpose, one of eight return current posts in Z pinch unit (45 mm from the wire array axis) was replaced by X pinch. The X pinch was produced by two crossed molybdenum wires with diameter of 20 μm. Current through the X pinch was 300–400 kA (about

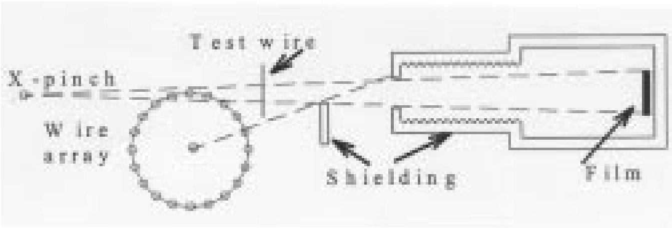

Fig. 2. A layout of X pinch backlighting of imploding wire array.

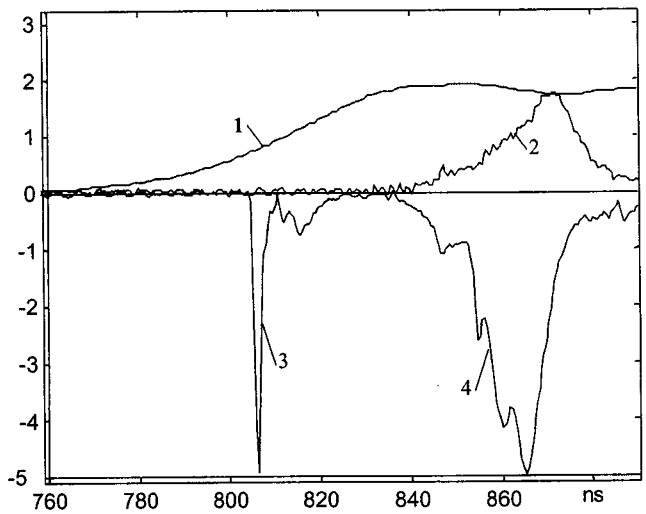

Fig. 3. Temporal profiles of: 1—current [2 MA/div], 2—soft X-ray radiation power [2 TW/div] of Z pinch (wire array 20 mm diameter, 60 tungsten wires of $d = 5$ μm), 3—radiation power [10 MW/div] of X pinch, recorded by silicon p-i-n detector behind 16 μm titanium filter in the range of 3–5 keV, 4—the same for Z pinch radiation.

1/8 of the total pinch current). The layout of X-ray backlighting is shown in Fig. 2.

The image of wire shadows was recorded by film, protected from direct and scattered radiation of Z pinch by means of screens and filters (titanium, 16 μm) situated between Z pinch and films. A silicon p-i-n detector behind the filter was used for measuring the moment and duration of X pinch radiation in spectrum range of 3–5 keV. The FWHM of the probing X-ray pulse of the X pinch recorded in quanta energy region 3–5 keV does not exceed 2 ns. The X-ray source size of X pinch for recorded quantum energy region does not exceed 2 μm. The evaluated spatial resolution of the technique at wire position is $\sim$1.7 μm. Typical profile of the current, the soft X-ray radiation of Z pinch, and the X-ray radiation of X pinch are presented in Fig. 3. The pulse of X pinch radiation appeared at 50–60 ns after the driving current start. This method was used to investigate the initial stage of implosion of the multiwire array of 20-mm diameter, which consisted of 60 tungsten wires of 5 -μm diameter.

The analysis of obtained experimental data shows that at 50–60 ns after current start the wires are recorded as objects with diameter 18–20 μm, so the diameter of wires has increased by factor of $\sim$3. Such effect was observed both for the wires with diameter of 5 μm at level of current $\sim$30 kA/wire and for the wires with diameter of 8 μm at level of current $\sim$50 kA/wire. The evaluation of expansion velocity of dense cores gives the value $\sim 10^4$ cm/s. At some images, the axial

Fig. 4. X pinch backlighting of selected wire of exploding array. The size of array wires at moment of X pinch probing is 18 μm. Parameters of array: tungsten, $D = 20$ mm; $N = 60$; $d = 5$ μm.

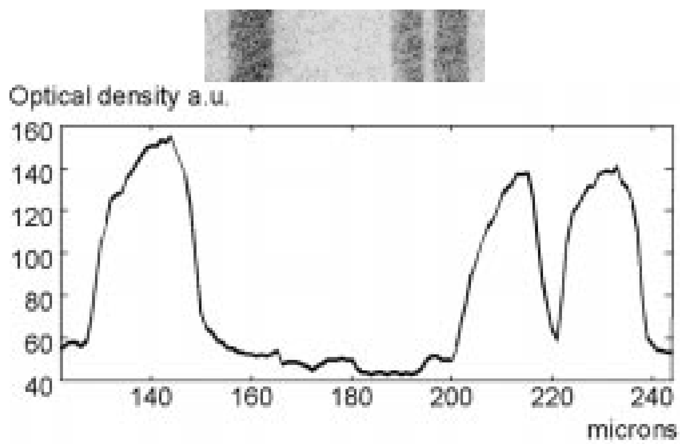

Fig. 5. X pinch backlighting of selected part of wire array. (a) X-ray image of selected part of wire array, (b) the optical density profile of that image along direction to array axis.

nonuniformity of dense substance of wires with the scale of 5–15 μm is remarkable. It is shown in Fig. 4. Note that the scale of a axial nonuniformity of dense cores doesn't coincide with the scale of axial nonuniformity of low-density plasma corona ($\sim$250 μm for W), mentioned previously. The results of X pinch backlighting of the part of the array are presented in Fig. 5(a) and (b). It is clearly seen that the optical density of the wires image, looking at the array axis, is smaller than the density of the outer side. It means that plasma-producing matter blows from internal side of the wires in most extent.

B. Measurements of Azimuthal Magnetic Field Inside of Wire Array

The results of azimuthal magnetic field measurement inside of imploding wire array are shown in Fig. 6. The miniature magnetic probe with diameter of loop about 0.3 mm was used to determine temporal profile of discharge current inside the radius of the probe location. The electrostatic screening by thin NbTi

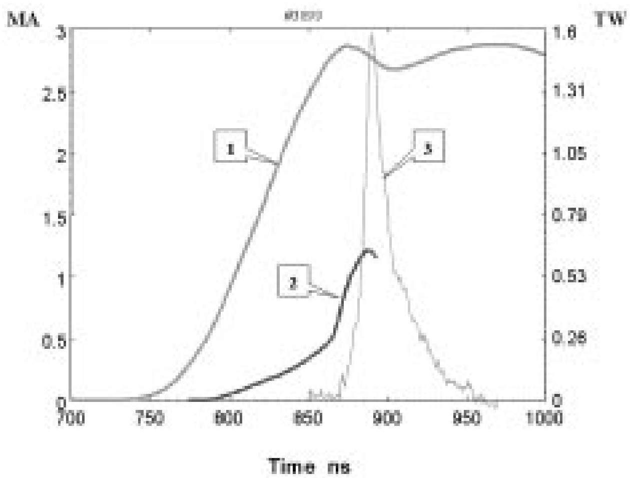

Fig. 6. 1) Temporal profiles of total discharge current through an array; 2) the current determined by azimuthal magnetic field probe signal at radius 5 mm; 3) soft X-ray power in range 100–2000 eV. Parameters of array: tungsten; $D = 20$ mm; $N = 80$; $d = 5$ μm; $M = 320$ μg/cm.

foil and the flat shaping of the probe provided its improved reliability and temporal resolution of $\sim$1.5 ns. The magnetic probe was installed inside the wire array at a distance of 5 mm from the central axis for the array with radius $R_L = 10$ mm. The other array parameters were: tungsten; $N = 80$; $d = 5$ μm. $M = 320$ μg/cm. In Fig. 6, the temporal profiles of the 1) total discharge current, 2) the current determined by magnetic probe at radius 5 mm, and 3) the soft x-power in range 100–2000 eV are presented.

There are the precursor and the main part on the magnetic probe signal. The precursor current which is $\sim$15% of the total current. It penetrates into the internal array region at the early stage of discharge. The time delay between the signals 1) and 2) gives the velocity of the precursor plasma $\sim 10^7$ cm/s. The total current achieves maximum at $\tau \sim 130$ ns after the current beginning, whereas the current on 0.5 R_L and the soft X-ray radiation just begin to rise intensively at this moment. Only a half of total current penetrates into $r < 0.5$ R_L region to the moment of maximum of X-ray radiation power. Therefore, the residual part of total current is captured by the external plasma in the region 0.5 $R_L < r < R_L$. Probably, the plasma production was too long in the case presented. Note, that total power of X-ray radiation in that case was only $W \sim 1.5$ TW. It is $\sim$3 times lower in comparison with the optimal case $R_L = 6$ mm, $\tau \sim 90$ ns, $W \sim 5$ TW.

IV. Simulation of Prolonged Plasma Production Effects

To simulate dynamics of plasma formed from the wire array we use one-dimensional (1-D) ideal MHD code presented earlier in [10]. The code takes into account prolonged plasma production by infinitely thin source uniformly distributed on the lateral cylindrical surface with radius which is equal to the initial radius of the array R_L. It neglects radial structuring of plasma producing matter and neglects plasma pressure as well, because it is typically much less than magnetic field pressure and density of kinetic energy for plasma flow formed by the process of prolonged plasma production [10]. Though the model is simple and doesn't take into account the array azimuthal structure, the code may simulate several interesting features of the process of compression of plasma formed from multiwire arrays. The code utilizes the following set of MHD equations in the region $0 < r < R_L$:

$$\frac{\partial}{\partial t} v_r + v_r \frac{\partial}{\partial r} v_r = -\frac{1}{8\pi r^2 \rho} \frac{\partial (B_\varphi r)^2}{\partial r} \tag{1}$$

$$\frac{\partial}{\partial t} B_\varphi + \frac{\partial}{\partial r} (v_r B_\varphi) = 0 \tag{2}$$

$$\frac{\partial}{\partial t} \rho + \frac{1}{r} \frac{\partial}{\partial r} (v_r r \rho) = 0. \tag{3}$$

The boundary conditions at $r = R_L$ are

$$(\rho v_r)|_{r=R_L} = -\dot{m}(t) \tag{4}$$

$$\left. \left(\rho v_r^2 + \frac{B_\varphi^2}{8\pi} \right) \right|_{r=R_L} = \frac{[B_{\varphi 0}(t)]^2}{8\pi} \tag{5}$$

$$-v_r|_{r=R_L} \leq \left. \frac{|B_\varphi|}{\sqrt{4\pi\rho}} \right|_{r=R_L}. \tag{6}$$

Here, v_r and ρ are radial component of velocity and density of plasma, respectively; B_φ is the azimuthal component of the magnetic field strength; and $B_{\varphi 0}(t)$ is determined as $B_{\varphi 0}(t) = 2I(t)/cR_L$, where $I(t)$ is the total discharge current. We admit the following form of the plasma production rate:

$$\dot{m}(t) = \begin{cases} C[I(t)]^\mu, & t \leq t_q \\ 0, & t > t_q \end{cases} \tag{7}$$

and the following simple form of current pulse:

$$I(t) = I_m t^2 \frac{(3t_j - 2t)}{t_j^3}. \tag{8}$$

The number C in (7) is determined by the condition that the total liner mass is transformed into plasma by the moment $t = t_q$. Equation (8) gives the current pulse with the maximum I_m reached at $t = t_j$.

The case $\mu = 1$, considered in [10], ensured formation of very compact and uniform plasma shell. Here, we present results of

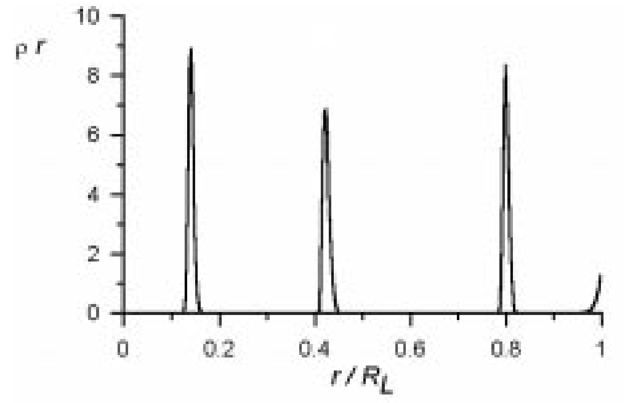

Fig. 7. Simulated density distribution for $t_q = 0.5t_j$ at the time moments: $t_q/t_j =$ 0.4, 0.9, 1.1 and 1.2. Scaled units are used for the vertical axis: $\rho_0 = \pi^{-1}(I_m t_j / cR_L^2)^2$ and $r_0 = R_L$.

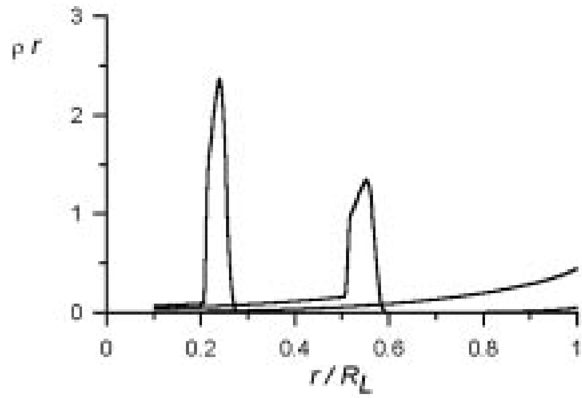

Fig. 8. Simulated density distribution for $t_q = 0.9t_j$ at the time moments: $t_q/t_j =$ 0.4, 0.9, 1.1 and 1.2. Scaled units are used for the vertical axis: $\rho_0 = \pi^{-1}(I_m t_j/cR_L^2)^2$ and $r_0 = R_L$.

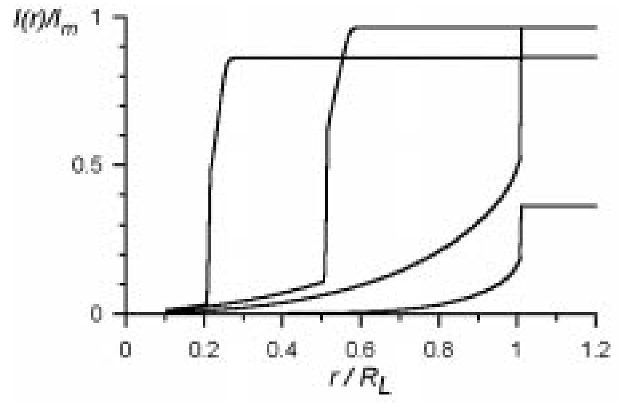

Fig. 9. Simulated current in the circle of radius r for $t_q = 0.9t_j$ at the time moments: $t_q/t_j =$ 0.4, 0.9, 1.1 and 1.2.

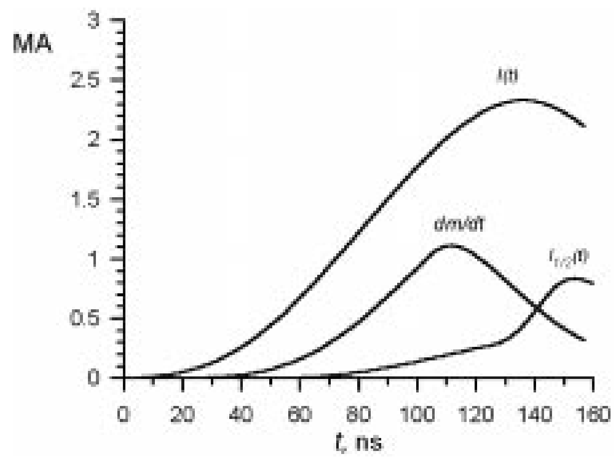

Fig. 10. Simulation of electric current inside the circle of 0.5 R_L radius in the model of prolonged plasma production. Total electric current (dotted line), plasma production rate in an arbitrary units (dashed line) and electric current inside the circle of 0.5 R_L radius (solid line) are shown.

the simulation for the case $\mu = 2$. There are two reasons for that choice. First, the simple model of plasma formation considered in [10] gives $\mu \approx 2$, and secondly, the results of our simulations with $\mu \approx 2$ are in agreement with the probe measurements of azimuthal magnetic field, presented previously.

Figs. 7–9 present results of the simulation with the same liner mass per unit length $M_L = 0.234(I_m t_j/cR_L)^2$ but with different t_q: a) $t_q = 0.5t_j$ (Fig. 1); and b) $t_q = 0.9t_j$ (Figs. 8 and 9). The number 0.234 is chosen from the condition that the implosion would take place at $t = 1.2t_j$ in the zero-dimensional model of liner compression. Figs. 7 and 8 show radial distributions of plasma density (multiplied by r) for the following time moments: $t/t_j =$ 0.4, 0.9, 1.1, and 1.2. Fig. 7 shows that if the plasma production finishes at the moment when the current is of order of half of its amplitude value or earlier. The plasma shell in the 1-D model is very thin, so its motion is similar to what the zero-dimensional model gives. Of course, this fact does not depend on specific form of $\dot{m}(t)$. Recall that such properties of 1-D model should lead to quick disruption of the plasma shell due to RT instability in real experiment.

Results of simulation for longer plasma production $t_q = 0.9t_j$ are presented in Figs. 8 and 9. Fig. 8 shows that the plasma shell with a moderate aspect ratio (∼5) is formed in this case. Such a plasma shell should be much more stable against RT instability in comparison with the previous case. In contrast to the case of $\mu = 1$, a plasma precursor is formed which moves in front of the main body of the plasma shell. This precursor reaches the axis at $t = 0.62t_j$. This precursory plasma forms a prepinch at the axis. The region $r < 0.1R_L$ is not shown in Figs. 8 and 9 because our present model is too simple to obtain valid parameters of the plasma in pinched state. The precursory plasma carries a magnetic flux, that can be seen in Fig. 9.

It is very important that a certain portion of total current is concentrated into the boundary layer existing during the whole period of the plasma production. Just produced plasma is accelerated to a finite drift velocity into this boundary layer. This boundary layer is infinitely thin in our simple model. Internal structure of such boundary layer is considered in [10]. Its width is determined by plasma resistivity and thermal transport, that gives a self consistent value of plasma production rate $\dot{m}$. The jump of magnetic field over the boundary layer creates a compression shock wave at the moment of sharp depletion of the plasma source. It propagates through the magnetized plasma and converges toward the discharge axis. This shock wave causes an additional compression of the plasma shell and its contraction in the radial direction, and may be easily seen in Figs. 8 and 9 as a forward edge of the main body of the plasma shell. The fact of additional plasma compression is common, it does not depend on rate of plasma source switching off. However, if the switching off is smooth enough, then the additional compression may be not accompanied by the onset of a shock wave.

Trying to understand the results of probe measurements of azimuthal magnetic field at $R_L/2$ radius, we performed simulation of dynamics of plasma formed by the process of prolonged plasma production assuming sufficiently smooth switching off of the plasma source. The plasma production rate $\dot{m}(t)$ before its maximum corresponds to the upper line of (7) with $\mu = 2$, but instead of instant switching off, we assume now an exponential decaying rate of plasma production with smooth conjunction of these two branches of $\dot{m}(t)$. Fig. 10 shows total current pulse, $\dot{m}(t)$ (in arbitrary units) and simulated current $I_{1/2}$ flowing inside the circle of $R_L/2$ radius. The simulation was performed with the same code. The integral of $\dot{m}(t)$ determines the total liner mass ($\sim$160 μg/cm); $R_L = 1$ cm. Comparing the profiles of the total current and the current at $r = 0.5R_L$ in Figs. 10 and 6, we may see their qualitative similarity: only a part of total current can penetrate to Z pinch axis, if plasma production is too long. Detailed quantitative comparison of the theory and the magnetic probe measurements will be done later.

V. Conclusion

The prolonged plasma production is an important property of current-driven implosion of wire arrays at the current rise rates $\sim$(0.5–1) 10^{14} A/s. It is a consequence of using of heterogeneous plasma producing medium.

X-rays images of the compressed wire arrays, presented in this paper, show that the dense compact core structure of exploded wires exist during the most period of current rise. The dense cores are asymmetric in the radial direction and expand with velocity of the order of 10^4 cm/s. In the same time, a hot plasma formed around the cores, flows toward the axis forming the prepinch. The plasma transfers magnetic flux, frozen in it. This flux is detected by magnetic probes. These measurements confirm theoretical estimations of the plasma production rate, previously published in [10]. Comparison of the magnetic probe data with the MHD simulation gives in result the reliable evidence of very gradual depletion of the plasma production source. The data show also that almost half of the total current can be shunted by the residual plasma even at the maximum of X-ray pulse.

Thus, the prolonged plasma production can determine the current and density profiles as before final stage of a Z pinch compression, so in the moment of Z pinch stagnation. From this point of view, the requirement that residual uncompressed plasma should not shunt the current at the discharge periphery becomes of greater importance. The conditions exist, when prolonged plasma production is not an obstacle for achievement of high-power X-ray emission from Z pinch. Presented experimental results on multiwire array implosion can be explained on the basis of prolonged plasma production without referring to multiwire array azimuthal structure.

Acknowledgment

The authors acknowledge useful discussion with R. B. Spielman and C. Deeney of Sandia National Laboratory, Albuquerque, NM.

References

[1] E. V. Grabovskii, V. P. Smirnov, and S. V. Zakharov *et al.*, “Theoretical and experimental investigation of Z pinch plasma,” *JETP*, vol. 109, no. 3, pp. 827–839, Mar. 1996.

[2] R. B. Spielman, C. Deeney, and G. A. Chandler *et al.*, “PBFA Z: 60 TW/5-MJ Z pinch driver,” in *Proc. Dense Z Pinches 4th Int. Conf.*, Vancouver, BC, Canada, May 1997.

[3] R. B. Baksht, I. M. Datsko, and A. A. Kim *et al.*, “Wire array implosion experiment on the inductive storage generator GIT-4 and GIT8,” in *Proc. Dense Z Pinches 4th Int. Conf.*, Vancouver, BC, Canada, May 1997.

[4] Yu. I. Bakshaev, A. V. Bartov, and P. I. Blinov *et al.*, “The experimental investigation of imploding plasma as a source of hard X-ray,” in *Proc. Dense Z Pinches: 4th Int. Conf.*, Vancouver, BC, Canada, May 1997.

[5] I. K. Aivazov, V. D. Vikharev, and G. S. Volkov *et al.*, “Experimental investigation of precursor appearance on at wire array axis,” *Sov. J. Plasma Phys.*, vol. 14, no. 2, pp. 197–203, Feb. 1988.

[6] A. V. Branitskii, E. V. Grabovskii, and M. V. Frolov *et al.*, “Peculiarities of wire resistance behavior on initial stage of explosion,” in *Proc. 12th Int. Conf. on High-Power Particle Beams. BEAMS’98*, M. Marcovits and J. Shilo, Eds. Haifa, Israel, June 1998, pp. 599–602.

[7] V. V. Alexandrov, A. V. Branitsky, and G. S. Volkov *et al.*, “Superfast multi-wire liner implosion physics study on Angara-5-1,” in *Inertial Fusion Sciences and Applications 99*, C. Labaune, W. J. Hogan, and K. A. Tanaka, Eds. Paris, France: Elsevier, Sept. 2000, pp. 591–596.

[8] E. V. Grabovskij, S. L. Nedoseev, and G. M. Oleinik *et al.*, “Angara-5 program: Development of bright X-ray sources for ICF based on superfast imploding plasma—Cold start and plasma compact implosion problem,” in *Proceedings of the Sixteenth International Conference on Fusion Energy Organized by the International Atomic Energy Agency (FUSION ENERGY 1996)*. Vienna, Austria: International Atomic Energy Agency, 1997, vol. 3, pp. 129–135.

[9] A. V. Branitskii, V. V. Alexandrov, and E. V. Grabovskii *et al.*, “Cold-start effects in experiments on the implosion of plasma liners in the Angara-5-1 facility,” *Plasma Phys. Rep.*, vol. 25, no. 12, pp. 976–993, Dec. 1999. Translated from *Fizika Plazmy*, vol. 25, no. 12, pp. 1060–1078, 1999.

[10] V. V. Alexandrov, A. V. Branitskii, and E. V. Grabovskii *et al.*, “Dynamics of heterogeneous liners with prolonged plasma creation,” *Plasma Physics Reports*, vol. 27, no. 2, pp. 89–109, 2001. Translated from Fizika Plazmy, vol. 27, no. 2, Feb. 2001, pp. 99–120.

[11] V. V. Alexandrov, E. A. Azizov, and A. V. Branitsky *et al.*, “Multiwire array implosion physics study and ‘Mol’ test-bed for ‘Baikal’ project based on 900 MJ inductive storage,” in *Proc. 13th Int. Conf. on High-Power Particle Beams, BEAMS’2000*, Nagaoka, Japan, June 25–30, 2000, pp. 147–150.

[12] S. V. Lebedev, F. N. Beg, and S. N. Bland *et al.*, “Physics of wire-array Z pinch implosions,” *Phys. Plasmas*, vol. 8, pp. 3734–3741, 2001.

[13] D. N. Kalantar and D. A. Hammer, “Observation of a stable dense core within an unstable coronal plasma in wire-initiated dense z pinch experiments,” *Phys. Rev. Lett.*, vol. 71, p. 3806, 1993.

[14] I. Yu. Skobelev, A. Yu. Faenov, and S. A. Pikuz *et al.*, “Study of plasma objects radiation properties by X-ray image spectroscopy,” *JETP*, vol. 108, no. 10, pp. 1263–1275, Oct. 1995.

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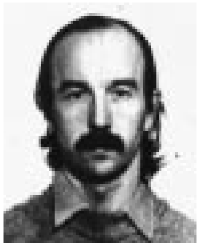

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