

## LIBS measurements on FTU tokamak

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### 1. Introduction

The monitoring of surface layer composition and the fuel gas content of the plasma facing components (PFCs) is extremely important for future fusion devices as ITER. Among the diagnostics suitable for complying with this request, the Laser Induced Background Spectroscopy (LIBS) represents an ideal candidate [1]: it is a well established tool for qualitative and quantitative analysis of surfaces, with remote analysis capability and micro-destructive characteristics.

In this paper first LIBS measurements on Frascati Tokamak Upgrade (FTU) are reported. The measurements, without plasma, under vacuum and in presence of the toroidal magnetic field, are representative of analyses that could be done in between ITER discharges.

### 2. FTU LIBS experimental details

Tungsten samples, coated with ~3µm thick Al-C-W mixed layer and Diamond Like Carbon (DLC) layer, co-deposited with a small amount of deuterium, were introduced, through a vertical port, in the FTU vessel, flush with the vacuum chamber (see Fig. 1). From the opposite vertical port the radiation at  $\lambda = 1064 \mu\text{m}$  of a Q-switched Nd-YAG laser (Handy Quanta Systems) was focused through an holed mirror to the sample. The delivered energy, as measured at the sapphire window entrance, was 215 mJ per shot, with a pulse duration of

8 ns and a repetition rate  $\leq 10$  Hz. For probing different areas on the sample it was rotated step by step around his vertical axis. Fig 2 shows the DLC sample after experiments still mounted on the sample-holder. Here the craters due to different laser pulse sequences are visible. The laser spot size, as measured from the crater

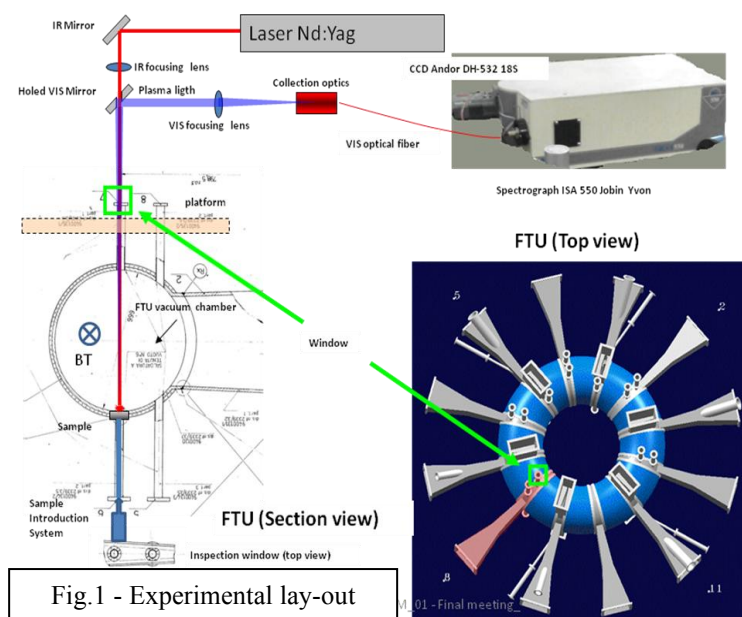


Fig.1 - Experimental lay-out

dimensions, was about 1-1.5 mm<sup>2</sup>; neglecting reflections on the sample and window it corresponds to a laser energy and power density of  $\sim 21.5 - 14.3 \text{ J/cm}^2$  and  $2.7 - 1.8 \text{ GW/cm}^2$ , respectively.

The detection of the light emitted by the plasma plume generated by the laser pulse was collinear with probing laser light: it was collected by the holed mirror and focused on a bundle of 12 optic fibres, with 100  $\mu\text{m}$  core, coupled to a TRIAX 550 ISA JOBIN-IVON spectrometer with diffraction grating of 1200 groves/mm (max. spectral resolution at 500 nm  $\sim 0.1 \text{ \AA}$ ). A delay time of 500 ns and integration time of 1000 ns were used. The spectroscopic LIBS signal was acquired with an ANDOR ICCD DH532-18F camera, model InstaSpec V, equipped with an 18 mm intensifier and a minimum gating time of 10 ns. All the equipment was located on the roof of the FTU cryostat. Experiments were carried out under vacuum ( $2 \times 10^{-4} \text{ Pa}$ ), with and without toroidal magnetic field.

### 3. Results

Despite the short time slot available for setting up the experimental layout and carrying out the measurements, the feasibility of in-situ LIBS diagnostic of surface layer composition inside FTU was demonstrated. In fig. 3 the lines Al I 394.4, 396.1 nm (from mixed sample) and CII 426.7 nm (from DLC sample), are shown as an example.

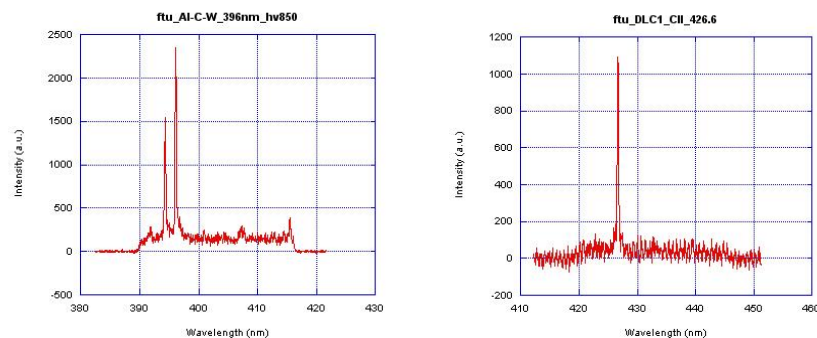


Fig.3 – LIBS spectra from mixed (left) and DLC (right) sample

Unfortunately deuterium line was not clearly detected, probably because of the very small deuterium content left in the samples after more than 8 months from its co-deposition. For the test with toroidal magnetic field, discharges with increasing magnetic field up to 4 T, were run on the mixed sample. For each value of the magnetic field a different point of

Fig.2-DLC sample



the sample was probed with a sequence of 10 laser shots at the same energy. The strong resonant aluminium atom lines (Al I 394.4 and 396.1 nm) were chosen to monitor the effect of the magnetic field on the detected line intensity. No reduction of collected signals was recorded with toroidal magnetic field up to 4 T; on the contrary a slight enhancement of emitted line intensity was found. In fig. 4 the intensity of Al lines is reported as a function of the toroidal field intensity (1.2, 2.5, 4 T). The emission intensity increases with the toroidal field intensity by a factor  $\sim 1.25$  from 1.2 to 4 T. In addition new emission lines become visible at  $B_T \geq 2.5$  T; the latter have been identified as WI at 400.9 and 407.4 nm.

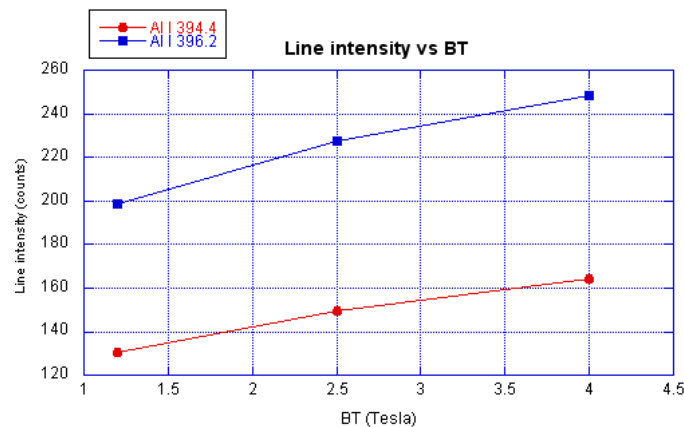


Fig.4 – Intensity of Al I lines vs. toroidal magnetic field intensity

#### 4. Discussion

Calibration free method [2] was applied to the recorded spectra to infer the concentrations of the mixed sample coating components, but for deuterium. This method call for plasma plume density and temperature to be known: they were evaluated from measurement of Stark broadening of the lines, resulting in  $n_e \sim 2 \times 10^{16} \text{ m}^{-3}$  and from Boltzmann plot method, resulting in  $T_e \sim 11500 \text{ °K}$ . The evaluated Al, C and W concentrations are reported in Table I, together with the ones measured by Energy Dispersive X-ray analysis (EDX) carried out “post mortem” on a clean zone of the coating far from laser spots. A satisfactory agreement between the results of the two methods can be seen. Concerning runs with  $B_T$ , for given plasma energy the presence of a magnetic field decelerates the plasma expansion, therefore increasing the effective density of the plasma in the emitting plume.

Table I – Concentration of mixed sample components by Calibration Free LIBS and EDX

Element	CFLIBS at/at [%]	EDX at/at [%]
W	$10 \pm 3$	$10.4 \pm 0.1$
Al	$24 \pm 5$	$21.7 \pm 0.2$
C	$66 \pm 13$	$64.6 \pm 1.2$

The deceleration of the plasma expansion under the influence of a magnetic field can be given as  $v_1/v_2 = (1-1/\beta)^{1/2}$  where plasma  $\beta (=8\pi nkT_e/B^2)$  is the ratio of the kinetic energy of the plasma to the magnetic energy and  $v_1$  and  $v_2$  are the expansion velocities in the absence and in the presence of the magnetic field, respectively [3]. The total optical emission from the plasma can be considered proportional to the square of density ( $n_i n_e$ ,  $n_i \sim n_e$ ), given by the ratio of total mass ablated (considered equal  $w$  and  $w/o$  magnetic field) to the volume of the hemispherical shape plasma plume  $V$ , and again to this volume; so the ratio of plasma emission in the presence ( $I_2$ ) and in the absence ( $I_1$ ) of the magnetic field is given by  $I_2/I_1 = (V_2/V_1) (v_1 t_1/v_2 t_2)^3 = (1-1/\beta)^{3/2} (t_1/t_2)^3$  where  $t_1$  and  $t_2$  are the emission time in the absence and in the presence of the magnetic field, respectively, that can be assumed to be equal. Therefore an enhancement of line intensity can be possible only at low values of  $\beta$ , when the plasma temperature is low. This enhancement in optical emission is probably due to the enhancement of the radiative recombination as a result of increased effective density due to magnetic confinement. In order that radiative recombination ( $\propto 1/T^{3/2}$ ) plays the main role in the optical emission enhancement the gate delay (between laser pulse and beginning of emitted light collection) has to be long enough to allow for a low plasma temperature. In our experiment the delay time is 500 ns and the plasma temperature is of the order of 1 eV, so that radiative recombination is the dominant process.

## 5. Conclusions

First in situ LIBS measurements on FTU machine were carried out, under vacuum,  $w$  and  $w/o$  toroidal magnetic field (up to 4 T) and with laser source and collecting optics at about 2 meters far from the sample. The concentration of the components (Al, C and W) deposited on a tungsten substrate were inferred by using the Calibration Free method and found in good agreement with EDX analysis. The magnetic field effect on LIBS spectra was evaluated by monitoring the two lines Al I 394.4 and 396.1 nm: slight increase of the line intensity was found with the magnetic field.

## Acknowledgments

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