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Development of laser-based technology for routine first wall diagnostic on the tokamak EAST: LIBS and LIAS

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Abstract. Laser-based methods combined with spectroscopy, such as laser-induced breakdown spectroscopy (LIBS) and laser-induced ablation spectroscopy (LIAS), are promising candidates for plasma-wall interaction studies. In this work, we report on the development of in situ laser-based diagnostics (LIBS and LIAS) for the assessment of static and dynamic fuel retention on the first wall without removing the tiles between and during plasma discharges in EAST tokamak. The in situ LIBS system was to be the routine diagnostic for fuel retention measurement on the first wall after different wall conditioning methods and daily plasma discharges. The results indicate that the LIBS will be a useful method to predict the wall condition of EAST tokamak for the discharge operation and wall conditioning methods. A timing system for LIAS was successfully commissioned at EAST. An approach to study dynamic retention in situ in the future is presented.

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Keywords: Plasma–material interactions, Plasma diagnostic techniques, Laser induced breakdown spectroscopy, Laser induced ablation spectroscopy

1. Introduction

Plasma–wall interaction (PWI) plays a key role in future fusion reactors. The lifetime of the first wall determined the availability of the fusion reactor, and the safety evaluation studies pointed out the risks of the potential accidents of fuel retained in the vacuum vessel, which could significantly impact the operation of a fusion reactor like ITER. The post-mortem analysis cannot meet the requirements of *in situ* characterization of fuel retention and impurity deposition in the future fusion device with the active cooled plasma-facing components (PFCs). To ensure the safety operation of the fusion device, there is an urgent need to develop in situ diagnostics to characterize the material deposition and fuel retention on the first wall, and to further understand the PWI processes for plasma performance. Laser-based methods are the most promising candidates and highly important for ITER and future fusion devices, as they are required to monitor the Tritium inventory without break of vacuum and allow the monitoring of PWI processes in realtime, compared to campaign-integrated results based on post mortem material analyis.

Two kinds of laser-ablation spectroscopy methods, namely laser-induced breakdown spectroscopy (LIBS) and laser-induced ablation spectroscopy (LIAS) are investigated for the characterization of the first wall in fusion devices [1, 2]. They are powerful tools for the in situ studies of fuel retention, deposition and material transport.

The basic idea of these two laser-based methods for *in situ* characterization of fuel retention and impurities deposition in fusion devices is to use intensive ns pulse laser to ablate the material of the first wall. LIBS is a well-established tool for qualitative, semi-quantitative and quantitative analysis of surfaces, with micro-destructive characteristics and some capabilities for stratigraphy[3]. The LIBS measurements can be carried out between plasma discharges. Laser-induced ablation produces a plasma plume by the laser radiation itself, which emits characteristic light radiation from which the amount of ablated species containing the information on wall condition can be evaluated. In recent years, a number of investigations have been carried out in the laboratory by many research groups to assess the feasibility of in situ LIBS in fusion devices[4]. The results indicated that the fuel (D) retention and impurities co-depositions could be measured by LIBS in the deposited layer. Additionally, an in situ LIBS using an available edge LIDAR laser system has been successfully applied for remote in-depth analysis of deposited layer on a divertor tile in the JET tokamak [5]. Moreover, an in situ LIBS system was successfully established to investigate fuel retention and impurity deposition on the first wall at the high field side in EAST superconducting tokamak[6]. The TEXTOR group has studied the feasibility of applying laser-induced breakdown spectroscopy for *in situ* characterization of deposited layers in TEXTOR tokamak [7, 8]. The FTU group carried out LIBS measurements at the Frascati Tokamak Upgrade (FTU) in the presence of a variable toroidal magnetic fields to simulate the environment of ITER discharges [9]. New emission lines became visible for $B > 2.5$ T. All experiments performed by these groups in laboratories and in situ worldwide demonstrated the feasibility of LIBS technique be a unique diagnostic tool for PWI studies in the fusion reactor.

LIAS measurement is performed during the plasma discharge. First, a laser pulse is used to ablate first wall material. Then the released particles then enter the edge plasma region. Here, the material is excited and ionized. The resulting line radiation of the excited atoms is observed by optical spectroscopy and converted into a fluence of released particles. With radiometric calibration, from the detected photon flux of dedicated species, the composition, the amount of ablated material as well as the retained fuel can be determined. The LIAS technique was developed in the TEXTOR tokamak. Here, quantitative deuterium retention measurements on carbon deposits were demonstrated and the interaction of the LIAS process with the edge plasma was modelled [10, 11]. The results of LIAS in TEXTOR showed the potential of measuring the dynamic fuel retention and recycling on the first wall in long pulse discharges.

Experimental Advanced Superconducting Tokamak (EAST) is a long pulse and high-performance device, which has recently achieved high confinement scenario in H-mode with a pulse duration over 60s. Here we report on the development of LIBS and LIAS diagnostics in the EAST tokamak. In the following paper, the major achievements of LIBS and LIAS in EAST tokamak will be presented. This paper summarizes the results of LIBS and LIAS carried out in the EAST tokamak to evaluate their perspectives for ITER and future reactors.

2.1 Experimental Setup

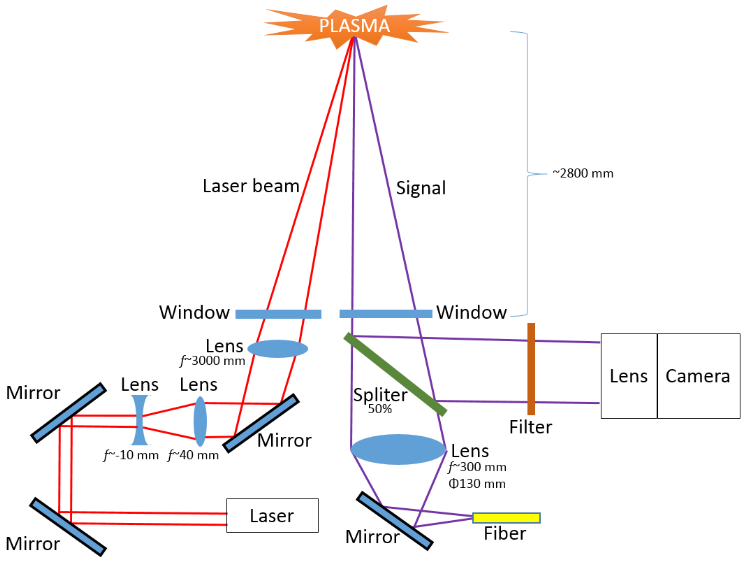

Figure 1. Schematic of LIBS and LIAS setup in EAST tokamak.

The schematic experimental setup of the *in situ* laser-based diagnostics is presented in Figure 1. This setup is based on the previous *in situ* LIBS system[6]. In 2015 EAST campaign, the *in situ* laser-based diagnostic wall system was upgraded with two motor stages for rotating the mirror and moving the fiber bundle, a broad beam splitter, and a high-speed camera equipped with interference filters. The laser diagnostics system consists of two parts: laser ablation and signal collection. The detailed descriptions are given as follows.

A Q-switched Nd:YAG laser (Brilliant Eazy, Quantel) operated at the wavelength of 1064 nm with 5 ns pulse with at 10 Hz repetition and pulse energy of 180 mJ / pulse was applied for material ablation. Initially, the laser beam is reflected two times to guide it towards EAST and then passed through a 3X beam expander to reduce beam divergence. After a moter-driven mirror the laser beam is focused by a plano-convex lens with 3000 mm focal length. Right after the lens it enters into the EAST vacuum vessel through a quartz window of 80 mm diameter.

The optical setup results in a laser spot diameter ~1.5 mm confirmed by camera measurements. A typical laser fluence to the material is 2.5 J/cm^2.

For observation of the LIBS and LIAS light a second window is used. Behind the window a 50/50 beam splitter provides light for a spectrometer and a fast camera equipped with interference filters. On the spectrometer side, the light is coupled to the fused quartz fibre bundle by a collection lens of 30 cm focal length. The collected light emission is delivered via an 1.8 m length optical fibre to a spectrometer (LIBS2500+ , Ocean Optics Inc.). The spectrometer is equipped with seven linear silicon CCD array detectors covering the range of 200 - 980 nm with a spectral resolution of 0.1 nm. It was calibrated using a radiometric source (DH-2000-CAL, Ocean Optics, Inc.). The spectrometer was synchronized with the laser operation and the EAST timing system. This enables to control the delay from the laser and the gate duration of the acquisition. Time-integrated spectra were recorded with the integration time of 1 ms. A reference laser was coaxial to the Nd:YAG laser for the location the position of the ablated spot.

2.2 Sample preparation

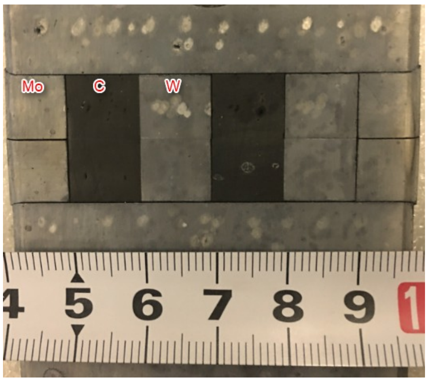

Figure 2. Sample tiles after the plasma exposure and laser ablation.

For the experiments presented here a matrix of sample tiles with the dimensions 10 mm × 10 mm × 3 mm were installed prior to the campaign at the EAST high-field side. In Figure 2., the laser ablated spot on the material surface can be observed. The materials of the sample tiles are Tungsten (W), Molybdenum (Mo) and Graphite (C). The W material was provided by the Advanced Technology & Materials Co. which manufactured the W/Cu divertor of EAST. The Mo sample material is a titanium-zirconium-molybdenum alloy (TZM) similar to the EAST first wall material. The C material is from the graphite tile of the lower divertor of EAST. It containes 1%B4C,2.5%Si, 7.5%Ti. Since the laser has a Gaussian-shape beam profile the changes in reflectivity observed in figure 2 are expected to be larger than the actual beam diameter. The tiles mounted on the wall were exposed for the whole campaign for *in situ* measurement and post-mortem analysis.

2. Results and discussion

3.1 LIBS results in EAST campaign

During the EAST experimental campaign of 2016 and spring 2017, LIBS measurements were carried out at *in vacuuo* conditions after the plasma discharge finished on a routine daily basis. Also, experiments were carried out after after wall conditioning (lithium coating, boron coating, etc.) finished. LIBS measurements were conducted on the Mo substrate with lithium coating. The vacuum had a residual pressure of 10^{-5} Pa and the toroidal magnetic field was 2 T. LIBS spectra were collected without delay time from the laser pulse with 1 ms exposure time.

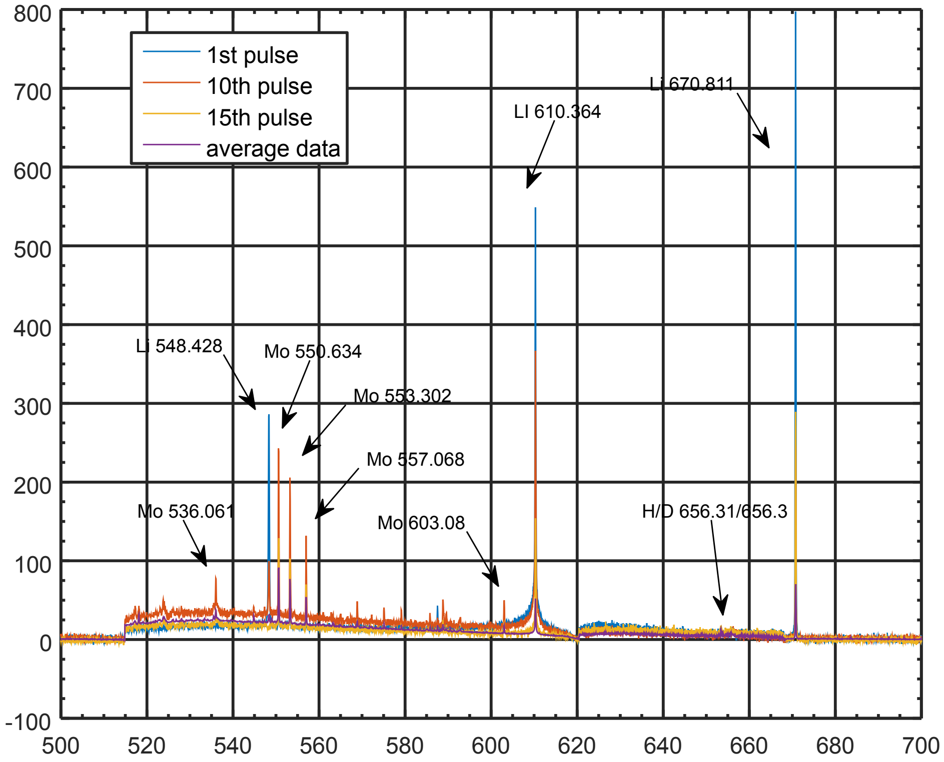

Figure 3. Typical spectral of in situ LIBS.

In Figure 3, typical LIBS spectra are shown. The spectral region between 500 nm and 700 nm has been selected, because in this range the Mo I (atomic) lines at 550.634 nm, 553.302 nm and 557.068 nm, Li I (atomic) at 610.364 nm and 670.811 nm, Li II (ionic) line at 548.428 nm with strong emission intensities are clearly observed. The observed Li and Mo transitions are indicated in the figure and assigned based on the NIST database. Also, the hydrogen isotope lines of H_α at 656.3 nm and D_α at 656.1 nm have been assigned.

To highlight the depth profiling capabilities of LIBS, a number of subsequent laser shots were repeatedly focused at a fixed position on the sample surface and the LIBS spectra as a function of the laser shot number were recorded for each measurement position.

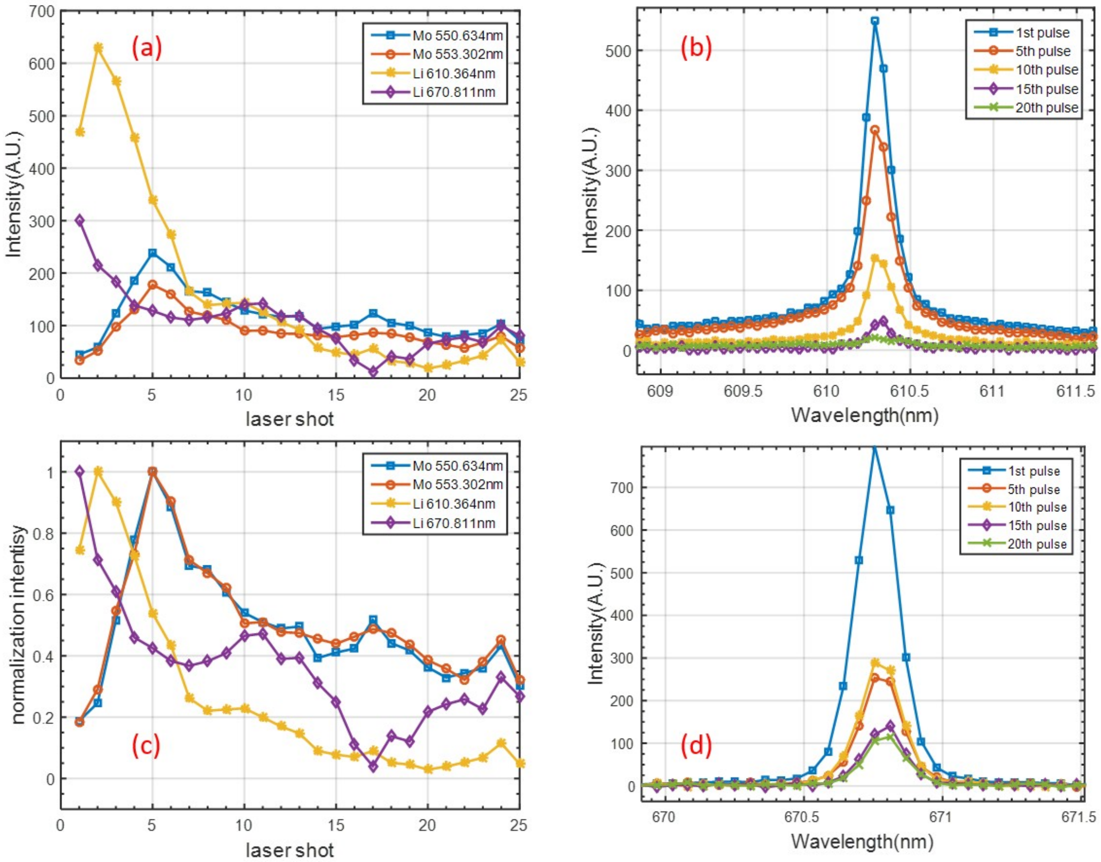

Figure 4. Depth profile of the lithium deposition.

The depth profile of lithium deposited layer as a function of the laser pulses number is shown in Figure 4. The intensity of the Li I (atomic) line at 610.364 nm and the 670.811 nm line were monitored as the marker of deposition layer whereas the Mo I emission line at 550.634 nm was monitored as the marker of the thin interlayer between the surface and the substrate. As shown in Figure 4(b) and (d), the intensity of Li I lines decreased with the laser pulse number. It is difficult to distinguish the interlayer of with the intensity of the Li and Mo lines in Figure 4(a). In Figure. 4(c), the Li and Mo lines are normalized to the maximum intensity observed during all pulses. As shown in the figure, the Li intensity decreases with the number of laser shots, but the Mo signal increases with the laser ablation shots. The interlayer was determined by the intersection of Mo and Li lines in Figure 4(c). After more than 20 laser shots, the intensity of Li I line of 610.364 nm decreases to the background level, and the Li deposited layer and Mo substrate can be distinguished clearly.

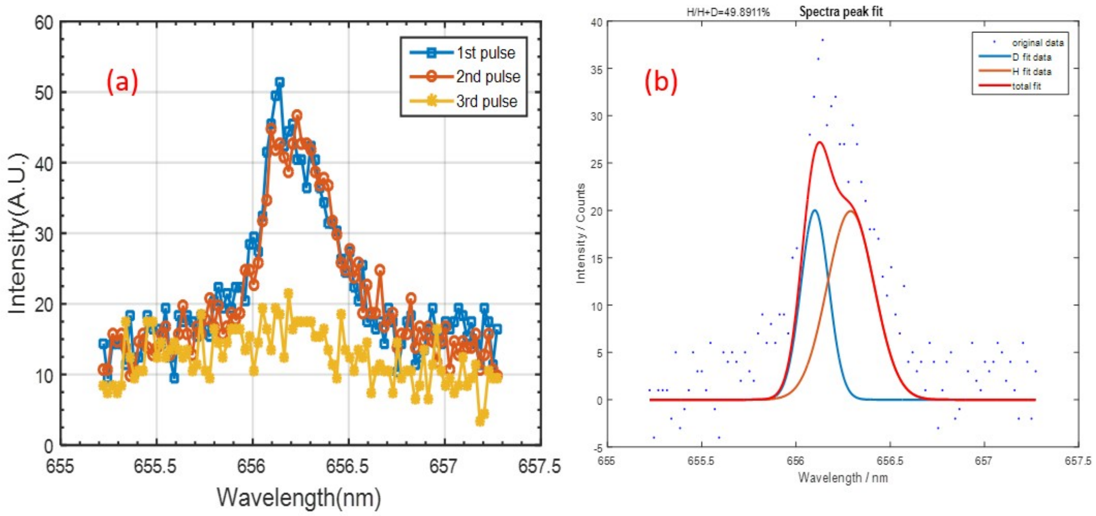

Figure 5. The fuel retention in the deposition layers.

In Figure 5 the LIBS signal measured in the Balmer-α emission spectral region of hydrogen (H_α) and deuterium (D_α) at 656.29 nm and 656.1 nm, respectively. However, the resolution of LIBS 2500 + spectrometer of 0.1 nm in the present optical setup was not good enough to clearly resolve these two peaks in the experiment. In order to obtain the H/(H+D) ratio from the measured spectra, a Voigt profile of two peaks was used to fit the LIBS spectra. As shown in Figure 5(b), the H/(H+D) is determined to be about 50% in the deposition layer. In Figure 5(a), the peak intensity of H/D at the first and second laser pulse is found to be almost the same level when the peak intensity decreases to the background level at the third laser shot. We conclude that both hydrogen isotopes were retained in the co-deposition layers. The calculate the laser ablation depth experiments in the laboratory were carried out after removal of the samples from EAST. In laboratory experiments at the same laser fluence about 100 nm deposition layer ablation rate per pulse is found. This value of laser ablation rate depends on many factors including the laser power, the profile of the beam, the focusing optics, the duration of the laser shot, and cannot be regarded as an absolute reference.

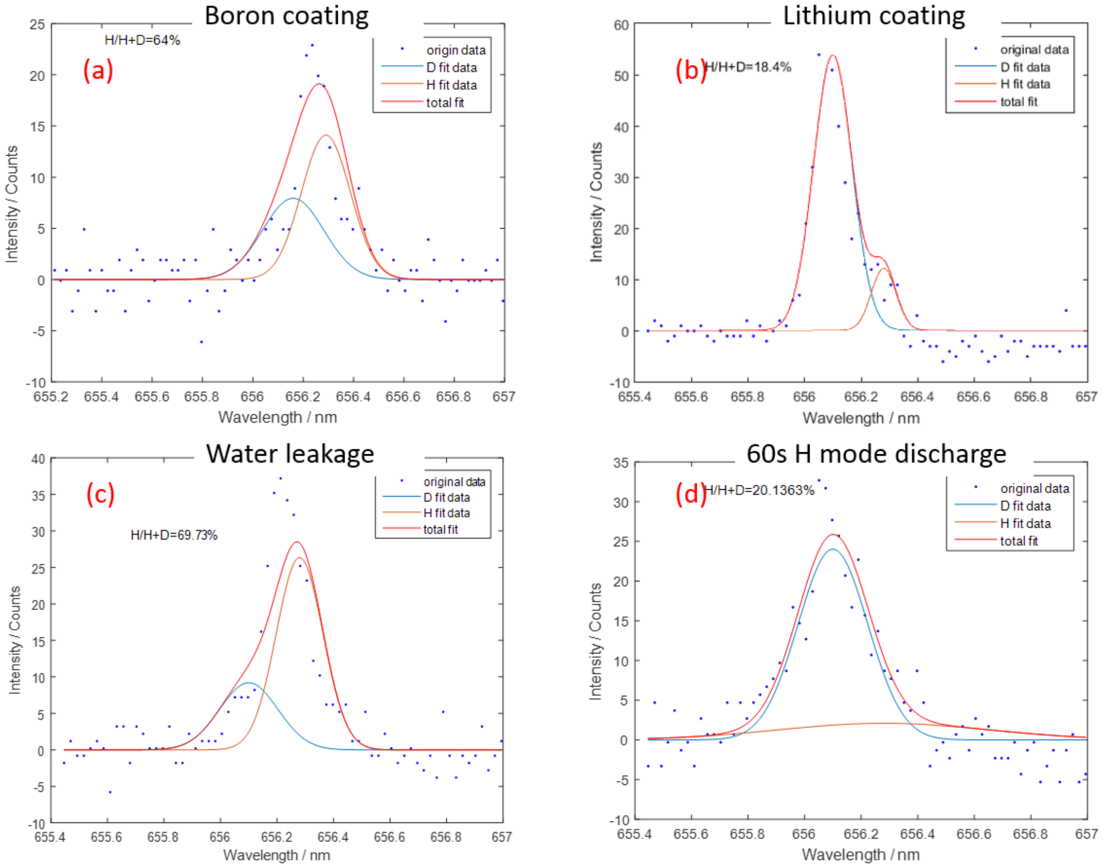

Figure 6: The H/(H+D) ratio in different conditions.

Since LIBS can well detect the hydrogen isotope from the co-deposition layers, it was routinely used on daily basis for monitoring H/(H+D) ratio of the first wall in EAST. In Figure 6, the H/(H+D) ratio measured under different conditions in the 2016 EAST campaign is presented. As shown in the graph of Figure 6(a), the H/(H+D) ratio was ~64% in the boron film which is attributed to the carborane ($C_2B_{10}H_{12}$) used for boronization. Other cleanings after boronization were necessary for hydrogen removal. In Figure 6(b), the H/(H+D) ratio after lithium conditioning is found to decrease to about 20%. This is attributed to the effective H impurity removal from gas-phase by the Li/H co-deposition process. Figure 6(c) shows the H(H+D) ratio after a water ingress due to a leak during the campaign. Here, the H/(H+D) ratio is found to increase to 70%, illustrating the requirement of baking and wall conditioning after water leakage. Finally, in Figure 6(d) the H/(H+D) ratio after long-pulse (60s) H-mode discharge is shown. However, it was hard to distinguish the Ha and Da by the fitting method. It seems a lot of fuel retained on the wall and the first wall was saturated after long-pulse and high-performance discharge. Wall cleaning methods are required to release the fuel. All the results of H/H+D ratio in different conditions indicated that LIBS could be a useful method for predicting of the wall condition of EAST tokamak.

3.2. LIAS system commissioning for dynamic retention studies

As LIAS is operated during the discharges it has the potential to study the dynamic retention in situ. A schematic illustrating the measurement strategy is shown in figure 7.

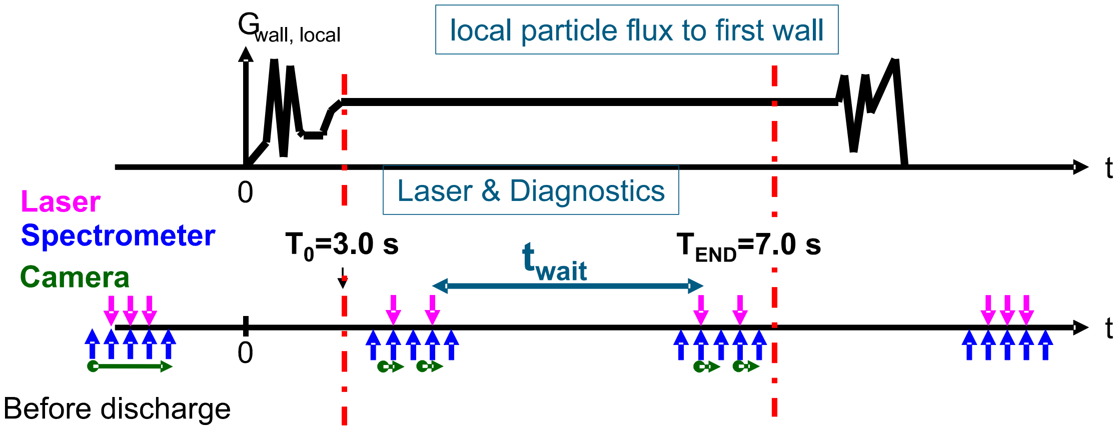

Figure 7: Measurement strategy for dynamic retention with LIAS

To investigate the dynamic retention the first wall location under investigation is preconditioned with several LIBS laser pulses prior to the discharge until the surface reaches a steady state situation. Then the discharge is started. During the start-up phase the particle flux to the surface is not well defined. Therefore, once the flat-top phase has been reached, several laser pulses are fired on the surface to remove possible co-deposits and to obtain a LIAS background signal. Then the timing system is used to wait a time t_{wait}. Subsequently, LIAS is performed again during the flat top phase to study the changes of the surface due to plasma exposure.

To allow for these measurements, the LIBS system was upgraded with a National Instruments timing system to allow operation synchronized to EAST operation. The system consists of a Compact Rack (NI PXI-1031, CPU: NI PXI8106). The real time system is handled by FPGA board (NI PXI-7833R) and connectivity to the EAST timing system as well as laser, fast camera and spectrometer are provided by an IO connection box (SCB-68).

To commission the system, LIAS measurements were conducted during non-dedicated experiments. The plasma background emission as well as the LIAS light was recorded by a fast camera equipped with a Hα/Dα interference filter. A total of 6 laser pulses were fired during EAST shot #63867. The discharge properties as a function of time are shown in figure 8. The laser was fired every 200 ms for t=3.5 s, 3.7 s and 3.9 s. Then the laser was not fired for 1.2 s to allow the particle flux to reach the first wall without being removed by laser pulses. Starting from t=5.1 s three more pulses were fired, again at 5 Hz. The time of the laser pulses are indicated by the dashed vertical red lines in figure 8. The plasma conditions for the 3rd and 4th laser pulse are nearly constant (p_3: t=3.9s: $n_e=2.857*10^{-19}$ m^3, pnbi1l=1.024 MW, p_4: t=5.1s: $n_e=2.818*10^{-19}$ m^3, pnbi1l=1.071 MW).

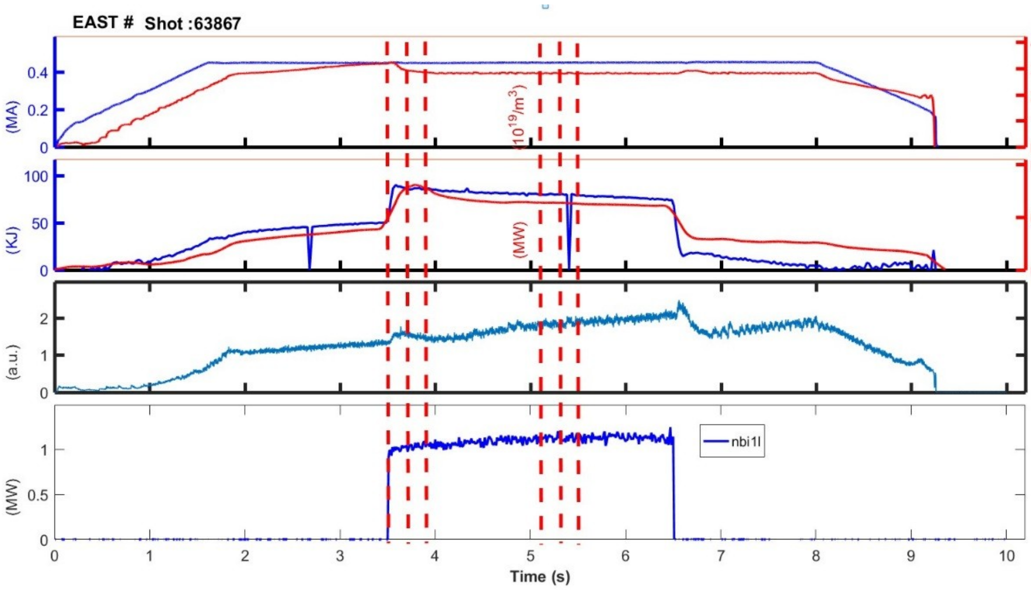

Figure 8: East parameters for #63867. The time for the LIAS laser pulses is indicated by dashed vertical lines.

During the experiment the fast camera was configured to record both background and LIAS light. The camera was triggered at 10 Hz by the National Instrument system to perform recording burst. Thus it was recording alternating a dataset with and without laser pulse. Each burst was recording images at 210,526 frames per second with an exposure time of 4.3 µs/frame and a dead time of 0.45 µs/frame. The burst recording duration was 41 frames. For analysis an area of interest (AOI) of the LIAS signal was selected in which the Hα/Dα emission during the LIAS pulse was clearly visible, but no perturbation due to Planck-radiation from the heated target surface was in the line of sight. The camera signal counts were integrated numerically. In figure 9 the cumulative sum of the AOI as a function of camera frame is shown for all data sets recorded during EAST shot #63867. Each dataset is displayed with a frame offset to allow for comparison. Note, that between the laser pulses the delay is 200 ms with the exception between laser pulse 3 and 4, where the delay is 1200 ms.

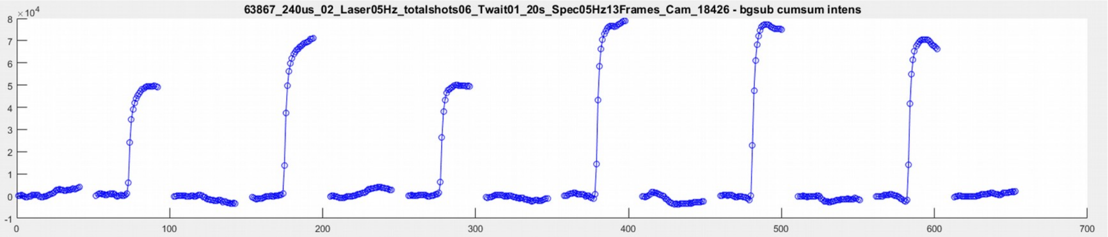

Figure 9: Cumulative sum for the Hα/Dα signal. Frames are shown with a manually added offset. The laser pulse is in the middle of each data set.

The experiment demonstrate the experimental capability to perform LIAS studies during EAST operation. From the non-dedicated experiments it is not clear if the signal increase between the 3rd and the 4th pulse is due to dynamic retention or due to changes in the plasma parameters of the discharge. This will have to be clarified in dedicated experiments.

3. Summary and Outlook

LIBS diagnostic was successfully set up in EAST tokamak and applied for daily routinely monitoring first wall conditions. The thickness of the deposition layers could be measured by LIBS. The H/H+D ratio in the deposition layers were measured after boron and lithium conditioning as well as after a water leakage and high performance discharge. The results indicate that the LIBS will be a useful method to predict the wall condition for the discharge operation and wall conditioning. LIAS diagnostic was commissioned at EAST. The piggyback experiment indicates LIAS could be suited for dynamic first wall condition measurements.

In the future, further developments of LIBS studies aim to determine the relative concentrations of the detected elements. With the development of the low tungsten divertor, the laser-based diagnostics of LIBS and LIAS for the divertor region monitor are considered.

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