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H_β-LINE PROFILE MEASUREMENTS IN OPTICAL DISCHARGES

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Abstract—In the electrical field of a focused beam of a cw or repetitively pulsed high power CO_2 laser, a so called optical discharge can be continuously sustained. Under cw conditions, using laser power up to several kW, the plasma has typically a charge carrier density of about $10^{24}\ m^{-3}$ and a temperature of about 2×10^4 K. The maintenance of the discharge requires gas pressures $\geqslant 0.5$ MPa in the discharge vessel. By applying a pulsed CO_2 laser system in our experiment with a maximum of 10^4 pulses/sec, 50 mJ/pulse, pulse length 0.2 μsec and average power 500 W, the plasma density during the laser pulse can be enhanced up to about the cut-off density at $\lambda = 10.6\ \mu m$ ($\approx 10^{25}\ m^{-3}$); the electron temperature can also be increased. This paper presents a short survey of the equilibrium state and energy balance of the cw and pulsed discharge. Experimental data concerning the minimum maintenance power and the temperature field of the cw discharge, as well as the temporal development of electron temperature and density in the pulsed discharge, are given. In particular, results are shown for optical discharges in hydrogen, where the Balmer H_β-line is studied in the cw discharge up to electron densities of $1.2 \times 10^{24}\ m^{-3}$ and in the pulsed discharge up to $5 \times 10^{24}\ m^{-3}$. Line profiles, asymmetry and broadening of the H_β-line are compared with theoretical data available in the literature.

1. INTRODUCTION

The development of powerful pulsed and cw lasers since the mid-1960s has encouraged scientists to study new phenomena occurring in a gas or on a solid or liquid surface during irradiation by strong laser light. In the electrical field of a focused laser beam oscillating with optical frequencies a discharge can be sustained. We call this an optical discharge (OD). The first experiments used pulsed laser systems, Maker et al;[1] later cw lasers were used, Raizer,[2] Generalov et al.[3] The experiments described below are characterized by the following data: as a light source an oscillator–amplifier CO_2-laser system of the axial type is used, which delivers cw power up to 5 kW running in the TEM_{OO} mode. Pulsed operation with a maximum repetition rate of about 10^4 Hz, pulse width 0.2 μsec, maximum power of 250 kW and average power of 1 kW is also possible. Typical parameters of the continuous optical discharge (COD) in H_2, Ar, N_2 and He are: pressure 0.5–20 MPa, equal temperature of charge carriers and neutrals $(1\text{–}2) \times 10^4$ K, and electron density $10^{23}\text{–}1.2 \times 10^{24}\ m^{-3}$. The pulsed optical discharge (POD) was exclusively studied in a hydrogen atmosphere under pressure of 1–5.5 MPa. The electron temperature unequal to the heavy particle temperature, reaches 10^5 K and the electron density is raised to nearly $10^{25}\ m^{-3}$ (cut-off density). The non-ideality factor in COD and POD experiments is about 0.1.

2. IGNITION AND MAINTENANCE OF OD

Ignition of OD is possible if the applied alternating electrical field in the laser focus accelerates, at random, a few electrons and if their final kinetic energy is sufficient to ionize neutrals. The developing avalanche can survive if the electron number during the build-up phase is not reduced too much by diffusion, recombination and attachment processes. Thus, a threshold field strength (intensity I_{th}) is needed to start the breakdown. Typical threshold intensities are of the order of $10^{13}\text{–}10^{14}\ Wm^{-2}$ for the CO_2-laser wavelength. This beam intensity in a focus is easily realized by chopping the laser between oscillator and amplifier by means of a toothed wheel (100 turns/sec,

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The cw maintenance intensity I_m, is much lower and can be estimated from a simple energy balance of the electrons. As can be seen from Fig. 1, the average laser intensity near the laser focus, assuming a focused laser beam of power P_L, can be written

$$I = P_L/\pi w_0^2. \tag{1}$$

The electron gas is powered by the process of inverse bremsstrahlung in the course of collisions between electrons and ions (atoms), where the absorptive regime in the beam direction has a length

$$L_{abs} \approx 1/K_\nu, \tag{2}$$

where the absorption coefficient (m^{-1}) is given by Offenberger et al[4] as

$$K_\nu = 2.25 \times 10^{-39} n_e^2 T_e^{-3/2}, \tag{3}$$

with n_e the electron density (m^{-3}) and T_e electron temperature (K). τ is the time of dwell of electrons in the absorption regime of volume $L_{abs} \cdot \pi w_0^2$. The laser beam has to supply at least the energy $P_{L_{min}} \cdot \tau$ to provide the ionization energy E_I for all electrons in the volume (where we neglect their kinetic energy), thus we have

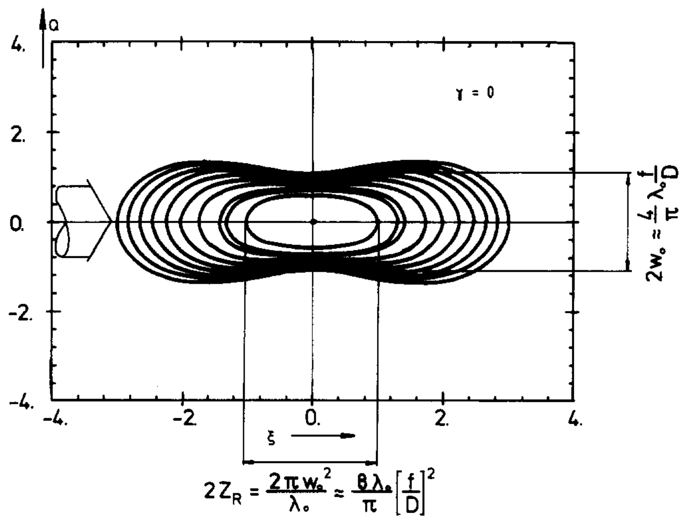
$$P_{L_{min}} \approx \frac{E_I \cdot n_e \cdot \pi w_0^2}{K_\nu \cdot \tau}. \tag{4}$$

The dwell time τ is governed by ambipolar diffusion losses, attachment, radiative and three-body collisional recombination losses. Introducing the diffusion length Λ and neglecting attachment we can write

$$P_{L_{min}} \approx \frac{w_0^2}{\Lambda^2}\frac{A(T_e)}{n_e} + w_0^2 \cdot B(T_e) + w_0^2 \cdot n_e \cdot C(T_e), \tag{5}$$

where A, B and C are related to the coefficient of diffusion, radiative and three-body collisional recombination. In low pressure OD the diffusion term governs the minimum maintenance power $P_{L_{min}}$, where the beam waist nearly cancels because $\Lambda \approx w_0$. At higher pressures the three-body recombination dominates, $P_{L_{min}} \sim w_0^2$ and, therefore, the advantage of optical focusing systems with large aperture is obvious (see Fig. 1). Figure 2 compares values of $P_{L_{min}}$ calculated according to Eq. (5) with experimental data determined from a hydrogen COD.

If the laser power P_L exceeds $P_{L_{min}}$ a COD burns in the vicinity of the focal point. With slowly increasing laser power the COD widens up and the position of maximum temperature is shifted more and more towards the focusing optical system, see Uhlenbusch.[5] A similar behavior can be found in POD.



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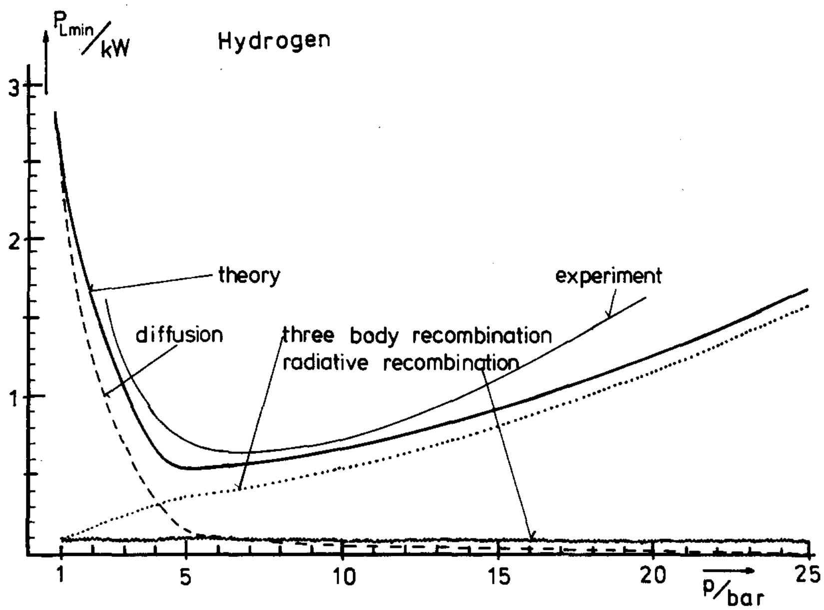


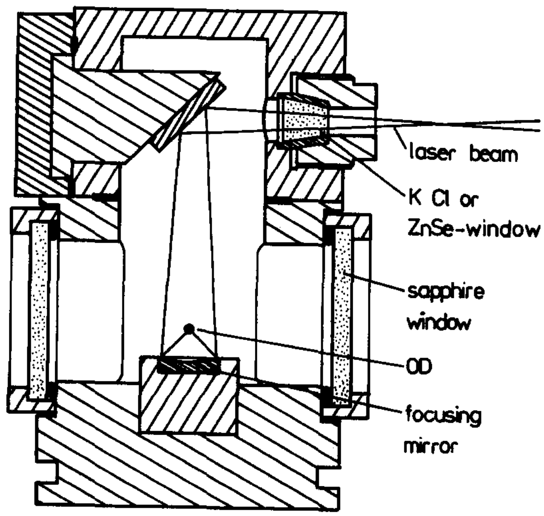
Fig. 2. Minimum maintenance laser power plotted vs pressure.

3. THE EXPERIMENTAL SET-UP

COD and POD are produced by the beam of a powerful CO_2 laser in the cw or pulsed mode and focused into a high pressure chamber (see Fig. 3).

To achieve good mode structure (OO-mode), stability of the laser beam, and high pulse repetition rate, the laser is built-up as an oscillator–amplifier system (see Fig. 4 and Mucha et al[6]).

The output of a maximum 80 W cw CO_2 laser oscillator running in the OO-mode is amplified by means of 14 discharge tubes of 0.61 m length each with superimposed axial gas flow. To produce POD, an intracavity CdTe Pockels cell is operated with a maximum repetition rate of 10^4 Hz, a rise time of 75 nsec and a pulse width of 500 nsec. The intracavity switching of the oscillator generates laser pulses with maximum 10^4 Hz repetition rate, 200 nsec pulse width, 2–4 mJ pulse energy and 10–20 kW peak power. After passing the amplifier, pulses of 50 mJ energy and 500 W average power are available. The maximum pulse power of around 250 kW is sufficient to ignite POD in hydrogen without any external agent. Ignition of COD is performed by a toothed wheel (see Fig. 4) brought in between oscillator and amplifier. Lateral ports of the discharge chamber (see Fig. 3) allow a thorough diagnosis of the COD plasma, see also Uhlenbusch.[5] We



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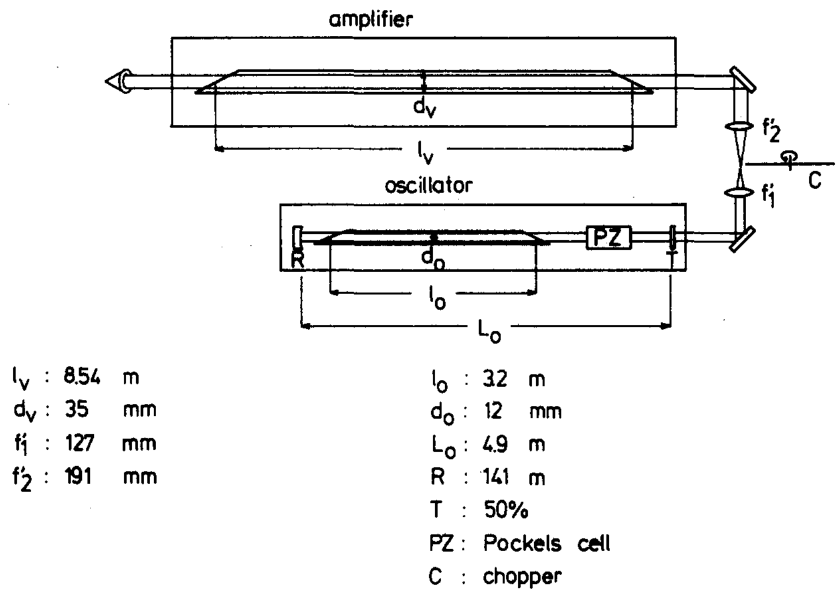
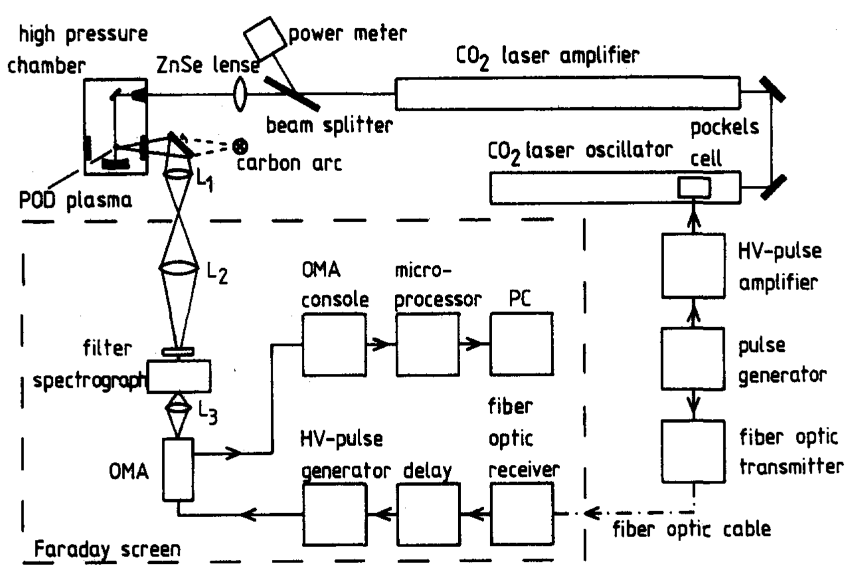


Fig. 4. The CO_2 laser system.

note that (i) spatially and time resolved absolute line and continuum spectroscopy, in connection with Abel's inversion, is a very useful tool to find local temperatures and densities in COD and POD and to derive gas temperatures from switched-off discharges; (ii) interferometry is applied to study the stability of COD and to measure temperature profiles in the vicinity of the optical discharge, see Carlhoff et al;[7] (iii) laser-Doppler-anemometry is used to measure the local flow field inside the discharge vessel during COD operation, see Krametz.[8]

The most significant information can be derived from spectroscopy. The complete set-up for spectroscopic measurements is shown in Fig. 5.

For COD side-on measurements the plasma is imaged by the two lenses, L_1 and L_2, on the entrance slit of a spectrograph ($f = 0.125$ m). The spectrally resolved side-on signals are recorded by an optical multichannel analyser (OMA system) with 500 channels. After averaging over 30 cycles the signals are stored on a disk. Spatial resolution is achieved by moving the lens L_2 horizontally across the plasma, thereby recording the spectral intensity and performing Abel's inversion at 50 positions. The procedure is repeated after having tilted the line of sight into another vertical position. Calibration is made with a tungsten ribbon lamp.



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In the case of POD, the OMA system is additionally gated by a pulse with 1.2 kV height, 100 nsec pulse width and the same repetition rate as the CO_2-laser pulse. By shifting the "time window" a temporal resolution of spectroscopic signals is possible. For calibration purposes a carbon arc is now used.

4. EXPERIMENTAL RESULTS

Applying the diagnostic techniques mentioned in Sec. 3, the density, temperature and flow field within and outside COD burning in argon, helium and hydrogen were measured. Thus, the local properties of the COD plasma as a function of laser power, pressure, working gas etc. were well known. COD plasmas are near to LTE conditions with $T_e \approx T_g$ and are quite convenient for producing electron densities up to $1.2 \times 10^{24}\,m^{-3}$ at moderate (2×10^4 K) temperature.

POD discharges in hydrogen of the type studied here reach nearly cut-off densities ($10^{25}\,m^{-3}$ for the CO_2 laser wavelength), electron temperatures in the 10^5 K regime with $T_e \neq T_g$, and PLTE conditions. In the following, the properties of COD and POD in hydrogen are studied with emphasis on the absolute spectral intensity of the H_β-line and its underlying continuum emitted by neutral hydrogen atoms.

In Fig. 6, a section of the H_β-line with the underlying continuum emitted by a COD plasma is shown. The ambient pressure was 1 MPa, the cw laser power supplied to the COD was 2.8 kW, the emitting volume had a temperature of 16,400 K and the appropriate electron density was $1.1 \times 10^{24}\,m^{-3}$. The resulting line width is 25.6 nm. Evaluation of this extremely broadened line profile is troublesome because the far wings were not measured, the blue wing is distorted by H_γ and the quadratic Stark effect induces asymmetrices of the line. For evaluation of this line, we proceed with the following trial and error method (see also Carlhoff et al[9]). Assuming an estimated n_e which follows roughly from the (full) line width $\Delta\lambda_{1/2}$ using Griem's[10] formula

$$n_e = C \cdot \Delta\lambda^{3/2}, \tag{6}$$

we can derive an appropriate $T_e \simeq T_g = T$ value from Saha's equation. Using this T-value, the absolute line intensity of the H_β line and the underlying continuum (dash–dotted line in Fig. 6)

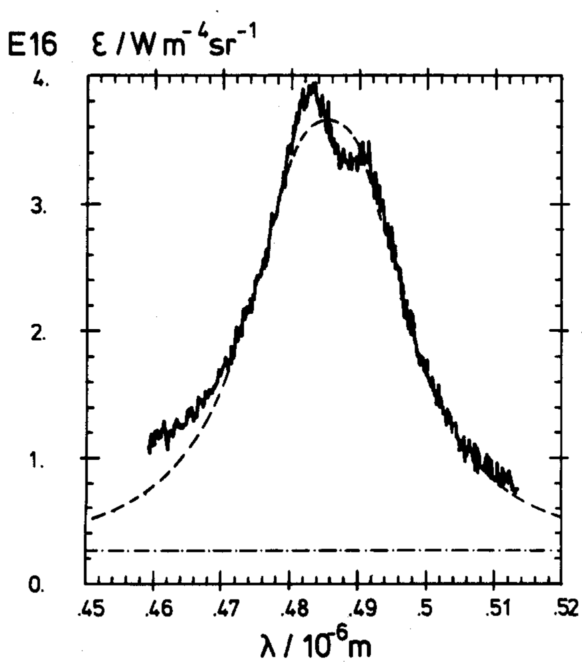

Fig. 6. Measured H_β-line profile from COD with fitted theoretical profile and continuum. $p = 10^6$ Pa.

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