*ISSN 1063-780X, Plasma Physics Reports, 2016, Vol. 42, No. 1, pp. 68–73. © Pleiades Publishing, Ltd., 2016.*
*Original Russian Text © V.P. Zimakov, V.A. Kuznetsov, N.G. Solovyov, A.N. Shemyakin, A.O. Shilov, M.Yu. Yakimov, 2016, published in Fizika Plazmy, 2016, Vol. 42, No. 1, pp. 74–80.*

**LOW-TEMPERATURE PLASMA**

# Interaction of Near-IR Laser Radiation with Plasma of a Continuous Optical Discharge

**V. P. Zimakov, V. A. Kuznetsov, N. G. Solovyov, A. N. Shemyakin, A. O. Shilov, and M. Yu. Yakimov**

*A. Ishlinsky Institute for Problems in Mechanics, Russian Academy of Sciences,*
*pr. Vernadskogo 101-1, Moscow, 119526 Russia*
*e-mail: yakimov@lantanlaser.ru*

Received March 19, 2015

**Abstract**—The interaction of 1.07-μm laser radiation with plasma of a continuous optical discharge (COD) in xenon and argon at a pressure of $p = 3–25$ bar and temperature of $T = 15$ kK has been studied. The threshold power required to sustain COD is found to decrease with increasing gas pressure to $P_t < 30$ W in xenon at $p > 20$ bar and to $P_t < 350$ W in argon at $p > 15$ bar. This effect is explained by an increase in the coefficient of laser radiation absorption to 20–25 cm$^{-1}$ in Xe and 1–2 cm$^{-1}$ in Ar due to electronic transitions between the broadened excited atomic levels. The COD characteristics also depend on the laser beam refraction in plasma. This effect can be partially compensated by a tighter focusing of the laser beam. COD is applied as a broadband light source with a high spectral brightness.

**DOI:** 10.1134/S1063780X15110100

## 1. INTRODUCTION

Continuous optical discharge (COD) [1] was obtained for the first time in 1970 [2, 3]. At present, it is applied as a plasma-based light source with a high spectral brightness in a wide wavelength range [4, 5]. Such light sources can be used in microelectronics, photoemission electron microscopy, and ellipsometry, as well as to measure the optical characteristics of materials. Practice shows that the most efficient is application of COD-based light sources in the far UV range ($\lambda < 300$ nm).

These applications became possible due to the appearance of high-efficiency near-IR lasers, in particular, diode lasers and ytterbium fiber lasers, as well as owing to the relatively low threshold power required to sustain COD by these lasers (a few tens of watts in xenon and several hundred watts in argon at high pressures [4–6]). When the laser power substantially exceeds the threshold value, the fraction of laser radiation absorbed by the COD plasma can reach 80% [4]. This, together with the high efficiency of fiber (30%) and diode (50%) lasers, provides high conversion efficiency (up to 15–20%) of the input electrical power into the broadband plasma radiation, close to that of traditional plasma-based light sources, such as xenon arc lamps.

The possibility of sustaining COD in high-pressure noble gases by lasers with a wavelength of $\lambda \approx 1$ μm at such low threshold powers [4–6] was rather unexpected. The matter is that, in the first experiments on sustaining light combustion waves [7, 8] performed with millisecond neodymium lasers ($\lambda = 1.06$ μm) with a high pulse energy, it was established that the threshold power required to sustain plasma in argon and air at atmospheric pressure amounts to several hundred kilowatts. This is about two orders of magnitude higher than the threshold power for plasma sustaining by CO$_2$ lasers with $\lambda = 10.6$ μm.

The same relation between the threshold powers required to sustain COD by radiation with different wavelengths follows from the consideration of mechanisms for the absorption of laser radiation by plasma in the continuous spectrum described by the Unsoeld–Kramers formula [1, 10]. Taking into account photoionization absorption (the Unsoeld correction), the contribution of which at $\lambda = 1$ μm is much higher than that at $\lambda = 10.6$ μm, insignificantly affects the above power ratio.

Estimation of the threshold power for sustaining COD according to the method [1] based on the calculation of the coefficient of laser radiation absorption by the Kramers formula with allowance for only the inverse bremsstrahlung mechanism yields about two orders of magnitude overestimated values of the threshold power as compared to those observed in [4–6]. Although just the Kramers formula was used by the authors of [5] when elaborating a theoretical model, they overlooked that their theory disagreed with experimental results, probably, owing to the applied character of that work.

In the present work, results are reported for the first time from the experimental study of the influence of absorption mechanisms on the threshold power for sustaining COD in xenon and argon by laser radiation with a wavelength $\lambda = 1.07$ μm at different gas pressures.

## 2. SUSTAINMENT OF COD BY LASER RADIATION WITH $\lambda = 1.07$ μm

The experiments were performed in several stages with different continuous and pulse-periodic fiber ytterbium lasers (manufactured at the NTO IRE-Polus, IPG Photonics Corp.) with powers $P$ from 200 W to 1.5 kW. The transverse distribution of laser radiation was close to a Gaussian beam or a mixed low-order mode. Some results were obtained with a YRL-QCW laser operating in the millisecond pulsed mode with a power from 300 W to 1.5 kW. In the focused beam of this laser, the propagation of a plasma wave was observed during one laser pulse from the instant of discharge initiation by an arc channel to the formation of a steady-state plasma, the energy balance conditions in which were close to those in a COD sustained by continuous radiation. The center of the lasing band corresponded to $\lambda = 1.07$ μm, and its width was from 3 to 5 nm, depending on the radiation power.

Plasma was initiated by a short-term arc discharge and then sustained by focused laser radiation inside a sealed quartz bulb of a standard xenon arc lamp with the filling pressure $p_0$ from 8 to 15 bar or a refillable arc lamp filled with xenon or argon at a pressure $p$ (Fig. 1). The focusing parameter $F = f/d$, affecting the shape and stability of the COD plasma (see Section 5 and also [9]), determines the beam converging angle $\alpha$ within which 86% of the laser radiation power propagates. The experiments were carried out at $F$ values from 3.3 to 15 and higher, at which $\alpha \approx 1/F$.

The above pressure range is of interest because it is the range in which the mechanism is manifested of laser radiation absorption due to bound–bound electronic transitions between energy levels of excited xenon atoms under conditions of strong Stark broadening in dense plasma that is in local thermodynamic equilibrium (LTE). At the laser wavelength $\lambda = 10.6$ μm, bound–bound transitions, as well as photoionization, play a minor role; thus, the absorption in this case is caused only by free–free transitions according to the inverse bremsstrahlung mechanism.

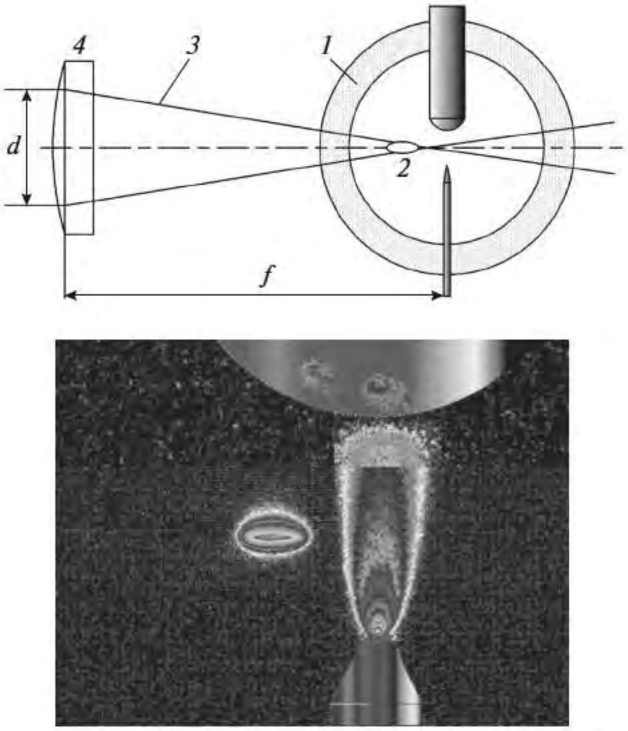

**Fig. 1.** Mutual arrangement of the COD plasma, initiating electrodes, and laser beam: (*1*) bulb with the gas and electrodes, (*2*) COD plasma, (*3*) conventional boundary of the laser beam, and (*4*) lens with a focal length $f$ ($d$ is the beam diameter in front of the lens). The false grey scale photo illustrates the initiation of COD from an arc discharge (the plasma glow is taken with a $10^5$-fold attenuation).

First of all, we experimentally determined how the minimum (threshold) power $P_t$ required to sustain COD depends on the gas pressure $p$. The dependence of the threshold power on the parameter $F$ turned out to be weak, because, near the threshold, refraction of laser radiation in the region of its interaction with plasma was small due to small dimensions of the plasma and its location near the focus. The threshold power level was achieved by either decreasing the laser power at a fixed pressure or decreasing pressure as the lamp was being cooled at a constant laser power. Thus, the pressure range in which COD was observed was limited from below by the maximum power of the laser and from above by the filling pressure of the lamp with allowance for its heating. The obtained experimental dependences for xenon and argon are shown in Figs. 2 and 3. The experimental points were approximated according to the formula $P_t(p) = P_h + P_r$, which follows from the analysis of the energy balance with allowance for laser radiation absorption and the removal of the absorbed energy due to heat conduction and radiation [1]. In this formula, $P_r = \dfrac{2\pi R_0^2 \varepsilon(T_k)}{3\mu_\lambda(T_k)}$ is derived from the radiative loss power of a cylindrical plasma layer of radius $R_0$ at a temperature $T_k$ and $P_h = \dfrac{2\pi\Theta(T_k)}{\mu_\lambda(T_k)}$ is derived from heat conduction losses, where $\mu_\lambda \sim p^2\lambda^2$ is the coefficient of laser radiation absorption and $\varepsilon \sim p^2$ is plasma emissivity. It can be seen that $P_r$ is proportional to $R_0^2$ and depends weakly on $p$ and that $P_h \sim 1/p^2$.

It was found that, for xenon, $p^2 P_h^{\mathrm{Xe}} = 7.7\ \mathrm{bar^2\ kW}$ and $P_r^{\mathrm{Xe}} = 7$ W, whereas for argon, $p^2 P_h^{\mathrm{Ar}} = 26\ \mathrm{bar^2\ kW}$ and $P_r^{\mathrm{Ar}} = 240$ W. The quantity $p^2 P_h$ has the meaning of the threshold power for sustaining COD at $p \approx 1$ bar under conditions in which the energy balance is dominated by heat conduction, while $P_r$ is the threshold power at high pressures under conditions of the radiative balance. These experimental data agree with the results obtained in [4–6] under other conditions and in narrower pressure ranges.

In our experiments, we also measured the powers of laser radiation incident on the plasma and transmitted through it, the spatial distribution of the laser intensity, and the spectral brightness of thermal plasma radiation from COD.

## 3. ABSORPTION OF NEAR-IR LASER RADIATION IN PLASMA

Figures 2 and 3 also show theoretical dependences of the COD threshold power with allowance for absorption only in the continuous spectrum (curves *2*), with allowance for the contribution of strongly broadened atomic absorption lines corresponding to transitions between high-lying excited energy levels of xenon and argon (curves *3*), and with allowance for the contribution of transitions from the lowest excited 4*s* argon levels and 6*s* xenon levels (curves *4*).

The COD threshold power was determined from the analysis of the balance between laser radiation absorption and energy losses due to heat conduction and radiation. The coefficient of laser radiation absorption in plasma was calculated by the Kramers classical formula with the Unsoeld correction, which takes into account photoionization [10]. To take into account absorption caused by intra-atomic transitions in strongly ionized plasma at a high pressure, we

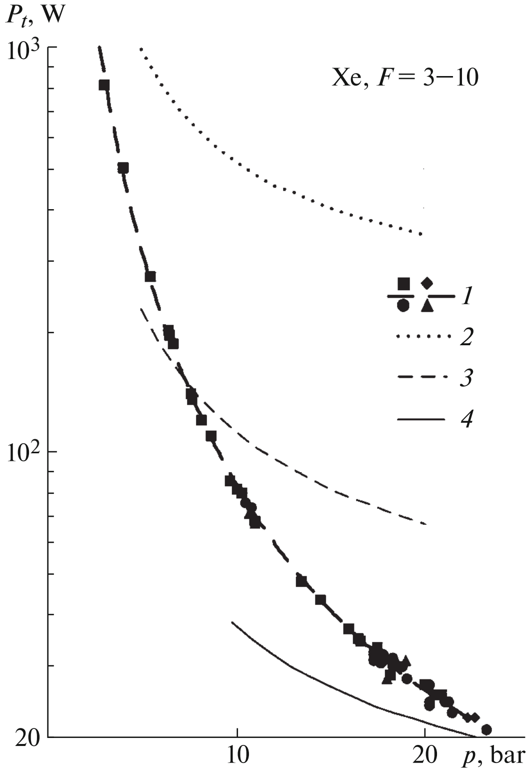

**Fig. 2.** Threshold power $P_t$ for sustaining COD in xenon as a function of the gas pressure $p$: (*1*) experimental data (different points correspond to different values of the focusing parameter $F$ in the range from 3 to 10); (*2*) theoretical estimation with allowance for both the inverse bremsstrahlung mechanism of laser radiation absorption and photoionization (the Unsoeld–Kramers formula [10]); (*3*) the same as in curve *2*, plus the contribution of the processes of laser radiation absorption involving bound electrons of xenon atoms with excitation energies of $E \geqslant 9.4$ eV; and (*4*) the same as in curve *2*, plus the contribution of the processes involving bound electrons with $E \geqslant 8.3$ eV.

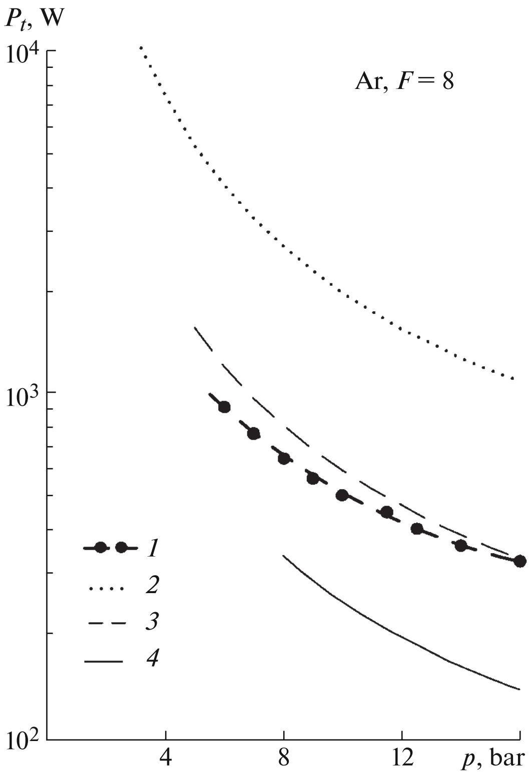

**Fig. 3.** Threshold power $P_t$ for sustaining COD in argon as a function of the gas pressure $p$: (*1*) experimental data obtained with the focusing parameter $F = 8$; (*2*) theoretical estimation with the coefficient of laser radiation absorption calculated by the Unsoeld–Kramers formula [10]; (*3*) the same as in curve *2*, plus the contribution of the absorption processes involving bound electrons with excitation energies of $E \geqslant 12.8$ eV; and (*4*) the same as in curve *2*, plus the contribution of the processes involving bound electrons with $E \geqslant 11.6$ eV.

applied an approach similar to the Unsoeld approach describing photoionization, as it was done in [11] to take into account the contribution of strongly broadened lines to the integral plasma radiation. The minimum COD threshold powers observed in our experiments corresponded to the values of the absorption coefficient $\mu \approx 20–25\ \text{cm}^{-1}$ in Xe and $\mu \approx 1–2\ \text{cm}^{-1}$ in Ar.

For xenon (Fig. 2) at relatively low pressures on the order of the atmospheric one, the threshold power for sustaining COD corresponds to the absorption mechanisms described by curve *2*, disregarding the possible contribution from intra-atomic transitions. This is because, at such pressures, the atomic absorption lines are relatively narrow and the laser wavelength $\lambda = 1.07\ \mu\text{m}$ is far from strong absorption lines of xenon. In the range of middle and high pressures, the Stark broadening of spectral lines makes it necessary to take into account the contribution to absorption from high-lying excited states of xenon (curve *3*). As the pressure increases further, the overlapping wings of spectral lines form a pseudo-continuum. In this case, it is necessary to take into account the integral contribution of all excited xenon states (curve *4*). Thus, the theoretical dependences calculated with allowance for different components of the coefficient of laser radiation absorption (Fig. 2) demonstrate that the contribution of electronic transitions between excited xenon states gradually increases in with increasing pressure because of the broadening of the energy levels of the xenon atom.

For argon (Fig. 3), good agreement was obtained without allowance for the levels lying below the 4*p* group (the excitation energy 12.8 eV), because the energy of a photon with the wavelength $\lambda = 1.07\ \mu\text{m}$ ($h\nu = 1.16$ eV) is lower than the energy of the 4*s*–4*p* transition of argon even in the case of strong broadening.

For xenon, the 6*s*–6*p* transitions lie closer to the laser radiation band and, due to the broadening, the role of 6*s*–6*p* transitions increases with increasing pressure, which leads to an increase in the absorption coefficient and the corresponding decrease in the COD threshold power at high pressures.

It follows from these data that it is possible to further decrease the COD threshold power by decreasing the laser wavelength. Comparison of the structures of the argon and xenon terms allows us to conclude that, for radiation with the wavelength $\lambda = 0.96\ \mu\text{m}$ ($h\nu = 1.3$ eV, which is close to the energy of the 4*s*–4*p* transition in argon), the pressure dependence of the COD threshold power should be similar to the analogous dependence for radiation with the wavelength $\lambda = 1.07\ \mu\text{m}$ in xenon with a correction for the higher thermal conductivity of argon. Thus, it can be expected that, for a diode laser with the wavelength $\lambda = 0.96\ \mu\text{m}$, the threshold power of sustaining COD in argon at a pressure of $p > 16$ bar is at a level of $P_t \approx 100–150$ W, i.e., about three times lower than that at the wavelength $\lambda = 1.07\ \mu\text{m}$.

## 4. THERMAL RADIATION AND PARAMETERS OF COD PLASMA

The brightness of the COD plasma is determined by its dimensions and temperature, which are established as a result of the balance between laser radiation absorption and plasma energy losses. Figure 4 shows the experimental data on the spectral brightness $I_p(\lambda)$ of the COD plasma sustained by laser radiation with the wavelength $\lambda = 1.07\ \mu\text{m}$ in xenon at a pressure of

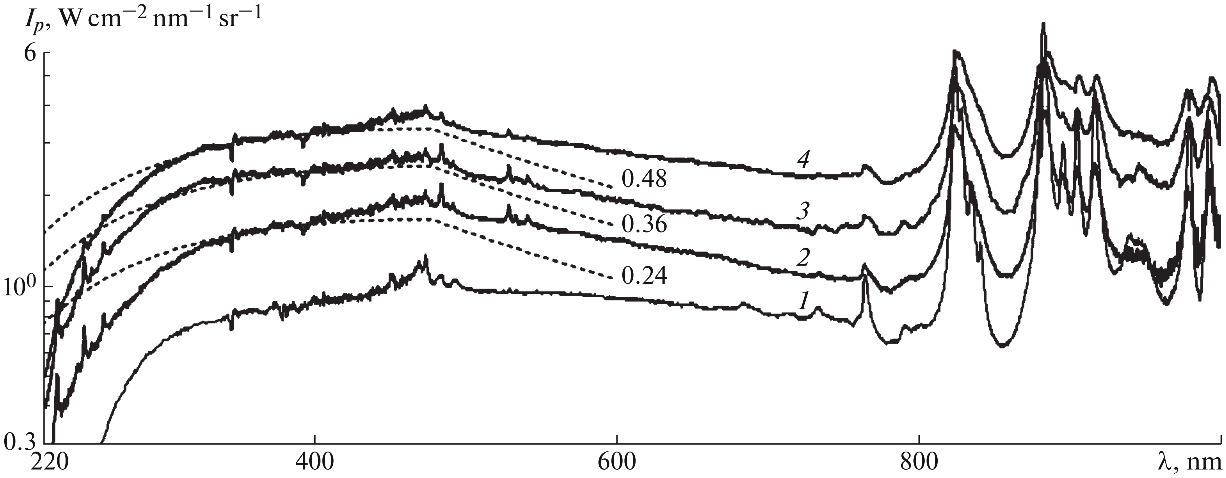

**Fig. 4.** Spectral brightnesses $I_p$ of the COD plasma and an arc discharge in xenon at a pressure of $p = 22 \pm 2$ bar (the COD is sustained by laser radiation with the wavelength $\lambda = 1.07\ \mu\text{m}$ and different powers *P*; the focusing parameter is $F = 3.3$): (*1*) arc discharge, (*2*) COD at $P = 65$ W, (*3*) COD at $P = 85$ W, and (*4*) COD at $P = 230$ W. The dashed lines show the results of calculations of the spectral brightness of a plane slab of LTE xenon plasma with a temperature of $T = 15$ kK and pressure of $p = 22$ bar for different slab thicknesses: $s = 0.24$, 0.36, and 0.48 mm. The calculation method is described in [10, 11].

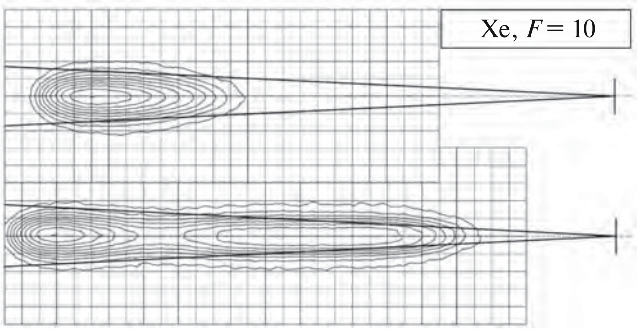

**Fig. 5.** Two different states of COD in xenon at a pressure of $p = 20 \pm 2$ bar, laser power of $P = 146$ W ($\lambda = 1.07$ μm), and focusing parameter of $F = 10$. Plasma is shown by contour lines of the brightness plotted with a step of 10% of the maximum brightness against the background of a coordinate mesh with a cell size of 0.1 × 0.1 mm. Laser radiation is incident from left to right. The straight lines show the optical axis and the beam boundary in the absence of plasma. The state of "short" plasma is on the top, and the state of "long" plasma with two temperature maxima is on the bottom. Both states can be stable at the given parameters [9].

$p \approx 22$ bar. The figure also presents the comparison of the brightnesses of the COD plasma and the arc discharge of a high-pressure xenon lamp. Data for the COD and arc discharge were obtained by comparing the measured brightnesses with the brightness of a reference source by using the same device under the same conditions. It can be seen that, as the laser power rises, the COD brightness increases and becomes several times higher than the brightness of the arc discharge, especially in the UV range, which indicates the higher temperature of the COD plasma. The high COD temperature is also indicated by the increase in the intensity of xenon ion lines as compared to the spectrum of the arc discharge.

The temperature of the COD plasma can be estimated by comparing the COD spectral brightnesses measured at different laser powers with those calculated by the method proposed in [10, 11] for a plane uniform plasma slab that is in the LTE state with a definite temperature. Since the experimentally observed increase in the COD spectral brightness with increasing laser power was accompanied by an increase in the plasma size in the observation direction, it can be supposed that the plasma temperature did not change and variations in the plasma brightness were caused by the change in the thickness of the radiating plasma layer. It turned out that, for the temperature of LTE plasma of $T = 15$ kK and the plasma slab thickness in the range of $s = 0.24$–$0.48$ mm, which corresponds to the actual transverse size of the COD plasma (see Fig. 5), the observed and calculated spectral brightnesses were in good agreement in a fairly wide spectral range (Fig. 4). These calculations are estimating in character, because they do not take into account variations in the temperature and plasma emissivity along the observation line. However, since the LTE approximation holds for the COD plasma, the calculated plasma temperature can be regarded as a certain average temperature, leaving aside the strong temperature dependence of the plasma brightness. The decrease in the actual plasma brightness as compared to the results of model calculations for the wavelength range shorter than 300 nm is due to the fact that the UV component is mainly radiated by the hottest central COD regions, which occupy a small volume and, thus, make a small contribution to the integral radiation. This is a manifestation of the inhomogeneity of the COD plasma, which was disregarded in the calculations.

## 5. EFFECT OF LASER RADIATION REFRACTION ON THE COD BEHAVIOR

An important factor affecting the plasma characteristics is refraction of laser radiation on the density gradients of neutral and charged plasma particles. Refraction leads to defocusing of the laser beam in the region where it interacts with the COD plasma and, thus, affects the shape, dimensions, and location of plasma. A specific feature of refraction of radiation with a wavelength of $\lambda \approx 1$ μm in the COD plasma is that the density gradients of neutral atoms and free plasma electrons introduce comparable contributions to the resulting refraction [9]. When the influence of refraction is strong, the plasma brightness increases weakly (or even decreases) with increasing laser power.

The refraction effects can be compensated by a tighter focusing of the laser beam. The higher the pressure (and, accordingly, the higher the absorption and refraction of laser radiation in the gas and plasma), the tighter the focusing should be. For a small focusing parameter $F$ (tight focusing), the COD plasma is located near the focus, its relative elongation is nearly proportional to $F$, the plasma absorbs well laser radiation, and its brightness increases with increasing radiation power (see Fig. 4). To sustain plasma with small linear dimensions and a high brightness, one should focus the laser radiation by a lens with a small focusing parameter $F$. If the parameter $F$ exceeds a certain value that depends on the gas pressure and the relative role of refraction, the plasma elongates and acquires a structure with two or three temperature maxima along the laser beam axis (the state of "long" plasma in Fig. 5). As the parameter $F$ increases further, stable operation of COD is violated, plasma shortens stepwise, its rear edge removes away from the focus, and the COD passes into a mode with low laser radiation absorption ("short" plasma). There is a rather wide intermediate region of $F$ values in which both above plasma states are observed at the same values of the laser radiation power and gas pressure, i.e., a hysteresis effect takes place. In this case, the state of "long" plasma is implemented when the laser power

DOCKET ALARM

# Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

## Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

## Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

## Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

## API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

### LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

### FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

### E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

**WHAT WILL YOU BUILD?** | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.