Implosion of Planar Wire Arrays in Microsecond Regime[1]

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Abstract – A set of planar wire array experiments was carried out on the GIT-12 generator at the current level of 2.2-3.7 MA. The GIT-12 generator operated in microsecond mode, so the implosion time was in the range from 600 ns to 1300 ns depending on the load parameters. Implosions of aluminum planar wire arrays was studied at varying wire diameters, wire gaps, and wire array masses. The implosion dynamics of planar wire arrays was simulated with the help of 0D-model. A good agreement between the experimental data and the simulations was observed when a uniform current distribution in the planar wire array was assumed in the simulation model. The Al K-shell radiation yield was measured for all load configuration. The maximum registered K-shell yield was 6 kJ/cm that is about 1.5 times higher in comparison with the results obtained earlier in the microsecond Z-pinch implosion experiments with the nested wire arrays and gas-puff-on-wire-array loads at comparable peak load currents.

1. Introduction

Beginning of the Z-pinch studies is dated back to 1950s. In the mid 1970s, the Z-pinch researches got their second wind because of significant progress in pulsed power [1, 2]. At present, the Z-pinches attract attention of scientists as one of the promising ways for realization of inertial confinement fusion [3] and the most powerful laboratory X-ray source [4]. During the last years, a variety of load configurations was studied, from the most simple like single gas puffs and wire arrays to multi-shell gas puffs loads and nested wire arrays and their combinations. Recently, a new load configuration, a planar wire array, was introduced [5].

A planar wire array is a Z-pinch load configuration, in which the wires are located in a row forming a vertical plane between the electrodes. The planar wire array is of interest with relation to the study of the plasma heating mechanisms different from the conversion of the Z-pinch plasma kinetic energy in the final stage of implosion. According to the results of experiments carried out in the University of Nevada, Reno [5], the planar wire arrays, while gaining less kinetic energy during the implosions, produced higher total x-ray yield and aluminum K-shell radiation yield in comparison with conventional cylindrical wire arrays. The authors consider this results as an evidence that other mechanism of energy coupling rather than kinetic dominates in planar wire array implosions, for example, the energy dissipation due to enhanced resistivity determined by the physical mechanisms suggested in [6]. The experiments [5] have been carried out in the fast (100 ns) implosion regime, and these are the only available experimental data to date. It is of interest to carry out experimental research of implosion dynamics of planar wire arrays and their radiative characteristics, and to investigate the potential of this load to increase the efficiency of a K-shell plasma radiation source operating in microsecond implosion regime. This paper presents the results of the first set of planar wire array experiments carried out in the microsecond implosion regime.

2. Experimental set-up and diagnostics

The experiments were performed on the GIT-12 generator. The generator was redesigned for the direct drive implosion experiments. Without the POS, the generator provided the current of 4.7 MA with the current rise time of 1.7 μs in a short-circuit load at charge voltage of 50 kV. When conducting Z-pinch experiments, the load parameters were varied so that the implosion time was in the range from 600 ns to 1300 ns, and the peak load current was between 2.2 MA and 3.7 MA, correspondingly.

The planar wire arrays were composed of fine aluminum wires. Wires with diameters of 20 μm and 35 μm were used. The wire array height was 2 cm. The length of wire arrays was 12.6 cm, except for two load configurations were the wire array length was 12 and 13 cm. Wire array parameters were varied in the course of the experiments. 20-μm wire arrays were composed of 26, 43 and 85 wires with the wire gap of

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5, 3, and 1.5 mm, correspondingly. 35-μm wire arrays were composed of 27, 43, 85, and 127 wires with the wire gap of 5, 3, 1.5, and 1 mm, correspondingly. Thus, the wire array mass were varied from about 200 μg/cm to 3300 μg/cm.

The following set of diagnostics was used in the experiments. Implosion dynamics was recorded by a visible light streak camera with a writing speed of 125 ns/cm. The input slit of the streak camera was set to sample across the radius of the Z-pinch viewing 2 cm on both sides of the Z-pinch axis. In some experiments, the streak camera was aligned to view implosions of the outer wires of a planar wire array. The K-shell radiation yield and power were measured by two x-ray vacuum diodes (XRD) with a copper cathode. The XRDs had the following filter set: 8.2 μm of aluminum, 2 μm of Kimfol, and 6 μm of Mylar. Total radiation yield was measured by a bare, time-integrated bolometer. Time-integrated pinhole camera produced the pinch image in the final stage of implosion in Al K-lines. The pinhole cameras was filtered by 25 μm of beryllium and 30 μm of Polypropylene.

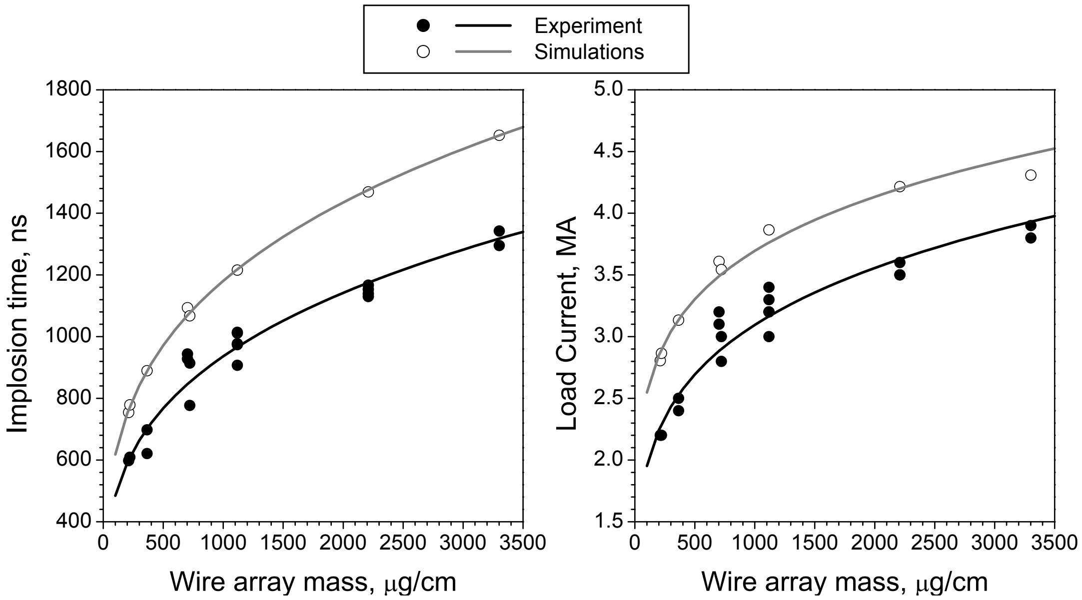

Fig. 1. Comparison between the experimental results and the results of 0D simulations for the case when the wire array implosion dynamics was simulated assuming that the load current flows only in the outer wires

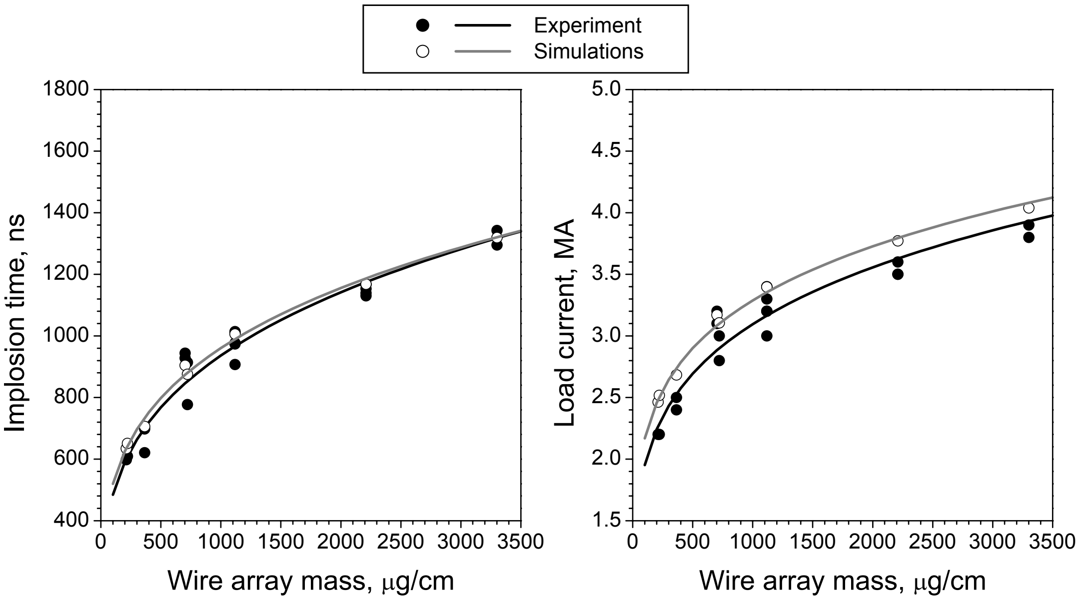

Fig. 2. Comparison between the experimental results and the results of 0D simulations for the case when the wire array implosion dynamics was simulated assuming that the load current is distributed evenly between the wires

3. Experimental results

For a given generator, the Z-pinch implosion time and the peak load current can served as an integral parameters which reflect the load implosion dynamics. Preliminary estimates of these parameters were carried out with the help of a simple 0D model which assumed that the load current flows only in the outer wires and the load mass increases as these wires move to the axis and undergo successive inelastic collisions with the wires located close to the axis. The results of these simulations and their comparison with the experimental data is shown in Fig. 1. As can be seen, the difference between the experimental and simulation data is rather large.

Much better agreement is provided by a slightly modified model which assumes that the load current is distributed evenly between the wires in the planar wire array. This case is illustrated by Fig. 2. The experimental and simulation data are in a good agreement. This model predicts also that the wires located closer to the Z-pinch axis should start their movement outwards first, and then to the axis. Such behavior was observed in the experiments (see Fig. 3). Therefore, the real current distribution between the wires should be close to the uniform one.

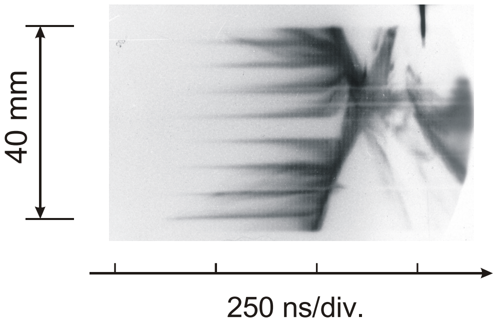

Fig. 3. Streak camera image of the planar wire array implosion (20-μm wire array, 26 wires, 5-mm wire gap). The streak camera views the region near the Z-pinch axis

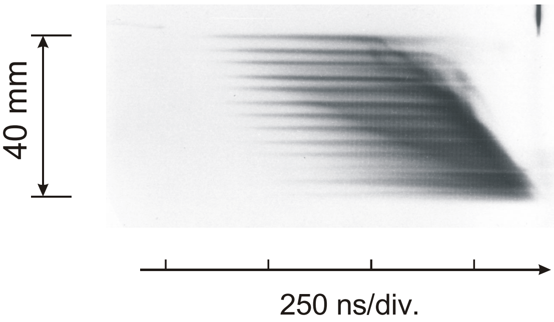

Fig. 4. Streak camera image of the planar wire array implosion (35-μm wire array, 43 wires, 3-mm wire gap). The streak camera views the implosion of the outer wires

However, the streak camera data show (see Fig. 3 and Fig. 4) that it is not exactly correct, at least at the beginning of implosion. The current appears first in the outermost wires (one can see that they flash first) and then spreads successively to the inner wires. It is reasonable to suggest that a model, which includes circuit equation taking into account the inductance of each wire and their mutual induction, should describe the experimental data more adequately. This will be our next step in modeling of the planar wire array implosion dynamics.

Let us consider the data on the Al K-shell radiation yield obtained during this set of experiments. Conventional models of the K-shell radiation, for example MKQ-model [7] and TWG-model [8], are based on the assumption that the kinetic energy gained by a Z-pinch during implosion play a key role in K-shell radiation emission. An important parameters is the kinetic energy per ion that sets a certain threshold, which should be exceeded to obtain a sizable K-shell radiation yield in the experiments. This models give reasonably good preliminary estimations of the expected K-shell radiation yield and were verified in the experiments carried out in different laboratories. For a given generator, the optimal load mass should exist, at which the K-shell radiation yield is maximal. At small masses (high kinetic energy per ion), the plasma is overheated and can not be an efficient radiator. At large masses (low kinetic energy per ion), the plasma does not reach the conditions to radiate efficiently.

The smallest wire array mass imploded in this experiments is slightly higher than 200 μg/cm. At this wire array mass, the Z-pinch implosion time was about 600 ns and the peak load current was 2.2 MA. As the mass was increased in the experiments, the peak implosion current increased (see Fig. 2), therefore the kinetic energy gained during implosion increased as well. However, the kinetic energy per ion actually decreased. From the standpoint of the conventional models, even the wire array with the mass of 200 μg/cm is an over-massed load for the given generator parameters. Further increase in the wire array mass should result in a reduction of the kinetic energy per ion and subsequent decrease in the K-shell radiation yield.

However, in the experiments appreciable K-shell radiation yields were obtained. Figure 5 shows the load current trace together with the registered K-shell radiation power. The measurements of K-shell radiation yield with the help of two XRDs located at the different angles to the wire array plane (0°, 30°, 60°, 90°) showed that the azimuth distribution of the K-shell radiation is uniform. Dependence of the K-shell radiation yield on the wire array mass is shown in Fig. 6. This dependence has a maximum both for the wire arrays composed of 20-μm-diameter wires and for the wire arrays composed of 35-μm-diameter wires. The maximum registered K-shell radiation yield was 6 kJ/cm. It is important to note that the wire array mass in that shot was 2210 μg/cm (35-μm-diameter wires, 85 wires, 1.5-mm wire gap); that is, the load was greatly over-massed. This experimental result gives grounds to discuss other possible mechanisms of energy coupling in addition to the kinetic mechanism.

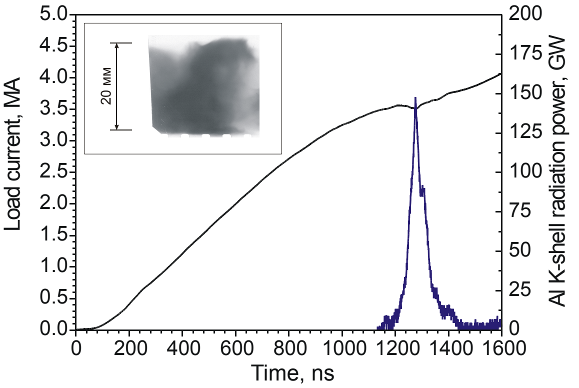

Fig. 5. Load current and Al K-shell radiation power registered in the planar wire array implosion (35-μm wire array, 85 wires, 1.5-mm wire gap). An inset shows the pinhole camera image of the pinch

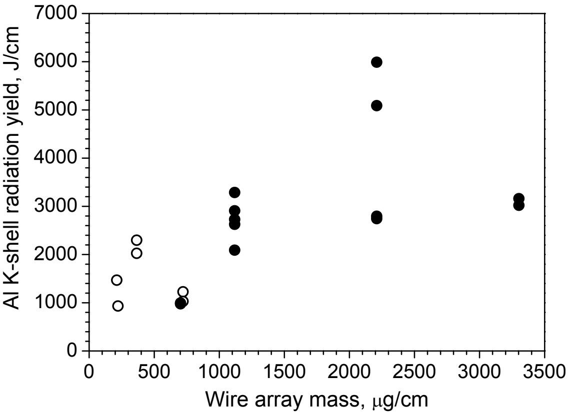

Fig. 6. Aluminum K-shell radiation yield as a function of the wire array mass (20-μm wire arrays – open circles; 35-μm wire arrays – solid circles)

Another interesting feature of the plot in Fig. 6 is a low K-shell radiation yield at the wire array mass of 700 μg/cm. It would be reasonable to expect a steady tendency for an increase in the K-shell radiation yield with the wire array mass until the optimal mass is reached. However, a drop in the K-shell yield is observed at the wire array mass of 700 μg/cm. These wire arrays had the smallest wire gap of 1.5 mm in the case of 20-μm-diameter wires and the largest wire gap of 5 mm in the case 35-μm-diameter wires. This lead to an assumption that the wire gap and the wire size can affect significantly performance of the planar wire array in respect to the K-shell radiation production.

A direct comparison have been made between the performance of a planar wire array and a cylindrical wire array. Comparison was made with the planar wire array configuration which produced the highest K-shell yield. The cylindrical wire array was composed of 84 wires with the diameter of 35 μm. Its initial diameter was equal to 65 mm. The wire array imploded at the peak implosion current of 3.7 MA and the implosion time of 1193 ns. As can be seen from Fig.2, this is very close to the implosion parameters of the planar wire array with the same mass. The Al K-shell radiation yield was only 2.3 kJ/cm.

4. Summary

The experiments with a planar wire array showed that it is a very promising load configuration. The maximum Al K-shell radiation yield registered in the experiments was 6 kJ/cm that is 1.5 times higher in comparison with the results obtained earlier in the microsecond Z-pinch implosion experiments with the nested wire arrays [9] and gas-puff-on-wire-array loads [10] at comparable peak load currents.

Generation of the K-shell radiation as a result of over-massed load implosions raises the questions about the mechanisms of the plasma heating in addition to the kinetic mechanism and why these mechanisms, if they exist, are more pronounced in the case of the planar wire arrays in comparison with the conventional cylindrical Z-pinch loads.

References

[1] N.R.Pereira and J.Davis, J.Appl.Phys. **64**, 1 (1988).
[2] D.D.Ryutov, M.S.Derzon, and M.K.Matzen, Reviews of Modern Physics **72**, 167 (2000).
[3] T.W.L.Sanford, R.E.Olson, R.L.Bowers *et al.*, Phys. Rev. Lett. **83**, 5511 (1999).
[4] C.Deeney, C.A.Coverdale, and M.R.Douglas, Laser and Particle Beams **19**, 497 (2001).
[5] V.L.Kantsyrev, A.S.Safronova, D.A.Fedin *et al.*, IEEE Trans. Plasma Sci. **34**, 194 (2006).
[6] L.I.Rudakov, A.S.Chuvatin, and A.L.Velikovich, "Enhanced resistivity in strongly nonhomogeneous wire-array plasma", Phys. Rev. Lett., submitted for publication.
[7] D.Mosher, N.Qi, and M.Krishnan, IEEE Trans. Plasma Sci. **26**, 1052 (1998).
[8] K.G.Whitney, J.W.Thornhill, J.P.Apruzese, and J.Davis, J. Appl. Phys. **67**, 1725 (1990).
[9] H.Calamy, F.Hamann, F.Lassalle *et al.*, in *AIP Conf. Proc. (6th Int. Conf. On Dense Z-pinches, Oxford, United Kingdom, 2005)* **808**, 2006, pp.15-20.
[10] A.V.Shishlov, R.B.Baksht, S.A.Chaikovsky *et al.*, "Gas-Puff-on-Wire-Array Z-Pinch Experiments on the GIT-12 Generator at Microsecond Implosion Times", IEEE Trans. Plasma Sci., submitted for publication.