THE APPLICATION OF SHADOW METHOD FOR ELECTRON CONCENTRATION MEASUREMENTS IN COLLIDING FLOWS OF EROSION PLASMA

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ABSTRACT: The purpose of this work is research of qausi-stationary plasma formations with high energy content for practical applications in high thermal physics and diagnostic of materials under extreme conditions.
Investigated interaction process is based on high-current discharges of plasma accelerators of 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 accelerator was mounted in a vacuum chamber by means of copper co-axial current supply. Visualization, photography and shadow investigation were made through special vacuum chamber optical windows. Each accelerator was put into operation by discharging a capacitor battery.
Shadowgraphs of colliding plasma flows were made using knife and slit method. As a light source a specially made argon flash lamp was used. A lamp operating voltage is 20 kV, light pulse duration is 3 μs. Averaged electron concentration in the interaction area was calculated from intensity distribution in shadowgraphs. In order to perform a correct shadow display a contribution of plasma intrinsic emission to the shadow pattern must be eliminated. To this effect a light filter system with transmission peak at 547 nm was mounted before the CCD-camera. At this wavelength the relative intensity in plasma spectrum is low while in argon lamp spectrum it is near-maximum.
A shadow pictures data processing revealed that the localized stable spherical plasma structure forms in a collision zone by 15 μs from accelerators operation start. An electron concentration inside this structure reaches a maximum value $8.4 \cdot 10^{16}$ cm^{-3} between 15 and 20 μs from accelerators operation start, at this moment a discharge current tops. After 20 μs electron concentration decreases and plasma structure downsizing occurs. The results of electron concentration calculation are in good agreement with data obtained by spectral method.

INTRODUCTION. In the study of transparent inhomogeneities is common to use shadow methods. For quantitative studies widely used photometric shadow techniques. Their main characteristic is that extended luminous body (the slit) is taken as the light source. In the focal plane of the detecting part objective lens is placed opaque diaphragm (knife), partially overlapping image of the light source. If optical inhomogeneity deflecting the light rays from their original direction appears in the device field, the image of the light source moves, changing the amount of screened by diaphragm light, and at the same time changing brightness of the observed screen or photographic plate. If different parts of the inhomogeneity deflect the rays at different angles, the slit image displacement is different for these parts. Therefore until the knife screens the image of the slit, each angle of deviation corresponds to a certain illumination of the screen. By measuring the absolute value of the illumination or its relative change, you can find the value of the deflection angle. This method of absolute photometry takes into account the shape and brightness distribution of the light source and the shape of the slit. It is also need to be calculated how changes in the screen illumination will correspond to every deflection angle of light rays [1].
Shadow diagnosis of the brightly glowing plasma is very difficult by the fact that for shadow images you need to use a brighter light source than the investigated plasma. For these purposes, such sources of light as a capillary discharge in argon, exploding wires, various flash lamp and pulsed lasers are used [2].

THEORY. To calculate the light path in the optical inhomogeneities a rectangular coordinate system was used and positioned so that the z axis is oriented along the probe radiation, y axis along the plasma flow axis of symmetry and the x axis is directed vertically upwards. 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 equation can be represented as [1, 2]:

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

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 of the instrument 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.
Colliding plasma flows belong to the class of inhomogeneities with axial symmetry, therefore, disregard the value of $\partial n/\partial y$ is justified by the fact that 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 [3, 4]:

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

The value of ε_x is experimentally measurable and is obtained from the results of photometric measurements of the shadow patterns of the colliding compressed plasma counter-flows 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 detecting part of the shadow device, ξ is width of the slit of the illuminating part of the shadow device and ε_x can be positive or negative.
For practical application of equation (2) Abel integral must be brought to the form solved for the derivative $\partial n/\partial r$. Multiplying equation (2) on $1/\sqrt{x^2-r^2}$ and integrating them over x^2, after simple transformations we obtain

$$\frac{1}{r}\frac{\partial n}{\partial r} = \frac{1}{\pi}\left[\frac{\dfrac{\varepsilon_x(R)}{R}}{\sqrt{R^2-r^2}} - \int_r^R \frac{\dfrac{\partial}{\partial x}\left(\dfrac{\varepsilon_x(x)}{x}\right)}{\sqrt{x^2-r^2}}dx\right], \tag{4}$$

where R is radius of the inhomogeneity section by the plane y = const.
Assuming that the light beam passing through the optical inhomogeneity is not deflected at the point $x = R$, equation (4) can be written as

$$\frac{1}{r}\frac{\partial n}{\partial r} = -\frac{1}{\pi}\int_r^R \frac{\dfrac{\partial}{\partial x}\left(\dfrac{\varepsilon_x(x)}{x}\right)}{\sqrt{x^2-r^2}}dx\,. \tag{5}$$

By re-integrating this equation we find

$$n(x) = n_0 - \frac{n_0}{\pi}\int_r^R \frac{\varepsilon_x(x)}{\sqrt{x^2-r^2}}dx\,, \tag{6}$$

where n_0 – refractive index of the undisturbed medium.
The density of free electrons in the plasma is determined from the relation [1]

$$n = 1 - \frac{\lambda^2 e^2 N_e}{2m_e c^2}\,, \tag{7}$$

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.

THE APPLICATION OF SHADOW METHOD FOR ELECTRON CONCENTRATION MEASUREMENTS IN COLLIDING FLOWS OF EROSION PLASMA

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 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 accelerator was 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 of the 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 was created the source of light based on a pulsed spark discharge in argon, 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. Shadow patterns were photographed with an exposure $\Delta t = 5$ μs.

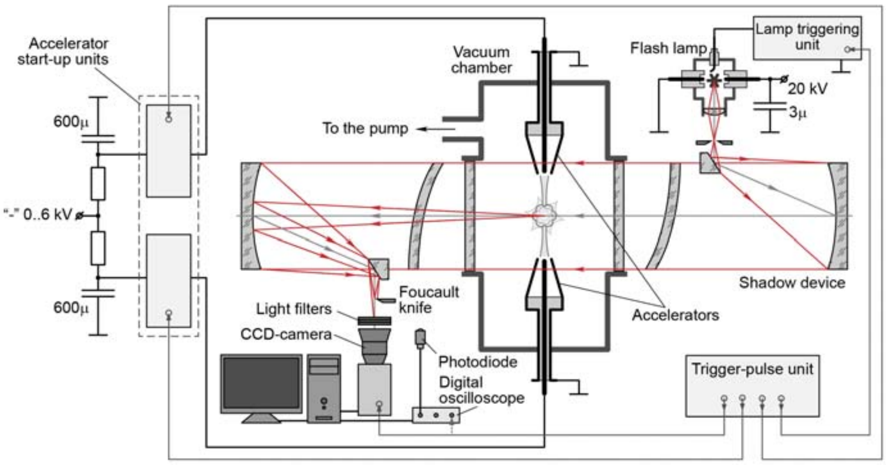


Fig. 1 Optical scheme of the experimental facility

In the illuminating part of the instrument 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 in the light source is close to its maximum (Fig. 2).

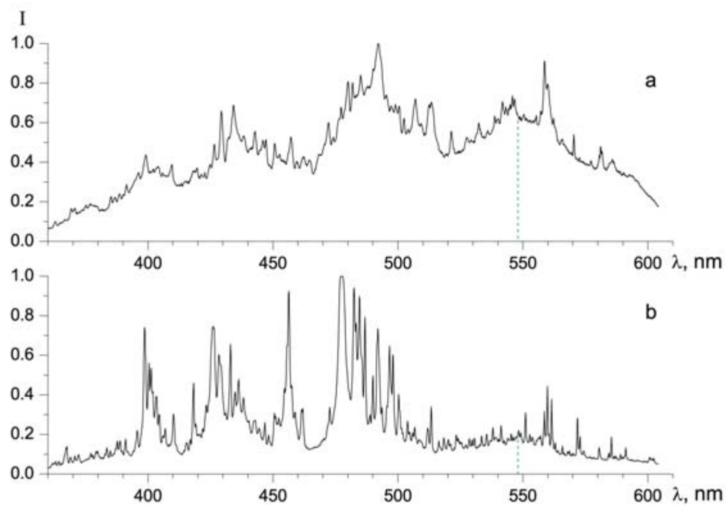
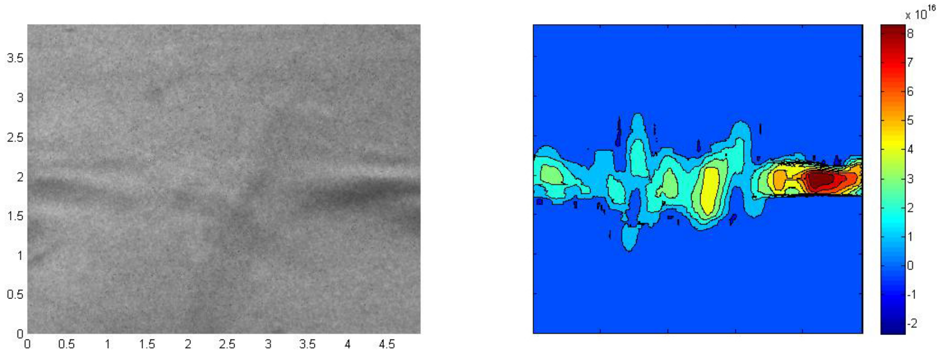
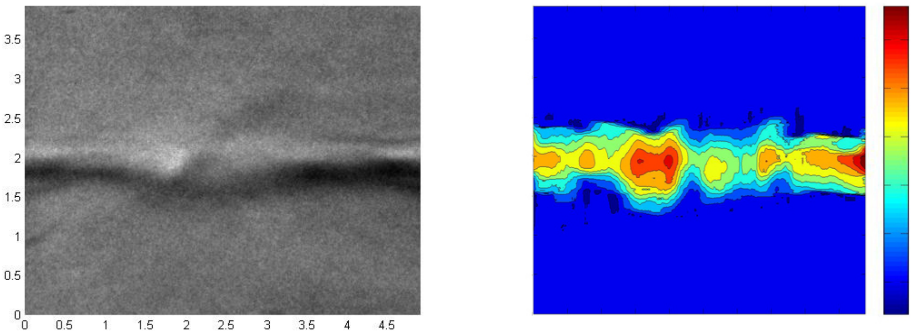


Fig. 2 The spectra of glowing: a) of light source argon plasma; b) of erosion plasma

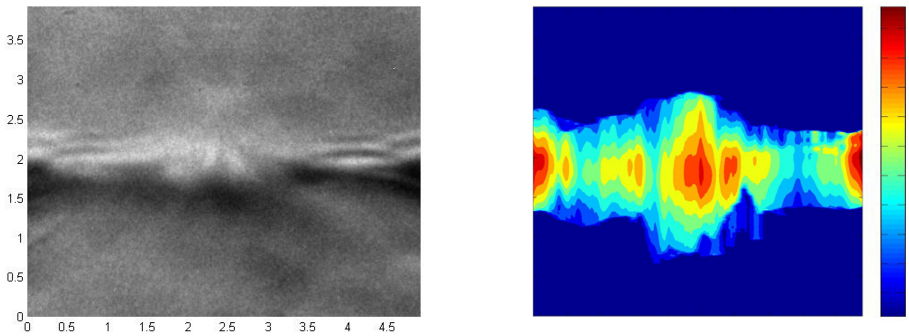
DISCUSSION. The interaction of plasma flows process was recorded by a digital speed camera PCO DICAM PRO with an exposure time 5 µs. The results of high-speed photography reproducing the dynamics of the plasma flows collision process are shown in Fig. 3. The time specified under the pictures is the time interval from accelerators start to beginning of exposure.



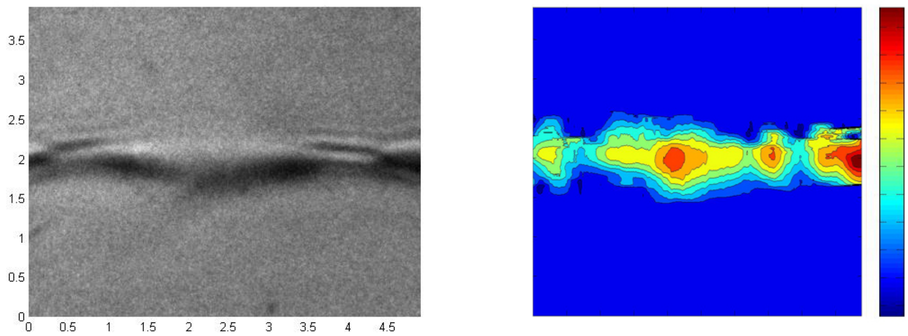
5 µs



10 µs



15 µs



20 µs

Fig. 3 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})

THE APPLICATION OF SHADOW METHOD FOR ELECTRON CONCENTRATION MEASUREMENTS IN COLLIDING FLOWS OF EROSION PLASMA

In the early stages of the forming of quasi-stationary plasma formations the determining factors are the processes of large-scale turbulence (Fig. 3 – 5 μs), then in the areas of plasma flows compression are observed the formation of localized regions with high free electron density (Fig. 3 – 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 $8.4 \cdot 10^{16}$ cm^{-3} for the investigated process forms (Fig. 3 – 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 [2, 5].

References

1. Vasilyev L.A. *Shadow methods*. Nauka, Moscow, 1968
2. Huddlestone R., Leonard S. (Ed.) *Plasma diagnostic techniques*. Mir, Moscow, 1967
3. Skotnikov M.M. *Qualitative shadow methods in gas dynamics*. Nauka, Moscow, 1976
4. Doroshko M., Penyazkov O., Rankin G., Khramtsov P. and Shikh I. *Talbot effect-based technique study of two-dimensional turbulent flow past a horizontal cylinder*. Heat and Mass Transfer, Minsk, 2005, pp. 210–214
5. Penyazkov O.G, Khramtsov P.P., Hryshchanka U.M. *Erosion plasma counter-flows interaction dynamics in a confined area. Alushta-2010. International Conference-School on Plasma Physics and Controlled Fusion. Book of Abstracts,* Alushta (Crimea), Ukraine, September 13-18, 2010