Interaction of plasma flows and magnetic field with the formation of a shock wave in nested arrays

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The results of plasma compression studies of nested wire and fiber arrays with current flowing through them are presented in this work. Experiments were made on the Angara-5-1 facility with current up to 4 MA. Current implosion of nested arrays represents a unique opportunity to simulate the interaction of a plasma flow with a magnetic field. Different plasma flow regimes in the space between the inner and outer arrays were obtained: sub-Alfven ($V_r < V_A$), super-Alfven ($V_r > V_A$) and a mode with the formation of a transition region — shock wave (SW) between the arrays, depending on the radii ratio of the inner and outer arrays. The dependence of these flow regimes on the plasma production rate of the inner and outer arrays is shown. At certain parameters of nested arrays, a quasi-closed shell is formed in the azimuthal direction around the inner array. At the same time, the plasma of the outer array surrounds the inner and stabilizes its compression. The suppression of MRT instabilities during plasma compression of the inner array leads to the formation of a stable, compact Z-pinch and the generation of a short-time soft X-ray pulse.

1. Introduction

The generation of powerful plasma flows and interaction with the magnetic field are of both fundamental and practical interest. One of the directions of studying plasma flows and creating powerful X-ray sources on their basis is associated with the current implosion of nested wire arrays \cite{1, 2, 3}. 

Studying the influence of physical processes arising from the interaction of plasma flows from an outer array with the magnetic field of an inner array during a current implosion of nested arrays is important for understanding the formation of the spatial-temporal structure of the Z-pinch, the dependence of the time profile and the peak power of the X-ray pulse.

The existence of three plasma flow regimes between inner and outer arrays (super-Alfven, sub-Alfven, and the flow with the formation of a shock wave) was predicted in the one-dimensional MHD model \cite{4} of a stationary plasma flow taking into account the extended plasma production of the inner and outer arrays of the nested array. According to this model, the realization of a particular mode depends on the ratio of the rates of plasma production in the inner and outer arrays and their radii. Inside the volume of such an array, there is a collision of the supersonic plasma flow generated from the material of the outer array by the current flowing through it, with the magnetic field generated by the current through the inner array.

A series of studies on the implosion and plasma dynamics in the nested arrays was performed on the Angara-5-1 facility. Data were obtained on the distribution of current, magnetic field, and plasma motion in the space between the inner and outer arrays. During plasma implosion of nested fiber-wire arrays, an experiment registered for the first time the
plasma motion mode characterized by a transition region forming in the space between the inner and outer arrays—the shock wave region where the transition from the super-Alfvenic \((V_r > V_A)\) plasma flow to the sub-Alfvenic \((V_r < V_A)\) flow occurs.

2. Formulating the problem

Experiments on compression of the plasma by the magnetic field nested arrays have been conducted on the Angara-5-1 facility with a discharge current of 3-4 MA. The nested arrays were connected to the facility electrodes, as shown in Fig. 1. This provided the simultaneous operation current over the outer and inner arrays. The current between the arrays was distributed depending on the ratio of their inductances.

Fig. 1. Nested array: the outer array consists of 4 kapron fibers located on the surface of a cone with a radius at the cathode \(r_{\text{cathode}} = 5 \text{ mm}\) and at the anode \(r_{\text{anode}} = 10 \text{ mm}\); the inner array is a cylinder of 40 W-wires located on the radius \(r_{\text{outer}} = 3 \text{ mm}\), the height of the arrays is 16 mm.

The cone geometry outer array is used to model three-dimensional effects during the plasma current implosion. The indicator of the three-dimensional compression of plasma flows is the image of the shock wave in the space between the arrays. Then a comparison of the shape of the shock wave in the simulation and in the experiment will make it possible to control the parameters of the spatial cumulation of compressible plasma flows in order to increase the kinetic energy density.

In this series of experiments, a set of diagnostic techniques was used that provided framing of plasma compression images of nested arrays in the optical and X-ray ranges of the Z-pinch emission spectrum. For this, two multi-frame X-ray cameras located at an angle of 90° (HMF 6, 10 frames) and 30° (REOP, 4 frames) to the axis of the nested arrays were used. The spatial resolution of X-ray cameras is in the range of 200–300 \(\mu\text{m}\) for photons with the energy of 20–500 eV. Exposure frames were from 1.5 ns to 5 ns. Three-frame shadow probing (LAS) was carried out with an SL233 laser beam at \(\lambda = 532 \text{ nm}\) and recorded with Canon EOS 450D digital cameras. The spatial resolution of laser diagnostics was no worse than 50–100 \(\mu\text{m}\). The exposure time of the laser beam was about 0.6 ns.

3. Experimental results

The results of experiments with cylindrical nested arrays were presented in [2]. It was shown that different plasma flow modes can be realized in the space between the arrays depending on the plasma production rate and the ratio of the radii of the arrays, and for a certain
ratio between the radii a closed plasma shell is formed around the inner array. In experiments with conical arrays, the ratio of the radii changes with height, and this allows us to obtain the spatial-temporal dependence of the formation of a shock wave region near the inner cylindrical array (W-array) in one experiment. Figure 2 shows frames of the X-ray and laser shadow images of compressing plasma in such nested arrays. From Fig. 2b, 2c, it is clear that at the plasma production stage at the time $t < T_{pl}$, the formation of a shock wave (SW) region is registered in the frame images (see frames $t_1$, $t_2$ and frames $t_1^*$, $t_2^*$) in the space between the arrays, near the inner array, where the kinetic pressure of the plasma flow from the outer array is balanced by the magnetic pressure of the discharge current of the inner array, i.e., when $\rho V_r^2 \approx B_{in}^2 / 8\pi$. The form of the shock wave, as well as its transformation in time, indicates a change in the interaction of plasma flows from the outer array with the magnetic field and the substance of the inner array. This is due to the redistribution of the discharge current between the arrays in the process of long-term plasma production due to the switching of a substantial fraction of the current into the inner array. Thus, the displacement of the shock wave region between inner and outer arrays is a visual indicator of the characteristics of plasma flows (their velocity and kinetic energy). At the time $t > T_{pl}$ (see laser and X-ray frames in Fig. 2), the final compression of the plasma and the destruction of the shock region by instabilities of the plasma flow from the outer array are observed. In this case, the plasma of the inner array (W-array) is compressed without visible inhomogeneities inherent in the development of magnetic Rayleigh-Taylor instabilities under compression of single W-arrays. As a result of this process, at times $t_4$ and $t_5$ (see X-ray frames in Fig. 2b), close to the moment of maximum SXR pulse (see curve 3 in Fig. 2a), a stable pinch is formed on the axis of the nested arrays.

It should also be noted that the use of a conical array in the outer array did not lead to a significant development of the zipper effect at the final stage of plasma compression of the inner array and the formation of a pinch. Most likely, this is due to the effective interaction of plasma flows from the outer array with the magnetic field of the inner cylindrical array.

4. **Conclusions**

1. It was found that the position of the shock wave region in the space between the arrays varies in time, and its shape allows estimating some parameters of the plasma flow of the outer array: its radial velocity $V_r$, plasma kinetic pressure $\rho V_r^2$, and the characteristic spatial scale of instabilities in the plasma flow.

2. The interaction of the plasma flows of the outer conical array with the magnetic field of the inner (cylindrical) array significantly reduces the development of the zipper effect at the final stage of plasma compression of the inner array and pinch formation.
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Fig. 2. The results of the experiment with nested arrays (shot # 6279): the outer conical array consists of 4 kapron fibers with a diameter of 25 μm, its linear mass is 22 μg/cm, the radius of the array is 10/5 mm; the inner array consists of 40 W-wires with a diameter of 6 μm, a linear mass of 220 μg/cm, the radius of the array is 3 mm. Array height is 16 mm; a) time dependencies: 1 – derivative of the total current; 2 – the voltage at the separatrix; 3 – SXR power pulse in the spectral range (hν > 100 eV); b) X-ray frame images (negative) of the nested array implosion, synchronized with those shown in Fig. 2a curves. In the same place, the $t_1$-$t_{10}$ frame registration times are indicated by vertical arrows (LAS). The anode is at the top, the cathode is at the bottom; c) frame images (positive) of the plasma of nested arrays, obtained using shadow laser probing at different times. Frame times $t_1$-$t_3$ are indicated by circles (LAS). The anode is at the top, the cathode is at the bottom.

References