Optimization of double shell hybrid gas-puff with outer plasma shell for efficient generation of K-shell radiation in the microsecond implosion regime

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Abstract. Studies of Z-pinch plasma as X-ray source were carried out on the GIT-12 generator (4.7 MA, 1.7 µs) in the IHCE SB RAS, Tomsk. The main purpose of the research was optimization of load parameters for efficient generation of the argon K-shell radiation in the microsecond implosion times. A new type of a Z-pinch load, a hybrid gas-puff with an outer plasma shell, was tested. The inner argon shell was actually a solid gas jet on the axis of the system with a small initial diameter. An outer deuterium shell played the role of an implosion stabilizer for the inner gas jet. The third component was the outer plasma shell that provided the initial conductivity. The combination of deuterium shell together with the outer plasma shell has proved its effectiveness in past experiments providing stable implosion at times of the order of a microsecond. In these experiments, the diameter of the inner argon jet was 20 mm, the diameter of the annular deuterium shell was 81 mm, and the outer plasma shell was generated by 48 plasma guns located at the diameter of 350 mm. To increase the K-shell radiation yield, density profile of Z-pinch matter was changed. K-shell radiation yield increased when the matter of the central argon jet did not propagate from the central region to the periphery. As a result, K-shell radiation yield increased to 1.5 kJ/cm, and the power increased to 535 GW/cm at a peak implosion current of 2.8 MA. This radiation yield reached 70% of the theoretically predicted yield calculated by the two-level model. In our earlier experiments with double shell argon gas-puffs, the efficiency of the K-shell plasma radiation source was only 60%. Thus, we consider the hybrid gas-puff with outer plasma shell as a promising load for our further research of the K-shell radiation generation at microsecond implosion times.
Keywords: z-pinch, hybrid gas-puff, K-shell X-ray radiation.

1. Introduction

Studies of the gas-puff Z-pinch plasma as a source of K-shell X-ray radiation have been carried out for decades. Since then, different Z-pinch configurations have been tested experimentally at various implosion times [1]. Generators with a current rise time of the order of 100 ns make it possible to use Z-pinch loads with a small initial radius (2–3 cm). At such initial implosion radii and times, the effect of RT-instabilities is minimal. Therefore, to achieve efficient generation of K-shell radiation is quite simple. Much effort has been expended on finding loads that provide stable compression and level the influence of instabilities on the K-shell radiation yield at implosion times of the order of 200 ns [1]. However, the problem of efficient radiation generation at microsecond implosion times has not yet been solved.

Experiments in this line of research have been carried out in recent years on the GIT-12 generator (4.7 MA, 1.7 µs). Different loads such as deuterium gas-puff with on-axis wires, double gas-puffs, and metal-puffs were used. Progress has been made in optimizing load parameters for a high K-shell radiation yield and ensuring stable implosion at microsecond times [2–6].

The use of multiple cascades has been applied for neon and argon gas-puffs [2]. The outer cascade was a hollow gas shell. The inner cascade was an argon jet on the axis of the system. Also, a plasma shell was generated outside the gas cascades, providing a uniform input of current into the load. Experiments with neon gas-puffs were successful [2]. However, experiments with argon gas-puffs did not show comparable results. As we assume, there were several reasons. Insufficient azimuthal uniformity of the outer argon shell leads to a decrease in the energy deposition during plasma stagnation. Also, there can be a high level of energy losses associated with the development of RT-instabilities [2].

To increase the K-shell radiation of the argon plasma radiation source, it was decided to change the outer cascade of the gas-puff, using deuterium instead of argon. The reason for this decision is as follows. The inner shell plays the role of a radiator, while the function of the outer shell is to stabilize the implosion and sharpen the current for the inner cascade. Selection of deuterium is explained by the fact that experiments with deuterium gas-puffs with an outer plasma shell demonstrated that such type of load provides stable implosion at microsecond times and high K-shell radiation yield. These statements have experimental confirmation. Experiments with hybrid deuterium gas-puff onto on-axis aluminum wires load have been carried out at the GIT-12, during which high yields of aluminum K-shell radiation were obtained [3].

This article is about the research of a hybrid (argon/deuterium) gas-puff with an outer plasma shell as a source of K-shell radiation and effect of the density profile on K-shell radiation. By changing the initial parameters of the gas-puff, we can change the density profile of the gas-puff in the interelectrode gap. Applying the snow-plow model [5, 6], we can estimate the density profile and its effect on the efficiency of the plasma radiation source. Analyzing the set of experimental data and simulation results, we have optimized the load to increase the K-shell radiation yield.

2. Experimental setup and diagnostics.

The experiments with a hybrid gas-puff Z pinches were performed on the GIT-12 generator (4.7 MA, 1.7 µs) at the Institute of High Current Electronics, Tomsk. This is a pulsed power generator capable of storing 2.6 MJ of energy at a charging voltage of 50 kV.

For the formation of the gas-puff cascades, a fast electromagnetic valve with separate plenums was used. The design of the valve allows us to fill the cascades with different gases and change their masses independently of each other. The inner cascade, an argon jet on the axis of the system, was formed using a nozzle with a diameter of 20 mm. The outer cascade was a hollow deuterium shell, which was injected into the interelectrode gap through a nozzle with an outer diameter of 81 mm. The outer plasma shell, which consisted of hydrogen and carbon ions, was formed by 48 plasma guns located at a diameter of 350 mm. The parameters of the outer deuterium cascade and the outer plasma shell were constant. Chosen values (linear mass of deuterium 90 µg/cm, injection time 280–320 µs, and linear mass of the outer plasma shell 5 µg/cm) proved to be efficient in terms of stable compression in the microsecond mode and efficient energy transfer to the radiator [3]. A schematic representation of the load unit is shown in Fig.1.
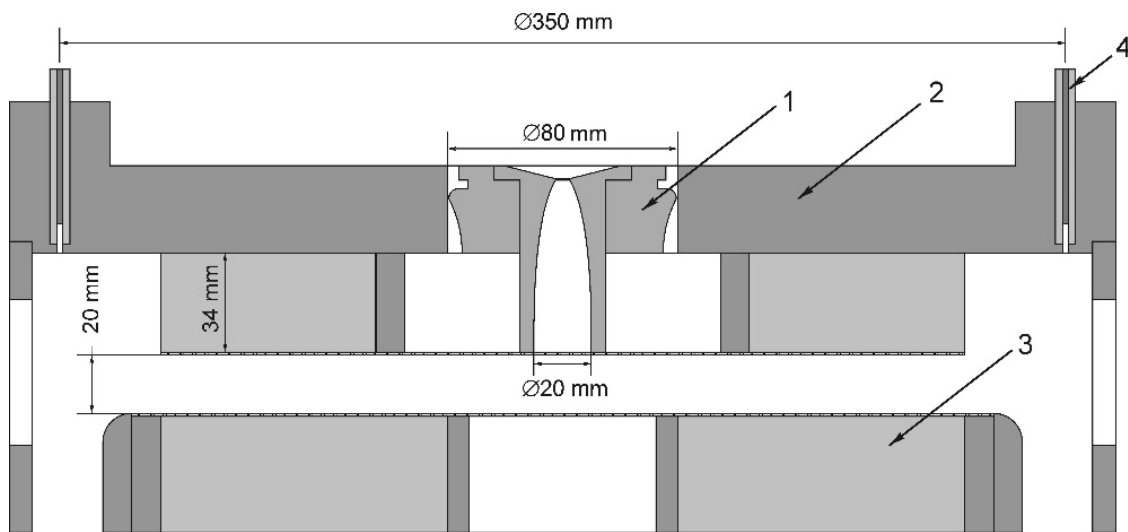

Fig.1. Scheme of the load unit of the GIT-12 generator: *1* – nozzles for gas injection; *2* – anode electrode; *3* – cathode electrode; *4* – plasma guns.

In the experiments, the following set of diagnostic equipment was used. The Z-pinch voltage and current were measured with an inductive voltage divider and inductive current grooves. Photoconductive detectors (PCDs) were used to detect K-line X-rays. The optical image of an imploding pinch was taken using Nanogate two-frame optical camera (with an exposure of 10 ns).

3. Experimental results and discussion

Experiments were devoted to the optimization of a double-shell hybrid gas-puff in terms of the implosion stability and K-shell radiation yield. As we already mentioned above, the great difficulty in implementing implosion from a large initial radius is that the development of RT-instabilities leads to a decrease in the K-shell radiation yield. In the images taken by the Nanogate optical camera with an exposure of 10 ns (Fig.2), we can see a fairly stable compression. Unfortunately, due to the limited frames (only two), it was not always possible to obtain images of a pinch for each shot.
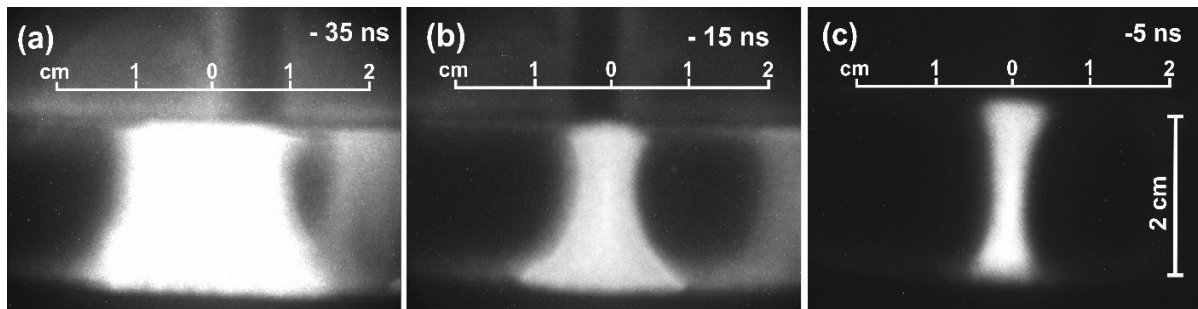

Fig.2. Images of a hybrid gas-puff taken with a 10 ns Nanogate optical camera in shot 2927 (a), 2921 (b), 2929 (c). The time shifts relative to the K-shell peak are given in the upper right corner of each image.

Thus, the problem of ensuring the stability of the implosion was solved. Let us now consider the solution of the second problem: the generation of K-shell radiation.

The main idea of the experiment was as follows. By changing the initial parameters of the gas-puff (injected linear mass, injection time, anode/cathode grid transparency), we can change the density profile of the gas-puff in the interelectrode gap. Analyzing the density profiles and another experimental data, we sought to understand how their change affects to the K-shell radiation yield. By correcting the density profiles, we tried to increase the K-shell radiation yield and the efficiency of the plasma radiation source. To estimate the efficiency of a load in terms of generating K-shell radiation, we used the ratio of the experimental K-shell radiation yield to the theoretical yield calculated for a given current using a two-level model [7]. This allows us to adequately compare the K-shell radiation yield for different current levels. We used the efficiency of the plasma radiation source as the main response when optimizing the load. The obtained results are shown in Fig.3 and Table 1.

In shot 2919, there was only a deuterium shell. Comparison of shots with a hybrid double shell load with shot 2919 allows us to estimate how much argon is propagated into the area of the load unit.

Initial scanning of argon jet linear masses from 80 µg/cm to 220 µg/cm at a gas injection time of about 350 µs and varying plenum pressure showed a proportional growth in the argon K-shell radiation yield. The maximum efficiency (67%) was obtained in shot 2922 with a linear mass of 220 µg/cm and at an injection time of 355 µs. Because of the design of our valve, a further raise of the linear masses was only possible by increasing the gas injection time. Shots 2924–2926 were carried out at the linear masses of argon jet of 250 and 310 µg/cm and the gas injection times

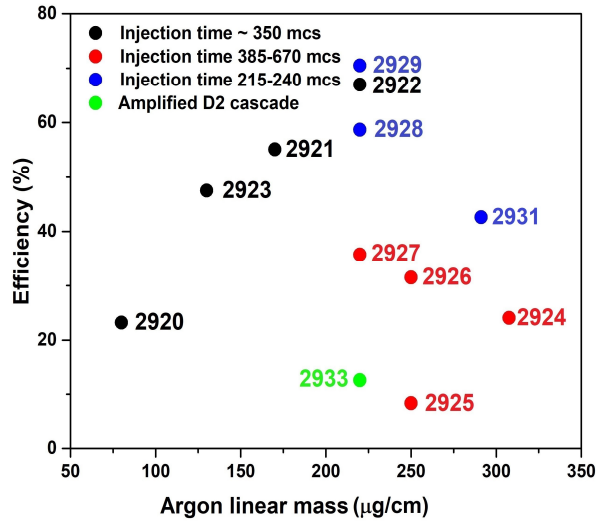exceeding 400 μs. As can be seen in Fig.3, the efficiency of the plasma radiation source dropped below 40%.

Fig.3. Experimental results (efficiency vs argon shell linear mass and injection time).

Table. 1. Experimental data

Shot №	Ar linear mass, μg/cm	Ar inj. time, μs	Masses 1–3 cm, μg/cm	Masses 3–5 cm, μg/cm	Masses 5–15 cm, μg/cm	I_{imp}, MA	t_{imp}, ns	$Y_{K\text{-shell}}$, kJ cm^{-1}	Eff., %
2919	–	–	24	21	44	2.65	687	–	–
2920	80	335	53	32	55	2.89	768	0.57	23
2922	220	355	56	28	52	2.89	776	1.66	67
2924	310	455	107	35	55	2.97	792	0.70	26
2925	250	670	140	43	56	3.05	797	0.24	8
2927	220	385	74	31	56	3.02	789	1.01	36
2929	220	240	42	20	42	2.76	740	1.51	70
2933	220	280	64	56	72	3.12	832	0.39	13

Obviously, the gas injection time has a very strong effect on the density profile. As we said above, the density profiles are reconstructed from the snow-plow model (for details see [5, 6]). The data presented in Table 1 show that an increase in the gas injection time above 355 μs leads to a noticeable growth in gas masses at radii of 1–3 cm, accompanied by a decrease in the K-shell radiation yield. Shots 2927 and 2931 support this observation. In shot 2927, the linear mass of argon jet was 220 μg/cm, the same as in shot 2922, but the gas was injected longer by 30 μs. Such a seemingly insignificant increase of the injection time led to a growth in mass at radii of 1–3 cm, and the efficiency of K-shell radiation dropped by almost a factor of two. In contrast, shot 2931 was made with the argon jet linear mass of 280 μg/cm, but the argon injection time was only 215 μs (this was achieved by using a nozzle with enlarged cross-section). Compared to shots 2924 (310 μg/cm, 455 μs) and 2926 (250 μg/cm, 400 μs), both the K-shell radiation yield and the efficiency of the plasma radiation source were higher in shot 2931.

Available experimental data allow us to make the following conclusion. In order to improve efficiency of the K-shell plasma radiation source, it is necessary to prevent the propagation of argon far from the pinch axis, or, in other words, the radiator matter should remain near the axis of the system. This is also confirmed by our earlier experiments (see [3, 6]). One way to affect the initial gas distribution is to vary the gas injection time. Another opportunity is to use the effect of grid transparency on the gas distribution in the interelectrode gap [8].

In shots 2928 and 2929, the argon injection time was reduced to 225 μs and 240 μs, respectively. In both shots, the transparency of the cathode grid in the center of the load unit was increased from 71% to 85%. In shot 2929, the anode grid was completely removed in front of the inner nozzle exit. Let us examine how the gas density distribution was changed in comparison with other shots, and how it affected the efficiency of the plasma radiation source.

Shots 2920–2923 were performed at varying argon plenum pressure, but the same gas injection time. Despite the fact that the linear mass of the argon jet changed almost three times, the masses of argon distributed over radii of 1–3 cm, 3–5 cm, and 5–15 cm remained practically the same. Shots 2924–2927 were carried out with increased argon injection times. Any changes in the mass of argon at radii of 5–15 cm were not observed. At radii of 3–5 cm, a noticeable increase in argon mass was only in shot 2925, where the argon injection time was 670 μs. And finally at radii of 1–3 cm, one can see a strong correlation between the injection time and the argon mass added to the deuterium shell. As mentioned above, the efficiency of the plasma radiation source dropped significantly at longer injection times.

In shot 2929, the masses at radii 3–5 cm and 5–15 cm are the same as in shot 2919 that was made with the deuterium outer shell only. It looks like we completely prevented the spread of argon from the load axis to a radius of more than 3 cm in shot 2929. The efficiency of the plasma radiation source reached 70%. It can be concluded that the best K-shell radiation yield and plasma radiation source efficiency were achieved when argon remained in the central region of the load unit. This tendency is illustrated by the histogram in Fig.4.

Let us look at the progress made in this set of experiments compared to our previous studies. In the experiments with double shell argon gas-puffs with an outer plasma shell, the maximum yield of argon K-shell radiation was 1.9 kJ/cm at the peak implosion current of 3.1 MA [2], and the corresponding efficiency of plasma radiation source was 60%. The hybrid argon/deuterium gas puff produced lower K-shell yield of 1.5–1.6 kJ/cm, but the peak implosion currents were also lower – 2.8–2.9 MA. Therefore, the efficiency of plasma radiation source was increased to 70%. This is not a significant breakthrough, but from our point of view we are moving in the right direction. In our future experiments with a hybrid load, we plan to provide an even greater localization of the argon jet near the axis of the load unit using a modified design of the central nozzle.
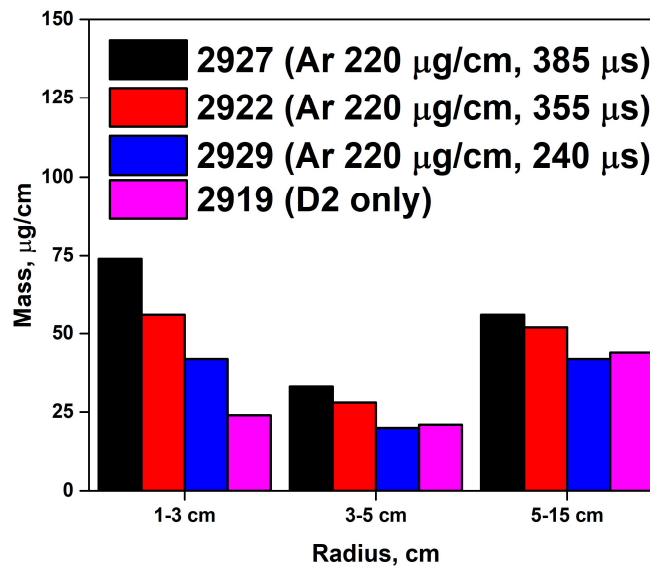

Fig.4. Masses at different radii for shots 2919, 2922, 2927, 2929. The efficiency of the plasma radiation source increases from left to right, from 2927 to 2929. In shot 2919 there was only deuterium shell.

At the end of the experiments with the hybrid gas puff, we made an attempt to increase the implosion time and peak current in the given load configuration. The obvious goal was to achieve a higher K-shell radiation yield at an increased current level. In shot 2933, the deuterium shell was made 50% more massive by both using a higher plenum pressure and a longer gas injection time. The latter, most likely, led to the distribution of a noticeable mass of deuterium to the periphery of the interelectrode gap. As a result, though the peak implosion current grew up to 3.1 MA, the argon K-shell radiation yield and the plasma radiation source efficiency dropped drastically. This result must be taken into account when planning our future experiments. Perhaps we will be able to increase the implosion time and the peak implosion current only by changing the plenum pressure of the deuterium shell and by increasing the injection time of the outer plasma shell.

4. Conclusion

The experiments aimed at optimization of a hybrid (argon/deuterium) gas-puff with an outer plasma shell as a source of K-shell radiation were carried out on the GIT-12 generator in the microsecond implosion regime. The results of the experiments showed how the distribution of the gas-puff matter affects the K-shell radiation yield and the efficiency of plasma radiation source. By changing the density profile of the gas-puff, it was possible to achieve the K-shell radiation yield of 1.5–1.6 kJ/cm at a current level of 2.8–2.9 MA. The load efficiency estimated in terms of the ratio of the experimental K-shell radiation yield to the theoretically expected yield reached 70%. The experimental data showed that such efficiency was achieved when the inner argon cascade localizes in the central region of the load unit and does not extend to the periphery, interacting with the outer deuterium shell. In our future experiments with a hybrid load, we plan to provide an even greater localization of the argon jet near the axis of the load unit using a modified design of the central nozzle.

Acknowledgement

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