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# First mirror contamination studies for polarimetry motional Stark effect measurements for ITER

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The motional Stark effect (MSE) diagnostic on the International Thermonuclear Experimental Reactor will need to guide the light through a labyrinth of mirrors to provide neutron shielding. Knowledge of how the mirrors change the polarization is essential for accurate determination of the $q$ profile. The optical properties of the plasma facing mirror are also expected to change with time due to deposition/erosion. For the purpose of examining this experimentally a detector system, identical to the JET MSE system, using twin photoelastic modulators was constructed. Measurements have been performed on freshly prepared mirrors, on mirrors after exposure to plasmas in Tore Supra, and labyrinth designs. The result shows a significant effect on the optical properties and demonstrate the need for *in situ* monitoring. The measured properties of the labyrinth closely follow the Mueller matrix formalism. With a correct choice of material the angle change introduced by the four mirrors furthest away from the plasma will be below 1°. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1779615]

## I. INTRODUCTION

The motional Stark effect (MSE) diagnostic has proven to be an essential instrument for accurate determination of the $q$ profile in plasmas.[1–3] Since this knowledge is of vital importance for the plasma behavior, a MSE diagnostic is planned for the International Thermonuclear Experimental Reactor (ITER).[4] The most common way to acquire the $q$ profile, called polarimetry, includes measurement of the linear polarization angle of the MSE-shifted components of $D_\alpha$. For this method to work well it is therefore necessary to know the impact on polarisation of all components in the collecting optics.

On ITER it is expected that the high neutron flux will damage the diagnostics unless they are properly shielded. The light will pass the shield through a labyrinth of mirrors before it reaches the detector and the impact of these mirrors on the polarization direction is of great concern. This concern is twofold. First, it is in the best interest to keep the overall influence small and, second, it is important to know how it evolves in time.

The plasma facing mirror will change its optical properties due to erosion/deposition of particles.[5] The details are difficult to predict accurately but it is possible to get more insight by measurements on mirrors that have been exposed to a tokamak plasma.

These two important aspects of the mirror labyrinth have been measured on a miniature of the proposed configuration. The first mirror samples were supplied from Tore Supra, and had been situated approximately 50 cm outside the last closed flux surface. The total plasma exposure time was estimated to be close to 12 h (One sample had been exposed for a shorter time but with a significant level of lower hybrid current drive heating, resulting in surface currents and mirror damage). Unexposed mirrors were tested for the characterization of the nonplasma facing labyrinth part.

The experimental setup is shown in Fig. 1. It consists of a white light source, a rotary stage with a linear polarizer, and a labyrinth of mirrors. These are followed by a polarization detection system similar to the current MSE diagnostic at JET,[6] composed of a twin photoelastic modulator (PEM), a linear polarizer, an optical filter, an avalanche photodiode detector with preamplifier, and an analog to digital converter card. Signals from the detector, the rotary stage, and the PEMs were collected and a digital lock-in program was used to calculate the detected polarization angle and to compare it with the angle of the rotary stage.

## II. THEORETICAL MODEL

The Stokes representation of light is suitable for models where coherence effects are small and unpolarized light may exist.[7] In this approach the light is represented by a $4\times1$ vector with components corresponding to different polarization. Interaction with optical elements is performed by multiplying the vector with an appropriate $4\times4$ matrix, called the Mueller matrix. The Mueller matrix for a mirror contains four unknown parameters: $R_s$, $R_p$, $\varphi_s$, $\varphi_p$, the absolute reflectivities, and the phase change upon reflection in the $S$ and $P$ plane. In this study these parameters are unknown and we seek to evaluate them through experimental measurements.

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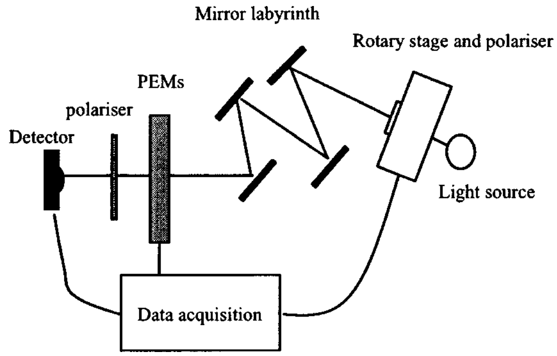


FIG. 1. Experimental setup. All parts were fastened on an optical table and the detector was shielded from background radiation.

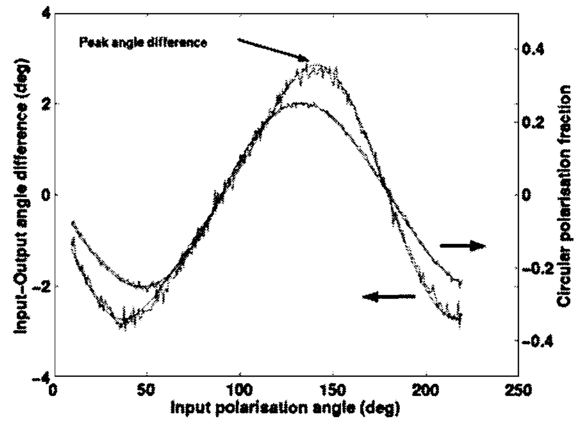


FIG. 2. Measurement and fit of linear polarization change and circular polarization fraction after a four Rh–mirror labyrinth.

These constants are different for each kind of mirror and prediction of them based on first principle is very difficult since it depends on several optical and physical properties of the mirror. Of special interest are the single and double interface models corresponding to a clean mirror or a mirror with a thin surface structure/layer.

Common ways to describe the optical properties of a material are the complex index of refraction $n_c = n - i \cdot k$ or the complex dielectric constant $\varepsilon_c = \varepsilon' + i\varepsilon''$. In this study we have used the former description.

In the single interface model the reflectivities and phase changes are calculated with the Fresnel equations, whereas in the two-interface model interference effects in the surface layer also have to be considered.[8] Several approaches are possible. Our choice was to use the equation

$$r = \frac{r_{12} + r_{23} \cdot e^{i2\beta}}{1 + r_{12} r_{23} e^{i2\beta}}, \qquad \beta = 2\pi n_{c2} \cdot \frac{h}{\lambda} \cdot \cos(\theta_2), \tag{1}$$

where $r_{12}$ and $r_{23}$ are the reflection coefficients for the two interfaces, $\lambda$ is the wavelength, $\theta_2$ is the complex angle of light in the layer, $n_{c2}$ its refractive index, and $h$ is its thickness.

In practice it proved to be difficult to extract more than two unknowns from the measurement. The model was therefore constrained to a substrate of known properties and the two fitted parameters were the thickness of the coating and the real part of its refractive index. The imaginary part was assumed to be zero.

## III. EXPERIMENTAL RESULTS

The setup and model was first tested on a number of freshly prepared unexposed metal mirrors. Au, Ag, Al, Rh, and stainless steel (SS). Gold in particular is interesting since it is inert and will have little or no surface layer, even though surface roughness and voids in the material may still be of importance. Measurement on gold confirmed the measurement procedure and also gave an idea of the accuracy we could expect from other materials.

Differences between the input and output polarization angle are shown in Fig. 2. The fitted angle difference is also shown and the expected variation with polarization shows a minimum at 0° and 90°. The precise form of the angle change as a function of polarization is different for each kind of mirror and is also strongly affected by the incidence angle of the light. General features are a smoothly varying function with none or a single zero-crossing between 0° and 90° and an amplitude that increases strongly with incidence angle. The circular polarization which is also shown in Fig. 2 shows a similar behavior but never has extra zero crossing between 0° and 90°.

A comparison between different materials can therefore be done based on the peak angle difference introduced by the mirror. Such a comparison is shown in Fig. 3. Mirrors of Rh, Au, or SS could readily be fitted with the single interface model but Ag and Al, which indeed have a protective coating, had to be fitted with the two-interface model.

There were in total four mirrors supplied from Tore Supra. One glass mirror with an Al coating (I), one SS mirror with an Al coating (II), one SS mirror without coating (III) and one unexposed reference SS mirror with Al coating (IV). The reference mirror probably had a surface oxide or protection for the Al but it was nevertheless possible to determine the optical properties using the single interface model. With that knowledge it was possible to measure the refractive index and thickness of the layers on mirrors I and II, however on mirror III the single interface model was adequate.

Mirror I had a 171 nm thick layer with refractive index

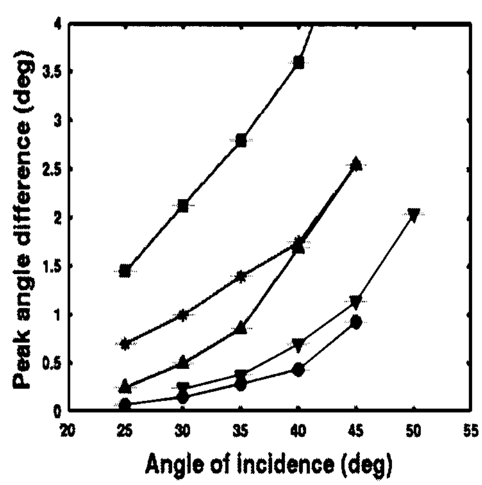


FIG. 3. Measurement of peak angle difference of unexposed single mirrors: Au (▼), Rh (*), SS (■), Ag (●), and Al (▲).

1.29, whereas mirror II had a 130 nm thick layer with refractive index 1.49. These results were an average of measurements taken over different angles of incidence. The results showed a small increase in thickness with increasing incidence angle, indicating a slight inadequacy of the two-interface model. Mirror III had a refractive index $n_c = 1.87 - i2.11$ but without a reference it could not give further information.

The maximum angle change introduced by the mirrors is shown in Fig. 4. Both mirrors I and II affect the polarization less after exposure than the reference mirror (IV). The amount of change in mirror properties is undoubtedly related to differences in the exposure history of the two samples.

Figure 2 also shows the result of a 4 Rh–mirror labyrinth with incidence angles as proposed in the present ITER MSE labyrinth design. Their respective incidence angles were 17°, 32°, 24.5°, and 21.5°. In the Stokes formalism several objects can easily be described by multiplying their Mueller matrices and the measurements show very close agreement with theory. The single mirror refractive index was measured to be $n_c = 1.85 - i5.15$ with a standard deviation of 0.12 in $n$, and 0.25 in $k$. Fitting to the labyrinth yields $n_c = 1.76 - i5.08$ which is within the uncertainty of the measurement. Predictions were also in line with measurements for labyrinths constructed using gold or silver mirrors although the peak angle differences introduced were less: 1.2° and 0.6°, respectively.

It was not possible to measure absolute reflectivities in this setup but they are nevertheless important. For example, after four SS mirrors the signal was so attenuated that it was impossible to get good data. Although not the prime concern of this investigation, it may become important if signal levels are low (like in the center of the plasma).

In these experiments we used fully polarized light but in ITER and other tokamaks the light is only partially polarized. This can have a serious impact on the polarization preserving properties of a labyrinth. Simulation with the two-interface model shows that the angle difference introduced by the mirrors is approximately tripled if the polarization fraction is 10% instead of 100%.

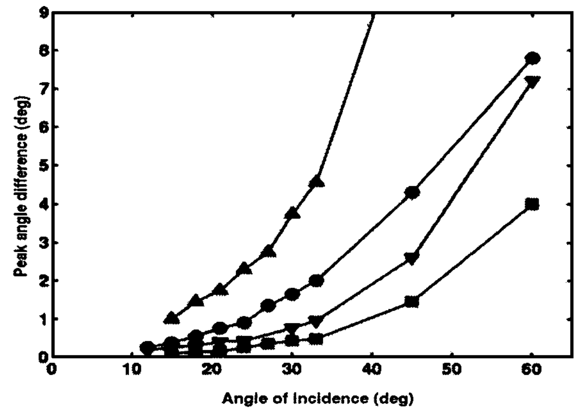


FIG. 4. Measurement of peak angle difference of exposed mirrors: SS (▲), Al on glass (▼), Al on SS (■), and Al on SS reference (●).

## IV. DISCUSSION

The measurements shown in Fig. 4 clearly point out that even after exposure times of only 12 h the effect of coating layers is already too large to neglect. This emphasizes the need for an *in situ* calibration system for the plasma facing mirror on ITER. It is possible that even the second mirror must have a monitor since the flux of particles may be non-negligible. Further investigation into this will be required.

An *in situ* calibration system could monitor the first mirror either at the same incidence angle but in an orthogonal plane or at a different angle but the same plane. Using a different angle requires a good model for the mirror or the extrapolated data will be inaccurate. Experimental results show that such a model will need to be more complex than the two-interface model. The reason may be attributed to voids or substrate imperfections but more likely it is due to nontransparency or nonuniformity (as function of thickness or surface coordinate) of the eroded/deposited layer.

All experiments with several mirrors show very close agreement with the Stokes formalism, therefore making prediction from simulation reliable for the labyrinth effect on polarization.

The choice of mirror material for the inner labyrinth mirrors is not as restricted as the first mirror and the choice should be a material with good polarization preserving properties as well as high reflectivity. Both Ag and Au perform well in this aspect.

Whatever material is chosen for the inner labyrinth and first mirror, the incidence angles should be kept as small as possible. A single mirror with 45° incidence angle will alone generate larger distortion than a labyrinth of four mirrors at 20°.

It may also be possible to reduce the problem by aligning the entire labyrinth in such a way that the $\pi$ and $\sigma$ polarization will lie close to the mirror S or P planes. This decision will depend on how the first mirror evolves and on the attainable individual channel calibration accuracy.

An even better way to reduce the problems may be to use symmetry effects that can appear in labyrinths. This is a very promising alternative that will be experimentally investigated further in the future.

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