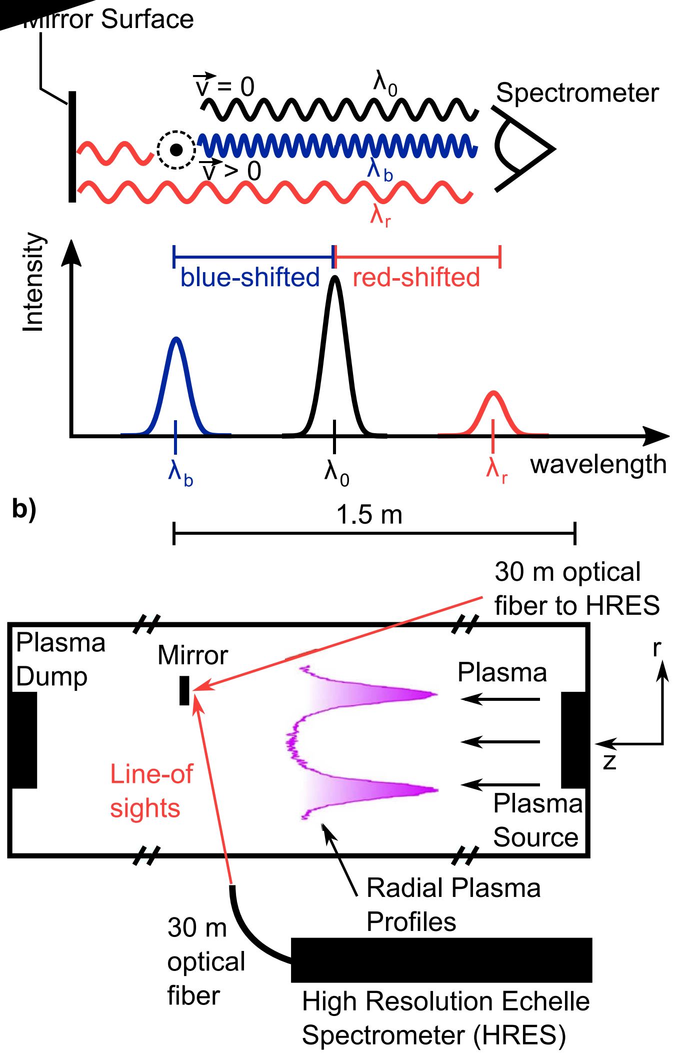

Fig. 1. (a) Schematic picture of the Doppler-shifted emission of a single monoenergetic atom moving with a velocity v from the mirror surface in direction of the spectrometer. (b) Schematically experimental setup of the presented measurements. The mirror is positioned in the upper maxima of the plasma profile. The upper port is the 35° observation port (for 35° measurement), the lower one is the side observation port for measurements at 70°. Both ports are connected by a 30 m optical multimode fiber to a high resolution echelle spectrometer (HRES).

the first glance is not severe, because many diagnostics such as the Motional Stark Effect (MSE) [9]), Beam-emission spectroscopy (BES) [10]) or the measurements of the Zeeman Effect [11] at the plasma edge utilizes exactly the H_α wavelength. Nevertheless, the *in situ* measurements of the spectral reflectance of mirrors at the H_β line would be specially favorable for the CXRS diagnostic in ITER, which is going to deliver the concentration of the helium ash from the analysis of the He II line ($n = 4 \to n = 3$). This transition is observed at the wavelength of 468 nm, being shifted only by 18 nm from the H_β line. As far as it is not expected that the reflectance changes within this wavelength interval considerably the DSRM diagnostic could potentially solve the calibration problem for the He II measurements. In addition to the measurements of the spectral reflectance, the question regarding the polarization of the reflected light frequently appears. For instance the derivation of the q-profile from the MSE data requires a precise information on the polarized reflectance. In this case the DSRM diagnostic should be able to provide such data as well, by adding a polarizer in the optical path of the DSRM diagnostic. The polarizer is used to distinguish

[redacted] operation.

We present here the steady-state [redacted] the new DSRM diagnostic. The steady-state experimental data for the H_β 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_β line measurements Cu was selected. The high reflectance at the H_α line with practically equal polarization components and at the same time moderate value of reflectance for the H_β 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 ≈ 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 $T_e = 3\cdots20$ eV and density $n_e = 10^{10}\cdots10^{12}$ 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_β 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_β line, the weak D_β 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_β wavelength agree with the theoretical values within of a few percents

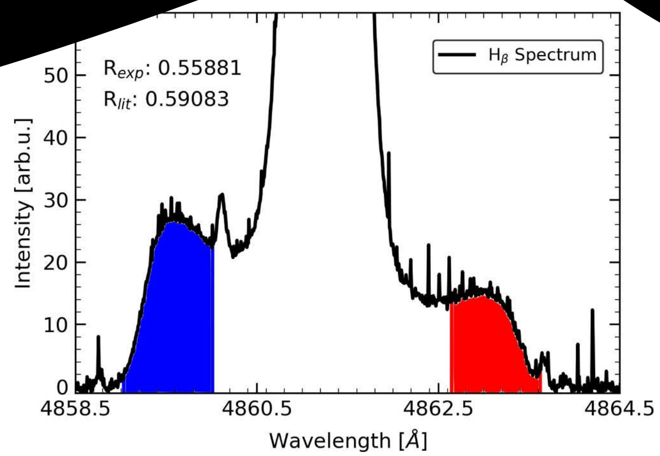

Fig. 2. Emission spectrum of fast atoms at the H_β line in front of the Cu mirror. The specular reflectance of 0.56 is obtained as the ratio between the integral of the red and the blue-shifted emission (the areas in which the integrals is calculated are colored in blue and red). The literature value of reflectance is 0.59 [12]. Measurements are performed in the Ar-H mixed gas discharge and the applied potential to mirror surface is -120 V.

similarly to the results for the H_α 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.

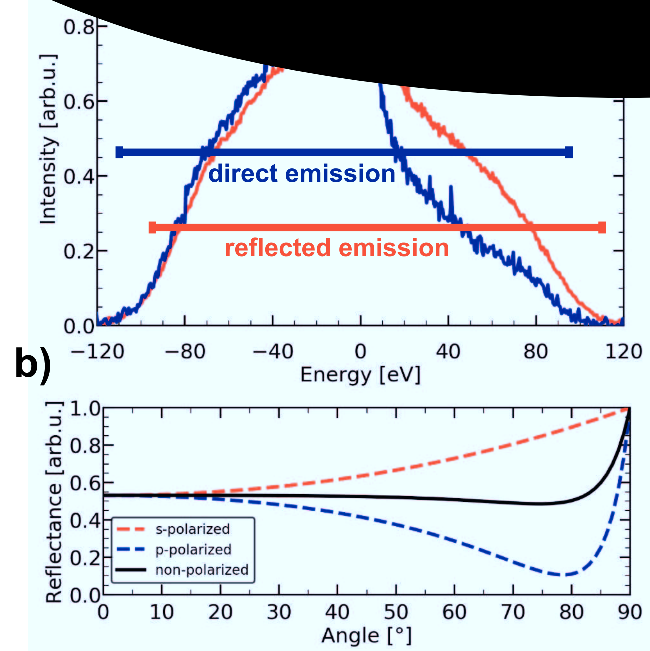

Fig. 3. Polarization measurement of a W mirror measured at an angle of 70° between line-of-sight and surface normal of the mirror. A negative voltage of -120 V was applied to the W mirror. (a) Emission spectrum of fast atoms observed at the angle of 70° using the polarization cube. The s-polarized light is depicted in red and the p-polarized in blue. (b) The theoretical curve of s and p-polarization for W according to [12].

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_α spectrum and thus the reflectance is measured every minute for about 60 minutes. The first and the last spectrum of this experiment is shown in Fig. 4 (a) 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

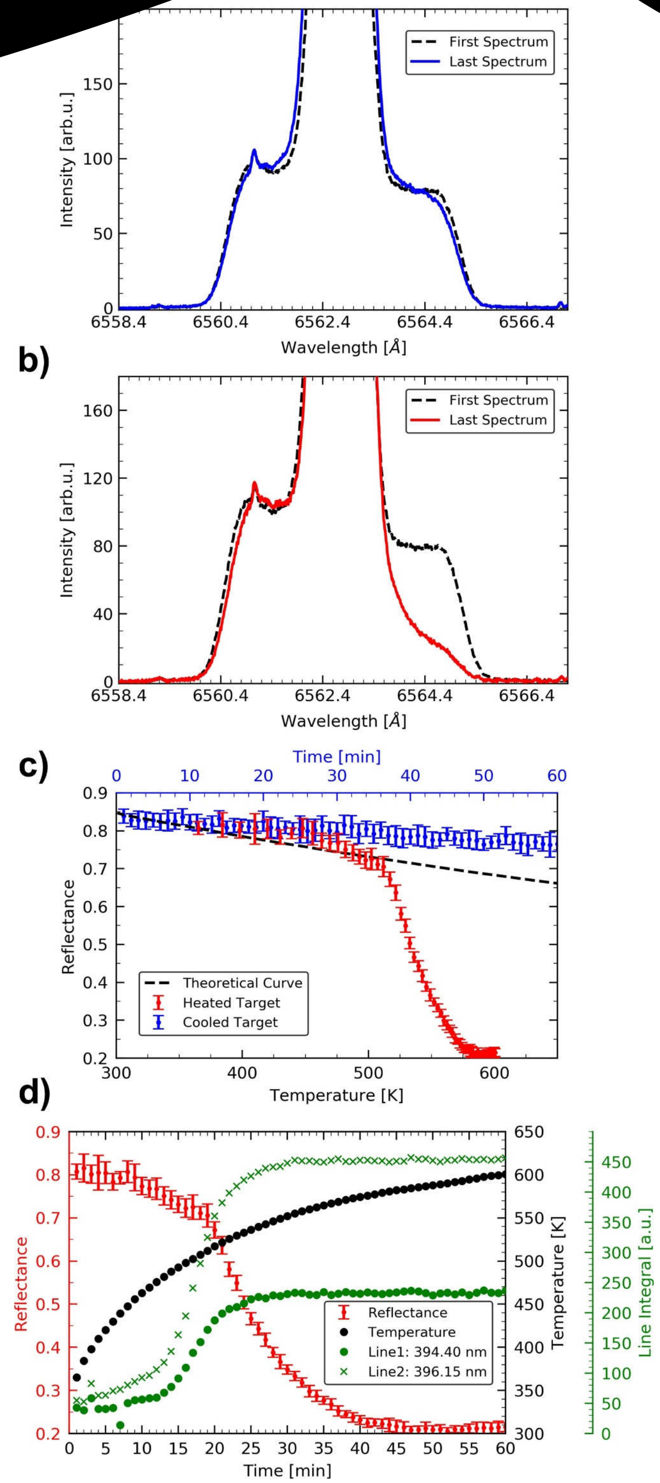

Fig. 4. *In situ* measurement of the degradation of reflectance of an Al mirror. For the measurements a negative voltage of − 100 V was applied. (a) The mirror was cooled and the temperature was held constant at about 300 K and the reflectance was measured every minute. The first (black line) and the last spectrum (blue line) are shown. (b) The same mirror like in (a) was heated up to 600 K. The reflectance is again measured every minute. The first (black line) and the last spectrum (red line) is shown. (c) Reflectance values for the measurement of (a) and (b). The reflectance of the cooled target is shown in blue and of the heated target in red. The blue data points belong to the blue top x-axis, the red and black data points belong to the black one. The black dotted line is the theoretical data, calculated using the Drude theory [13]. (d) Time-dependence of the measured reflectance (red points), temperature of the mirror (black points) and emission of Al lines (green points and crosses) for the heated target. Note that the color of the y-axis indicates the data points it belongs to.

[redacted] show [redacted] 500 K. In this [redacted] iation shows a good [redacted] pendence of the refractive index [13,16]. [redacted] picted 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 **D**oppler-**S**hifted **R**eflectance **M**easurement (DSRM) diagnostic. First, we have shown that one can measure the reflectance of mirrors also at H_β 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 [redacted] mirror and analyze the abilities DSRM diagnostic relevan[redacted]usion plasmas and beyond.

Acknowledgement

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