Interaction between a CO\textsubscript{2} laser beam and an atmospheric pressure argon plasma jet

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Abstract: This paper deals with the experimental study of the interaction between a pure argon plasma column and a low power CO\textsubscript{2} beam laser (power lower than 20 W). The laser plasma interaction is completely described using inverse bremsstrahlung. Emission spectroscopy measurements don’t show any temperature increase, but the modulation of the laser power allows to produce a photoacoustic effect.

Keywords: Argon plasma, inverse bremsstrahlung, photoacoustic effect.

1. Introduction

Laser plasma interaction [1] is currently employed to carry out informations on a plasma and to determine parameters such as species densities or temperatures. It is clear that the wavelength value and the power of the laser allow to produce different kinds of interactions, leading to different effects such as laser induced fluorescence (LIF), four waves mixing . . .

In the case of a CO\textsubscript{2} laser beam that operates in the infrared part of the electromagnetic spectrum (wavelength $\lambda=10.6$ µm), laser plasma interaction can be physically interpreted by the induced motion of free electrons in the electrical field of the electromagnetic wave. Collisions between electrons and heavy particles of the plasma (neutral atoms and ions) then explains the absorption of electromagnetic energy from the electromagnetic wave to the plasma. This process of inverse bremsstrahlung is common for arc plasmas for infrared wavelengths and was earlier studied by Chapelle et al.[2].

This paper presents an experimental study of the interaction of a pure argon plasma column and a low power CO\textsubscript{2} laser beam performed by emission spectroscopy an atomic argon lines and by recording the sound produced by the absorption of the time modulated CO\textsubscript{2} laser beam.

2. Theoretical background

Heating of a plasma by absorption of laser energy occurs by inverse bremsstrahlung whereby the laser radiation is absorbed by free electrons [3, 4, 5, 6]. The electrons will then transfer energy to ions and neutral atoms by collisions. The absorption coefficient $\alpha$ (in cm\textsuperscript{−1}) for inverse bremsstrahlung is given by:

$$\alpha = 7.8 \times 10^{-9} \frac{Z_i N_e^2 \ln A}{\nu^2 T_e^{3/2} \left(1 - \frac{\nu^2}{\nu_p^2}\right)^{1/2}}$$  \hspace{1cm} (1)$$

where $Z_i$ is the ionic charge, $N_e$ the electron density (in cm\textsuperscript{−3}), $A$ the high-frequency screening parameter, $T_e$ the electron temperature in eV, $\nu$ the laser frequency and $\nu_p$ the plasma frequency.

According to equation (1), we see that $\alpha$ is proportional to $T_e^{-3/2}$; thus, the efficiency of inverse bremsstrahlung will increase as electron temperature decreases. In other words, inverse bremsstrahlung preferentially heats low energy electrons, keeping the plasma close to thermodynamic equilibrium allowing us to use common local thermodynamic equilibrium assumption to interpret the emission spectroscopy data.

3. Experiment

To study the interaction of an electromagnetic wave with a plasma we have applied two types of diagnostics: the optical emission spectroscopy and the photoacoustic effect investigation. At first, the diagnostics of the plasma column was performed by recording spectral lines of neutral argon.

The plasma source presented in figure 1 operates with DC current at atmospheric pressure with pure argon. The anode is a disc (diameter: 10 cm) made in copper, and water cooled. The cathode is a tungsten cylinder of 3.2 mm diameter, water cooled. To obtain a stable plasma column, the distance between the anode and the cathode tip is fixed at 6 mm for an argon flow of 3 Nl/min and a current intensity of 100 A.

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![Figure 1: Plasma source (free burning arc).](image-url)
equipped with a 1200 grooves/mm grating working in the first order. Photodetection is made with intensified controller model 1455 of Princeton Instrument with a single line of 770 intensified pixels of a matrix CCD possessing an internal Peltier cooler, and it is linked to a detector controller model 1461.

4. Results and discussion

The diagnostic of the plasma jet has been made by recording the ArI line at 696.5 nm side on in order to perform Abel inversion on the line profile. The full width at half maximum (FWHM) of each line profile was determined with a fitting procedure based on a theoretical lorentzian line profile. The Stark broadening parameters of the ArI 696.5 nm line then allowed to obtain the electron density as a function of the radius in the plasma jet, and finally the electronic temperature by considering a local thermodynamic equilibrium model (T&Twinner software) [9].

Figures 4 and 5 respectively present the electron density profile and the electronic temperature profile obtained with the operating conditions of the plasma column presented before.

Figure 2: Experimental setup.

The plasma torch is put vertically on a lateral translation device equipped with stepped motors (CharlyRobot) allowing to scan the position of the plasma jet in order to perform Abel inversion during the plasma diagnostic operation.

The CO₂ laser used in this experiment is a 20 W CO₂ laser (Synrad, Mukilteo, WA, USA), with a wavelength of 10.6 µm. The laser beam is gaussian with a radius of 3 mm. The power of the laser was measured using the laser power meter Power Wizzard 250 (Synrad, Mukilteo, WA, USA). In order to increase the laser power density in the interaction area with the plasma column, the laser beam is focalized with a ZnSe lens (focal distance of 127 mm). This allows to obtain a power of 325 W on the focusing point which radius is 2.86 × 10⁻⁴ m [7].

The experimental setup employed to study the photoacoustic emission of the arc column [8] is presented in figure 3.

Figure 3: Experimental setup for photoacoustic study.

The CO₂ is modulated using a frequency generator (model TG1010 from Thurlby Thandar Instrument). The acoustic signal is recorded with a high sensitivity Brel & Kjaer microphone. In order to extract the acoustic signal from the noise present in the laboratory, we have used a lock in amplifier (model SR850 Stanford Research Sys-
ature variation is visible by the spectroscopic diagnostics, we can calculate the power absorbed by the plasma column by measuring the power of the laser with and without plasma. The power of the laser without the plasma is $P_0 = 12.57$ W, and reaches the value $P_1 = 10.17$ W when the plasma is switched on. The power absorbed in the middle is thus 2.4 W, that is approximately 20% of the total power of the laser.

The energy of the laser being deposited on the perpendicular direction of the observation direction, the zone warmed by the laser is weak compared with the zone studied by spectroscopy (see figure 6). We think that the temperature variation produced by the laser, observed in the perpendicular direction of the laser beam is too weak to be detectable in these experimental conditions. We thus chose to study the effect of the laser by recording argon lines in the direction of the laser beam, by using an optical fiber: we did not carry out any change in the argon lines intensities.

![Figure 6: Plan of the arc column (seen by the top)](image)

Experimental results obtained with the photoacoustic mounting are presented in figure 7 for a laser modulated at the frequency of 4 kHz. The fast Fourier transform of the microphone signal (figure 8) shows a peak at 4 kHz, coming from photoacoustic effect produced by the modulated laser absorbed. Let us underline a peak located at the frequency near 100 Hz produced by the electrical power devices.

![Figure 7: Sound amplitude (laser modulated at 4 kHz)](image)

![Figure 8: Fast Fourier Transform of the signal presented in figure 7.](image)

The evolution of the sound amplitude as a function of the laser frequency modulation is presented in figure 9. For modulation frequencies lower than 1300 Hz, there is no sound emission. Between 1450 Hz and 5000 Hz, we notice an increase of the sound amplitude. These results are not in agreement with the theoretical predictions of photoacoustics that foresee a decrease of the sound amplitude with an increase of the laser frequency modulation.

We have to keep in mind that the acoustic wave is generated at the focusing point of the laser beam in a moving medium, because the velocity of the arc column. The interpretation of the behavior of the sound amplitude as a function of the laser modulation frequency needs further work to be clearly interpreted.

![Figure 9: Sound amplitude as a function of the laser modulation frequency.](image)

5. Conclusion

The interaction of a CO$_2$ laser beam with a free burning arc operating in pure argon has allowed us to produce a photoacoustic effect, corresponding to the conversion of the laser radiation into an acoustic wave. In addition, we think that the behavior of the sound amplitude when the laser frequency modulation increases is linked to the velocity of the arc. This effect could be a possible way to measure the arc velocity.
References


