Study of Planar Wire Arrays at Microsecond Implosion Times[1]

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Abstract – This paper presents the results of experiments with aluminum planar wire arrays carried out on the GIT-12 generator. The GIT-12 generator was operated in the microsecond regime providing a peak current of 4.8 MA in 1.7 μs in a short-circuit load. During the experiments, the load parameters such as a wire diameter, a gap between the wires, the number of wires, and the total planar wire mass and width were varied. The choice of the planar wire array parameters was done with the help of preliminary 0D simulation of implosion dynamics. The load parameters were chosen so that the implosion time and the peak implosion current were almost the same for all load configurations. Therefore, the energy deposited to the plasma due to kinetic mechanisms was also almost the same for all planar wire array configurations tested in the experiments. In the experiments, the implosion dynamics and the aluminum K-shell radiation yield were registered. The experimental data on the K-shell radiation yield and power at varying load parameters are presented.

1. Introduction

A planar wire array is an interesting z-pinch object. In this wire array configuration, the wires are arranged in a row, forming a plane between the electrodes of a high current generator. In contrast to cylindrical wire arrays, where the initial mass is located in a narrow plasma shell, in a planar wire array the mass is radially distributed. If implosion stability issues are not involved, such load configuration does not look optimal from the point of view of efficient x-ray radiation production.

However, the first experiments carried out by Dr. V. Kantsyrev and his colleagues [1, 2] and subsequent experiments performed by this team on the Zebra generator at the University of Nevado, Reno [3, 4], showed that the planar wire arrays can efficiently produce x-ray radiation. In fact, the radiation power and yield registered in the planar wire array experiments were comparable or even higher than that observed in the best cylindrical wire array implosions studied on this generator.

Since the energy gained by the plasma due to kinetic mechanism is lower in case of a planar wire array having the same dimensions as a cylindrical wire array, a question of additional mechanisms of plasma heating arises. A possible mechanism was discussed in [5], where enhanced Ohmic heating due to Hall resistivity effects was considered. However, it is impossible to make a final conclusion at present. Further experimental studies are necessary, and the proposed model should be benchmarked against a larger body of experimental data. The work in this direction may promote our understanding of basic z-pinch physics issues.

Another reason to start the experiments with planar wire arrays on the GIT-12 generator was our interest to investigate the potentials of this load to increase the efficiency of a K-shell plasma radiation source operating in the microsecond implosion regime. The first experiments showed that a planar wire array is a very promising load configuration for the microsecond K-shell plasma radiation sources [6]. 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 [7] and gas-puff-on-wire-array loads [8] at comparable peak load currents.

This paper presents the results of our resent experiments with Al planar wire arrays at microsecond implosion times. The goal of these experiments was to study the dependence of the K-shell radiation yield on the initial planar wire array parameters such as the total wire array mass, the wire diameter, and inter-wire gap. The Al K-shell spectrum was recorded by a time-integrated crystal spectrograph with a convex mica crystal.

2. Experimental arrangement

The experiments were performed on the GIT-12 generator. Operating without the POS, the generator provides the peak current of 4.7 MA with the current rise time of 1.7 μs in a short-circuit load. Two implosions regimes were tested. In the first regime, the implosion time was 1050 ± 50 ns, and the peak implosion current was 3.8 MA. In the second regime, the implosion time was 850 ± 50 ns, and the peak implosion current was 3.2 MA.

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The planar wire arrays were composed of fine aluminum wires with the diameter of 15, 20, 35 μm. A new design of wire mounting system was used, which provides more accurate wire alignment and better electric contact with the electrodes of the generator. This was done as an attempt to reduce the scatter of experimental data on the Al K-shell radiation yield observed in our previous experiments. The wire array height was 1.8 cm; the maximum array width allowed by the mounting system was 17.6 cm.

As it was mentioned above, two implosion regimes with different implosion times were investigated. In the first regime, the implosion time was 1050 ± 50 ns that corresponds to the regime, which provided the maximum K-shell radiation yield in our previous experiments. However, it is impossible to reach this regime with an inter-wire gap larger then 2 mm when the wires with diameters of 15 μm and 20 μm are used. In this case, a wire array width larger than 17.6 cm is required. So, the second regime with implosion time of 850 ± 50 ns was chosen to provide wider scaling over the inter-wire gap values.

In order to provide the specified above implosion times, the appropriate initial parameters of the wire arrays were chosen on the base of preliminary 0D simulations. The model assumes resistive division of the load current between the wires. Under the action of $j \times B$ force the wires are accelerated to the system axis and undergo successive inelastic collisions. The simulations were terminated when the outermost wires reach the radius of 1 mm. The initial parameters of wire arrays used in the experiments are listed in Tables 1 and 2. Besides the implosion time estimations, the model allows calculation of the total energy deposited to the wire array due to the kinetic mechanism. This energy was calculated as a sum of the wire array kinetic energy at the final moment of implosion and the wire internal energy gained during the wire collisions. A short-circuit current trace was used for preliminary estimations of the load parameters. After the experiments, the real current traces were used for the simulations to obtain more accurate estimation of the deposited energy.

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 250 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. The K-shell radiation yield and power were measured by two vacuum x-ray diodes (XRD) with a copper cathode filtered by 0.2 μm of aluminum, 2 μm of Kimfol, and 30 μm of Polypropylene. The yield and power were determined as the average value of the data provided by two detectors. A time-integrated pinhole camera produced the pinch image in the final stage of implosion. The pinhole camera had the following set of filters: 25 μm of beryllium and 30 μm of Polypropylene. Estimations of the electron plasma temperature were based on measurements carried out with the help of two photoconducting detectors (PCD) as described in [8]. PCD 1 was filtered by 3 μm of palladium and 20 μm of Polypropylene; PCD 2 was filtered by 30 μm of Teflon and 20 μm of Polypropylene.

Table 1. Initial parameters of planar wire arrays with the expected implosion time of 1050 ns

Wire diameter, μm	Wire number	Inter-wire gap, mm	Array width, cm	Array mass, μg
35	35	5	17	910
35	53	3	15.6	1378
35	71	2	14	1846
35	85	1.5	12.6	2210
35	113	1	11.2	2938
20	87	2	17.2	739
20	165	1	16.4	1401
15	175	1	17.5	836

Table 2. Initial parameters of planar wire arrays with the expected implosion time of 850 ns

Wire diameter, μm	Wire number	Inter-wire gap, mm	Array width, cm	Array mass, μg
35	29	5	14	754
35	37	3	10.8	962
35	49	2	9.6	1274
35	75	1	7.4	1950
20	35	5	17	297
20	59	3	17.4	501
20	77	2	15.2	654
20	105	1	10.4	891
15	59	3	17.4	282
15	87	2	17.2	415
15	145	1	14.4	692

3. Experimental results and discussion

The streak camera images show that implosion dynamics of a planar wire array is far from 0D as it was assumed in the simulation model. There are strong evidence of the presence of a plasma precursor and a trailing mass. However, the implosion times predicted by the simulations, which were carried out with the use of experimental current traces, are close to that observed in the experiments. In the worst cases, the difference reaches 10%, and in most of shots, it is less than 5%.

The energy deposited to the plasma ranges from 63 to 80 kJ/cm (the average value is 72 kJ/cm) for the first implosion regime. In the second implosion regime, the deposited energy is between 41 and 56 kJ/cm, with the average value of 49 kJ/cm. Since the wire array masses vary in a wide interval, it is of interest to calculate the range of values of η parameter. The η parameter is defined as the energy deposited in the plasma per ion divided by the minimum energy needed to ionize to the K-shell and heat the electrons to promote the K-shell radiation [9]. The requirement $\eta \geq 1$ should be met to observe a measurable amount of K-shell radiation in the experiment. For the first implosion regime η = 0.6÷2.1; for the second implosion regime η = 0.5÷3.7. Therefore, one can expect a decaying dependence of the K-shell yield on the wire array mass as η reduces below unity at high masses.

The dependence of the Al K-shell radiation yield on the planar wire array mass for the first implosion regime is shown in Fig.1. There was no opportunity to collect significant statistics for each load configuration. Therefore, in order to characterize the scatter of the K-shell yield, five shots with identical planar wire arrays (30-μm wires, 79 wires, inter-wire gap is 2 mm, wire array mass is 1509 μg/cm) were carried out. The results of these shots are shown by asterisk in Fig. 1. The black horizontal line represents the mean value, and the grey lines mark the standard deviation of the data.

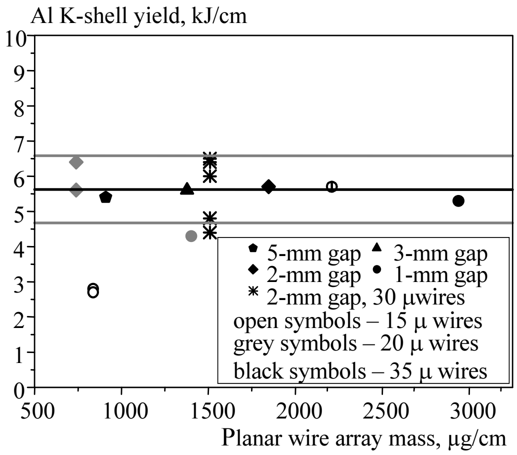

Fig. 1. Al K-shell radiation yield as a function of the planar wire array mass for 1050-ns implosions

For the arrays composed of 35-μm wires, the variation of the yield with the mass is not observed. Even the arrays with the mass higher than 2000 μg/cm produced the K-shell yield of about 5.5 kJ/cm, though the η parameter was below unity. In all shots carried out in the first implosion regime the plasma temperature is between 500 and 625 eV (the average value is 550 eV), that is close to the optimum temperature of 575 eV for aluminum. Observed results are difficult to explain in the frame of conventional theoretical approach. It is reasonable to assume that only a part of the initial wire array mass participates in the generation of the K-shell radiation. However, why the radiating mass does not change with the variation of the initial wire array mass is not clear. The change of the inter-wire gap does not affect the yield as well. 20-μm arrays produced a bit lower yield, when the inter-wire gap was 1 mm. However, even in this case, the observed yield is close to the lower boundary of the data deviation. And only in case of 15-μm arrays with the inter-wire gap of 1 mm, the radiation yield decreased significantly. Undoubtedly, the decrease in the K-shell yield is associated with the use of wires with a smaller diameter and/or the smaller inter-wire gap, since the 30-μm and 20-μm wire arrays with almost the same mass produced twice more x-ray radiation.

The results for the second implosion regime are shown in Fig. 2. The 35-μm array again showed little variation of the K-shell radiation yield with the mass. These data was used to characterize the data scatter in this case. The radiation yield is almost twice lower than that in the first implosion regime. This can be easily understood taking into account the fact that the deposited energy is 1.5 times lower in this case.

However, for the arrays composed of 20 μm and 15 μm wires, the tendency for an increase of the K-shell yield with a decrease of the inter-wire gap was observed. In the shot with the 20-μm-wires and the inter-wire gap of 2 mm, the K-shell yield was 5.4 kJ/cm, i.e. at the level of 1050-ns implosions. This fact raises a consequent question if the K-shell yield in the first implosion regime can be also increased by a proper choice of the load parameters.

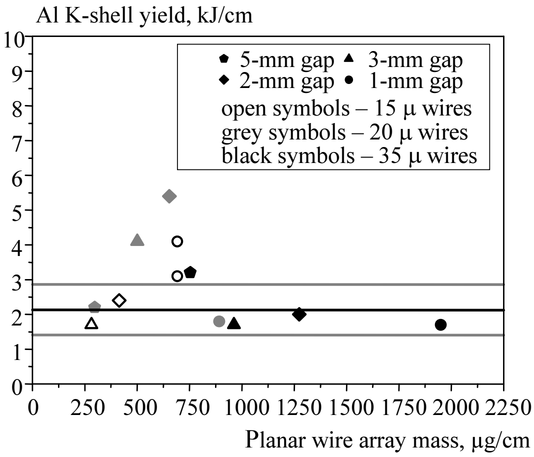

Fig. 250. Al K-shell radiation yield as a function of the planar wire array mass for 850-ns implosions.

Additional information about influence of the initial load parameters on the radiation properties of the planar wire arrays is provided by the experimental data on the K-shell radiation power. Figs. 3 and 4 show the dependence of the peak K-shell radiation power on the inter-wire gap for both implosion regimes. The open symbols show the average values, and the solid symbols marks the highest and the lowest radiation powers registered. The scatter of power values is significantly higher that that for the K-shell radiation yield. It is necessary to note that the radiation pulse shapes differ drastically even for shots with the identical initial load parameters. Nevertheless, a general conclusion can be drawn regarding the optimal inter-wire gap. At both implosion regimes, 2-mm inter-wire gap provides the maximum radiation power. This result is different from the results of fast planar array implosions reported in [3], where higher radiation power was observed at an inter-wire gap of 0.5–1 mm.

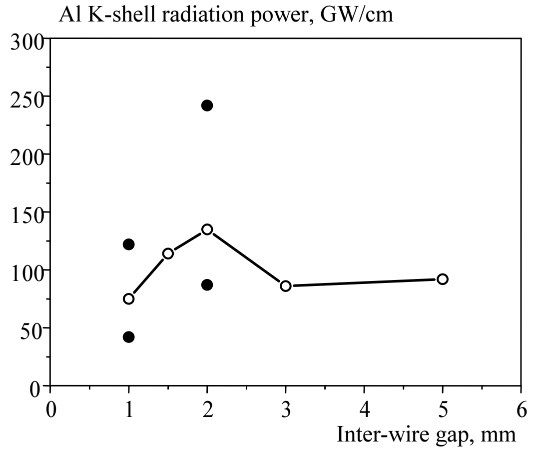

Fig. 3. Al K-shell radiation power as a function of the inter-wire gap for 1050-ns implosions

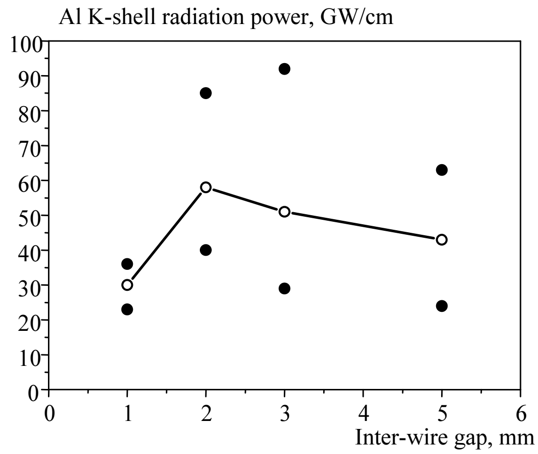

Fig. 4. Al K-shell radiation power as a function of the inter--wire gap for 850-ns implosions

4. Summary

In summary, a set of experiments with planar wire arrays was carried out on the GIT-12 generator to provide data on their x-ray emitting performance and implosion dynamics at microsecond implosion times. The radiative properties of the planar wire arrays were studied at varying load parameters.

Pre-shot simulations of planar wire array implosion dynamics were performed to determine the initial load parameters. The 0D model that assumes resistive division of the load current between the wires was used. The simulations were repeated after the experiments with the use of the real current traces. The accuracy in predictions of the implosion times is better than 10%. The simulations were used also to estimate the energy deposited to the plasma due to the kinetic mechanism.

In 1050-ns implosion time shots, the K-shell radiation yield did not show any significant dependence on the initial wire array mass or the inter-wire gap. The maximum radiation yield in Al K-lines of 6.5 kJ/cm and the maximum radiation power of 200 GW/cm were registered. Even overweight loads with the η parameter less than unity produced significant K-shell radiation output.

In 850-ns implosion time shots, the tendency for an increase of the K-shell yield with a decrease of the inter-wire gap was observed for the arrays composed of 20-μm and 15-μm wires. The data on the K-shell radiation power suggest that the optimal inter-wire gap is close to 2 mm.

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