

Generation of Ar K-shell radiation using a hybrid gas puff with an outer plasma shell

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Abstract. In our work, we investigated a new type of load, a hybrid gas puff with an outer plasma shell, as a plasma radiation source for efficient production of K-shell radiation at microsecond implosion times. The hybrid load had the following structure: an inner argon jet injected on the axis of the system, an outer deuterium shell formed at a diameter of 80 mm, and an outer plasma shell located at a diameter of 350 mm. The experiments have been carried out on the GIT-12 generator (4.7 MA, 1.7 μ s) that operated in a microsecond mode. The experiments showed that the hybrid load is capable to provide a stable Z-pinch compression at implosion times of 750–800 ns. The experimental data on the Ar K-shell radiation yield were compared with the theoretical predictions to estimate the efficiency of a new type of Z-pinch load. The maximum registered Ar K-shell radiation yield was 1.7 kJ/cm that corresponds to the efficiency of the plasma radiation source of almost 70%. Therefore, we consider this type of Z-pinch load as promising and plan to continue our research in this direction.

Keywords: z-pinch, plasma radiation source, K-shell radiation, gas puff, high-current generators, microsecond implosion regime.

1. Introduction

Z-pinch plasma has been studied as a powerful laboratory source of soft x-rays for almost half a century [1]. The Rayleigh-Taylor instabilities, which develop during implosion, are a natural limitation preventing the efficient transfer of the generator energy to the plasma. In the mid-1990s and early 2000s, various methods of stabilization were tried. The most productive idea was to create structured loads with tailored density profile to reduce the level of instabilities [2, 3]. The use of double and triple gas puffs with an inner cascade in the form of a solid gas jet made it possible to achieve efficient generation of Ar K-shell radiation at implosion times of 200–300 ns on various high-current generators [4–7]. This approach was also successful in experiments with neon gas puffs at implosion times of the order of a microsecond [8]. However, the efficiency of the Ar K-shell plasma radiation source operating in the microsecond implosion mode turned out to be very low (less than 50 %) [8, 9].

Further progress was made in experiments on the GIT-12 generator, where a double gas puff with an outer plasma shell was used as a load [10]. Compared to the triple Ar gas puffs, the radiation yield increased almost four times, which is an undoubted achievement under the conditions of a specific high-current generator. However, the registered radiation yield was only 60% of the theoretically expected one for a given current level.

The main idea of using an outer plasma shell was to form a uniform, well-conducting current sheath at a large initial radius, which would minimize the amount of matter not involved in the implosion process and reduce current losses during the plasma stagnation on the system axis as a result of current switching to the periphery. The first experiments with the use of an outer plasma shell were carried out with deuterium gas puffs [11]. The neutron yield was increased by an order of magnitude to $(2-3) \cdot 10^{12}$ neutrons per pulse. Even a single-shell gas puff with an initial diameter of 80 mm provided stable implosion at times of 700–800 ns. Apparently, this is due to the fact that during the time of gas injection into the interelectrode gap, deuterium had time to propagate up to the radius of the outer plasma shell, forming a density profile decreasing from the center. And this, according to [3], should contribute to the stabilization of the implosion process. It is the success in experiments with deuterium that allowed us to use this approach in experiments with Ne and Ar K-shell plasma radiation sources.

Finally, in recent years, two more new types of loads have been studied on the GIT-12 generator for generating radiation in aluminum K-lines: a metal-puff Z-pinch with an outer plasma shell [12] and a deuterium gas puff with an outer plasma shell and aluminum wires located on the axis [13]. In both series of experiments, it was possible to achieve a high efficiency of the plasma radiation source at implosion times close to a microsecond. A distinctive feature of both loads is that the radiating matter is initially concentrated on the axis of the system.

Based on the currently available experimental data, it seemed logical to use the following type of a hybrid load as a plasma radiation source. An inner cascade plays the role of an emitter and consists of a basic matter that provides K-shell radiation yield (in our case, argon). The inner cascade is a solid gas jet on the axis of the system with a small initial diameter. The outer cascade, which plays the role of an implosion stabilizer, should ensure the transfer of generator current to the inner cascade. The outer cascade is a hollow gas shell propagating outward to large initial radii. The gas density profile falling from the axis outward should provide a stable implosion for hundreds of nanoseconds while the generator current is rising. It is preferable to use a light gas (for example, hydrogen) for this gas shell, which, due to the high particle velocity, will ensure filling of the interelectrode gap to large initial radii, without unnecessarily increasing the mass of the substance in the anode-cathode space of the generator. The third component is the outer plasma shell, which provides the initial conductivity and reduces the negative effects of "cold start". This paper presents the results of the first experiments with this type of load for generating radiation in argon K-lines.

2. Experimental setup

The experiments were conducted on the GIT-12 generator [14]. The installation was configured to operate in microsecond mode, i.e. without plasma opening switches. At a charging voltage of 50 kV, the generator provides a current pulse with an amplitude of 4.7 MA and a rise time of 1.7 μ s in a short-circuited load.

The hybrid load consisted of an inner central argon jet, an outer deuterium shell, and an outer plasma shell. A schematic drawing of the load is shown in Fig.1. The gas cascades were injected using an electromagnetic valve with two independent plena [15]. The central jet nozzle had a diameter of 20 mm, and the outer annular nozzle had a diameter of 80 mm. The outer plasma shell was created at the diameter of 350 mm with the help of 48 plasma guns. Both the gas valve and the plasma guns were located on the anode side. The anode and cathode planes were formed by a stainless-steel mesh with a transparency of 71%. In some shots, the transparency of the cathode mesh was increased to 85% in the central region. The interelectrode gap was about 20 mm.

The following diagnostic tools were used in the experiments. The parameters of the high-current discharge were controlled by voltage, current, and dI/dt sensors, which are included in the standard set of generator diagnostics. Implosion dynamics was monitored by a two-frame electron-optical digital complex "NANOGATE FRAME-9" (with 10 ns minimum exposure time) and a streak camera with the writing speed of 250 ns/cm. The pinch image in Ar K-lines was recorded with a pinhole camera placed behind a composite filter from Be 25 μ m + Teflon 20 μ m.

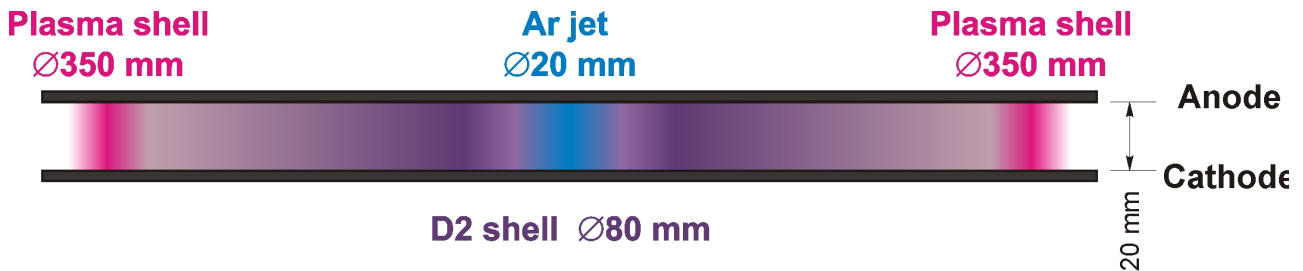


Fig.1. Schematic drawing of a hybrid gas puff with an outer plasma shell.

The Ar K-shell radiation power and yield were measured by two photoconducting detectors (PCD) and an x-ray vacuum diodes (XRD). The desired spectral range was selected using sets of different filters. PCD1 and PCD2 were filtered by Ti 6.35 μm + Polypropylene 10 μm filter and Teflon 30 μm + Polypropylene 20 μm , respectively. XRD1 with a copper photocathode was placed behind Teflon 20 μm + Polypropylene 20 μm filter. XRD2 with an aluminum photocathode filtered by 3 μm of Mylar was used to measure x-ray radiation in a softer spectral range. Detectors sensitivity was calculated using the data from [16, 17]. The overall uncertainty of the K-shell yield measurement was estimated as 15%. Additional information on the parameters and dynamics of the imploding current sheath were provided by three magnetic probes (B-dots) placed at radii of 30 mm, 60 mm, and 90 mm. The neutron yield was measured using a silver activation counter located radially at a distance of 4.55 m.

3. Discussion of experimental results

The experimental session consisted of seventeen shots in total. Two of them were performed with the deuterium gas puff only. Based on the results of these shots, we could be convinced that the parameters of the plasma and deuterium shells provide us with the optimal implosion regime observed in our previous experiments [18, 13]. The main criteria for the optimal regime for us were the neutron yield at the level of 10^{12} neutrons per pulse, the amplitude of the voltage pulse in the final stage of implosion close to or even higher than 1 MV, and the characteristic behavior of the dI/dt oscillogram, which has two dips at the moment of pinch stagnation on the axis. Under the conditions of our generator, this regime is ensured at a plasma shell injection time of $1.8 \pm 0.2 \mu\text{s}$ and a deuterium shell injection time of $300 \pm 20 \mu\text{s}$. In the course of further experiments, the parameters of the plasma and deuterium shells remained unchanged. The main part of the experiments was devoted to obtaining the dependence of the K-shell radiation yield on the mass of the central argon jet. Summary of the experimental data is given in Table 1. Several shots were aimed at finer optimization with an attempt to change the initial distribution of the Ar jet in the interelectrode gap. An analysis of these experiments is presented elsewhere [19].

The mass of the central Ar jet varied from 80 $\mu\text{g/cm}$ to 280 $\mu\text{g/cm}$, that is, more than three times. Some of the shots were carried out at a gas injection time of 335–355 μs . The other part of the shots was made with a gas injection time of 215–230 μs and the cathode mesh transparency of 85 %. These loads showed similar implosion dynamics and response in terms of K-shell radiation yield. With an increase in the gas injection time above 385 μs , the radiation yield dropped sharply.

Table 1. Summary of the experimental data

Shot No.	Ar jet mass, $\mu\text{g/cm}$	Ar jet injection time, μs	Peak current, MA	Implosion time, ns	K-shell yield, kJ/cm	K-shell power, GW/cm	Radiation pulse FWHM, ns	$\frac{Y_{KExp}}{Y_{KTheor}}$
2920	80	335	2.89	768	0.57	110	2.8	0.23
2921	170	355	2.87	772	1.33	390	2.4	0.55
2922	220	355	2.89	776	1.66	580	2.8	0.67
2923	130	345	2.90	762	1.18	600	1.6	0.48
2928	220	225	2.90	791	1.46	530	2.0	0.59
2931	280	215	2.85	782	1.06	350	2.0	0.45
2932	170	230	2.97	812	1.2	480	2.0	0.45
2934	220	255	2.32	607	0.09	30	2.4	0.07

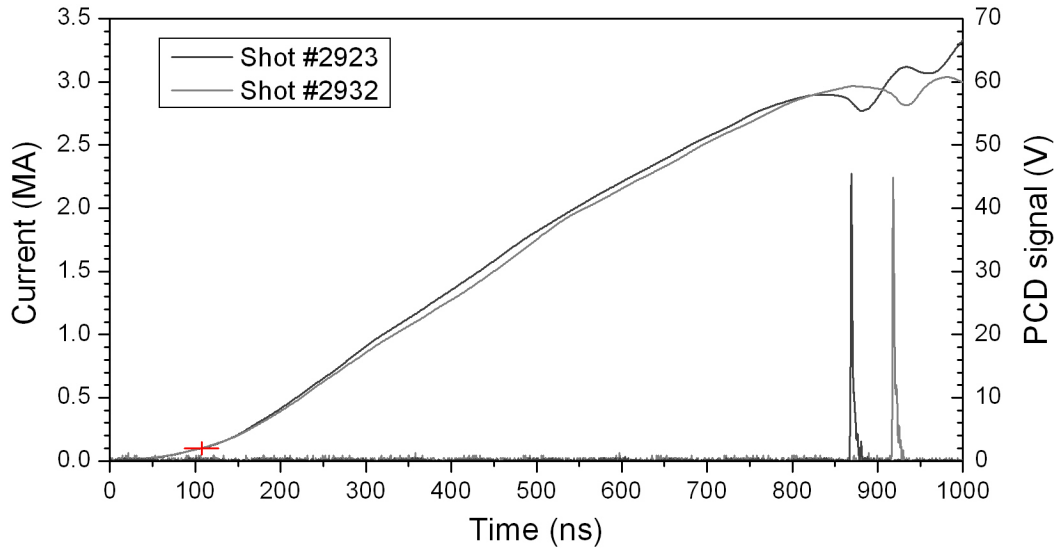


Fig.2. Typical current and PCD traces. The red cross marks the time when the generator current reaches the level of 100 kA.

Fig.2 shows typical current and PCD traces for shots with minimum and maximum implosion times. We define the implosion time as the time interval between the moment when the generator current reaches the level of 100 kA (marked with a red cross in the figure) and the peak of the X-ray detector signal. Compared to the shot with the deuterium shell only, the implosion time increased on average by 90 ns, and the peak implosion current by 250 kA. Variation of the mass of the central Ar jet has little effect on the implosion time and peak current. The spread in these parameters is 50 ns and 112 kA, respectively. And if we exclude shot #2932 from consideration, in which the injection time of the plasma shell was 1.97 μ s, this spread becomes even smaller – 30 ns and 40 kA. Obviously, the implosion time and the peak implosion current are largely determined by the parameters of the deuterium and outer plasma shells. The propagation of argon in the radial direction due to reflection from the cathode and anode meshes at the chosen gas injection times leads to approximately the identical effect, regardless of the mass of the central Ar jet, which remains mainly concentrated near the axis of the system.

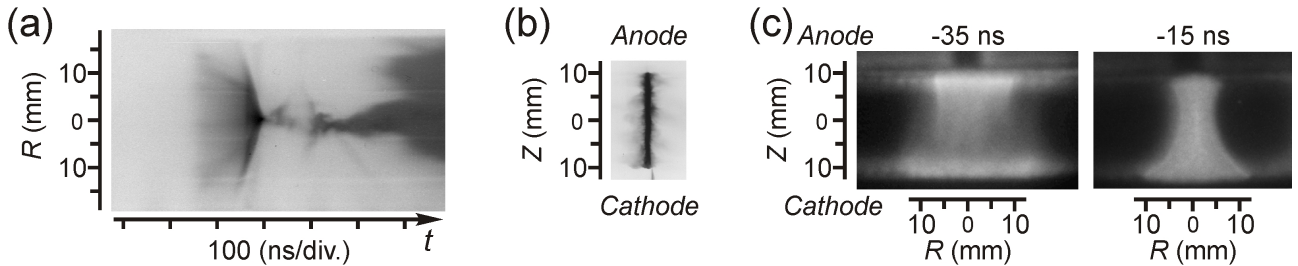


Fig.3. Radial streak-camera image (a), x-ray pinhole image (b), and frame camera images (c) obtained in Shot #2921. Time zero corresponds to the peak of PCD signal.

Typical streak-camera, pin-hole camera, and frame camera images are shown in Fig.3. The streak camera image shows some interesting features of the hybrid gas-puff dynamics in the final implosion stage. The moving plasma shell enters the field of view of the camera approximately 50 ns before the pinching of the plasma on the axis. The shell moves at a velocity of $(3-3.2) \cdot 10^7$ cm/s. However, about 100 ns earlier, the light emission appears at a radius of about 15 mm. The radius of the light emitting region decreases with time. This can be interpreted as the penetration of a part of the current into the region of the central Ar jet and the beginning of its implosion. We observed something similar earlier in experiments with deuterium gas puffs and an

aluminum wire located on the axis. In those experiments, light emission from the wire started 120–150 ns before the implosion of the deuterium gas puff [13]. Nevertheless, there is one significant difference. In order to explode a wire with a diameter of 100 microns, a current with an amplitude of several kiloamperes is sufficient. For the implosion of a gas jet at a velocity of $7 \cdot 10^6$ cm/s, as is observed in the streak-camera image, a significantly higher current is required. It is necessary to estimate the required current amplitude, at least within the framework of a simple snow-plow model, in order to unambiguously interpret the experimental observations.

The above features of the hybrid gas-puff implosion do not prevent the formation of a compact pinch. The pin-hole camera registers a pinch with a diameter of less than 1.5 mm (see Fig.3b). This agrees well with the data obtained with X-ray detectors. As shown in Fig.2, the PCDs register a single narrow K-shell radiation pulse with a FWHM not exceeding 3 ns (see Table 1). Even the radiation pulse, which is recorded by XRD2 in the softer spectral range, has a FWHM of no more than 12 ns. The emission of Ar K-shell radiation occurs along the entire length of the pinch from the anode to the cathode. The formation of such a pinch implies that the implosion is sufficiently stable. This is confirmed by frame-camera images (Fig.3c). One can see the zippering of the plasma column from the anode to the cathode, but the development of instabilities at the outer boundary is not observed. Thus, it can be concluded that the hybrid gas puff with an outer plasma shell is capable of providing stable compression at implosion times of the order of a microsecond.

Stable implosion is not an end in itself, but a means to achieve efficient production of K-shell x-rays. The experimental dependence of the Ar K-shell radiation yield on the mass of the central argon jet is shown in Fig.4. As the mass of the central jet increases from 80 $\mu\text{g/cm}$ to 220 $\mu\text{g/cm}$, the radiation yield increases, and a further increase in mass leads to its decrease. In the best shot, the K-shell radiation yield reached 1.66 kJ/cm at a peak implosion current of almost 2.9 MA. The radiation pulse had a FWHM of 2.8 ns, and the K-shell radiation power was 580 GW/cm. Have we made any progress? In our previous experiments, we used a double argon gas puff with an outer plasma shell [10]. With this load, we obtained the Ar K-shell radiation yield of 1.9 kJ/cm at a peak implosion current of 3.1 MA. Taking into account the difference in peak currents, the radiation yields appear to be comparable. However, for a quantitative assessment, it is better to use such a parameter as the efficiency of the plasma radiation source (PRS), which we define as the ratio of the experimental radiation yield to the theoretically expected radiation yield at a given current level.

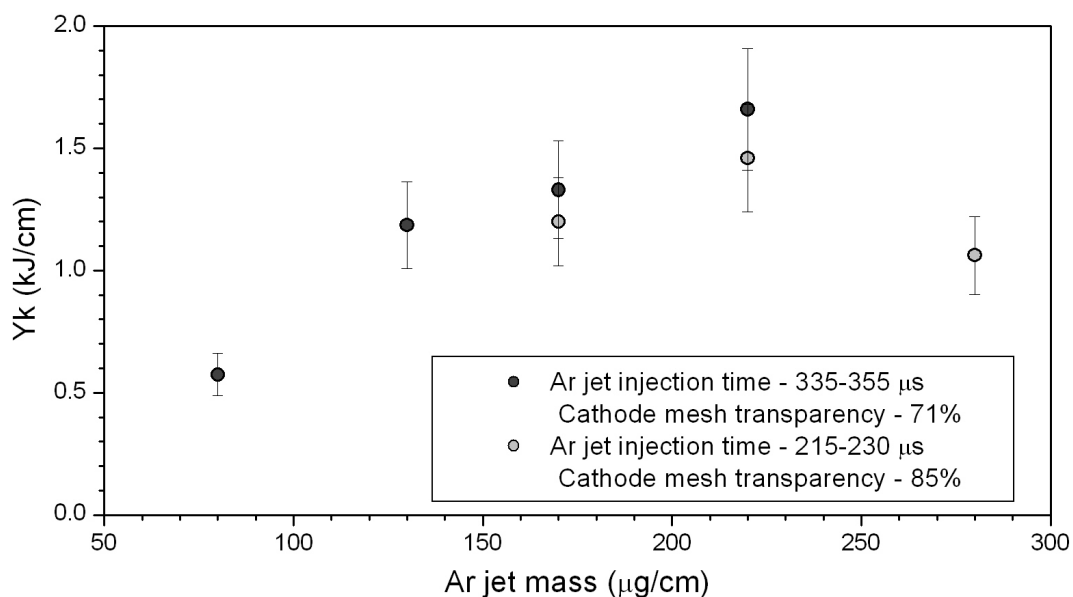


Fig.4. Experimental dependence of the Ar K-shell radiation yield on the mass of the central Ar jet.

For this series of experiments, this parameter (Yk_{Exp} / Yk_{Theor}) is indicated in the last column of Table 1. The two-level model [20] was used to calculate the theoretical radiation yield. According to [10], the highest PRS efficiency of the double gas puff with an outer plasma shell was 0.6, and the hybrid load demonstrated slightly higher efficiency of 0.67. The remaining parameters of the radiation pulse allow direct comparison. Despite the fact that the radiation yield in the case of the double gas puff was slightly higher, the radiation power was only 188 GW/cm, i.e. three times lower compared to the hybrid gas puff. This is in good agreement with the fact that the FWHM of the radiation pulse in the case of a double gas puff was 7 ns. If we compare the pinch images obtained with the pin-hole camera, then the average pinch diameter in the case of a hybrid gas puff will be at least two times smaller. From our point of view, in the very first experiments, the hybrid gas puff with the outer plasma shell demonstrated a very good potential as a microsecond K-shell plasma radiation source. We hope that in the course of our further research we will be able to find ways to increase the efficiency of this plasma radiation source without compromising its already achieved positive qualities.

Finally, let us look at another shot, the data of which are presented in Table 1. Shot #2934 was performed with the parameters of the central Ar jet optimal for this series of experiments, but without the outer deuterium shell. This experiment can be considered as an attempt to reduce the load even more and make it similar in structure to the metal-puff Z-pinch [12]. However, in contrast to the metal-puff Z-pinch, the argon of the central jet cannot propagate in the interelectrode gap in the radial direction to a considerable distance in order to completely compensate for the absence of the deuterium shell. As a result, the implosion time was reduced to 607 ns, and the peak implosion current was reduced to 2.32 MA. The K-shell radiation yield should decrease due to the decrease in the peak implosion current. In addition, the efficiency of the plasma radiation source should also decrease, since the mass of the central jet becomes not optimal for the given current level. Assuming a drop in PRS efficiency to 0.2, the expected radiation yield would be about 200 J/cm. However, as can be seen from Table 1, the K-shell radiation yield reached only 90 J/cm that corresponds to the PRS efficiency of 0.07. There must be some other reason for such a sharp drop.

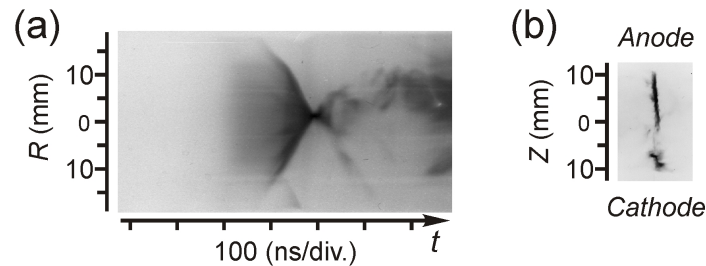


Fig.5. Radial streak-camera image (a) and x-ray pinhole image (b) obtained in Shot #2934 performed without the outer deuterium shell.

Fig.5 shows the streak camera and pin-hole camera images obtained in this shot. In the streak camera image, one can see only the main implosion (no any inside earlier compression) with a velocity of $1.8 \cdot 10^7$ cm/s. However, brighter areas are visible inside the imploding jet, which can be interpreted as separate current channels. The presence of current channels can prevent the formation of a compact pinch. Unfortunately, we were unable to obtain the images from the frame camera in this shot, but the stability of the implosion can be qualitatively assessed from the pin-hole camera image. A compact pinch was formed only on the anode side, but even in this region the pinch has a slight lateral inclination. In the middle part, closer to the cathode, a discontinuity is observed, at least in the spectral range of argon K-lines. Finally, an extremely unstable segment of the radiating plasma is observed near the cathode. The presented observations are quite sufficient to explain such a sharp drop in the K-shell radiation yield in this experiment. Apparently, in this case, the presence

of an intermediate deuterium shell is a necessity. However, it is quite possible that in experiments on fast generators, when the plasma shell can and should be placed on a much smaller initial radius, this load will turn out to be quite efficient.

4. Conclusion

The first experimental study of the hybrid gas puff with the outer plasma shell as a microsecond plasma radiation source of Ar K-shell x-rays has been carried out on the GIT-12 generator. In comparison with other types of Z-pinch loads studied earlier [8, 10], the hybrid gas puff has demonstrated its advantage in many important parameters, such as implosion stability, duration and power of the radiation pulse, and the efficiency of the plasma radiation source. Despite all these improvements, the experimentally observed Ar K-shell radiation yields still remain below the theoretically achievable values. Thus, our future research will be aimed at finding approaches to achieve the maximum efficiency of plasma radiation sources.

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5. References

- [1] Giuliani J.L., Comisso R.J., *IEEE Trans. Plasma Sci.*, **43**, 2385, 2015; doi: 10.1109/TPS.2015.2451157
- [2] Gol'berg S.M., Velikovich A.L., *Phys. Fluids B: Plasma Phys.*, **5**, 1164, 1993; doi: 10.1063/1.860974
- [3] Velikovich A.L., Cochran F.L., Davis J., *Phys. Rev. Lett.*, **77**, 853, 1996; doi: 10.1103/PhysRevLett.77.853
- [4] Shishlov A.V., Baksht R.B., Chaikovskiy S.A., et al., *Laser Phys.*, **6**, 183, 2006; doi: 10.1134/S1054660X06010178
- [5] Sze H., Banister J., Failor B.H., et al., *Phys. Rev. Lett.*, **95**, 105001, 2005; doi: 10.1103/PhysRevLett.95.105001
- [6] Levine J.S., Banister J.W., Failor, B.H., et al., *Phys. Plasmas*, **13**, 082702, 2006; doi: 10.1063/1.2221660
- [7] Comisso R.J., Apruzese J.P., Mosher D., et al., *Proc. 16th IEEE Pulsed Power Conf.*, Albuquerque, USA, 1773, 2007; doi: 10.1109/PPPS.2007.4652535
- [8] Shishlov A.V., Baksht R.B., Chaikovskiy S.A., et al., *Plasma Devices Oper.*, **13**, 81, 2005; doi: 10.1080/10519990512331334588
- [9] Zucchini F., Calamy H., Lassalle F., et al., *Proc. 7th Int. Conf. on Dense Z-Pinches*, Alexandria, USA, *AIP Conf. Proc.*, **1088**, 247, 2009; doi: 10.1063/1.3079740
- [10] Shishlov A.V., Kokshenev V.A., Kurmaev N.E., et al., *Russ. Phys. J.*, **62**, 1243, 2019; doi: 10.1007/s11182-019-01841-6
- [11] Klir D., Kubes P., Rezac K., et al., *Phys. Rev. Lett.*, **112**, 095001, 2014; doi: 10.1103/PhysRevLett.112.095001
- [12] Shishlov A., Kokshenev V., Roussikh A., et al., *Proc. 2020 7th International Congress on Energy Fluxes and Radiation Effects (EFRE)*, Tomsk, Russia, 61, 2020; doi: 10.1109/EFRE47760.2020.9242061
- [13] Klir D., Shishlov A.V., Kokshenev V.A., et al., *Phys. Plasmas*, **28**, 062708, 2021; doi: 10.1063/5.0054683
- [14] Bugaev S., Volkov A., Kim A., et al., *Russ. Phys. J.*, **40**, 1154, 1997; doi: 10.1007/BF02524303

- [15] Baksht R., Fedyunin A., Chuvatin A., Rouaie C., and Etlicher B., *Instrum. Exp. Tech.*, **41**, 536, 1998.
- [16] Day R., Lee P., Saloman E., Nagel D., *J. Appl. Phys.*, **52**, 6965, 1981; doi: 10.1063/1.328653
- [17] Henke B., Gullikson E., Davis J., *At. Data Nucl. Data Tables*, **54**, 181, 1993; doi: 10.1006/adnd.1993.1013
- [18] Klir D., Shishlov A.V., Kokshenev V.A., et al., *Plasma Phys. Control. Fusion*, **57**, 044005, 2015; doi: 10.1088/0741-3335/57/4/044005
- [19] Cherdizov R.K., Kokshenev V.A., Kurmaev N.E., et al., *Proc. of 8th Int. Cong. on Energy Fluxes and Radiation Effects, 2–8 October, Tomsk, 2022*; doi: 10.56761/EFRE2022.S2-O-019901
- [20] Mosher D., Qi N., Krishnan M., *IEEE Trans. Plasma Sci.*, **26**, 1052, 1998; doi: 10.1109/27.700887