In situ measurement of the spectral reflectance of mirror-like metallic surfaces during plasma exposition

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ABSTRACT

Visible spectroscopy in fusion plasmas crucially depends on the optical properties of first mirrors withstanding a considerable amount of radiation and particle fluxes. As a result of this interaction the optical properties of the mirrors could be changed so that a cleaning of the mirror is regularly required. Thus the reflectance of the first mirror must be monitored in situ. The newly developed Doppler-Shifted Reflectance Measurement (DSRM) diagnostic provides the spectral reflectance of mirrors in the absence of any calibration sources. It is based on the emission of fast H/D atoms in a low density Ar-H plasma by applying a negative potential on the order of −80...−200 V to the mirror surface. Until now, the experimental data were restricted to measure only the fast atom emission at the Hα line. In this work we prove that the new technique also provides the mirror reflectance at the Hβ line (Cu) (486 nm) relevant for the charge-exchange recombination spectroscopy (CXRS) measurements of the He II line (468 nm) in ITER. Moreover, the DSRM diagnostic remains sensitive to the polarization of the reflected light of a W mirror. We present the first experimental data on the time-dependent regime of operation: in situ monitoring of the degradation of an Al mirror is shown as a function of the mirror temperature. The passive heating of the mirror was performed by the plasma itself, which makes the separation between the impact of high temperature and plasma erosion on the mirror reflectance for the temperatures above 500 K impossible. A very good agreement of the experimental and the theoretical data calculated using the Drude theory for the temperature below 500 K is found. For the temperatures above 500 K the degradation of the reflectance of the mirror is determined by the erosion of Al, which is confirmed by monitoring the Al I spectral lines in unison.

1. Introduction

The knowledge of the optical properties of first mirrors in fusion devices is crucial for optical diagnostics to work properly. It is known that the first mirrors need to withstand plasma radiation and particles fluxes and thus can be damaged during the plasma operation [1]. The mirror cleaning systems are discussed currently in the laboratory [2,3] and fusion devices [4] highlighting the importance and urgency of the development of an in situ mirror reflectance monitoring system. The degradation of the reflectance of a mirror results in a loss of the measured signal. This requires the development of monitoring sources for the first mirrors. Independently of standard solutions by placing calibration lamps in the optical labyrinth with limited access [5], we have recently developed a new in situ diagnostic to measure the mirror reflectance during the low-density gas discharges (10⁻³...10⁻¹ Pa) which may be applied for cleaning. The Doppler-Shifted Reflectance Measurement (DSRM) diagnostic utilizes the Doppler effect in front of the mirror and is based on the emission of fast reflected H or D atoms after the collision of ions which are accelerated in the Child-Langmuir sheath with the mirror surface (Fig. 1 (a)). The DSRM uses the same optical path in the measurement setup and calibration sources are not required anymore. The detail study of the emission of fast atoms in low-pressure gas discharges, the favorable operating regime (Ar-H mixed plasma, flow ratio ≈1, pressure p < 0.1 Pa) of the DSRM diagnostic and comparison between literature values and experimental data can be found in the Refs. [6–8]. The spectral reflectance at a wavelength λs of the mirror can be determined by calculating the ratio of the red and blue-shifted signal, which is discussed in detail in [6].

With the emission induced by H atoms, the reflectance of mirrors can be potentially measured at the wavelength of Hα, α... lines. Until now, the DSRM data were obtained for the Hα line. This restriction at
between the s and p-oriented reflectivity of the light from the mirror surface. Finally, the new approach should be able to provide the temporal variation of the reflectance, due to a temperature degradation of the mirror surface or to mirror cleaning processes during the plasma operation.

We present here the steady-state and time-dependent results using the new DSRM diagnostic. The steady-state experimental data for the $H\beta$ line and the sensitivity of the DSRM diagnostic to the polarization are presented. The W mirror was selected for the polarization measurements as W for example is used as plasma-facing material and the difference between the s- and p-polarization at the Brewster angle is about a factor of four, according to [12]. One expects a strong reduction of the red-shifted part of emission if measured at this angle. For the $H\beta$ line measurements Cu was selected. The high reflectance at the $H\beta$ line with practically equal polarization components and at the same time moderate value of reflectance for the $H\beta$ line and rather different values of polarization makes Cu attractive for testing the abilities of DSRM diagnostics. The choice of an Al mirror was dictated primarily by the restriction of experiment to perform the heating of the mirror by the plasma itself (passive heating) so that the temperatures above $\approx 1000$ K are not expected. Furthermore, theoretical calculations of the temperature dependence of the spectral reflectance are available and the change of the reflectance is the highest for Al [13].

2. Experimental Setup

The measurements are performed at the linear magnetized plasma device PSI-2 in Jülich [14,15]. In the plasma of PSI-2 the cylindrical symmetry of the plasma source results in a hollow plasma profile with two maxima of the electron temperature $T_e = 3\ldots20$ eV and density $n_e = 10^{19}\ldots10^{21}$ cm$^{-3}$. The tested mirror is positioned in one of the maxima of the plasma profile (Fig. 1 (b)). The gas flux can be adjusted freely and was set to a fixed value of 40 sccm for each gas. Our measurements were performed in a Ar-H mixed plasma with a composition of 1: 1. The emission spectroscopy of fast atoms was performed using the front optics and high resolution spectrometer shown in Fig. 1 (b) and described in details in [6,7]. The measurements for Cu and W were performed at the angle 35° and 70° relative to the normal. Unfortunately it is not possible to observe the mirror at these angles, in contrast to the 35° and 90°, simultaneously. For the measurements at the angle of 70° a new polarization cube (CCM1-PBS251 manufactured by Thorlabs) was installed between the vacuum window and the collecting front optics. Thus, the s and p-polarization of the mirror were measured simultaneously at this angle which was controlled by the back illumination of two fibers from the spectrometer side. For the time-dependent measurements of reflectance two different target holders were used. The first one can be cooled, keeping the mirror temperature constant around 30°C. The second target holder allows to heat the mirror using the plasma as a heating source.

3. Measurements of reflectance for Cu and W mirror

The results of the measurements of the $H\beta$ line for Cu, observed at an angle of 35°, are shown in Fig. 2. The spectrum is obtained by applying a negative potential of $-120$ V to the mirror. The emission consists of background $H\beta$ line, the weak $D_\beta$ line and the emission caused by fast reflected atoms at the blue-shifted wavelengths relative to the unshifted one. The red-shifted part of emission observed at the wavelengths of 486.3 nm is provoked by reflection at the Cu mirror of photons emitted by atoms moving away from the mirror. The non-overlapping parts of the signal are shown in blue and red colors respectively. The ratio of the integrals between the red- and the blueshifted emission gives the value of the reflectance one is interested in. For the Cu mirror the experimental value equals to 0.56 whereas the theoretical one [12] gives the value 0.59. Thus, the measurements of reflectance for the $H\beta$ wavelength agree with the theoretical values within of a few percents.
similarly to the results for the $H_\beta$ line.

Emission of spectral lines in fusion plasmas takes place in a strong magnetic field so that the Zeeman or Stark effect dominates over the fine structure separation by orders of magnitude. Until now the DSRM diagnostics was applied to obtain the values of specular reflectance, and the polarization properties of mirrors were not considered at all. However, in specific cases such as MSE diagnostics one has to know not only the value of reflectance but also its polarization components. We have tested if the DSRM diagnostic could potentially provide these data as well. For the polarization measurements a new W mirror was used. The theoretical calculations of Werner et al [12] show that the difference of s and p-polarization at the angle of 70° is a factor of four and the Brewster angle for W equals to 78.7°. In Fig. 3 the measured emission spectrum of fast atoms in front of the W mirror is shown.

As one can see in Fig. 3 (a), only the red-shifted component of the measured spectrum is polarized. The blue-shifted signal remains the same: the directly observed emitted light induced by the fast atoms is not interacting with the mirror surface. In contrast the red-shifted component is the result of such interaction and the polarization properties of the mirror impact its intensity. We are able to measure a clear difference between s and p-polarization for the red-shifted signal. However, the p-polarization is reduced by a factor of two and not by a factor of four as one would initially assumed (see Fig. 3 (b)). The reason lies in the overlapping of the wavelength interval of direct and reflected signal as after the backscattering process the atoms have a certain energy and angular distribution. If the line-of-sight coincides with the surface normal the profiles of the line shapes of the red and the blue-shifted components are completely separated from each other. However, by increasing the observation angle the overlapping increases (see Fig. 3 (a)). At the observation of 45° the emission of the reflected atoms in the energy range of $|E_0/2:E_0|$ could be clearly separated, where $E_0$ is the maximal energy of the backscattered fast atom. We measure at the angle of 70°, this means that two distributions functions (of the direct and reflected emission) are overlapping on a wide range and thus the observed red-shifted component also includes a blue-shifted part (like indicated by the horizontal lines in Fig. 3 (a)). It limits the application of the DSRM diagnostic at larger angles as the polarization components s or p could be not so easily derived as for the angle of 35°. In fact one has to develop a model for the distributions function of the reflected atoms and use this model and the spectroscopic data to calculate the reflectance. In this case the overlapping will be no longer an issue, because the distributions functions are known and the blue-shifted part on the red-shift side can be subtracted out.

4. In situ measurement of the surface degradation of the Al mirror

Beside the polarization measurements also the degradation of the mirror surface is of special interest, because the reflectance of the first mirrors most probably decreases during the plasma exposure. This can lead to a reduced performance of the plasma diagnostic which uses the mirror.

We have designed the following experiment to demonstrate the properties of the DSRM diagnostic. First, the Al mirror is cooled and the temperature is kept constant at around 300 K. The $H_\beta$ spectrum and the measured reflectance is depicted in Fig. 4 (c) in blue color. As can be seen, neither the Doppler-shifted components nor the reflectance change within the error bars. The results are identical to the previous measurements for Pd [6] demonstrating the degradation on the order of $1-2\%$.

This demonstrates two aspects: If the mirror is held at a low temperatures our measurement technique does not influence the optical properties of the mirror within such a time interval. Furthermore we are able to measure the reflectance in situ during the plasma operation. The situation completely changes if the mirror is heated up by the plasma. The temperature curve during the measurement is shown in Fig. 4 (d). It was measured every second and for the plot the mean value over one minute is calculated. The experiment started at a mirror temperature of around 380 K and it rose up to around 600 K. The first and the last spectrum are shown again in Fig. 4 (b). The dramatic degradation of reflectance of Al happens during the plasma operation and the DSRM diagnostic is able to track this change. As can be seen in Fig. 4 (c) and (d) the spectral reflectance at the beginning stays nearly constant at a
value of 0.81 up to 10 min after the start of the exposure. The temperature at this point is around 440 K. After this the spectral reflectance show a faster decrease to a value of around 0.71 at the temperature of 500 K. In this temperature interval of 380 K - 500 K the observed variation shows a good agreement with the theoretical temperature dependence of the refractive index [13,16]. The theoretical data are depicted in Fig. 4 (c) using the dashed black curve. The data is calculated using the Drude theory [13]. One should mention that the measurements of spectral reflectance at elevated temperatures are usually performed using lasers [17] and are extremely seldom. The change in temperature leads to a change of the reflectance of Al mirror on the level of 15%. After this, a rapid drop of reflectance is observed to a value of 0.21 after 45 min of exposure and heating. During the last 15 min the spectral reflectance stays constant at this value for the rest of the experiment. This decay can be hardly explained with only a temperature dependence. It is most probably the result of the limitation of the mirror heating process by plasma: sputtering at elevated temperatures causes the degradation of the mirror. One of the most possible explanation of such behavior is a creation of so-called adatoms at the surface [18]. In order to prove this we also monitored the emission of two Al lines at 394.4 nm and 396.2 nm. The line intensities are shown in Fig. 4 (d) using the green dots and crosses. The drop of reflectance at about 500 K is accompanied by an increase of Al erosion in the experiments. The Al lines emission is increased by a factor of 5 - 10 during 15 min. Interesting, that the growth of erosion is shifted by about 5 - 10 minutes before the drop of reflectance happens: a layer of approximately 1 μm has to be removed during the sputtering of the Al by Ar to affect the spectral reflectance. The surface was completely destroyed and diffuse after this experiment. The analysis of the last spectrum shown in Fig. 4 (b) provided the value of reflectance of 0.21. The value of 0.19 was obtained in the laboratory after the experiment. Thus, even in the case of diffusive surfaces the DSRM diagnostic provides a reasonable agreement with standard methods. Obviously the DSRM diagnostic is able to trace the degradation of mirror reflectance at elevated temperatures however an active heating of the mirror would simplifies the separation between the temperature effect and enhanced sputtering. We are going to implement it in the near future.

5. Conclusion and Outlook

In this work we have shown the new aspects of the Doppler-Shifted Reflectance Measurement (DSRM) diagnostic. First, we have shown that one can measure the reflectance of mirrors also at Hγ wavelength, which is relevant for the helium ash measurements. Secondly, we demonstrated that the diagnostic remains sensitive to the polarization properties of the first mirrors. Here, however, the values of s and p-polarization can be not derived directly at high angles around 70° using the simple approach presented in [6]. Since the possibility to determine the polarization properties of the material is independent of the material itself, also Mo or Rh mirrors [19] (which are promising candidates for ITER) can be analyzed with the DSRM diagnostic. A further modeling of emission of fast atoms is required. Because of this we could not provide the polarization coefficients directly but we can quantify that the reflected light from the mirror surface is polarized like expected.

Finally we have measured the degradation of an Al mirror surface in situ during the plasma exposition. In the case of the mirror held at the room temperature of 300 K practically no drop of reflectance within one hour of plasma operation was detected. The situation changes dramatically by heating the mirror. The reflectance drops according to the Drude model up to the temperatures of 500 K. Unfortunately, for higher temperatures the enhanced sputtering of Al prevent us to conclude if the theoretical data are also valid. The dramatic drop of reflectance to the value of 0.21 is caused by the sputtering confirmed by simultaneous monitoring of the Al line. The results of the measurements are again in good agreement with the value of 0.19 obtained in the laboratory. In the forthcoming experiment we are going to install an active heating
system to the mirror and analyze the abilities DSRM diagnostic relevant for fusion plasmas and beyond.

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