Physics Of ICF Related Multiwire Array Implosion


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At the present time an investigation into the process of current-driven implosion of cylindrical tungsten wire arrays is under way as applied to the ICF research [1-3]. The best parameters have been attained at the Z facility in the Sandia Laboratory [2]: on conducting a current of 20 MA with a rise time of 105 ns through a wire liner at the moment of the liner collapse a soft X-ray radiation (SXR) pulse is generated with an energy of 2MJ, a peak power of 200 TW and a FWHA duration of 5.5 ns.

The investigations performed at the Angara-5-1 facility have shown that after first several nanoseconds of current flowing plasma is generated on the surface of a wire and the current from the wire is switched to the plasma corona. The system includes low density plasma and a dense core. The core keeps its initial position for a significant period of the liner pulse duration and serves as a stationary plasma source. The plasma being continuously generated is accelerated to the liner axis by Ampere’s force. This plasma is considerably thick and transfers some fraction of the current.

For a better understanding of physics of the wire array implosion process of great interest are investigations into the spatial mass and current distributions inside the array during this process. The current work deals with these investigations performed at the Angara-5-1 facility and presented in three sections:

- current distribution inside the array during implosion,
- plasma density distribution during implosion using a method of X-ray probing,
- electron density distribution during stagnation using a laser interferometer.

I. THE INVESTIGATION OF THE CURRENT DISTRIBUTION INSIDE THE ARRAY IN THE PROCESS OF IMPLOSION

An azimuthal magnetic field was measured with miniature probes of small diameter arranged inside and outside the liner being compressed. The liner of a linear mass of 220 µg/cm and 20 mm in diameter, comprising of 40 tungsten wires 6 µm in diameter served as a load. The liner height was 15mm. Two magnetic probes were placed on different radii of 6.5 and 8.5 mm at an angle of 90° to one another.

Experiments show that at an early stage of implosion an azimuthal magnetic flux penetrates into the liner. The precursor current was found to attain 100 kA. A current inside the circumference with a radius being equal to 0.65 of the initial one appears in forty nanoseconds after the current initiation. Before a main current plasma comes, the current having penetrated inside the 6.5 mm radius smoothly rises in 100-110 ns up to 300-400 kA which is about 15% of the total current at this moment. In a number of runs this current value may vary from 3 to 15% of the total current. The main current shell at the moment of its passing through the probe has a width of a leading front of 2 mm exceeding that of the classical skin-layer.

By the moment of maximum compression a marked current fraction (around half) flows on the liner periphery, i.e. outside the cylinder 0.65 cm in radius.
II. THE INVESTIGATION OF THE PLASMA DENSITY DISTRIBUTION IN THE PROCESS OF IMPLOSION USING A METHOD OF X-RAY PROBING

One of the ways to perform such investigation is to illuminate a liner to be compressed with a separate point source of soft X-ray radiation and to detect a shadow observed. An X-pinch is a convenient and widely used source for X-raying imploding wires [6]. One of eight return-current posts (spaced 45 cm from the liner axis) was substituted by an X-pinch. The latter consists of some crossing molybdenum wires 20 μm in diameter being in contact with one another in their center in the point of interception. The current through the X-pinch was 300-400 kA (about 1/8 of the total liner current). The image was recorded by two photographic films arranged one after the other. In order to make a transition from the density of darkening to that of the liner substance possible in front of the film some samples with measured mass of the same substance (tungsten - in the given case) were placed. To check spatial resolving power of the method used and determining the size of the source special test wires 5-6 μm in diameter were located close to the liner. Both shadows of the current-driven liner and test wires were simultaneously obtained on the same photographic film. From these measurements the size of the X-pinch was found to be less than 2 μm. The corresponding spatial resolution of the method at the liner under study was ~0.7 μm.

Probing in different shots took place in 60-80 ns after applying current to the load. By the moment of the operation some of the wires had almost completely expanded, but some remained in the form of dense cores with a diameter being 3-4 times greater than that of the initial wires. Besides, different types of wire luminosity in the visible range were fixed at the onset of implosion (including those appeared along the wire length). This means that the plasma-producing process proceeds nonuniformly. The experiments have shown that in 60-80ns after current start the wires of array are augmented in a diameter in 3-4 times at level of current ~30-50kA/wire. The evaluation of expansion velocity of dense cores gives the value ~10^4 cm/s.

The mass remained in the dense cores was estimated to be about 70% of the initial one. The rest of the wire mass (~30% of the initial mass) was spread over a radius of ~200 μm close to the initial wire position. It should be noted that a fairly small fraction of the plasma extended beyond the liner borders: low density plasma was observed at a space of ~100 μm from the wire.

Close to the core an axial plasma density nonuniformity of 200 μm corresponding to that visible in the liner images in self X-ray radiation has been found. In a number of experiments a 20-30 μm inner axial nonuniformity of the core itself has been found as well. This scale of the non-uniformity of dense cores does not coincide with the axial non-uniformity scale of surrounding low density plasma mentioned above.

III. THE INVESTIGATION OF THE PLASMA CONCENTRATION DISTRIBUTION DURING STAGNATION USING A METHOD OF LASER INTERFEROMETRY

For the purpose of finding a spatial distribution of electron density on the periphery of the wire array a laser shift interferometer was employed. The investigation into the electron concentration was performed at the moment of stagnation.

In the physics of implosion of vital importance is amount of substance left on the periphery of an initial wire array at the moment of final compression. Due to nonuniformity of the plasma-producing process it turns out that at this moment a certain amount of plasma may be produced on the periphery of the array. This plasma is capable of partial shunting the current. The estimations have shown that plasma with a small mass fraction (a few percent of
the initial wire array mass) can carry a noticeable current fraction and, thereby, reduce output characteristics of the implosion process.

The present section is devoted to the investigation into the mass quantity available on the periphery of the initial wire array at the moment of pinching. The array 12 mm in diameter consisted of forty tungsten wires 6 μm in diameter each. In a number of runs the value of local electron density on the initial array periphery achieved \( \sim 10^{18} \text{cm}^{-3} \). The layer thickness at this density ranged from 0.3 to 3 mm. Under assumption of an ion plasma charge of \( \sim 10 \), at the moment of pinching there are some regions where the local linear mass was estimated to be \( \sim 10^{-30} \mu g/cm \), i.e. about 10% of that for the initial wire array. Dependence of recorded mass at periphery of initial array position on delay between laser pulse and time of SXR maximum is presented on fig.1. It is clearly to see that recorded mass diminishes with diminishing this delay, but only to level 10-30μg/cm. Thus, after the SXR maximum 90% total liner mass is on the axis (inside a diameter of 6 mm), the rest 10% - between diameter of 6 and 12 mm.

Voltage measured on a radius of 6 cm is indirect evidence for the presence of plasma on the periphery of the initial wire array. At the moment of pinching the voltage on a gap of 1 cm should exceed 1 MV. However, the voltage taken in its maximum does not exceed 0.5 MV, which is indicative of the fact that not all the current flows through the pinch. The presence of plasma on the periphery at the moment close to that of maximum compression may be observed with the help of alternative diagnostic techniques: an optical streak image of luminosity of the liner radial cross-section and instant pictures of Z-pinch in self SXR at the time close to maximum compression.

The question is how a mass could remain on the periphery of the wire array by the moment of maximum compression. The total mass had to be displaced by current towards the center. One of the explanations is as follows. In the process of implosion the plasma-producing process can be of a nonuniform character. By the moment of the maximum compression a major fraction of the plasma-forming substance had already transited into plasma and been displaced towards the center together with a frozen-in magnetic field. However a fairly small fraction of the substance in the form of drops and small localized wire residuals could remain. The substance of these residuals does not prevent from penetrating the magnetic flux into the near-axis discharge area. On the surface of the residuals the process of hot plasma production still goes on. This plasma is seen in the interferograms taken by a laser shift interferometer on the periphery of the wire array.

So, by use of the given technique based on the above-said interferometer we have managed to detect the plasma on the periphery of the initial wire array at the moment of maximum compression. It can be stated that by this moment (in\( \sim 120-150 \) ns after the current initiation) a local maximum electron density of \( \sim 10^{18} \text{cm}^{-3} \) is to be attained inside the initial wire array at a distance of 0.3 to 3 mm from the initial wire location. Under assumption of a mean ion charge of 10 for tungsten this gives a local linear liner mass of 30 μg/cm, which is 10 percent of the initial one. This plasma is likely to be produced from small localized wire residuals. A
fraction of the generator current flows through this plasma. This fact is in coincidence with current measurement inside liner during implosion.

SXR pulse duration is of 6-8 ns, which confirms good quality of the compression process.

IV. SUMMARY

As a result of the investigations performed the precursor characteristics and the plasma structure and concentration have been determined in the process of wire array implosion. The data confirm the concept of prolonged plasma production: for a long period of current flowing through the wire array in the process of implosion hot plasma drains off dense stationary cores and accelerates towards the center by Ampere’s force. By the moment of maximum compression a certain mass fraction remains on the periphery where a marked current fraction flows.

Quantitative data on implosion of wire arrays at the Angara-5-1 facility are as follows:

- The precursor current achieves 100kA.
- Current inside a circle with a radius being equal to half the initial one appears in 40 ns after its onset.
- The main current shell at the moment of its passing through the probe has a width of a leading front of 7 mm exceeding that of the classical skin-layer.
- Wires loose their mass at different velocity. The mass of dense cores is ~70% of the initial one in 80 ns after current onset. The rest of the wire mass is spread over a radius of ~200 μm.
- The wire diameter became 3-4 times greater in this time.
- Low density plasma is observed outside the liner on a size of ~100μm.
- At this time axial stratification of plasma density close to dense cores has a characteristic size of 200μm, and that of this core density is 30μm.
- By the moment of maximum compression about half the current flows on the liner periphery. At this time up to 10% of the liner mass is present on the periphery of the initial wire array.

V. REFERENCES