Research and Development of Optical Diagnostics for ITER

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Abstract. Common components for some of the optical diagnostic for ITER have been designed and developed. The design of the front-end optics has been optimized paying special attention to the selection of materials and to an arrangement of each component, and by analyzing the heat deposition. The effect of thermal deformation to the optical properties such as the measured position and the resolving power is also estimated by using an optical design code. Results indicate that mirrors can be cooled by thermal conduction using mirror holders made of high thermal conductivity materials such as copper alloy. By using many uniformly spaced cooling channels on the mounting module the effect of thermal deformation to the optical properties can be made small. A shutter is designed for installation in the mounting module. An irradiation test of the bearing is necessary and the mockup testing for endurance in the high vacuum and high temperature environment are required. In order to extend the measured area toroidally a micro lens array has been introduced and a mockup test carried out. The result indicates that the micro lens array is effective to increase the signal without reducing the poloidal resolution. An in-situ calibration method using a newly developed micro retro-reflector array has been developed and a mockup test carried out using prototypes of optical components. The result indicates that the reflected light can be measured but it is necessary to reduce the reflection of the end plate of the optical fiber and the micro lens array.

1. Introduction

In ITER, many optical diagnostic systems are prepared to measure plasma parameters such as impurity species/density/influx, ion temperature, plasma rotation, safety factor, fuel density, impurity behaviors [1]. The major difference of ITER compared to present day tokamaks is the fusion performance such as fusion power and longer plasma duration. Typical time duration is about up to 400 s with the fusion power of 500 MW. Optical components of optical diagnostic systems for ITER must withstand the harsh environment such as higher temperature, higher magnetic field and higher radiation of neutrons, gamma-rays and/or high energy particles. The fast neutron flux near the first wall is ~ 3 x 10^{18} $m^{-2}s^{-1}$.

On the other hand, optical diagnostic systems are expected to have capabilities of the measurement with a higher special resolution, with the long lifetime, with an in-situ calibration method to know the sensitivity change and with the maintenance of systems easily. Therefore, it is important to understand the change of the characteristics of materials in the ITER environment. Most of optical diagnostic system consists of mirrors, lenses and the movable component such as a mechanical shutter, a steeling mirror, alignment optics, their combination, and the holding system. To realize the diagnostic system in the ITER environment, a selection and a development of components is important and the mitigating method is adopted where it is possible.

The design work of optical components used in ITER is carried out by using both the code analysis and the mockup test. The heat analysis, the neutron analysis and the EM analysis will be carried out for the feedback the results to the design in order to assess the effect to the optical properties such as a measured position and a special resolution and the neutron shielding capability after the optical components designed. The mockup test is also carried out to check the optical properties estimated by the code analysis and the productivity study of the components for the feedback to the design. The heating and the vibration test will be also necessary to check the stiffness of a designed optical component. In this article, we present details of the common components of the optical diagnostic such as designs of the front-end optics and the movable system such as the mechanical shutter and the optical alignment system, and the mockup tests of the measured optical system and new calibration method based on the research and development of the Impurity Influx Monitor (divertor).

2. Issues of Optical Diagnostics and Design Concept in ITER

In order to realize the measurement with a higher special resolution and an accuracy of position, optical components must be installed on the designed position and keep the position against the thermal deformation by the baking and/or the neutron heating, and the vibration during the plasma discharge and disruptions. For a long lifetime, a selection of materials and an arrangement of each component are important to prevent the degradation of optical properties. The arrangement of optical components near the plasma which determine the optical properties is very important to sustain the shielding capability of the neutron and/or the gamma-ray. Optical components will be maintained at the hot cell remotely. Therefore, it is necessary for easy maintenance to reduce the number of interfaces of each component and between components and the neutron shield. It is also important that the optical path can be easily aligned.

Optical components near the plasma are installed on the neutron shield in the port where the nuclear heating power is about 0.2 MW/m^3 in the upper port and 0.4 MW/m^3 in the equatorial port. For this component, the cooling method is a key issue to sustain the optical properties such as a measured position and resolving power. The material of components is another key issue. In order to select materials used in ITER environment, an irradiation test has been carried out during the engineering design activity (EDA) phase [2]. The arrangement of optical components near the plasma that determine the optical properties is very important to sustain the shielding capability of the neutron and/or the gamma-ray. One example of the front-end optics is shown in the next section. In this example, the plasma is measured through the small aperture in order to protect a plasma facing mirror from the particle bombardment and the deposition of impurities.

In the optical diagnostic system, the movable system is used as a shutter, a steeling mirror and an optical alignment system are included. The movable system consists with an optical component such as a mirror and a shutter, a moving mechanism such as a bearing and linear guide, driving mechanism and actuator. The key components are a moving mechanism and an actuator used in the ITER environment. A moving mechanism such as a bearing will be used in the temperature up to 240 °C, the magnetic field strength of up to 5 T and higher vacuum condition of up to 1 x 10^{-5} Pa. Therefore, it is important to select materials used in the bearing Grease cannot be used in an ultrahigh vacuum, a high temperature environment. Solid lubricants such as Molybdenum disulfide (MoS_2), Diamond-like carbon (DLC), Tungsten diselenide (WSe_2), Tungsten sulfide (WS_2), and Molybdenum diselenide ($MoSe_2$) can be used in such a harsh environment. Because the magnetic filed strength of 0.5 T at just outside of the port, the electro-magnetic motor cannot be used in this area. In the section 4, the design of a mechanical shutter which solves these problems is shown as one example.

The intensity of the light is determined by the emissivity of the measured light and the measured area. In the optics measured though the small apparatus and with the high special resolution, the detected signal is small in the case to measure the weak light. In some optical diagnostics, higher spatial resolution is expected only in the poloidal direction. In this case, measured area can be extended toroidally for collecting light from lager area. In the section 5, it is introduced one possible method to extend the measured area toroidally combined by Cassegrain type collection optics and newly developed micro lens array and the results of the mockup test.

Because installation of a light source in the vacuum chamber of ITER is not feasible, we consider in-situ sensitivity calibration using a standard light source located outside of the vacuum chamber. An in-situ calibration method for each diagnostic system must select the suitable method. In section 6, an in-situ calibration system using a micro retro-reflector array is described as one possible method.

3. Front-end Optics

The front-end optics installed close to the plasma is used not only for keeping mirrors on the designed position but also for cooling the mirror. The mechanical design of the front end optics has been carried out based on the optical design of Impurity Influx Monitor (divertor) as one example. In this design, optical components of the upper port are installed inside the diagnostic pipe with inner diameter of 300 mm. The mirror holder shown in Fig. 1 is composed of three mirrors and a mechanical shutter, which are installed on the mounting module made of stainless steel 316 with the diameter of 300 mm and the length of 600 mm. In order to remove the nuclear heating power, the mounting module has many cooling channels. The diameter of the cooling channels is 16 mm and total length is 7.405 m and 42 elbows are used to make cooling channels. The volume ratio of cooling channels to the mounting module is about 8 %. To simplify the cooling method, the mirror and mirror holders are cooled by the thermal conduction. The first mirror (M1) is made made of molybdenum because of the lifetime against the particle bombardment and/or the neutron and gamma-ray irradiation [3] and others (M2 and M3) are made of aluminum alloy because of the higher reflectivity from the UV to near IR wavelength range. The temperature of M2 and M3 mirrors does not exceed 300 °C and flat temperature profile on the mirror surface is favorable in the point of view of the thermal deformation. The

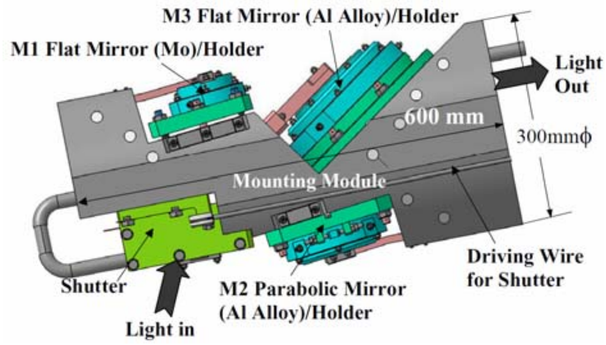

FIG. 1 Mechanical design of front-end optics for Impurity Influx Monitor (divertor)

TABLE 1: MODEL OF FRONT END OPTICS FOR THE THERMAL ANALYSIS IN UPPER PORT

	Cooling method of mirrors
Model A	● The kinematic mount type optical alignment is installed on all mirror holders. ● Mounting module and mirror holders are made of SUS316. ● The heat anchor (Cu Mesh Belt) is connected from mounting module to all mirror holders.
Model B	● The kinematic mount type optical alignment system is installed on M1 mirror holders only.
Model C-1	● Remove the heat anchor from M2 and M3 mirror holders
Model C-2	● M2 and M3 mirror holders are made of the cupper alloy
Model C-3	● All mirror holders are made of the cupper alloy.

optimization of the cooling method of the mirror is carried out by using a steady state heat analysis code assuming a constant nuclear heating of 0.2 MW/m^3. It is also assumed that the temperature of the cooling water is 150 °C and the flow rate is 5 l/min. Models analyzed here are summarized in Table 1. Figure 2 shows the temperature on each mirror surface in each model. In the case of model A, the temperature on M3 mirror and M3 mirror holder exceeds 400 °C because the heat anchor and several bolts connected to conduction through the mounting module are insufficient to remove the large amount of nuclear heating. By removing the kinematic mount type optical alignment from M2 and M3 mirror holder and to contact to the mounting module tightly, temperature on the M2 and M3 mirror holders decreased drastically. From results of Model C-2 and C-3, it is also useful for the reduction of the temperature rise to use high thermal conductivity materials for mirror holder. An increment of the temperature is less than 50 ºC and the uniform temperature profile is obtained. It indicates that mirrors can be cooled by the thermal conduction using mirror holders made of high thermal conductivity materials such as copper alloy and making many cooling channels on the mounting module uniformly [4]. The maximum thermal deformation of the mounting module is 0.151 mm and the thermal deformation on the mirror surface is less than 0.1 mm. In order to estimate the effect of the heat deformation to the optical properties, a ray-trace analysis is carried out by using the optical design code. In this calculation, it is assumed that the thermal deformation of a mirror surface changes the tilt angle of each mirrors and thermal deformation of the mounting module changes the angle of the light to the vacuum window. From this calculation, the measured position is moved less than 20 mm by the thermal deformation, but the size and the shape of spot is almost same. This means that the effect of thermal deformation to the optical property is small in this design. In order to use the front end optics near the plasma in ITER, further analysis such as the neutron analysis and the EM analysis and the mockup test for the study of the manufacturability, the cooling capability and the vibration test are necessary.

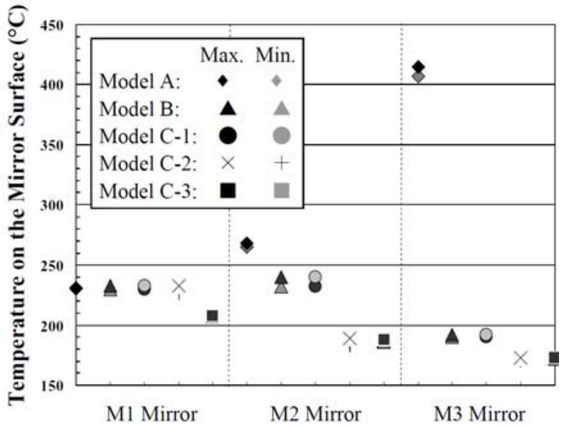

FIG. 2 Temperature on each mirror surface on the upper port calculated in the case of models tabled in Table 1 assuming the constant nuclear heating of 0.2 MW/m^3.

4. Moving System

The mechanical shutter driven by a wire has been designed for the upper port optics in order to analyze the temperature profile in the constant nuclear heating power as shown in Fig 3. The shutter designed here is kept normally open by the spring and mainly closed during the glow discharge cleaning (GDC) for the protection of the plasma facing mirror. A newly developed micro retro-reflector array (size = 10 mm × 10 mm) used for in-situ calibration is mounted on the shutter plate. The selection of materials of the bearing, a spring and a driving wire is important because their characteristics can change due to the neutron and gamma-ray irradiation and the large heat load. Here, the shutter plate made of titanium alloy,

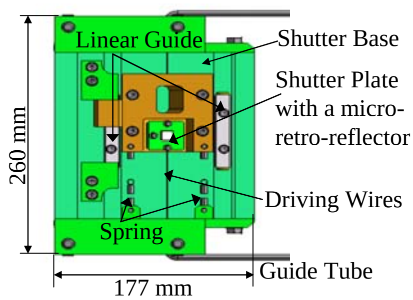

FIG. 3 Mechanical design of shutter driven by wire

driving wire made of stainless steel 316 and the spring made of Inconel 750X are used because it can be used in the higher temperature up to 500 °C and the characteristics such as the wire diameter and the strength of the spring are not changed by the irradiation of the neutron and/or the gamma-rays. The silicon nitride (Si_3N_4) is a candidate for the material of a linear guide due to the hardness and the strength. A lubricant is not used. A piezo-motor is considered as an actuator. For removing nuclear heating power, cooling channels are made in the shutter base and the shutter plate is connected to the base by the heat anchor such as the copper mesh. Heat analysis indicates that the temperature rise is less than 60 °C and a thermal deformation is less than 0.2 mm. The measured position and the resolving power are not changed by this thermal deformation. This means that the nuclear heating power is removed sufficiently by the cooling method [2]. For the use of this shutter in the ITER environment, the irradiation test of the linear guide and the piezo-motor is necessary and the mockup test for an endurance test in the high vacuum and high temperature environment is also necessary.

5. Optical Properties

The micro lens array consists of many fused silica micro lenses. Each micro lens is a thin spherical lens (r =3.3 mm) with height of 0.25 mm, thickness of 6.7 mm and effective width of 2 mm. The micro lens array is set on the collection optics. An optical fiber, which has a core diameter of 200 μm and a clad diameter of 250 μm, is attached on the end on the micro lens to guide the light to spectrometers. The irradiance distribution on the image plane has been analyzed by using the optical design code and the analysis indicates that the spatial resolution of 37 mm will be achieved [4, 5].

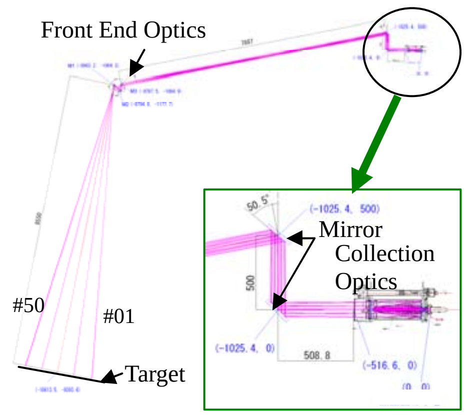

FIG. 4 Schematic View of the Mockup Test of Measured Optics

The mockup test was carried out by using prototypes of the micro lens array (50 channels), metal mirrors, Cassegrain collection optics and a standard light source. The micro lens array is manufactured by metal mold casting. Figure 4 shows the schematic view of the measured optics. The light is placed after the first mirror (M1). In this test, the fiber bundle coupled to the micro lens array is used. In this fiber bundle, 50 fibers are attached to each micro lens. The measurement of the spectrum is carried out with and without the micro lens array. Figure 5 shows the ratio of the intensity of measured spectrum normalized by that without the micro lens array. The measured intensity with the micro lens array is three times higher than that without the micro lens array. The difference of the intensity is due to the difference of characteristics of each micro lens (size, surface of the lens). From these results, the micro lens array is effective to increase the signal.

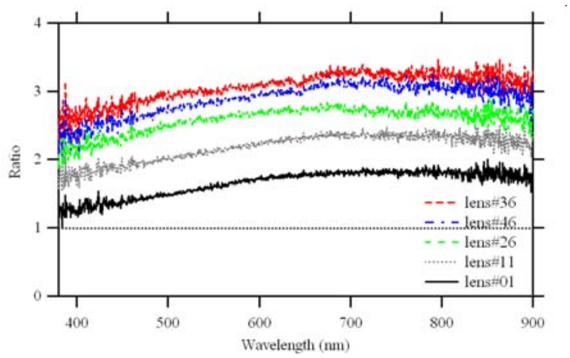

FIG. 5 The ratio of Measured Spectrum with and without Micro Lens Array

In order to check the special resolution, the light source is connected to the output of the optical fiber and measured at the image plane. The image size calculated by the optical design code is about 20 mm in the poloidal direction and 120 mm in the toroidal direction. The measured value is about the same as calculated value. Before use of the micro lens in ITER, the productivity of the die used in the metal mold casting must be improved and irradiation test of the micro lens array is necessary.

6. Development of In-situ Calibration Method

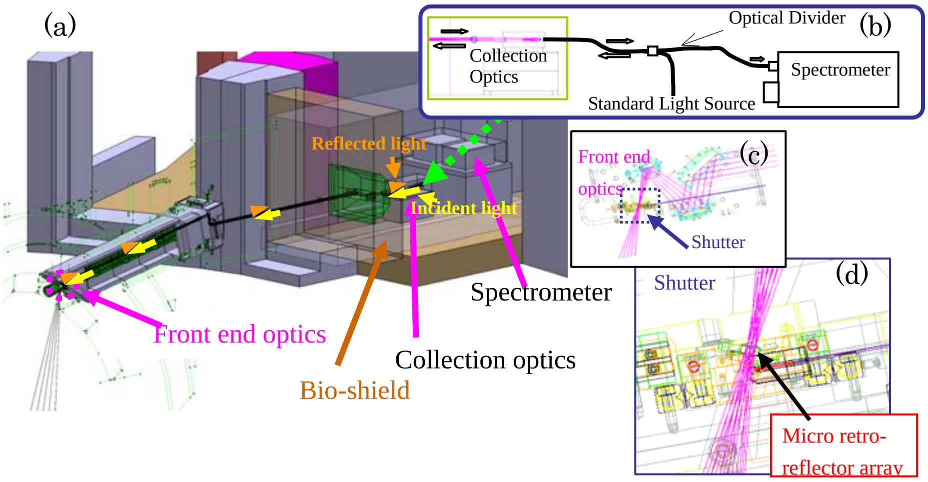

FIG. 6 Principle of the in-situ calibration method (a), optics in the light source and measured system by using the optical divider (b), details of the front-end optics in the upper port (c) and the arrangement of the micro retro- reflector array on the shutter (d)

A standard light is set behind the bio-shield or in the diagnostic room and the light is applied to the micro retro-reflector array mounted on a shutter through the same optics for plasma measurement with the collection optics as shown in Fig. 6. The reflected light is measured with a spectrometer to evaluate the sensitivity change of the optics. During the plasma measurement, the micro retro-reflector array will move backward into the shelter to prevent the particle bombardment and the impurity deposition. Ray-trace analysis has indicated that a reflected light comes back and focuses on the same area from which the rays start [6,7].

The mockup test was carried out by using prototypes of the micro retro-reflector array manufactured by electro-forming method, metal mirrors, Cassegrain collection optics and an optical divider. In this test, two Mo mirrors and three Al mirrors are used. The optical divider used here is bundled 3 fibers in the one FC connector on the one side and connected 3 fibers to one FC connector on the other side. The light from the standard lamp (Hamamatsu L7810) is coupled to the one of the three fibers of the optical divider by using an achromatic lens. The ND filer is

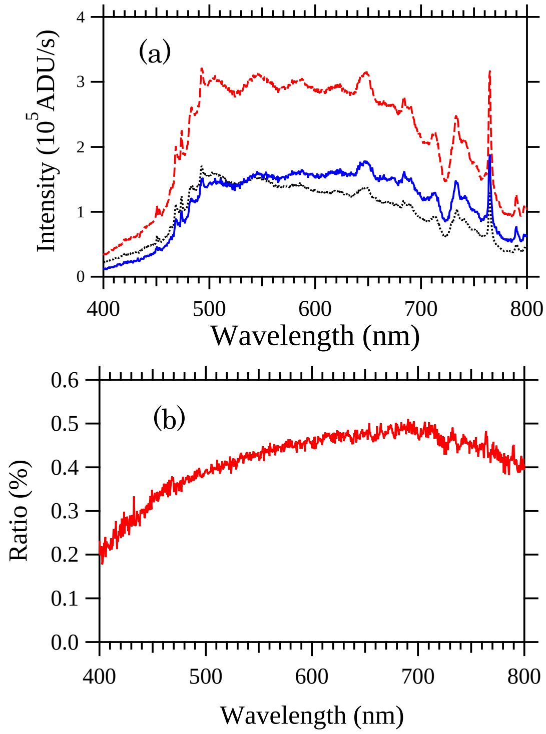

FIG.7 Obtained signal with the micro retro-reflector array (dashed red), without the micro retro-reflector array (dotted black) and the subtracted spectrum (solid blue) (a) and the calculated intensity ratio of incident and returned light (b)

inserted between the fiber and the achromatic lens to avoid the saturation of the spectrometer. The output of the optical divider is connected to a 10 m long optical fiber that is set on the focal plane of the prototype Cassegrain optics. The micro retro-reflector array is set on the same position as the shutter. Reflected light is collected through Cassegrain optics and is coupled to the optical fiber. One of the two other fibers of the optical divider is connected to the spectrometer (B&WTEK BTC112E). The obtained signal in the wavelength range of 400 to 800 nm is shown in Fig. 7 (a). The signal without the micro retro-reflector array is mainly due to the reflection at the end face of optical fiber. The returned light is estimated as a difference of the measured signals with and without the micro retro-reflector array. The ratio of the incident light to returned light is calculated by measured incident light intensity as shown in Fig. 7 (b). The ratio depends on the wavelength which is mainly due to the optical properties such as reflectivity of mirrors and transmissivity of lenses used. The calculated ratio uses the measured reflectivity of the micro retro-reflector array, the expected reflectivity of Mo and Al mirrors and the expected transmissivity of SiO_2 and CaF_2 lenses. Expected values are about two times higher than that measured. This may be due to the difference of the reflectivity of the prototype metal mirrors from that expected. Because the NA of the Cassegrain optics used in this test is 0.01 which is about 1/10 of the optical fiber used (NA = 0.2), the ratio will be increased as increasing NA of the collection optics. In the optical design, the micro lens array is used to expand the measured area toroidally for the collection optics [2]. It was known from the mockup test that the reflectivity of the end plate of the micro lens array is too large to measure the returned light from the micro retro-reflector. For the optical fiber, the reduction technique of the reflection of the end face is almost established. The reduction of the reflectivity of the end plate of the micro lens array is necessary. The irradiation test is also necessary before this arrangement can be used in the ITER environment.

7. Summary

Detailed design of the common components for the optical diagnostic in ITER such as the front-end optics, the shutter mechanism and a new calibration method have been carried out. The principal results are as follows;

1. The design of the front-end optics has been carried out. The cooling method of the mirrors is optimized by using steady state heat analysis code. The effect of the thermal deformation to the optical properties has been estimated by the optical design code.
2. The shutter is designed to be installed in the mounting module. Heat analysis indicates that the temperature rise is less than 60 °C and a thermal deformation is less than 0.2 mm. The irradiation test of the bearing is necessary and the mockup test for an endurance test in the high vacuum and high temperature environment is necessary.
3. In order to extend the measured area toroidally the micro lens array is introduced and the mockup test is carried out. The result indicates that the micro lens array is effective to increase the signal without the reduction of the poloidal resolution.
4. An in-situ calibration method using the micro retro-reflector array has been developed and the mockup test has been carried out. Results indicate that the reflected light can be measured but it is necessary to reduce the reflection of the end plate of the optical fiber and the micro lens array.

In order to use the designed optical components in the ITER environment, further analysis such as the neutron analysis and the EM analysis, and the mockup test for the study of the productivity, the cooling capability, an endurance and vibration tests are necessary.

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