ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 701–705

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Speckle interferometry diagnostic for erosion/redeposition measurements in tokamaks

E. Gauthier *, G. Roupillard

Association EURATOM-CEA, CEA/DSM/DRFC, Bât. 506, CEA-Cadarache, 13108 St Paul Lez Durance, France

Abstract

In order to measure erosion/redeposition during long duration discharges, a new diagnostic based on speckle interferometry is proposed. First experiments performed on carbon fiber composite materials have shown that this technique is able to measure a modification of the surface in the range of 1 μm. Further experiments have been performed on different materials using a second wavelength in order to increase the dynamic range from 0.1 to 100 μm and to perform 3D measurements of the surface. A diagnostic based on two-wavelength speckle interferometry to measure in situ erosion/redeposition during a single discharge on the CIEL limiter is under development.

PACS: 52.55.Fa
Keywords: Tokamak; Erosion; Redeposition; Speckle; Tore Supra; Interferometry laser

1. Introduction

Carbon material is widely used in present tokamaks because of its good thermomechanical properties and low atomic number allowing a comparatively high impurity content without severe contamination of the plasma. Nevertheless, using carbon as plasma facing component (PFC) in the next step devices such as ITER will induce a major problem: erosion and subsequent redeposition.

Physical and chemical sputtering cause a large erosion on the neutralizer plate of the divertor, decreasing the lifetime of the tiles and therefore may strongly affect the duty cycle of the tokamak. As a direct consequence of the erosion, the redeposition of carbon combined with hydrogen atoms, known as codeposition process, forms a carbon layer with high hydrogen content. Extrapolation from present tokamaks shows that the tritium inventory in ITER will reach the limit value, set at 350 g, within few discharges [1]. Then, operation has to be interrupted for safety reasons until tritium removal is achieved by the use of conditioning techniques.

The aim of the CIEL project (Composants Internes Et Limiteur) [2] is to obtain high performance discharges, up to 1000 s in Tore Supra. Over such durations, erosion and redeposition processes may become significant even for a single shot. Being in contact with the plasma, the toroidal pumped limiter (TPL) is the most relevant PFC where erosion/redeposition should be monitored. Since the limiter is actively cooled, the surface temperature remains below the radiation enhanced sublimation (RES) temperature threshold of 1000 °C and RES should not occur in normal operation. Due to the large uncertainties on the neutral flux impinging on the limiter, chemical erosion has not been taken into account in this part. Due only to the ion bombardment, the thickness of the eroded material is estimated from the relation:

$$e = \varphi t Y \frac{M}{\rho \mathcal{N}}, \tag{1}$$

where e is the erosion (m), φ the ion flux (part $m^{-2}\,s^{-1}$), t the duration of the discharge (s), Y the sputtering yield

* Corresponding author. Tel.: +33-4 42 25 42 04; fax: +33-4 42 25 49 90.
E-mail addresses: gauthier@pegase.cad.cea.fr, e.gauthier@cea.fr (E. Gauthier).

0022-3115/03/$ - see front matter
PII: S0022-3115(02)01448-4

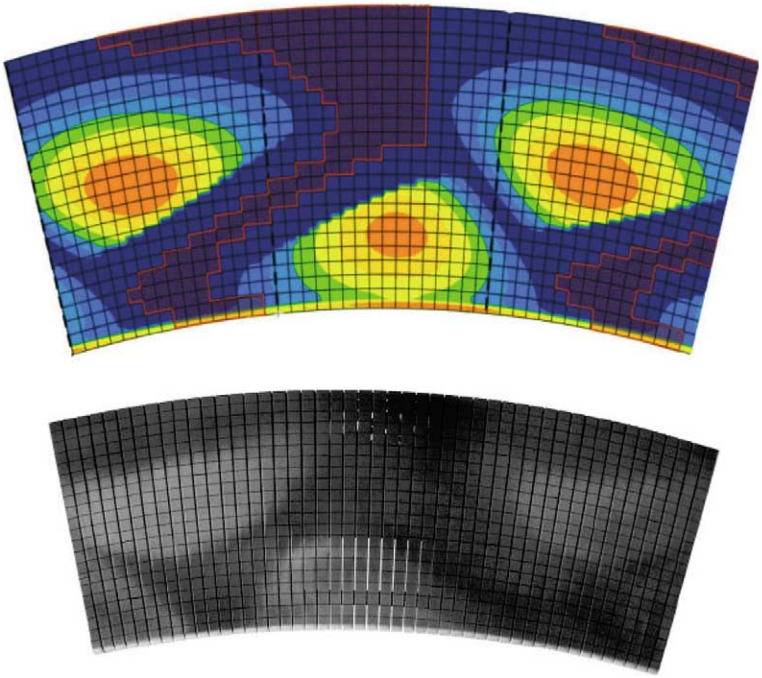

Fig. 1. Power flux on part of the TPL (~50 × 120 cm) calculated with the Tokaflux code, the red area corresponds to the surface receiving a high flux and the blue area to a low flux. The second image, taken with CCD camera shows the surface aspect after few weeks of operation. The surface modification attributed to erosion/redeposition is well correlated with power flux deposition.

of the material, M the molecular mass of the material, ρ the density of the material and $\mathcal{N}$ is Avogadro's number.

Taking into account the physical sputtering yield of deuterium ions on carbon with an averaged value of 2×10^{-2} [3], an ion flux of 5×10^{22} $m^{-2}\,s^{-1}$ and carbon density of 1.8 $g\,cm^{-3}$ (CFC material) we obtain an erosion rate of about 10 μm per 1000 s discharge. This erosion is not uniform but depends on the ion flux distribution on the surface of the limiter. Modelling performed with the Tokaflux code [4] has shown a strong variation on a short spatial scale due to toroidal field ripple and self-shadowing effects, as can be seen in Fig. 1. Therefore, erosion/redeposition measurements should not be performed at a single position but 2D measurements are required. Erosion/redeposition measurements performed previously on long term samples in Tore Supra have shown that the net erosion can be strongly reduced due to redeposition [5]. Analysis of these experiments gave on the inner bumper limiter an averaged carbon redeposition fraction of about 99%, reducing by two orders of magnitude the net erosion rate. Then, the order of magnitude for the erosion and redeposition process, which is anticipated on the TPL in Tore Supra for a single discharge of 1000 s, is in the range of 0.1–10 μm. On such a scale and without in-vessel intervention, only optical measurements seem to be able to provide valuable information. Therefore it has been proposed to develop a diagnostic based on interferometry in order to measure modification on CFC tiles in the range of 0.1–10 μm.

2. Speckle interferometry

From analysis of literature, speckle interferometry has been retained [6] as the most promising technique. The principle of speckle interferometry is presented in Fig. 2. A laser beam reflected from the surface interferes with a reference beam on a black and white CCD camera. Displacements of the surface in the direction of the laser beam modify the interference fringes. Erosion and redeposition is similar to an out-of-plane displacement, which can be related to a phase shift. Measurements need to be performed before and after surface modification [7]. Both the reference and object beams interfere on each pixel of the CCD camera with an intensity value of:

$$I_{\text{before}} = I_0[1 + m\cos(\varphi - \varphi_R)],$$

where I_0 is the laser intensity, m is the fringe contrast factor, φ and φ_R, respectively the phase shift of the object and reference.

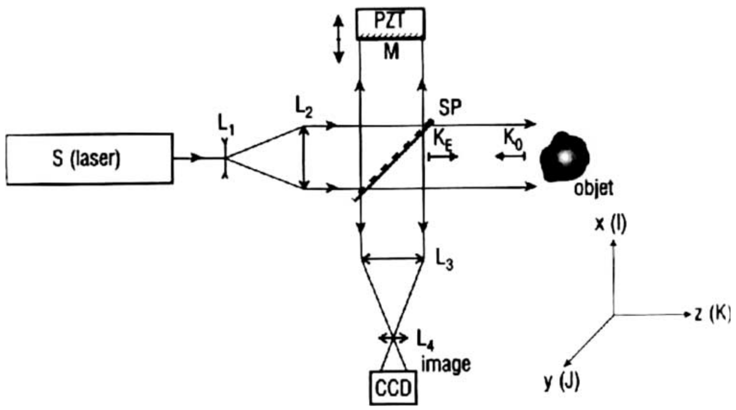

Fig. 2. Speckle interferometer set-up. The laser beam is divided into two parts by the beam splitter (SP), in the first branch of the interferometer, the mirror (M) is mounted on a piezo electric quartz (PZT) moving along the *x*-axis, in the second branch, the beam is reflected on the object. Both beams recombine on the CCD camera. Once the object has moved along the *z* direction, a second speckle interferogram is performed. From the difference between the two phase images, the displacement of the object can be measured.

After modification of the surface, the intensity is:

$$I_{\mathrm{after}} = I_0[1 + m\cos(\varphi - \varphi_{\mathrm{R}} + \Delta\varphi)],$$

where $\Delta\varphi$ is the phase shift induced by the surface modification.

In order to obtain quantitative measurements of the phase shift $\Delta\varphi$, we use a technique called phase-shifting [7]. Using a mirror mounted on a piezo electric transductor (PZT) reflecting the reference beam, it is possible to introduce a well-known phase shift in the cosine function. Several images of the object, with different positions of the PZT, are stored. The numerical analysis of these data allows to extract the phase measurement on each pixel of the camera. Comparing the two phase images, before and after modification, one obtains $\Delta\varphi$ and the displacement of the object in the direction out of the plane.

3. Results

First experiments have been conducted in order to test the feasibility of such a technique on a carbon fibre material. A CFC tile (32 × 20 mm) brazed on a copper plate and a frequency-doubled Nd:YAG laser at 532 nm were used, three images were recorded with a CCD camera using the phase shifting technique. By applying a slight mechanical pressure on the top part of the sample, a very small displacement of the tile perpendicular to the laser beam is induced. Then, after displacement, three other phase-shifted images were recorded. We can see in Fig. 3, the image of the CFC sample as seen by the CCD camera and the displacement calculated from the analysis of the speckle interferometer. The displacement value converted in a color scale is shown in Fig. 3(b) (full scale is 1.2 μm). The theoretical resolution depends on the interfringe value $i = \lambda/2$ and on the camera resolution, in our case $i = 266$ nm and a 8 bit camera gave a theoretical resolution of about 1 nm. Actually, the experimental resolution achieved in our experiments was about one order of magnitude larger than the theoretical value. These results show that speckle interferometry can be used on CFC materials and provides quantitative information on surface displacement. Nevertheless, in a tokamak environment this technique cannot be applied to measure in situ erosion/redeposition on PFC, because of vibration, thermal dilatation of the internal and external components. Therefore, it has been proposed [8] to apply two-wavelength speckle interferometry in order to obtain a three dimensional (3D) measurement of the limiter. The use of a second wavelength allows to obtain a relative displacement as described previously and additionally the 3D shape of the object [9]. Moreover, according to the specific value of the second wavelength, it is possible to cover a wide dynamic range in the measurement. The dynamic range and the resolution depend directly on the value of the interfringe i. By using two wavelengths, the interferogram figure results with a synthetic wavelength, Λ defined as:

$$i = \frac{\Lambda}{2} = \frac{\lambda_1\lambda_2}{2|\lambda_1 - \lambda_2|}.$$

By changing the difference between the two wavelengths, it is possible to vary the synthetic wavelength from 0.5 to thousands of micrometers. In order to qualify the two-wavelength speckle interferometry, first experiments have been performed on several materials. A continuous and tuneable dye laser with an output energy of 400 mJ was used. The laser beam was transmitted to the speckle interferometer through a 50 m optical fibre. The

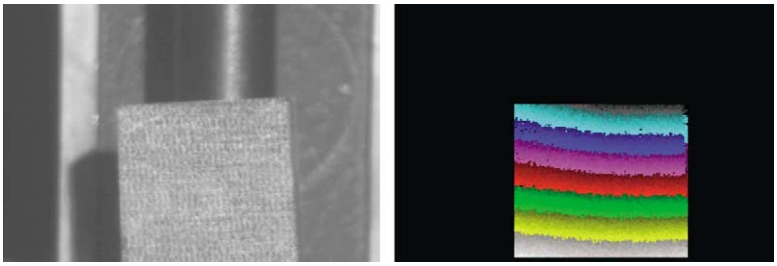

Fig. 3. CCD view of a CFC tile (horizontal dimension is 20 mm) and displacement measured by speckle interferometry. Each color is about 0.15 μm and the full scale (grey) corresponds to a displacement of 1.2 μm in the direction perpendicular to the surface.

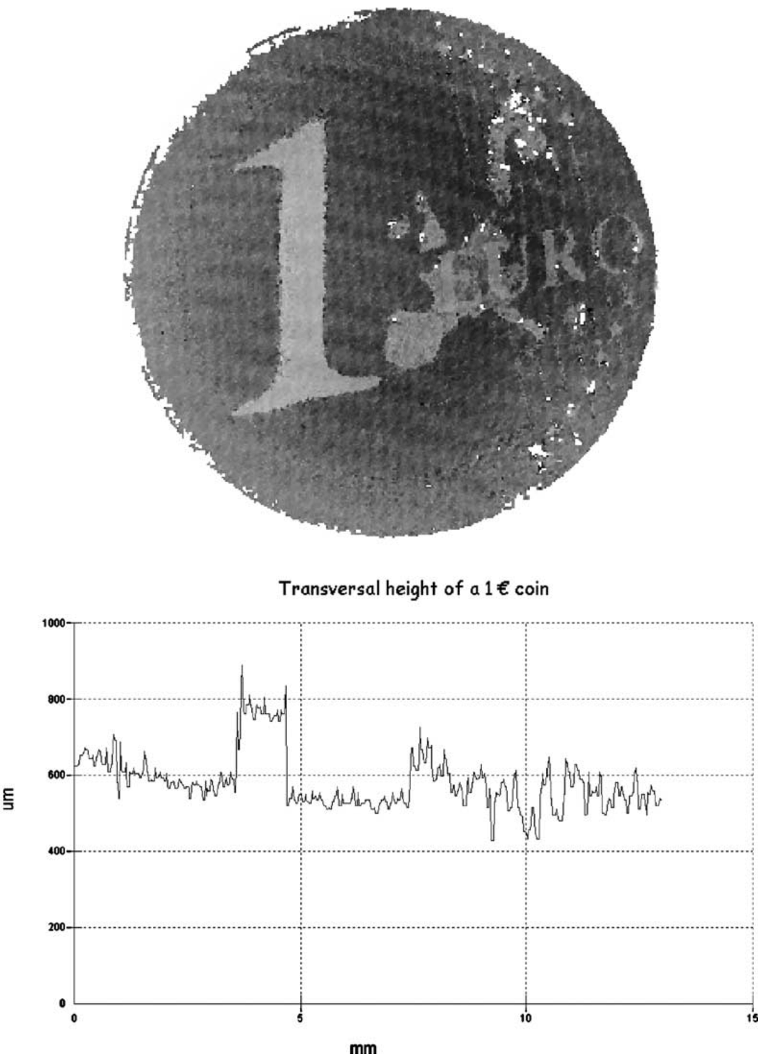

Fig. 4. Contour plot of a 3D measurement of 1 € coin and horizontal line profile.

wavelength was continuously varied with a minimum step of 10^{-4} nm. The Fig. 4 shows the contour plot of a 3D view of 1 € coin as well as a line profile across the relief showing a value in the range of 200 μm. These figures were obtained using 572.250 and 573 nm wavelengths, resulting in a synthetic wavelength of 437.2 μm.

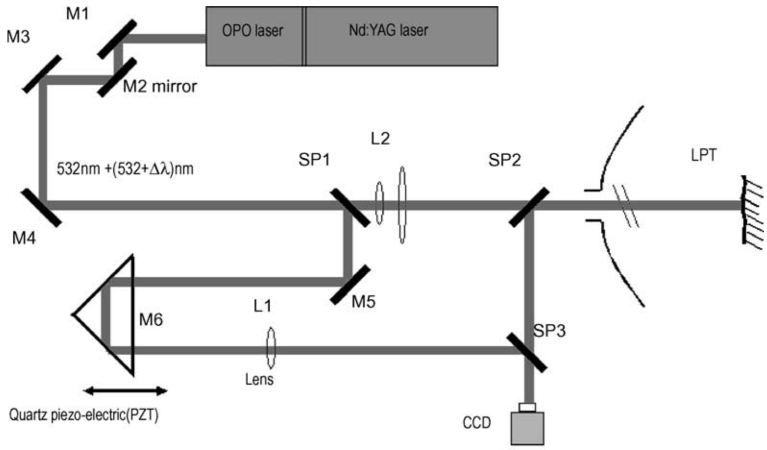

Fig. 5. Experimental set-up of a two-wavelength speckle interferometer diagnostic.

Further experiments are planned to be done on calibrated samples in order to cover the full range from 0.1 μm to 10 mm.

Because of these very promising results, we are planning to develop a diagnostic based on two-wavelength speckle interferometer to be installed on Tore Supra. Fig. 5 shows the experimental set-up of such a diagnostic, which would be mounted on a vertical upper window. Nevertheless, prior the installation on a tokamak, further developments need to be done on the optical bench in order to define the specifications of the laser (wavelength, energy, coherence length, etc.) and to demonstrate the reliability of such an optical diagnostic in a tokamak environment.

4. Conclusion

The speckle interferometry technique has been successfully tested on a CFC tile and is able to measure surface displacement in the range of tens of micrometers. The use of a second wavelength allows to increase the dynamic range and provides 3D shape measurements. First experiments performed with a continuous laser using two wavelengths at 572.250 and 573 nm provided 3D measurements of a 1 € coin. The dynamic range of the depth measurement can be modified by changing the difference between the two wavelengths. Based on this two-wavelength speckle interferometer technique, a diagnostic for in situ erosion/redeposition measurements on CIEL limiter is under development at Tore Supra.

Acknowledgements

The authors thank A. Petit, D. L'Hermite, M. Géléoc, E. Lizon for help and support during the experiments performed in their laboratory in CEA Saclay and for fruitful discussions.

References

[1] G. Federici et al., J. Nucl. Mater. 266–269 (1999) 14–29.
[2] P. Garin, Fusion Eng. Des. 49&50 (2000) 89.
[3] W. Eckstein et al., IPP9/82, Feb. 1993.
[4] R. Mitteau, these Proceedings. PII: S0022-3115(02)01522-2.
[5] E. Gauthier et al., J. Nucl. Mater. 220–222 (1995) 506.
[6] G. Roupillard, CFP/NTT.2000.031, CEA Cadarache, 2000.
[7] P. Smigielski, Holographie industrielle, ed. Teknea, 1994, ISBN 2-87717-041-1.
[8] G. Roupillard, Proceeding Second Soc. Fr. Optique Conference, Trégastel, 2001.
[9] A.W. Koch et al., rep IPP4/271, Nov. 1995.