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Colorimetry in Nuclear Fusion Research

Gen Motojima

Abstract

Colorimetry is a unique technique among research fields. The technique is also utilized in nuclear fusion research. The motivation is to evaluate the wide range of distribution of the deposition layer on the surface of the vacuum vessel. The deposition layer affects the control of fuel particles. Therefore, the result from colorimetry can contribute to the study of particle control in fusion plasma. In a particle control study, global particle balance analysis is usually conducted. Also, long-term samples irradiated by plasma have been analyzed. Colorimetry has the role of a bridge between these analyses. In this chapter, a demonstration of colorimetry in fusion devices is introduced.

Keywords: nuclear fusion, colorimetry, color analyzer, reflection rate, deposition layer, wall retention, Large Helical Device, Wendelstein 7-X

1. Introduction

We are now facing challenging times in the global environment. While people's social lives are becoming more affluent, global changes (a global crisis, if you will) such as global warming must be solved on a global scale. The world is aiming to become carbon neutral by 2050. Here, carbon neutrality, which is often used in conjunction with the term “a decarbonised society”, is a concept that aims to limit carbon dioxide emissions, which are the main cause of global warming. To achieve carbon neutrality, hydrogen is attracting attention as the energy of the new age. Hydrogen is considered to be the most abundant material in the universe and can be used as heat energy through combustion. The main advantage of the use of hydrogen is that hydrogen does not produce carbon dioxide when it is used as energy. The energy efficiency of hydrogen is so high that it is even used as fuel for rockets. Nuclear fusion energy is the key energy source, using hydrogen as a fuel.

Nuclear fusion is a reaction in which two or more nuclei are transformed into nuclei of higher atomic numbers. The easiest fusion reaction to initiate on the earth is a nuclear reaction in which helium (He) and neutrons (n) are produced from deuterium (D) and tritium (T). 17.6 MeV ($=2.82 \times 10^{-12}$ J) of energy is released in a single nuclear reaction. The reaction equation can be expressed as an Eq. (1).

The nuclear reaction of 1 g of D-T fuel corresponds to the thermal energy of the combustion of about 8 tons of fossil fuel oil. For a reaction as shown in Eq. (1) to

occur, it is necessary to increase the relative velocity of the nuclei so that the kinetic energy is greater than the electric potential energy at the position where the nuclear force is effective. The relative velocity of hydrogen can be increased by heating it to a high temperature and by the increase of the thermal motion of the nuclei. For a fusion reaction to occur on earth, the hydrogen fuel particles would have to be heated to several hundred million degrees. In such a high-temperature state, the constraint of electrical attraction between nuclei and electrons is broken and they become discrete. This state is called “plasma”. There are several ways to confine the plasma, but here we introduce research on fusion plasmas with the “magnetic confinement method”. Few readers may be able to imagine the relevance of colorimetry to fusion research. The author hopes that this chapter will make the reader aware that colorimetry is a method that can make a significant contribution to fusion research. Especially, colorimetry helps the understanding of particle control in nuclear fusion research.

2. Contribution of colorimetry to nuclear fusion research

To gain stable fusion energy, a stable fuel supply control is necessary. For performing fuel particle control, understanding of the particle absorption process at the plasma-facing wall is an important issue, as well as the establishment of a fuel supply method. For example, in the Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS) in Japan, which is one of the largest superconducting machines among helical plasma experimental devices [1], a global particle balance analysis was carried out in a 48-minute-long helium discharge with a total heating power of 1.2 MW using ion cyclotron heating and electron cyclotron heating, and dynamic wall retention of fuel particles was found [2]. It has been found that the dynamic wall retention can be explained by the temperature dependence of the particle retention of the plasma-facing walls composed of the divertor plate (carbon) and the first wall (stainless steel) [3–5]. In this discharge, 60% of the fuel particles were absorbed by the wall, and long-term samples irradiated by plasmas showed that the absorbed amount increased linearly with the thickness of the carbon-based deposition layer [5]. To understand the particle retention in the wall, it is important to identify “where” and “how much” the deposition layer is distributed in the vacuum vessel over a wide area. However, it is not practical to evaluate the thickness of the deposition layer on all the plasma-facing walls of the vacuum vessel using irradiated samples, because it takes time to analyze the samples and only a limited number of samples can be installed in the vacuum vessel. Therefore, a new method has been devised: color analysis. So far, color analysis has been carried out on plasma experimental devices such as the TEXTOR-94 and ASDEX-U [6, 7]. In these machines, the hue of the color was measured to assess the thickness of the deposition layer. For this purpose, a CCD camera was used in the TEXTOR-94 and an imaging camera was used in the ASDEX-U. Although, there have been reports of using cameras to evaluate the thickness of deposition layers in the past, the measurement area is still limited, and it is difficult to extend the measurement to a wide area in a vacuum vessel. In addition, when analyzing a shiny object such as metal, the reflected light from the specular reflection is strong. Therefore, the position of the sensor is affected by this effect. Thus, the color analysis of the object may not be accurate due to the strong influence of the specular reflection. The earlier study of color analysis indicates that the measurement area was not sufficient, and the accurate reflection rate was difficult to be evaluated in the metal object.

In this chapter, we introduce an example of the application of the color analysis method to the LHD using a color analyzer, which can be utilized on the metal

Figure 1.
 The process from colour analysis to deposition layer thickness evaluation.

surface and evaluate the thickness of the deposition layer over a wide area. To evaluate the thickness of the deposition layer by color analysis, four processes are carried out, as shown in **Figure 1**. The evaluation of the thickness of the deposition layer from the color analysis is a four-step process, as shown in **Figure 1**. Process 1 is a color analysis using a color analyzer. Process 2 shows that the color analysis measurement is equivalent to the reflection measurement from a physical point of view, and Process 3 shows that the relationship between the reflection and the thickness of the deposition layer can be explained by the single-layer model. Finally, in Process 4, the thickness of the deposition layer is evaluated from the results obtained from color analysis. In this chapter, each process is explained in detail.

3. Compact color analyzer

A compact color analyzer (model: DM-1) manufactured by Hitachi Metals in Japan was used to evaluate the thickness of a wide range of deposition layers on the first wall of the LHD vacuum vessel [8]. A photograph of the color analyzer is shown in **Figure 2(a)**. The main feature of this analyzer is that it has an LED integrating sphere inside the analyzer. The internal structure of the integrating sphere is shown in **Figure 2(b)**. The light emitted from the LED is injected into the object as a homogeneous standard light by a diffuser. After that, the photodiode sensor captures the light reflected from the object, which includes both positive reflection and diffusive light. Then, numerical values output as the intensity of three specific types of light, so-called R, G, B (Red, Green, Blue), with central peaks at red (615 nm), green (540 nm) and blue (465 nm). This color analyzer can measure not only R, G and B but also hue, saturation and brightness. The specifications of the color analyzer are given in **Table 1**.

The color analyzer is lightweight, small in size, and user-friendly, so that it can be easily carried into the vacuum vessel opened to the atmosphere after the plasma experiment. In addition, the measurement time is only about 3 seconds, which makes it possible to measure many points in a short time. Furthermore, the internal memory enables continuous data storage, and the rechargeable battery eliminates the need for a continuous AC power supply. Here, to evaluate the accuracy of the color analyzer, we calibrated it using about 400 color sample books (DIC Color Guide, 19th Edition, PART1, 3) whose R, G and B values were known in advance [9]. A summary of the calibration results is shown below; the R, G and B values have an offset, and their values are all similar. The R, G and B values have similar characteristics of sensitivity with high sensitivity in large values and low sensitivity in small values. A high RGB value indicates that the image is close to white, and

(a) Portable Colour Meter with Integrating Sphere DM-1
(Hitachi Kinzoku, 2014)

Figure 2.
(a) Photograph of the colour analyzer (model: DM-1) and (b) Operation principle of colorimetry method. Formation of incident light from the integrating sphere and capture of light reflected from the target [10].

Measurement	RGB (Red, Green, Blue) HSV (Hue, Saturation, Value)
Measurement window diameter	Φ8.1 mm
Internal diameter of integrating sphere;	Φ47 mm
Light source	White LED
RGB range	0~1023
Weight	~160 g
Measurement time	3 seconds
Record	USB memory installed in analyzer

Table 1.
Specifications of the colour analyzer.

a low RGB value indicates that the image is close to black, i.e., the image is more sensitive when the color is white and less sensitive when the color is black. This is similar to the human eye in general, which finds it more difficult to distinguish the difference in color between black than white. From the viewpoint of the evaluation of the deposition layer, it is desirable to have sensitivity up to the region of low RGB value, and further development of the color analyzer is expected in the future.

4. Experimental results

4.1 Relation between reflection rate and RGB values measured by the color analyzer

In this section, the physical meaning of the RGB values measured by the color analyzer is considered. As described in Section 2, the value measured by the color analyzer expresses the intensity of the reflected light from an object by spectroscopic RGB values of specific wavelengths in visible light. The correlation between the reflection rate and the RGB values was investigated using long-term samples irradiated by plasma, installed in the vacuum vessel of the LHD. The long-term irradiated samples are made of substrates of stainless steel and are placed on the first wall of the toroidal section at various locations from the inside to the outside of the torus. They are exposed to the plasma during one experimental cycle (see **Figure 6(b)** for the locations). The optical reflection spectra of these samples, which were removed from the vacuum vessel after the plasma experiment, were evaluated using spectroscopic ellipsometry. At the same time, the RGB values of the samples were measured with a color analyzer. **Figure 3** shows the relationship between the RGB values and the reflection rate. The reflection rates were obtained by averaging the values at the

Figure 3.
The relationship between the RGB values measured by the colour analyzer and the reflectance measured by the spectroscopic ellipsometer [11].

wavelengths of red (615 nm), green (540 nm) and blue (465 nm) from the optical reflection spectra. For reference, the unexposed samples are plotted on the same graph. The reflection rate and the RGB values show a linear relationship, indicating that the RGB values measured by the color analyzer express the reflection rate. The surface roughness of the sample may also affect the RGB values. However, the cross-section of the sample observed by Transmission Electron Microscopy (TEM) shows that the surface roughness is less than 100 nm, which is lower than the wavelength of visible light, so the effect of surface roughness is considered to be small.

4.2 Evaluation of the thickness of the deposition layer by TEM cross-sectional observation

In the previous section, it was confirmed that the RGB values measured by the color analyzer are equivalent to the reflection rate. To estimate the thickness of the deposition layer from the reflection rate, it is necessary to clarify the relationship between them. The cross-sections of the long-term installation samples were cut by the Focus Ion Beam (FIB), and the thickness of the deposition layer of the long-term irradiated samples was evaluated by TEM observation. **Figure 4** shows the TEM images of each sample. In some samples, it is difficult to identify the interface of the deposition layer, and tungsten is deposited on the surface of the sample to prevent surface damage during FIB cutting. Although, the TEM images show interesting features such as directional structures in the deposition layer and blistering of the substrate, we will only focus on the thickness of the deposition layer in this chapter. **Figure 5** shows the relationship between the thickness of the deposition layer, evaluated from the TEM images, and the reflection rate measured by the color analyzer and spectroscopic ellipsometer.

4.3 Relationship between the experimental results and the single-layer model

To discuss the relationship between the thickness of the deposition layer and the reflection rate, we consider a single-layer model. In the model, we assume a simple

Figure 4. TEM cross-sectional images of long-term irradiated samples [11].

Figure 5.
Relationship between thickness of deposition layer and reflection rate using single layer model [11].

three-layers: the atmospheric layer, the deposition layer and the substrate layer. The reflection rate, R_{ref} , can be expressed as follows [12].

$$\phi = \frac{2\pi N_f \cos \theta}{\lambda}, \tag{2}$$

$$r = \frac{r_0 + r_1 \exp(i2\phi)}{1 + r_1 r_0 \exp(i2\phi)}, \tag{3}$$

$$R_{\text{ref}} = |r|^2 \tag{4}$$

where ϕ , λ and θ are the phase difference, the wavelength of the incident light and the angle of incidence of the light, respectively. N_f and d are the refractive index and thickness of the deposited layer, r is the electric field ratio of the reflected light to the incident light, and r_0 and r_1 are the Fresnel reflection coefficients at the air-deposition layer boundary and the deposition layer-substrate layer boundary, respectively. This simple model shows that the reflection rate is nonlinearly dependent on the thickness of the deposition layer. For the polarization of the light, the ratio of S-wave to P-wave is assumed to be 1:1. The refractive index of the deposition layer was set to $n = 1.24$ and $k = 0.98$ based on the results of ellipsometric measurements. The refractive index of the stainless steel substrate is assumed to be $n = 1.5$, $k = 2.9$. The relationship between the thickness of the deposition layer and the reflection rate of the single-layer model is shown by the solid line in **Figure 5**. A clear dependence of the reflection rate on the thickness can be observed in the range of 10 nm to 100 nm. We now look at the thickness dependence of the reflection rate of the single-layer model. While there is a dependence of the reflection rate between 10 nm and 100 nm, the dependence becomes weaker when the thickness of the deposition layer is below 10 nm or above 100 nm. This may be because the reflection rate of the substrate dominates for the thin layer and the reflection rate of the deposition layer dominates for the thicker

layer. The dependence of the single-layer model is similar to the experimental results of the reflection rate using a color analyzer and spectroscopic ellipsometry. Therefore, the relationship between the reflection rate and the thickness of the deposition layer can be explained by the single-layer model.

4.4 Evaluation of reflection rate distribution and thickness distribution of deposition layer on the first wall of helical coils

The reflection rate of the first wall on the helical coil in the same toroidal section, where the long-term irradiated samples described in 3.2 were installed, was measured using a color analyzer after the opening to the atmosphere in the vacuum vessel. The measured number of stainless steel protection plates was 530. The reproducibility of the measurements was confirmed by performing the measurements twice. **Figure 6(a)** shows the results of the reflection rate

Figure 6. (a) CAD showing the measured reflection rate, (b) developed view, and (c) deposition layer thickness distribution evaluated from reflection measurements [11].

measurements [11]. On the outside of the torus, the RGB values of most of the protection plates are low and the reflection rate is low. On the other hand, inside the torus, the RGB values are high, and the reflection rate is high except near the divertor plate. For clarity, **Figure 6(b)** shows the development figure of the measured stainless steel plates. These results suggest that deposition is dominant outside the torus, while erosion is dominant inside the torus. The reflection rate of the deposition layer is determined by the balance between erosion and deposition processes, which depends on the distance from the plasma and the view from the divertor plate. The RGB values are higher when the stainless steel plate is closer to the plasma and lower when it is farther from the plasma [9]. This relationship of the distance between the protection plate and the plasma with the reflection rate is interesting (for details, refer to [9]). Using the reflection rate measured by the color analyzer, and assuming that the thickness of the deposition layer follows the single-layer model, the thickness distribution of the deposition layer on the helical coil was evaluated. **Figure 6(c)** shows the thickness distribution of the deposition layer evaluated from the reflection rate measurement. As predicted from the reflection rate measurements, deposition is dominant on the outside of the torus, while erosion is dominant on the inside of the torus except near the divertor plate. In terms of the distribution of the deposition layers, 37% of the layers were 10 nm thick, 44% were 10–100 nm thick, and 19% were thicker than 100 nm. 60% of the first wall of the helical coil in the toroidal section was covered by the deposition layer. This result suggests that the region covered by the deposition layer shows an important role in the wall absorption of fuel particles. Quantitative comparison with global particle balance analysis is also performed using this experimental result, please refer to Ref [3].

Colorimetry has been applied to plasma experimental devices other than the LHD. Here we introduce an example of the application of colorimetry on the Wendelstein 7-X (W7-X) device at the Max-Planck-Institute for Plasma Physics in Germany [10]. Similar to the LHD, the W7-X is a large superconducting stellarator device [13]. **Figure 7** shows the results of colorimetry measurements in the W7-X on the surface of the panels covering the vacuum vessel and the evaluation of the deposition layers in different experimental campaigns. **Figure 7(a)** shows

Figure 7.
Colour pattern of first wall panels after (a) OP1.2a and (b) OP1.2b in W7-X [10].

the estimated deposition layer after the experimental campaign of OP1.2a, where the average thickness of the deposition layer is predicted to be 10 ca. On the other hand, the deposition layer after the experimental campaign of OP1.2b is shown in **Figure 7(b)**. The thickness of the deposition layer is evaluated to be 25 ca. Thus, colorimetry provides useful information for discussing strategies for removing the deposition layer.

5. Summary

In this chapter, a color analysis method using a color analyzer is introduced, and it is shown that it is possible to evaluate the deposition layer formed on the plasma-facing wall by color analysis. As an example, the color analysis of the first wall on the helical coil of the LHD shows that the thickness distribution of the deposition layer on the inner and outer sides of the torus is different. Also, the different deposition layer thickness has been obtained in the different experimental campaigns in the W7-X. Although, color analysis is useful for surface analysis of plasma-facing walls, it may not be an in-situ diagnosis, because the current method requires a color analyzer to be brought into the vacuum vessel for measurement. However, using the principle of evaluating the thickness of the deposition layer from the color analysis, it could be applied as an in-situ diagnostic measurement. For example, if the color analyzer is held by a robot arm and operated remotely, in-situ diagnosis is possible. The color analysis method using the color analyzer has already been applied not only to the LHD and W7-X but also to the QUEST at Kyushu University and the GAMMA10 at Tsukuba University in Japan. In the future, color analysis will facilitate the understanding of the plasma-wall interaction in fusion plasma.

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Abbreviations

He	helium
n	neutron
D	deuterium
T	tritium
LHD	Large Helical Device
NIFS	National Institute for Fusion Science
TEXTOR-94	Toroidal Experiment for Technology Oriented Research (TEXTOR)-94
ASDEX-U	Axially Symmetric Divertor Experiment Upgrade (ASDEX-U)
CCD	Charge Coupled Device

LED	Light Emitting Diode
RGB	Red, Green, Blue
AC	Alternating Current
TEM	Transmission Electron Microscopy
FIB	Focus Ion Beam
W7-X	Wendelstein 7-X
QUEST	“Q-shu” University Experiment with Steady-state spherical Tokamak
GAMMA10	a tandem mirror machine in Plasma Research Center at University of Tsukuba

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