Gasdynamic effects in optical discharges produced by periodic pulse femtosecond laser

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Abstract. Quasi-stationary gas streams in argon (10 bar) were observed for the first time being generated by periodic-pulse optical discharge produced by laser pulses of less than 500 fs pulse length with energy up to 200 μJ/pulse and repetition rate 1.66×10 kHz. Optical discharge was obtained in laser beam focused by off-axis (90°) parabolic mirror. In experiments the shape of the discharge zone was varied accordingly to the laser beam waist shapes varied from astigmatic to non-aberrated ones depending on the parabolic mirror tilt. Intense convective streams flowing out of the discharge volume were observed by schlieren technique. The gas streams produced could be directed normally to the laser beam axis, at some angle to the beam axis or along the beam axis toward the laser or in opposite direction. It was found that the directions of the streams produced, dynamics of their formation and their intensity were governed by the shape of the discharge zone. It was revealed that most intense and fast forming streams produced were directed normally to the laser beam axis. Two opposite streams are induced by the discharge located in astigmatic beam waist in a form of flattened “disk” ~10 μm thick and ~100 μm wide. The streams were directed normally to the “disk” surfaces. The energy spent on the gas flow acceleration was estimated to be up to 30% of thermal component of energy dissipated in plasma. When the focusing mirror was aligned to get no astigmatism, the gas flow generated was directed along optical axis toward the laser or backward in some cases. Refraction of the incident laser beam on the refraction index gradients of heated and excited gas injected by backward stream was followed by oscillations of the discharge zone location and generated stream direction. Discharge became stable when the gas streams were co-directional, normal or angled to the laser beam. Further studies are required to define mechanisms and possible applications of the phenomena observed.

1. Introduction
High energy dissipation density peculiar for optical discharges may induce considerable gasdynamic perturbations in the plasma forming gas capable of affecting the plasma characteristics. In the case of periodic-pulse optical discharges potentially important for various applications, repeated gasdynamic perturbations may acquire cumulative effect disturbing operation of the device employing optical discharge.

One of the main features of periodic-pulse optical discharges produced by sub-picosecond or femtosecond scale pulses is outstanding stability from pulse to pulse [1]. However at repetition rates higher than several hundred hertz a drop in stability was found [1].

As it is shown below in this paper the reason of the instability is quasi-stationary gas stream generated by pulse-periodic plasma. In this paper it was found for the first time in the experiment that
periodic-pulse optical discharge in focused beam of femtosecond laser generates quasi-stationary directional gas streams and also the conditions were found when the stream generated is directed toward the laser along optical axis.

Till now generation of directional gas jets following laser breakdown was reported many times in literature. The reason of directional flow generation followed by intrinsic asymmetry of energy release during laser breakdown was recognized in early papers, [2] for instance. Gas flow generated after a single laser pulse along optical axis both either toward the laser or in opposite direction was reported in [3]. It was found in [3] that the direction of the gas flow is determined by exact position of a point of laser breakdown initiation with respect to the focal point: the initiation point (and then the flow generated) may be randomly displaced to the laser or backward. The authors of [4] controlled the direction of axial gas flow formation after laser breakdown by producing artificial point of initiation on the optical axis of the main beam with external laser breakdown. All the papers mentioned above (and many papers not mentioned) were reported formation of the decaying streams following single laser breakdown. Quasi-stationary gas streams produced in a pulse-periodic discharge with high repetition rate were first reported in [5]. Authors [5] used Q-switched high power CO₂-laser to study gas dynamics of periodic-pulsed optical discharge. Together with other effects they have found relatively low pulse energy regimes when directional quasi-stationary gas flow along optical axis was generated either directed toward the laser (predominantly), or in opposite direction. Physical reasons of the reported pulse-periodic optical discharge flow generation appear to be similar to those of a single shot flow.

Papers [6, 7] reported on the first experimental observation of unusual forced convection in pulse-periodic optical discharge where quasi-stationary gas flow generated was directed normally to the gravity force direction. The unusual convection flow was produced in so called “quiet” optical discharge, sustained in high pressure xenon by periodic laser pulses of intensity lower than breakdown at high pulse repetition rate. The discharge plasma was characterized by relatively low absorption (around few percent) and power dissipation not higher than 50 μJ/pulse. It was highly symmetric and steady, exhibiting just two distinct phenomena: considerable distortion of passed through laser beam and intense transversely directed gas flow generation. The formation of the transversely directed flow was discussed in [7] based on known mechanisms of the collapse of laser pulse produced heated gas cloud. Nevertheless definite mechanisms of the phenomenon observed still remain unclear.

In this paper the experiments on flow generation in optical discharges produced by femtosecond periodic-pulse laser are presented. The energy parameters of the laser used (up to 260 μJ/pulse, up to 10 kHz repetition rate) make the conditions of pulse-periodic optical discharge produced close to that of [6, 7]. Main purpose of the investigation was studying the dependence of the gas flow generation on the configuration of the discharge zone. Different optical breakdown configurations could be created with femtosecond laser by varying beam waist shape of the laser beam focused by off-axis parabolic mirror with controllable astigmatism.

2. Experimental layout
The laser source used in the experiments is a commercial S-pulse femtosecond amplifier (Amplitude Systèmes), delivering periodic pulses of two preliminary tuned pulse energy levels 135 and 260 μJ/pulse. Fixed pulse repetition rates 1.66, 3.33, 5 and 10 kHz were used. Pulse length was τ=450 fs, wavelength λ=1023 nm, beam diameter was d=2.5 mm at the laser output. The output beam spatial characteristics are close to that of a ground transverse mode: beam propagation factor M²=1.2 corresponding to beam parameter product BPP≈0.4 mm·mrad or far field divergence of θ=0.63 mrad (full angle). The diameter of the focused beam waist d₀≈10 μm could be achieved when focusing by an objective with a f-number f/f=5.8 (or f/5.8), where d is the beam diameter in the objective principal plane, f is the focal length (correspondent numerical aperture NA = 0.086). Peak power of the laser radiation delivered is in the order of 1 GW. Power density in the beam waist thus could be up to 10¹⁵ W/cm² allowing to obtain multiphoton ionization controlled optical breakdown.
The intensity of the focused beam available up to $10^{15}$ W/cm$^2$ is approximately two orders of magnitude higher than that required for multiphoton ionization of noble gases for the wavelength used [8]. In practice when focusing the radiation inside a chamber with up to $p = 10$ bar argon, the $f$-number being $f/5.8$, with pulse energy above 50 μJ/pulse, the plasma occur near the beam waist where intensity exceeds multiphoton ionization threshold.

A scheme of the experimental set up, allowing to sustain periodic-pulsed optical discharge, control the parameters of the laser radiation passed through the plasma, and acquire shadow images of the plasma and convective flows generated by it, is shown in figure 1.

![Figure 1. The experimental set up for investigating quasi-stationary plasma sustained by femtosecond periodic laser pulses in argon $p = 10$ bar. The $F$-number is $f/5.8$ (NA = 0.086), the laser pulse power is $P_L \leq 1$ GW, the average power is $P = 0.5 \pm 1.5$ W, the pulse length is $\tau < 500$ fs, pulse repetition rate is $f_r = 1.66; 3.3; 5; 10$ kHz. $\alpha$, $\beta$ – discharge chamber and focuser tilt angles.](image)

Laser radiation was inserted into high pressure chamber through bare quartz glass window. Then laser beam was focused by off-axis ($90^\circ$) parabolic mirror of effective focal length 15 mm with $F$-number $f/5.8$. The mirror aperture 12 mm was considerably higher than the laser beam width. Minimal diameter of the beam in the focus was about 10 μm.

Figure 2 shows focused beam waist transformations that could be produced by tilting the chamber and focusing mirror by the angle $\alpha$ (as shown in figure 1 and figure 2, d). In properly adjusted position (figure 2, b) the beam waist was nearly cylindrical $\sim 100$ μm long (doubled Rayleigh length) and $\sim 10$ μm diameter. When mirror was tilted at $\alpha = \pm 0.38^\circ$ (figure 2, a, c) beam becomes astigmatic with two widened waists sized $\sim 100$ μm long (the same Rayleigh length) $\sim 50$ μm wide (widened along one of the transverse axes) and $\sim 10$ μm thick. Distance between these two waists was $a \approx 200$ μm, the axes of their widening were perpendicular to each other. If $\alpha$ was increased, the distance $a$ and the waists widths were further increased proportionally.

Chamber was filled with argon 10 bar above atmospheric (11 bar absolute pressure). High pressure was required to promote laser plasma formation and to enhance sensitivity of gas flow visualization by schlieren technique. Due to multiphoton ionization as predominant ionization mechanism when high intensity femtosecond laser radiation is employed, high density plasma is to be produced near the beam waist where laser beam intensity achieves maximum value. The gas was heated up to the high temperature in the process of electron-ion recombination following the laser pulse. As a result high brightness zone of recombination and thermal radiation sized $l \sim 100\div200$ μm was formed in the vicinity of the beam waist. Size and shape of this zone were determined by current position of the off-axis parabolic mirror. Tilting parabolic mirror from properly adjusted position in the limits of
$\alpha = \pm 0.8^0$ led to astigmatism aberration with the distance between two astigmatic foci up to $a = 0.45$ mm (figure 3).

Figure 2. Calculated ray traces of the laser beam near the focus at different off-axis parabolic mirror $f/5.8$ (d) tilt angle $\alpha$. The laser radiation is directed upward. $\alpha$ angle (d) corresponds to that in figure 1. Three cross sections of each beam depicted are shown to the right in a), b), c). Thicker lines on the cross sections represent real beam boundaries corrected by the real beam divergence. Red lines mark beam waists of predominant plasma location.

Figure 3 shows the appearance of the discharges observed near the beam waists; lines show the boundaries of the laser beam, the optical axis and locations of the foci. Figure 3, a) represents plasma in the bottom astigmatic focus seen from the edge, widened along the axis normal to the picture plane.

Figure 3. Spatial characteristics of time-average discharge plasma light emission. a) $\alpha \approx 0.7^0, a \approx 0.4$ mm; b) $\alpha \approx -0.8^0, a \approx 0.45$ mm, c) $\alpha \approx 0^0, a \approx 0$ mm, where $\alpha$ – tilt angle of parabolic mirror, $a$ – astigmatism parameter. Dashed lines show beam boundaries in the picture plane, solid lines to the left – beam boundaries in perpendicular plane. Horizontal lines show locations of foci. Arrows on the bottom margin – beam direction. Frame size 0.5x1 mm$^2$. Ar, $p = 10$ bar, $f/5.8, f_r = 5$ kHz.
Figure 3, b) shows astigmatic focus plasma “face” view in the bottom focus widened in the plane of the picture. Figure 3, c) depicts the discharge in the beam waist of the properly adjusted off-axis parabolic focusing mirror. Plasma was mainly located in the bottom beam waist located closer to the laser, just faint glowing could be seen in another astigmatic focus. Beam waists of predominant plasma location are marked in figure 2 by red lines.

Laser plasma broadband light source LPS-50 [9] was used as high brightness point source for schlieren system. The radiated body was elliptical, vertically elongated 300×200 μm. Collimating and objective lenses of schlieren system has focal distances 400 mm and 110 mm correspondingly. The objective lens was adjusted to create plasma image together with schlieren image on the watching screen. Horizontal or vertical Foucault knife, placed in the objective lens focus behind the lens, was used depending on the major orientation of the density gradients of interest in the gas.

3. Results of the experiments

While periodic-pulsed laser radiation having wavelength λ = 1023 nm, pulse repetition rate \( f_r = 10 \) kHz and pulse length \( \tau = 450 \) fs being focused in argon under pressure \( p = 10 \) bar with an intensity \( I_L = 10^{14} \div 10^{15} \) W/cm², regular light emission in a form of up to 100 ns long flashes, repeating with the laser pulses, was observed in the focus area.

The discharge observed mainly demonstrated stable bright broadband light emission in the focus area without perturbations but in some cases was notably pulsing. The behavior depended on the adjusting of the focusing mirror – best adjustment characterized by maximum absorption of the laser power gave maximal pulsing.

The light emission was white; time average spectrum was uniform with strong UV continuum and intense Ar atom spectral lines in near-IR, looking similar to the recombination one (figure 4). Significant ultraviolet component of plasma emission spectrum, passed through laser beam distortion, as well as formation of laser-induced convective flows out of the discharge zone indicated possible high gas temperature achieved in the discharge zone. The plasma radiation waveform in figure 5 shows that noticeable plasma light emission followed by plasma heating occur even after the end of the ultrashort laser pulse. A stable (in most cases) distortion picture of the laser beam passed through the gas interaction area, as well as near-stationary convective flows, allows us to talk about quasi-stationarity of the pulse periodic discharge under consideration.

Taking into account the losses in the beam path from laser to the discharge chamber, monitoring of the passed through laser beam power revealed that time average laser radiation power incident to the focus area did not exceed 0.85 W. Plasma absorption in argon, 10 bar was from 35% to 60% depending on the tilt of the focusing mirror (or 0.3÷0.5 W time average power, or 30÷100 μJ/pulse). Energy dissipation level like that is comparable to that of related experiments with nanosecond laser published by the authors [6, 7]. Absorbed energy like that could provide gas temperature up to 10 kK in the volume of focal zone up to 10⁻³ cm³. Periodically and accurately repeated over and over heated gas expansions followed by collapses of the hot gas clouds with high repetition rate give rise to the directional stream formation discussed below in the paper.

The plasma emission waveform (figure 5) and plasma integral emission appearance shown in figure 3 suggests that the plasma follows the laser intensity above multiphoton ionization threshold. The plasma size along the laser beam is ~100 μm (figure 3), the light emitting channel diameter is of the order of magnitude of the laser beam waist widened by gasdynamic expansion during recombination radiation time ~100 ns.

Time average intensity patterns taken at the laser beam cross section 81 mm behind the beam focus, demonstrating changes in the laser beam distortion depending on plasma location and controlled astigmatism are shown in figure 6.

With the occurrence and development of the plasma in the astigmatic focus, the laser beam diameter at 81 mm behind the focus is seen to become contracted along one of transverse axes and expanded along another, as shown in figure 6, a), b).

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Figure 4. Quasi-stationary periodic-pulsed discharge plasma emission spectrum observed near the focus area of the laser beam in Ar, \( p = 10 \) bar. Laser radiation line with maximum at \( \lambda = 1022 \) nm is strongly widened by self-phase modulation effect. Intense UV continuum indicates high electron temperature \( T_e > 1 \) eV.

Figure 5. Waveform of a broadband plasma emission intensity pulse \( I(t) \) from the optical discharge volume in argon \( p = 10 \) bar, \( f/5.8 \), \( \tau_{FWHM} = 70 \) ns, \( f_p=5 \) kHz.

Figure 6. False color time average intensity distributions of the laser beam 81 mm behind the discharge. Ar, \( p = 10 \) bar, \( f/5.8 \), \( f_p=5 \) kHz. Outer solid line circle 40 mm dia. – window aperture. Dashed line circle – laser power meter aperture. Inner solid line is encircling 86% of non-distorted beam (without plasma). a) \( \alpha \approx 0.38^0 \), \( a \approx 0.2 \) mm (corresponding to figure 3, a); b) \( \alpha \approx -0.38^0 \), \( a \approx 0.2 \) mm (as in figure 3, b); c) no astigmatism, gas flow is directed toward the laser (figure 3, c); d) the same, but opposite flow direction. Patterns a), b), d) are stable, c) exhibits noticeable oscillations.
The axes of the distortion of the beam was correspondent to the axes of flattened shape of astigmatic laser beam waist in which the discharge was located (figures 3, a), b), correspondingly). Ultrashort laser pulse wavefront distortion may be caused by nonlinear interactions with high pressure gas in the beam waist together with induced thermal length formed in the beam waist due to prolonged action of the thermal energy release and convective heat transfer by quasi-stationary gas flow.

For a time of 100–300 μs between successive pulses free electrons under examined pressure \( p = 10 \text{ bar} \) recombine and cannot contribute to the laser beam distortion nor absorption. However, heated gas and some amount of atoms in electron-excited states remain in the focus zone since the previous pulse. These atoms can provide some initial absorption at \( \lambda = 1023 \text{ nm} \) due to broadened spectral transitions of argon. Some ideas on the thermal lens induced may be derived from the beam distortion observed. For the estimation, a temperature dependence of the refraction index of Ar under \( p = 10 \text{ bar} \) has to be used.

The heated volume width is definitely wider than \( \sim 10 \mu \text{m} \) beam width, characterizing heated volume width just after laser pulse, according to further expanding of the gas heated zone during plasma recombination radiation pulse \( \sim 100 \text{ ns} \) long with the sound speed in argon above 320 m/s. During the pulse, the heated gas area expands up to about \( \sim 75 \mu \text{m} \) diameter.

Estimation for the energy required heating a cold gas, originally located in an astigmatic waist volume of \( \sim 10 \mu \text{m} \) width, \( \sim 100 \mu \text{m} \) diameter up to \( \sim 10 \text{ kK} \) temperature, gives about \( \sim 10 \mu \text{J} \), which is \( \sim 10\% \) of the laser pulse energy and corresponds to the observed laser radiation absorption-emission budget in the laser discharge mode.

In the case of figure 6 c), d) when the gas flow is collinear with a beam axis, the passed through beam is distorted as well. The considerable difference between figures 6, c) and 6, d) is that intensity distribution in figure 6, c) oscillates in dynamics, whereas that of figure 6, d) is steady. Figure 6, c) in fact represents time average of the figure 6, d) provided the structure in figure 6, c) rotates irregularly around the center.

Definite distortion of intensity distributions of the laser beam after passing the discharge zone (figure 6) and the plasma shadow images around the discharge area (figure 7, 8) show that quasi-stationary energy dissipation zone is developed in the beam waist together with quasi-stationary convective flows in a form of an expanding streams emitting out of the discharge area directed normally, along or angled to the optical axis.

Typical schlieren images of the heated gas streams flowing out of the discharge zones are shown in figure 7. The images in figure 7, a)-c) were taken under conditions correspondent to that of figure 3, a)-c) showing the appearances of time average discharge plasma light emission. The streams are seen flowing out of a small zone roughly corresponding to the volume occupied by the discharge plasma.

Most experiments were carried out at maximum time average laser power, achieved at 5 and 10 kHz repetition rate. The intensity and dynamics of the streams generated were almost proportional to the laser average power.

The flow development in time is given in figure 7 in form of a series of successive shadow images, taken with 20–100 ms intervals. Time marks on the frames are counted since the first frame, up to 20 ms since the pulse start.

Frames on the line figure 7, a) present the streams generated by the plasma located in astigmatic beam waist of flattened “disk” shape seen from the edge as shown in figure 3, a). Corresponding calculation of laser beam ray tracing is presented in figure 2, c), while intensity pattern in the cross section of passed through beam is shown in figure 6, a). Data was taken for incident pulse energy (output energy minus reflections from input window and absorption in parabolic mirror) 180 μJ/pulse, pulse repetition rate 5 kHz, average laser power absorption is 35%. The last value is relatively low accordingly to high astigmatism \( \alpha \approx 0.4^\circ \), \( a \approx 0.25 \text{ mm} \).

Figure 7, b) represents the flow generated by plasma “disk” disposed facing the observer, while the gas streams are directed on the observer and backward. The frame line in the figure corresponds to focusing mirror adjusting as in figure 2, a), plasma configuration as in figure 3, b) and passed through beam intensity pattern as in figure 6, b). This series of frames taken at slightly lower astigmatism
(α ≈ -0.33°, a ≈ 0.2 mm) and correspondingly higher part of laser energy absorption 40%. Incident laser pulse energy and repetition rate are 85 μJ/pulse at 10 kHz.

When moving focusing mirror tilt from astigmatic to proper adjusting position the absorbed energy was increased and the gas streams directions were transformed. Frames in figure 7, d) show the formation of Λ-shaped stream composed of two streams angled to the optical axis corresponding to intermediate position of the focusing mirror between astigmatic and zero tilt. Related parameters are: α ≈ 0.2°, a ≈ 0.15 mm, 85 μJ/pulse at 10 kHz, laser power absorption in focus area 50%.

Turning the focuser closer to zero tilt one could observe that the angle between two streams is gradually decreased turning the streams closer to each other and to the laser beam axis.

**Figure 7.** Frame sequences of building up quasi-stationary convective streams out of the discharge zone after short interruption of the laser beam. a) sidewise streams: α ≈ 0.4°, a ≈ 0.25 mm; b) stream on camera α ≈ -0.33°, a ≈ 0.2 mm; c) toward the laser: α ≈ 0°, a ≈ 0 mm; d) Λ-shaped, angled to laser beam axis: α ≈ 0.2°, a ≈ 0.15 mm. Pulse repetition rate 5 or 10 kHz. White dot in focus – discharge zone. Frame size b) 10×10 mm², the rest shown at the same scale. Beam axis and boundaries are shown by lines, beam direction – by arrows. Time marks on the frames are counted since the first frame, up to 20 ms since the pulse start. Focusing mirror edge could be seen in some frames c) and d).
In the position near zero astigmatism laser beam power dissipation in plasma achieved 55±60%, and both gas streams joined in one, directed backward along the laser beam axis, as shown on frames of figure 7, c). Corresponding beam and plasma appearances are shown in figures 2, b); 6, c); 3, c). The convective flow along the optical axis directed toward the laser obtained with properly adjusted focusing mirror is neither quite stationary nor symmetric. It can be seen from oscillating plasma position in a set of successive frames of figure 7, c) and passed through beam pattern (figure 6, c).

Series of frames from figure 7 were taken after short time interruption of continuously repeated pulsing. After turning on lasing and establishing quasi-stationary regime of burning periodic-pulse discharge lasing was interrupted for a second to film the development of the gas streams. To get an idea how the gas flow will develop after interruption for much longer time than one second (cold start) a series of experiments were performed filming heated gas cloud produced by trains of certain number of pulses. In the arrangement corresponding figure 7 a), b) the result did not differ much from start after 1 s interrupt – the dynamics of gas streams development was almost the same. Different situation occurs when the conditions correspond to figure 7, c): properly adjusted focuser with minimal astigmatism (figure 8). There was no definite direction seen in most cases after several hundred pulses in the train, thus it took a longer time up to several tenths second at 5 or 10 kHz repetition rate to develop directional flow in this case.

![Figure 8](image)

**Figure 8.** The development of heated gas cloud depending on number of laser pulses from cold start. Proper focuser alignment, no astigmatism. Ray traces on the right frame represent the laser beam as it is on the frames. Beam is directed upward. Definite flow direction can be seen after several hundred pulses. Incident energy 170 μJ/pulse at 5 kHz.

### 4. Discussions on the results

Streams of the heated gas seen in schlieren images as dark and light turbulent jets directed aside or along the laser beam axis, flow out of the discharge center, as it could be concluded from photos. The streams bear no resemblance to thermal gravity convection, because directions of the streams do not depend on the orientations of the laser beam and the discharge zone against the gravity force. Moreover, a conclusion can be made from the successive pictures showing the dynamics that flow velocity observed is considerably higher than that of thermal gravity convection of a gas under the same conditions. Declination of the streams observed under the influence of thermal gravity convection could be seen when both pulse energy and pulse frequency were decreased substantially.

Filming schlieren images showed that the appearance and directions of the streams depend on the tilt angle of the parabolic focusing mirror from properly adjusted position. The results obtained in current experiments on the effect of the laser beam waist configuration on the energy dissipation zone shape and the appearance of the gas streams generated are summarized in figure 9, a), b), c).

Gas streams induced by the energy deposition zone in a form of flattened irregular disk ~10 μm thick and ~50±100 μm wide were flowing out directed normally to the “disk” surfaces to the right and to the left from vertically arranged laser beam axis when seen from the “disk” edge, as shown in figure 9, a). Overall gas flow rate in two streams can be estimated from successive frames showing dynamics of establishing steady flow (figure 7, a) to be in the order of \( Q \approx 1 \text{ cm}^3/\text{s} \). Presuming that the gas is flowing out of the discharge zone through the area \( S \approx 10^{-4} \text{ cm}^2 \) one can obtain estimation for the flow
velocity $V = \frac{Q}{S} \leq 100$ m/s. The next estimation for the time average power required for pumping the gas (Ar, $p = 11$ bar, density $\rho \approx 17$ kg/m$^3$, depending on gas temperature) through the discharge zone at the velocity $V$ gives in turn $P \approx Q \frac{\rho V^2}{2} \approx 0.1$ W or up to $\sim 30\%$ of thermal part of the laser power dissipated in the discharge. Gas temperature of the stream can be estimated based on the balance of absorbed and dissipated energy or independently from temperature gradient sensitivity of the schlieren method. Both estimations give for gas temperature several tens degrees centigrade.

Figure 9. Schemes of the arrangement of the laser beam near the focus, discharge zones and gas streams generated: a) astigmatic focusing of the laser beam; b) intermediate case of slight astigmatism; c) properly aligned confocal laser beam. Beam boundaries are shown by solid and dashed lines. Bottom and upper ellipses represent laser intensity isolines in the beam cross sections. Solid arrow lines show generated gas streams. Shadowed bodies represent discharge zones. Cameras represent view points of figure 7. Upward arrows show the direction of the incident laser beam. Undulating upward arrow c) illustrates incident beam distortion.

A-shaped stream is observed when astigmatic foci are spaced at about doubled Rayleigh length. In this case flattened shape of astigmatic beam waist that could be obtained in geometrical optics consideration differs from real beam waist shape governed by wave properties of the real beam. Closer consideration gives more likely prismatic shape of the discharge zone that may be responsible for A-shaped stream (figure 9, b).

The result of longer flow formation time in the case of minimal astigmatism and highest laser energy absorption seems paradoxical. Nevertheless, this result corresponds to those of experiments on gasdynamics of a single-pulse laser breakdown [2–4] and periodic-pulse breakdown [5], because in all these experiments gas streams were developed along optical axis as the result of interacting oppositely directed streams produced during collapse of initially asymmetric hot gas cloud. Together and simultaneously with directional streams vortices were formed taking considerable part of energy of the discharge pulse transmitted to the gas motion. In some cases referred above formation of vortices absorbed all the kinetic energy and directional streams did not formed at all.

Heated and excited gas flowing backward the incident laser beam caused the appearance of noticeable fluctuations of plasma position and passed through beam intensity pattern, which are explained by distortions of the beam wave front on the refraction index gradients of the upstream flow.
Fluctuations of the discharge zone caused in turn fluctuations of the gas stream generated as well.

5. Summary and conclusion
As it was found out in the present study, quasi-stationary gas stream generated due to gasdynamic effects in periodic-pulse laser produced plasma can cause plasma instabilities, being directed oppositely to the incident laser beam. The incident beam is then subjected to the refraction on the refraction index gradients in the heated and excited gas flow, resulting in oscillations both of the discharge plasma and associated gas flow. From the other hand, when the discharge is located in astigmatic focus, or the gas stream generated is directed along laser beam away from laser and focusing optics, or to the sides normally or angled to the optical axis, the discharge area remains stable without noticeable instabilities.

It was also shown that the direction and intensity of the gas flow depend strongly on the shape of the energy deposition zone of the optical discharge. In the case of multiphoton ionization as main energy dissipation mechanism in the optical discharge produced by femtosecond periodic-pulsed laser, the shape of the energy deposition zone is determined by the shape of the focused beam in the vicinity of the beam waist. The last was changed in current experiments by inserting controllable aberrations in the focused beam wavefront. In the case of the off-axis parabolic mirror used in the experiments different beam waist configurations were produced by small tilts of the focusing mirror from properly aligned position.

Intense convective streams flowing out of energy deposition volume were observed by schlieren technique. Laser-induced gas streams observed could be directed normally to the laser beam axis, at some angle to the laser axis or along laser axis directly to the laser or in opposite direction. It was found that most intensive and fast establishing streams were produced directed normally to the laser beam. The streams produced by the discharge located in the astigmatic beam waist in a form of flattened “disk” were flowing out in opposite directions normally to wide “disk” surfaces. The energy spent on the gas flow acceleration was estimated to be up to 0.3 of thermal power dissipation energy.

When the laser beam was focused with minor astigmatism the gas flow generated was mainly directed along optical axis oppositely to the laser beam direction. In this case much more successive pulses were required to form directed flow than in the case astigmatic “disk”-like discharge zone. When the number of pulses in a single pulse train of 5 kHz repetition rate used in the tests was lower than 400-500 the cloud of heated gas produced was normally turbulent with no definite discharge. In contrast in the case of astigmatic focus discharge the streams directed to the sides from optical axis was definitely formed after several or several tens pulses.

Finally it is worth mentioning once again that the phenomenon of convection observed in these experiments cannot be explained by thermal gravity convection mechanism, as the directions of the streams produced were not generally related to the gravity force direction and the gas velocity in the streams was estimated to be significantly higher than that of the gravity convection. As can be seen from the experimental results represented in present paper and related results of other papers cited, directional gas streams studied are produced through gasdynamic mechanism.

Actual realization mechanisms of the phenomena observed and ideas of possible applications require further studies.

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