Investigation into the processes of plasma production on the surface of electrodes made from different materials on Angara-5-1.

V Aleksandrov, I Frolov, E Grabovsky, A Gribov, Ya Laukhin, K Mitrofanov, G Oleinik, I Porofeev and V Smirnov.

1 SSC RF TRINITI, 142190, Troitsk, Moscow reg., Russia
2 Kurchatov Institute, Moscow, Russia
E-mail: oleinik@triniti.ru

Abstract. The results of an experimental research of formation of plasma on irradiated by soft x-ray radiation electrodes from lead and stainless steel at linear density of a current about 1 MA/cm at Angara-5-1 facility are presented. It is shown, at the specified density of a current and soft X-ray power density of 0.1 TW/cm$^2$ plasma appears on a surface of electrodes. The velocity of plasma expansion reaches 50-100 km/s. Presence of soft X-ray radiation essentially changes dynamics of expansion of plasma in an interelectrode gap. Distinctions in dynamics of behaviour of plasma on electrodes from stainless steel and from lead are found.

1. Introduction
In the concept of the repetitive thermonuclear Z-pinch-based [1] reactor it is necessary that the processes proceeding on the surface of vacuum magnetically insulated transmission lines (MITL) should be investigated. The linear current density at the electrode can achieve 10 MA/cm. At these linear densities the electrode will explode forming a plasma layer on its surface. A normal operation of such MITL depends on the parameters of this plasma layer, which can result in ion and electron current leakage through a vacuum gap of MITL and in shunting by plasma. The rate of plasma production on the electrode surface could be also raised by soft X-radiation (SXR). Some alternatives of a generator for a repetitive facility are considered where the MITL electrodes are made from different materials. The present work is devoted to an experimental investigation into the process of the plasma production on SXR radiated electrodes of stainless steel and lead at linear current densities of an order of 1 MA/cm. The work is aimed at developing and refining the results of work [2].

2. Experiment arrangement
The experiments were carried out on the Angara-5-1 facility [3].

Figure 1 displays a layout of the wire array and the studied electrodes. The wire array is 18 mm in height and 8 mm in diameter. The array contains 40-60 tungsten wires 6-7 μm in diameter. To locate the wire array there are symmetrical cavities with their diameters of 10 mm in the investigated anode and cathode parts, respectively. The wire array is 1 mm distant from the electrode. The distance between the investigated anode and cathode parts is 3-5 mm.
To compare the plasma expansion dynamics in only one shot half of the studied stainless steel anode was covered with lead foil 100 μm thick. The line separating the covered and uncovered electrode part passed through the electrode axis. To keep the anode surface flat a sample 100 μm thick was taken in the very point of the electrode where lead is to be fixed. The same lead foil was fixed on the cathode in the same manner. The photos of the anode and cathode electrodes studied are shown in figure 2. On mounting the electrodes were oriented so that the anode part covered with lead was over the cathode part covered with lead. Besides, the line separating the covered and uncovered electrode parts was oriented in the direction of observation. In figure 1 this direction is normal to the drawing plane. Such arrangement of the experiment made it possible to observe the difference in the plasma parameters in one shot that improves the experiment reliability.

![Figure 2. Photos of investigated electrodes, left - anode, right cathode. The central hole diameter is 10 mm, the square size on paper is 5 mm. The left half of the studied surfaces (24 mm diameter) of each electrode is covered with lead.](image)

The set of diagnosis techniques used in the test involved the following.

The full current flowing through the liner was detected by B-dot probes located on a radius of 55 mm from the liner axis. The voltage was taken on a radius of 6 cm with an inductive divider [4]. The set of four XRD was 3.5 m distant from the wire array in the radial direction. The time resolution of XRD was 0.7 ns.

The optical streak camera was used to detect the plasma glow in the visual spectral range. The time resolution is 0.3 ns. The spatial resolution on the object was under 80 μm. The device was adjusted so that the light can fall into its slit from a narrow region spaced 1.5 mm over the cathode.

A X-ray camera CXR6 on the basis of a MCP was used to detect images in SXR. The time of frame exposure was 3 ns, the sensitivity in the range (0.1–10) keV.

3. Experimental results

In this experiment in different shots the lead foil position varied. In some shots the electrode parts covered with lead foil were located at the right and uncovered ones at the left when viewed from the observation side. In other shots - on the contrary. This made possible the test of the technique and exception of uncertainties attributed to a possible dependence of the relative aperture of the detector upon the position of the object studied and the difference in the realization of implosion processes in different shots.

The current amplitude was about 2 MA, its rise time is ~ 95 ns. The minimum radius of the investigated electrodes is 5 mm, so the maximum linear current density was found to be 0.6 MA/cm. The maximum magnetic field on the electrode surface ~ 0.8 MG.

The detected SXR power was about 1.5 TW. Since in the given construction at a distance of 3.5 m from the wire array one could observe only 5 mm of the entire Z-pinch length, it can be considered that the linear SXR source emits 1.5 TW/0.5 cm = 3 TW/cm. For such a source at a distance of 5 mm from it the density of power flux was estimated as a maximum of 0.9 TW/cm².

Presence of soft X-ray flux with power flux density ~1TW/cm² is the main reason of ablation. Influence of current with linear density of 0.8 MA/cm is weaker.
As mentioned in previous section, the plasma expansion was recorded by optical streak camera in visible range and by taking frame pictures in the SXR. The results obtained by these two techniques were different and are described below in sections 3.1 and 3.2.

3.1. Plasma expansion in visible range

Figure 4 presents a comparison of two detected optic streak camera images. In the first shot (left part of the figure 4) the electrode parts covered with lead foil were located at the right and those uncovered at the left when viewed from the side of observation. In the second shot (right part of the figure 4) their position was quite contrary. A conventional representation of the lead foil position is given in the upper part of the figure 4. In the bottom of figure 4 a comparison of two detected images is presented. It is easy to see in both images the appearance of plasma glow near the cathode just after final compression of pinch. But the obtained images evidence the absence of any reliable difference in the plasma glow over the both stainless steel and lead cathodes.

3.2. Plasma expansion in SXR range

Figure 5 presents 5 frame pictures of the imploding liner and electrode plasma glow in the SXR (at the left). The right part of figure 5 shows time dependencies of the current derivative through the discharge, synchronization of frames and SXR power.

The left side of electrodes was from lead, the right – from stainless steel.

The 1st frame was made at the maximum of SXR. In this moment the voltage between anode and cathode was about 0.7MV. The initial distance between anode and cathode was 4.5mm, as before shot, the same for lead and stainless steel. The evaluation of the electric field at radius 5mm is 1.5MV/cm.

On the next frames it is seen plasma expansion from the electrodes. It is seen the difference in plasma velocity expansion. For lead this velocity is smaller (0.53*10^7 cm/s), than for stainless steel (0.83*10^7 cm/s). More heavy ions move with the smaller velocity. It should be emphasized that this velocity is obtained from the movement of bright (in SXR) region.

Bright luminescence in the middle of anode-cathode gap on the last frame - the result of collision of ablating plasma from stainless steel anode and cathode.

The energy flux density was estimated as ~6kJ/cm^2. It is seen that under this condition for electrodes from lead after 20 ns from SXR maximum the anode-cathode gap is not closed.
4. Conclusion
The production and dynamics of the near-electrode plasma on the electrodes from stainless steel and lead have been investigated. The distance between the investigated anode and cathode was 3-5 mm. The maximum linear current density was 0.6 MA/cm and the time of rising to its maximum was about 100 ns. The maximum magnetic field on the electrode surface was 0.8 MG. The electric field at radius 5mm reached 1.5MV/cm.

Plasma ablation is seen in visible and soft X-ray spectral region. However, the difference of plasma ablation from stainless steel and lead electrodes is not detected in visible range, but only in SXR range. So, the plasma image is more representative in SXR range. The plasma velocity expansion for stainless steel was 0.8*10^7 cm/s and for lead - 0.5*10^7 cm/s.

The energy flux density was estimated as ~6kJ/cm^2. After 20 ns from max SXR the anode-cathode gap was not closed. Under above-said circumstances the energy could be transferred to the load via MITL from the lead electrodes.

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