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Experimental Research of Dynamics and Macrostructure of Light Erosion Radiative Plasmodynamic Discharges

A Pavlov, Y Protasov, V Telekh, T Tshepanuk

Bauman Moscow State Technical University, Moscow, 105005, Russia

E-mail: stcpe@bmstu.ru

Abstract. The investigations of dynamics and macrostructure (spatial and temporal distributions of charged particles) of optic-plasmadynamic discharges with light erosion mechanism of plasma formation and generation of accelerated gas–plasma flows of various chemical composition in the wide range of dynamic and energy & power characteristics are presented. The plasma was heated as a result of the thermalization due to shock interaction of high kinetic energy plasma flows with a gas medium, which works as a stopping barrier for such discharges. It was shown that the deceleration of the radially inhomogeneous flow at a deformable gas barrier has an essentially two-dimensional nature: a complex system of conical shock wave forms in a hypersonic plasma flow.

1. Introduction

High current light erosion optic-plasmadynamic discharges (OPDD) are produced due to light erosion mechanism (generation, heating and acceleration of irradiating plasma jets) in which electromagnetic energy is converted to kinetic energy of a quasi stationary irradiating gas–plasma flow. Those are discharges with extremely high specific heat input ($W/S \sim 10^{11}$–10^{13} W/m^2, $Wt_{1/2} > 10^5$–10^7 J, W – power, $t_{1/2}$ – the discharge current half-cycle, S – the area of the midsection to cut electrodes [1], [2]).

Studies of OPDD are stimulated by the prospects of their use as high power and manufacturable sources of UV and VUV spectra for lithographic processes [3], [4], as well as shock wave (SW) and radiating plasma flow generators [1], [5]–[8]. These devices can be used for modeling of thermophysical and optical-plasmadynamic processes in high density radiation plasma flows–matter interactions [9]–[11] (for example, for dry surface cleaning in flat panel displays and printed circuit boards manufacture), in the surface plasma metallurgy for structural surface modification of construction materials exposed to compression plasma flows [12], [13], and also for plasma chemistry applications such as implementation of special conditions for photochemical reactions [9]. One of the fastest growing areas of research in recent years at the interface of physics and medicine is active particles and radicals impact on biological objects (molecules, cells, tissues), for the formation of which gas discharge plasma VUV-radiation is used [9], [11], [14].

Effective radiation plasma dynamic sources requirements are [5]: 1) the light erosion mechanism of radiating gas discharge plasma generation and the shock-wave mechanism of heating; 2) the effective conclusion of photon energy from an emitting area; 3) a technological method of energy accumulation and input.

One possible solution to this problem is an erosion type magneto-plasma compressor (MPC) [15] as a highly efficient generator of the accelerated gas–plasma flow in which the kinetic energy may be converted in different ways into heat energy of shock-compressed plasma, which is accompanied by generation of high-brightness radiation. Structurally, the MPC consists of shaped coaxial electrodes separated by a dielectric sleeve. The plasma-forming substances are products of electrodes erosion and dielectric sleeve ablation. The plasma acceleration is carried out under the action of pondermotive forces arising from the interaction of the discharge current radial component with the azimuthal component of its own magnetic field. The plasma acceleration is accompanied by plasma flow electromagnetic cumulation along the system axis, its own magnetic field of the discharge confines plasma flow in the MHD-compression zone.

The results of the dynamics and macrostructure of optical-plasmadynamic discharges in gases are summarized. In these discharges, the plasma heating is effected by thermalization of the kinetic energy of plasma flows, when the shock wave interaction with a gas medium acts as a barrier.

2. Experimental setup

The radiating plasmadynamic discharges created in the erosive type impulse electromagnetic plasma accelerator with coaxial and edge geometry electrodes (diameter 6 and 20 mm) and an ablative PTFE plasma-forming sleeve were researched (*I*) (fig. 1). The gas discharge chamber (*II*) was pumped before each discharge up to the pressure $p_0 \leq 1$ Pa and filled with gas (Ne, Xe, Ag, air) up to the pressure $p_{g0}=2\cdot10^3–10^5$ Pa. The capacitor storage device (*22*) (7.05 kJ, 28 kV) charged up to the voltage of 15–25 kV was switched with accelerator electrodes of a controlled discharger (*21*), the discharge was periodic with damping (7–9 half-cycles of current); full energy deposition into the discharge was ~ 70% of the stored energy, of which 40% is enclosed in the first half-cycle of the discharge current, current maximum was $I_{\max}$ ~ 350–850 кA and duration of half-cycle ~ 3.1–9.6 μs. The polarity of electrodes was selected according to the recommendations [15]: if the central electrode during the first half-cycle had negative polarity, then threshold conditions of plasma focus formation considerably decrease, the main discharge characteristics – working media coefficient of use, degree of flow compression, etc. improve, and the discharge light output increases.

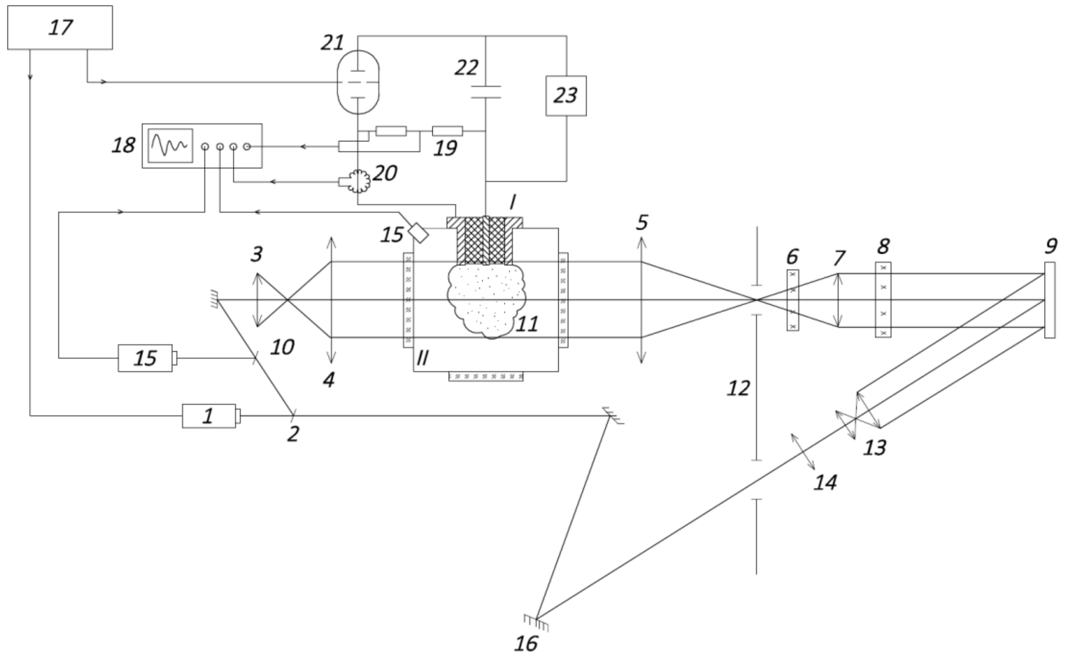

Figure 1. Experimental setup scheme: 1 – laser; 2, 10 – beam splitters; 3, 4, 5, 7, 14 – lenses; 6 – wedge; 8 – optical filter; 9 – screen; 11 – phase object; 12 – pinhole; 13 – beam expander; 15 – photoelements; 16 – mirrors; 17 – pulse generator; 18 – oscilloscope; 19 – voltage divider; 20 – Rogovski coil; 21 – discharger; 22 – capacitor store; 23 – power supply.

Measurements of a discharge current were carried out by Rogovski coil (*20*), working in the current transformer mode. According to current oscillograms (the discharge half-cycle, the relation of the current maximum values in the first and second half-cycles), complete inductivity of a circuit $L \approx 100$ nH and its pure resistance $R \approx 0.03$ Ohm are defined. The maximum value of current in the first half-cycle when the capacitor charging to U=20 kV made $I_{\max} \approx 250$ kA. Estimates of the pure resistance of discharge and its inductivity gives: $R_D \approx 0.02$ Ohm, $L_D \approx 15$ nH.

Laser plasma diagnostics was performed using the light field mode of Toepler's schlieren scheme and two-frame holographic interferometry. Single impulses of Nd:YAG laser radiation (*1*) were formed by giving a sequence of synchropulses from a pulse generator (*17*) from the discharge ignition (*21*) and with the required delay (0–15 μs) on the laser electro-optical shutter. The moment of laser operation in relation to the discharge current was controlled by an oscilloscope (*18*) to which channel signals came: from Rogovski coil (*20*), from a voltage divider (*19*), from photoelements (*15*) registering a laser impulse and discharge radiation.

The parallel beam of probe radiation created by the telescope from microlens *3* and lens *4* and had an aperture ~ 150–190 mm. After passing through phase inhomogeneity *11* it was focused by lens *5* (fig. 1) with focal length of 0.75 m on the pinhole with a diameter of 1.8 mm in the screen *12*. Own discharge emission is cut off by the filter (*8*). For obtaining schlieren images mirror *2* was opaque and for interferometry – beam-splitting; in the latter case, the registered screen *9*, besides the object beam, got the reference beam passing through the mirror *16*, which equalized optical path. The telescope *13* and the lens *14* are designed to match the laser radiation spatial structure of both interferometer paths.

The spatial resolution of the laser diagnostic setup was specified by the resolution of the optical system (~50 μm), and temporary one bythe laser pulse duration (~ 50 ns). Minimum detectable by schlieren-images integral concentration gradient for electrons was 10^{18} cm^{-4}, for Ne atoms – $2*10^{19}$ cm^{-4}. For interferometry – the measurement range of quasistationary (in relation to changes during the exposure) electronic concentration distributions N_e have been limited from below by registered shift of periods, and from above by imposing of periods and made for $\int N_e dx$ about $10^{17} – 2*10^{20}$ cm^{-2}. For N_e distributions which are quickly changing in time (for example because of the plasma forming movement or the advanced turbulence), the interference pattern disappeared exceeding $(\partial \int N_e dx) dt$ at the level 10^{25} cm^{-2}s^{-1} (because of bands shift during registration). Visible and near UV light pulses were detected by photoelements.

3. Experimental results

At interaction of the accelerated plasma flow with a gaseous medium, the complex shock wave structure is registered in these experiments. The dynamics of the discharge development can be observed in a series of the schlieren images (fig. 2) and interferograms (fig. 3) for discharge in neon with initial pressure 28.7 and 73.3 kPa. Electron density spatio-temporal distribution (fig.3 d–f) in discharge is received by interferograms treatment (fig.3 a–c).

The zone, characteristic for the plasmadynamic discharges, of the increased density and temperature (MGD-compression zone) is formed before a central accelerator electrode after a gas pushing off; that demonstrates the strong focusing of a flow internal part in an interelectrode interval. Around this zone at different density and chemical composition of gas the conical shock front is registered, and the smaller base of the truncated cone surface is based on the edge of the central electrode (as, apparently, shock wave (SW) formation in this case is due to the interaction of highly focused plasma flow with the edge of the accelerator central electrode). Before the accelerator end faces another conical shock wave converted by the cone big base to the accelerator end is observed (fig. 2 e, f). Narrowing and widening conical shock waves are also observed behind the line of the intersection of these two gas dynamic discontinuities, which, for their part, are reflected by axial flow and the external border of the plasma formation. The originating system of gas dynamic discontinuities reminds the structures which are formed in case of the hyperacoustic expansion in the flooded space of a gas dynamic nozzle [16], but there is no perfect analogy here.

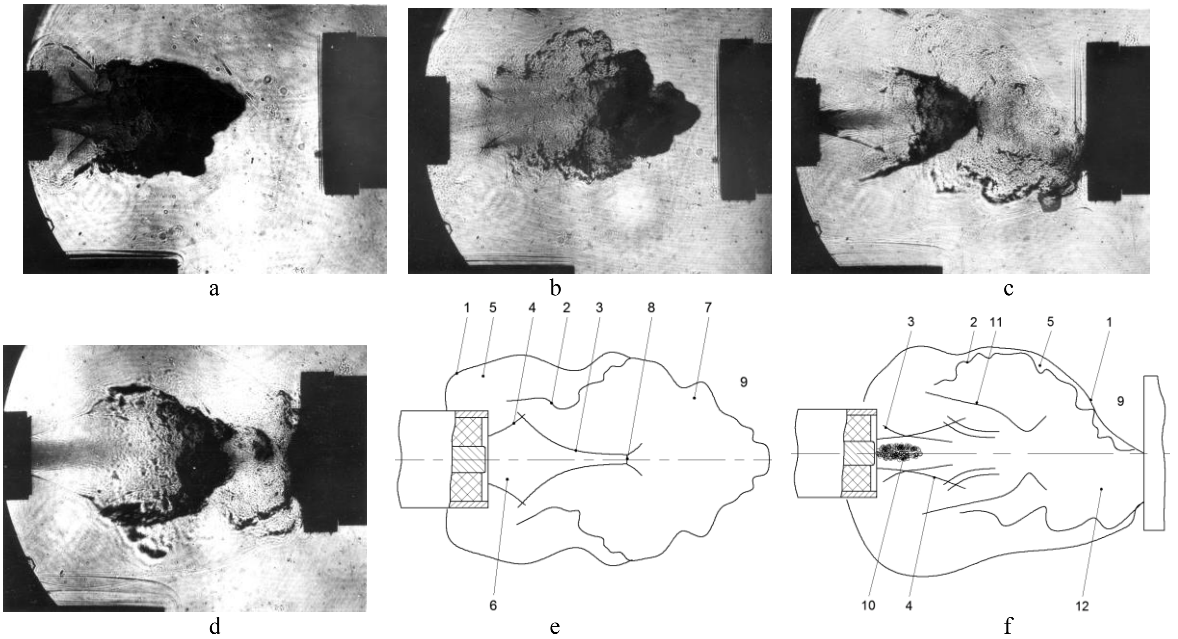

Figure 2. Schlieren photos (a – 3.7, b – 4.2, c – 6.2, d – 7.4 μs) and discharge internal structure (e – 4.2, f – 6.2 μs): 1 – shock wave in gas; 2 – plasma–gas interface; 3 – conical shock wave; 4 – focus shock wave; 5 – impact compressed gas; 6 – erosion plasma flow; 7 – plasma and gas turbulent mixing zone; 8 – Mach's disk; 9 – undisturbed gas; 10 – focus zone; 11 – first and second half-cycles plasma mixing zone and shock front; 12 – first half-cycle collapsing plasma; Ne, P = 28.7 kPa.

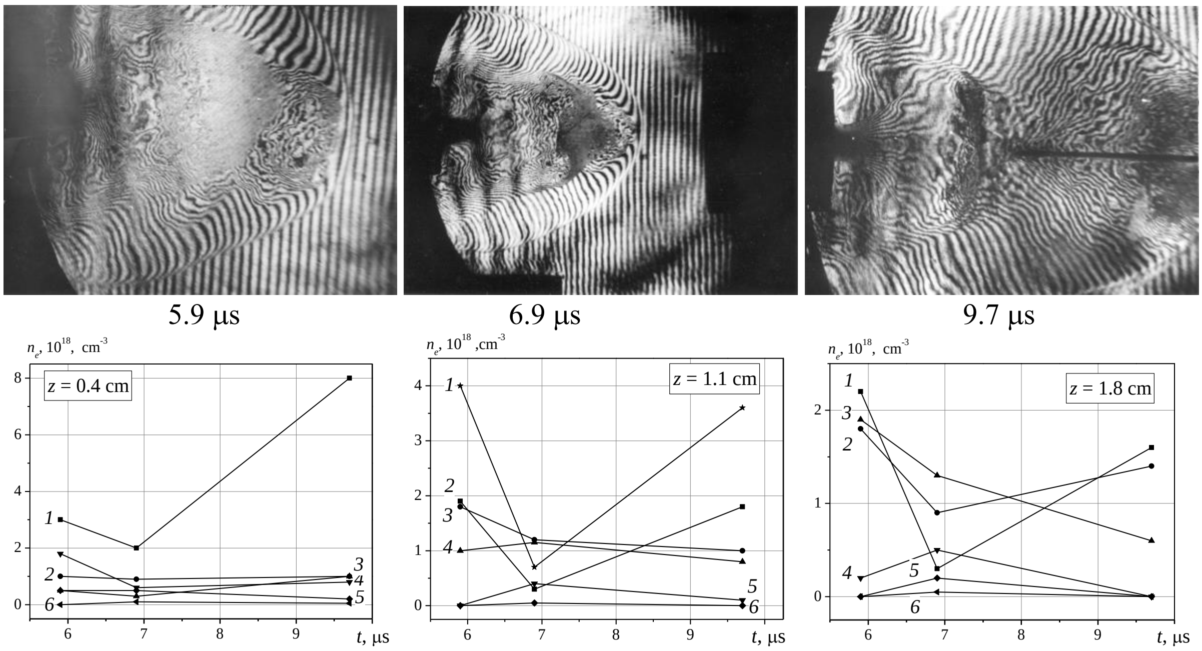

Figure 3. Interferograms (a – 5.9, d – 6.9, c – 9.7 μs) and electron density spatio-temporal distribution in discharge obtained by interferograms treatment (radial sections numbers: 1 – r = 0 cm; 2 – 0.5; 3 – 1.0; 4 – 1.5; 5 – 2.0; 6 – 2.5; z is flow axis); Ne, P = 73.15 kPa.

There is thermalization of a part of plasma elementary volume kinetic energy when passing each shock wave; as a result, in the researched discharge (in comparison with vacuum plasmadynamic discharges [15]) the compression efficiency on the axis significantly increases, characteristic values of flows speed decrease to ~ 30–35 km/s, the radiating capability and plasma temperature grows to ~ 3–6 eV. Gas is affected by light erosion plasma total pressure equal to a gas dynamic flow pressure that will be approved with representation of the plasma piston [17], [18]. The luminescence area consists of some radiating zones located in all plasma structures. In the SW head part the non-uniformly emitting front is watched, which is possible due to non-uniformity of spatio-temporal discharge formation at initial stage and development further of hydrodynamic instabilities. Let us note that the speed of the emitting front, as well as all current macrostructure, weakly depends on a gas sort if initial densities match and is generally specified by initial power and accelerator configuration.

The registered conic gas dynamic discontinuities in plasma at the discharge evolution move up and down the flow and change the slope relative to the axis that cannot be explained only with the movement of a deformable gas barrier. So, at the end of each current half-cycle the first of the specified shock waves departs further from a compression zone, increasing the slope relative to the axis, the second shock wave, on the contrary, moves towards the axis, etc.; such movement of gas dynamic discontinuities is connected with non-stationary character of plasma flows.

Besides, additional complication of interaction pattern is entered by the light erosion plasma forming inertia leading to mismatch between a blow-in of erosive weight and of input energy power deposition in discharge; this strongly influences parameters of flows and shock-compressed plasma [5], [19]. Light radiation from discharge plasma arrives on erosive dielectric and electrodes and during a pause of a discharge current when an electromagnetic acceleration is absent. As a result, during this time in front of the accelerator the light erosion vapors are collected, and the plasma flow of the following half-cycle should punch formed “cork”, forcing out vapors to an axis and from the accelerator. The shock wave structure which is formed before the accelerator central electrode at the beginning of the discharge second, third, etc. half-cycles (fig. 2 c, d, 3 f – c) confirms it.

Thus, due to non-stationary character of a power input during the discharge the radiating zones arise and move, therefore the total radiation impulse has the complex time dependence which does not repeat generally the dynamics of a power input. Such flow structure is unstable in relation to turbulization – in the schlieren images (fig. 2 a – d) intensive turbulization in the discharge head part during the first half-cycle is observed. That is accompanied by the perturbation appearance (the size of 0.1–0.5 cm) on the shock wave front propagating in the unperturbed gas. One more type of non-uniformity is observed near contact border plasma–gas. It is a “cellular” structure with a cells size about 0.3–0.5 cm. Observed plasma turbulization significantly affects the spectral–energy characteristics of the OPDD.

Two zones, as it has been established during the studies of spatio-temporal structure, define the discharge light output: a plasma focus zone and plasma–gas shock wave interaction zone. In the acceleration of SW ($\rho_{ro}<10^5$ g/cm^3) during the discharge initial stage (τ < T/8) intensity of plasma focus zone radiation considerably exceeds the brightness of a shock braking zone. Further there is an alignment of radiation intensity from both zones. With transition to the braking mode ($\rho_{ro} > 2{\cdot}10^5$ g/cm^3) braking shock wave intensity increases and intensity of this zone luminescence is compared to radiation from the plasma focus zone, and at the subsequent moments considerably exceeds it. With gas density growth, the increase in MGD-compression zone radiation intensity is observed, this is related to an intensification of shock wave processes at discharge plasma radial expansion and with photoionization strengtheningleading to reradiation from VUV to more long-wave range.

4. Conclusion

The results of experimental investigation of dynamics and macrostructure (spatial and temporal distributions of charged particles) of a new class of optical-plasmadynamic discharges with light erosion mechanism of plasma formation and accelerated gas–plasma flows generation, with high specific characteristics of a power contribution, in the wide range of dynamic characteristics are presented. The structure of these discharges is investigated using laser diagnostics with high spatial and temporal resolution. The complex system of conical shock waves in hypersonic plasma flow is found. Kinetic energy thermalization has multistage character because of essential not onedimensionality of accelerated plasma flow with gas interaction. This considerably changes the luminescence body shape and radiating plasma parameters and thus significantly influences discharge light efficiency. The investigated discharges are of interest as sources of powerful short-wave radiation, shock waves and dense multiply ionized plasma.

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