Soft x-ray source based on the point Z-pinch for pulse radiography

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Abstract. This article presents the study of the influence of the cathode material of a plasma injector on the parameters of the x-ray source of a point Z-pinch (PZ-pinch). The experiments were carried out on the compact pulse power radiograph PR-PZP-M1 (210 kA, 220 ns). The new type of the plasma injector based on a ceramic insulator and a composite cathode is developed and tested in the experiments. PZ-pinches based on tin, silver and gold were studied. It was shown that tin is the most applicable material to the PZ-pinch formation in terms of radiography. The PZ-pinch mass optimization has been carried out to obtain the brightest x-ray source with minimum sizes. The achieved x-ray source diameter is $12 \pm 3 \mu m$, height is $18 \pm 5 \mu m$ in the spectral range $h\nu = 1–3$ keV.

1. Introduction

Nanosecond pulsed radiography in the soft x-ray range (quanta energy of 1–10 keV) is an effective diagnostic tool for structure investigations of dynamic plasma objects [1–6]. Currently the radiography techniques based on X-pinch as a probe x-ray source are well developed [2, 5–8]. Unique x-ray source parameters of the X-pinch (micron sizes and x-ray picosecond duration) enable to obtain high contrast radiograph images of objects under investigation.

Along with the traditional approach to use the radiographs based on the X-pinch, a method to create point x-ray source based on using of the miniature plasma metal jet was developed at the IHCE SB RAS (Tomsk) [9]. To form the jet, the plasma gun based on the high-current arc discharge was used. The arc is initiated by a breakdown over the dielectric surface in vacuum [9]. After the plasma jet with the necessary parameters is formed in the interelectrode gap, the compact pulse power radiograph PR-PZP-M1 (210 kA, 220 ns) is turned on. When the Lorentz force of the radiograph current compresses plasma jet, the neck is formed. Further compression of the neck leads to the appearance of a hot spot radiating x-rays [9]. This source was named PZ-pinch (point Z-pinch). The main advantage of the PZ-pinch is the possibility of its repeated use without opening of a vacuum chamber.

In [9], it was shown that among such materials of a cathode for a plasma gun as aluminum, copper, iron and tin the best output characteristics of the x-ray source (x-ray source size and x-ray radiation yield) have been achieved for the tin PZ-pinch. Note that in case of X-pinch the most brightness x-ray source with smallest sizes is realized when wires materials with the high
atomic number $Z$ [10] (molybdenum, tungsten, gold, silver etc) are used. For this reason, in the presented experiments we investigated cathodes made from tin, silver and gold, because these materials have the high atomic number at the low melting temperature (in comparison with Mo or W). Besides, we investigated the plasma guns with the ceramic insulator and composite cathode for a PZ-pinch formation.

2. Experimental setup

2.1. The pulse power generator and the plasma gun design

The experiments were carried out on the compact pulse power generator PR-PZP-M1 providing the current through the plasma load of 210 kA at the current rise time of 220–225 ns [11]. The image of generator is shown in figure 1.

The arc current rise time was 1 $\mu$s. The plasma jet was injected into an interelectrode gap of a pulse power generator through 1.5 mm hole in a ground electrode. The grounded electrode was the anode for both the pulse power generator and the plasma gun. Then the plasma jet was compressed under the influence of the Lorentz force arising when the generator current flows through this plasma. The interelectrode gap of the pulse power generator was 1.3 mm. The process of an x-ray source formation is described in more detail elsewhere [9].

It should be emphasized that the material of the plasma gun insulator plays a significant role in the formation of a plasma flow. Earlier in the construction of plasma guns, insulators made of plastic (polyethylene or kaprolon) were used. But the light ions (especially hydrogen) availability in the plasma jet leads to the significant radial plasma expansion because of the high thermal rate of the substance ions with the low atomic weight. The using of the ceramic insulator makes it possible to reduce significantly an amount of the light ions in the plasma.

Figure 1. Photo of the compact pulse power generator PR-PZP-M1.
Figure 2. (a) The unit load: 1—ceramic insulator; 2—plasma gun cathode; 3—plasma gun anode and generator anode; 4—generator cathode; 5 and 6—molybdenum inserts in electrodes. (b) The composite cathode of a plasma gun with an insert of working material indicating the dimensions of the cathode in mm.

jet. In addition, the ceramic insulator enables to use the plasma gun to the PZ-pinch formation inside the high-vacuum systems that is very important in terms of the technical conditions of some experiments. Designs of the unit load and the cathode are shown in figure 2.

The main problem of the transition to ceramic insulator became a low durability of the plasma injector when to use of the usual type cathode. Experimentally was defined that, in order to increase the durability of the ceramic insulator of the plasma injector, it is necessary to use the composite cathode consisted of the stainless steel rod with insert from the work material of the arc. Such a constructive decision leads to an increase in the service life of the insulator up to 30 operations without reassembling. This result is comparable with the plasma injectors based of the plastic insulators. The design of the composite cathode is shown in figure 3. When the steel tube was absent between the insulator and the work metal the ceramic insulator was broken after five shots.

2.2. Experimental technique
The plasma gun and pulse power generator currents were measured by Rogowski coils. In the experiments, a diamond radiation detector (DRD) from Alameda Applied Sciences Corporation was used as an x-ray pulse diagnosis. The DRD was located behind the aluminum foil filter with the thickness of 5 µm on distance of 130 mm from the source. The sensitivity of the bare DRD in the radiation quanta range of 0.1–5.0 keV is $5.5 \times 10^{-4}$ A/W.

The x-ray source size we estimated using the method of measuring the penumbra width of the test object in the radiograph image [9, 12]. The test object was a tungsten wire mesh with wire diameter of 40 µm. It was located behind the composite filter of the kapton with thickness of 8 µm and the kimfoil with thickness of 4 µm with the aluminum coating layer of 0.4 µm. For obtain the x-ray image of the test object was used the Micrat-ORTO film. The scheme for obtaining an x-ray image of a test object as well as the registration scheme of an x-ray pulse is shown in figure 3. The 40 µm tungsten wire image and its densitogram is shown in figure 4.
3. Experimental results

Traces of the generator current and the DRD signal are shown in conjunction with the x-ray radiograph images of the test object obtained at the same experiment with the tin PZ-pinch in figure 5. The experimental data shown in figure 5 are presented for two different shots. As can be seen in figure 5, the soft x-ray source of the PZ-pinch can be a single radiating point or a several hot spots, located along the Z axis of the PZ-pinch by distance of 20–80 $\mu$m from one another. The similar situation is observed in the experiments with the X-pinch [13].

The joint analysis of the DRD signal with the radiograph image shows that DRD is not able to resolve of x-ray pulses of two different hot spots of the source in the time [see figure 5(b)]. This indicates that the actual x-ray pulse duration is below of the time resolution limit of the measuring system that equals about 1 ns. The measuring system includes the DRD, the signal cable and the oscilloscope TDS-3054C (Tektronix Inc, Oregon, USA) with bandwidth of 500 MHz. Thus, we obtain the transient response of the DRD on the x-ray radiation pulse. Therefore, the x-ray pulse duration (FWHM—full width at half maximum) is 2–3 ns and not depends of the plasma injector cathode material.

The main initial parameter in Z-pinches that influences on x-ray source output characteristics all else being equal is the pinch linear mass. Variation of the linear mass leads to changing of the delay of the x-ray generation regarding the beginning of the current that influences on the value of the current density and the plasma temperature in the moment of maximum compress of the pinch. In case of the PZ-pinch the linear mass depends of the vaporized substance amount by the arc discharge burning that is determined of the delay of the PZ-pinch current beginning regarding the arc current beginning.

Sizes of the x-ray source in the spectral range $h\nu = 1–3$ keV for tin, silver and gold PZ-pinches are presented in table 1. The size values presented in table 1 were averaged over entire of the experiment series for each material. The table shows that the source size for all studied materials is the same on average. However, the tin PZ-pinch has the smallest scatter of the source size from shot to shot. Also the X-pinch source sizes in the same spectral range are shown in table 1. It is obviously that the X-pinch source is smaller in size; however a spatial resolution of the PZ-pinch is enough to radiography in most cases. It should also be noted that the PZ-pinch x-ray source height is approximately two times its diameter in most cases.

Since the actual duration of the x-ray pulse of one hot spot is shorter than the width at half maximum of the detector signal, only the total pulse energy of all the hot spots forming the source can be estimated from the radiation detector signal. Dependencies of the pulse energy of
Figure 4. The x-ray radiograph image of the 40 µm W wire, its densitogram and distribution of the linear density calculated based on the wave optics: \( L \) is the wire image width at level 10% \( (D_{0.1}) \) of the maximal blackening density of the film \( D_0 \); \( L_{gm} \) is the width of the ideal image equals to the multiplication of the wire diameter by the geometric magnification factor. The intensity distribution in the shadow area calculated based on wave optics for the source size of 12 µm is shown by the red line.

Table 1. Size of x-ray source in the spectral range \( h\nu = 1–3 \) keV for PZ-pinches with different wire materials.

| Material | Source diameter, µm | Source height, µm |
|----------|---------------------|-------------------|
| Sn       | 12 ± 3              | 18 ± 5            |
| Ag       | 14 ± 5              | 22 ± 7            |
| Au       | 12 ± 6              | 23 ± 10           |
| Mo (4 × 25 µm) | 7 ± 2     | 15 ± 3           |

the x-ray pulse time for PZ pinches based on Sn, Ag, and Au, as well as for the X-pinch of four molybdenum wires with a diameter of 25 µm (Mo 4 × 25 µm) are shown in figure 6. The range of operating delays of x-ray generation is much narrower for the tin PZ-pinch [see figure 6(a)]. The highest x-ray yield is also observed in the case of a tin PZ-pinch, which is comparable to the pulse energy of Mo 4 × 25 µm X-pinch.
Figure 5. Waveforms of the generator current and the DRD signal along with x-ray radiograph images of the test object obtained at the same experiment with the tin PZ-pinch for two different shots (a, b).

Note that the radiograph image sharpness depends on several factors: the number of hot spots into source, the size of the single hot spot and the x-ray pulse power. To estimate the influence of these factors on image sharpness, the specific energy (pulse energy per cm$^2$ of the source surface area) can be used. Specific energy can be determined as follows:

$$W = \frac{E}{S_{\text{source}}} = \frac{E}{N S_{\text{HS}}}$$  \hspace{1cm} (1)

where $E$ is the x-ray pulse energy; $S_{\text{source}}$ is the source surface area; $S_{\text{HS}}$ is the surface area of single hot spot; $N$ is the number of hot spots forming the source. The average hot spot size $S_{\text{HS}}$ from table 1 was used in the calculation to simplify the estimates. The number of hot spots $N$ was determined by the number of test-object images in the radiographic frame. Each hot spot is a separate radiation source and forms its own image of the test-object on photographic film. The corresponding dependences of the specific energy on the x-ray pulse energy calculated for different numbers of source hot spots are shown in figure 7. Open circle indicate the values of the pulse specific energy obtained in the experiment.

As can be seen in figures 6 and 7, the maximal x-ray yield and the maximal probability of a single x-ray source formation are provided in the case of a tin PZ-pinch. Wherein the optimal operating mode of the tin PZ-pinch is such mode when delay between the current beginning and the x-ray radiation pulse is $150 \pm 20$ ns [see figure 6(a)].

In case of the silver PZ-pinch [see figure 6(b)] the highest x-ray radiation intensity is obtained when the x-ray pulse appears $190 \pm 20$ ns after the beginning of the generator current. However,
in this area two or more of x-ray sources is observed on the radiograph images of the test-object [see figure 7(b)]. The more acceptable operating mode in terms of radiography is implemented at shorter times of x-ray pulse appearance (110 ± 10 ns). For this purpose, it is necessary to reduce the delay of the generator current regarding to the arc current. Under this condition a single x-ray source is formed and observed a trend to reducing of the source diameter to 9 ± 2 µm. However, in this case the x-ray pulse amplitude is decreased three times. In case of the gold PZ-pinch [see figure 6(c)], a significant reduce of the x-ray yield in compare of tin and silver is observed. In addition, the gold PZ-pinch was the worst in terms of radiography [see figure 7(c)].

It should be noted that the tin PZ-pinch is even more attractive than the X-pinch in terms of radiography in the spectral range of $h\nu = 1–3$ keV. The X-pinch has a more stable source size and an x-ray yield from shot-to-shot [see figure 6(d)], and also makes it possible to obtain radiograph images with a higher spatial resolution in comparison with the PZ-pinch, especially in the spectral region $h\nu > 3$ keV. But an X-pinch has a higher probability of formation of two or more hot spots [see figure 7(d)]. In the case of the PZ pinch, the cathode erosion can influence on the x-ray emission stability. But evident advantage of the PZ-pinch is a possibility to use the plasma gun up to 30–100 shots depending on the cathode and the insulator materials.

Figure 6. Dependencies of the pulse energy of the x-ray pulse time for PZ-pinches based on Sn (a), Ag (b), and Au (c), as well as for the X-pinch Mo 4 × 25 µm (d).
Figure 7. Dependences of the pulse energy density upon the x-ray pulse energy calculated for different numbers of hot spots of the x-ray source for PZ-pinch es based on Sn (a), Ag (b), and Au (c), as well as for the X-pinch Mo 4 × 25 µm (d).

4. Conclusion

A new type of plasma injector with a ceramic insulator and a composite cathode was developed. In experiments, it was shown that the resource of the plasma injector is more than 30 shots. Thus, this type of plasma injector is not inferior in terms of this indicator to previously developed analogues.

The effects of the plasma gun cathode material and the plasma injection delay relative of the beginning of the pulse power generator current on the parameters of the soft x-ray source of PZ-pinch have been investigated. The tin, silver and gold PZ-pinches were investigated. It was shown that in case of the tin PZ-pinch the x-ray source with minimum sizes at maximum x-ray yield is formed. The source diameter is 12 ± 3 µm, height is 18 ± 5 µm in the spectral range $h\nu = 1–3$ keV.

In case of silver PZ-pinch the x-ray source with minimum sizes was realized when the PZ-pinch linear mass is less of the optimum value in terms of the x-ray yield. The gold is the worst material for PZ-pinch formation among those studied.

In conclusion, it should be noted that both methods of forming the x-ray source in the spectral range $h\nu = 1–3$ keV (X-pinch and PZ-pinch) make it possible to obtain x-ray images with a spatial and temporal resolution of $\sim 10\,\mu\text{m}$ and $\sim 1\,\text{ns}$ respectively. The further development of
the PZ-pinch along with the X-pinch will significantly extends opportunities of the application of such soft x-ray radiation sources for radiography in the future.

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