Bistable behavior of a continuous optical discharge as a laser beam propagation effect

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ABSTRACT

Two stable configurations of a continuous optical discharge (COD) were observed in experiments with plasma sustained continuously in xenon at high pressure by radiation of a medium power CW ytterbium fiber laser.

One is the plasmoid of relatively small length with one temperature maximum and laser beam absorption of 10-30%. The other one is the plasma formation stretched along the laser beam with two or three local temperature maxima. The laser beam absorption in the second plasma configuration is increased dramatically up to 70-80% due to increased plasma length.

Both plasma shapes were obtained under close conditions, so that oscillations between the two states were possible and also have being observed.

The effect was studied and explained on the base of simplified consideration of the laser beam propagation through lens-like plasma medium surrounded by refractive near-spherical bounds between cold and hot gas.

Other experimental results on the sustaining conditions of COD and plasma properties are also presented.

Keywords: laser sustained plasma, continuous optical discharge, COD, laser beam refraction, ytterbium fiber laser, plasma bistability

1. INTRODUCTION

Continuous optical discharge (COD) in which dense plasma is sustained due to absorption of CW laser radiation is now one of a few and maybe most effective and convenient method to produce stationary plasma with temperature 20-25 kK under atmospheric and elevated pressure in the laboratory. The phenomenon of COD was theoretically predicted and first obtained in the experiment in A.Ishlinsky Institute for Problems in Mechanics in 1969-1970[1,2].

The review of the main results of theoretical and experimental studies of COD carried out since that time may be found in[3,4]. For years as the possibilities of producing COD have being further developed with the improvement of high power CW lasers, mainly CO_2-lasers, general COD characteristics and sustaining conditions were found experimentally, COD plasma diagnostics were developed, theoretical models for calculation and prediction COD properties were created. Nevertheless in spite of the success in COD studies and understanding, its industrials and technological applications are greatly limited by high maintenance and operation costs together with relatively low efficiency of high power CO_2 lasers, almost exclusive used for COD production and investigation.

Now we can observe a tremendous upgrowth of the industrial solid state lasers technologies. The combination of the characteristics of modern industrial fiber or disc solid-state CW lasers, such as output laser power, laser efficiency and high beam quality, just of mass produced models, are close or above that of gas lasers applied in industry for years. Good choice as candidate laser for COD sustaining at 1.07 um wavelength may be modern industrial solid state ytterbium fiber

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laser[6]. Now multikilowatt CW ytterbium lasers of up to tens kilowatts output power are available as well as perfect beam quality very high brightness CW lasers of up to 6 kW output power. Total efficiency of high power fiber lasers may achieve from 20% up to 30% depending on beam quality.

Till now authors know one or two correspondences that may be treated as containing some scientific information on the practical realization of COD with lasers emitted radiation around 1.07-1.09 um[5,16], and there are a big lack of detailed papers reported on systematic scientific studies of the properties of COD plasmas and its sustaining conditions by radiation around 1 um in more or less wide range of parameters. Nevertheless the results of studies like that if they were carried out would have decisive impact on the real prospects of the near-IR lasers in the promising field of dense plasma sustaining and generation.

The studies are required because laser beam absorption mechanisms around 1 um laser wavelength are different than that of around 10 um, where COD is studied relatively well. For instance, the quantum energy of CO_2 laser radiation is $h\nu$ = 0.117 eV is too low for photoionization (bound-free) absorption mechanism to be effective, so that radiation of CO_2 laser is absorbed mainly through inverse bremsstrahlung mechanism (free-free transitions). The quantum energy of the ytterbium laser is $h\nu$ = 1.16 which may also cause photoionization from the upper levels of the electronically excited atoms – they only should already be thermally excited – or photoelectronic transitions between the upper levels. If one takes into account that absorption through free-free transition is proportional to λ^2, he will recognize that bound-free and bound-bound transitions are the only possibility for the continuous optical discharge to be realized around 1 um. Different absorption mechanisms should lead to different properties of COD plasmas produced by CO_2 or Yb laser radiation.

In this paper we have summarized our first results obtained on the sustaining of COD with ytterbium fiber lasers at λ = 1.07 um in Xe under high pressure from 10 up to 22 bar. The lasers we have used in the experiments operated at low order mixed transverse mode (M^2 = 5) and close to the lowest order transverse single mode (M^2 < 1.1). Continuous optical discharge obtained with these two different lasers also demonstrated distinctly different behavior, which may be also attributed to the shorter wavelength. The most interesting effects observed with single mode laser – two locally stable plasma states and transition between that states – should be treated as the effect of the shorter wave beam propagation in plasmas. The data obtained in the paper may be already used for theoretical generalization and estimations of the effectiveness of plasma generation with lasers around 1 um in various gases at different pressures.

2. LASER POWER REQUIRED TO SUSTAIN COD (PRELIMINARY ESTIMATIONS)

Preliminary estimations of the laser power required to sustain COD were done for xenon at elevated pressure as the most favorable gas to sustain COD because of its low thermal conductivity and low ground state ionization energy (I = 12,12 eV). Let us estimate minimum laser power required to sustain COD (so called threshold of sustaining) by laser radiation at λ = 1.07 um in xenon under high pressure p = 15 bar. The estimation may be done on the base of simplified energy balance considerations as it was done in [7]. Focused laser beam at λ = 1.07 um has relatively small diameter from several to several tens microns depending on the focusing lens and beam quality [6]. The estimation is further simplified by the fact that near the threshold plasma is localized near the focus where plasma dimensions are small and plasma thermal radiation losses proportional to the plasma volume are small. Also near the threshold the absorption of the laser beam is also small due to small plasma length along the beam pass, so that one can treat laser beam as not attenuating in plasma (low absorption approximation). So laser power deposited and removed by thermal conductivity, which are equal in stationary case, may be written as [7]:

$$\mu_\lambda(T)P = A\pi\Theta(T), \qquad (1)$$

where Θ – heat flux potential ($\Theta(T) = \int_0^T C(t)dt$, where $C(t)$ – heat conductivity depending on temperature), P – laser beam power, A – geometry factor, depending on radial temperature profile (suppose A ≈ 2 [7]), $\mu_\lambda(T)$ – laser beam absorption coefficient. Θ and μ are sharply increased with temperature at 10-15 кK, while their ratio defining P ~ $\Theta(T)/\mu_\lambda(T)$ have minimum, which magnitude $(\Theta/\mu_\lambda)_{min}$ may be used for the threshold laser power estimations, transforming formula (1) to the expression for a threshold power P_t:

$$P_t = 2\pi\left(\frac{\Theta}{\mu_\lambda}\right)_{min} \quad (2)$$

Dependence $\Theta(T)$ can be found from known temperature dependence $C(t)$ for equilibrium xenon plasma when electron component of thermal conductivity dominates (see [8] for instance). Dependence $\mu_\lambda(T)$ can be found by Kramers-Unsoeld formula [9] that describes free-free and bound free absorption processes and does not take into account absorption due to possible bound-bound transition. Plots $\Theta(T)$, $\mu_\lambda(T)$, and $\Theta(T)/\mu_\lambda(T)$, for Xe at p = 15 бар, are presented at Fig.1.

Threshold laser beam power for λ = 1.07 um for sustaining COD in xenon under the pressure p = 15 бар, calculated from data presented in Fig. 1 by formula (2), is about $P_t \approx 180$ W. Thus one can found that in the pressure range p = 10-20 bar the estimation for P_t is varied correspondingly from 310 to 125 W decreasing with pressure.

If one turn to more detailed computer based calculations for the spectral absorption continuum μ_λ (also without taking to the account bound-bound processes)[10-12] for the pressure p = 15 bar and wavelength λ = 1.07 um, our estimation for COD sustaining threshold power should be further increased up to $P_t \approx 550$ W because of the decreased value of the calculated continuum absorption coefficient of $\mu_\lambda \approx 0.5$ см$^{-1}$ – considerably lower than used in our rough estimation on Fig. 1.

To estimate possible bound-bound transitions component in the laser beam absorption coefficient, that is not so easily calculated, we can use experimental data for radiation absorption in the center of the spectral emission line of the cathode region of high pressure xenon arc discharge, presented in [13]. At measured pressure p ≈ 16 bar, temperature 11 kK and absorbing plasma thickness d = 0.15 cm, the absorption in the center of spectral line λ = 1.053 um was measure to be 28.5%, which correspond to absorption coefficient value $\mu_\lambda \approx 2$ cm^{-1} at $T \approx 11$ kK. Based on the data from Fig. 1, where both $\Theta(T)$ and $\mu_\lambda(T)$ are growing with T, but their ratio $\Theta(T)/\mu_\lambda(T)$ weakly depends on T and have minimum in the temperature region of interest, let us use value $\mu_\lambda \approx 2$ cm^{-1} for COD threshold estimation to obtain $P_t \approx 50$ W for the laser radiation at wavelength λ = 1.053 um. But at λ = 1.07 um situation may be different because this laser wavelength does not coincide with stronger emission/absorption lines λ = 1.053 um and λ = 1.089 um in this spectral region.

Thus different estimations based both on the rough analytical and more precise computer calculations, as well as on the experimental data on the absorption coefficient of the radiation with wavelength around λ = 1.07 um in plasma under p = 15-16 bar lead to the COD sustaining threshold values which differ more the by the order of magnitude $P_t \approx$ 50-550 W. Nevertheless this estimations could help us to define required laser power which can guarantee COD sustaining in the experiment – above 1 kW.

3. SUSTAINING COD IN XENON WITH LOW ORDER MIXED MODE Yb LASER

We have used ytterbium fiber laser YLS-1[6] granted by NTO "IRE-Polus" (Russian branch of IPG Photonics, Inc.) especially for our experiment. The experimental layout is presented at Figure 2.

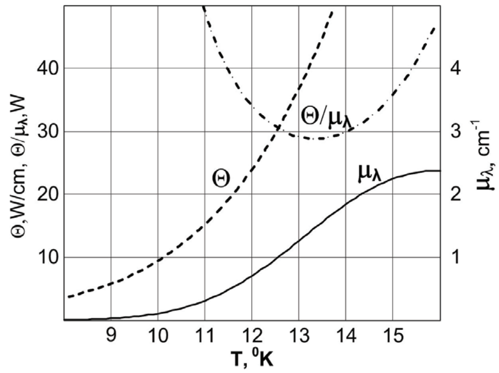

Figure1. Temperature dependences of a heat flux potential Θ(T), laser radiation absorption coefficient μ_λ(T), and threshold laser power factor Θ(T)/μ_λ(T),for xenon under p = 15 bar.

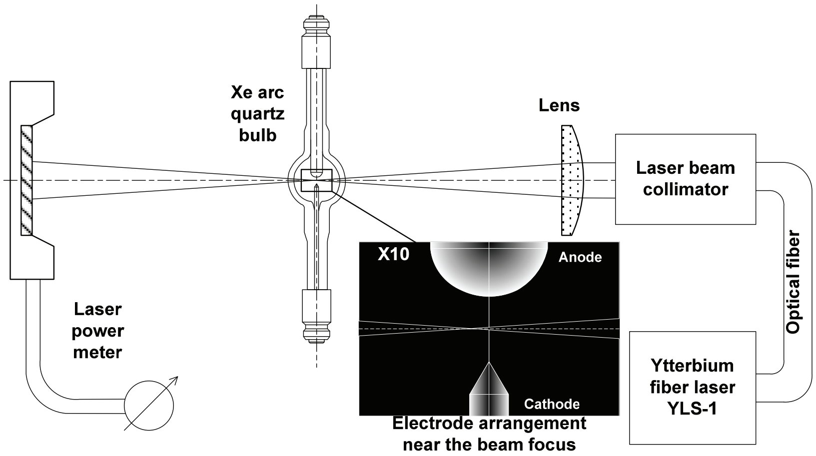

Figure 2. Experimental set up for sustaining COD and measuring sustaining beam characteristics.

Laser maximum power was 1 kW CW, beam quality corresponded to mixed low order mode of up to 3-rd order with $M^2 = 4.9$, laser emitted radiation in spectral band centered at $\lambda = 1.07$ um with width changed from 2 to 5 nm as the power was increased. Focused beam spot diameter was about 50 um with F/7.2 beam focusing number.

Stable xenon plasma sustained by absorption of a part of incident laser radiation was obtained at p = 14-18 bar inside the spherical quartz bulb of a standard high pressure xenon arc lamp. The lamp was filled with p = 11 bar of xenon at room temperature, and during the experiment temperature of the bulb has being changed in the limits of 100-200^{0}C depending on the incident and absorbed laser power. Incident laser power was varied in the limits P = 50-200 W.

Laser sustained plasma has being initiated from an electric arc column when laser power was increased above the threshold value. COD threshold value in Xe at p ≈ 15-16 bar was found to be $P_t \approx 50$ W. Upper power level of 200 W in the experiment was limited by safety reasons to protect 200W arc lamp from overheating.

Plasma was located in the convergent part of the focused laser beam, with rear front displaced by 0.3-1 mm from focal point toward the focusing lens (Figure 3). The plasma ball shape was corresponded to the conical shape of the sustaining beam, so that the diameter of the glowing part of the plasma ball defined through the plasma image luminosity isolines was close to the beam diameter but slightly higher.

The dimensions of plasma were measured as dimensions of plasma image luminosity isoline on the level of ~20% of maximum luminosity. When incident power has being set slowly growing from 55 to 185W, plasma length was increased correspondingly from 0.6 to 1.2 mm and its diameter from 0.23 to 0.42. Beam diameter corresponded to the plasma front edge (closest to the lens) was then changed from 0.1 to 0.3 mm.

Incident laser power fraction absorbed in plasma was increased with incident power tending to saturation at 30%. Mean absorption coefficient defined from Beer-Lambert law was decreased from 3.5-3.6 cm^{-1} at lowest COD supporting incident power 55 W to 2.7-2.8 cm^{-1} at upper power limit. Absorption at the lowest power limit is higher because in this case plasma diameter is twice higher than beam diameter, so that beam is passed through the most heated central parts of the plasma. At the upper power limit plasma diameter is closer to the beam one while a periphery of the beam cross section is less absorbed in the outer cold plasma layers.

Deposited power density in the volume of beam-plasma interaction is achieved 3 MW/cm^3. Plasma energy balance has being studied by absorbed power measurements and absolute plasma radiation balance measurements, the last has being compared to that of standard electric arc xenon lamp of equal power. It was found that radiated power fraction in spectral region from 200 to 1100 nm is on the level of 50-60% of the absorbed laser power. Residual power is removed out of the plasma volume by heat conductivity and convection.

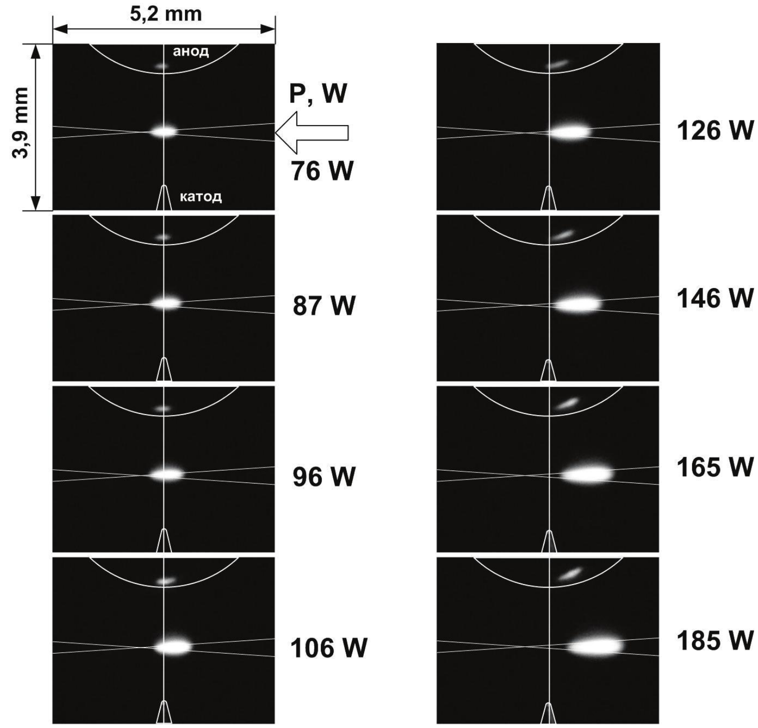

Figure 3. Plasma appearance, position and dimensions of COD sustained by CW Yb fiber laser YLS-1. Electrodes and laser beam arrangement are depicted by solid white lines. Photos were taken with light attenuation by 10^5 times.

When compared to thermal radiation of an electric arc lamp, COD plasma luminosity is about or higher than most luminous part of the arc column near the arc cathode. Also COD thermal radiation spectra demonstrate intensive continuum in the violet and ultraviolet parts of spectrum, giving the evidence of high plasma temperature.

3. ON THE MECHANISMS OF HIGH LASER RADIATION ABSORPTION IN PLASMA

It was treated for a long time since COD was obtained for the first time with CO_2 laser (λ = 9.4-10.6 um) that near infrared lasers ($\lambda \approx 1$ um) can not be used for efficient sustaining of COD because of low absorption coefficients of laser radiation and correspondingly high sustaining threshold[7,9]. This thesis has being confirmed by experimental data obtained for so called laser combustion waves sustained by radiation of powerful long pulsed Nd-glass lasers (λ = 1.06 um, pulse energy about kilojoules, pulse length – milliseconds) in the atmospheric pressure air[14]. In this case bound-bound transitions apparently did not contribute to the laser beam absorption, because absorption coefficient at λ = 1.06 um was 200 times lower than that for λ = 10.6 um, as it is predicted by Kramers-Unsoeld formula[9].

In the case of high pressure xenon high absorption coefficients observed in our experiments could not be explained only by free-free and bound-free transitions. As can be seen from COD power threshold estimations in the above chapter, absorption is being mainly determined by interatomic bound-bound transitions between energy levels of the upper excited states of xenon. Spectral band of YLS-1 laser radiation centered at λ = 1070 nm is 2-5 nm wide. Laser band is close to the lines of the emission spectrum of xenon plasma centered at λ = 1053, 1071, 1076, 1084, 1090 nm. The only Xe line within the band of the laser (λ = 1071 nm) is the weakest line. The strongest lines in close vicinity of the laser band (λ = 1053 nm and λ = 1090 nm) may participate in the absorption only with their wings. The last presumption is confirmed by our observation that laser radiation spectrum is subjected no change after passing through absorbing plasma. As the pressure and temperature increased, emission and absorption lines are broadened by collisional and Stark broadening, so that line participation in absorption becomes more and more significant with pressure.

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