Development of Divertor IR Thermography for ITER*)

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Infrared (IR) thermography is a useful diagnostic tool for measuring surface temperatures on divertor plates by using light emitted in the IR range. Japan plans to procure and develop divertor IR thermography for the ITER project. The system design, optical design, and evaluation of detected photons have already been conducted. All optical devices will be installed in the occupied space without interfering with other devices. The required spatial resolution of 3 mm on divertor plates is satisfied by the designed optics. The gamma-ray dose rate at 10^6 s after shutdown of operations (shutdown dose rate) in the interspace is low (15 - 20 μSv/h). Two color detectors and a spectroscopic system are designed using mirrors with high reflectivity in the range 1 - 5 μm. From the evaluation of detected photons, sufficient photons at 3 and 5 μm can be detected at low emissivity (ε = 0.2).

Keywords: infrared thermography, divertor, spectroscopy, ITER, diagnostics

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1. Background

High heat flux on divertor plates (~10 MW/m^2) is one of the important issues for the operation of the ITER. For measuring surface temperatures on divertor plates, infrared (IR) thermography is a useful diagnostic tool, in which temperatures are determined from light emitted in the IR range. In fact, IR thermography has been widely used for divertors in various fusion devices [1–7]. In the ITER project, there are two IR systems: the visible/IR camera and divertor IR thermography [8]. Japan will procure a divertor IR thermography system and develop it for use in high-temperature, high-magnetic-field, high-neutron-flux environments in the ITER.

2. Introduction to Divertor IR Thermography

At present, development of divertor IR thermography is in the design phase. The divertor IR thermography is installed at equatorial port #17; thus, the viewing area includes divertor plates and part of the baffles of one toroidal section. The main role of the instrument will be to study physics study; therefore, high time and high spatial resolutions are required. Wavelengths will be measured over a wide range of 1 - 5 μm.

Table 1 shows the measurements requirement for divertor IR thermography [9]. The range of surface temperatures to be measured on divertor plates is 200 - 3600 °C. The time resolution should be 2 ms at temperatures below 1000 °C and 20 μs at temperatures above 1000 °C. A high time resolution of 20 μs is required to study the edge-localized mode. A high spatial resolution of 3 mm is required to obtain surface temperatures of divertor tiles because tile edges shine brightly. The length of a tile in the poloidal direction is 20 mm for carbon fiber composite (CFC) and 12 mm for tungsten (W); the length of a tile in the toroidal direction is 28 - 30 mm for both materials.

Table 1 Measurement requirements for a divertor IR thermography system for ITER.

Range of surface temperature	Resolution		Accuracy
	Time	Spatial	
200 - 1000 °C	2 ms	3 mm	10%
1000 - 3600 °C	20 μs		

The constraints and difficulties in the design can be summarized as follows:

1. The spatial resolution should be 3 mm on the far divertor plates that are inclined to the sight line.
2. For neutron flux, it is necessary to consider nuclear heating of optics and dose rates, and then set the detector in a position that is not affected by neutron flux from the plasma.
3. Because the space for optics is limited, optics should be installed in an occupied space without interfering with other devices.
4. It is necessary to observe photons over a wide wavelength range of 1 - 5 μm without chromatic aberration.
5. Because photons decay on passing through multiple optical devices and the emissivity of W is low, the intensity of detected photons should be evaluated.

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In this study, the system design, optical design, and evaluation of detected photons are presented while considering these constraints and difficulties.

3. System Design

This section describes the arrangement of equipment for divertor IR thermography. Front-end optics is located in a port plug to collect light emitted from divertor plates and baffles and to transfer the intermediate image to relay optics. The relay optics is positioned in an interspace and transfers the intermediate image to detection optics, which is located behind a bio-shield. The detection optics is located in the port cell and creates an image on detectors and a spectrometer. The data acquisition and control systems are arranged in the diagnostics room.

The detection system consists of two color systems and a spectroscopic system. Light emitted from the divertor plates passes through the front-end and relay optics and is separated by a half mirror; one beam is sent to the two color systems and the other to the spectroscopic system. For the two color systems, a dichroic mirror separates light into two beams, one for each two IR detector with a filter wavelength of either 3 or 5 µm. For the spectroscopic system, light from 100 spatial points is selected from the image by an IR fiber. This light is resolved to 30 points in the wavelength range of 1 - 5 µm by the spectroscope and then imaged on an IR detector.

In present, one of the candidates of a detector is InSb of FLIR SC7500. The detected range of wavelength is 1.5 - 5.1 µm and the pixel pitch is 30 µm. For a full image of 320 × 256 pixels, the sampling rate is 380 Hz (2.6 ms). However, the image is limited to 64 × 2 pixels at a maximum sampling rate of 31.8 kHz (31 µs). At present, there is no two-dimensional detector satisfying the required time resolution of 20 µs. It is necessary to investigate an IR detector that satisfies the measurement requirements; in addition, development of an appropriate electronic circuit for the detector is important.

4. Optical Design

An overall view of the optical design for divertor IR thermography is shown in Fig. 1. There are two optical paths for outer and inner divertor plates with observation surfaces inclined to the line of sight. The distance to the observed divertors is 10.4 m for the outer plates and 5.7 m for the inner plates. To cover the required observed area, the angles of the field of view are ±2.5° for the outer and ±4.0° for the inner plates. The occupied space in the port plug is limited, as shown in Fig. 1. All optics are located in the center region without interfering with other diagnostic instruments.

4.1 Front-end optics

In the front-end optics, the first mirror is made of Mo and the others are made of Al. The diameters of the fourth mirror for the outer plates (35 mm) and the third mirror for the inner plates (42 mm) provide the aperture diameter of the optics. Therefore, the required 3 mm resolution on the

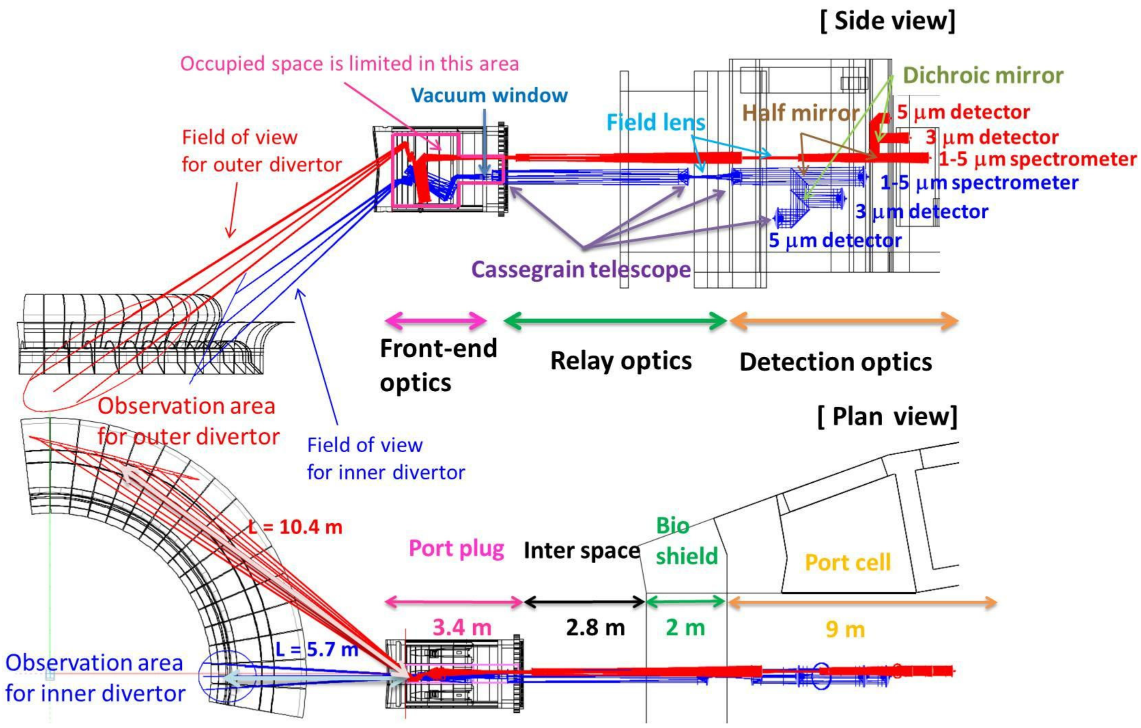

Fig. 1 Overall view of the optical design for divertor IR thermography. The upper portion is the side view and the lower portion is the plan view.

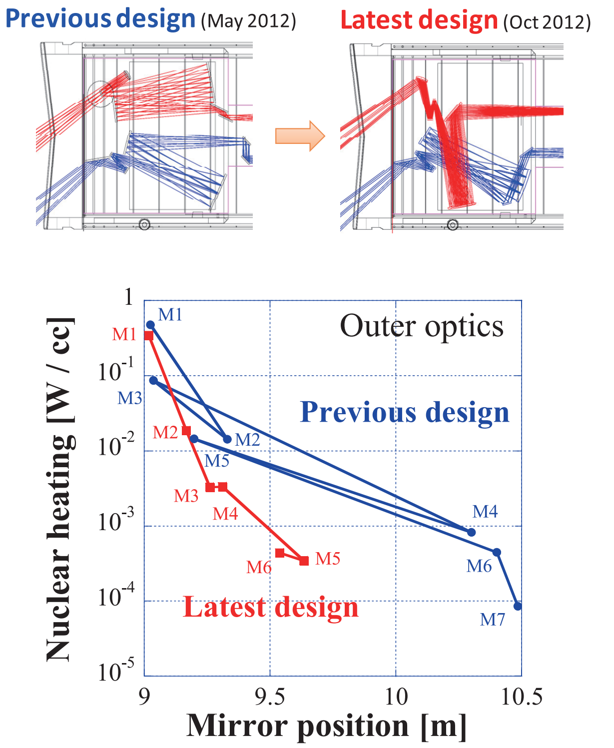

Fig. 2 Nuclear heating of mirrors for outer optics in the previous and latest designs.

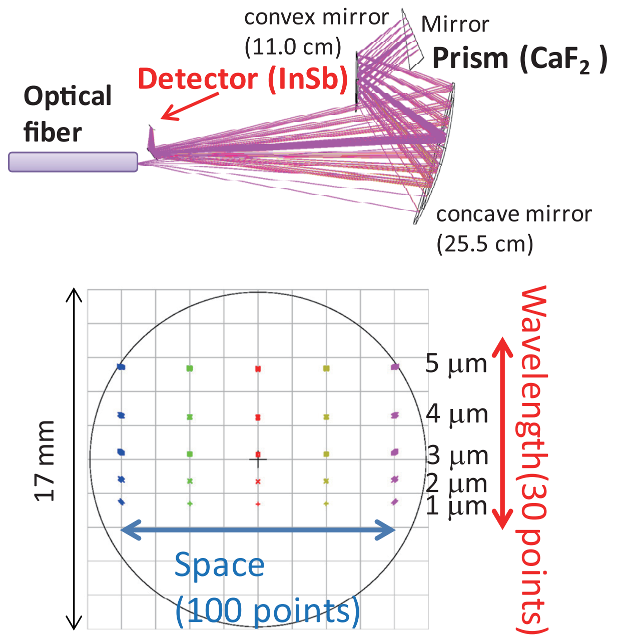

Fig. 3 Optical design of the spectrometer in the range 1 - 5 µm and the spot diagram on the detector.

divertor plate is satisfied on the basis of an evaluation of the diffraction limit. Sapphire has a preferable transmission rate of 1 - 5 µm and a robust characteristic against radiation by neutrons (~10^{20} cm^{-2}) [10].

A neutron analysis of the front-end optics was performed. We used the calculation code MCNP version 5 with the B-lite model and FENDL 2.1 library. The neutron source was assigned to be the ITER in inductive operation. The nuclear heating of mirrors for outer optics is shown in Fig. 2. In the figure, the results for the previous optical design are compared with those for the latest optical design. In the previous design, the gamma-ray dose rate at 10^6 s after shutdown of operations (shutdown dose rate) was 31 µSv/h in the interspace; this is higher than the required value of 10 - 20 µSv/h. In the latest optical design, the shutdown dose rate decreased from 31 µSv/h to 15 - 20 µSv/h.

In addition, a lower nuclear heating of the mirrors is preferable to reduce the cooling load for the mirrors. Therefore, we modified the previous optical design for observing the outer divertor area to include a dogleg structure; this helps shield the optics from neutron flux. Even though the optical design is modified, the spatial resolution in the measurement requirements is still not satisfied. The nuclear heating of mirrors was less than 0.1 W/cc, except for the first mirror. The nuclear heating of the first mirror was 0.5 W/cc; this heat may be removed using water at a temperature of 30 °C. The mechanical design of the cooling system for the mirrors is now being developed and a heating analysis will be performed.

4.2 Relay optics

For the relay of images over a long distance (~5 m) within a limited space, two Cassegrain telescopes are used to make an almost parallel beam. Part of the emission light is lost by eclipse due to the secondary mirror. The rate of rays passing through the entire optical system is 57 % for the outer plates and 51 % for the inner plates. The Cassegrain telescopes focus the image on the position of the field lens.

4.3 Detection optics

The intermediate image is divided into three optical paths, and each is imaged on a detector. The paths and detectors include a 1 - 5 µm spectroscope and 3 and 5 µm detectors. At the spectroscope, light with wavelength in the range 1 - 5 µm can be resolved on the detector within an appropriate size of 17 mm, as shown in Fig. 3. The inclined surface of the detector is an issue in the optics, and it is necessary to adjust the mirror position. The temperature on the divertor is derived from data of a single color, the ratio of photons in two colors, spectroscopic data, and combinations of these.

5. Evaluation of Detected Photons

The photons detected by one pixel of the detector are evaluated through the optics by Planck's radiation equation,

$$P_{\mathrm{div}} = \varepsilon \times (2\pi hc^2/\lambda^5)/\{\exp(hc/\lambda kT_{\mathrm{div}}) - 1\},$$

where P_{div} are the photons from the divertor plate, ε is the

Table 2 Reflectivity and transmission rate through optical components for the outer divertor plates.

	Wavelength			Number of components
	1 μm	3 μm	5 μm	
Mirror refrectivity (Mo)	0.641	0.980	0.984	1
Mirror refrectivity (Al)	0.943	0.983	0.986	13
Window transmission rate (Sapphire)	0.866	0.846	0.777	2
Lens transmission rate (CaF_2)	0.938	0.940	0.945	1
Half mirror (Si) transmission rate	0.450	0.450	0.450	1
Rays through rate in whole optics	0.57			
Total transmission rate	**0.051**	**0.13**	**0.12**	

emissivity of the divertor plate, h is Planck's constant, c is the speed of light, λ is the wavelength of the measured emission light, k is Boltzmann's constant, and T_{div} is the surface temperature on the divertor plate. From the solid angle of the optics Ω, the total transmission rate of the optics τ_{total}, and the bandwidth of the optical filter, the detected photons can be evaluated. Note that the emissivity on the divertor plate and total transmission rate of the optics change because of deposition and erosion caused by neutron flux. Therefore, an in situ calibration method is required. To evaluate the accuracy of resulting temperatures (10 % is required), it is necessary to evaluate all noise, such as bremsstrahlung light from the plasma, light reflected from the first wall, emission from hot optical components, and detector noise.

The emission from a divertor plate passes through many optical components. The reflectivity and transmission rate of optical components for the outer divertor are shown in Table 2. The total transmission rate of the optics was evaluated from reflectivity, transmission rate, and rays-through rate in the entire optics because of the Cassegrain telescopes.

The dependence of detected photons on surface temperatures of divertor plates is shown in Fig. 4. The detected photons were evaluated in the low-emissivity case (W). The emissivity was assumed to be 0.2, neglecting the dependence of emissivity on wavelength and temperature. The distance between the outer divertor plate and the optical aperture was 10.4 m, the diameter of the optical aperture was 35 mm, the solid angle was 8.9×10^{-6} sr, the observed area was 1.5 mm × 1.5 mm, and the bandwidth of the optical filter was ±10 %. At wavelengths of 3 μm and 5 μm, sufficient photons will be detected. However, photons with a wavelength of 1 μm will be insufficient at temperatures below 400 °C because the shot noise of the detector is more than 10 % of the detected photons.

Figure 5 shows the effects of divertor surface temperature on the normalized ratios of detected photons; in the figure, the number of detected photons is normalized by the number detected at 3600 °C. The figure shows that above 1000 °C, the ratios of 1 μm/3 μm and 1 μm/5 μm photons are approximately linear in the surface temperature, whereas below 1000 °C, the relations are nonlinear. However, the ratio of 3 μm/5 μm increases monotonically and can be used from 200 °C to 3600 °C. Therefore, the two color systems using the ratio of detected photons at wavelengths of 3 μm and 5 μm are good candidate. The centers of wavelength and bandwidth still need to be optimized.

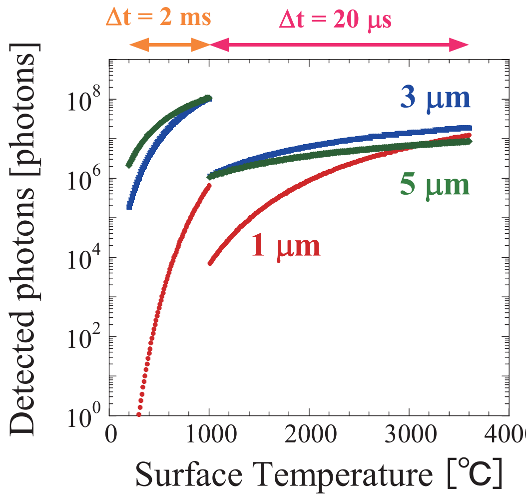

Fig. 4 Dependence of detected photons on the surface temperature of divertor plates.

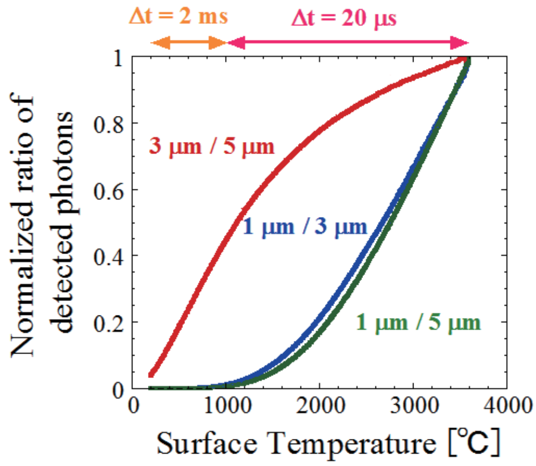

Fig. 5 Effects of surface temperature of the divertor plates on the ratios of detected photons normalized by values at 3600 °C.

Bremsstrahlung light was calculated using distributions of n_{e}, T_{e}, $n_{\mathrm{D/H/T}}$, and n_{imp} for ITER inductive operation (ELMy H-mode, I_{p} = 15 MA, t = 400 s), as shown in Fig. 6. Bremsstrahlung light has its highest intensity in the sight lines, and the wavelength is 4 μm with a bandwidth of ±10 %. The intensities of photons are higher than that of bremsstrahlung light, except for the low-temperature range below about 500 °C. We anticipate that the effects of bremsstrahlung on detected photons can be estimated from spectroscopic data.

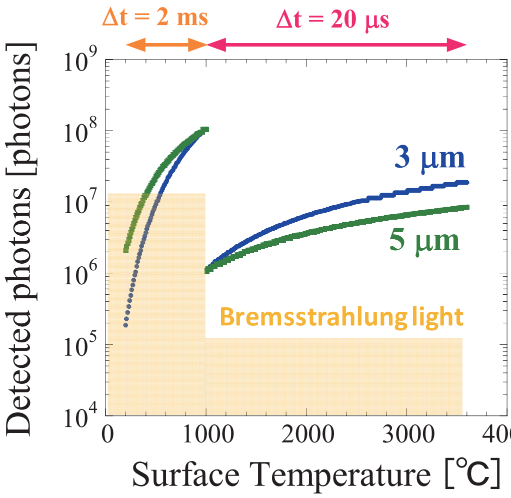

Fig. 6 Dependence of detected photons at wavelengths of 3 and 5 μm on surface temperature and intensity of bremsstrahlung light over the same range of temperature.

6. Laboratory Experiments and Simulations

To obtain accurate temperatures on divertor plates, it will be important to develop a calibration method for emissivity on the tungsten surface and transmission rate through the optics. The emissivity will change because of the deposition of plasma particles and impurities, such as Be, C, W, and the erosion of divertor plates. In addition, the evaluation of the effects of reflections by the first wall is a critical issue. In the future, laboratory tests will be performed by using such components as IR detectors, a pulse IR laser, a black-body source, and optics. By using the optical software "LightTools" from Synopsys, Inc., modeling of the designed optics and simulations will be started. These laboratory experiments and simulations will advance development of a highly accurate IR thermography system for fusion devices.

7. Summary

System design, optical design, and evaluation of detected photons have been performed to support development of a divertor IR thermography system for ITER. All optical equipment has been installed in the occupied space without interfering with other devices. The required spatial resolution of 3 mm on divertor plates is satisfied by the designed optics. The shutdown dose rate in the interspace is now at a low level (15 - 20 μSv/h). Two color systems and a spectroscopic system have been designed using mirrors with high reflectivity in the range 1 - 5 μm. From the evaluation of detected photons, sufficient photons at 3 and 5 μm can be detected at low emissivity ($\varepsilon = 0.2$). The intensity of photons higher than that of bremsstrahlung light will be obtained, except in the low-temperature range. In the future, we will perform laboratory experiments and simulations for calibrating emissivity and transmission rates.

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