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Speckle interferometry diagnostic for erosion/redeposition measurement in tokamaks

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Abstract

For erosion/redeposition measurement in tokamaks, an optical method based on temporal phase shifting speckle interferometry is in development at CEA Cadarache. Measurement performed on carbon material allowed us to develop a procedure for erosion/redeposition measurement during a plasma discharge. In order to measure reliable amount of eroded and redeposited material in tokamaks during a plasma discharge, the optical method has been adapted to tokamaks environment. Such improvements allowed to perform shape measurements on ITER divertor mock-up and erosion measurement on the Toroidal Pumped Limiter in realistic tokamak conditions.

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1. Introduction

For plasma facing components (PFCs) in tokamaks, carbon (in the form of carbon fibre composite CFC) is widely used. The reasons are its good thermomechanical properties and its low atomic number inducing a weak fuel dilution when carbon atoms migrate into the plasma. Nevertheless, using carbon as PFCs in the next step devices (ITER) will induce two major problematic mechanisms: erosion and redeposition.

Physical and chemical sputtering cause a large erosion on PFCs where heat (5 MW m^{-2}) and particle flux (10^{19} m^{-2} s^{-1}) are important. This mechanism decreases the lifetime of PFCs and strongly affects the duty cycle of the tokamak. The main consequence of erosion is the redeposition of carbon combined with hydrogen atoms. This mechanism, known as codeposition, leads to the formation of carbon layer with high hydrogen content. Extrapolation from present tokamaks shows that the acceptable limit of tritium in ITER could be reached in a few days or week of operation [1]. The time to reach this limit strongly depends on the assumptions made for the plasma edge conditions, erosion yields, and other factors. When the limit is reached, plasma discharges have to be stopped for safety reasons until tritium removal is achieved.

Since 2001, the whole chamber of Tore Supra has been protected with actively cooled components [2]. The Toroidal Pumped Limiter (TPL), made of high heat flux elements covered with carbon fibre composite (CFC), is the main PFCs of CIEL Project (Composants Internes Et Limiteurs), located at the bottom of the vacuum vessel. This project aims at obtaining steady state plasma discharge during

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1000 s. Over such durations, erosion and redeposition mechanisms on TPL may become significant during one plasma discharge. Indeed, plasma wall interaction is mainly concentrated on this PFCs. Modelling performed with the Tokaflux code [3] has shown a strong variation on a short spatial scale due to toroidal field ripple and self shadowing effect. Erosion occurs in the convective area and can lead to an erosion of about 10 μm during a 1000 s long discharge. Redeposition mainly occurs in the shadowed areas. On the TPL, such regions correspond to the private flux region at the surface of the limiter where sub-millimetre flakes are observed [4] and to the shadow in the gaps between tiles where hard layers are observed [4]. These two mechanisms lead researchers to develop new measurement techniques in order to characterize the amount of eroded/redeposited material during a plasma discharge. Some techniques based on quartz microbalance [5] and laser telemetry [6] have provided measurement of erosion and redeposition in tokamaks. However, microbalances can only provide an integrated result and the spatial resolution achieved with laser telemetry remains limited (>2 mm). To achieve in situ erosion/redeposition measurements with high spatial resolution, we are developing [7,8] an imaging method based on temporal phase shifting speckle interferometry.

2. Erosion/redeposition measurements by speckle interferometry

To provide quantitative measurement on eroded and redeposited material and its spatial location during a plasma discharge we apply interferometer method using temporal phase shifting speckle interferometry. In order to provide information on shape modification, we need an optical configuration with a high sensitivity in the Z-direction. For this reason, we choose a Michelson interferometer with collimated beam. The optical setup is presented in Fig. 1. The laser beam reflected from the observed surface interferes with the reference beam on a the CCD camera. To achieve the temporal phase shifting method, a mirror mounted on a piezoelectric component introduces a well-known phase shift δ_i between the two beams. In temporal phase shifting, the interferogram obtained from the interferences of two light beams is given by:

$$I_i(x,y) = I_B(x,y) + I_M(x,y)\cos(\Phi(x,y) + \delta_i),$$

where $I_B(x,y)$ is the background intensity, $I_M(x,y)$ is the modulation intensity and $\Phi(x,y)$ is the optical phase to be measured. In the classical 4-bucket algorithm, four interferograms $I_i(x,y)$ $(i = 1–4)$ are recorded with different phase-shifts $\delta_1 = 0$, $\delta_2 = \pi/2$, $\delta_3 = \pi$ and $\delta_4 = 3\pi/2$ and the phase map is calculated using the four-quadrant arctangent function:

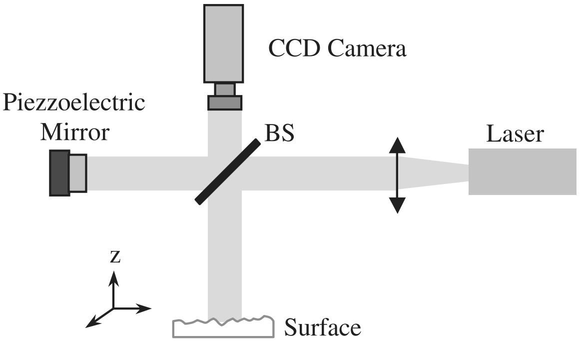

Fig. 1. Michelson interferometer in collimated beam configuration. The reference beam, reflected on the mirror mounted on a piezoelectric and the light diffused by the object interfere on the CCD camera.

$$\Phi(x,y) = \arctan\left(\frac{I_4(x,y) - I_2(x,y)}{I_3(x,y) - I_1(x,y)}\right).$$

Erosion and redeposition lead to a variation of the optical phase. As a consequence, to calculate the eroded/redeposited material quantity during a plasma discharge, we need to determine the quantity $\Delta\Phi(x,y) = \Phi_{\text{after}}(x,y) - \Phi_{\text{before}}(x,y)$. However, this phase is wrapped into the interval $[0, 2\pi[$. In order to extract quantitative information, we have to spatially unwrap this phase image. This process works only if the phase is spatially well-sampled. For this reason, we use the two wavelengths-method which permits to provide variable dynamic range and variable Z resolution. By using two wavelengths, we obtain a phase image with a variable synthetic wavelength depending on the two wavelengths λ_1 and λ_2:

$$\Lambda = \frac{\lambda_1\lambda_2}{|\lambda_1 - \lambda_2|}.$$

To demonstrate the feasibility of this method for erosion/redeposition measurements, some experiments have been conducted on CFC tiles. The erosion mechanism was generated by use of a pulsed laser (YAG Laser, 532 nm, energy per pulse = 150 mJ) focused on the CFC surface: several series of incident laser pulses on the surface permitted to achieve laser ablations. In this experiment, we only treat calculation of eroded material quantity.

Redeposited material quantity calculation would be conducted in the same way.

The process used to determine the eroded volume is presented schematically in Fig. 2. Two phase maps

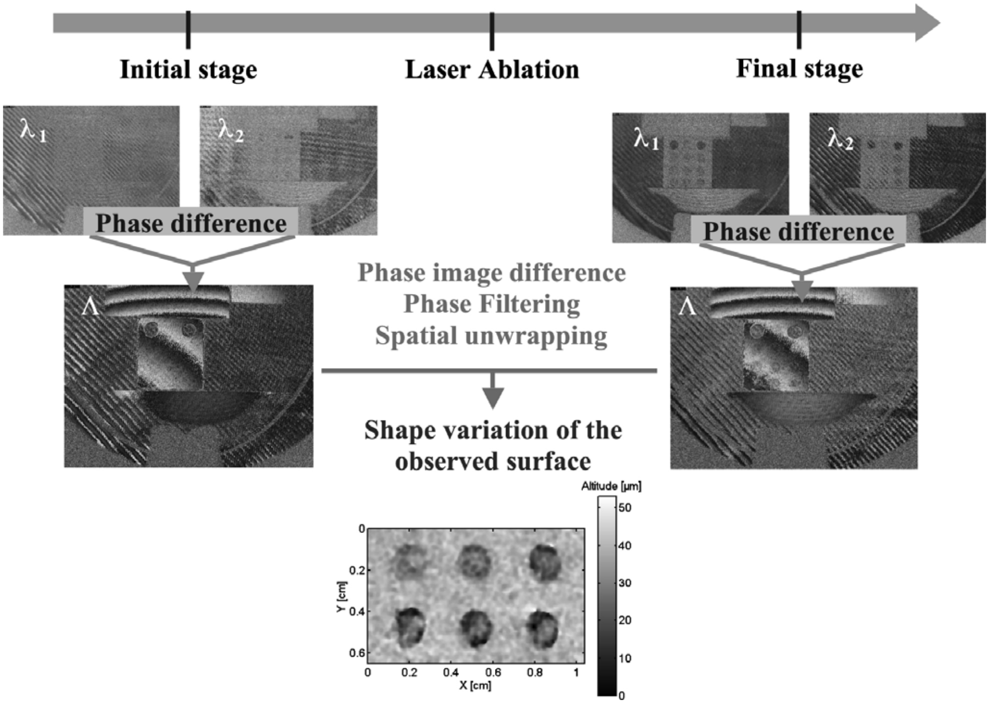

Fig. 2. Schematic process of erosion redeposition measurements on laser ablation by means of 2-wavelength speckle interferometry. Phase measurements before (initial stage) and after (final stage) at two different wavelengths λ_1 and λ_2 provide phase images at the synthetic wavelength Λ. From the difference of phase images at Λ, after filtering and unwrapping, we obtain the shape modification of the surface.

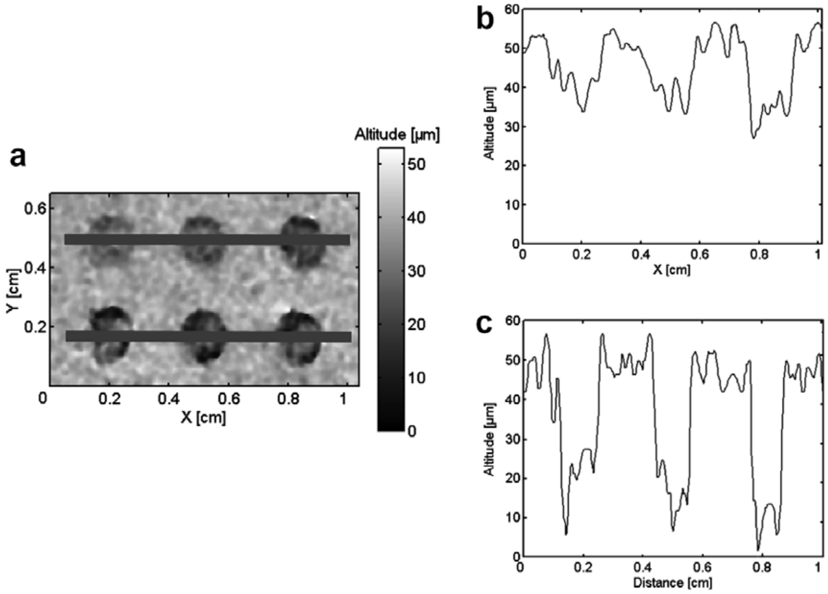

Fig. 3. (a) Shape modification of the surface due to laser ablations (6 impacts) on CFC tile. (b) Horizontal profile on the three upper laser impacts (10–20 μm). (c) Horizontal profile on the three lower laser impacts (20–40 μm). Altitude '0' corresponds to the minimum of height of the three dimensional image (a).

at two different wavelengths λ_1 and λ_2 are recorded before and after the laser pulses have been applied to the observed surface. Then, phase images at the synthetic wavelength Λ are calculated. The difference of the two latter phase maps gives us the phase change due to laser ablations. This phase difference is filtered (to reduce phase noise) and spatially unwrapped to provide the shape variation undergone by the observed surface during this experiment.

In Fig. 3, we present the surface modification on six different laser impacts obtained with variable exposition time (5 s for the upper left hand corner ablation to 30 s for the bottom right hand corner by step of 5 s). For speckle interferometry, we use two wavelengths set at $\lambda_1 = 562\,000$ nm and $\lambda_2 = 562\,800$ nm, which gives a synthetic wavelength of $\Lambda = 395$ μm. As it can be seen on the two horizontal profiles, we measured laser ablations with depth lying between 10 μm and 40 μm. Comparison of the results with confocal microscopy [9] leads to the same depth determination.

This experiment demonstrates the feasibility of speckle interferometry to obtain 3D measurements and shape variation between two different stages. From this shape variation, we can deduce the localization of erosion and redeposition mechanisms and furthermore the eroded/redeposited material quantities. However, these measurements are not relevant for a tokamak if we do not take into account the environmental and geometrical constraints imposed by a fusion device.

3. Measurement on plasma facing components

In this part we will adapt the previous method to the tokamak environment. One of the most important disturbance generated by tokamaks, for interferometry measurements, is vibration. Vibrations can be considered as random displacements of the observed surface in the optical axis direction (Z-axis). On Tore Supra, low frequency (<150 Hz) vibrations with amplitudes from 0 to 1 μm were measured. As vibration amplitudes are in the same order as the wavelength ($\lambda = 500$ nm), such displacements introduce random phase-shift between each interferograms. In this condition, the previous classical 4-bucket algorithm fails and no reliable phase data will be available. To solve the problem of vibrations, we developed a random phase shifting algorithm [10] in order to extract phase distributions from randomly phase-shifted interferograms. As the intensity varies sinusoidally with the phase-shift δ_i and with the phase $\Phi(x,y)$, we use an iterative procedure. In the first step, we generate an arbitrary set of phase-shifts and the phase map is calculated by using a least square method. Indeed, at each point (x,y), the intensity $I_i(x,y)$ is fitted to a sine curve of known period and variable phase and amplitude. In the next step, introducing the phase image deduced from the previous step, a new set of phase-shifts is calculated with the same least square method. This procedure is iterated until a condition of convergence is verified. This condition is reached when the maximum incremental value of phase-shift between two iterations becomes smaller than a value chosen by the user. This method validated on vibrating surfaces provides highly repeatable results. Indeed, we obtain a Z resolution of $\Lambda/18$ which is similar to that one obtained with the classical 4-bucket algorithm without vibration ($\Lambda/20$).

Next, in order to characterize the erosion/redeposition mechanisms into a tokamak, we need to observe a large part of PFCs. In Tore Supra, due to the toroidal periodicity of the heat flux deposition on the PFCs, a 50×50 cm^2 observation area would be sufficient, in theory, to completely characterize

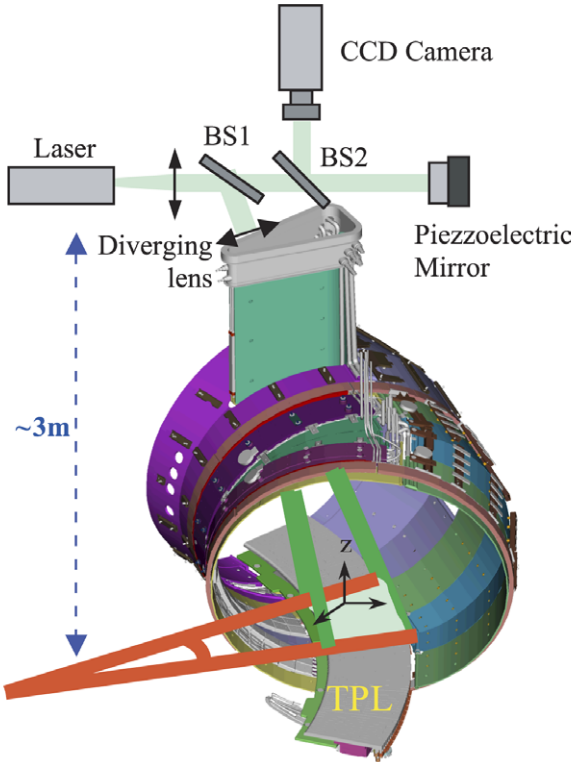

Fig. 4. Schematic view of the diagnostic implemented on Tore Supra.

erosion and redeposition mechanisms in the whole chamber. However, in collimated beams configuration, the observable surface is limited by lens diameters. On a tokamak, the limiting factor will be the window size (≈ few cm^2). In this condition, the accessible surface would be about only few cm^2 (1 or 2 CFC tiles on the TPL for example). This is the reason why diverging beam is planned to be used for the illumination beam. Fig. 4 shows a possible setup of such configuration on the tokamak Tore Supra. The beam splitter BS1 and the diverging beam allow to illuminate a large part of the Toroidal Pumped Limiter and the beam splitter BS2 permits the recombination of the object and the reference beams on the CCD camera.

On our test bench, ITER-relevant experiments were achieved on a TPL sector and on the ITER divertor in realistic tokamak conditions: random vibrations in the Z-axis direction, diverging illumination beam, large distance between camera and surface with variable reflectivity. The CCD images and the phase maps ($\Lambda = 790$ μm) are presented in Figs. 5 and 6. The interference fringes are not only due to the shape of the surface but also to the diverging beam. The contribution of the diverging beam in the phase image is constant and will be suppressed when the phase difference will be calculated. Only phase change due to surface deformations will be measured. On the phase image of the TPL, we can observe the stainless steel support on which

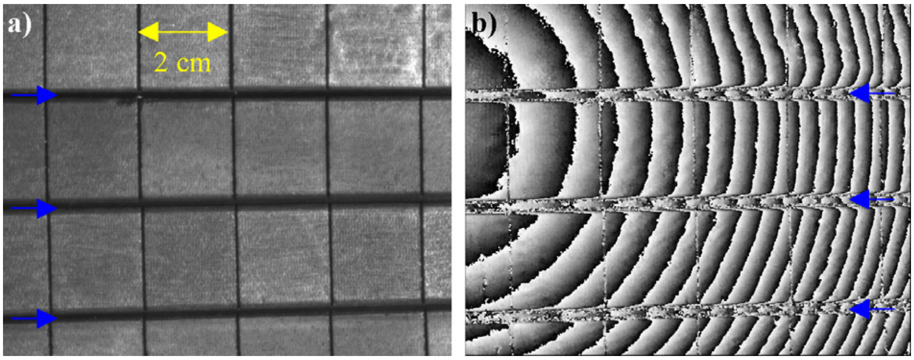

Fig. 5. Measurement on the Toroidal Pumped Limiter: (a) CCD view of the toroidal pumped limiter (20 × 18 cm^2). (b) Phase image of this surface ($\Lambda = 790$ μm) calculated in presence of vibrations at a distance of 160 cm from the camera. Interference pattern is due to both shape of the object and the diverging beam. Blue arrows represent the gap between fingers where stainless steel support is observable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

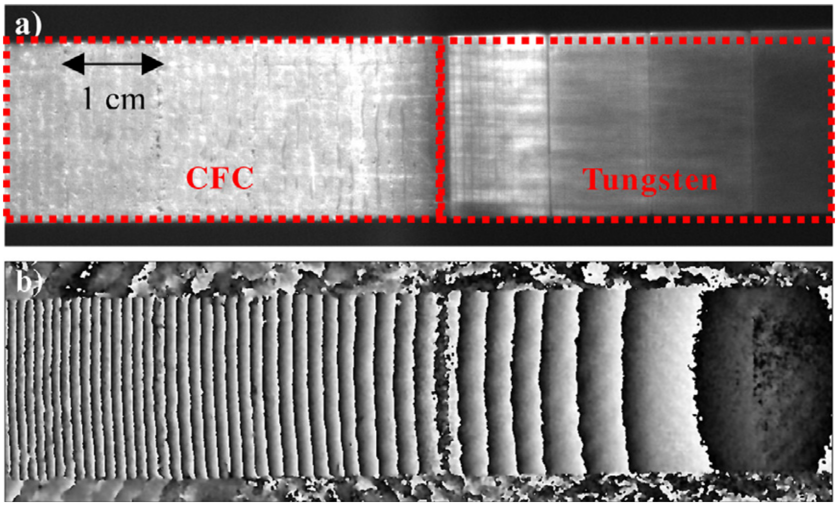

Fig. 6. Measurement on the ITER Divertor: (a) CCD view of the ITER Divertor. Tungsten tiles on the right hand side and CFC tiles (inner target) on the left hand side. (b) Phase image of this surface ($\Lambda = 790$ μm) calculated in presence of vibrations at a distance of 160 cm from the camera. Interference pattern is due to both the shape of the object and the diverging beam.

fingers are settled. This support provides a reference in the Z direction and allows us to detect possible displacements between two series of measurement.

4. Conclusion

In this paper, we demonstrated the feasibility of speckle interferometry to produce quantitative information on erosion and redeposition mechanisms. Measurement on a CFC tiles permitted to measure laser impact depth of about 10 μm. We took into account the tokamak environment, we have shown that we are able to measure the amount of eroded/redeposited material by using two-wavelengths speckle interferometry and temporal phase shifting.

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