PULSE ELECTROTHERMAL PLASMA ACCELERATORS AND ITS APPLICATION IN SCIENTIFIC RESEARCHES

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This paper presents the pulse electrothermal plasma accelerator erosion type. Formation of dense plasma bunches occurs under atmospheric pressure through the development of high-current arc discharge in a cylindrical channel bounded by dielectric walls. Mode of operation accelerator is hydrodynamic. It is demonstrated the possibility use it to obtain microsecond high-current electron beams without vacuum conditions, the synthesis of nanoscale materials, the excitation of elastic pulses in the fluid.

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INTRODUCTION

Concentrated plasma flows and powerful plasma bunches with high energy characteristics are widely used in scientific research and modern high technology. They are required for filling by the plasma of thermonuclear traps, the implementation of collective methods charged particles acceleration, for creating powerful sources of optical radiation, modification of surface properties of materials, for the operation plasma-chemical reactors, generating elastic pulses in continuous media. To solve these problems, there is a need in the formation and transporting plasma bunches with energy from tens of kJ to MJ and above. In this connection the heightened interest represent the pulsed plasma sources. At present there are many generators and pulsed plasma accelerators, whose operation is based on different physical principles and effects [1 - 9]. But the whole their combination can be divided into two groups: the vacuum and sources operating at atmospheric pressure. To solve a number of problems are necessary one, and in some cases it is advisable use the other. It is for this reason there is no need to consider the advantage of the plasma source of one group compared to another. It all depends on the task, i.e. needs and those and others. This paper investigates a pulse electrothermal plasma accelerator (ETPA) operating at atmospheric conditions, which can be used as a multifunction device for solving a number of scientific and technological problems. It is this type of plasma accelerator has recently caused increased interest, as among physicists and engineers.

1. PULSED ELECTROTHERMAL PLASMA ACCELERATOR

1.1. MATHEMATICAL MODEL

ETPA or plasma end erosional accelerator was first time mentioned in literature in [10]. The principle of action is based on the of pulse electric energy liberation high power in a channel bounded by cylindrical dielectric walls. The substance in the discharge channel comes at the expense of electrode erosion and evaporation of the wall material. Expiration plasma flow occurs from the nozzle in the form of hole disposed in one end of an accelerator. To this category of the accelerators also includes the plasma accelerators operating on the basis of a high-current capillary discharge with an evaporating wall [11 - 13].

When describing the operation ETPA it is important to know how the energy is redistributed in the discharge channel between the internal energy of the plasma, the work of expansion, by radiation, etc. This task is not trivial and has no universal solution. S.I. Braginskii known model [14] allows to obtain an analytical solution for a variety of gasdynamic parameters in a linear increase of the current. However, in [15] was proposed a simple model, as the author claims, allowing to calculate impact loads at arbitrary parameters of the discharge-chamber and an electrical circuit. It is this model is the most appropriate in the description of the ETPA.

To describe the processes for development (channel) stage of electric discharge in a one-dimensional radially symmetric formulation in this work the author proposed a system of equations gas dynamics in Euler variables that has the following form:

$$\frac{\partial \rho}{\partial t}+v\frac{\partial \rho}{\partial r}+\rho\frac{\partial (rv)}{r\partial r}=0, \quad (1)$$

$$\rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}\right)+\frac{\partial p}{\partial r}=0, \quad (2)$$

$$\frac{\partial}{\partial t}\left(\rho\varepsilon+\frac{\rho v^2}{2}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left[r\rho v\left(\varepsilon+\frac{p}{\rho}+\frac{v^2}{2}\right)\right]+ +\frac{1}{r}\frac{\partial (rq)}{\partial r}=\frac{j^2}{\sigma}. \quad (3)$$

Here ρ – density t – time, v – velocity, r – Euler coordinate (radius), p – pressure, ε– specific internal energy, q – heat flux at the expense of thermal conductivity, j – current density in the channel, σ – the plasma electrical conductivity. Integrating equation (3), over the cross section of the channel, the ordinary differential equation is obtained for total plasma energy W, per unit length of channel:

$$\frac{dW}{dt}+p\frac{d\left(\pi a^2\right)}{dt}=Q_j,$$

where a – the radius of the plasma channel, I – current, $Q_j=\sigma I^2\left(\pi a^2\right)^{-1}$ – total Joule energy contribution (per unit length). All interested gasdynamic parameters can be found by further solving the remaining equations.

1.2. DESCRIPTION AND OPERATION

This paper describes the accelerator, construction of which is shown in Fig. 1 at the top, and circuit diagram is shown below in the same figure.

The body 1 is made of a rigid thick-walled paper bakelite tube length 40 cm. Inner diameter – 8 mm, wall thickness of 1 cm. The edges of the dielectric housing are pressed by metal cups of 3 and 4. To glass 3 by a threaded connection attached removable rod electrode 2 with 6 mm in diameter, acting as cathode. Removable rod electrode 2 with 6 mm in diameter is attached to the glass 3 by a threaded connection acting as cathode. One end of the electrode enters in the internal channel of housing a second deduced outwards. The anode is a metal cup 4 with a hole 5 and 6 mm in diameter. The distance between the cathode and the annular anode was regulated in the range of 8 to 15 cm. Anode 4 is grounded and voltage is applied to rod cathode from the capacitive energy storage unit. Any metals may be used as the material of the cathode rod. Working pressure is atmospheric, working gas is air. The cathode is designated by the letter *A* and an anode – *B* on Fig. 1 below.

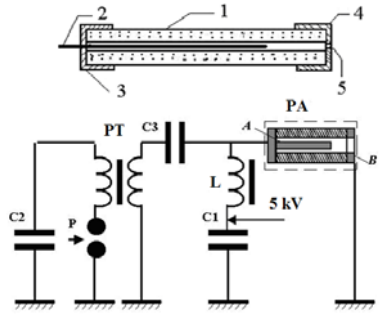

Fig. 1. Electrothermal plasma accelerator at the top and electric power scheme – down

Electrical block diagram of the plasma accelerator consists of a capacitive energy storage unit and trigger circuit. Capacitive storage C1 = (1.5…3.0) · 10^{-3} F operating voltage up to 5 kV, the maximum accumulated energy ranged (18.75…37) kJ. Triggering circuit includes elements the capacitor C2, controllable discharger P and pulse transformer PT. The trigger is an important element in the pulsed-power devices. In this connection the magnetic key containing a ferromagnetic core with a rectangular hysteresis loop is suggested for switching high-current pulse circuits. Its function is to prevent the passage of high-voltage trigger pulse in high-current circuit capacitive storage. This key greatly exceeds the known manageable three-electrode dischargers on operational characteristics. A detailed description of the element bases the whole scheme and obtained current-voltage characteristics is given in [16, 17].

As a result, the capacitive storage charging and exposure to the trigger pulse between the cathode and the anode was initiated by intense pulsed arc discharge of high pressure, limited dielectric narrow channel. The pressure in the channel increases up to hundreds of atmospheres during discharge. Thus there is a pulse injection of a dense gas-plasma bunch through the annular anode into the environment. The operating mode of the plasma accelerator is gas-dynamic. Under the received estimates plasma parameters are: the temperature 1…2 eV and density of about 10^{16} cm^{-3}, respectively. The discharge is accompanied by an intense glow and sound effects. Fig. 2 shows the photograph of a plasmoid obtained using violet filter. The length of the glowing formation reaches 0.8 m.

The gas plasma bunch expiration into the environment occurs through the annular anode. Expiration takes place in the adiabatic regime at supersonic speed. This is confirmed by the formation of consolidations which can be seen in the photo, and direct measurement of the velocity using optical sensors. Fig. 3 shows the typical wave-forms of the current and voltage applied to the accelerator electrodes of the A and B and the time dependence of the resistance discharge channel. Discharge duration was 1.4 ms, the maximum current up to 4 kA. Their processing allows us to estimate the energy released in the discharge gap.

Fig. 2. Photo of the plasma bunch

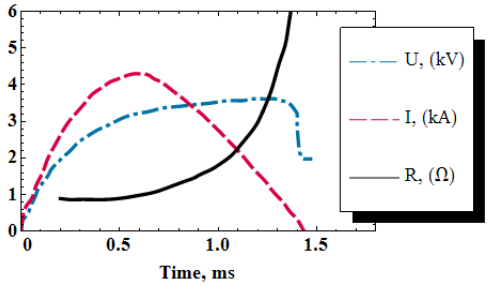

Fig. 3. Typical waveforms of the discharge current, voltage and the time dependence of the resistance discharge

2. FORMATION OF HIGH-CURRENT ELECTRON BEAM WITHOUT VACUUM CONDITIONS

Formation of the accelerated electrons with nanosecond pulse in the discharge of high pressure is a phenomenon known [18 - 20]. Acceleration is due to the effect of runaway electrons [21, 22]. This section presents the research results of formation the high-current microsecond electron beam in the channel of the arc discharge ETPA. The acceleration of the electrons was under the influence of an additional high-voltage pulse generated by means of a two-stage Marx generator (MG). MG is not shown in Fig. 1. The voltage amplitude was of 250 kV with pulse duration of 5 ms at the base. Pulse shape was bell curve. The impulse expiration of dense plasma bunch into the environment through the annular electrode ***B*** occurs as a result the development of high-current discharge and pressure increase to hundreds of atmospheres. This is followed by a rarefaction wave, and the pressure at the end of a pulse is lowered to a value significantly below atmospheric (1…5 Torr can reach). This is evidenced by the presence of residual stress in the waveform Fig. 3. That is electric strength of the gap is restored. This is also confirmed by the time dependence of the resistance the discharge channel, which is represented in Fig. 3. Consequently, the operating point on the Paschen curve is

shifted to left branch, which corresponds to the region rarefaction. At this time the negative accelerating voltage pulse was applied to electrode A (see Fig. 1), which was generated by MG. Under these conditions the current in the discharge circuit, the voltage applied to the electrodes, the X-ray and microwave radiation from the discharge channel were detected. The results of these measurements are shown in waveforms of the Fig. 4. The nature of the current and voltage (waveforms ***a*** and ***b***), and the presence of X-ray and microwave radiation (waveforms ***c*** and ***d***), indicate the presence of accelerated electrons in the channel of ETPA.

Let us give estimates, confirming possibility of occurrence of accelerated electrons in the experimental conditions. For non-relativistic electron runaway phenomenon will occur if brake force is less than the electrostatic force caused by the action of an external electric field. Braking force in this case is due to ionization losses and is described by known Bethe – Bloch formula:

$$F(\varepsilon) = -\frac{n_0 e^4 Z}{8\pi\varepsilon_0^2} \ln\frac{2\varepsilon}{I}, \qquad (4)$$

where e is the electron charge, ε is its kinetic energy; n_0 is a concentration of gas molecules; Z is atomic number; I is average energy for inelastic losses; ε_0 is the electric constant. Acceleration occurs (runaway electrons) if the value of the critical field above $\boldsymbol{E_c}$ is determined by expression:

$$E_c = \frac{e^3 n_0 Z}{4\pi\varepsilon_0^2 \cdot 2.72 \cdot I}. \qquad (5)$$

As follows from [20], the relation (5) is transformed into formula convenient for practical estimates:

$$\frac{E_c}{P} = 3.88 \cdot 10^3 \frac{Z}{I}, \qquad (6)$$

where E_c / P and I is measured in V/cm·Torr and eV, respectively. Air I can be taken equal to 15…80 eV.

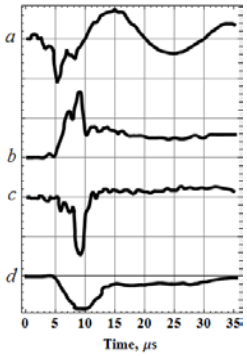

Fig. 4. a – the current in the discharge circuit MG; b – the accelerating voltage; c – the X-rays; d – detected microwave signal in the wavelength range 10…3 cm. The sensitivity of the rays: current – 1 kA / div, voltage – 125 kV / div

Estimate of the magnitude ratio E_c / P of according to the formula (6) allows us to conclude the possible existence of the effect of runaway electrons in the experimental conditions. These estimates are given in [23].

In such a way as a result of studying it is demonstrated the possibility of obtaining a microsecond high-current electron beam in a channel arc pulsed plasma accelerator without vacuum conditions.

3. PRODUCTION OF METALLIC NANOSTRUCTURES

Currently, there are various formation methods dielectric, semiconductor and metal nanoparticles and nanostructures [24, 25]. Known technologies are divided into two main groups: top-down and bottom-up. The first group is based on obtaining nanoparticles from macroscopic objects, the second group – for synthesizing nanoparticles by a merger of individual atoms and molecules.

The gas-phase synthesis method of nanoparticles (bottom-up) is the simplest and most promising for practical applications in which the evaporation of metal, alloy or semiconductor occurs followed by condensation of steam. For example, this is the easiest way to obtain powders nanocrystals, nanoparticles and isolated clusters.

Equipment using the principle of evaporation and condensation differ in input method the evaporated material, method for supplying energy to evaporate, the working environment, etc. Electrothermal heating method substance for the synthesis of nanoparticles is used in [26, 27]. However, in the above devices synthesized nanomaterials are scattered on the solid angle almost equal to 4π. But ETPA allows to form the directional flow substance that substantially increases its manufacturability for use in as nanophysics and in plasma technologies. Furthermore, the temperature of the metal vapor sharply decreases and its rapid condensation occurs in the plasma jet as a result of turbulent mixing. In [28] it was demonstrated the possibility of synthesis of nanoscale materials using ETPA and presents photographs obtained nanostructures of different materials. However, in these systems formation mechanism nanostructures remains is unexplained: formation of nanoparticles is due to condensation of supersaturated vapor electrode material or at the expense splashing of the dripping liquid metal?

Chemical analysis of their composition was carried out to determine the mechanism of formation the nanoparticles in thermal systems. For this purpose X-ray fluorescence analysis was used. Studies have been performed by Thermo Scientific ARL OPTIM'X WDXRF Spectrometer. The X-ray spectra of nanostructures on glass substrates and spectra of the electrode material were analyzed. As a result, it was possible to compare the elemental composition of the starting material with the composition of the synthesized nanostructures. Table 1 shows the results of this comparative analysis for bronze cathode. The table on the left (in bold) is given the elemental composition of the nanoparticles on the glass, and the right-chemical composition of bronze cathode. From this table it follows that the elements of Si, Ca, Na, Mg, etc., which are present in the list on the left and absent on the right, in the mass percentage terms composition is ≈ 81% and reflects the chemical composition of the glass.

Mass fraction of copper in bronze is 82 %, and in nanostructures accounts for only 5.56 %. But this number should be multiplied by the ratio of 100/19 ≈ 5.26, to get a true composition of the element in the bronze nanoparticles. Then we obtain magnitude of about 31%. This is significantly less than its content in bronze. Sim-

ilar regularity is observed for the other elements. Thus the percentage is different for the same elements of the cathode and synthesized nanostructures on substrates at substantially. It should be noted that elements such as Ge, Hg, Ta, Zn, W is not detected in the nanostructures. Similar regularity is typical of other alloys used as the cathode. This confirms the fact that the formation of nanostructures in this experiment is caused not the result of splashing of droplets of the parent metal, but exclusively due to the nonequilibrium condensation of supersaturated vapor metals. This experiment also confirms the fact that the ETPA can be effectively used as a reactor for the synthesis of nanoscale materials.

The elemental composition of nanostructures and the cathode material for bronze

El	m/m%	StdErr%		El	m/m%	StdErr%
Si	55,19000	0,25000		Cu	82,02000	0,20000
Ca	11,29000	0,16000		Al	12,17000	0,20000
Na	10,64000	0,15000		Mn	2,39000	0,08000
Al	6,30000	0,12000		S	0,60300	0,03800
Cu	5,56000	0,11000		Cl	0,51200	0,04100
Fe	4,27000	0,10000		Si	0,47100	0,04600
Mg	3,34000	0,09000		W	0,37300	0,02200
K	1,32000	0,06000		Fe	0,34600	0,01700
Ti	0,54700	0,02700		Ni	0,24500	0,01200
Px	0,48800	0,02400		Au	0,22100	0,02700
Sx	0,33200	0,01700		Zn	0,17600	0,00900
Mn	0,30700	0,01500		Ta	0,15000	0,07000
Ni	0,16700	0,00800		Ca	0,13900	0,01200
Cl	0,09970	0,00870		Hg	0,09600	0,01900
Cr	0,09470	0,00470		Cr	0,05350	0,00550
Zr	0,01640	0,00290		K	0,02280	0,00830
Ar	0,01470	0,00610		Ge	0,01390	0,00620
Rb	0,01250	0,00240			100,00220	
Sr	0,00580	0,00260				
	99,99480					

4. EXCITATION ELASTIC OSCILLATIONS IN THE FLUID BY PLASMOID

Powerful generators of elastic pulses are widely used for the intensification of technological processes occurring in the liquid phases, sensing and location of the world ocean, for deep sonic tool that provides search, identification and quantitative characteristics of minerals, as well as for enhanced recovery of hydrocarbons. To solve the above problems need to excite oscillations at frequencies of hundreds of hertz, and this requires the introduction to liquid high pulse energy. Therefore to excite oscillations are usually used generators operating on the basis of an electrical discharge in the liquid [29, 30].

Solid explosives are used less often. But to realize the electric discharge of high power in liquid requires a high energy release rate, which, as is known, leads to the appearance a shock wave. Energy contained in the shock wave is dissipated as heat at a negligible distance from the discharge. In the shock wave can be concentrated to 70 % of the energy input into the liquid [31, 32]. As is known, high-frequency harmonics dominated by in the spectrum of the shock wave. Furthermore, the shock wave leads to damage of structural elements emitter, to cavitation phenomena. In this mode of excitation of oscillations extends beyond linear acoustics. In this connection for the generation of acoustic fields of high power promising is the use of plasma bunches. Their difference and advantage compared with explosive sources of energy is that by using plasma bunches with sufficiently high power characteristics, can be controlled rate of energy input.

It is this fact avoids the shock wave.

Physical processes occurring during operation of pulse emitters acoustic vibrations in the fluid now fairly well understood and widely implemented. Generation mechanism in this case is as follows. Pulsed release of energy in the liquid shall form divergent the gas-vapor cavity, leading to a positive pressure pulse. After the cessation of energy expansion is due to the reserve of the internal energy cavity, and then - at the expense of the kinetic energy acquired liquid, which is accompanied by a negative pressure pulse. Expansion stops when the pressure in the cavity equal to the pressure of saturated water vapor ~ 2 kPa. From that moment the compression begins on, which is accompanied by another increase in pressure. In an environment thus there are waves of compression and rarefaction. The process of free pulsation spherical cavity (in an infinite medium) is described by Rayleigh equation, which in this case has the form:

$$2\pi\rho R^3\dot{R}^2 + \frac{4}{3}\pi P_0 R^3 = E\,, \qquad (7)$$

where R – the radius of the cavity, $\dot{R}$ – its first derivative with respect to time, P_0 – hydrostatic pressure, ρ – the density of the liquid, E – the energy in the cavity. The period pulsation cavity was determined by the known Willis formula

$$T = 1{,}14\rho^{\frac{1}{2}} E^{\frac{1}{3}} P_0^{-\frac{5}{6}}, \qquad (8)$$

at that, the maximum radius of the cavity $R_{\max}$ is connected with the input energy ratio

$$\frac{4}{3}\pi P_0 R_{\max}^3 = E\,. \qquad (9)$$

However, to maximize the acoustic parameters at low frequencies the nature of energy input into the liquid medium must satisfy several conflicting requirements. On the one hand for generating a low frequency $f \sim T^{-1} \sim E^{-1/3}$, as follows from (8), it is necessary to ensure the maximum possible input energy E with high bulk density, which is achieved by using a source developing high power. On the other – the high rate of energy release (burst) can lead to the formation of a shock wave.

To avoid a shock wave must comply with the conditions stated in [29]

$$\frac{E}{\rho c^5 \tau^3} < 1, \qquad (10)$$

that can be achieved by adjustment of rate energy supply.

Here τ – the time of release of energy that can be adjusted by the injection of plasma bunches in liquid, the c – velocity of sound.

In this connection a very promising for this purpose are the ETPA. In [33] the results of the first experiments are presented on the excitation of acoustic pulses in liquid by the plasma bunches.

In this case the lower part of the accelerator was immersed in a water tank, as shown in Fig. 5. The lower ring electrode – 3, was at ground potential, rod – 2, upper – with the working voltage of 5 kV, S – capacitive storage unit. Variable inductance $L = 0.3$ mHn was used in the discharge circuit to adjust the pulse width

and to prevent the passage of high-voltage pulse to the circuit capacitive storage S.

The discharge chamber of the accelerator is filled with air under atmospheric pressure. Dielectric strength of the air gap in the chamber was significantly higher operating voltage 5 kV, so a generator of high-voltage pulses with amplitude of up to 100 kV used to run the scheme. Electrical discharge in the channel of the accelerator was initiated up and developed in the air, and the plasma bunch formed by accelerator, was injected into the liquid.

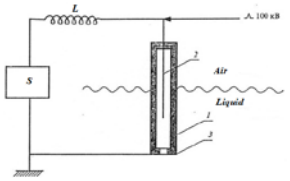

Fig. 5. The experimental scheme

The walls of the tank (pool) with dimensions 2×2×2 m were covered with thick foam rubber 10 cm to reduce the reflected signals. The pressure of the acoustic wave was measured with a calibrated sensor. The results of these measurements are shown in Fig. 6,a. Thus in the liquid the compression pulse with an amplitude of up to $2.6 \cdot 10^5$ Pa and duration of 0.8 ms and at the base is excited, and as shown from waveform, there is the small amplitude rarefaction pulse with negative pressure $2.5 \cdot 10^4$ Pa and duration of 0.4 ms.

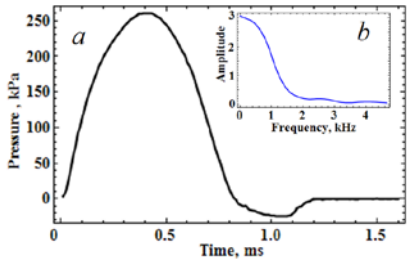

Fig. 6. The pressure profile (a) and spectrum (b) of the acoustic wave

These experiments showed that the speed control of energy release completely have excluded the formation shock waves and high-frequency harmonics

An important characteristic of the acoustic emitters is the spectral composition of the generated pulse. Fig. 6,b shows the spectrum reconstituted by Fourier transformation of the pressure pulse waveform.

As might be expected, most of the oscillation power is concentrated in the low-frequency of the spectrum up to 2000 Hz. It is this frequency range is an attractive for solution of the totality scientific and applied problems mentioned at the beginning of this section. Thus, the ETPA may be used for generating powerful acoustic pulse in the liquid.

CONCLUSIONS

The research resulted in can draw the following conclusions:

1. Pulsed electrothermal plasma accelerator erosion type allows obtaining concentrated supersonic plasma flows. Formation of the plasma bunch occurs at atmospheric pressure through the development of a high-current arc discharge in a cylindrical channel bounded by dielectric walls. This accelerator can be used as a multifunctional device for solving a number of scientific problems.

2. In particular, it is shown the possibility formation of a high-microsecond electron beam outside vacuum conditions. The beam is formed in the discharge channel of the accelerator as a result of additional impact high-voltage pulse. Acceleration is carried out at the expense the phenomenon of runaway electrons.

3. It is demonstrated the possibility of using the accelerator as a reactor for the synthesis of nanoscale materials; it is established the mechanism of their formation in electrothermal systems. Nanoparticle formation is due to nonequilibrium condensation of supersaturated vapor electrode materials.

4. For the first time it is shown the possibility of generation the powerful acoustic pulses by using the injection of dense plasma into the liquid. Speed control of energy input into the liquid allows avoids the shock and excites of elastic oscillations of high power in the mode of linear acoustics.

REFERENCES

1. I.E. Garkusha. High Current Plasma Accelerators: Physics and Applications // *Journal of Kharkiv National University. Physical series "Nuclei, Particles, Fields*". 2013, iss. 1, p. 28-39.
2. V.E. Fortov. *Encyclopedia of Low Temperature Plasma*. Vol. III. Moscow: "Nauka". 2000, 505 p.
3. I.A. Glebov, F.G. Rutberg. *Moschnye generatory plazmy*. Moscow: "Energoatomizdat". 1985, 153 p. (in Russian).
4. A.I. Morozov. *Fizika i primenenie plazmennyh uskoriteley*. Minsk: "Nauka i tehnika", 1974, 399 p. (in Russian).
5. Yu.E. Skvortsov. Impulsnye plazmennye uskoriteli bolshoy moschnosti // *Voprosy atomnoy nauki i tehniki. Series "Termoyadernyy sintez"*. 1983, v. 2, p. 12-25 (in Russian).
6. A.I. Morozov, L.S. Solov'yov. Stationary Plasma Streams in a Magnetic Field // *Voprosy Teorii Plazmy*. 1974, v. 8, p. 3-87 (in Russian).
7. V.I. Tereshin et al. Investigation of Powerful Quasi-stationary Coaxial Plasma Accelerators with Rod Electrodes / *Ionnye Inzhektory i Plasmennye Uskoriteli*. Moscow: "Energoatomizdat". 1989, p. 106-123 (in Russian).
8. A.Yu. Voloshko et al. Study of Two-stage Quasistationary Plasma Accelerator (QSPA) with Rod Electrodes // *Sov. J. Plasma Phys.* 1990, v. 16, p. 85-91.
9. N. Talukdar, T.K. Borthakur, N.K. Neog. Studies on X-ray and Neutron Emission from 2.2 kJ Plasma Focus Device // *Problems of Atomic Science and Technology*. 2013, № 1, p. 125-127.
10. L.Ya. Minko. *Poluchenie I issledovanie impulsnyh plazmennyh potokov*. Minsk: "Nauka i Tehnika". 1970, 235 p. (in Russian).
11. E.M. Golubev, A.M. Pukhov, V.L. Smirnov. Poluchenie i diagnostika nizkotemperaturnoy erozionnoy plazm vysokogo davleniya // *ZTF*. 1997, v. 67, № 4, p. 126-128.
12. M.N. Zharnikov, A.S. Kamrukov, I.V. Kozhevnikov, et al. Generatsiya krupno masshtabnyh izlu-

chayuschih vihrevyh struktur pri tormozhenii impulsnyh plazmennyh struy v vozduhe // *ZTF*. 2008, v. 78, № 5, p. 38-46 (in Russian).
13. A.Ya. Ender, V.I. Kuznetsov, I.N. Kolyshkin, et al. Features of Jets Formed by Erosive Capillary Discharges // *The Open Plasma Physics Journal*. 2011, v. 4, p. 40-54.
14. S.T. Braginsky. K teorii razvitiya kanala iskry // *ZETF*. 1958, v. 34, iss. 5, p. 1548-1557 (in Russian).
15. S.H. Kolgatin. Prostaya model dlya issledovaniya dinamiki razvitoy stadii bystroprotekayuschego elektricheskogo razryada v gaze I zhidkosti // *ZTF*. 1995, v. 65, № 7, p. 10-18 (in Russian).
16. Yu.E. Kolyada, V.I. Fedun, I.N. Onishchenko, E.A. Kornilov. The Use of a Magnetic Switch for Commutation of High-current Pulse Circuits // *Instruments and Experimental Techniques*. 2001, v. 44, № 2, p. 213-214.
17. V.I. Fedun, Yu.E. Kolyada, O.N. Bulanchuk. The Using Permalloy Core for the Switching of the Plasma Gun Electrical Circuit with a Capacitive Storage // *CPE-2007. 5th Intern. Conf.* Gdansk, Poland, 2007, ISBN:1-4244-1055-X. p. 1-4.
18. R.C. Noggle, E.P. Kuger, J.R. Wayland. A Search for X-rays from Helium and Air Discharges at Atmospheric Pressure // *J. Appl. Phys.* 1968, v. 39, № 10, p. 4746-4748.
19. Yu.A. Stankevich, N.A. Kalinin. Bystrye elektrony i rentgenovskoe izluchenie nachalnoy stadii razvitiya impulsnogo iskrovogo razryada v vozduhe // *DAN SSSR*. 1967, v. 177, № 1, p. 72-73 (in Russian).
20. L.V. Tarasova, L.N. Khudyakov, T.V. Loikaw, V.A. Zuckerman. Bystryee lektrony i rentgenovskoe izluchenie nanosekundnyh impulsnyh razryadov v gazah pri davleniyah 0.1…760 Torr // *ZTF*. 1974, v. 44, № 2, p. 564-568 (in Russian).
21. A.V. Gurevich. K teorii effekta ubegayuschih elektronov // *ZETF*. 1960, v. 39, № 5 (11), p. 1296-1301 (in Russian).
22. Yu.D. Korolev, G.A. Mesyats. *Fizika impulsnogo proboya gazov*. Moscow: "Nauka". 1991, 224 p. (in Russian).
23. Yu.E. Kolyada. Formirovanie impulsnyh silnotochnyh elektronnyh puchkov v nevakuumnyh usloviy // *Pisma v ZTF*. 2000, v. 26, № 16, p. 52-56 (in Russian).
24. V.V. Klimov. *Nanoplazmonika*. Moscow: "Fizmatlit", 2009, 480 p. (in Russian).
25. A.I. Gusev. *Nanomaterialy, Nanostructury, nanotehnologii*. Moscow: "Fizmatlit", 2009, 416 p. (in Russian)
26. I.E. Kareev, V.P. Bubnov, D.N. Fedutin. Elektrodugovoy vysokoproizvoditelnyy reaktor dlya sinteza sazhi s vysokim soderzhaniem endoedralnyh metallofullerenov // *ZTF*. 2009, v. 79, № 11, p. 134-137 (in Russian).
27. M.A. Sinaysky, A.V. Samokhin, S.A. Kornev, et al. Harakteristiki dispersnogo sostava nanoporoshkov, poluchaemyh v plazmennom reaktore s ogranichennym techeniem // *4th Vserossiyskaya konferentsiya po nanomaterialam*. Moskva. 01-04 March 2011. M.: IMET RAS, 2011, p. 126 (in Russian).
28. Yu.E. Kolyada, V.I. Fedun, et al. Formation Mechanism of the Metallic Nanostructures Using Pulsed Axial Electrothermal Plasma Accelerator // *Problems of Atomic Science and Technology. Section* "*Plasma Electronics and New Methods of Acceleration*". 2013, № 4, p. 297-300.
29. K.A. Naugolnykh, N.A. Roy. *Elektricheskie razryady v vode*. Moscow: "Nauka", 1971, 155 p. (in Russian)
30. V.V. Ivanov, I.S. Shvets, A.V. Ivanov. *Podvodnye iskrovye razryady*. Kiev: "Naukova Dumka", 1982, 192 p. (in Russian).
31. R.H. Cole. *Underwater explosions*. Princeton: Princeton Univ. Press., 1948, 437 p.
32. Yu.S. Yakovlev. *Gidrodinamika vzryva*. Leningrad: "Sudpromgiz", 1961, 320 p. (in Russian).
33. Yu.E. Kolyada. Generatsiya akusticheskih poley pri inzhektsii plotnyh plazmennyh sgustkov v zhidkost // *Dopovidi Natsionalnoï Akademii Nauk Ukrainu.* 1999, № 6, p. 91-95 (in Ukrainian).

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ИМПУЛЬСНЫЙ ЭЛЕКТРОТЕРМИЧЕСКИЙ ПЛАЗМЕННЫЙ УСКОРИТЕЛЬ И ЕГО ПРИМЕНЕНИЕ В НАУЧНЫХ ИССЛЕДОВАНИЯХ

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Описан импульсный электротермический плазменный ускоритель эрозионного типа. Формирование концентрированных плазменных сгустков происходит при атмосферном давлении за счёт развития сильноточного дугового разряда в цилиндрическом канале, ограниченном диэлектрическими стенками. Режим работы ускорителя гидродинамический. Продемонстрирована возможность его использования для получения микросекундных сильноточных электронных пучков вне вакуумных условий, синтеза наноразмерных материалов, возбуждения упругих импульсов в жидкости.

ІМПУЛЬСНИЙ ЕЛЕКТРОТЕРМІЧНИЙ ПЛАЗМОВИЙ ПРИСКОРЮВАЧ І ЙОГО ЗАСТОСУВАННЯ В НАУКОВИХ ДОСЛІДЖЕННЯХ

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Розглянуто імпульсний електротермічний прискорювач плазми ерозійного типу. Формування згустків щільної плазми відбувається при атмосферному тиску за рахунок реалізації потужнострумового дугового розряду в циліндричному каналі, обмеженому діелектричними стінками. Режим роботи прискорювача гідродинамічний. Продемонстрована можливість його використання для отримання мікросекундних сильнострумових електронних пучків поза вакуумних умов, синтезу наноматеріалів, збудження пружних імпульсів у рідині.