Development of Impurity Influx Monitor (Divertor) for ITER

Hiroaki OGAWA, Tatsuo SUGIE[1)], Satoshi KASAI, Atsushi KATSUNUMA[2)],
Hirotsugu HARA[3)] and Yoshinori KUSAMA

Japan Atomic Energy Agency, Naka, Ibaraki 310-0193, Japan
[1)]ITER-IT, Naka, Ibaraki 310-0193, Japan
[2)]Nikon Co., Shinagawa, Tokyo 140-0015, Japan
[3)]Toyama Co., LTD., Zama, Kanagawa 228-0003, Japan

(Received 4 December 2006 / Accepted 13 March 2007)

The optical design of Impurity Influx Monitor (divertor) was carried out for new ITER design and ray-tracing analysis shows that the spatial resolution of ITER requirement (50 mm) will be achieved by these optical systems designed here. The mechanical design of front end optics also carried out based on the optical design and results of port integration. In the upper port, front end optics can be installed inside the pipe of inner diameter of ϕ300 mm. In the equatorial port, all the optical component are placed to avoid the interaction with other diagnostic equipments. Heat analysis was carried out for the optimization the cooling method of mirrors, mirror holders and mounting modules to reduce the temperature rise caused by the nuclear heating. It indicates that mirrors can be cooled by the thermal conduction using mirror holders made of a copper alloy and making many cooling channels on the mounting module. Finally, the effect of the thermal deformation to the optical properties is estimated by using the optical design code.

Keywords: ITER, impurity, spectroscopy, optical design, mechanical design, front end optics, heat analysis, nuclear heating

DOI: 10.1585/pfr.2.S1054

1. Inroduction

The main function of the Impurity Influx Monitor (divertor) is to measure the parameters of impurities and isotopes of hydrogen (tritium, deuterium and hydrogen) in the divertor plasmas by using spectroscopic techniques in the wavelength range of 200-1000 nm. The detailed requirements are shown in references [1, 2]. The expected impurities are carbon, tungsten, beryllium and copper originating from the divertor target plate and from the surface of the first wall in the main chamber. Neon, argon, krypton or other impurity gases injected into the plasma for radiation cooling in the divertor and the plasma edge will also be observed [1–3].

In the divertor plasma, many spectral lines from neutral and ionized atoms are emitted from vacuum ultraviolet to visible region due to low electron temperature and high electron density. In present tokamak experiments, visible spectrometer is used to study the divertor plasma, because no vacuum extension is necessary. In ITER (International Thermonuclear Experimental Reactor) divertor diagnostics, same technologies can be applied except that the measurements are required for the full duration of the ITER pulse (> 600 s) and special provisions are necessary to measure in the harsh environment for diagnostic components such as high temperature, high magnetic field, high vacuum condition and high radiation field.

author's e-mail: ogawa.hiroaki5l@jaea.go.jp

The ITER international team and the Japan Home Team (Japan Participant Team) had designed the Impurity Influx Monitor (divertor) during the EDA and CDA phases [4–9]. Because the machine size of ITER was reduced after EDA phase, interfaces between ITER and the monitor changed. In order to install in the present ITER, changes in the design of the monitor are required.

In this article, new optical design compatible with new interface is described. The mechanical design of the front end optics installed on the port plug based on the optical design is also described. Finally, result of the heat analysis by assuming constant nuclear heating and effect of the heat distortion to the optical properties is reported.

2. Design of System

Impurity Influx Monitor (divertor) observes divertor region using four optical systems; i) central optics with mirrors installed in the divertor cassette, ii) side optics through the gap between the divertor cassettes, iii) optics from the equatorial port, iv) optics from the upper port as shown in Fig. 1. The two-dimensional measurement in the poloidal plane will be performed by using these four optical systems.

The four optical systems mentioned above are complementary to each other. The optical system with mirrors installed in the divertor cassette has a better spatial resolution along the divertor plates from the bottom to the top

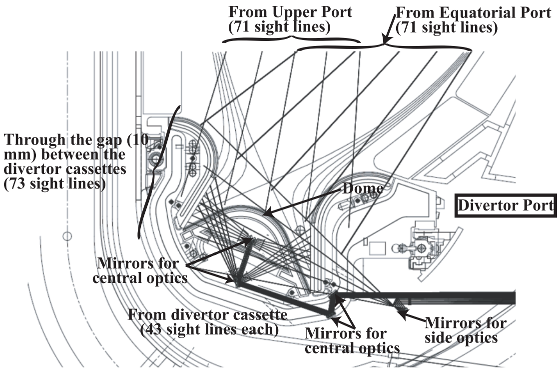

Fig. 1 Schematic view of the impurity influx monitor (Divertor) for ITER.

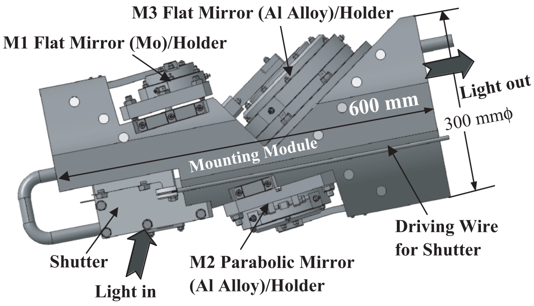

Fig. 2 Mechanical design of the front end optics in the upper port.

region of the plate, because the lines of sights are almost perpendicular to the plates. In addition, the signals are not affected by the emissions from the main plasma, because the lines of sights do not pass through the main plasma. However, the range of the observation is limited to a small area near the divertor. The optical system through the gap between the divertor cassettes observes divertor plasmas from the strike point to the X-point, but does not observe the divertor plate itself. The optical systems from the upper port and from the equatorial port will be able to observe large area of the divertor plasmas except the area near the inner and outer strike point, respectively. The lines of sights are almost parallel to the divertor plates. It causes the better spatial resolution in the radial direction but worse along the divertor plate.

In the previous design, the collection optics for each viewing fan was composed of off-axis aspherical mirrors and had different optical parameters. To simplify the optics, the design of the collection optics will be changed from an off-axis aspherical mirror system to a simple Cassegrain telescope system composed of simple spherical mirrors and lenses and the collection optics for each viewing fan having same optical parameters. In addition, a micro lens array will be inserted just in front of the fiber bundle to expand the observed area toroidally to increase the light detected. This micro lens array is piled up many micro lenses, which is thin spherical lens with height of 0.25 mm, thickness of 7.35 mm and effective width of 2 mm.

The optical design has been carried out by using a ray-trace analysis. For each viewing fan, rays are emitted from five points of the micro lens array and go to the divertor plate through a collection optics, a relay optics and a front end optics. The analysis indicates that the spatial resolutions performed by the central optics, the side optics, the equatorial port optics and the upper port optics will be ≤ 10 mm, ≤ 35 mm, ≤ 48 mm and ≤ 37 mm, respectively. From this result, the optics designed here will meet the ITER requirement for spatial resolutions (< 50 mm) [9].

The mechanical design of mirror holders for the front end optics of the upper and the equatorial port has been carried out. Optical components in the upper port are installed inside the pipe with inner diameter of 300 mm replaced with that for the remote-handling of the port plug. Three mirrors and the mechanical shutter are mounted on the mounting module of 300 mm diameter and 600 mm long as shown in Fig. 2. The mounting module is manufactured by machining and drilling the solid bar steel (monolithic structure). Cooling channels are constructed by drilling the mounting module and weld the plug except for the inlet and outlet of cooling water. The mounting module made of stainless steel 316 is also used as a neutron shield. Copper alloy with higher thermal conductivity is selected as a material of mirror holders from the heat analysis described in Section 3. Only mirror holder for the plasma facing mirror (M1) has a kinematic mount type optical alignment to adjust the tilt angle of the mirror before the installation inside the pipe. The ray-trace analysis by the optical design code ZEMAX indicates that other two mirrors must be installed with accuracy of ± 0.1 degree to keep the ray through the center of the shutter plate and to reduce the displacement of the measured positions by removing the optical alignment from M2 and M3 mirrors. This accuracy can be achieved by using the conventional machining technology.

In order to avoid the interaction with other diagnostic system such as the radial neutron camera, MSE (Motional Stark Effect) and IR (Infra-Red) TV, the optical path in the equatorial port is not simple compared with that in the upper port. Therefore, two mounting modules connected by the pipe are used in present design, that is, plasma facing mirror (M1) to the third mirror (M3) are mounted in the one mounting module (Mounting Module 1) and the forth and fifth mirrors are mounted in the other mounting module (Mounting Module 2) as shown in Fig. 3. The materials of the mounting module and mirror holders are the same as those in the upper port. The kinematic mount type optical alignment is also installed on the M1 mirror holder. The mounting module is manufactured by welding the solid plate with sufficient thickness for making cooling channels. The cooling channels are constructed by machining the grooves on the plate and welding a closure plates. Mirror holders are bolted on the mounting module.

The mechanical shutter driven by a wire and/or a rod is

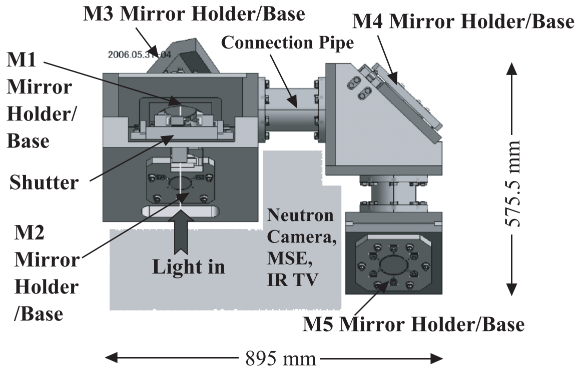

Fig. 3 Mechanical design of the front end optics in the equatorial port.

also designed. Shutter designed here is normally open kept by the spring and mainly used during discharge cleaning for the protection of the plasma facing mirror. The micro retro-reflector array (size = 10×10 mm) used for in-situ calibration is mounted on the shutter plate. The shutter plate is made of titanium alloy and driving wire is made of stainless steel 316. The silicon nitride (Si_3N_4) is a candidate for the materials of a bearing and a linear guide. The ultra-sonic motor is considered as an actuator. The irradiation test is necessary for a bearing, a linear guide and an ultra-sonic motor to use in the ITER environment.

3. Heat Analysis

In order to reduce the temperature rise caused by the nuclear heating, the mounting module has many cooling channels. On the other hand, it is difficult to make cooling channel on the mirror and/or the mirror holders because it is difficult to connect cooling water pipes to many components by remote handling. In present design, the mirror and mirror holders are cooled by the thermal conduction. The first mirror (M1) is made of molybdenum and others are made of aluminum alloy in the upper port optics. 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 optimization of the design of the mirror holders is carried out by using ANSYS code. Models analyzed here are summarized in Table 1. In this code, the radiation heat from plasma and the sliding on the surface and/or edge of each component are not considered and only steady state analysis is carried out. Additionally, a constant nuclear heating of 0.2 MW/m^3 is assumed in the upper port. Figure 4 shows the temperature on the each mirror surface in each model. As a result of model A, the temperature on M3 mirror and M3 mirror holder exceeds 400°C because the thermal conduction through the heat anchor and several bolts connected to the mounting module is insufficient to remove the large amount of nuclear heating. By changing the design to remove 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. The temperature of mirror surface in the Model C-3 is summarized in Table 2. The heat distortion of mirror surface calculated by using this temperature profiles is also summarized in Table 2. 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 distortion to the optical property, ray trace calculation is carried out by using ZEMAX 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

Table 1 Models of front end optics for the thermal analysis in the 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 hear anchor (Cu Mesh Belt) is connected from mount 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.

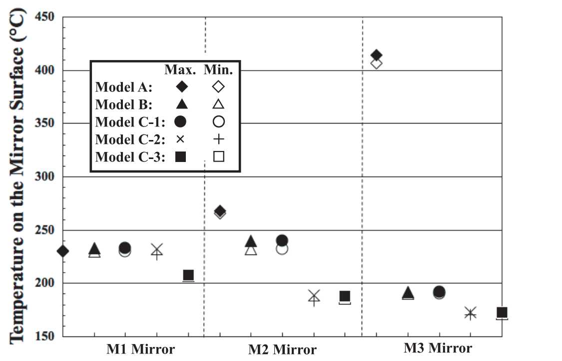

Fig. 4 Temperature on each mirror surface on the upper port calculated in the case of models tabled in Table 1 assuming the constant nuclear heating of 0.2 MW/m^3.

Table 2 Temperature and thermal strain on each mirror surface in the upper port.

	Temperature	Thermal Deformation
M1	207.0~207.8 °C $\Delta T = 0.8$ °C	0.014~0.036 mm $\Delta L = 0.022$ mm
M2	185.5~188.1 °C $\Delta T = 2.6$ °C	0.079~0.1116 mm $\Delta L = 0.032$ mm
M3	171.6~127.7 °C $\Delta T = 1.1$ °C	0.025~0.111 mm $\Delta L = 0.086$ mm

property is small in this port.

For the front end optics of the equatorial port, heat analysis is carried out by assuming the nuclear heating of 0.4 MW/m^3. The mounting module is complex configuration compared with that of the upper port. It is effective for reduction of the temperature and the temperature gradient on the mounting module and/or mirror surface to make many cooling channels on the mounting module. After the optimization of the design, the maximum temperature is about 291°C and difference of the temperature is about 150°C on the mounting module as shown in Table 3. These values are higher than those in the upper port. The thermal deformation is also calculated by using this temperature profiles. The maximum thermal deformation is about 1 mm which is one order magnitude compared with that in the upper port. The temperature profile and thermal deformation on the mirror surface is also summarized in the Table 3. The thermal deformation on the mirror surface is about 0.2 mm which is two times larger than that in the upper port.

From the calculation by the same assumption for the upper port, the measured positions are displaced about 150 mm by the thermal deformation. This displacement is not small but it is possible to observe the measured positions by using the alignment optics installed on the collection optics and to adjust by using the optical alignment installed on the just behind the vacuum window.

4. Summary

The design work of Impurity Influx Monitor (divertor) was carried out for new ITER design and following results are obtained.

(1) Ray trace analysis for each viewing fan indicates that the optics designed here will meet the ITER requirement for spatial resolutions (< 50 mm).

(2) The mechanical design of front end optics in the upper and equatorial port is carried out based on the optical design mentioned above and the results of the integration to the port plug.

(3) Heat analysis indicates that it is possible for mirrors to be cooled by the thermal conduction using mirror holders made of a material with high thermal conductivity such as a copper alloy and making many cooling channels on the mounting module.

Table 3 Temperature and thermal strain on each mounting module and mirror surface in the equatorial port.

	Temperature	Thermal Deformation
Mounting Module 1	149~291 °C $\Delta T = 142$ °C	0~1.091 mm $\Delta L = 1.091$ mm
Mounting Module 2	151~232 °C $\Delta T = 81$ °C	0~0.441 mm $\Delta L = 0.441$ mm
M1	257~263 °C $\Delta T = 6$ °C	0.424~0.552 mm $\Delta L = 0.128$ mm
M2	212~214 °C $\Delta T = 2$ °C	0.348~0.526 mm $\Delta L = 0.178$ mm
M3	199~200 °C $\Delta T = 1$ °C	0.322~0.475 mm $\Delta L = 0.153$ mm
M4	232~233 °C $\Delta T = 1$ °C	0.031~0.211 mm $\Delta L = 0.180$ mm
M5	232~231 °C $\Delta T = 1$ °C	0.009~0.211 mm $\Delta L = 0.202$ mm

(4) The effect of thermal deformation to the optical properties is also calculated by using the optical design code. In the optics on the upper port, it is small. But in the equatorial port, the measured positions are displaced about 150 mm by the thermal deformation.

From above mentioned results, the monolithic structure such as the front end optics of the upper port is favorable in the point of view of the cooling.

Acknowledgement

The authors are grateful to Drs. A. Costley and C. Walker for their fruitful discussion and comments.

[1] A.E. Costley, K. Ebisawa, P. Edmond *et al.*, "Overview of the ITER diagnostic system", in Proceedings of the International Workshop on "Diagnostics for Experimental Fusion Reactors" (1997).
[2] International Tokamak Activity Web page on Diagnostics; Measurement requirement for ITER, http://www.rijnh.nl/ITPA/.
[3] T. Sugie, A. Costley, A. Malaquias, C. Walker, J. Plasma Fusion Res. **79**, 1051 (2003).
[4] K. Ebisawa, "Divertor impurity monitoring system", in ITER Design Description Document (1998).
[5] T. Sugie, H. Ogawa, A. Katsunuma *et al.*, "Divertor impurity monitoring system", Final report for the design task D 323-J1, TA No: S 91 TD 31 95-08-04 (1998).
[6] T. Sugie, H. Ogawa, A. Katsunuma *et al.*, "Design of divertor impurity monitoring system for ITER (II)", JAERI-Tech 98-047 (1998).
[7] T. Sugie, H. Ogawa, T. Nishitani *et al.*, Rev. Sci. Instrum. **70**, 351 (1999).
[8] T. Sugie, A. Costley, A. Malaquias *et al.*, "Spectroscopic Measurement System for ITER Divertor Plasma", Proc. 30th EPS Conf. on Contr. Fusion and Plasma Phys. **27A**, P-4.63 (CD-ROM) (2003).
[9] H. Ogawa, T. Sugie, A. Katsunuma and S. Kasai, "Design of Impurity Influx Monitor (Divertor) for ITER", JAEA-Technology 2006-015 (2006).