Impact of plasma and ion beams obtained in plasma focus installation on the surface of solids

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Abstract. In the article the interaction of argon and nitrogen plasma with the surface of solids (silicate glasses and metal plates) was studied. The experiments were done on Plasma Focus setup (PF-4, Lebedev Physical Institute). It was found that independently of the working gas and the material of the plates on their surface, small-sized local fracture regions of $\sim$ 1-3 mm in diameter are observed, which are surrounded by the region of action of a plasma a larger size 7-8 mm. It is assumed that these regions can be formed as a result of the action of beams of fast ions with energy of more than 40 keV. Damages of a larger size can be explained by the action of the plasma jet of the working gas and plasma bunches. In the small local area of damage, there are accumulations of foreign impurities: copper, carbon, iron, etc.

1. Introduction

It is known that plasma produced in installations such as plasma focus (PF) has a complex structure due to the specific compression of the current-plasma shell (CPS) in strong magnetic and electric fields [1-3]. Compression of CPS leads to the formation of both a plasma jet working gas, and a jet of "metallic plasma", formed during ablation of the anode installation. These plasma jets are directed in one direction (from the anode) along the axis of the installation and are separated in time into several tens of nanoseconds. The plasma jet of working gas is compact enough in contrast to the "metallic plasma", which moves in a cone with the angle of $\sim$ 40-45$^\circ$.

Recently, laser probing has revealed that plasma clots (bunches) with transverse dimensions of $\sim$1 mm and lengths of $\sim$ 3 mm are formed in PF installations of Mather type [4-6]. The electron density in the plasma bunches is $\sim$10\textsuperscript{19} cm\textsuperscript{-3}. These compact dense formations have high velocities $>10^7$ cm/s at a kinetic energy of 2 Joules [6].

In addition to the above-mentioned energy fluxes, fast-ion and electrons beams with energies of more than 40 keV are observed in the PF. Estimates show that the energy transferred by these beams is comparable to the energy of jets and plasma bunches [7].

To solve applied problems in PF installations, the properties of the above-mentioned energy flows are of great importance, the high energy flux density ($10^{10}-10^{12}$ W/cm\textsuperscript{2}) in which allows performing various technological operations [8,9].

The aim of the work was the experimental observation of the interaction of these energy flows with the surface of solids in a PF installation.
2. Experimental methods
The experiments were performed on the Plasma Focus installation PF-4 (Lebedev Physical Institute). Installation parameters: energy stored in the capacitor bank - 3.5 kJ; the maximum current is 250 kA; a quarter of the period of the current pulse is 2.5 µs (Fig. 1). The discharge chamber of the facility was filled with gases either Ar or N₂ to a pressure of 1-1.5 Torr.

![Figure 1. Oscillogram of the derivative of the current.](image1)

![Figure 2. Holder of glass samples (a); holder of metal samples (b).](image2)

The glass samples were cut from photographic plates 1.5-3.0 mm thick with a size 40x40 mm; samples of metal foils < 1 mm in thickness had dimensions of 20x20 mm. Before plasma irradiation, the samples were washed with water and degreased with ethyl alcohol.

Glass and metal plates were introduced into the chamber of the PF with the use of holders, shown respectively in Figures 2a and 2b. Three samples were placed on the holder. The density of the energy flux of the plasma jet on the sample was controlled by changing the distance X from the surface of the sample to the anode of the installation (Fig. 2a, b). Irradiation of the samples was carried out at a temperature of 300K. The magnitude of the energy fluxes was controlled by the amplitude of the peculiarity on the derivative of the current (Fig. 1).

3. Experimental results
Fig. 3 shows the plates of silicate glasses irradiated with an argon plasma at X = 3 cm at comparable energies in a plasma jet. It can be seen that on the surface of the glasses local fracture regions with a characteristic size of the order of 2-3 mm are observed. Around these areas are visible zones of action of a larger size ~7-8 mm. With sufficient magnification inside the local areas of damage, external impurities are visible, usually copper (Fig. 2a). The rest of the glass plate is usually covered with a
thin layer of copper coming from the anode unit of the PF facility. It should be noted that over time, the zone around the local areas is discolored and the interaction patterns of the plasma jet with the glass surface lose their contrast and become difficult to distinguish. With large features on the derivative of the current U >70-100 V, the observed picture practically disappears due to the emergence of new areas of damage that merge with local regions of destruction.

**Figure 3.** Silicate glass 2.5 mm thick irradiated with argon plasma X = 3 cm: a - amplitude of the peculiarity U = 30; 30; 60; 70; 60 V. b - U = 25; 30; 60; 40; 70; 50; 60 V.

**Figure 4.** Copper plates 0.7 mm thick irradiated with a nitrogen plasma X = 8 cm: (a) the amplitude of the peculiarity U = 10; 15V. (b) - the amplitude of the peculiarity - 20V.

Figure 4 shows copper plates irradiated with nitrogen plasma. It can be seen that local damage areas <1 mm are observed on the surface of the plates, surrounded by an area of influence of a larger size ~7-8 mm. Around the local areas of damage there are visible accumulations of particles in the tenth and hundredths of millimetres. The analysis of impurities on a scanning EVO-40 microscope with an X-Flash X-ray attachment showed that these particles include chemical elements: carbon, copper, aluminium, iron, oxygen, etc. [10]. A particularly clear picture of the interaction of energy flows with the surface of a metal plate is observed with a single plasma pulse and higher values of the peculiarity. Fig. 5 shows a series of photographs of the energy impact with various metals: iron, copper and aluminium.

Figure 5a shows a foil of Fe after irradiation with nitrogen plasma when the specimen is rigidly fixed (adaptation Fig. 2b). In this case, the pattern of the deformation of the sample is observed in the form of a hemispherical segment, in the center of which there is a well of diameter ~2 mm and the surrounding region of the plasma impact of ~ 7-8 mm in size. Fig. 5b shows the deformation of the Cu foil after the action of argon plasma, which was in the free-standing state in the adaptation (Fig. 2b). It can be seen that the foil is strongly deformed in the direction of motion of the plasma and in the center there is a hole of diameter ~ 2 mm. The observed patterns of deformation of metal plates are characteristic for the case of an axisymmetric application of the central force on a circular plate [9]. In
our case, the role of the central force is performed by a plasma bunch. Figure 5c shows an Al plate 50 mm in diameter irradiated with five pulses of argon plasma at a distance from the anode of $X = 7$ cm. In the center of the plate, a light region measuring $\sim 1-1.5$ mm is visible. It can be seen that with the removal from the anode, the effect on the Al surface of the plate decreases.

![Figure 5. Interaction of nitrogen (a) and argon plasma (b, c) with the surface of metal plates:](image)

**Figure 5.** Interaction of nitrogen (a) and argon plasma (b, c) with the surface of metal plates:

- a - Fe foil 170 µm thick, $X = 3$ cm, $U = 100$ V, $N = 1$ pulse;
- b) Cu foil 50 µm thick, $X = 3$ cm, $U = 30$ V, $N = 1$ pulse;
- c) Al plate 1 mm thick, $X = 7$ cm, $N = 5$ pulses, $U = 50-60$ B.

Fig. 6a shows a Fe plate 1.5 mm thick irradiated with five pulses of a nitrogen plasma with a peculiarity amplitude of 100 to 140 V. The surface of the plate is strongly fused and differs significantly from the pattern observed upon exposure to a single plasma pulse (Fig. 5). Fig. 6a, b shows Cu foils (50 µm thick) and Al (80 µm thick) irradiated with a single pulse of argon and nitrogen plasma with a peculiarity amplitude of 120 and 80 V, respectively. It can be seen that with a diameter of a diaphragm aperture $Ø = 15$ mm, in both cases there is a complete melting of the material.

### 4. Discussion of the results

As follows from the above results (Figures 3, 4), at small energy flux densities (a small amplitude of the peculiarity on the derivative of the current), small-size local regions of action with dimensions close to ”plasma bunches” are observed on glass and metal plates [5-7]. They are always surrounded by areas of influence of a larger size. Also, the outflow of foreign impurities by the plasma flow from the area of action is observed. With an increase in the amplitude of the peculiarity at the derivative of current $>80$ V, the area and magnitude of the disruption on the surface of the metal plates increase until the sample material is completely melted and destroyed (Fig. 6).

![Figure 6. Irradiation of a plate of Fe (a) and aluminium foil with nitrogen plasma (c); argon plasma of Cu (b) foil at a peculiarity amplitude of $>80$ V and anode distance of $X = 3$ cm.](image)

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In this case, it is not possible to determine the ratio of the contribution of plasma bunches, ion beams and a plasma jet to the energy impact on the materials. As follows from the results presented, the dimensions of the region of the action of the plasma at a distance $X = 3$ cm are quite large $\sim 15-20$ mm, which indirectly indicates that the plasma jet diverges rapidly in space. It follows from [6] that
the plasma bunches also increase rapidly in transverse dimensions (5 times at a distance of 1 cm) and at a distance of 3 cm from the anode, their size is compared with the size of the plasma jet. Thus, the most likely cause of small-size local damage is the action of fast-ion beams whose spatial divergence is insignificant due to the high velocity of their propagation in comparison with thermal velocity of beam particles. Another indirect confirmation is the darkening of the glass in the region of the effect (Fig. 3), which, as is well known, is usually observed during the formation of colour canters during the deceleration of charged particle beams. The generation of such particle beams in the PF installations is possibly associated with accelerating processes that arise in the plasma due to the development of plasma instabilities.

5. Conclusion
The presented experimental results make it possible to draw the following conclusions: the effect of plasma on materials is inhomogeneous: regions of a larger size on the order of 7-8 mm are observed, within which local disruptions with a diameter of 1-3 mm are located. Small-size local regions can be formed as a result of the action of fast-ion beams. Areas of a larger size arise when exposed to a plasma jet and plasma bunches.

Acknowledgments
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6. References
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