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First wall surface characterisation with laser based methods

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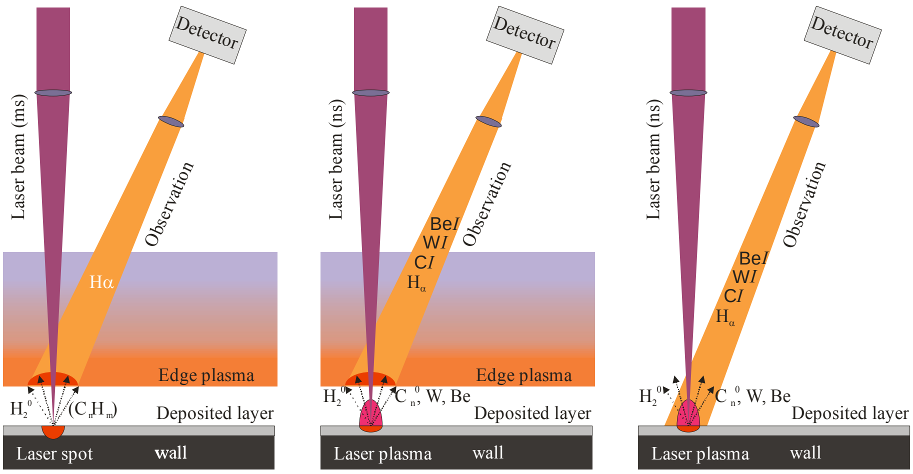
Introduction:

There is a strong request to monitor the status of the wall conditions at ITER in order to predict the production of dust and flakes, and the tritium inventory associated with it, which is limited for safety reasons [1]. Laser based methods in combination with spectroscopy are proposed as possible diagnostic for in-situ characterisation of the plasma facing components (PFC), which will be beryllium in the main chamber, tungsten at the baffles and carbon fibre composites at the divertor tiles [2], [3], [4]. Depending on laser pulse duration and power density these methods are directed to monitor the inventory of hydrogen isotopes (Laser induced desorption spectroscopy, LIDS) or the composition of deposits during tokamak discharges (laser induced ablation spectroscopy, LIAS) . Additionally, laser induced ablation can be used in between discharges to monitor the characteristic line radiation of the laser plasma itself, which is known traditionally as laser induced breakdown spectroscopy (LIBS) [5]

Principles of laser based diagnostics



a) LIDS b) LIAS c) LIBS

Figure 1: Schematic set-up for laser based methods for wall characterisation

A schematic set-up for these laser based methods for the characterisation of the first wall is shown in figure 1. The laser beam is focussed onto a surface at the PFC which in practice will be several metres away. Therefore lasers with low divergence are required to provide the necessary power densities at the surfaces for LIDS and LIAS, respectively. The induced line radiation of the released particle in the edge plasma (e.g. H_α, C*I*, W*I*, Be*I*) will be ideally collected coaxially to the laser beam.

Laser induced desorption spectroscopy

LIDS (fig. 1a) uses a relatively long pulse duration of a few ms with power densities of typically 50-100 kW/cm^2. This is needed to rise the surface temperature of the spot exposed to the laser well above the desorption temperature, about 2000 K in case of C and W and about 1000 K in case of Be. During the laser pulse impinging on C or W, the temperature of a layer of about 200 µm increases by heat conduction to a temperature above 1200 K necessary for the desorption of hydrogen isotopes. In case of carbon layers with co-deposited hydrogen H_nC_m molecules are desorbed at first followed by H_2 molecules. Atomic hydrogen released at higher temperatures could not be observed in these experiments spectroscopically.

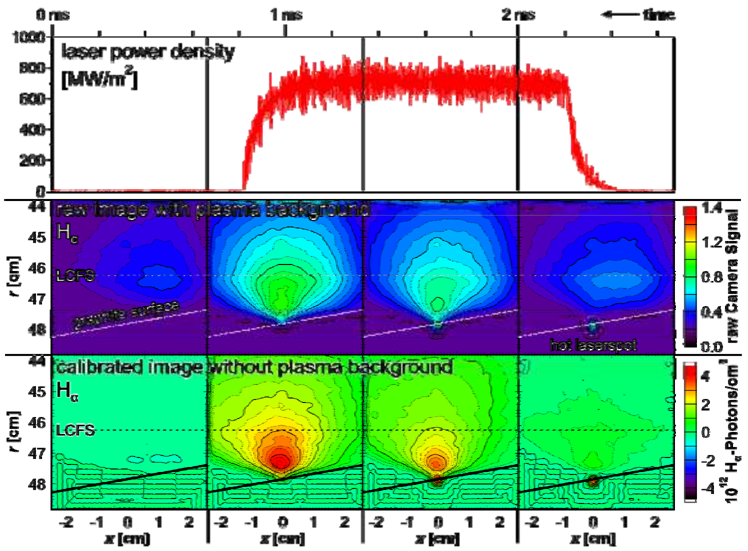


Figure 2: temporal development of the laser power density (top), H_α raw (middle) and H_α desorption signal (bottom) from a hydrocarbon layer in TEXTOR (frame rate 1500 Hz)

Figure 2 shows the result of D-release in a single laser shot that depletes the gas content to more than 95%. The signal drops to zero before the end of the laser pulse proving the nearly total removal of the hydrogen content in the exposed surface layer. Within the pulse duration the lateral expansion of the hot laser spot by horizontal heat transfer is small and can be neglected.

The intensity of the H_α line emission was deduced from the intensity increase of the Balmer radiation above the plasma background. The natural background fluctuations within the typical time scale of the laser desorption of 1ms determine largely the signal to background ratio and thus the lower sensitivity limit of the method. The measured absolute intensities are then converted into a fluence which represents the co-deposited inventory of hydrogen isotopes. The conversion factors are dependent on the edge plasma parameter and have been evaluated both from edge modelling (Eirene) and experimentally using the desorption of carbon layers with calibrated hydrogen inventory (TDS or NRA). Both methods agree reasonably.

Laser induced ablation spectroscopy

LIAS (fig. 1b) can use the same experimental set-up but applies Q-switched lasers which produce short laser pulses of a few ns with much higher power densities in the range of GW/cm^2.

This is far above the heat of evaporation leading to surface material ablation. Usually the hot laser pulse forms a plasma that recombines rapidly within about 1 µs duration.

The depth of the crater caused by a single laser pulse is determined both by the penetration of the laser light, which depends on the wavelength and the material extinction coefficient and by the heat propagation during the pulse time. These quantities are typically about 0.5 µm for carbon deposits. If lasers with much shorter pulse durations (ps or fs) will be applied the crater depth depends only on the penetration depth of the laser radiation and the fast heat transfer of the electrons to the bulk and vapour, respectively and can thus be much smaller[6].

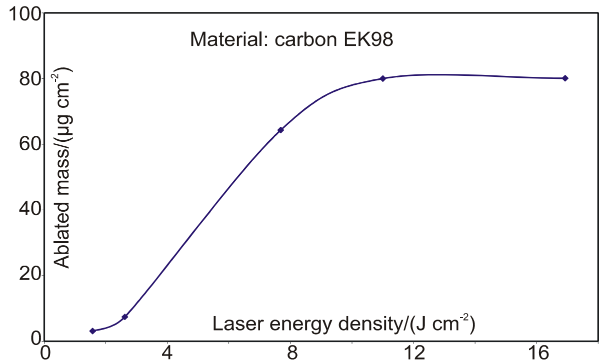


Figure 3: dependence of ablated carbon mass (normalised) on energy density by single Ruby laser pulse and multiple exposure

The LIAS diagnostic is applied during the tokamak discharge where the released neutral particles can penetrate into the edge plasma. There they are excited and generate a characteristic line radiation, which is observed by spectroscopic methods. The line spectra give the information about the composition of the deposited layer, the retained hydrogen isotopes [7] and the amount of ablated material. This requires however the knowledge about the local edge plasma parameters, the atomic data of the evaporated wall species and information on the distribution of atoms, molecules and clusters that leave the surface.

Figure 3 shows the removal rate for the bulk graphite material used in TEXTOR (EK98) depending on the laser energy density for 10 ns laser pulses. The data show a saturation as a function of laser energy density between about 8-10 J/cm^2. There is no sharp threshold visible, at which the ablation starts. This is due to the Gaussian like intensity profile of the laser used at present. A sharp threshold can only be expected if the laser beam intensity would have a “top hat” distribution. With increasing power the edges of the Gaussian power density profile excesses increasingly the threshold for evaporation. The crater depth in a carbon deposit in a GDC deposition apparatus on carbon is significantly larger than that of the bulk material.

Laser induced breakdown spectroscopy

widely applied for remote material investigations in industrial processes commonly performed under low or atmospheric pressure. For in situ measurement in a tokamak the method should be qualified for the UHV pressure conditions in tokamaks unless the torus canbe filled with a inert gas to some low pressure in between shots. Application under UHV conditions is usually connected with a significant reduction in sensitivity. During the lifetime of the laser plasma the cloud expands about 1 cm and the radiation from this volume must be collected from a large distance and analysed spectroscopically. However, the measurement can be performed at high detectors sensitivity due the absence of background radiation. The collection of light must be delayed with respect to the laser pulse to discriminate the continuum radiation caused by Bremsstrahlung of the hot laser induced plasma [8], [9]. In ITER a better performance is expected to be achieved if the diagnostic is mounted on a remote arm such that the detection of the light is much nearer to the laser plum [10]

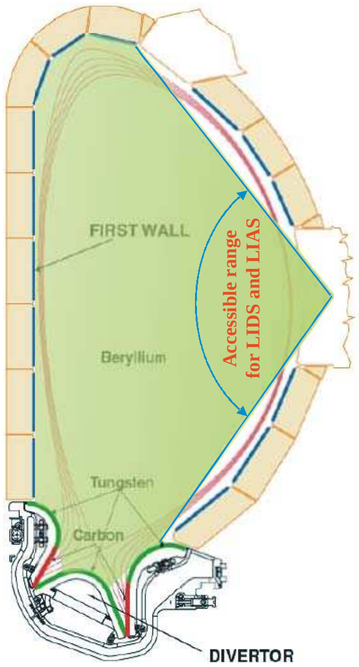


Figure 4: accessible range for laser based characterisation at ITER

Application at ITER

At ITER an experimental set-up is under investigation that allows the application of all 3 method in one system (figure 4). The laser light is guided via mirrors from outside the biological shielding to a hole in the first wall where it is focussed onto a wall segment at a not to shallow angle of incidence to provide the necessary laser energy density. Already at $\pm 20^0$ normal to the laser beam a 35% higher power is necessary which has to be provided with a very low divergence of ≤ 1mrad. The line radiation of the laser induced particle emission will be collected coaxially through a small hole in the plasma facing mirror. In figure 5 the principle accessible range for the diagnostic from the mid-plane of ITER is shown, which covers already a wide range of the poloidal cross-section. Measurements at the low field side of the wall and in deeper areas of the vertical divertor target would require other locations for laser entrance and observation.

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