Developing a new high-power flash X-ray apparatus with harmonized magnetic and electrical fields

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Abstract. This work presents the design and characteristics of the 700-kilovolt pulsed X-ray apparatus, based on a principally new electro-physical structure. The main idea of this structure is that Blumlein pulse-forming system (transmission line, PFL), the primary and secondary circuit inductances and the capacitance of the secondary circuit of the Tesla transformer, running in the first half-wave occupy the same volume in space and do not impede each other. This kind of circuit design and the packing density as related to the pulse output dose is unrivalled throughout the world. The dependence of dose on the forming line voltage, and the flash duration on the different apparatus construction are measured.

1. Introduction

Earlier, the Institute of Hydrodynamics of the Siberian Branch of the Academy of Sciences of the USSR developed a series of pulsed X-ray apparatuses PIR-600 with a three-electrode tube IA8. The apparatuses were widely used in the USSR and are still used in many testing laboratories in Russia [1, 2]. Although the forming line is used in these apparatuses, the duration of the discharge of the pulsed X-ray tube for the load (150 ns) is such that this line operates as a conventional capacitance. The aim of this work was to create new types of an apparatus with a short X-ray flash, in which the forming line can operate both in Blumlein pulse-forming system mode (BPFS) and in the double-folded pulse forming line mode (PFL).

2. Operation modes and the design features of the apparatuses

The circuit design of the apparatus is a Tesla pulse resonance transformer with a primary voltage of 20 kV, operating in the shock excitation mode. The shape of the oscillations in the secondary circuit (no-load) is shown in figure 1a. The coupling coefficient is close to 0.6. In spite of the fact that it is possible to obtain higher efficiency in the second half-wave, the first half-wave of oscillations was chosen to increase the speed and reliability of operation of the apparatus [3]. To increase the speed, there are no ferromagnetic cores in the transformer. As a result, the delay from starting the primary spark gap of the transformer to the radiation output is 600 ns (figure 1b).
As a basis for the high-voltage electrodes of the forming lines the body and electrodes of the well-proven PIR-600 series generator were used. Figure 2 shows two options of the apparatus construction: option 2a is a simplified version, in which an IMA5-320D diode tube with spark gaps was used instead of a three-electrode IA8, and option 2b is a version with an IMA5-320D tube and a Blumlein pulse-forming system mode (BPFS). In both versions, the tube is shunted by the inductance \( L_3 \).

In both constructions, the forming line, the inductance of the primary and secondary circuits, and the secondary circuit capacitance of the Tesla transformer operating in the first half-wave occupy the same volume. Thus, it was possible to minimize the mass and dimensions of the apparatus. Due to the absence of separate blocks and connecting electrodes between them, the energy transfer losses between the compartments are reduced.

To place the inductances inside the pulse forming line, its electrodes are made magnetically transparent (figure 3), but they are not transparent to the electric field and good conductive along the pulse forming line axis. To obtain this, the aluminum walls of the cylindrical electrodes are perforated with the slits and windows lengthwise. The secondary winding \( L_2 \) is placed between the ground and high-potential forming line electrodes (figures 3 and 4). The pitch of the turns of the secondary winding changes in such a way that the electromotive force induced at a particular turn of the coil would match with the voltage of the capacitive ground-to-high-voltage divider \( \frac{C_2'}{C_1} \). Thus, for \( L_2 \), the principle of non-charge is observed (figure 4), in which the total charge at each turn is equal to zero [1, 2]. If this is not done, with an abrupt discharge of the storage line, and when the wave passes along the forming line in the secondary winding, there will be interturn breakdowns. For the first time this problem was encountered in the development of the ELIT accelerator [4] and the development of the first pulsed X-ray apparatuses of the PIR series [2, 5].
If the secondary inductance of the Tesla transformer is quickly closed to the ground or to a low-resistance load, the charge drains of the first several turns on the high-potential side of the winding and almost all the secondary circuit voltage appears to be applied to these several turns. As a result, a breakdown occurs between the turns with the destruction of the insulation. The placement of the secondary winding $L_2$ into the cylindrical capacitor of the forming line with the radial turn density

$$\frac{\delta N}{\delta r} \sim \frac{1}{r^3}$$

allows, in the first approximation, fulfilling the condition of uncharged turns [6].

This way the voltage dissipates evenly along the turns. The measured time of the PIR-600M flash with a triode X-ray tube with the explosive emission of IA8 is $\sim 150$ ns, whence the discharge current per tube is $I = 1000$ A and the equivalent resistance of the X-ray tube is about 600 Ohm. In this scheme, a spark gap is not used, its role being played by a three-electrode tube. That is, in the prototype PIR-600M apparatus, the secondary capacity was discharged into the tube as a concentrated capacitance of 250 pF, and not as a line with the matched wave impedance. To reduce the flash time, it was decided to switch to the circuits with the diode tubes, the nanosecond high-pressure spark gaps and the two types of forming lines. The use of a diode tube with the spark gaps makes it possible to operate the secondary circuit capacitance electrodes in the mode of the forming line. The current passing through the X-ray tube increases by an order of magnitude.

The diode X-ray tube with the explosive emission IMA5-320D [7, 8] has the diameter of the annular cathode of 8 mm, the diameter of the tungsten needle cathode in the cathode region of 2.4 mm, the apex angle of the anode cone $– 14^\circ$ (the clearance anode-cathode of 2.8 mm).

Since the nanosecond spark gap sharpeners for 600 kV and above are dangerous due to the high volume of pressurized gas inside and are rarely manufactured by industry, it was decided to use two series-connected spark gaps PO-89 ($S_1$ and $S_2$ in figure 2) for 200-350 kV with a capacitive divider to equalize the voltage [9].

The forming lines (triaxial) consist of an internal electrode with the diameter of 80 mm and the length of 370 mm, a middle electrode with the diameter of 160 mm and the length of 460 mm, and a tank electrode with the diameter of 240 mm and the length of 640 mm (figure 2). The impedance of the external section of the discharge circuit is 16 Ohm, the impedance of the internal section being 26 Ohm. The capacity of the BPFS is 53 pF. When discharged to an X-ray tube, the BPFS behaves like a source with the wave impedance of 42 Ohm. The total capacitance of a PFL is 250 pF. The line represents two sections in series. They have the wave impedances of 16 and 26 Ohm and the capacities of 174 and 77 pF, respectively. The current passing through the tube in the version with the BPFS is about 4000 A and in the version based on the PFL the current is 8000 A.
3. Dependence of the dose per flash on the voltage of the forming line

Since there was a set of spark gaps RO-89 for different voltages, varying the number of spark gaps and the voltage of their breakdown, it was possible to get the dependence of the dose on the voltage of the forming line for one flash for the PIR-600UV apparatus (figures 2a and 5). It is seen that the dependence is close to the linear one over a wide range of voltages. In this case, the dose for the flash is almost one and a half times higher than that for the PIR-600M apparatus with a triode tube.

![Figure 5](image.png)

**Figure 5.** Dependence of the dose on voltage of the pulse forming line – for one flash at the distance of 21 cm.

4. Comparison of the characteristics for various modifications of the apparatus

To measure the dose and time characteristics, we used a detector of the duration and shape of the X-ray pulse on a plastic scintillator based on polystyrene with the addition of paraterphenyl scintillators (pPT, C_{18}H_{14}), diphenyloxazolyl benzene (POPOP, C_{24}H_{16}N_{2}O) and a fast photomultiplier FEU-87 with the rise time of the anode current pulse <2.5 ns. The characteristic response time of the entire detection path is less than 5 ns. As shown by the comparison of measurements of different dosimeters, at the dose rate of $\frac{dD}{dt} > 10^6 \frac{R}{S}$ the thermoluminescent scintillation dosimeters and the small-size ionization chambers – dosimeters DK-02 – behave most adequately. The dose measurements were carried out with their help.

The penetrating ability of the radiation and the sensitivity were measured by X-raying step wedges and test wires using the ImagePlate detector.

The shapes and durations of X-ray flashes are shown in figure 6. For the version of the PIR600UV apparatus, made according to the scheme from figure 2a, the flash duration at half-height was less than 24 ns (Table 1), which is five times better than that of the devices of the previous generation. In this case, the dose of X-ray radiation measured at the distance of 21 cm increased from 128 to 200 mR.

The version of the PIR-700D apparatus (with BPS, figure 2b) has an even shorter flash (less than 13 ns) and the dose from 30 to 90 mR. In this case, the transmitting ability of this modification is higher than that of the PIR600UV and the previous generation apparatus, which allows us to speak of a higher radiation hardness.

The PIR-600UV has a maximum dose for one flash (200 mR at the distance of 21 cm from the focus) and the maximum dynamic range of the images can be obtained. This assembly is recommended for shooting with high X-ray radiation hardness in a wide range of thicknesses.
The PIR-700D apparatus with the X-ray tube IMA5-320D has the maximum sensitivity behind the steel barrier, significantly exceeding the other configurations of the LIH SB RAS devices and the Arion-600 (Argument-600) [10, 11]. We can assume that the radiation spectrum of the given configuration of the apparatus is the most convenient for X-raying through the massive obstacle.

![Flashes from various apparatuses](image)

**Figure 6.** Shapes of the X-ray flashes from various apparatuses.

The short duration of the flash is 24 ns and 13 ns for the PIR-600UV and PIR-700D instead of 150 ns (for the prototype - PIR-600M) makes it possible to reduce the dynamic blur of the image by an order of magnitude.

Increasing the dose characteristics by one and a half times (for the PIR-600UV in comparison with the PIR-600M) allows moving the X-ray unit from the subject, thereby reducing the geometric blurriness and the danger of destruction of the apparatus.

**Table 1.** Output characteristics of different apparatuses

| Apparatus        | X-ray tube (BPFS/PFL) | Spark Gap (if present) | Flash duration at half-height (at base) | Dose per 1 flash at 21 cm from focus | Number of brightness gradations by ImagePlate (1 flash at 0.5 m) | Tube voltage, kV | Maximum steel wall thickness for the visibility of 1.7 mm copper wire behind it, mm | Maximum X-ray transmissivity for steel, mm (1 flash at 0.5 m) | Advantages |
|------------------|-----------------------|------------------------|----------------------------------------|------------------------------------|-----------------------------------------------------------------|----------------|----------------------------------------------------------------------------------|-------------------------------------------------------------|------------|
| PIR-600M (1984)  | I8                    | PFL                    | 150 (250)                              | 128                                | 24816                                                           | 460            | 33                                                                              | 38-44                                                      | Maximum X-raying thickness                          |
| PIR-600UV        | IMA5-320D             | 2x300 kV spark gaps    | 24 (38)                                | 30                                  | 185-220                                                         | 460-504        | -                                                                               | -                                                          | Maximum dynamic range, maximum dose                |
| PIR-700D         | IMA5-320D             | 2x300 kV spark gaps    | 13 (38)                                | 30-90                               | 21072                                                           | 38             | 33                                                                              | 33-38                                                      | Maximum sensitivity                                |
| ARION 600/       | ARGUMENT-600          | BPFS                   | 10 (38)                                | 80                                  | 13456                                                           | 13456          | 38                                                                              | 38-44                                                      | Maximum X-raying thickness                          |
Conclusions

- Two pulse X-ray apparatuses with a high operating voltage (from 500 to 700 kV) have been developed and created on the basis of a fundamentally new electro-physical structure in which the pulse forming line, the inductance of the primary and secondary circuits and the secondary circuit capacitance of the Tesla transformer operating in the first half-wave occupy the same volume in space.
- The secondary winding of the Tesla transformer is placed between the low-potential and high-potential electrodes of the pulse forming line in such a way that the principle of non-charge is observed, when the electrical charge at each winding turn is equal to zero, which excludes the inter-turn electrical breakdowns and the breakdowns between the winding and the body.
- For both modifications – the PIR-700D apparatus with a Blumlein pulse-forming system and the PIR-600UV apparatus with a double-folded pulse forming line, the dose characteristics, the duration and shape of the X-ray flash, the X-raying thickness and sensitivity have been measured.
- The measured dose dependence per one flash for the apparatus with a pulse forming line at different voltages on the forming line within the range from 180 to 500 kV is close to the linear one.
- The reduction of the dynamic unsharpness due to the reduction in the duration of the flash by an order of magnitude and the reduction of the geometric blurring due to an increase in the dose per flash make it possible to obtain better X-ray images and to expand the class of fast processes studied.

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