Quasi-stationary convection in a periodic-pulsed optical discharge in high pressure rare gas

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Abstract. Unusual convection flows were observed in stabilized pre-breakdown phase of the periodic-pulsed optical discharge (POD) called “quiet” POD. The discharge was a relatively weakly glowing plasma filament sustained by focused \( \lambda = 1.064 \) \( \mu \) m laser pulses with repetition rate of \( f_r = 50\text{--}100 \) kHz at the intensity several times below than that required for the optical breakdown to occur. No strong shock waves or irregular turbulence around the discharge were observed, in contrast to breakdown types of POD. Significant laser beam refraction measured in the beam cross-section behind the discharge zone was explained by the gas heating in the discharge up to 10 kK, providing high gradients of gas density and refraction index. Intense convective flow was detected on the schlieren images as thermal traces of the laser-induced gas streams flowing from the discharge zone, directed mainly normally to the optical axis. Repeated relaxation of the gas expanding after being rapidly heated by the laser pulse is proposed to explain the effect. The periodic-pulsed discharge located in the elongated beam waist generates an anisotropic heated region with gas streams and vortices, which may form the observed regular convective flow at the late stages of expanding.

1. Introduction

Laser induced quasi-regular convection stream that could not be explained by thermo-gravity mechanism together with surprisingly strong laser beam refraction were two most interesting manifestations of the unusual optical discharge phenomenon of stable sustaining of pre-breakdown phase of the periodic-pulsed optical discharge (POD) observed by the authors of the paper in high pressure xenon in the vicinity of the focused beam waist.

The possibility of a non-breakdown plasma sustaining in a periodic-pulsed optical discharge (POD) in a focused periodic-pulsed Yb\(^{3+}\) laser beam (\( \lambda = 1.07 \) \( \mu \) m) with pulse frequency being above 2 kHz, radiation pulse length of 200 \( \mu \)s, and pulse power above 200 W in high-pressure (\( p = 10\text{--}20 \) bar) xenon was found and investigated in [1]. The characteristics of this type of POD were found to be closer to those of continuous optical discharge (COD) than to those of an optical breakdown or laser spark [2, 3]. In the non-stationary phase POD plasma brightness and the intensity of its ion spectral lines considerably exceeded those of COD plasma under similar conditions [4] indicating higher temperature of POD plasma. After the end of each laser pulse POD plasma recombines in a characteristic time of 10 to 20 \( \mu \)s, with the gap between pulses up to 200 \( \mu \)s or even more, while plasma initiation in the next pulse is still possible. In 200 \( \mu \)s after the pulse end the concentration of free electrons or ions in the gas is not enough to re-initiate discharge. The initial laser radiation
absorption in the next pulse occurs due to electronic transitions between energy levels of the excited xenon atoms that preserved the excited state to the front of the next pulse.

The current paper experiments deal with a different kind of POD, which may be characterized as pre-breakdown phase of the periodic-pulsed optical discharge. This kind of POD differs from those described in the above paragraph and [1] primarily by temporal characteristics of the lasers used [5, 6]. A Q-switched periodic-pulsed fiber laser of YLP series from IPG Photonics Corp. was used in present experiments [6]. The laser average power is \( P = 50 \) W, pulse repetition rate \( f_r = 50 \div 100 \) kHz, pulse energy up to \( E = 1 \) mJ, the pulse FWHM \( \tau = 170 \) ns. YLP series is characterized by high pulse-to-pulse stability at the level of a fraction of a percent. The laser radiation wavelength is \( \lambda = 1.064 \) \( \mu \)m.

Though the beam quality of the laser was high, the intensity of the focused beam in the range of \( 10^9 \div 10^{10} \) W/cm\(^2\) was roughly an order of magnitude lower than that required for an optical breakdown at this wavelength in pure high-pressure noble gases [3]. Practically, when the laser beam is focused inside a quartz bulb under \( p = 8 \div 16 \) bar of xenon, the focal ratio being \( F = f/d < 4 \), where \( d \) is the beam diameter on the lens, \( f \) is the focal length (the numerical aperture \( NA > 0.125 \)), with high pulse repetition rate and pulse energy close to the maximal \( E = 1 \) mJ, the laser breakdown will occur, but not in each pulse, since it needs initiation from the dust suspension particles produced by erosion of the auxiliary electrodes in the gas volume after electric spark or short-time arc discharge. If voltage of several hundred volts is applied to the electrodes, laser breakdowns will stop due to removing the dust particles by the ionic wind.

In experiments with the YLP laser, a new quasi-stationary POD mode, which can be characterized as a pre-breakdown POD mode, has been obtained by the authors. It could be possible mainly because of strict pulse-to-pulse repeatability of the laser beam characteristics. This kind of POD differs dramatically in its properties from the periodic-pulsed optical breakdown [7, 8] as well as from POD [1] and COD [2, 4], which means that one can speak about a self-contained phenomenon of pre-breakdown POD or “quiet” laser spark, or “quiet” POD.

The “quiet” spark does not occur in a focused beam by itself, initiation by casual ordinary optical breakdown flash or by electric spark or arc discharge flash is required for its occurrence. The “quiet” spark does not stand out with a bright light, a close look is required to notice it in a daylight, but it distorts the transmitted laser beam almost as COD does [4, 9]. It also creates laser-induced convective flows in the gas, clearly visible on schlieren images of the discharge region.

2. Experimental layout

Even though periodic-pulsed sustaining of quasi-stationary laser plasma is similar to POD with sub-millisecond long pulses in its nature, the reason in significant differences between POD and the “quiet” POD is applying high power short laser pulses in the latter case. In the experiments the laser pulse power was up to \( P_L = 6.5 \) kW, pulse width being \( \tau_{FWHM} = 170 \) ns. The laser pulse and discharge glow pulse waveforms are shown in figure 1.

![Figure 1. Waveforms of laser pulse power \( P_L(t) \) (the dashed line) and integral discharge glow intensity \( I_p(t) \) from the region of interaction between laser radiation and xenon, \( p = 15 \pm 1 \) bar, \( F = 7 \), \( \tau_{FWHM} = 170 \) ns, \( f_r = 50 \) kHz.](image-url)
The pulse frequency is $f_r = 50$ kHz, the pulse energy is up to $E = 1$ mJ, the wavelength is $\lambda = 1.064$ µm. The beam shape is close to the ground transverse mode with propagation ratio $M^2 = 1.8$ and beam parameter product $\text{BPP} = 0.5 \text{ mm·mrad}$, which gives estimation for beam diameter near the beam waist $d_0 \approx 20 \div 30$ µm, focal ratio being $F = f/d = 7$. The uncertainty of $d_0$ is particularly brought by optical distortion of the beam in the walls of the quartz bulb.

With $F = 7$ power density up to $I = 2 \times 10^9$ W/cm$^2$ could be achieved, which allowed the possibility of an optical breakdown (ordinary laser spark) only in presence of initiation centers (dust) at pulse repetition rate of $f_r = 50$ kHz. When using a shorter focus lens with $F = 4.5$ achievable power density raised up to $I = (5 \div 7) \times 10^9$ W/cm$^2$, which provided ordinary laser spark flashes in a wider pulse energy range, but narrowed the “quiet” POD observation range at the same time.

Standard xenon short arc lamps of 50 W, 150 W and 1000 W rated input electric power with filling pressures of $p = 15$ bar, $p = 14$ bar and $p = 8$ bar respectively were used as xenon filled quartz bulbs. The pressure in the lamp was increased due to heating, the smaller the lamp was, the more it was increased. A laser beam of a diameter $d = 7$ mm at the output of the laser collimator was focused near the xenon bulb center with lenses of focal length $f = 30$ mm or $f = 50$ mm, which gave the focal ratios $F = f/d = 4.5$ and $F = 7$, respectively, or numerical apertures $NA = 0.11$ and $NA = 0.08$.

The lamp electrodes were used for initiating plasma with a spark or a short-term arc discharge; moreover, high continuous voltage up to $V = 1.5$ kV could be applied to the electrodes, which could be used to remove the dust and the charged particles from the lamp volume.

A scheme of the experimental set up, allowing us to sustain a quasi-stationary “quiet” POD with a periodic-pulsed laser, investigate the intensity distribution of the laser radiation passed through the plasma, and acquire schlieren images of the plasma region and convective flows generated by it, is shown in figure 2.

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![Figure 2. The experimental set up for investigating quasi-stationary plasma sustaining with nanosecond repeating pulses of pre-breakdown intensity in $p = 8 \div 16$ bar xenon. The focal ratio is $F = 4 \div 7$ ( NA = 0.08 \div 0.12 ), the laser pulse power is $P_L = 3 \div 6$ kW, the average power is $P = 25 \div 50$ W, the pulse length is $\tau_{\text{FWHM}} = 170$ ns, pulse repetition rate is $f_r = 50 \div 100$ kHz.](image-url)
placed in the corresponding beam waist behind the lens projecting schlieren images onto a watching screen, was used depending on the major orientation of the density gradients investigated in the gas.

3. Results of the experiments

3.1. Plasma appearance and observation conditions

While periodic-pulsed laser radiation with a wavelength of $\lambda = 1.064 \mu m$, a pulse repetition rate $f_r = 50$ kHz and pulse width $\tau_{FWHM} = 170$ ns being focused in xenon under the pressure $p = 8\div 16$ bar to achieve an intensity in the focus $I = 1\div 5$ GW/cm$^2$, a very regular glowing in the form of about 100 ns long flashes, repeating with the laser pulse repetition rate, could be observed in the vicinity of the beam focus after initiation procedure. The intensity threshold of the phenomenon was about $I_t = 1$ GW/cm$^2$ at xenon pressure $p = 14\div 15$ bar and about $I_t = 2$ GW/cm$^2$ at xenon pressure $p = 8\div 10$ bar.

The discharge observed, as opposed to the laser spark (figure 3), demonstrated relatively weak and quasi-stable glow near the beam waist without perturbations typical for a laser spark.

![Figure 3. Quasi-stationary periodic-pulsed glowing discharge zone observed near the waist of the focused laser beam (a) against common laser spark (b). The ratio of the brightness of these two discharges is about several orders of magnitude. The inter-electrode gap (a) is 2.5 mm.](image)

The glow looked white; the visible spectrum was uniform with no strong lines, similar to the recombination spectrum of xenon. Significant gas heating, leading to the refraction and distortion of the transmitted laser beam, as well as formation of a laser-induced convective stream directed perpendicularly to the laser beam axis, were observed near the interaction region.

The time-average laser radiation absorption was less than 5% and so it was measured with high standard deviation more than 30%. The laser radiation and plasma radiation waveforms in figure 1 show that notable plasma glowing and thus the laser radiation absorption occur close to the end of the laser pulse. Low brightness of the plasma emission, low laser radiation absorption, and high pulse-to-pulse stability set the phenomenon observed apart from other periodic-pulsed optical discharge types. A stable distortion pattern of the laser beam passed through the interaction area, as well as quite stationary convective flows, allows us to talk about quasi-stationarity of the “quiet” POD itself.

An ordinary laser spark (figure 3, b) has also been observed in the same set up with the same laser at maximum laser radiation power. To obtain the laser spark, an accurate adjustment of the beam focusing was required, using a short-focus lens with $F = 4.5$ and passing the laser beam through the bulb wall area with minimal optical aberrations. Under these conditions relatively regular flashes of the laser spark could be observed, though the laser breakdown did not occur in each pulse. Since the intensity was set below the breakdown level, random factors contributed to the breakdown development, such as presence and migration of dust and active particles, ions and excited atoms.
inside the lamp bulb due to irregular flows created by shockwaves generated after laser spark flashes. High laser pulse repetition rate also contributed in the breakdown threshold reduction.

The occurrence of an ordinary laser spark was followed by the raise of laser radiation absorption, while the “quiet spark” pre-breakdown plasma could be observed, apart from a glow in the focus region, by a thermal lens, manifested itself in the distortion of the transmitted laser beams, both green laser beam used to obtain schlieren pictures and discharge-sustaining IR-beam.

Casual laser breakdown flashes did generally lead to initiation of the quasi-stationary glowing of the “quiet” POD, which was then stably sustained after decreasing the power density down to 1 GW/cm$^2$ under the pressure $p = 14\pm15$ bar.

Figure 4, (a) shows the appearance of the glow observed in the focus area; the beam borders, the optical axis, and the focus position are also shown by lines. The glowing intensity distribution on the image in arbitrary units with real linear sizes is shown in figure 4, (b).

The laser pulse waveforms (figure 1) and the integral plasma glowing shown in figure 4 allow us to conclude that the discharge is an initial stage of an optical breakdown which does not develop due to the lack of the laser intensity and pulse width. The plasma size along the laser beam is $\sim 1$ mm (figure 4), the glowing channel diameter is of the order of magnitude of the laser beam waist (several tens microns), and the plasma recombination radiation pulse width is $\sim 100$ ns.

For a time of 20 $\mu$s between the pulses free electrons in the examined pressure range $p = 8\div16$ bar recombine and cannot be responsible for the laser radiation initial absorption. However, heated gas and some atoms in electron-excited states remain in the focus zone since the previous pulse. These atoms can provide the initial radiation absorption at 1.064 $\mu$m due to broadened 6s–6p (5d–6p, 6p–6d) spectral transitions. For example, the closest strong enough absorption line with a center at $\lambda_c = 1.053$ $\mu$m corresponds to 5p$^4$(5$^2$P$^o$)$^6$6p$^5$(5$^2$P$^o$)$^6$ transition. The temperature estimation with an induced heat lens, the nature of the glowing, high stability and repeatability also tell us about a possibility of initial absorption with the 5p$^5$ 6s group meta-stable and resonance levels.

The authors have not succeeded in initiating a continuous optical discharge with the “quiet” spark, probably due to its bright phase being short-lived and, thus, average electron and electron-excited atom concentration being too low for COD initiation even when the provided laser radiation power is high enough.

![Figure 4](image_url)

**Figure 4.** Spatial characteristics of the time-average discharge glow. (a) Pattern of a discharge glow. White lines show the optical axis, focus and laser beam borders (solid lines). (b) 2-D plot of the discharge glow. Plasma length is $\sim 900$ $\mu$m, its diameter is $30\div40$ $\mu$m. Xenon, $p = 15$ bar, $F = 7$, $P_L = 6$ kW, $P = 50$ W, $\tau_{FWHM} = 170$ ns, $f_r = 50$ kHz.
Figure 5. The distortion of the radiation intensity distributions of the YLP laser beam after passing through the interaction region. The average laser power $P$ is varied. The beam was focused with $F = 7$ inside a bulb of a short-arc xenon lamp ($p \approx 16$ bar), $f_r = 50$ kHz. The measurements was made at a distance of 39 mm behind the focus point, the frame size is $6 \times 6$ mm$^2$. The symmetry axis of the pictures has no assigned direction. The real gravity vector is normal to the picture plane.
3.2 Laser beam distortion by an induced thermal lens

Figure 5 depicts the results of measurements of the laser beam average intensity distributions at a distance of 39 mm behind the lens focal plane, showing changes in the laser beam distortion by a “quiet” POD plasma, depending on the radiation average and pulse power.

With the occurrence and development of the glowing plasma, the laser beam diameter at 39 mm behind the focus is seen to become about 2 times smaller. Authors applied the method of a negative thermal lens analysis developed in [9], which presumes optical characteristics of the gas in the glowing region can be modeled as a cylindrical domain in which the refraction index is radially distributed according to parabolic law, with a minimum in the axis. Estimations followed by the model [9] show that the beam distortion observed in the cylindrical interaction region of 1 mm length and 0.1 mm diameter can be explained by assuming that the refraction index difference between the axis and the edge is 0.004, which corresponds to the temperature difference of 7 to 10 kK between the axis and the edge of the region examined, when filled with Xe, \( p = 15 \) bar. For this estimation, the temperature dependence of the refraction index at \( p = 15 \) bar pressure mentioned in [4] has been used.

The heated region diameter estimation of 0.1 mm comes from the 30 \( \mu \)m beam diameter, corresponding to the heating start region, according to further expanding of the gas heated zone for a 170 ns long pulse with the sound speed in xenon being 240 m/s. During the pulse, the heated gas region diameter expands up to about 100 \( \mu \)m diameter.

Estimation of the energy required for heating a cold gas, originally located in a waist volume of 30 \( \mu \)m diameter, 1 mm length, up to 10 kK temperature, gives the value of about 40 \( \mu \)J, which is 4% of the laser pulse energy and corresponds to the observed laser radiation absorption in the “quiet spark” discharge. Time average energy balance of the “quite” POD was similar to that of COD [4] with thermal conductivity as dominating energy dissipation mechanism.

3.3 Laser–induced convection

The analysis of the obtained intensity distributions in the laser beam after passing the glowing zone (figure 5) and the plasma shadow images in the “quiet” laser spark mode (figures 6, 7) showed that changes are observed starting from approximately 0.5 to 0.6 mJ pulse energy, which can be interpreted as generation of quasi-stationary convective flows in a form of an expanding flat stream emitted from the centre of laser beam focus area mainly directed normally to the optical axis. This is not gravity convection, as the flow direction does not depend on the orientations of the laser beam and the bulb against the gravity force.

**Figure 6.** A schlieren image of the plasma with the convective flows (a) and the corresponding image of the plasma glowing (b) with beam border lines (solid) and symmetry lines (dash-dot) shown in the focus area \( (F = 7) \). The radiation is directed from the left to the right.
A typical schlieren image of the region around the “quiet” POD showing the convective flow observed is presented at figure 6, (a) together with a picture of the discharge glow (b). The flow is seen to come out of a small volume approximately corresponding to the glowing zone center in the form of the darker “wings” stretched normally to the optical axis on the schlieren image which indicates the heat build-up zone borders.

The convective flow image is not quite stationary and not quite symmetric. The flow evolutions are given in figure 7 in the form of a series of the discharge region schlieren images, made with 1 s intervals.

Streams of the heated gas, seen on schlieren images as dark stripes at one or both sides from the laser beam optical axis, do not flow from the discharge center symmetrically and almost normally to the optical axis, as it could be concluded from some photos. The flow periodically turns out to be seen as if it was flowing to one side, i.e. mainly down in figure 7.

![Figure 7](image)

**Figure 7.** Sequential shadow images of the region around the interaction zone, taken with 1 s intervals, showing the convective flow temporal evolution. The frame actual size is 3.2×2.4 mm². There is no plasma in the first frame; the lines show the beam borders, the optical axis and the focus location. 150 W short arc lamp electrode tips are seen near the center on both upper and bottom sides of the frames, the inter electrode gap is 2.2 mm. The xenon pressure is \( p \approx 15 \) bar. The gravity force vector is directed upwards in this experiment.
This direction is not related to the gravity force direction, as the flow behavior is quite similar when the optical axis is oriented vertically.

Since the gravity force direction has practically no effect on the convective flow pattern, a conclusion can be made that the flow velocity is considerably higher than that of the gravity convection of a gas heated up to the same temperature.

In figure 5, changes of the passing beam refraction pattern are related to strong convective flows occurring when the average radiation power achieves $P = 35$ W (pulse energy is $E = 0.6$ mJ). The assigned axis of symmetry, alongside which the intensity distribution of transmitted laser beam expands and transforms further after the distortion in the interaction zone, appears simultaneously with the convective flow formation and generally coincide with the premature direction of the convection. The assigned direction of the convection flow appeared to occur due to random factors, such as mutual arrangement of the point of the discharge, electrodes and walls of the quartz bulb.

As it was found in the experiments, the convection flows formed in the “quiet” POD prevented stationary discharges (particularly, arc discharge and COD) from being sustained in combination with the “quiet” POD. When the authors tried to subject the stationary discharge plasma to the periodic-pulse laser radiation of the short high intensity pulses to obtain fast local heating of stationary plasma, the formation of “quiet” POD disturbed the stability of stationary discharges. All attempts to increase the laser pulse energy in the “quiet” POD caused growing plasma oscillations of stationary discharges until they went out.

4. Discussions of the results

Based on the obtained discharge heat trail schlieren images, an assumed convection flow pattern in the discharge zone is presented in figure 8 with arrows. The quasi-stationary gas flow comes into the discharge zone from opposite sides along the laser beam axis and spreads asides from the axis as a flat stream. This stream was not generally symmetric and had a dominant direction, apparently due to random factors, involving discharge volume geometry. The stream in the schlieren projection looks predominantly flat, just slightly widening, which can be explained by the interaction of the flow observed with toroidal or semi-toroidal vortical convection cells formed close to it and shown in figure 8 as couples of closed flow lines on both sides from the discharge heat trail located in the flow part coming out of the discharge zone.

Such a complicated gas flow pattern can appear as a result of periodic-pulsed heating and the following expanding and relaxation dynamics of the gas in POD. Just after the laser pulse when high-temperature small cylindrical gas volume stretched along the beam axis begins to expand, a cylindrical shock wave coming from the optical axis to the periphery is formed. The shock wave is followed by formation of a volume of moving heated gas core, which relaxation generates interacting gas flows of various directions. At long times of heated gas core relaxation, the flows can transform into directed jets and vortices.

![Figure 8. The assumed convection pattern in the discharge zone. The conditions and the schlieren pattern correspond to a frame from figure 7. The thinner solid lines show the laser beam conventional border, the dashed line shows the optical axis. Arrows show schematically the directions of the convective gas flows.](image-url)
Calculations [11] show a flow pattern similar to that presented in figure 8, which can be formed within approximately 50 μs during relaxation of the plasma core produced in a single laser breakdown. In the authors’ experiment, the pulse period was from 10 to 20 μs, and the flow picture observed was formed due to many successive pulses. The “quiet” POD mode allowed the flow pattern to be stationary and achieve the quasi-static convection mode, which in first approximation corresponds to the flow pattern at long relaxation times after a single laser breakdown.

It is stated in [11] that the flow pattern is difficult to observe at long relaxation times after a single laser breakdown due to gas cooling. Indeed, in many calculations and experiments, for example, in well-known papers [12-13], they generally just examine and register asymmetric axial flows and single vortices, developing within short time right after the laser breakdown, before the gas has cooled. The pattern of a flat expanding stream between a symmetric pair of vortices appearing at long expanding times has not been observed in experiments before present studies.

5. Summary and conclusion
The phenomenon of sustaining a stable glowing plasma filament in high pressure xenon under periodic-pulsed laser radiation with intensity lower than required for the optical breakdown of the gas has been observed in the experiments.

The phenomenon observed differs from well known optical breakdown or laser spark phenomena with relatively low plasma light emission, low laser radiation absorption, high stability and strict pulse-to-pulse repeatability. The laser intensity threshold of maintaining this new type of POD, which can be called “pre-breakdown” or “quiet” POD, is at least an order of magnitude lower than required for an optical breakdown to occur. It also should be emphasized that time average energy balance of pre-breakdown POD is similar to that of COD with predominant thermal conductivity losses.

The observed significant laser beam intensity distribution distortion after passing the discharge zone was used to estimate gas heating in the interaction area up to 10 kK, which could provide high gradients of gas density responsible for laser radiation refraction in the discharge zone.

The authors also have found that gas heating in “quiet” POD is followed by a laser-induced gas stream flowing out of the discharge zone, directed mainly normally to the optical axis, well seen on the schlieren images. The phenomenon cannot be explained through gravity convection mechanism, as the flow direction does not depend on the gravity force direction and the gas velocity is estimated to be significantly higher than that of the gravity convection. The pattern of convection flows generated by a “quiet” POD looks very similar to that formed at final relaxation stages after a single optical breakdown.

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

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