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STUDIES AND CHARACTERIZATION OF QUASI-STATIONARY COMPRESSION PLASMA FLOWS GENERATED BY GAS-DISCHARGE AND EROSIVE PLASMA ACCELERATORS

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Abstract. The results of investigations on compression plasma flows generated by gas-discharge magnetoplasma compressors and erosive plasmadynamic systems are presented. Electron temperature and plasma concentration in such quasi-stationary plasma accelerators (plasma guns) both were measured with spatio-temporal resolution. The characterization of quasi-stationary plasma flows was conducted using the dynamic coefficients specifically introduced. These coefficients were calculated based on the temporal evolution of the electron density and temperature in plasma obtained in these experiments.

1. INTRODUCTION

One of the major scientific and practical problems in plasma physics is development of methods for obtaining high-energy directional dense plasma streams including compression plasma streams, and controlling their parameters. Such plasma streams open up essentially new opportunities for fundamental research into dynamics of plasma formations in electromagnetic fields of the complex configuration. In addition, they are of interest owing to application of such plasma flows in various technological processes (processing and hardening of surfaces, deposition of coatings, etc.).

Earlier we investigated physical processes in gas-discharge quasi-stationary plasmadynamic systems operating at different input energy (for example, magnetoplasma compressor (MPC) with storage energy up to 30 kJ and quasi-stationary high-current plasma accelerator (QHPA) such as P-50M), capable to generate compression plasma flows (CPFs) [1-4]. Such accelerators are placed in the vacuum chambers as their operations demand working gases to be fed into the discharge devices. Besides, for the first time we have received compression erosive plasma flows, generated by specially designed erosive plasmadynamic systems operating in the air at atmospheric pressure [5]. Only a material of an inner electrode determines the composition of compression erosive plasma flows.

In the present paper, the results of spectroscopic investigations of both the gas-discharge MPC of compact geometry, and the erosive plasmadynamic systems are presented. These investigations made it possible to calculate dynamic coefficients suggested in [4-5] that show a degree of "stationarity" of the basic thermodynamic parameters of compression flows in studied plasmas accelerators.

2. EXPERIMENTAL SETUP

The gas-discharge compression plasma flows were obtained using a MPC of compact geometry powered with a capacitive storage (C_0 = 1200 μF) operating at initial voltages, U_0, from 3 up to 5 kV [6-9]. The MPC discharge device (Fig. 1) with an outer electrode 5 cm in diameter and 12 cm in length is mounted in a vacuum chamber measuring 30 x 30 x 150 cm. The discharge device of MPC-CG employing hydrogen as plasma-forming substance operates with pulse system of gas feed.

The discharge duration in the MPC is up to 100 μs and the peak value of discharge current, depending on initial parameters of discharges, ranges from 70 to 120 kA (Fig. 2).

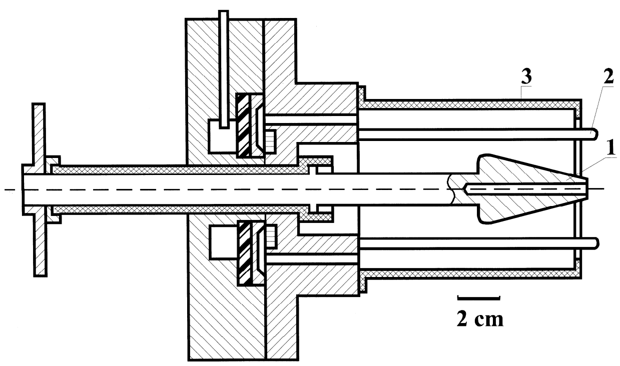

Fig. 1. Scheme of MPC discharge device: 1 - cathode, 2 - anode rods, 3 - cover.

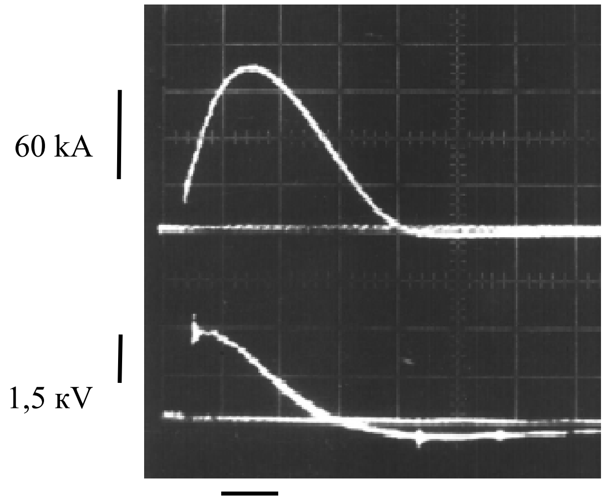

Fig. 2. Oscillogram of the discharge current and voltage in MPC-CG. Bar size is 25 μs.

Under these conditions, a CPF 6-10 cm long and 0.7-1 cm in diameter forms at the outlet of the MPC discharge device (Fig. 3). The CPF retains stability for about 80 μs; thereafter it starts diverging in a half-angle of 5 to 15^o. The plasma velocity in compression flow varies in the range of (4–8)·10^6 cm/s, depending on the MPC initial parameters.

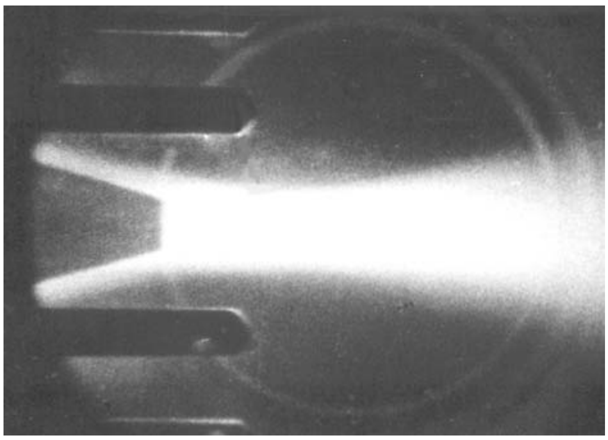

Fig. 3. Photograph of CPF: exposure time 2 μs.

The schematic of the discharge device of the erosive system intended to generate CPFs in ambient air is shown in Fig. 4 [5]. The outer electrode of the discharge device is sectionalized (made of a set of rods). The energy storage ($W_0 \sim$ 15 kJ, C_0 = 1500 μF) is sectionalized as well, each section of the capacitor bank being connected to an inner electrode and to one of rods (sections) of an outer electrode. Thus, the whole battery is involved in the formation of the plasma flow from the inner electrode, whereas only one section of the battery is involved in the formation of a plasma jet from each of the rods of the outer electrode. Such a discharge system generates four current-carrying plasma jets (1 per each of 4 rods comprising the outer electrode), and the stable main compression erosive plasma stream from the inner electrode (Fig. 5).

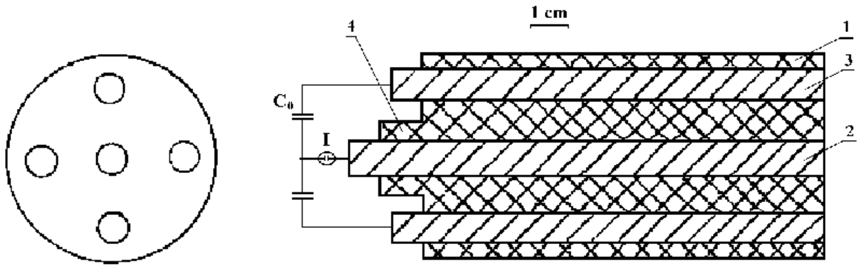

Fig. 4. Diagram of the discharge device of the erosive system: 1 - insulator-body, 2 - inner electrode, 3 - roads of outer electrode; I - ignitron, C_0 - energy storage.

The main compression plasma stream and the outer plasma jets are compressed due to the interaction of their currents with azimuth self-magnetic field. Since currents in the compression stream and in the outer jets flow in the opposite directions, the electrodynamic interaction between them causes these jets to repulse from a compression stream due to which the erosion products of the outer electrode do not get in the main stream. In addition, by the same reason the resulting magnetic field maximum of currents of the plasmadynamic system should be located in an area between the compression stream and the outer plasma jets, which not only influences positively the flow macro stability, but also results in the effect of magnetic self-isolation of a separating dielectric of the discharge system.

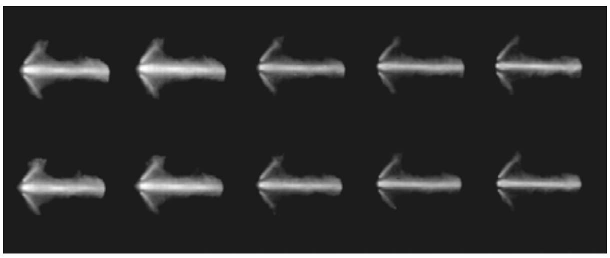

Fig. 5. Photograph of compression erosive plasma flow.

Formation of the erosive compression plasma stream comes to an end ~ 25 μs from the beginning of the discharge current. From this time, the compression stream of 1-2 cm in diameter and ~ 15 cm long becomes macro stabile, and a material of the inner electrode governs its composition, as spectroscopic studies show. High stability of the erosive plasma stream along with its small divergence, as well as rather great the flow length/diameter ratio indicate the compressive character of the plasma flux. Shown in Fig. 6 are typical oscilloscope traces of the discharge current and voltage in the erosive system.

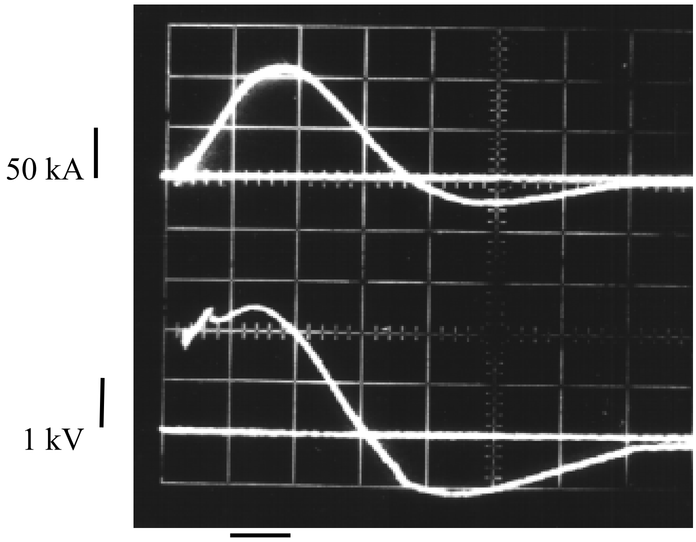

Fig. 6. Oscillogram of the discharge current and voltage in the erosive system at U_0 = 5 kV. Bar size is 25 μs.

3. STUDIES OF GAS-DISCHARGE MPC

Spectroscopic studies of the compression plasma flow in MPC of compact geometry were carried out with the use of a spectrograph ISP-30 combined with spectrochronograph SP-452. The image of the cross section of a compression flow 3 cm apart from an edge of the inner electrode was projected at the spectrograph slit. The plasma emission spectra in 300-700 nm wavelength ranges show continuous radiation, lines of atomic hydrogen and the most intense (resonant) lines of atoms of elements comprising a material of electrodes. When decreasing a mass flow of working gas, the line intensities of the electrodes material, as well as the number of lines is increasing.

The electron concentration N_e in the compression plasma flow was determined via the line H_β broadening caused by the linear Stark effect. The N_e definition relative error in the method under experimental conditions achieves 30%

due to the presence of continuous radiation. The temporal dependence of electron concentration in the CPF is shown in Fig. 7. It should be noted that the N_e values shown in Fig. 7 are averaged along the line of sight, as well as over the exposure time, defined by the spectrochronograph shutter (~ 10 μs).

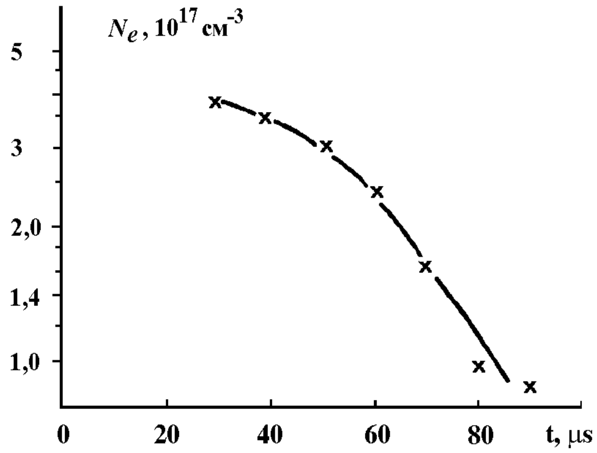

Fig. 7. Temporal dependence of electron concentration in the CPF of MPC.

Electron temperature T_e in the plasma flow was determined from the relative intensities of H_β and H_γ lines only for a time interval from 35 to 40 μs. At the 10 g/sec mass flow rate of hydrogen and the peak discharge current of 80 кA, the electron temperature in a compression flow 3 cm apart from an edge of the cathode makes (25-30)·10^3 K.

4. THE STUDIES OF EROSIVE PLASMADYNAMIC SYSTEM

Spectroscopic examinations of compression erosive plasma flows were carried out with the aid of a VFU-1 high-speed camera operating in a mode of a cinespectrograph due to a spectral attachment based on a diffraction grating. Frames of emission spectrum of erosive plasma flows are shown in Fig 8a.

The electron concentration in the plasma flow was determined by method based on broadening of spectral lines of the copper caused by quadratic Stark effect. Chosen for this purpose was the autoionisation copper line Cu I with λ = 458,7 nanometers since it has a high value of lower level, and its self-absorption is low. Lines selected for processing featured clearly observable asymmetrical contours which can only be attributed to Stark broadening alone (neither Doppler, nor natural broadening result in contour asymmetry). Doppler broadening of CuI line (458,7) at T = 15·10^3 K was as small as 0,05 A^0, while the instrumental one - 1 A^0 (the value of instrumental broadening was accepted equal to the half-width of the narrowest line in a stepwise spectrum of iron), so they were taken into consideration by a simple subtraction of their values from a half-width of a line specified. Due to the presence of continuum and a considerable value of the natural broadening of the autoionization Cu line caused by the spreading of the autoionization level, the relative error in definition of the electron concentration is great enough and makes ~ 50 %. The temporal dependence of electron concentration N_e of a compression erosive plasma flow in a cross-section ~9 cm apart from the edge of the discharge device is shown in Fig. 8b.

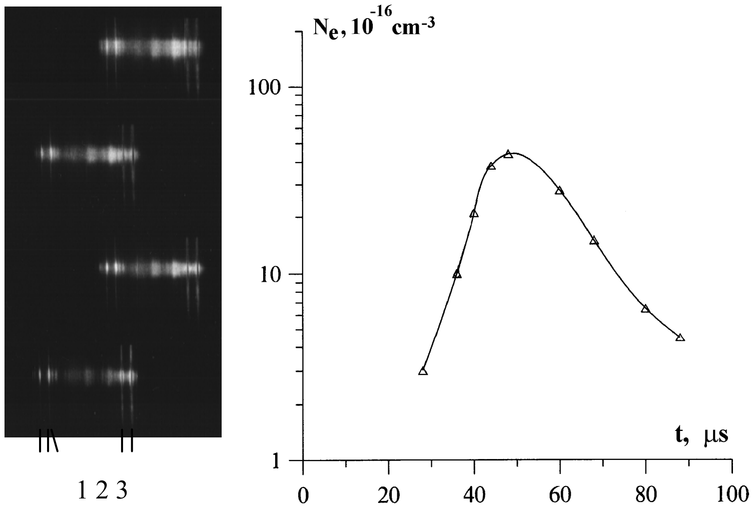

Fig. 8. Frames of emission spectrum of erosive plasma flows (left): 1 - line Cu II 456 nm, 2 - line Cu I 459 nm, 3 - line Cu I 465 nm, 4 - line Cu I 515 nm, 5 - line Cu I 522 nm. Temporal dependence of electron concentration (right).

Spectroscopic investigations have shown that the compression erosive plasma flow demonstrates large opacities. Under these conditions, a reliable method of determination of plasma temperature is the method of photoelectric recording of radiation [5]. Using this method it was possible to determine the spectral density of energy emission (SDEE) of radiation b_λ of a compression flow and its spectral absorption constants α_λ.

Knowing b_λ and α_λ, from Kirchhoff law and Plank formulas for a black body one may to find the true plasma temperature:

$$T = \frac{hc}{\lambda k \cdot ln(\dfrac{2hc^2\alpha_\lambda}{\lambda^5 b_\lambda})}.$$

Experiments on recording plasma radiation of a compression erosive flow and definition of its spectral absorption constants were carried out as shows a drawing in fig. 9. Radiation was recorded by calibrated photodiodes FD-5G combined with sets of optical filters, which were cutting out spectral ranges of 465 - 555 and 745 - 1120 nm.

The self-exposure to radiation of plasma was provided with the flat mirror 4 mounted behind a beam-splitting plate 3. Plasma radiation of a compression flow was selected with two rectangular diaphragms the size 1×10 cm, inserted in each measuring channel. One of photodiodes (7) recorded a radiation flow *(Φ_s)* of explored source, whereas the second one (8) – a radiation of the source plus the radiation that was reflected from a mirror and passed through plasma (total flow Φ_Σ). Photodiodes were placed at equal distances (~ 1,5 m) from the emitting source. Such an arrangement of photodiodes, taking into account linear dimensions of the source, made it possible to consider it point source.

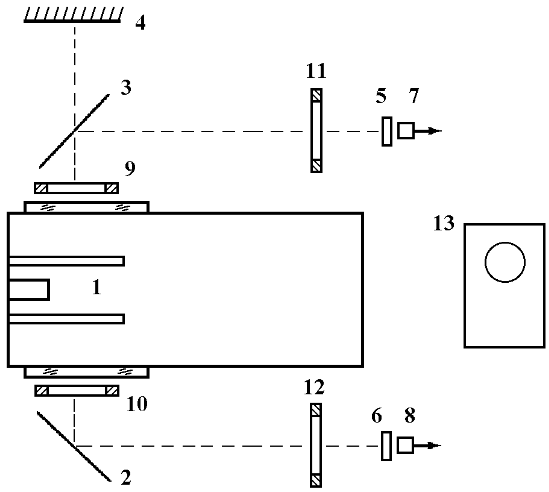

Fig. 9. Block diagram of experiments on recording plasma radiation: 1 - discharge device; 2,3 - beam-splitting plate; 4 - flat mirror; 5,6 - optical filters; 7,8 - photodiode; 9-12 - diaphragm; 13 - oscillograph.

In experiment conditions, radiation flow through plasma is:

$$\Phi_{trans} = I_s \Omega_{reff} (1-\rho_3)^2 \rho_4 (1-\alpha_\lambda) = \Phi_s \frac{\Omega_{ref}}{\Omega_s} (1-\rho_3)^2 \rho_4 (1-\alpha_\lambda),$$

where I_s - radiant intensity of the source; α_λ - a spectral absorption constant of plasma; Ω_{ref} - a spatial angle in which the photodiode 8 records the emission reflected from the mirror 4; Ω_s - a spatial angle in which the photodiode 7 records the emission of the source; ρ_3 - reflectivity of a beam-splitting plate 3, and ρ_4 - reflectivity of the mirror 4.

Let's write down the expression for the total emission flow recorded by the photodiode 8:

$$\Phi_\Sigma = \Phi_s + \Phi_{trans} = \Phi_s[1 + \frac{\Omega_{ref}}{\Omega_s}(1-\rho_3)^2 \rho_4 (1-\alpha_\lambda)],$$

from which it is easy to find α_λ:

$$\alpha_\lambda = 1 - \frac{\Omega_{reff}}{\Omega_s}(\frac{\Phi_\Sigma}{\Phi_s} - 1)\frac{1}{(1-\rho_3)^2 \rho_4}.$$

Shown in Fig. 10 are the time variations of spectral absorption constants α_λ, for spectral intervals of 465-555 and 745-1120 nm.

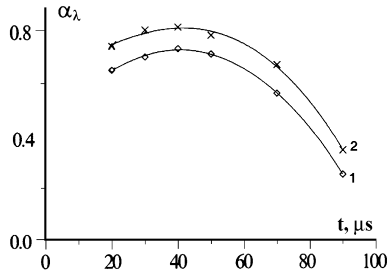

Fig. 10. Time variations of spectral absorption constants α_λ, at U_0 = 5 kV for spectral intervals: 1) 465-555 nm; 2) 745-1120 nm

As already noted, to calculate plasma temperature it is necessary to know also spectral density of energy emission b_λ of a compression flow. It can be calculated, if one knows spectral density of radiant energy E_λ of a plasma flow which is determined by integration on time of a signal from the photodiode recording radiant power P_λ.. For this purpose, the mirror in Fig. 9 was removed, and in front of photodiodes, the optical filters that were cutting out different spectral ranges were placed.

Values of plasma temperature in both of these spectral intervals within the limits of experimental error were identical, which proves the reliability of results obtained. Time dependence of plasma temperature of a compression erosive flow is shown in Fig. 11.

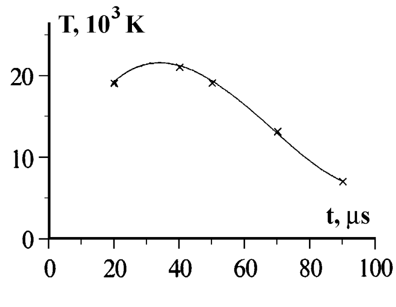

Fig. 11. Time dependence of plasma temperature of a compression erosive flow at U_0 = 5 kV.

5. DISCUSSION

To gain an idea of how the behaviour of the basic thermodynamic parameters, N_e and T_{pl}, corresponds with a discharge current (i.e. to estimate a degree of "stationarities" of these parameters), let us calculate for them the dynamic coefficients $\eta(t)$, suggested in [4,5]. For the electron concentration of $\eta_N(t)= N_e(t)/ I_d(t)$, and for temperature – $\eta_T(t) = T_{пл}(t) / I_d(t)$.

Calculated data $\eta_N(t)$ for a compression flow generated by discharge MPC-CG, are shown in Fig. 12. As may be seen, $\eta_N(t)$ at a steady-state stage of a compression flow (from ~ 30 μs) is essentially invariable. This means that the electron concentration tracks a discharge current, i.e. the compression plasma flow is quasi-stationary.

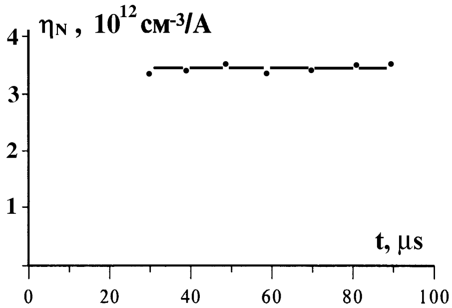

Fig. 12. η for compression plasma flow of MPC-CG.

Results of calculations $\eta(t)$ for erosive plasmadynamic system are shown in Fig. 13. One can see that for the most part of a quasi-stationary stage of discharge $\eta_N(t)$ and $\eta_T(t)$ are practically constant, i.e. N_e and T_{pl} for this time interval "follow" a discharge current. At the beginning of discharge $\eta_N(t)$ decreases, i.e. N_e rises more slowly, than I_d, which may be associated with a delay in ejecting the working substance (erosion of electrodes) relative to a discharge current.

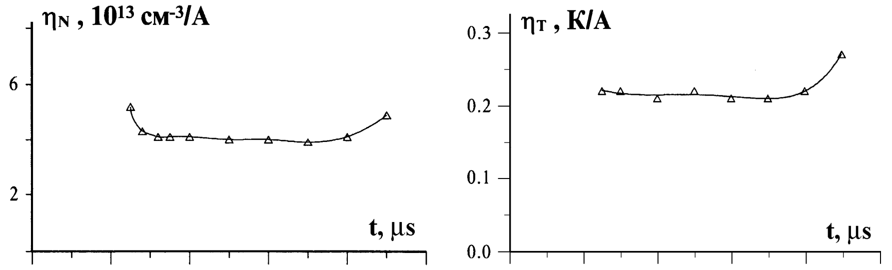

Fig. 13. η for erosive plasmadynamic system: η_N (left); η_T (right).

Comparatively small increase in both η_N *(t)* and η_T *(t)* at the end of the discharge which implies that velocity and temperature of plasma at this time decay more slowly than a discharge current, may be explained by certain inertia of process of a plasma flow collapse (relative to a discharge current).
Thus, as the studies show, a compression plasma flow at a stage of the steady existence is quasi-stationary (i.e. its key parameters "follow" a discharge current) both in the gas-discharge MPC-CG and in erosive plasmadynamic system.

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