Simultaneous imaging/reflectivity measurements to assess diagnostic mirror cleaning[a)]

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Practical methods to clean ITER's diagnostic mirrors and restore reflectivity will be critical to ITER's plasma operations. We describe a technique to assess the efficacy of mirror cleaning techniques and detect any damage to the mirror surface. The method combines microscopic imaging and reflectivity measurements in the red, green, and blue spectral regions and at selected wavelengths. The method has been applied to laser cleaning of single crystal molybdenum mirrors coated with either carbon or beryllium films 150–420 nm thick. It is suitable for hazardous materials such as beryllium as the mirrors remain sealed in a vacuum chamber. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4733538]

I. INTRODUCTION

ITER's diagnostic mirrors will necessarily be exposed to plasma and results from contemporary tokamaks suggest that degradation of mirror reflectivity could occur in less than 10 ITER discharges.[1] Laboratory tests of mirror cleaning techniques are necessary to identify effective methods to restore reflectivity.[2] This task is complicated by potential toxicity of beryllium mirror coatings and the need to assess whether the mirror surface has been damaged by the cleaning technique. Previous work used specialized equipment at the JET beryllium handling facility.[3,4] In this paper, we describe a combined imaging/reflectivity technique used to assess laser mirror cleaning of beryllium and carbon coated mirrors that remained sealed in a vacuum chamber.

II. EXPERIMENTAL SETUP

Single crystal molybdenum mirrors of the type envisioned for use in ITER were supplied by Technical University Applied Physics, Ltd. and had an 18 mm diameter reflective surface. They were coated with either carbon or beryllium films 150–420 nm thick at the Plasma Interaction Surface Component Experimental Station (PISCES) facility at the University of California in San Diego (UCSD) Center for Energy Research.[5] Four mirrors were coated with carbon by a RF plasma source using a methane gas fill. Another three mirrors were coated with beryllium using the witness plate manipulator system in the PISCES B linear plasma device.[6] A 2.4 mm wide mask covered a central strip of the mirrors to provide an uncoated reference surface for reflectivity measurements. Previous measurements at UCSD of similar Be coated mirrors showed that high levels of porosity in the coating strongly reduced the reflectivity to levels much lower than the nominal reflectivity of beryllium.[7]

The mirrors were installed in a conflat spool piece with a viewport (Fig. 1). For the beryllium mirrors, this installation was done at UCSD, the chamber filled with argon at atmospheric pressure and the mirrors shipped to Princeton for

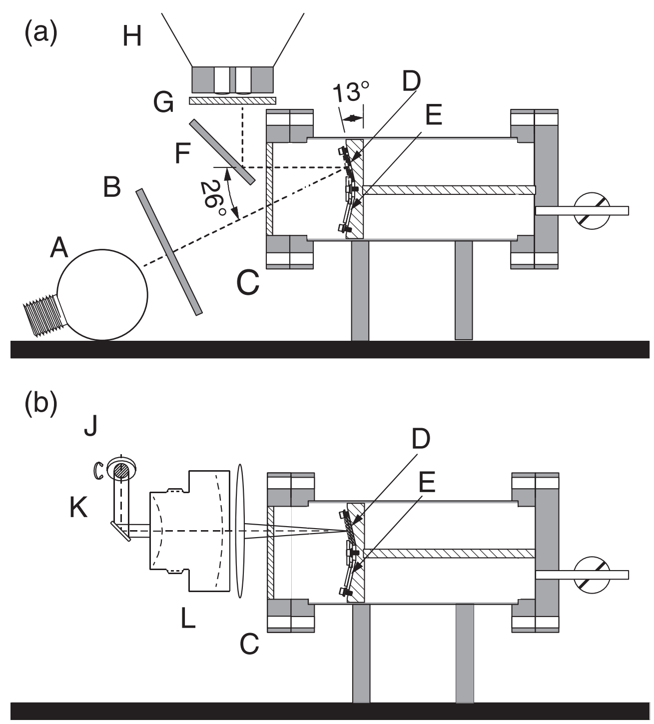

FIG. 1. (a) Side view of setup for measuring reflectivity. Light from a source (A) is further homogenized by a ground glass screen (B) and passes through a viewport (C) to illuminate a coated Mo mirror (D) or, if the chamber is rotated, an Al reference mirror (E). The mirror is imaged by a digital microscope (H) via a 45° mirror (F). An optional optical filter (G) can be placed over the microscope objective for narrow band imaging. (b) Side view of setup for laser scanning. A Nd laser beam normal to the page is directed by two orthogonal scan mirrors (J, K) to a field lens (L) that focuses it on the mirror in the chamber.

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laser treatment and reflectivity measurements. To avoid personnel exposure the Be coated mirrors remained sealed in the chamber throughout the measurements and the chamber will be returned to UCSD for disposal.

The experimental system was designed to meet the following objectives: (i) high resolution imaging at the several micrometer level to detect any damage to the mirror surface by the laser but with a relatively large distance (∼100 mm) between the mirror and microscope objective; (ii) spatially resolved measurements of the specular reflectivity of the mirror surface at different wavelengths before and after (iii) laser treatment of specific areas on the mirror, – all with the mirrors remaining sealed in the chamber. The imaging/reflectivity technique conveniently enables measurement of individual uncoated areas, coated areas, and coated areas after treatment with a range of laser parameters.

A NRC DC-5 stereo digital microscope was used to image the mirrors. The microscope has a built-in color digital camera enabling simultaneous imaging in the blue/green/red wavelength bands with 1200 × 1600 pixel image resolution. Four images were averaged in the acquisition software to minimize numerical noise. There was a small background offset with a dark image that was subtracted to derive the actual image intensity. The camera "gamma" factor was set to one for a linear response. The gain and exposure time were adjusted to ensure that the image was within the 8 bit range of the detector. A plot of image intensity vs. exposure time showed a R^2 correlation coefficient above 0.9999 confirming the linearity. For narrow band reflectivity measurements a 50 mm diameter optical filter was inserted in the optical path before the microscope objective. Two filters were used: (i) 486.1 nm (H-beta) central wavelength, 10 nm bandpass, 50% peak transmission and (ii) 656.3 nm (H-alpha) central wavelength, 10 nm bandpass and peak transmission 55%. With a 0.25× additional objective lens the microscope working distance is 125 mm, compatible with the experimental geometry and the field of view is 27 mm × 20 mm, which nicely matches the 18 mm mirror diameter. There is a 4× zoom option for a close up field of 6.7 × 5 mm^2, with one pixel corresponding to 4.3 μm. The images are recorded as .bmp files and an interactive data language (IDL) program was used to extract the intensity data and plot line outs of the blue/green/red intensity of selected bands on the mirror.

Three coated Mo mirrors and an aluminum first surface mirror were mounted symmetrically at a 77° angle to the axis of a 4 5/8 in. (117 mm) vacuum spool piece with a viewport at one end (Fig. 1). A vacuum valve and pressure gauge were mounted on the opposite end together with the internal mirror mounting hardware. A 45° mirror was used to change the microscope viewing axis to horizontal. The spool piece was mounted on a cradle and could be rotated to bring each mirror into the view of the microscope. In this way the intensity reflected by the reference aluminum mirror was directly compared to the intensity reflected from the coated Mo mirrors. The microscope collects light over an angle of 3.8° so any mirror surface damage by the laser that scattered reflected light out of this cone (diffuse reflectivity) would be apparent as a loss of reflectivity.

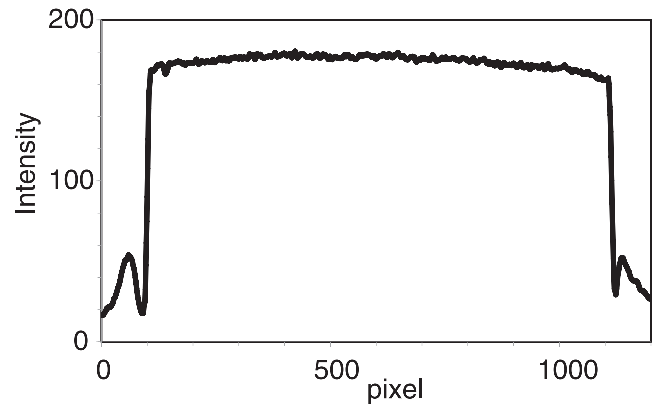

FIG. 2. Lineout of the aluminum reference mirror illustrating uniformity of illumination.

A multimode 1.06 μm Nd laser system developed for laser marking was used to treat the mirrors (Quantronix Corp. Model 118F with Q scan marking head). With an RF powered Q switch the pulse repetition rate was 8 kHz, the pulse duration was 220 ns and the average power 125 W at a lamp current of 35 A. The laser beam was coupled to the scanner via an armor jacketed 5 m long, 600 μm fused silica fiber with antireflection coatings on the fiber ends. Fiber optic coupling from a remote laser to the tokamak vessel will be essential in future applications of laser mirror cleaning to tokamaks and this feature adds realism to the present tests. The laser beam is steered at high speed by two orthogonal mirrors on a trajectory controlled by programming a computer interface (Fig. 1(b)). The laser spot profile was smooth and, measured from the ablation track on a painted surface, was typically 1 mm wide. After the laser scan the mirror chamber was transferred to the microscope cradle for reflectivity measurements.

III. RESULTS

The microscope is focused on the mirror, but sees an out-of-focus image of the illumination source. For reflectivity comparisons across the mirror it is important that the illumination field on the mirror be as uniform as possible and this was conveniently achieved with an 80 mm diameter 62 W light bulb with an internal high diffusivity coating positioned 110 mm from the mirrors (Fig. 1(a)). An additional ground glass screen provided further homogenization. The illumination field is uniform within ±6% as illustrated in Fig. 2. The lamp output was remarkably stable with time. After a 15 min warm up, the variation in the intensity measured in the microscope images was 4% (3 sigma) over 6 h. The molybdenum mirror was rotated into position and imaged under the same conditions as the aluminum mirror. The reflectivity in the 400–700 nm wavelength region for aluminum is 91%–92% (as derived from the optical constants by the imd code[8]). The ratio of the intensity of an uncoated region of the molybdenum mirror to the aluminum mirror (assigned a reflectivity of 90%) yielded a molybdenum reflectivity of 53% which is consistent with the theoretical value of 57%,[8] both averaged over the 400–700 nm region.

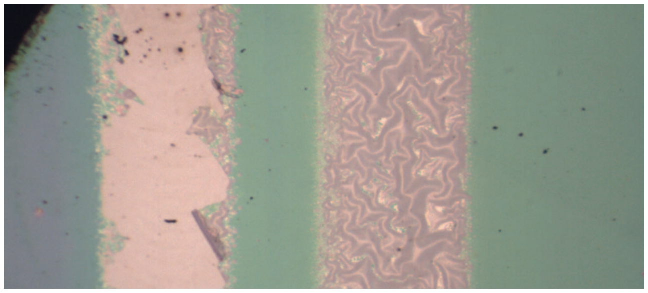

FIG. 3. Image of a molybdenum mirror coated with 422 nm of carbon after laser scans on left at 0.9 J/cm^2 showing film removal and on right at 0.7 J/cm^2 with film buckling. The laser track is 1.1 mm wide.

An image of a molybdenum mirror coated with 422 nm of carbon after two laser scans in air is shown in Fig. 3. Some restoration of reflectivity after laser treatment is apparent in a brighter image along the laser path. However, the image shows film peeling and buckling that reveals the laser/film interaction at various laser intensities. The restoration of reflectivity can be directly gauged by comparison to the uncoated region on the Mo mirror. Figure 4(a) shows a selected strip of a 179 nm carbon coated mirror imaged in 486 nm light showing vertical laser tracks. Below is a plot of the reflectivity derived from image (a) and the corresponding Al reference image. The broad central feature indicates the 52% reflectivity of bare Mo. Some laser tracks show excellent restoration of reflectivity after laser scanning under vacuum conditions. In the rightmost track the reflectivity is restored to 53%, the same level as uncoated Mo, after a laser scan at 1.6 J/cm^2.

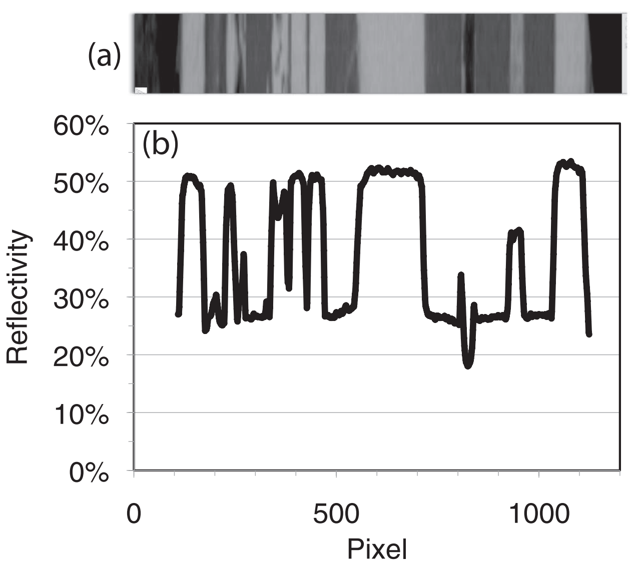

FIG. 4. (a) Selected strip of a 179 nm carbon coated mirror imaged in 486 nm light and showing vertical laser tracks. The image is expanded 5× in vertical direction. (b) Lineout of corresponding reflectivity derived from image (a) and the Al reference image. The broad central feature indicates the reflectivity of bare Mo of 52%. Some laser tracks show excellent restoration of reflectivity in the coated regions by the laser. In the rightmost track the reflectivity is restored to 53%, the same level as uncoated Mo, after a laser scan at 1.6 J/cm^2.

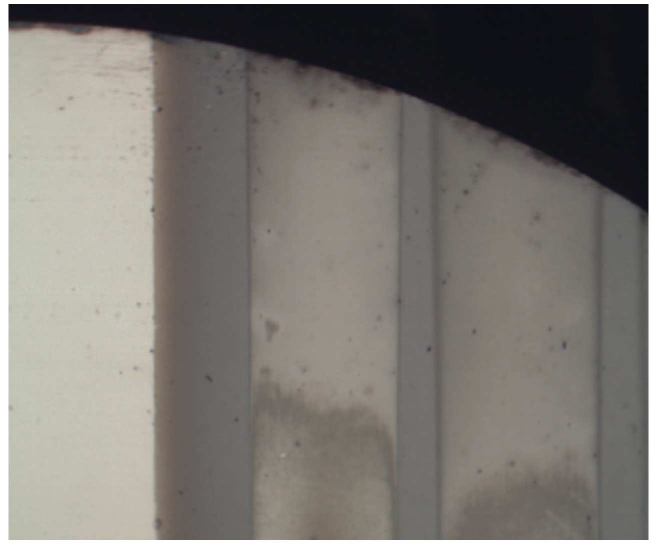

FIG. 5. Beryllium coated molybdenum mirror. The light stripe on the left is bare molybdenum; the two 1 mm wide strips on the right were treated with laser scans at 1.6 J/cm^2. Some reflectivity is restored, but not to the uncoated level.

The molybdenum mirrors coated with 150–200 nm of beryllium showed different behavior. The coating was grey with none of the interference colors apparent in the carbon films. The laser was scanned in one pass with a focal intensity of 1.6 J/cm^2 at speeds of 1360–85 mm/s (6–104 overlapping laser spots). A modest amount of the reflectivity was restored (from R = 25% to 37%), but the effect resembled melting and sagging of the coating (Fig. 5). It appears that a shorter duration laser pulse is needed to clean beryllium films. Due to space limitations a complete account of the reflectivity results will be reported separately.

ACKNOWLEDGMENTS

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