Effect of the gas distribution on implosion dynamics and the K-shell yield of the neon gas-puffs with the outer plasma shell

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Abstract. The experiments have been carried out on the GIT-12 generator to characterize the effect of the anode and cathode meshes installed on the path of the gas flow on the initial gas density distribution, the gas-puff implosion dynamics, and the resulting radiative characteristics of the Ne K-shell plasma radiation source (PRS) operated in the microsecond implosion regime. The experiments showed that the obstacles located directly on the way of the main gas flow have the greatest influence on the gas distribution in the interelectrode gap of the generator. At all other factors being the same, the presence or absence of the anode and cathode meshes changed significantly the implosion dynamics and radiative characteristics of the Ne K-shell PRS. In our experiments, we observed two-fold decrease in the K-shell radiation yield and more than four-fold decrease in the K-shell radiation power. These observations should be taking into account in development of the gas-puff loads for Z-pinch experiments.

1. Introduction
For almost forty years gas-puff Z-pinches have been investigated as a K-shell plasma radiation source [1]. A natural limitation that reduces the efficiency of such radiation sources is Rayleigh-Taylor instabilities that develop during implosion of the plasma shell. In the mid-90s, the idea of using load with structured gas density profiles [2, 3] to reduce the level of instabilities was adopted. Since then, various types of Z-pinch loads (solid fill gas puffs, multi-shell gas puffs, etc.) have been studied both theoretically and experimentally. The result of these efforts was the development of such load configurations that provide theoretically expected yields of the K-shell radiation at implosion times up to 200-300 ns [4-6]. Nevertheless, the problem of efficient generation of the K-shell radiation at microsecond implosion times requires further research.

A new type of load configuration, a gas puff surrounded by a plasma shell, has been employed in experiments on the GIT-12 generator (4.7 MA, 1.7 μs) at microsecond implosion times. Optimization of the load parameters in the experiments with deuterium Z-pinches allowed us to increase the neutron yield by an order of magnitude [7]. The experiments with neon gas puffs have also demonstrated that a gas puff with an outer plasma shell has higher efficiency as a K-shell plasma radiation source in comparison with the traditional gas-puff loads at microsecond implosion times [8].

In this paper we present complementary studies on the effect of the gas distribution on implosion dynamics and the K-shell yield of the neon gas-puffs with the outer plasma shell. The initial gas
density profile in the interelectrode gap is of great importance when running the experiments with gas-puff Z-pinches. First, the proper choice of the gas distribution allows matching a load with a current generator; this usually means that the final stagnation occurs close to the maximum of the generator current. Second, the integral characteristic of the distribution, the total gas puff mass, should correspond to the expected energy deposition to the Z-pinch plasma [9]. The minimum energy per ion has to be provided in order to produce x-rays in the K-shell spectral region. Third, as it was mentioned above, the initial gas density distribution can affect significantly the stability of the implosion. A good example of such influence is recent experiments with metal-puff Z-pinches [10].

A detailed review of the gas puff hardware and methods of the gas density measurements is given in [1]. The authors point out that all approaches to the gas density measurements have not been implemented in situ. In real experiments, the gas flow can interact with different parts of the experimental chamber. How strong can be the influence of this interaction on the initial gas density profile and, subsequently, on the gas-puff implosion dynamics is an interesting question from our point of view. In this work we have made an attempt to characterize the effect of the anode and cathode meshes installed on the path of the gas flow on the initial gas density distribution, the gas-puff implosion dynamics, and the resulting radiative characteristics of the Ne K-shell plasma radiation source (PRS) operated in the microsecond implosion regime.

2. Experimental set-up
The experiments have been carried out on the GIT-12 generator [11]. The generator was operated in the microsecond mode, i.e. without the plasma opening switch. At the charging voltage of 50 kV, the generator provides a peak current of 4.7 MA with a current rise time of 1.7 µs in a short-circuit load.

![Figure 1](image1.png)

**Figure 1.** Schematic drawing of the experimental chamber (a); picture of the cathode with the breakdown pins installed at the radii of 50 mm and 60 mm (b), the picture of the anode with the anode mesh reduced to the diameter of 130 mm (c).
A Z-pinch load consisted of a neon double gas puff surrounded by a plasma shell. A schematic drawing of the load assembly is shown in figure 1a. The plasma shell composed of hydrogen and carbon ions was created by 48 plasma guns located at the diameter of 350 mm. The mass of the plasma shell was determined by a time delay between triggering of the plasma guns and the onset of the generator current. At the time delay of 1.7-1.8 µs, the linear mass of the plasma shell was about 5 µg/cm.

The Ne double gas puff was formed with the help of an electromagnetic valve [12]. An outer gas shell was injected into the interelectrode gap through a nozzle with an outer diameter of 100 mm. An inner cascade was a solid gas jet at the system axis formed by a nozzle with an outer diameter of 20 mm. The valve has separate plenums for the outer and inner cascades. This allowed independent regulation of the gas-puff masses. The mass of the gas puff is determined both by the initial plenum pressure and by the time of the gas injection into the interelectrode gap. The evaluation of the injected masses has been carried out before each shot by the method describe in [13]. It is necessary to note that the estimation of the gas-puff masses does not take into account the interaction of the gas flow with the anode and cathode meshes. The anode and cathode meshes, which define the interelectrode gap, were made of the stainless steel and had the transparency of 70%. The distance between the nozzles and the anode mesh was 34 mm, and the interelectrode gap was 22.4±0.6 mm. The cathode and anode electrodes are shown in figure 1bc.

In the experiments with Ne K-shell plasma radiation source, we used a standard electrophysical diagnostic complex of the GIT-12 generator, which allows measuring of the generator voltage and current. The diagnostics of the Z-pinch plasma included the following. The time-integrated x-ray image of the Z-pinch was obtained by a pinhole camera filtered by beryllium foil with a thickness of 25 µm. In the optical spectral range, the implosion dynamics was recorded with the help of a streak camera with a writing speed of 250 ns/cm and a frame camera, which allowed obtaining two frames with the minimum exposure time of 10 ns. Measurements of the Ne K-shell radiation power and yield were carried out with the help of two vacuum x-ray diodes (XRD) with aluminum photocathodes. XRD 1 was filtered by Mylar 3 µm + Al 9.2 µm + Kimfoil 2 µm; XRD 2 was filtered by Kimfoil 6 µm + Al 0.6 µm. Two photoconducting detectors (PCD) registered continuum radiation with the energy above 1.5 keV. Three single-turn B-dot probes were located on the cathode side at the distances of 30.5 mm (K1), 60 mm (K2), and 90 mm (K3) from the Z-pinch axis. The B-dot probes gave us the information about the properties of the current sheath and its implosion dynamics.

Figure 2. An electrical scheme (a) and a general view of the breakdown pin (b).
Spreading of the gas in the radial direction due to interaction of the gas flow with the anode and cathode meshes was studied with the help of breakdown pins. A breakdown pin is a piece of RK-50-2 cable with removed insulation. A standard cable armature was replaced by a steel tube with the inner diameter corresponding to the diameter of the cable insulator. DC voltage of 800 V was applied between the cable conductor and the grounded tube. In vacuum this voltage is not enough for the breakdown along the insulator surface to occur. As the gas flow spreads, the gas density in the pin location area increases. At some point, a surface breakdown of the insulator occurs. The resulting voltage pulse marks the time when the gas flow reaches the breakdown pin. An electrical scheme and a picture of the breakdown pin are shown in figure 2. Figure 1b shows the breakdown pins installed on the cathode at the distance of 50 mm and 60 mm from the axis.

3. Experimental results and discussion

The experiments have been carried out in two steps. At the first step, the breakdown pins were used to observe the influence of the anode and cathode meshes on the spread of the gas in the radial direction in the interelectrode gap. At the second stage, we observed the effect of the anode and cathode mesh configurations on the implosion dynamics and radiative characteristics of the Ne double gas puff with the outer plasma shell. Let us consider the results of these experiments.

First of all, the breakdown pin was installed in the valve test stand instead of one of the pressure probes. The pressure probes are located in the nozzle volume just upstream of the nozzle critical cross-section. The pressure curve obtained with the pressure probes is then recalculated to the linear gas-puff mass as described in [13]. It was found out that the pin breakdown took place at a very low pressure simultaneously with the start of the pressure build up in the nozzle volume. The time delay between the valve triggering and the breakdown of the pin or/and the start of the pressure curve was 2350±60 µs.

Then the breakdown pins were installed in the experimental chamber of the GIT-12 generator. The pins were located 3-4 mm above the cathode plane. The measurements of the pin breakdown time during the gas injection into the interelectrode gap have been carried out at three different locations of the pins: 50 mm, 60 mm, and 105 mm from the system axis. The tests have been conducted with no meshes installed, with only the cathode mesh installed, and, in the case of 105-mm radial location of the pins, with both anode and the cathode meshes installed. The experimental results are shown in figure 3. The data points represent the average breakdown time for five tests. The error bars show the standard deviation of the experimental data.

![Figure 3. Breakdown time at different radial position of the breakdown pins.](image-url)
Analysis of the obtained experimental data allows the following conclusions. Under the conditions of the GIT-12 generator experimental set-up, the presence of the anode and cathode meshes promotes the gas distribution in the radial direction. In the experiments with Ne double gas puff with the outer plasma shell, which are described below, the characteristic time between the valve triggering and the onset of the generator current was in the range from 2800 µs to 3050 µs, which corresponds to the gas injection time from 450 µs to 700 µs. Taking this into account, it can be expected that, with both anode and cathode meshes installed, there is a radially falling gas density profile at the radii of 50 mm and higher. It is necessary to note that such gas density profile should improve the implosion stability according to [2]. On the other hand, in the absence of both meshes, it is highly probable that the plasma shell and the outer gas shell are separated by the vacuum volume. These two extreme cases should lead to different implosion dynamics in the experiments with the double gas puffs with the outer plasma shell and result in different performance of the plasma radiation source. This was verified experimentally at the second stage of the research.

The effect of the anode and cathode meshes was investigated after the main experimental session that was devoted to optimization of the Ne K-shell PRS. The results of those experiments will be published elsewhere. Here we just specify the data relevant to the discussion. The plasma guns delay was 1.8±0.1 µs. The total linear gas-puff mass varied from 450 µg/cm to 600 µg/cm, and the gas injection time was in the range from 450 µs to 700 µs, as mentioned above. The Ne K-shell yields of 13 kJ/cm and higher were registered in the shots with the total linear gas-puff mass of 550 µg/cm and less, and the gas injection time up to 600 µs. The highest radiation yield of 14.7 kJ/cm was measured in Shot #2070. The K-shell radiation power reached 720 GW/cm, and the FWHM of the radiation pulse was 10.5 ns. The parameters of the gas puff were the following: the outer shell mass – 200 µg/cm; the inner jet mass – 300 µg/cm; the gas injection time – 500 µs. The peak implosion current was 3.46 MA, and the implosion time was 986 ns. Shot #2070 was chosen as a referent point for the comparison.

It is worth to introduce one more parameter for the comparison that we will call the efficiency of the plasma radiation source. Let us determined the efficiency of the PRS as a ratio of the experimental K-shell radiation yield to the theoretically expected radiation yield at a given peak implosion current. The theoretical radiation yield was calculated with the help of the two-level model, assuming the final pinch radius of 1 mm. As it was shown in [8], under such assumption the model provides rather good fit to the experimental data obtained in different laboratories.

In order to observe influence of the anode and cathode meshes on the implosion dynamics and the radiative characteristics of the Ne PRS, the diameter of the meshes was reduced to 130 mm in Shot #2074 and Shot #2081 (see figure 1c), and then to 80 mm in Shot #2075. The parameters of the gas puff were the same as in Shot #2070.

Reduction of the meshes to the diameter of 130 mm did not have a really significant effect. Reflection of the gas was eliminated at large radii, but the meshes were still located on the way of the main gas flow from the outer nozzle. In Shot #2074, the current sheath arrived 60-70 ns earlier at the radii of 90 mm and 60 mm, and 47 ns earlier at the radius of 30.5 mm by comparison with Shot #2070. The implosion time was 45 ns less, and the peak implosion current reduced by 130 kA. Such changes could be expected since smaller mass was distributed on a large radius. The K-shell radiation yield reduced to 12.7 kJ/cm, however the radiation power exceeded 800 GW/cm. The efficiency of PRS was 137%, which is less than in Shot #2070 (146%), but it is typical for the shots that produced the yields above 13 kJ/cm at slightly higher implosion currents.

To compensate the reduction of the gas mass distributed at large radii, the plasma guns delay was increased to 2.9 µs in Shot #2081. This resulted in the growth of the peak implosion current and the implosion time to 3.5 MA and 1025 ns, correspondingly. The K-shell radiation yield increased to 13.9 kJ/cm at practically the same PRS efficiency.

Completely different results were obtained in Shot #2075, when the anode and cathode meshes were reduced to the diameter of 80 mm. This is illustrated in figure 4. Compared to Shot #2070, the current sheath arrived at the radius of 90 mm almost 150 ns earlier. The current inside the radius of
60 mm appeared just 16 ns later, which are 290 ns earlier than in Shot #2070. However, the current rise rate was much lower. The K-shell radiation power reached the maximum at 752 ns, and the peak implosion current was 2.74 MA. Streak camera pictures showed that the implosion was not uniform. Streams with a higher brightness can be seen in the streak camera image. It is possible that in the absence of the cathode mesh the current was concentrated near the cathode ribs located radially.

![Figure 4. Streak camera images, B-dot and XRD signals for two shots with different electrode mesh configurations.](image)

The K-shell radiation yield dropped to 6.6 kJ/cm. This reduction in the K-shell yield was related not only to the lower implosion current, but to the decreased PRS efficiency as well. The efficiency of the radiation source in this shot was only 109%. In this experimental session, such low PRS efficiency was observed only in the shots with a high gas-puff mass and/or a high gas injection time. Non-uniform implosion led to a wide radiation pulse with FWHM of 20 ns, therefore the radiation power was only 150 GW/cm.

### 4. Summary

The experiments carried out on the GIT-12 generator with the Ne K-shell PRS based on the Ne double gas puff with the outer plasma shell demonstrated that the parts of the experimental chamber (the anode and cathode meshes, in our case) can play an important role in creation of the initial gas distribution in the interelectrode gap. The obstacles located directly on the way of the main gas flow have the greatest influence on the gas distribution. At all other factors being the same, the presence or absence of the anode and cathode meshes changed significantly the implosion dynamics and radiative characteristics of the Ne K-shell PRS. In our experiments, we observed two-fold decrease in the K-shell radiation yield and more than four-fold decrease in the K-shell radiation power. These observations should be taking into account in development of the gas-puff loads for Z-pinch experiments.
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