International Journal of Engineering, Mathematical and Physical Sciences
ISSN: 2517-9934
Vol:6, No:11, 2012

Energy Density Increasing in the Channel of Super-High Pressure Megaampere Discharge due to Resonance of Different Type Oscillations of the Channel

Ph. G. Rutberg, A. V. Budin, M. E. Pinchuk, A. A. Bogomaz, A. G. Leks, S. Yu. Losev, and A. A. Pozubenkov

Abstract**—**Discharges in hydrogen, ignited by wire explosion, with current amplitude up to 1.5 MA were investigated. Channel diameter oscillations were observed on the photostreaks. Voltage and current curves correlated with the photostreaks. At initial gas pressure of 5-35 MPa the oscillation period was proportional to square root of atomic number of the initiating wire material. These oscillations were associated with aligned magnetic and gas-kinetic pressures. At initial pressure of 80-160 MPa acoustic pressure fluctuations on the discharge chamber wall were increased up to 150 MPa and there were the growth of voltage fluctuations on the discharge gap up to 3 kV simultaneously with it. In some experiments it was observed abrupt increase in the oscillation amplitude, which can be caused by the resonance of the acoustic oscillations in discharge chamber volume and the oscillations connected with alignment of the gas-kinetic pressure and the magnetic pressure, as far as frequencies of these oscillations are close to each other in accordance with the estimates and the experimental data. Resonance of different type oscillations can produce energy density increasing in the discharge channel. Thus, the appropriate initial conditions in the experiment allow to increase the energy density in the discharge channel.

Keywords**—**High-current gas discharges, high pressure hydrogen, discharge channel oscillations.

M. E. Pinchuk is with the Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (corresponding author to provide phone: 303-555-5555; fax: 007-571-5056; e-mail: pinchme@mail.ru).

Ph. G. Rutberg, is head of with Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (e-mail: rc@iperas.nw.ru).

A. V. Budin is with the Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (e-mail: avbudin@mail.ru).

A. A. Bogomaz is with the Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (e-mail: rc@iperas.nw.ru).

A. G. Leks is with the Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (e-mail: avbudin@mail.ru).

S. Yu. Losev is with the Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (e-mail: losev.ieeras@mail.ru).

A. A. Pozubenkov is with the Institute for Electrophysics and Electric Power of Russian Academy of Sciences, St.-Petersburg, Russian Federation (e-mail: rc@iperas.nw.ru).

I. INTRODUCTION

ACHIEVEMENT of the greatest possible energy density in the channel of high-current discharge is being the topical scientific problem [1]. In particular, the increase in initial density at formation of pinch discharges allows to increase its radiative characteristics significantly. Producing of substance with extreme parameters represents the important physics task, actual for many critical technologies [2].

In suggested work the research results are presented for discharges in hydrogen at current amplitudes of 0.5-1.6 MA and the initial gas pressure up to 160 MPa, that corresponds to particles concentration before the discharge over 10^{22} cm^{-3}. During researches at initial gas pressure of 5-35 MPa the mode of the discharge channel contraction [3], [4], connected in our opinion with achievement of a critical current of radiative contraction (Pease - Braginsky's generalized current [5]) has been observed. At initial pressure up to 10 MPa registration of soft x-ray radiation (SXR) from the channel was made and it is established, that channel contraction is followed by SXR radiation [4]. Before the main contraction the fluctuations of intensity of SXR with frequency of 100-250 kHz were registered. In an optical range the fluctuations of channel diameter which correlated with fluctuations of voltage on an arch and pressure on a wall of the discharge chamber also were observed.

At the initial pressure of hydrogen of 80-160 MPA which are created by preliminary adiabatic compression of gas [6], the growth of amplitude of acoustic pressure fluctuations upon a wall of the discharge chamber (up to 150 MPA) and synchronous with it the growth of fluctuations of voltage drop on the discharge gap (up to 3 kV) are observed. These values in some times exceeds ones registered at initial pressure of 5-35 MPa.

The possible way of increase in the energy input in the arch channel, and increase in plasma specific energy is submitted below on the basis of analysis of the aforementioned phenomena.

II. Experimental Installations

Experiments were performed on two electrodischarge installations, theirs detailed description is presented in [6], [7]. The electrode system have axisymmetric geometry, the distance between electrodes could vary from 0.5 cm up to 5.0 cm. The central electrode insulated from the chamber's housing serves as the cathode, and the chamber casing plays the role of the anode. Steel, copper and tungsten have been used as the electrode material. Arc ignition is performed by wire explosion. At the initial instant the wire joins the cathode with the anode. The time length of the first half-period of the discharge current is 70-150 µs and current rise rate is 10^{10}-10^{11} A/s. The energy input in arc achieved 0.5 MJ. The energy source is the capacitive battery [8]. More detailed description of the experiments and diagnostic methods can be found in [3], [4].

III. Experiment Results and Discussions

A. Discharge at initial gas pressure of 5-35 MPa

Evolution of the discharge channel is accompanied by fluctuations of its diameter (Fig. 1 and 2). The correlation analysis shows a direct connection between the fluctuations of the channel diameter determined on photostreaks and peculiarities on the curves of voltage and current.

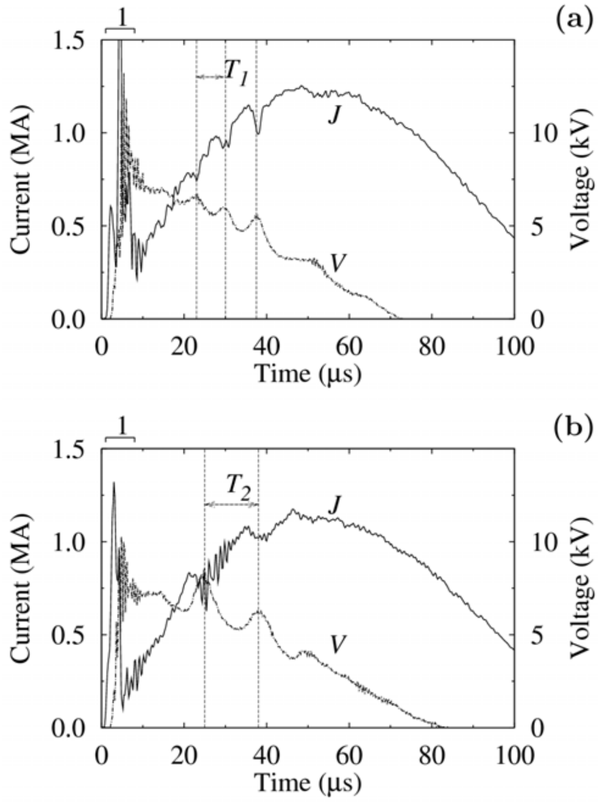

Fig. 1 Current J and voltage V for discharge in hydrogen at P_0 of 7 MPa: (a) steel electrodes and copper igniting wire; (b) tungsten electrodes and tungsten igniting wire; 1 - wire explosion stage. Input energy into arc is ~300 kJ. Interelectrode gap is 16 mm

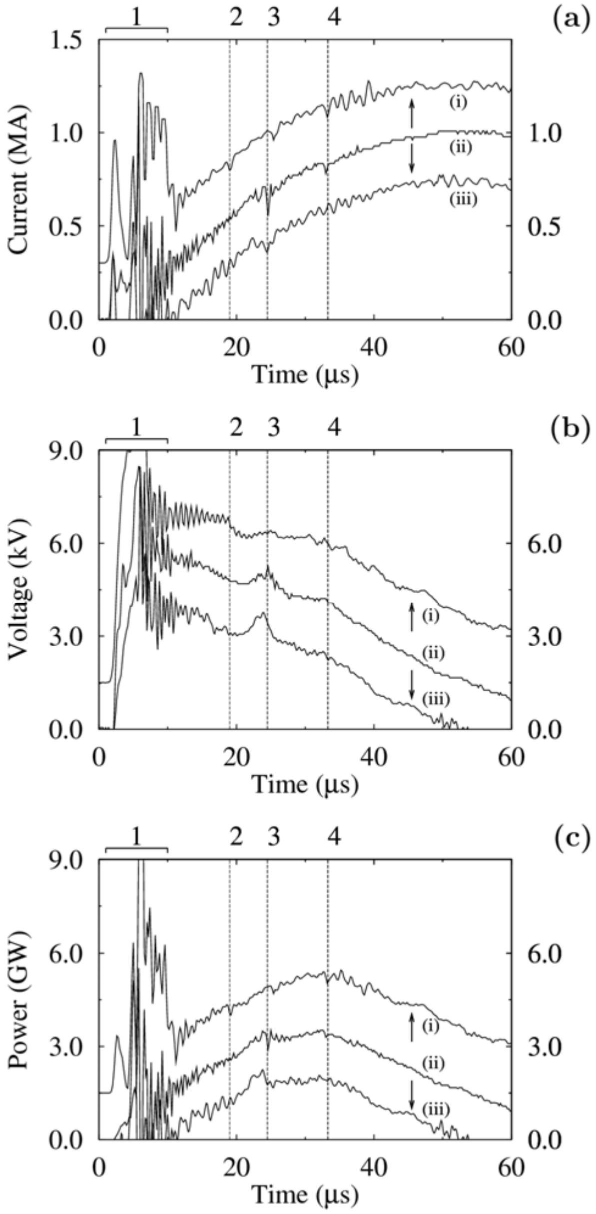

Fig. 2 Discharges in hydrogen at P_0 of 7 MPa for steel electrodes and copper igniting wire: (a) – current curve, (b) – voltage, and (c) – power; (i) discharge chamber diameter is of 63 mm; (ii) Ø 55 mm; (iii) Ø 43 mm; 1 - wire explosion and current pause stage; 2,3,4 - time instants of more characteristic feature on curves; Curves of (i), (ii) and (iii) are very close, but curves (i) and (iii) are shifted for visual clearness. Input energy into arc is ~150 kJ. Interelectrode gap is 10 mm

Peak on the voltage curve corresponds to instant of channel contraction. Before and after the basic contraction the fluctuations of intensity of arc x-ray radiation with frequency of 100-250 kHz were registered, which correlated with fluctuations of channel diameter, current, voltage and pressure on a wall of the discharge chamber. The observed interrelation of diagnostic signals allows to use curves of current, voltage, soft x-ray radiation and pulse pressure for the analysis of behavior of channel diameter in absentia of photostreaks and other direct optical measurements.

Fluctuations of the channel diameter in the concerned range of initial gas pressure, in our opinion, are connected to alignment of gaskinetic and magnetic pressure in the discharge channel.

In this case their period according to [9] in case of homogeneous current density is estimated as follows:

$$T=\frac{56r^2}{J}\sqrt{\frac{mn}{\gamma-1}}\ \text{(s)},$$

where: r - radius of the discharge channel (cm); J - current (A); m - atom mass of metal in the channel (g); n - concentration of metal in the channel (cm^3). The competition between pressure of plasma being outward and the magnetic force $J\times B$ working inward, compels pinch oscillate radially.

The experiments which have been carried out with tungsten and copper wires and corresponding materials of electrodes (Fig. 1a and 1b) confirm, that ratio for periods of oscillations $T_1/T_2\sim(m_1/m_2)^{1/2}$ on curves of voltage and current is hold. That allows to assuming, that the discharge channel surrounded with the dense hydrogen environment consist of metal plasma.

Change in the discharge chamber diameter does not result in displacement of the instant of the channel contraction (Fig. 2), that allows to confirm with full certainty that the observable fluctuations are own fluctuations of the channel, rather than caused by acoustic waves of pressure reflected from the chamber walls, and to count insignificant the influence of these waves on characteristics of the discharge. It is necessary to note, that these fluctuations generate intensive cylindrical waves of pressure in the discharge chamber volume, which reflects from the chamber walls and focused in its center.

A. Discharge at initial gas pressure of 80-160 MPa

At transition to essentially greater initial density of working gas the growth of amplitude of fluctuations of acoustic pressure upon a wall of discharge chamber and synchronous with it growth of fluctuations of voltage on the discharge gap is observed. Amplitude of these fluctuations and number of fluctuations in each experiment increases with growth of initial density of hydrogen.

On the pulse pressure oscillograms it is precisely visible a site corresponding to a pulse of discharge current, described by presence of high-frequency fluctuations (Fig. 3). Slow growth of pressure on Fig. 3c is caused by preliminary piston compression of gas [6], the subsequent fast growth occurs owing to heating gas by a pulse of current, and at last the recession of pressure occurs because of the outflow of gas from the chamber after the diaphragm breaking.

The frequency estimation of pulse pressure high-frequency fluctuations (Fig. 3b) shows that characteristic frequency of pressure waves coincides with ones on voltage curve (Fig. 4). Substantial growth of fluctuations amplitude gives the basis to assume, that under the given conditions the role of acoustic fluctuations healthy increase.

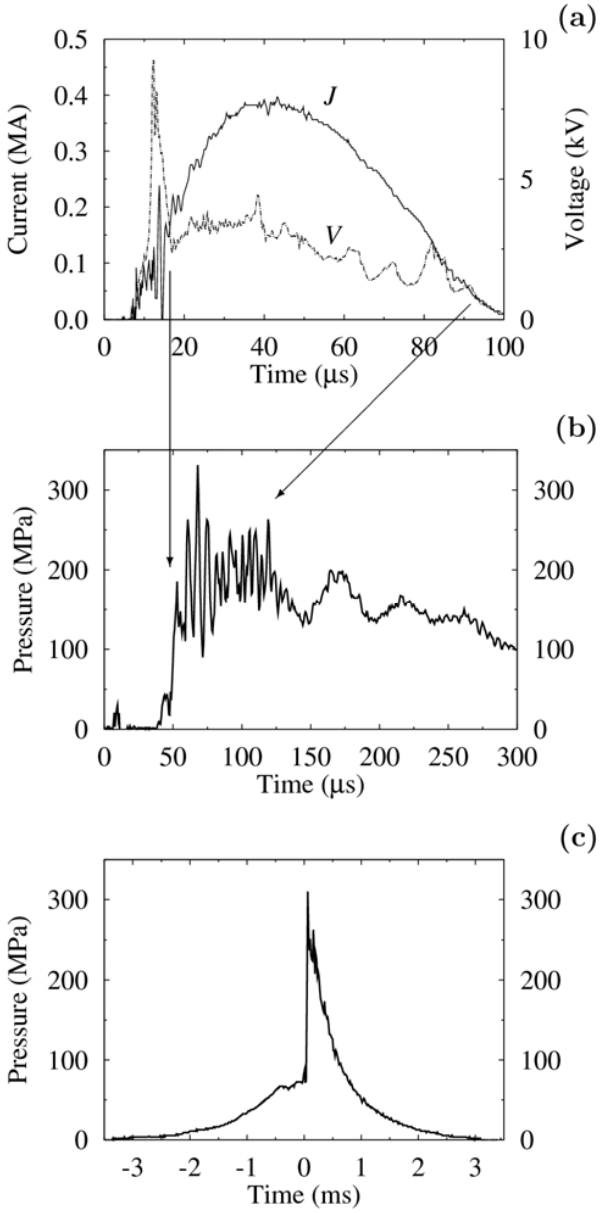

Fig. 3 Discharges in hydrogen at P_0 of 84 MPa (just before discharge ignition, $\rho = 3.5\times10^{-2}$ g/cm^3) for tungsten electrodes and copper igniting wire: (a) – current and voltage curves, (b) – pulse pressure due to current pulse, (c) – pulse pressure for full experiment time (see [6] for better understanding). Arrows between (a) and (b) show time on current curve corresponding time on pressure curve. Input energy into arc is ~60 kJ. Tungsten electrodes with Ø 6 mm. Interelectrode gap is 12 mm

Let's estimate the value of channel radius change which is necessary to receive the registered values of voltage fluctuations amplitude under the formula:

$$E_1 / E_0 = (r_0 / r_1)^{1.8} \quad (1)$$

where E_0, r_0 and E_1, r_1 - electric field strength and channel radius before and after contraction accordingly.

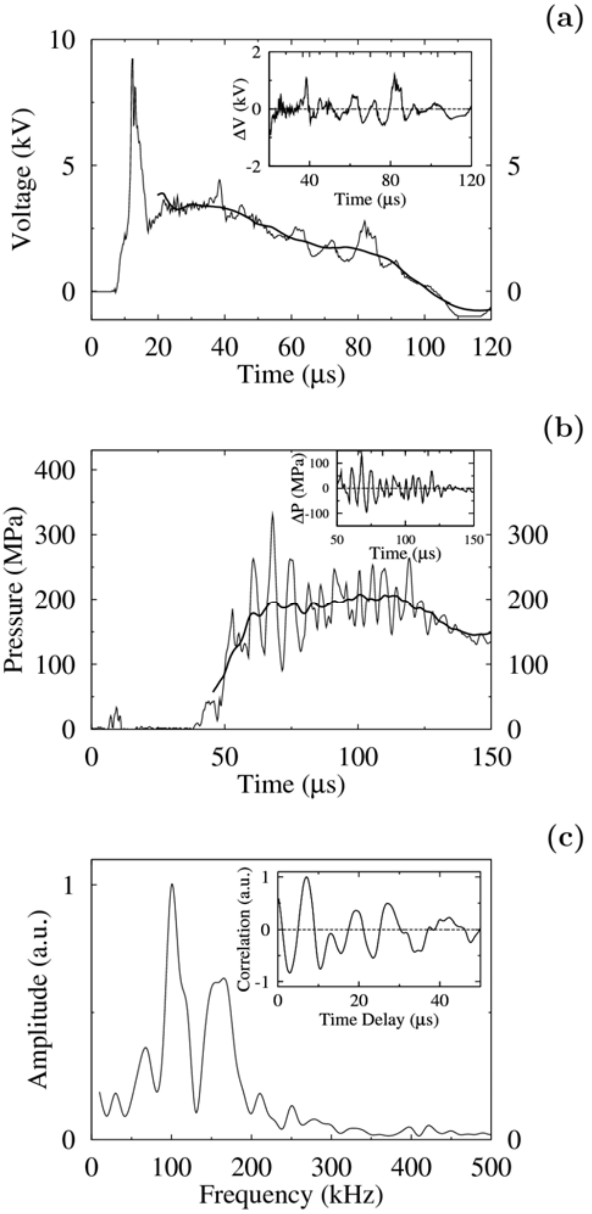

Fig. 4 Discharges in hydrogen at P_0 of 84 MPa (just before discharge ignition, ρ = 3.5×10^{-2} g/cm^3, experiment as on Fig. 3) for tungsten electrodes and copper igniting wire: (a) – voltage V, average voltage V_{20} on 20 μs time base and differential curve of voltage $\Delta V=V-V_{20}$, (b) – pulse pressure P, average pressure P_{20} on 20 μs time base and defered curve of pressure $\Delta P=P-P_{20}$, , (c) – Amplitude spectrum of correlation function between differential curves of voltage ΔV and pressure ΔP and the correlation function $f(\Delta V,\Delta P)$. Input energy into arc is ~60 kJ. Tungsten electrodes with Ø 6 mm. Interelectrode gap is 12 mm

Simultaneously with it we shall calculate the amplitude of channel radius change on the basis of the amplitude of pressure fluctuations, which value is defined from a ratio:

$$P_m = \Delta r\, \omega\, \rho\, c, \quad (2)$$

where P_m – pressure on the border of the discharge channel, Δr - amplitude of displacement, ω - circular frequency of fluctuations, ρ - hydrogen density after preliminary adiabatic compression, c - average sound velocity in the discharge chamber volume at the instant, corresponding to current maximum. Value of P_m is calculated in view of cylindrical geometry from the registered pressure on the wall to pressure on radius of the discharge channel.

It is naturally to assume, that the least attenuation will be for fluctuations, which frequency is close to frequency of the steady stable acoustic fluctuations in the discharge chamber volume. For real geometry of the discharge chamber, period of these acoustic fluctuations is defined under formula $T=1.5R/c$, where R-discharge chamber radius.

For the experiment in Fig. 3 at the initial pressure of 84 MPa, where fluctuations on the oscillogram of pressure are expressed most distinctly, amplitude of the registered pressure on the wall P = 77.5 MPa; r_1 = 2.1 cm; r_0 = 0.35 cm; with = 3.67×10^5 cm/s; ρ = 3.47×10^{-2} g/cm^3; then, according to (2), Δr = 18×10^{-2} cm.

Similarly using the voltage oscillogram, where fluctuations are most distinctly expressed, we determine E_0 = 1.9 kV/cm; E_1 = 5.1 kV/cm; r_0 = 0.35 cm, and from (1) displacement of the channel Δr = 15×10^{-2} cm. As we see, the done estimations of change in channel radius in two ways gave close results.

This fact allows to draw a conclusion, that in case of high initial gas pressure the acoustic fluctuations arising in all volume of the discharge chamber and compressing the discharge channel play the prevailing role in a power balance of system. The registered fluctuations of pressure and electric field strength, which amplitude grows with increase of gas initial pressure, can be caused by repeated passage of sound waves of pressure, reflected from the walls. Thus there should be a change of their frequency owing to heating of working gas in the discharge chamber volume. The example of the consecutive build-up of oscillations is presented on Fig. 5.

B. Energy balance

Let's consider the power balance in the discharge at initial pressure of 80-160 MPa near the current maximum. For the experiment presented in a Fig.3 the discharge channel parameters determined by conductivity and pressure are:

T = 10^5 K, n_i = 1.6×10^{20} cm^{-3}, r = 0.35 cm. Radiation mean free path by Rosseland is l_R~10^{-2} cm - in these conditions the model of black body surface radiation is fair. Power balance at presence of acoustic fluctuations will be:

$N_1 + P_a + P_b \approx J\,E\,l$, where N_1 - power of radiation in the band transparency of hydrogen (quanta with energy hν<13.6 eV), P_a - full radiated acoustic power on the walls, P_b - power of acoustic fluctuations converging in the channel axis, l - discharge channel length.

$P_a = I\,2\pi R^2 \frac{\lambda}{l}$, where $I = \frac{1}{2}\frac{P_m}{\rho c}$ — intensity of acoustic radiation on a wall of the discharge chamber of radius R with characteristic wave length λ, and $P_b = I\,2\pi\,r\,l$.

Then, $N_l = 1.6\times10^8$ W; $P_a = 4.2\times10^8$ W; $P_b = 1.5\times10^8$ W; $N_l + P_a + P_b = 7.3\times10^8$ W; $J\,E\,l = 7.6\times10^8$ W.

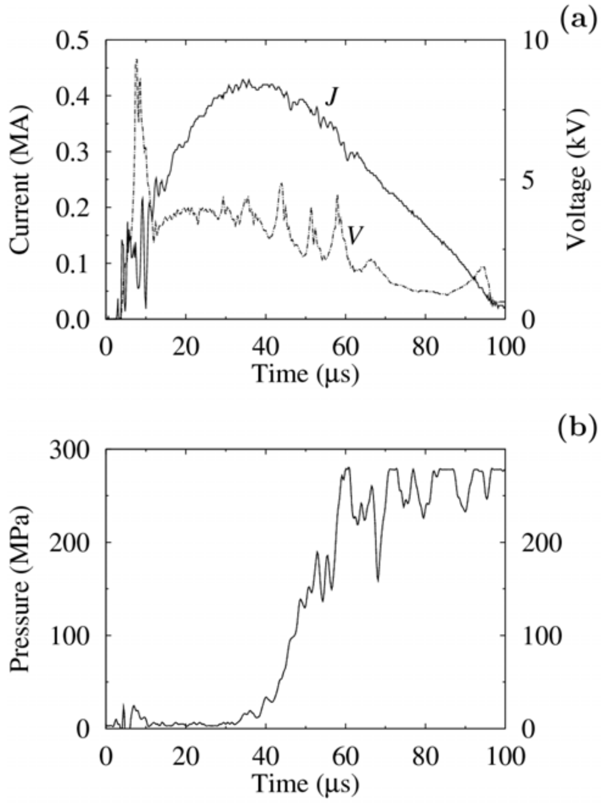

Fig. 5 Signal oscillations for discharge in hydrogen at P_0 of 157 MPa (just before discharge ignition, ρ = 5.6×10^{-2} g/cm^3): (a) – current *J* and voltage *V*, (b) – pulsed pressure. Input energy into arc is ~75 kJ. Tungsten electrodes with Ø 6 mm. Interelectrode gap is 12 mm

From here it follows that significant part of electric power enclosed in the arc, is spent for the creation of acoustic fluctuations.

IV. Conclusion

It has been shown, that expansion of the discharge channel under its formation and subsequent own fluctuations of its diameter, caused by alignment of magnetic and gaskinetic pressure, are a source of intensive cylindrical waves of pressure in the discharge chamber volume, which reflects from the chamber walls and focused in its center. At high density of working gas the acoustic fluctuations play a significant role in a power balance of system. Under the corresponding initial parameters the frequencies of own channel fluctuations and steady stable acoustic ones will be close. Then the resonance of these fluctuations is possible.

Abrupt increase in the fluctuations amplitude, which is most distinctly seen on a voltage curve, is submitted in a Fig. 6 (marked by arrows). Thus, the selection of corresponding initial conditions of the experiment allows to essentially increase the power input in arc, and correspondingly plasma energy density in the channel.

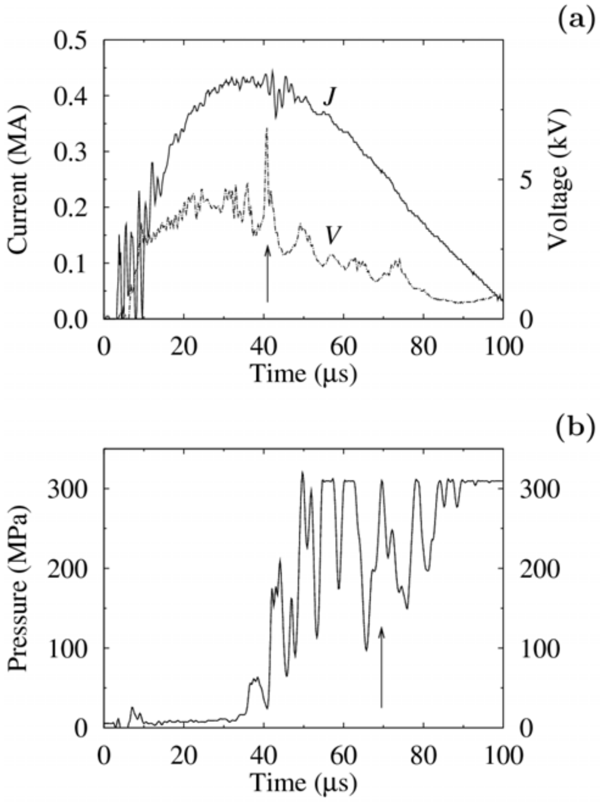

Fig. 6 Signal oscillations for discharge in hydrogen at P_0 of 104 MPa (just before discharge ignition, ρ = 4.2×10^{-2} g/cm^3): (a) – current *J* and voltage *V* and (b) – pulsed pressure. Corresponding maximum splashes of the signals marked by arrows. Input energy into arc is ~75 kJ. Tungsten electrodes with Ø 6 mm. Interelectrode gap is 12 mm

Acknowledgment

This work was supported in part by the Russian Foundation for Basic research under Grant № 10-08-00739a.

References

[1] D. D. Ryutov, M. S. Derzon, and M. K. Matzen, "The physics of fast Z-pinches," *Rev. Mod. Phys.*, vol. 72, no 1, pp. 167-223, January 2000.

[2] Ph. Rutberg, "*Physics and Technology of High-Current Discharges in Dense Gas Media and Flows*," Nova Science Publishers Inc., New York, 2009, p. 214.

[3] A. A. Bogomaz, A. V. Budin, S. Yu. Losev, M. E. Pinchuk A. A. Pozubenkov, F. G. Rutberg, and A. F. Savvateev, "Attainment of the Pease-Braginskii current in an ultra-high discharge," *Plasma Phys. Rep.*, vol. 34, no. 5, pp. 366-375, May 2008 [*Fizika Plazmy*, vol. 34, no. 5, pp. 404-413, 2008].

[4] Ph. G. Rutberg, A. A. Bogomaz, M. E. Pinchuk, A. V. Budin, A. G. Leks and A. A. Pozubekov, "High-current discharge channel contraction in high density gas," *Physics of Plasmas*, vol. 18, no. 12, pp. 122702-(1-9), December 2011, DOI: 10.1063/1.3662053/.

[5] R. Lebert, A. Engel and W. Neff, "Investigations on the transition between column and micropinch mode of plasma focus operation," *J. Appl. Phys.*, vol. 78, no. 11, p. 6414-6420, November 1995.

[6] A. V. Budin, A. F. Savvateev and P. G. Rutberg. “A two-stage launcher-accelerator working on hydrogen,” *Instrum. Exp. Techn*., vol. 47, no. 4, April 2004, pp. 534-538 [*Prib. Tekhn. Eksp.*, vol. 47, no. 4, pp. 125-129, 2004].

[7] A. V. Budin, S. Y. Losev, M. E. Pinchuk, Ph. G. Rutberg and A. F. Savvateev♣, “An Experimental Stand for Studying a High-Current Discharge in a Dense Gas,” *Instrum. Exp. Techn.*, vol. 49, no. 4, pp. 549-552, April 2006 [*Prib. Tekhn. Eksp.*, vol. 49, no. 4, pp. 106-109, 2006].

[8] P. Yu. Emelin, B. E. Fridman, and Ph. G. Rutberg, “E7-25 capacitor energy storage,” *Instrum. Exp. Tech*., vol. 36, no. 5, Sept.-Oct. 1993, pp. 730-733 [*Prib. Tekhn. Eksp.*, vol. 36, no. 5, pp. 109-115, 1993].

[9] L. S. Solov’ev, “Dynamics of a cylindrical Z pinch,” *Plasma Phys. Rep.*, vol. 10, no. 5, 1984, pp. 1045-1050 [*Fizika Plazmy*, vol. 10, no. 5, pp. 602-607, 1984].