Electrode material influence on emission properties of a low inductance vacuum spark

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Abstract This paper presents results of a study of the x-ray emission and the composition of the material ejected from the inter-electrode gap of a high-current, low-inductance vacuum spark. Pairs of electrodes made of different materials (Fe, Cu, Mo, W, Pb) were used. The most stable reproducibility of x-ray radiation emission is found to be with the Fe and Mo cathodes.

1. Introduction
A plasma source based on the high-current, low-inductance vacuum spark (LIVS) discharge [1-5] is promising for a large variety of applications. Such plasma sources are well suited for wide spectra of technological processes due to the extreme plasma parameters, the construction simplicity and low cost. Furthermore, studies of the plasma parameters, the emittance characteristics and the detail of the processes in the hot spot (HS) area – highly ionized, high energy, dense plasma formation in the plasma inside LIVS – are of great interest for larger machines due to the similarity of the processes occurring in all z-pinch-based devices.

A large number of factors (such as material and the shape of the electrodes, the stored energy, the discharge current, the initiation method and the trigger energy) affect stability of the plasma parameters, making it hard to optimize LIVS-based devices for a practical application. The lack of full physical understanding of correlation among all the processes in the inter-electrode gap of a LIVS discharge (from the moment of ignition to HS dissipation) makes the systematic work on collecting the data on various factors that can affect LIVS discharge development dynamics extremely important.

X-ray and material emission characteristics of the LIVS discharge plasma with different electrode materials are presented in this paper. Experiments were carried out at NRNU MEPhI Plasma Physics department on the “PION” device [6].

The first stage of commissioning of “PION” included the work aimed at stabilizing HS as the x-ray source. Keeping the interelectrode distance and the single electrode material (iron) fixed, different trigger systems (different energetics, electrode shapes and insulator materials) were tested. The trigger system was found to make a strong impact on reproducibility of the x-ray emission parameters.

Two systems described below – with the “worst” and “best” reproducibility e are shown in figure1. In the “worst” system (b), less than 20% pulses were followed by the x-ray burst, cf. more than 80% in

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the “best” one (a). Figure 2 shows the scatter of the starting time and the amplitude of x-ray burst occurrence (the x-ray burst duration is less than 1 ns) from more than 500 discharges. Black and grey areas are for the “best” and “worst” trigger system respectively.

Figure 1. Trigger systems schematic: (a) – HS detected in more than 80% pulses, (b) – HS detected in less than 20% pulses.

Figure 2. HS x-ray intensity and time of appearance range in series.

The electric parameters of the selected trigger subsystem are the following: the peak voltage is 40 kV, the pulse duration 400 ns, the front rising rate $2 \times 10^{11}$ V/s and the peak current 100 A. The HS formation moment was detected by the Rogowski coil (in the current transformer mode) and the x-ray pin-diode ($h \nu > 5$ keV).

2. Electrode material influence on the x-ray emission characteristics
To determine the electrode material influence on the x-ray emission properties of LIVS, several pairs of the electrodes (anode-cathode) were used: Cu-Pb, Cu-Cu, Cu-Fe, Cu-Mo, Cu-W, Fe-Cu, Fe-Fe, Fe-Mo, Fe-W. The experiments were conducted using the “best” trigger system (figure 1(a)). 100 pulses were shot for each pair. The operating voltage was 15kV.
The Cu anode exhibits the maximum HS appearance probability in the cases with the Fe and Mo cathode (90% and 70% respectively). This pair shows the minimum scatter of the HS occurrence time. No HS were detected in the case of the Pb cathode.

The Fe anode showed similar results for the HS appearance probability (100% and 80% for Fe and Mo cathode, respectively) with the minimum scatter of the HS occurrence time in this study. Table 1 presents the HS formation probability for the material combinations studied.

Table 1. LIVS discharge x-ray emission.

| Anode material | Cathode material | Fraction of discharges in the HS mode (%) | Maximum magnitude of the x-ray pulse (a.u.) | X-ray radiation emission timepoint (ns) |
|----------------|------------------|------------------------------------------|------------------------------------------|---------------------------------------|
| Cu             | Cu               | 45                                       | 70                                       | 1000±300                              |
| Cu             | Pb               | 0                                        | -                                        | -                                     |
| Cu             | Fe               | 90                                       | 140                                      | 900±100                               |
| Cu             | Mo               | 70                                       | 100                                      | 900±100                               |
| Cu             | W                | 40                                       | 60                                       | 1000±300                              |
| Fe             | Cu               | 50                                       | 70                                       | 900±200                               |
| Fe             | Fe               | 100                                      | 150                                      | 950±50                                |
| Fe             | Mo               | 80                                       | 130                                      | 900±100                               |
| Fe             | W                | 40                                       | 180                                      | 900±150                               |

3. Composition of the material eroded from the electrode and ejected from the inter-electrode gap

Data on the electrode erosion material were investigated. Intense material flow from the inter-electrode gap could be the source of the fast film deposition on the diagnostic windows (quartz or beryllium). This deposition can change the parameters of the input (laser diagnostics) or output (visual, UV, x-ray) radiance. This study yields information about the rate of material deposition on the structures inside the vacuum chamber at different distances from the plasma source.

For this analysis, substrates made of laboratory glass were used. Four substrates were used for each experimental series at four different positions (40, 57, 140 and 210 mm from the gap). These substrates were subjected to 50 pulses. Scanning electron microscopy was then used to analyze their surface.

Scanning electron microscopy was carried out using HITACHI TM-1000 with maximum magnification of 10000. This limitation did not allow us to see granulation of the refractory electrode materials (W, Fe, Mo) because the deposited structures were smaller than the resolution of the microscope, whereas the element analysis detected the presence of the electrode material there. Carbon was always found on the surface, making not more than 7-8% of the deposits (the microscope cannot detect carbon).

The results with the Cu anode for the substrates at the 40 mm distance are shown below. At this distance, strong electrode material deposition was detected for all the electrode pairs. At 210 and 140 mm noticeable deposition was only seen with the Cu and Pb cathodes. At the distance of 57 mm from the inter-electrode gap, there was a strong deposition on the substrates in all cases. But in the cases with the W and Fe cathodes there were glass materials (Si, Ca) on the substrate surface. This means that the deposited layers are more inhomogeneous and have a smaller thickness in these cases.

Figure 3 presents images of the substrate surface (the distance from the interelectrode gap is 40
mm) with the Cu anode and Pb cathode. The image portrays a solid Pb coating on the substrate surface (the element analysis showed 100% Pb). The surface is coated with cellular formations of the size of approximately 600 nm. These formations are apparently droplets of the melted cathode material. Bigger drops (5-10 µm) with the same small structures on them are also seen on the background of the uniform coating.

![Image](image1.png)

**Figure 3.** Substrate surface image (40 mm distance) with the Pb cathode.

![Image](image2.png)

**Table 2.** Element compound of the test substrate surface.

| Cathode material | Anode material, % (Cu) | Cathode material, % | Silicium, % | Calcium, % | Cell size on surface of test substrate, nm |
|------------------|-------------------------|---------------------|-------------|------------|------------------------------------------|
| Pb               | 0                       | 100                 | 0           | 0          | 700±100                                  |
| Cu               | 100                     | 100                 | 0           | 0          | 500±100                                  |
| Fe               | 15–26                   | 37–40               | 22–27       | 10–15      | 400±100                                  |
| W                | 22–51                   | 0–49                | 23–30       | 10–17      | <200                                     |

Deposition patterns are nearly the same for all the cathode materials tested – the difference is only in the cell size (see table 2) and the presence of the test substrate material on the surface.

4. **Conclusions**

The selection of the cathode material strongly affects the x-ray emission characteristics. The best x-ray reproducibility from pulse to pulse is registered for the Fe and Mo cathodes. A stable pinch effect with a relatively small time scatter (100-200 ns) is detected for these cathodes.

The analysis of the corpuscular flow composition (from scanning electron microscopy of the glass substrates) also reveals a strong dependence on the cathode material selection. The predominantly cathode material is detected in the case of the low melting temperature of the cathode material (Pb). With higher melting temperature (Fe and Mo) the percentage of the cathode material decreases, whereas the fraction of the anode material (Cu) grows. In the case of the Fe or W cathode there are glass composition elements on the substrate surfaces. This indicates a lower thickness of the layers deposited on the substrate surface.
References
[1] Kuznetsov A P, Byalkovskii O A, Gubskii K L, Kozin G I, Protsenko E D, Dodulad E I and Savjolov A S 2014 Plasma Physics Reports 40 290-297
[2] Beilis I I, Boxman R L, Goldsmith S and Paperny V L 1999 Applied physics letters 75 2734
[3] Krasov V I, Paperny V L, Korobkin Yu V, Romanov I V, Rupasov A A and Shikanov A S 2007 Technical physics letters 33 941
[4] Bashutin O A, Alkhimova M A, Vovchenko E D, Dodulad E I, Savelov A S and Sarantsev S A 2013 Plasma Physics Reports 39 900-909
[5] Baronova E O et al. 2012 Plasma Physics Reports 38 751-760
[6] Sarantsev S A, Dvoyeglazov Ya M and Raevskiy I F 2015 Physics Procedia 71 133-137