Electron concentration measurements in colliding erosion plasma flows by shadow method

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ABSTRACT. The aim of this work is research of qausi-stationary high energy plasma formations. Investigated interaction process is based on high-current discharges of plasma accelerators of erosion type in vacuum. Shadowgraphs of colliding plasma flows were made using knife and slit method. As a light source a specially made argon flash lamp was used. An electron concentration in collision region reaches a maximum value $8.4\cdot10^{16}$ cm^{-3} between 15 and 20 μs from accelerators operation start.

INTRODUCTION. At present a close attention is paid to the development of physic technical concepts of making new plasma systems to obtain highly concentrated energy flows for photochemistry, high-temperature thermal physics, new material synthesis, and to use them as the base for new technologies and technological processes aimed at the modification of the material properties in extreme regimes of action [1–4]. The investigation of physical processes of interaction between plasma flows can help in solving a variety of actual scientific and industrial problems in quantum electronics, radiation plasma dynamics, diagnostic of materials under extreme conditions, etc [5–10]. When colliding, the accelerated plasma flows may open up certain possibilities in producing new plasma formations [11–13].

For quantitative shadow studies of transparent inhomogeneities widely used photometric shadow techniques [14]. Shadow diagnosis of the brightly glowing plasma is very difficult by the fact that for shadow images we need to use a brighter light source than the investigated plasma. For these purposes, such light sources as a capillary discharge in argon, exploding wires, various flash lamp and pulsed lasers are used [15].

THEORY. To calculate the light path in the optical inhomogeneity a rectangular coordinate system is used and positioned so that the z axis is oriented along the probe radiation, y axis along the plasma flows and the x axis is directed vertically. Assuming that the deflection of light in the inhomogeneity is small, we can neglect the curvature of the light path in it, and assume that the beam propagates straight, very little deviating from the path by which he would have gone in the absence of heterogeneity.

Under these assumptions, the Euler equations can be represented as [14, 15]:

$$\mathrm{tg}\varepsilon_x \approx \int_{z_1}^{z_2} \frac{d\{\ln[n(x,y,z)]\}\,dz}{dx}, \qquad \mathrm{tg}\varepsilon_y \approx \int_{z_1}^{z_2} \frac{d\{\ln[n(x,y,z)]\}\,dz}{dy}, \tag{1}$$

where the quantities ε_x and ε_y are projections of the light deflection angles, z_1 and z_2 are the coordinates of the points of entrance of the light beam into the optical inhomogeneity and exit from it, n is the refraction coefficient of medium.

The slit in the illuminating part was set horizontally, and it may be assumed thereby that the shadow device is sensitive only to deviations of light leading to a vertical displacement of the slit image. So, the value $\partial n/\partial y$ can be ignored, that is the dependence of the refractive index on y coordinate is ignored (the light beam is confined to any section y = const).

Investigation of axisymmetric inhomogeneity is easier in a cylindrical coordinate system. In the transition to it from the rectangular coordinate system the equations (1) are transformed into an integral equation of Abel type [16, 17]:

$$\varepsilon_x = \frac{2}{n_0} \int_x^R \frac{\partial n}{\partial r} \frac{x}{\sqrt{r^2 - x^2}}\, dr\,. \tag{2}$$

The value of ε_x is experimentally measurable and is obtained from the results of photometric measurements of the shadow patterns of plasma flows collision with the use of the formula

$$I(x,y) = \frac{1}{2} I_0 + \frac{\varepsilon_x F}{\xi} I_0\,, \tag{3}$$

where $0.5I_0$ is the shadow pattern intensity in the absence of the optical inhomogeneities, F is focal length of the objective of the shadow device detecting part, ξ is the slit width of the shadow device illuminating part and ε_x can be positive or negative.

After transformations equation (2) can be written as

$$n(x) = n_0 - \frac{n_0}{\pi} \int_r^R \frac{\varepsilon_x(x)}{\sqrt{x^2 - r^2}}\, dx\,, \tag{4}$$

where n_0 – refractive index of the undisturbed medium.

The density of free electrons in the plasma is determined from the relation [14, 18]

$$n = 1 - \frac{\lambda^2 e^2 N_e}{2 m_e c^2}\,, \tag{5}$$

where λ is probe radiation wavelength, e is electron charge, N_e is electron density in plasma, m_e – electron mass, c – speed of light in free space.

EXPERIMENTS. General scheme of the experimental facility is shown in fig. 1. Investigated interaction process is based on high-current discharges of plasma accelerators of

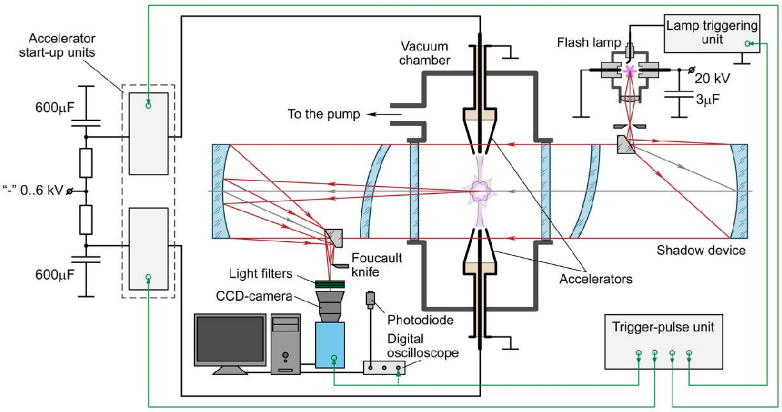


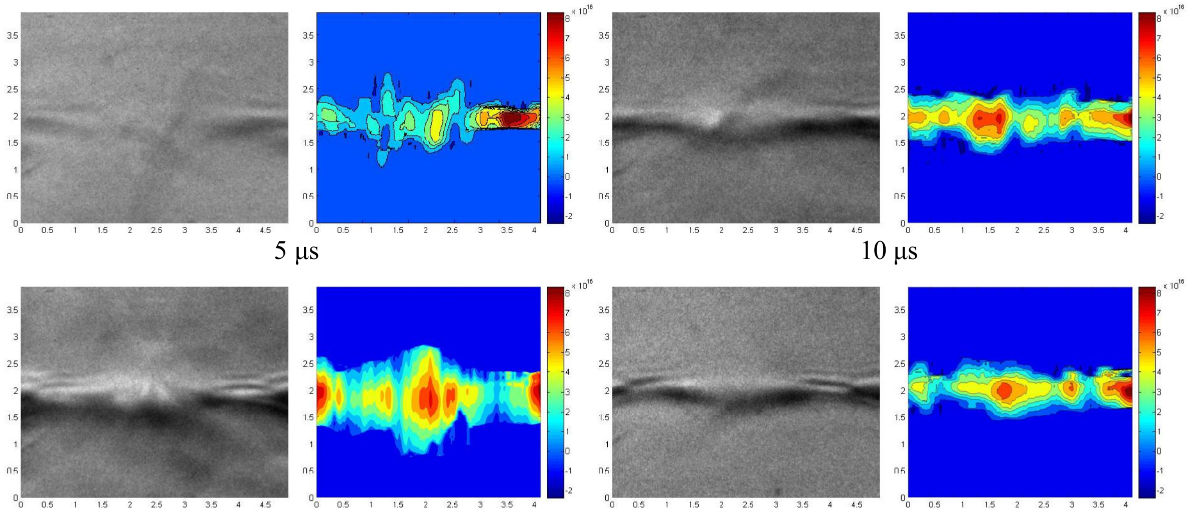
Fig. 1. Optical scheme of the experimental facility

erosion type in vacuum. An end erosion plasma accelerator is a system of two coaxial copper electrodes separated by a caprolone insulator. An outer copper electrode is shaped as a convergent nozzle. The accelerators were mounted in a vacuum chamber by means of copper co-axial current supply. Each accelerator was put into operation by discharging a capacitor battery. Shadow measurements were performed on an IAB-451 shadow device using knife and slit method. The focal length of the detecting part objective is F = 1917 mm at a diameter of the observed field of 200 mm. The width of the slit in the illuminating part of the instrument was equal to $\xi = 0.2$ mm. The slit was placed horizontally. For the shadow images that are suitable not only for qualitative but also for quantitative interpretation the light source based on a pulsed spark discharge in argon was created, which allows to obtain a light pulse with duration of 3 μs (at the level 0.7 of maximum light intensity). A lamp operating voltage is 20 kV.

In the illuminating part of the device system of light filters having a light transmission maximum at the wavelength $\lambda = 547$ nm was placed. For the shadow photograph of luminous plasma taken we must be sure that the plasma emission is not detected by the camera, while the radiation from the light source has been registered. For this purpose were selected light filters with a bandwidth at a wavelength at which the relative intensity in the spectrum of the plasma is small, and the relative intensity of the discharge spectrum of the light source is close to maximum.

RESULTS AND DISCUSSION. The process of the interaction of plasma flows was recorded by PCO DICAM PRO digital hi-speed camera with an exposure time 5 μs. The results of high-speed photography reproducing the dynamics of the plasma flows collision process are shown in fig. 2. The time specified under the pictures is the time interval from accelerators start to beginning of exposure.

In the early stages of the forming of quasi-stationary plasma formations the determining factors are the processes of large-scale turbulence (fig. 2 – 5 μs), then in the areas of plasma flows compression are observed the formations of localized regions with high free electron density (fig. 2 – 10 μs). After 15 μs from the beginning of the accelerators work region of increased electron density is moving to the central area between the accelerators and stable localized plasma spherical formation in center of which electron density reaches its maximum value $8.4\cdot10^{16}$ cm^{-3} for the investigated process forms (fig. 2 – 15 μs). After 20 μs from accelerators start decrease of free electron density and the reduction of the geometric dimensions of the generated plasma formation are observed. These computational results confirm the data previously obtained by spectral method [10, 13, 15].



5 μs

10 μs

15 μs

20 μs

Fig. 2. Results of shadow method diagnostics of the plasma flows collision (on the left are the shadow patterns, on the right are the calculated distributions of electron density, cm-3)

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