Acoustic resonances in a pressurized discharge volume with xenon and instabilities of periodic-pulse optical discharges

M A Kotov, S Yu Lavrentyev, N G Solovyov, A N Shemyakin, M Yu Yakimov

Ishlinsky Institute for Problems in Mechanics RAS, 101-1 Vernadskogo pr., Moscow, Russia, 119526

yakimov@lantanlaser.ru

Abstract. One of the factors inducing instability from pulse to pulse of periodic-pulse optical discharge (POD) or continuous optical discharge with deep periodic-pulse pumping modulation, or combined POD (CPOD), is the excitation of resonant acoustic oscillations in a pressurized discharge volume. In this work authors studied the violation types of the regular pulsations of CPOD thermogravitational convection plume in a closed discharge volume with xenon at a pressure of 15-45 bar, arising at certain periodic-pulse modulation repetition rates in the range 1-50 kHz. It was found that simultaneously with the appearance of failures in the behaviour of the convective plume and plasma stability, which in some cases led to the extinction of the discharge, resonant acoustic oscillations were excited in the discharge volume. Schlieren patterns of the gas around the discharge and the frequency spectra of the excited acoustic vibrations were recorded. Several types of instabilities were found that correspond to different modes of resonant vibrations. It was also found that at certain acoustic oscillation frequencies the convection process was stabilized with the suppression of regular pulsations.

1. Introduction

Continuous optical discharge (COD) [1, 2] is now widely used technology for broadband high spectral brightness light sources, mainly due to the development of high-performance diode and fiber lasers in the near-IR range, as well as the ability to sustain plasma in high pressure rare gases with laser radiation with a wavelength of ~ 1 µm at relatively low threshold power [3, 4].

In [5], the mechanisms of laser radiation absorption that determine the threshold power and characteristics of COD plasma in high-pressure xenon and argon were studied for the first time when sustained by Yb³⁺ laser radiation at a wavelength of λ = 1.07 µm with plasma temperature of up to 15 kK and pressure of plasma-forming gas p = 3-25 bar. The observed drop in a threshold power of sustaining COD with an increase of pressure to Pₜ < 30 W in xenon at p > 20 bar and Pₜ < 350 W in argon at p > 15 bar was explained by an increase of laser radiation absorption coefficient up to 20 cm⁻¹ in Xe and up to 1+2 cm⁻¹ in Ar due to 6s–6p transitions in Xe and 4s-4p in Ar between the broadened excited energy levels of atoms. The structure and stability of COD were also depended on laser beam defocusing due to refraction in plasma and the degree of its compensation during focusing. High spectral brightness, compactness and uniformity of the plasma without the electrodes and other sources of impurities in the plasma-forming gas, make COD the promising technology for the use as a broadband high spectral brightness radiation source for spectroscopy, polarimetry, ellipsometry, microscopy, luminescent, fluorescent and schlieren research methods and other applications requiring...
light sources with high spectral brightness, especially in the ultraviolet range, and also with the use of fiber optics devices. The possibility of periodic-pulse (PP) mode of maintaining the optical discharge, discovered in [6], opened the prospects of further significant increase in the spectral brightness of stationary (continuous and PP) optical discharges (OD), especially in the ultraviolet wavelength range.

Since the OD plasma is an extremely small radiation source, possible applications impose special requirements on its spatial and temporal stability. Despite the fact that the plasma sustained by laser radiation is tied to the focal point when the laser beam is tightly focused, and the intensity, power, and wavelength of laser radiation are usually strictly stabilized, the presence of high density and temperature gradients in the discharge volume generates, in general, non-stationary convective flows of plasma-forming gas, which require special and not always effective measures for their stabilization [7, 8]. One of the main causes of COD plasma pulsations is periodic fluctuations of the convective plume formed around the discharge as a local source of high-intensity heat. The baroclinity of the medium created by stationary OD leads to the fact that the thermogravitational convection in the vicinity of the OD acquires a vortex character. There is a periodic formation of toroidal vortices in the convective zone with their subsequent detachment from the main convective flow. As a result, there are regular pulsations of the convective plume in the vicinity of the discharge, accompanied by pulsations of the position and brightness of the plasma. The pulsation frequency rises from 40 to 53 Hz with an increase in gas pressure from 15 to 45 bar. The study of the behavior of the convective flow that induces spatial and temporal instability of the OD, and in particular the prospective POD, is important for further development of optical discharge technology.

It is also known that during periodic-pulse modulation of electric arc discharges in lamps, instabilities develop due to the generation of sound vibrations in a closed discharge volume with a frequency close to the modulation frequency [10, 11]. At some frequencies being in resonance with the natural frequencies of the discharge volume as an acoustic resonator, sufficiently strong instabilities are developed that can extinguish the arc discharge. This is, first, a low-order acoustic resonance, with a wavelength corresponding to the maximum size of the discharge volume, taking into account its shape. Instabilities can also occur at higher frequencies. To estimate the resonant frequencies, one can proceed from a simplified form of the discharge volume, which in the case of standard arc lamps approaches a spheroid [12, 13]. The differences are due to the presence of electrodes, as well as high temperature gradients inside the discharge volume, which affects the resulting frequency through the dependence of the speed of sound on temperature.

The main possibilities, advantages and prospects of using the POD and CPOD techniques for further improving the characteristics of radiation sources based on optical discharges are shown in [9]. In order to realize additional opportunities to increase the brightness of the optical discharge plasma, especially in the UV range, it is necessary to take into account the features of the gasdynamic and acoustic effects of periodic-pulse OD modes on the plasma-forming gas.

The instabilities of POD and CPOD associated with the generation of acoustic vibrations in a discharge volume have not been studied till now. In this paper, the hydrodynamic and acoustic effects that lead to instability of OD up to extinction are studied on the basis of observations of CPOD convective plume by schlieren technique with simultaneous registration of resonant acoustic mode excitation.

2. Experimental layout
CPOD in xenon under a pressure of 15 to 45 bar was sustained in an experimental unit with two intersecting laser beams, as shown in Fig. 1, a). To sustain CPOD, a standard PLD-40 diode laser module was used as CW laser [14], and a more powerful PLD-70 laser diode module [14] with similar characteristics was used as a periodic-pulse laser. The current through the diodes was regulated using a transistor driver, in the case of periodic-pulse mode controlled from the sinusoidal sound frequency generator or pulse generator. Fig. 1, b) and 2, a) show characteristic oscillograms of irradiation at a distance 15 cm produced by CPOD plasma, detected by photomultiplier (PMT) sensitive to the visible radiation. In order to produce the irradiation waveform shown in Fig. 2, a) the driver was triggered by
a sinusoidal audio frequency generator, and for the waveform in Fig. 1, b) – by a pulse generator. In the first case, the duration of the laser pulses was changed with the repetition rate while duty cycle factor was maintained constant equal 0.3. Pulse duration and period of pulse generator could be set independently.

The CPOD sustaining layout was similar to that described in [9]. The discharge was initiated by a short-term electric discharge, and then CPOD was sustained due to absorption of laser radiation in plasma. The plasma was localized at the intersection of two focused beams of CW and periodic-pulse diode laser. The frequency of laser pulses could vary from several hundred Hertz up to 50 kilohertz, and the pulse duration could set from 10 to 100 μs.

Fig. 1, b) and 2, a) show how plasma generated irradiation increases on the arrival of the next laser pulse and decreases after it ends. Since OD plasma is transparent to its own radiation in the visible region, the irradiation registered by PMT can be considered to be proportional to the volume of the plasma to the first approximation.

The periodic movement of the plasma boundaries of CPOD can generate high-frequency harmonics of acoustic waves in the discharge volume. For illustration, fig. 2, b) shows the frequency spectra of harmonics of the plasma created irradiation waveforms obtained by fast Fourier transform. The spectra in fig. 2, b) show a relatively high intensity of several harmonics in the oscillogram of the plasma radiation up to 80 kHz.

Since we are interested in how the dynamics of the plasma affects the generation of acoustic waves, we believe that the acoustic wave is emitted as a result of the movement of the plasma front. Depending on the specific nature of the movement, the displacement amplitude of the plasma fronts can be proportional to the change of the plasma volume (expansion along one axis), to the square root of the volume (simultaneous expansion along two axes) or to the cubic root of the volume (expansion in all directions).

In fig. 2, a), b) the result of a simple calculation is presented, which shows that the specificity of the plasma motion does not have a large effect on the composition and relative amplitude of acoustic harmonics. The shape of the plasma produced irradiation signal is such that when taking the square or cubic root from it, the amplitude of the signal changes, but the shape changes insignificantly. Accordingly, the Fourier spectrum of the signal changes little. Thus, to a first approximation, it can be assumed that the pulsating plasma emits acoustic harmonics, regardless of the specific nature of its motion.
Figure 2. a) Oscillograms of CPOD produced irradiation $I$ with $\sqrt{I}$ and $\sqrt[3]{I}$, arbitrary units b). Fourier spectra of plasma produced irradiation waveforms $fft(I)$ with $fft(\sqrt{I})$ and $fft(\sqrt[3]{I})$. Curves and corresponding signs on Y-axis are highlighted in color. $f_p = 10$ kHz, $\tau = 30$ μs.

At certain repetition rates of the CPOD modulations resonant acoustic waves occurred in the discharge volume. Sound waves amplified due to resonance were recorded using a piezoceramic sensor connected to a quartz bulb by a glass rod that was tightly attached to the bulb surface. The piezoceramic sensor was pressed to the grinded end of the rod at a distance of 30 mm from its point of contact with the bulb using another rod of the same diameter with an adjustable force. The piezoceramic sensor signal was fed through an amplifier to a digital oscilloscope with frequency measurement and fast-Fourier-transform (FTF) function. The signal of the piezo pickup can be saved on external media for later mathematical processing.

Schlieren patterns of a convective plume were obtained with a schlieren technique by transmission of the CPOD own radiation through the area around the discharge, collecting and collimating the radiation using a spherical mirror, as it was done in [16, 17], or by using of the radiation from a separate point source of LPi-50 type based on COD [15], by collimating the radiation with a lens. In the schlieren images of stationary OD, the convective plume of a gas heated to a high temperature is clearly visible. Convective flow occurs due to thermogravitational convection of the gas surrounding the plasma, which is heated by heat transfer from the laser radiation absorption core. Due to these processes, about a fifth of the laser radiation power incident on the plasma is dissipated under conditions typical for broadband radiation sources [9].

Two xenon filled quartz bulbs were used in current experiments. The first one was standard short-arc lamp Osram 150W2 under fill pressure 12-12.5 bar, not exceeding 22 bar when heated by the discharge. The other one was specially designed bulb at fill pressure 30 bar, rising up to 45-50 bar with the discharge. The results of Capter 3 of the paper were obtained with this special bulb.

3. Regular and irregular pulsing of stationary OD

In [16, 17] we investigated the instability of convection that causes fluctuations in the brightness of COD plasma and affects the stability of its parameters, which are important for applications. It was shown that regular fluctuations in the brightness of COD plasma with a characteristic frequency of 39-53 Hz, which increases with increasing gas pressure in the lamp, occurred due to hydrodynamic effects. Fluctuations in the convective plume were accompanied by periodic formation of toroidal vortices with a pulsation frequency. The dependence of the oscillation frequency of COD convective plume on the pressure obeys the similarity law, similar to that known from the study of flickering flames. The oscillation frequency of the convective plume practically does not depend on the power of the laser radiation supplied to the plasma.
Figure 3. The successive frames of a regular pulsation period, as described in [16, 17], registered in CPOD with pulse repetition rate $f_p = 4.24$ kHz, pulse duration $\tau = 25 \mu$s, pulse amplitude is $P_p = 55$ W while CW laser power $P = 25$ W. Lamp type OSRAM 150W2 with inner surface of the bulb close to spheroid with semi-axes $a = 14$ mm, $b = 6.5$ mm, Xe, $p = 22$ bar. Initiating electrodes are seen in the lower part of the frame. The frame size is 6.4×4.8 mm².

In the case of CPOD the convective plume pulsates (fig. 3) in the same way as in the case of COD, except for cases that occur at certain pulse repetition rates. Boundaries between hot and cold regions in the convective plume are seen in fig. 3, the boundaries branching-off captured in bottom frames indicates the formation and separation of the toroidal vortex. The oscillation period is $\sim 40$ Hz. In the CPOD scheme (fig. 1, a), when the pulse repetition rate was gradually changed from 1 to 40 kHz and the convective plume was simultaneously observed, a set of narrow frequency intervals was detected, in which there was a violation of the regularity of pulsations. Simultaneously with the appearance of significant low-frequency oscillations of the plasma and surrounding gas, which sometimes led to the extinction of the plasma, an increase in the amplitude of acoustic vibrations was registered, usually at several resonant frequencies in the range from 7 to 50 kHz and higher, close to or multiples of this pulse repetition frequency.

Figure 4. Violation of regular pulsations with the formation of giant vortices captured under the same conditions as in fig. 3. The repetition rate of giant vortices formation is $\sim 7$÷14 Hz. Initiating electrodes are seen in the lower part of the frame. The frame size is 6.4×4.8 mm².

Fig. 4 shows a frame sequence in which a violation of the regularity of convective plume pulsations is captured in the form of the development of a giant toroidal vortex, the size of which is much higher than the size of the vortices formed during regular pulsation. In the case in fig. 4 the vortex is developing and detaching from the main flow. In some cases, the development of such instability leads to suppression of vertical plume, or temporarily, or followed by a transfer into another quasi-stationary state such as shown in fig. 6, b).
4. Types of irregularities in convective plume pulsing

In total, there were four main types of violation of the regularity of convective plume pulsations found. Each type had its own set of acoustic resonant frequencies that were excited simultaneously. Fig. 5 shows schlieren patterns of various types of violations in the regularity of convective plume pulsations together with corresponding spectra of resonant acoustic vibrations registered in the case. Fig. 6 shows cases when the excitation of resonant acoustic vibrations in the discharge volume led to the suppression of regular pulsing of the convective plume and to its transformation.

Figure 5. Types of violations of regular pulsations of a convective plume of a combined optical discharge, pulse repetition rates and spectra of resonant acoustic vibrations. a) Side-to-side oscillations, resonant sound frequencies 13/26 kHz; b) formation of giant vortices, sound frequencies 15.5/31/46.5 kHz; c) plume radial pulsing, sound frequencies 17.2/34.4 kHz; d) plume over expanding, sound frequencies 29.9/40.2/51 kHz. Xe, \( p \approx 45 \) bar. Frame size 4.5×4 mm².
Figure 6. Cases of stabilization of a convective plume under the influence of resonant acoustic vibrations. 

a) Stationary tilt of the plume, resonant sound frequencies 8.25/16.5 kHz. 
b) Quasi-stable horizontal heated gas spreading, sound frequencies 16/23/46 kHz. Frame size 4.5×4 mm².

The frames shown in the figures are taken from schlieren video shooting at a speed of 500 frames per second with a shutter speed of 2 ms per frame. The captions under the schlieren frames in fig. 5, 6 show the frequency of periodic-pulse modulation (pulse repetition rate $f_p$), and on the right are the corresponding frequency spectra of resonant acoustic vibrations registered by a piezoceramic sensor.

Figure 7. Schlieren patterns taken for comparison (frame size 4.5×4 mm²): 

a) a frame without plasma: initiating electrodes and inhomogeneities of the quartz walls are seen in the field of view; 
b) convective plume without pulsing at $f_p = 27.5$ kHz; 
c) regular plume pulsing ($f = 52$ Hz in Xe, $p = 45$ bar, as in [17]) at $f_p = 5.07$ kHz, the detachment of toroidal vortex is captured at the top.

Fig. 7 for comparison shows the frames obtained a) without plasma, b) convective plume without pulsations (at some pulse repetition rates, it was possible to observe such quasi-stabilization for a short time), c) normal fluctuations of the plume, which could be observed at all pulse repetition rates, when there were no resonant phenomena.

Using the data [12, 13], it was possible to estimate the main acoustic resonant frequencies in the discharge volume at a given temperature and establish an approximate correspondence between the observed sound frequencies and the excited modes of vibrations. For example, it is easy to see that the case of stabilization of the torch in fig. 6, a) corresponds to the simultaneous excitation of the first and second harmonics of the sound vibration of the minimum frequency along the major axis of the spheroid. Radial types of instability in fig. 5, c) corresponded to the excitation of radial modes. Transverse stabilization in fig. 6, b), as well as fluctuations of the plume from side to side along the horizontal axis and giant vortices were formed when vibrations were excited along the minor axis of
the spheroid in the vertical direction. The expansion of the plume (fig. 5, d) appeared to occur when mixed resonant modes of radial and transverse type were excited. It should also be noted that mixed-type instabilities were often observed. The formation of giant vortices could be combined with fluctuations of the plume from side to side, passing from one type of instability to another, and radial pulsations were often combined with the overexpansion of the plume.

5. Summary and conclusion

In this paper the authors have studied the peculiarities of convective plume pulsations in an important case of combined optical discharge (CPOD) supported simultaneously by two lasers: continuous and periodic-pulse at pulse repetition rates from hundreds hertz to several tens kilohertz.

It was found that the regular pulsations of the convective plume of a combined discharge as a whole are similar to the case of continuous optical discharge. An important difference is that in the case of CPOD periodic-pulse the convective plume pulsation regularity is violated at pulse repetition rates corresponding to multiple fractions of a certain set of resonant acoustic frequencies excited in the discharge volume as an acoustic resonator.

The reason for these violations is the excitation of resonant acoustic oscillations in the discharge volume. As an acoustic resonator standard quartz bulb with a pair of initiating electrodes inside filled with xenon at 15÷45 bar as a plasma-forming gas, has a high Q-factor, which makes it possible to excite high-frequency resonant acoustic oscillations at pulse repetition rates down to 10 times below the excited acoustic frequency at relatively low amplitude of the exciting harmonic.

Several types of violation of the convective plume oscillations regularity upon excitation of resonant acoustic vibrations were found. In most cases the disturbances cause obvious low-frequency fluctuations in the velocity and direction of convective flows in the vicinity of the plasma, which lead to a violation of the regime of plasma sustaining up to the extinction.

In some cases, in particular, when the lowest-frequency fundamental mode of oscillations in the discharge volume is excited, on the contrary, the plasma stabilizes with the suppression of its regular oscillations, apparently as a result of the formation of a directed gas flow at the plasma location under the influence of acoustic oscillations of a certain amplitude and frequencies. The presence of a directed gas flow is indicated by the convective plume inclined to the vertical position or even the horizontal position of the plume indicating gas spreading to the sides, observed simultaneously with the acoustic vibrations at 22.38 kHz.

The following main types of convective plume oscillations were discovered, caused by the excitation of resonant acoustic vibrations in the discharge volume in the form of spheroid with semi-axes $a = 10$ mm, $b = 6.5$ mm:

1. sharp irregular oscillations of the plume from side to side, occurring together with acoustic frequencies around 13 and 26 kHz;
2. the development and separation of giant vortices, observed with acoustic frequencies around 11/22/33 kHz or 15.5/31/46.5 kHz.
3. the super-expansion of the plume, observed with acoustic frequencies over 30 kHz;
4. strong radial pulsations of the plume with simultaneous excitation of acoustic vibrations with frequencies around 17 and 34 kHz, often leading to the extinction of the discharge;
5. stabilization of the plume due to formation of a directed gas flow under the effect of resonant acoustic vibrations observed at sound frequencies of 8.15÷8.25, 22.38, 27.5, 30.8 kHz, while the most stable plume was observed at a main acoustic mode in given discharge volume.

The excitation frequencies of especially strong resonant oscillations, leading to the extinction of the plasma in the range of pulse repetition rates from 3 kHz to 11 kHz, coincided with multiple fractions of the resonant frequencies corresponding to transverse-radial vibrations causing instabilities such as a giant vortices, plume expansions, and radial pulsations. The development of these instabilities caused the extinction of the plasma.

Instabilities expressed in lateral displacements or oscillations of the plume from side to side, sometimes leading to temporary or permanent suppression of regular pulsations, correspond to
different types of resonant vibrations along the major semiaxle of the equivalent spheroid. Instabilities of this type, if they did not lead to plume stabilization, caused strong low-frequency pulsations of the convective plume and plasma itself, but they did not lead as a rule to the extinction of the plasma.

At pulse repetition rates less than 1 kHz plasma stability disturbances were not observed.

Thus, it was shown that during periodic-pulse modulation of CPOD with repetition rates from 1 to 40 kHz, the regularity of pulsations of the convective plume and CPOD plasma stability are violated at pulse repetition rates corresponding to multiple fractions of the resonant acoustic frequencies of the discharge volume as acoustic resonator. The reason for the instability is the excitation of resonant acoustic oscillations in the discharge volume. To maintain the stability of the operation of optical discharges in periodic-pulse or combined modes, it is necessary to take into account the possibility of exciting resonance acoustic oscillations and to avoid operation at pulse repetition rates the same or multiple to the frequencies of certain acoustic modes in a discharge volume.

Acknowledgements

The work was supported in parts by state assignment AAAA-A20-120011690135-5 and RFBR project 18-01-00534 A.

References

[1] Raizer Yu P 1970 *Sov. JETP Lett.* 11 120-123
[2] Generalov N A, Zimakov V P, Kozlov G I, Masyukov V A, Raizer Yu P 1970 *Sov. JETP Lett.* 11 302-304
[3] Smith D K, et al. 2008 patent US7435982; 2012 patent US8309943
[4] Horne S, Smith D, Besen M, Partlow M, Stolyarov D, Zhu H, Holber W 2010 *Proc. SPIE* 7680 76800L [https://doi.org/10.1117/12.850269](https://doi.org/10.1117/12.850269)
[5] Zimakov V P, Kuznetsov V A, Solovyov N G, Shemyakin A N, Shilov A O, Yakimov M Yu 2016 Plasma Phys. Rep. 42 68–73 [https://doi.org/10.1134/S1063780X15110100](https://doi.org/10.1134/S1063780X15110100)
[6] Rudoy I G, Solovyov N G, Soroka A M, Shilov A O, Yakimov M Yu 2015 Plasma Phys. Rep. 41 858–861 [https://doi.org/10.1134/S1063780X15100086](https://doi.org/10.1134/S1063780X15100086)
[7] Antsiferov P S, Koshelev K N, Krivstun V M, Lash A A 2015 patent EP2933823A1; 2016 patent US9357627B2
[8] Arp U, Vest R, Houston J, Lucatorto T 2014 *Applied Optics* 53(6) 1089-1093 [http://dx.doi.org/10.1364/AO.53.001089](http://dx.doi.org/10.1364/AO.53.001089)
[9] Zimakov V P, Kuznetsov V A, Rudoy I G, Solovyov N G, et al. 2015 *Physical and Chemical Kinetics in Gasdynamics* 16(2) [http://chemphys.edu.ru/issues/2015-16-2/articles/548/](http://chemphys.edu.ru/issues/2015-16-2/articles/548/)
[10] Gallo C F, Courtney J.E. 1967 *Applied Optics* 6(5) 939-941; Gallo C F, Lama W L 1977 *Applied Optics* 16(4) 819-820
[11] Sasaki T, Ishii H, Muroi N 1978 *Electrical Engineering in Japan* 98(6) 10-17
[12] Chen Pei-Tai 1996 *J. Acoust. Soc. Am.* 100(5) 2980-2988
[13] Chang C T M 1970 *J. Acoust. Soc. Am.* 49 611–614
[14] IPG Photonics PLD-9xx Diode Lasers [https://www.ipgphotonics.com/en/products/lasers/diode-laser-systems/diode-lasers/pld-diode-lasers#][https://www.ipgphotonics.com/en/products/lasers/diode-laser-systems/diode-lasers/pld-diode-lasers#]
[15] Zimakov V P, Kuznetsov V A, Lavrentyev S Yu, Solovyov N G, Shemyakin A N, Shilov A O, Yakimov M Yu 2016 *Physical and Chemical Kinetics in Gasdynamics* 17(2) [http://chemphys.edu.ru/issues/2016-17-2/articles/653/](http://chemphys.edu.ru/issues/2016-17-2/articles/653/)
[16] Zimakov V P, Lavrentyev S Yu, Solovyov N G, et al. 2018. *Physical and Chemical Kinetics in Gasdynamics* 19(4) [http://chemphys.edu.ru/issues/2018-19-4/articles/754/](http://chemphys.edu.ru/issues/2018-19-4/articles/754/)
[17] Lavrentyev S.Yu., Solovyov N.G., Shemyakin A.N., Yakimov M.Yu. 2019 *J. Phys.: Conf. Ser.* 1394 012012 [https://iopscience.iop.org/article/10.1088/1742-6596/1394/1/012012/pdf](https://iopscience.iop.org/article/10.1088/1742-6596/1394/1/012012/pdf)