H_a- Line Characterization of Electronic Density in Plasmas Generated by Laser Shock Processing

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OUTLINE:

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- Experimental Results
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    - Electron Temperature
    - Relative Atom and Ion Densities: Saha Equation
- Summary and Conclusions
- Acknowelwdgements
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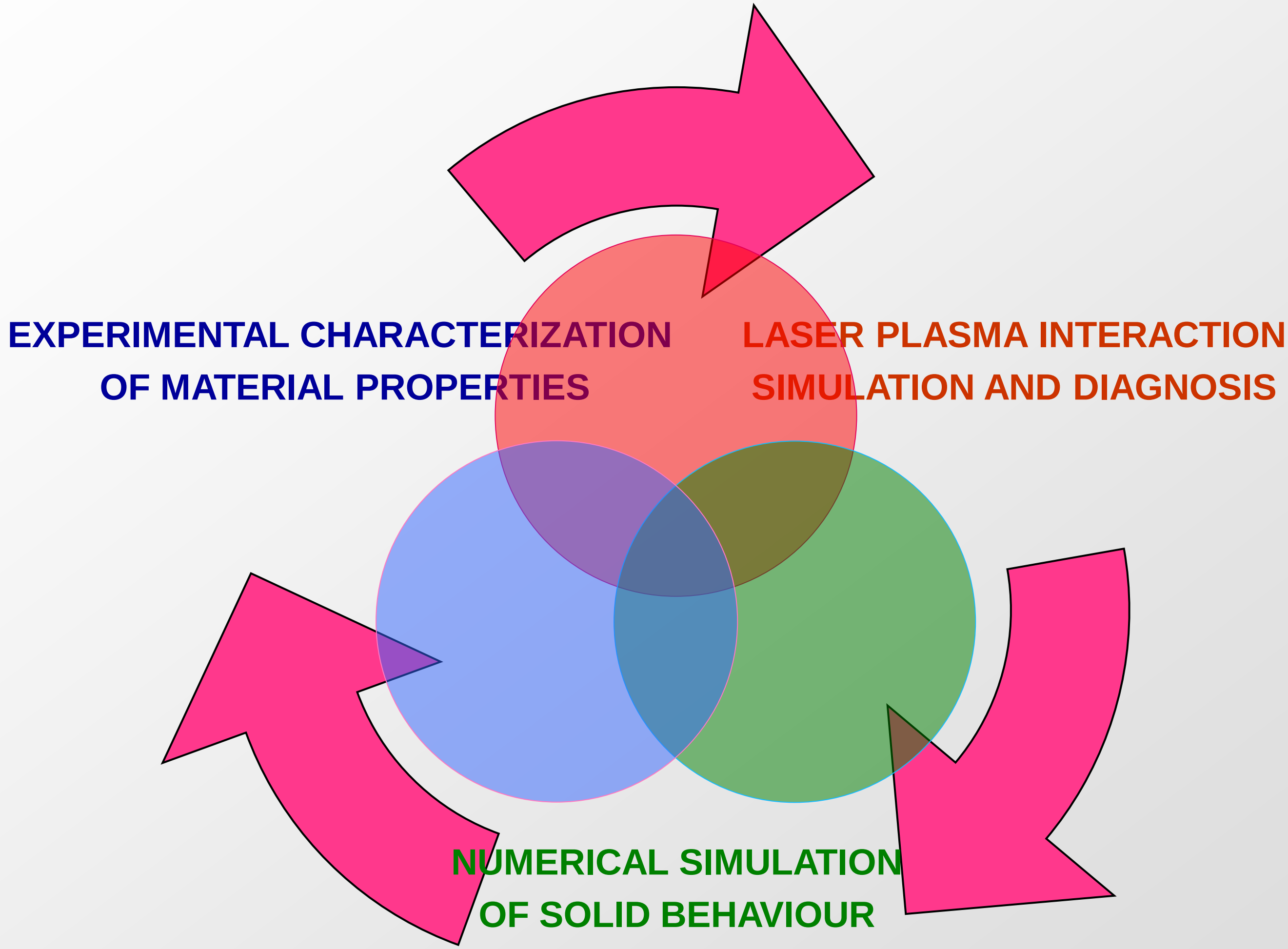
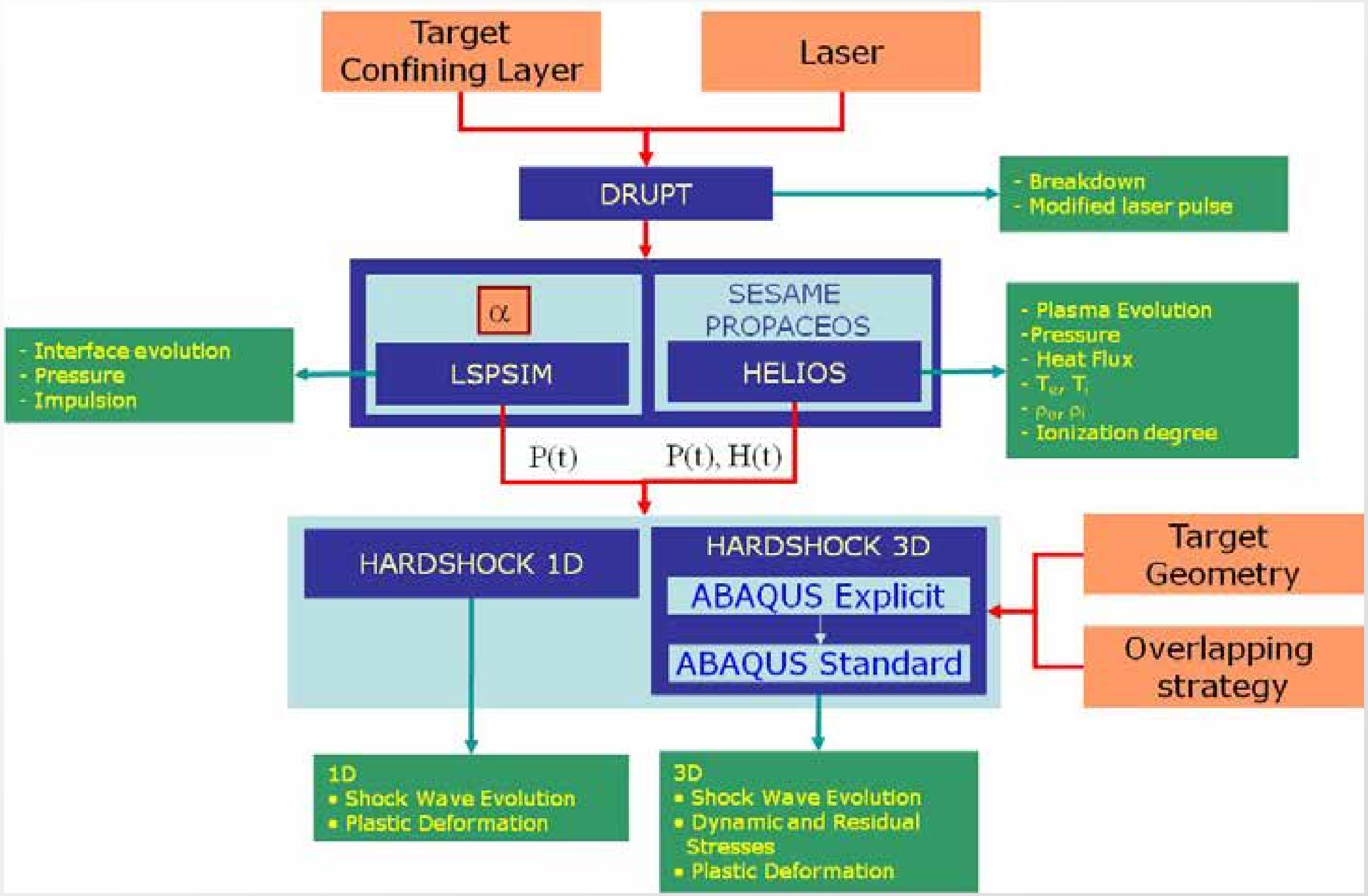
INTRODUCTION

- Laser Shock Processing (LSP) is based on the application of a high intensity pulsed Laser beam ($I > 10^9$ W/cm^2 ; $T < 50$ ns) on a metallic target forcing a sudden vaporization of its surface into a high temperature and density plasma that immediately develops inducing a shock wave propagating into the material.
- One of the physical processes that should be deeply studied consists of the interaction between plasma and the surface of the material and how it can be affected by mechanisms different from the mere mechanical interaction with the shock wave. To study such process, it is necessary to know the properties of plasma generated by the interaction between the laser and the metallic surface. This type of plasma studies have been realized for years and they are known as Laser Induced Breakdown Spectroscopy (LIBS).
- The difference of this research with the classical LIBS technique either in air or in liquid medium, depends on the shielding the flow water applies on the emission of every present species in the plasma but for the Hydrogen emission.

The UPM Laser Centre Approach to LSP Development

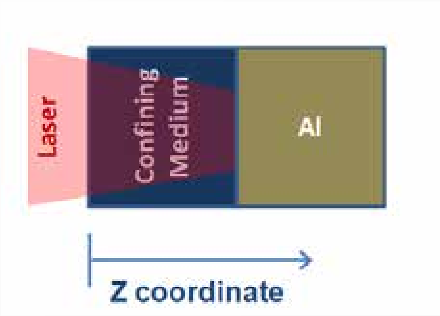


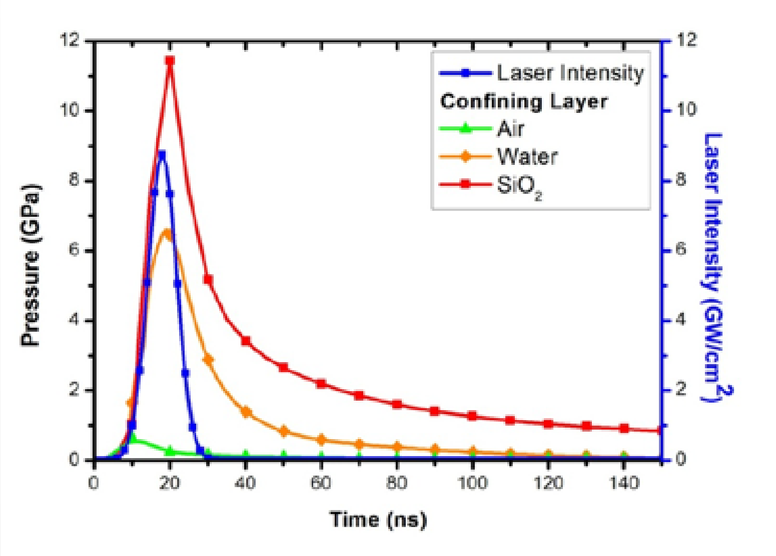
The SHOCKLAS Calculational System

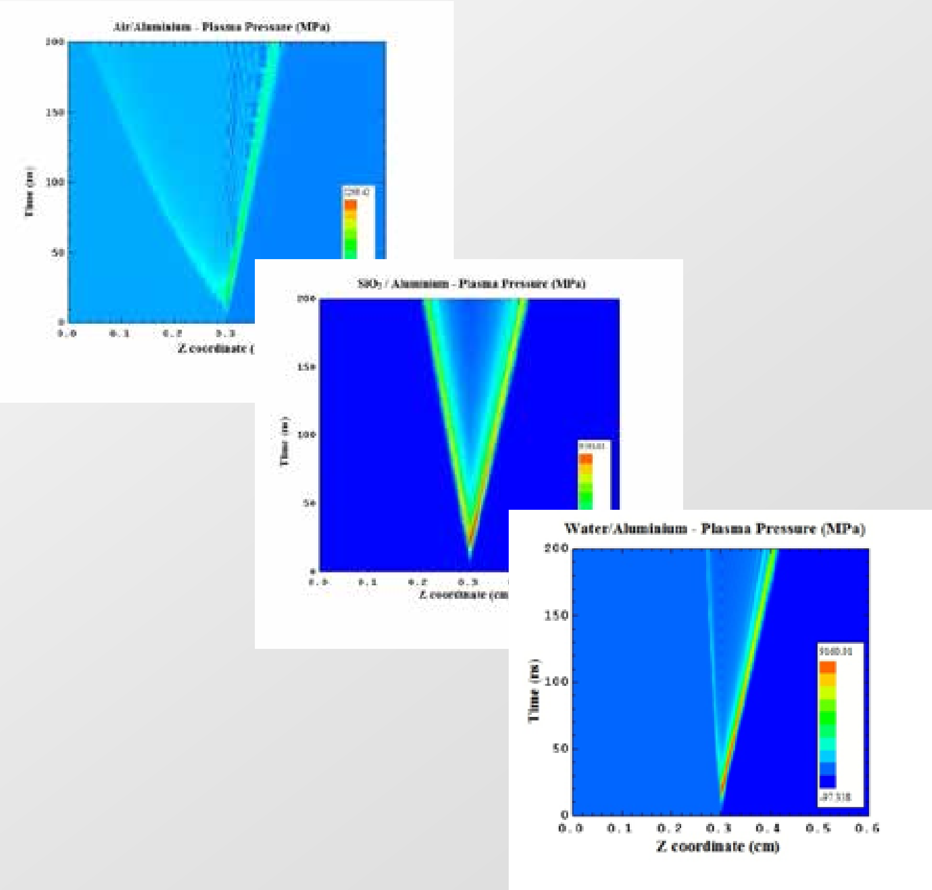


CONSISTENT MODEL FOR CONFINED PLASMA EXPANSION IN LSP

HELIOS — Analysis of relative influence of confining material







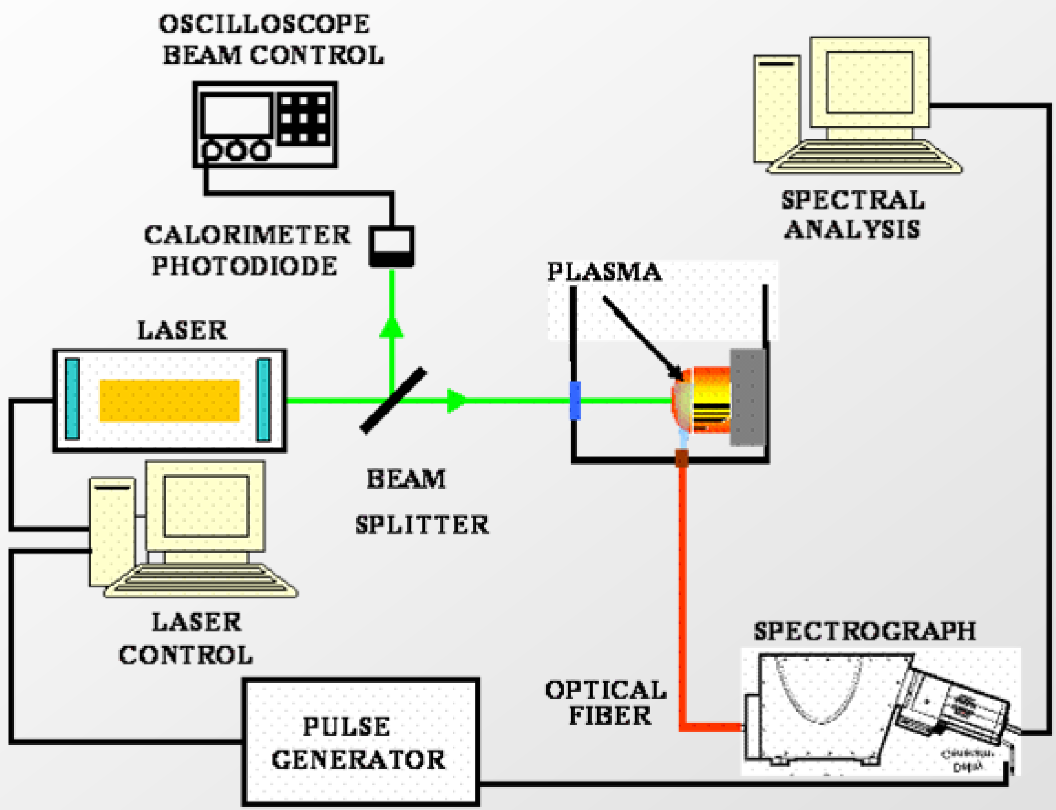
INTRODUCTION

- In this work, by using the classical LIBS technique, the plasma density has been measured using H_{α}-line. H_{α}-line is a well isolated line, it gives large signal to background ratio, it lasts a long time after the termination of the laser (up to 10 μs), its Stark width is relatively large and does not exhibit self-absorption.

- This procedure has been realized in experiments with a sample of aluminum (Al2024-T351) in air, wet air and water flow. Also, where possible (air and wet air) other species have been used (Al II, Cu I, Mg I and Mg II) in an attempt to estimate the plasma temperature.

- The measures were realized with different delay times after the laser (4-8 μs) and with a measure time window of 1 μs.

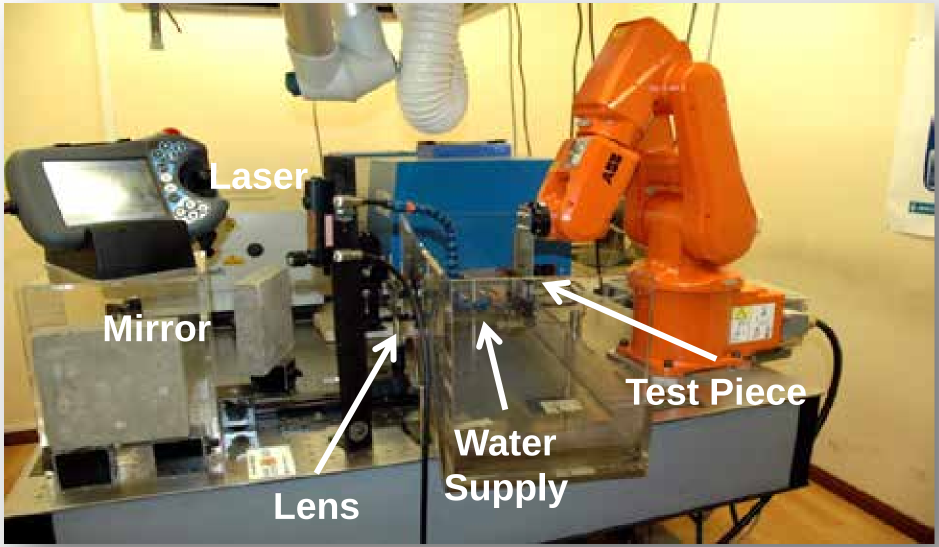
PROCESS EXPERIMENTAL SETUP

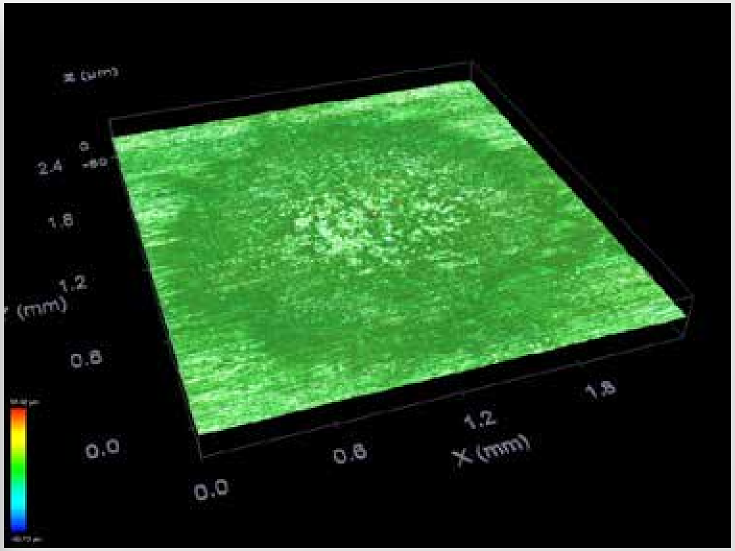


The reported LSP treatments were performed using a Q-switched Nd:YAG laser with a wavelength of 1064 nm, 10 ns pulse length and 2.5 J per pulse, focused onto a sample. This device is similar to those used in the LIBS experiments.

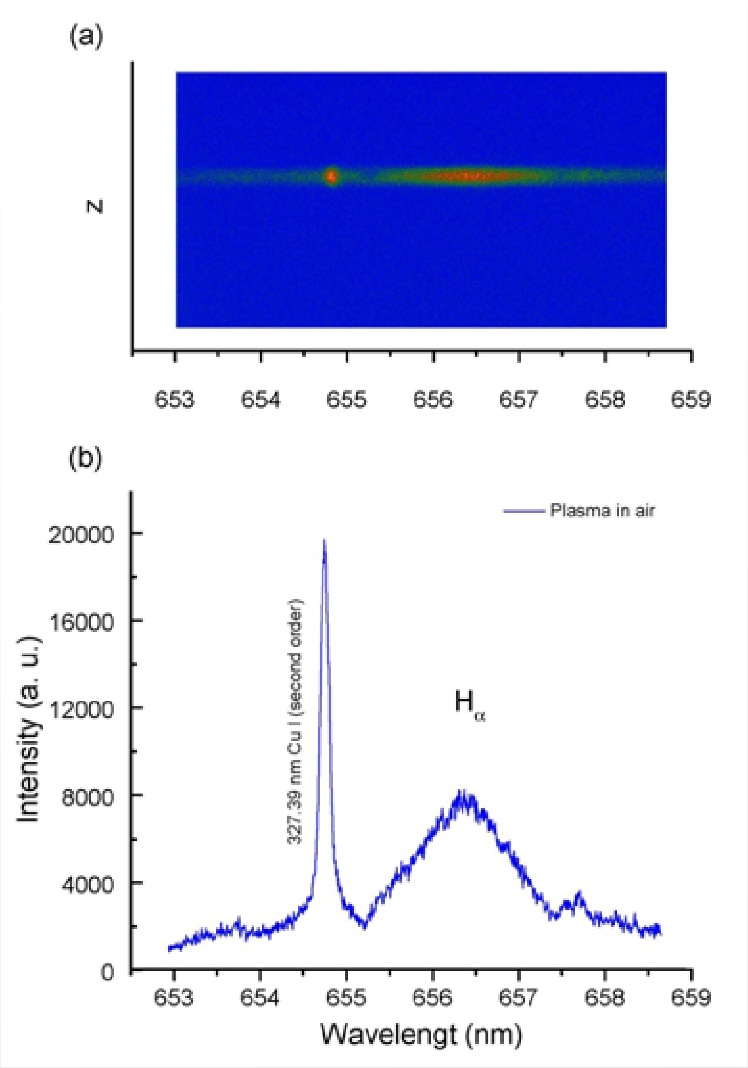
PROCESS EXPERIMENTAL SETUP

The target used is a certified aluminum based alloy (Al2024-T351) with a Mg content of 1.16 %. The spot size, measured at the target surface, was a circle of diameter 2.0 mm.





PROCESS EXPERIMENTAL SETUP



A CCD bidimensional camera, 1024 x 1024 pixels (26 x 26 μm^2 size per pixel) has allowed to study the plasma spatially.

The camera is time-controlled both in gate and delay with a maximum resolution of 100 ns.

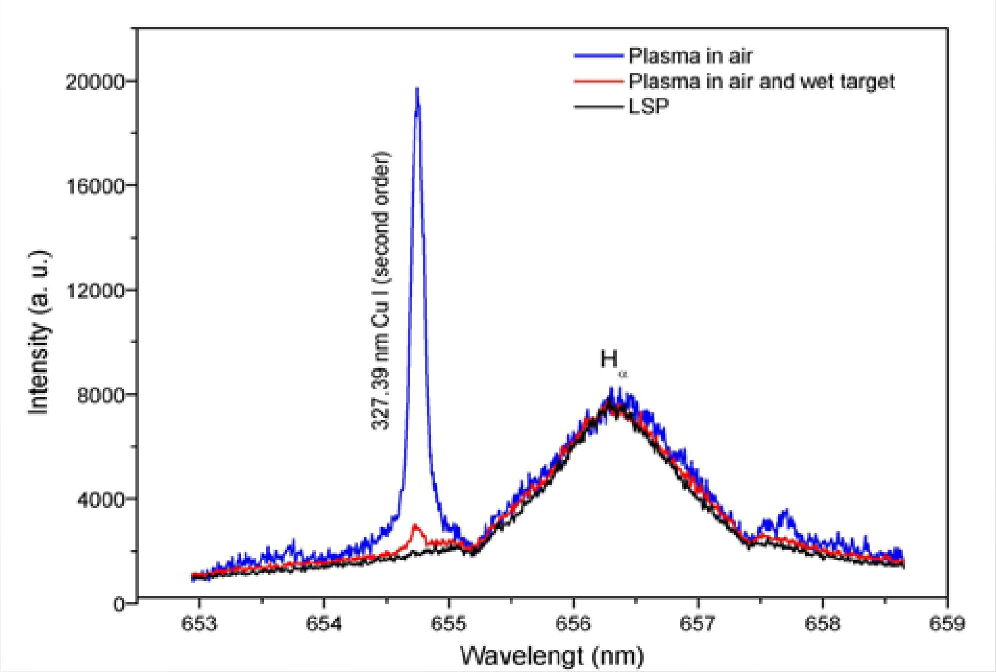
The spectrometer is equipped with a diffraction grating of 1800 groves/mm and covers a wavelength region from 100 to 700 nm.

(a) Spectrally resolved image of the plasma at 5 μs after laser pulse with a wavelength range 653-659 nm

(b) Spectra extracted from this image of the H_α line in air.

EXPERIMENTAL RESULTS

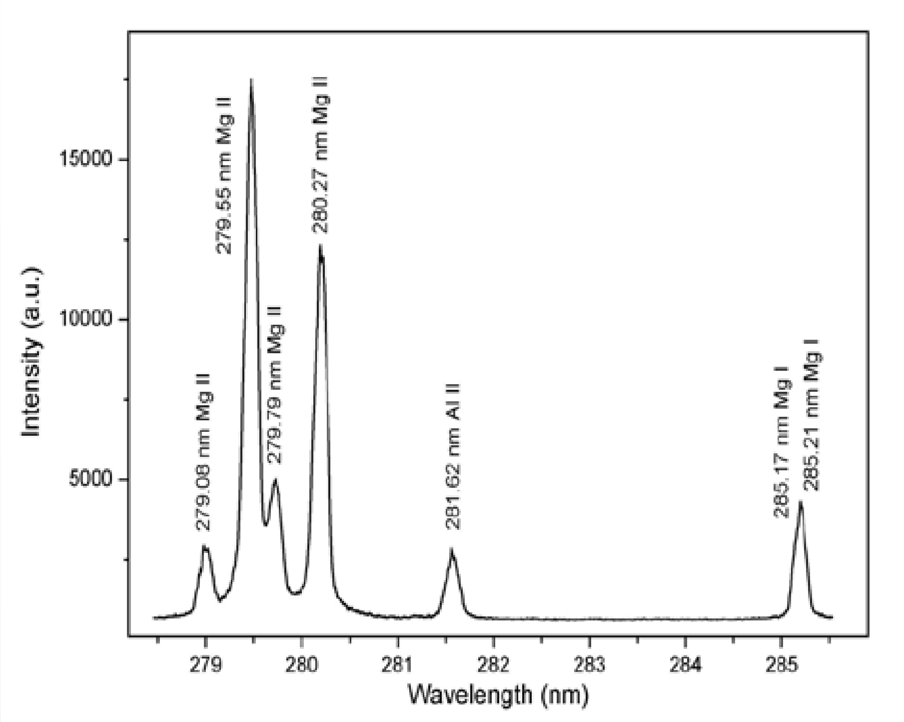
Emission obtained with a time delay of 5 μs after laser pulse: the presence of the hydrogen H_α-line in all conditions studied (in air, wet target, LSP experiments) is observed.



In all three cases presented (5 μs after laser pulse) H_α line does not widen or move. This means that the electron density and the temperature are the same within the experimental uncertainties in both three cases regardless of the amount of water.

EXPERIMENTAL RESULTS

In the experiments in air, in order to obtain an estimation of the temperature, Boltzmann's plots were used with different species (Mg I, Mg II, Cu I, Cu II,...). The self-absorption of the experimental intensity of the used spectral lines has been corrected by estimating the self-absorption (SA) coefficient [El Sherbini et al. (2005)].



A sample of the emission spectral from plasma at 5 μs delay time from laser pulse with different spectral liners (Mg I, Mg II, Al II).

Electron number density determination

$$N_e = 8.02 \cdot 10^{12} \left(\frac{\Delta l_{1/2}}{\alpha_{1/2}} \right)^{3/2} cm^{-3}$$

$\Delta\lambda_{1/2}$: FWHM of the line in Å,

$\alpha_{1/2}$: half width of the reduced Stark profiles in Å

(a weak function of electron density and temperature through the ion–ion correlation and Debye-shielding correction and the velocity dependence of the impact broadening). Precise values of ($\alpha_{1/2}$) for the Balmer series can be found in Griem (1974, 1997).

Electron number density determination

Electron density number of plasmas studied in this work under different conditions (air, wet target and LSP) and a various delay times from laser pulse.

Delay time after laser pulse, t (μs)	FWHM ($\Delta\lambda_{1/2}$) Å			N_e (10^{17} cm^{-3})		
	Air	Wet target	LSP	Air	Wet target	LSP
4	14.33 ± 3%	14.53 ± 3%		1.72 ± 3%	1.75 ± 3%	
5	13.11 ± 3%	13.18 ± 5%	12.30 ± 4%	1.50 ± 3%	1.51 ± 5%	1.36 ± 4%
6			11.79 ± 3%			1.28 ± 3%
7			9.13 ± 3%			0.87 ± 3%
8			9.06 ± 3%			0.86 ± 3%

EXPERIMENTAL RESULTS

Electron temperature

For a transition from a higher state i to a lower state j:

$$I_{ij}^{\lambda} = \frac{A_{ij} g_i}{U(T)} N e^{-\frac{E_i}{kT}}$$

$$Ln\left(\frac{I_{ij}^{\lambda}}{A_{ij} g_i}\right) = Ln\left(\frac{N}{U(T)}\right) - \frac{E_i}{kT}$$

with:

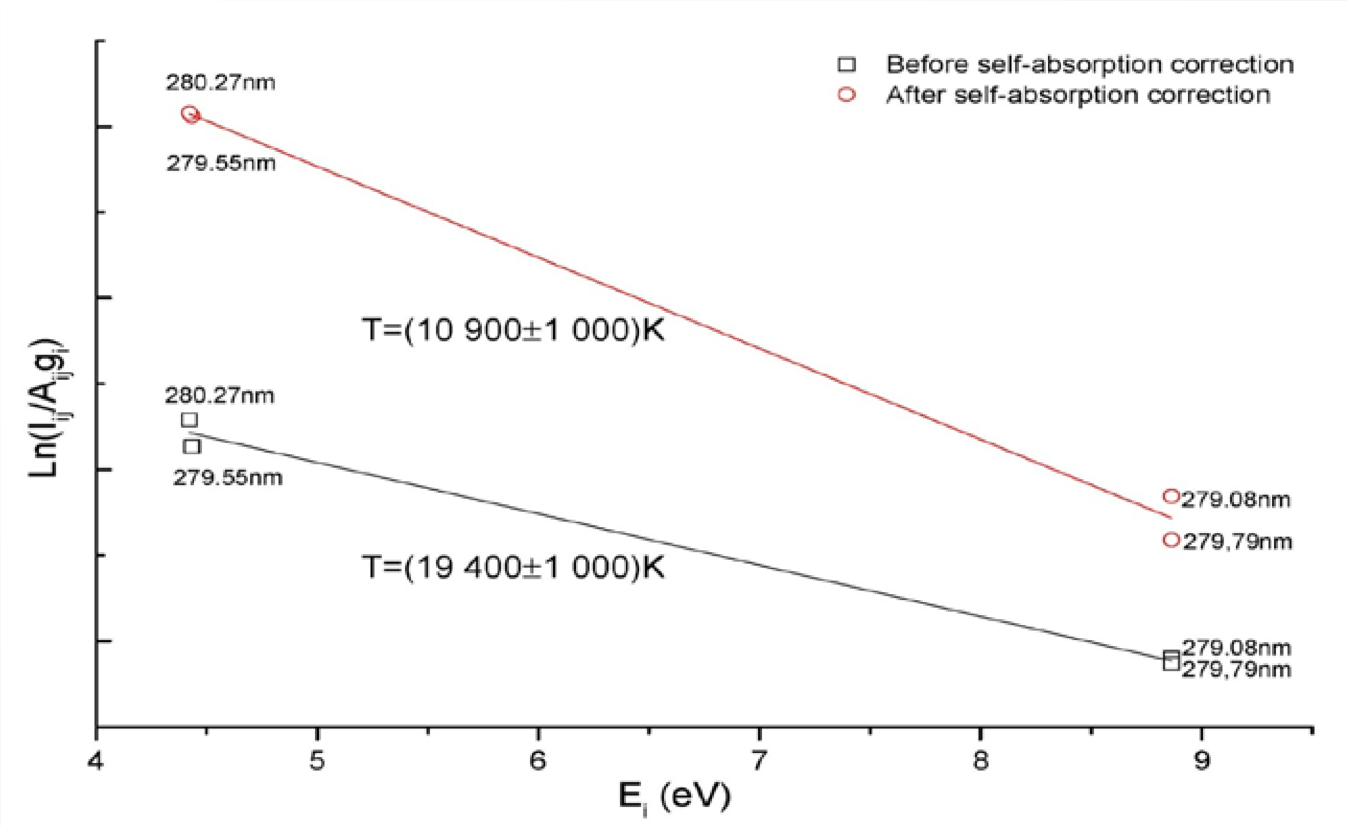
I_{ij}^{λ}	:	Measured integral line intensity in counts per second,
A_{ij}	:	i® j transition probability,
λ	:	Wavelength of the transition,
E_i	:	Excited level energy,
g_i	:	Statistical weight of level i,
U(T)	:	Atomic species partition function,
N	:	Total density of emitting atoms,
k	:	Boltzmann constant,
T	:	Absolute temperature.

Plotting $\ln(I_{ij}^{\lambda}/A_{ij}\ g_i)$ vs. E_i , for lines of known transition probability (Boltzmann plot), the resulting straight line has a slope -1/kT, so that the temperature can be obtained without a precise knowledge of the total density of atoms or the atomic species partition function.

EXPERIMENTAL RESULTS

Electron temperature

Boltzmann plot for Mg II spectral lines from Laser Induced Plasma (Al2024-T351 target) in air. Spectra was recorded at 5 µs delay time from laser pulse.



Relative atom and ion densities: Saha equation

In local thermodynamic equilibrium (LTE), it is possible to estimate the relative densities of the various ionic species present in the plasma as a function of electron density and temperature using the Saha-Langmuir equiation.

$$\frac{N_e N^z}{N^{z-1}} = \frac{2U^z(T)}{U^{z-1}(T)}\left(\frac{2\pi mkT}{h^2}\right)^{3/2} e^{-\frac{E_\infty^{Z-1}-\Delta E_\infty^{Z-1}}{kT}}$$

where:

N_e	:	**Electron number density,**
E_∞^{z-1}	:	**Ionization energy of species z −1 for isolated systems,**
ΔE_∞^{z-1}	:	**Correction of this quantity for interactions in the plasma,**
m	:	**Electron mass.**

The applicability of these equations relies on the validity of LTE hypothesis

Relative atom and ion densities: Saha equation

The McWhirter´s criterion (McWhirter 1965) was used to check the condition for the validity of the LTE. The electron number densities determined in our experiments are well within the range in which the LTE conditions are valid, equation:

$$N_e \geq 1.6 \times 10^{12} T^{1/2} (\Delta E)^3$$

with

N_e (cm^{-3})	**:**	**Electron number density,**
T (K)	**:**	**Plasma electron temperature,**
ΔE(eV)	**:**	**Energy difference between upper and lower states of all the investigated transitions.**

SUMMARY

- A Q-switched laser of Nd:YAG (of 2.5 J per pulse) focused on an aluminum sample (Al2024-T351), in different situations (in air, wet sample and LSP conditions), has been used for the plasma diagnosis produced by laser (LPP). The Stark broadening of the H_α line of Hydrogen (656.27 nm) has been used to estimate the electron density of plasmas obtained in different conditions and particularly in LSP conditions.
- In the case of air, this measure has been contrasted with the value obtained with the line of 281.62 nm of Al II. In our conditions this line presents self-absorption, what means that its usage is inadvisable. In order to make temperature estimation, Mg II spectral lines of plasma in air have been used with previous self-absorption quantification.
- The measures were realized with different delay times after the laser pulse (1-8 μs) and with a time window measure of 1 μs.

CONCLUSIONS

- The electron density obtained in the LSP case (4- 8 µs delay time from laser pulse) was in the range of 10^{17} cm^{-3} for the shortest delays until 10^{16} cm^{-3} for greater delays.
- Temperatures between 12 000 and 9 000 K have been estimated for plasmas in LSP conditions through extrapolation of temperatures in air.
- Such knowledge of electron densities and temperatures allows the calculation of ionized species populations once the LTE hypothesis McWirther criterion has been checked to be fulfilled (future work).
- As a summary, Hydrogen H_α line (656.27 nm) spectroscopy has proved to be a extremely useful tool in order to overcome the plasma diagnosis difficulties arising in LSP conditions due to water confinement emission screening.

ACKNOWLEDGEMENTS

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Thank you very much for your attention !

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