Progress of Gamma Ray Irradiation Experiments on ITER Diagnostics from JADA*)

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(Received 28 December 2022 / Accepted 5 February 2023)

The Japan domestic agency (JADA) is responsible for procuring five diagnostic systems for ITER: the microfission chamber (MFC), poloidal polarimeter (PoPola), edge Thomson scattering (ETS), divertor impurity monitor (DIM), and divertor infrared thermography (IRTh) systems. Components of these systems that will be installed in high radiation zones must undergo radiation resistance tests to ensure reliability. The JADA diagnostic group has been conducting gamma ray irradiation experiments on diagnostic components at QST since 2018. The MFC is a neutron diagnostic system that uses uranium fission chambers, the mineral-insulated cables of which were evaluated for corrosion resistance. In-situ observations of the MFC preamplifier have been launched. The PoPola provides the plasma current profile by detecting the polarizations of far-infrared laser beams at their inlets and outlets. Irradiation tests confirmed the durability of PoPola piezo actuators. The ETS is a laser-aided diagnostic to measure electron temperature and density in plasmas from scattered spectra. Laser-induced damages to the optical elements caused by irradiation were investigated. The DIM is a spectroscopic system having a wavelength range of 200 nm to 1000 nm. The effects of irradiation on optical devices, metal mirrors, and radiation-resistant optical fibers were investigated. The IRTh is an infrared thermography system to observe the surface temperature of the divertor. The optical elements and electrical devices of the IRTh have undergone irradiation experiments. The progress of the gamma ray irradiation experiments on the ITER diagnostic systems from JADA are reported.

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Keywords: ITER, diagnostic system, gamma ray, MFC, PoPola, ETS, DIM, IRTh

DOI: 10.1585/pfr.18.2405014

1. Introduction

The ITER diagnostic systems must cope with several loads such as radiant heat from plasmas, electromagnetic forces and vibrations from disruptions, electromagnetic noise, radiation, and nuclear heat [1]. From the viewpoint of nuclear safety, the ITER diagnostic systems must also meet several strict requirements based on nuclear standards including radiation shielding, activation after shutdown, maintenance of tritium confinement boundaries in the event of an accident, and structural design integrity. Thus, the ITER diagnostics systems must undergo preliminary design reviews (PDR) and final design reviews (FDR) according to stringent quality assurance plans. Furthermore, a manufacturing readiness review (MRR) is carried out before manufacturing the systems.

Many studies have been conducted for the ITER project because of the effects of gamma rays on equipment. In the ITER Engineering Design Activities phase (1992-2001), the ITER Home Team reported on the physical and mechanical properties of key components, and the principal irradiation test results and impact on ITER diagnostic design solutions for R&D activities [2, 3]. Subsequently, the different ITER diagnostic systems were assigned to the participating parties' domestic agency (DA), and each DA then conducted their own research. Gamma ray and neutron irradiation have been used to develop in-vessel diagnostic equipment [4]. Gamma ray resistance tests to evaluate the transmittance of candidate glasses and optical fibers have been conducted to demonstrate suitability for ITER diagnostics [5, 6]. Neutron and gamma ray irradiation experiments of piezo elements and electronic devices were also carried out [7]. In addition to these, many other studies have been conducted.

The Japan Domestic Agency (JADA) procures five plasma diagnostics systems: the microfission chamber (MFC), poloidal polarimeter (PoPola), edge Thompson scattering (ETS), divertor impurity monitor (DIM), and divertor infrared thermography (IRTh) systems. Components of plasma diagnostics that will be installed in the ITER tokamak building must be radiation resistant. In the tokamak building, the zone in which the plasma diagnos-

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*) This article is based on the presentation at the 31st International Toki Conference on Plasma and Fusion Research (ITC31).

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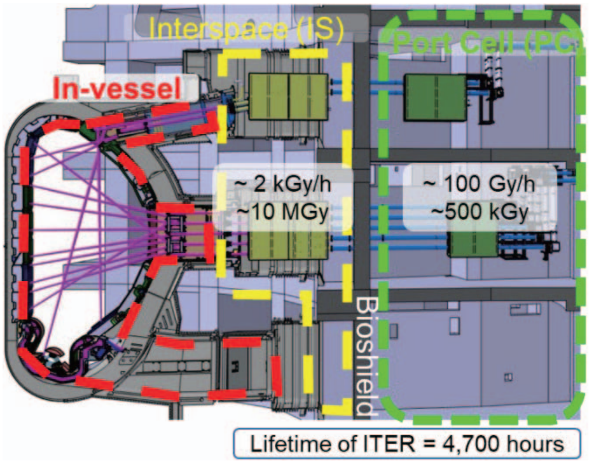

Fig. 1 Radiation zones for ITER diagnostics.

Table 1 Gamma ray irradiation experiments for ITER diagnostics at TARRI.

	MFC	PoPola	ETS	DIM	IRTh
2018			Glasses	Glasses Polka-dot beam splitter Optical fibers Mo Mirrors	Glasses Optical fibers
2019			Glasses Piezo elements Beam dumper	Optical fiber Mo Mirrors	Glasses
2020	MI Cable	Piezo elements Dew point thermometer		Optical fibers Optical filters	Glasses OE/EO converting unit
2021	Preamp	Piezo elements	Optical fibers Glasses	Optical fibers	Glasses
2022			Glasses	Optical fibers	Piezo element encoder

tics are installed is divided into 3 zones: in-vessel, interspace (IS), and port cell (PC), as shown in Fig. 1. irradiation is enormous. The shutdown dose rates (SDDR) for each instrument are calculated by the responsible officers for each system. Irradiation experiments for the JADA diagnostic group are performed at the Kyoto University Research Reactor (KUR), the details of which will be referenced elsewhere. In the interspace (IS), between the vacuum vessel and bioshield, the maximum dose rate and total dose have been calculated as 2 kGy/h and 10 MGy, respectively, without shielding. In the port cell (PC), outside of the bioshield, the maximum dose rate and total dose have been calculated as 100 Gy/h and 500 kGy, respectively, without shielding [8]. These values correspond to the absorbed dose received during 4700 hours of operation over 20 years in the ITER environment with no additional shielding. One issue during the maintenance phase will be that wet air will be used as a vacuum fill gas to prevent tritium from being absorbed into vacuum equipment. Corrosion of in-vessel items by residual gamma rays under humid conditions must be considered accordingly. The major effects of gamma rays on ITER plasma diagnostic equipment are reduced transmittance caused by the generation of color centers in optical elements, and the deterioration of electronic parts. This series of gamma ray irradiation experiments were started from April 2018 at TARRI (Takasaki Advanced Radiation Research Institute), part of QST. The preparations of the specimens and post-experiment observations were performed at NFI (Naka Fusion Institute), part of QST. The experimental results are considered in the design to further improve the diagnostic systems.

In this paper, we report the progress of gamma ray irradiation experiments on the ITER plasma diagnostic systems from JADA.

2. Gamma Ray Irradiation at TARRI

The gamma ray irradiation experiments were performed at three different irradiation facilities at TARRI: the food irradiation building; No. 1 Co-60 irradiation facility; and No.2 Co-60 irradiation facility. The food irradiation building had two cells with a dose rate ranging from 10^{-4} kGy/h to 10^{-1} kGy/h, however, this facility was shut down in March 2022 [9]. The 6th cell in the No. 2 Co-60 irradiation facility was mainly used for scheduled irradiations, and the 1st cell in the No. 1 Co-60 irradiation facility was used for in-situ irradiations. As their names imply, these facilities use ^{60}Co for their radiation source, which is prepared by the nuclear transmutation of natural ^{59}Co by using neutrons from a nuclear reactor. ^{60}Co emits gamma rays with energies of 1.173 MeV and 1.333 MeV during the process of β-decay to ^{60}Ni having a half-life of about 5.271 years. The gamma rays used for irradiation have roughly the same number of neutrons for the two energies. The absorbed dose in Gy was calculated by using the spatial distribution of the collision air kerma converted from the irradiation dose (R) measured by an ion chamber survey meter or measured by using poly methyl methacrylate (PMMA) dosimeters (Radix W) [10]. A Radix W plate was placed at each end of the samples, and the average value was used to approximate the actual absorbed dose. The dose absorbed by the sample cannot be measured directly, thus the absorbed dose has a margin of error of about 10%.

3. Gamma Ray Irradiation Experiments During the Design Phase

Since 2018, gamma ray irradiation experiments of the ITER plasma diagnostic systems have been carried out at TARRI. Table 1 summarizes the progress of gamma ray irradiation experiments for each system.

In this section, the progress of the gamma ray irradiation experiments for each of the five ITER diagnostic systems are described.

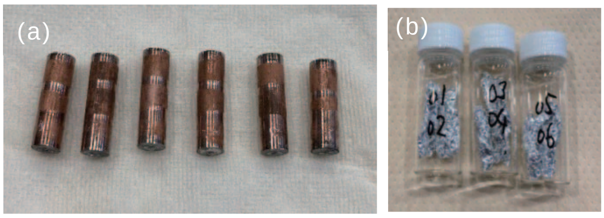

Fig. 2 MI specimens for gamma irradiation. (a) Cut MI cables (b) Specimens wrapped in Al placed in vials.

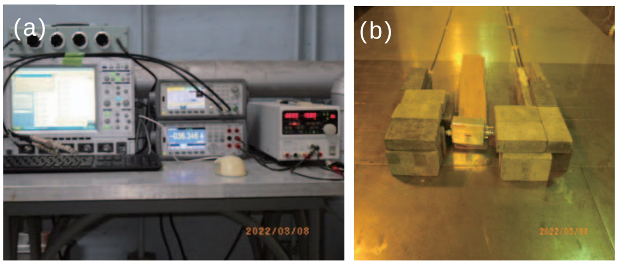

Fig. 3 Experimental apparatus of MFC preamplifier. (a) Electronic measuring equipment outside the cell. (b) Preamplifier with shielding blocks in the 1st cell of No. 1 Co-60 irradiation facility.

3.1 MFC

The MFC is a neutron detection system for fusion plasmas, which uses fission of uranium [11]. Multiple detectors will be installed on the inner wall of the vacuum vessel. Of the five diagnostic systems JADA procures, the MFC is the first system to be installed in the vacuum vessel. Because of its in-vessel parts and being a non-optical system, the MFC is affected more by neutrons than gamma rays. Neutron irradiation experiments were conducted at Osaka University and Kyoto University, the details of which will be reported elsewhere. As for gamma ray irradiation, experiments on the deterioration of the mineral insulated (MI) cables and the in-situ effects on the preamplifier electrical signal were performed.

Specimens of the MI cable were cut to 6.6 mm in diameter and 40 mm in length, wrapped in aluminum foil so as not to spill the insulating material, and placed in a vial (30 mm in diameter × 70 mm in height). Figure 2 shows the samples prepared for irradiation at a dose rate of 1.7 kGy/h up to 1 MGy. SEM observations of the samples before and after irradiation did not show any change except for slight oxidation of the outer copper coating.

In-situ experiments for the preamplifier were performed, the experimental apparatus for which is shown in Fig. 3. The preamplifier was placed at the position of intended radiation dose in the cell, while the other equipment, including a signal generator, measurement instruments, and a power supply were placed outside the cell. Coaxial cables for input signal, output signal, and low voltage power supply were connected to the preamplifier through feedthroughs. High voltage power supply cables were not used because no MFC detectors were connected. The irradiation sequence was a dose rate of 10 Gy/h up to 50 Gy, then a dose rate of 25 Gy/h up to 100 Gy. Pulse signals with different amplitudes and sine signals with different frequencies were input into the preamplifier during the irradiation to investigate the effects of gamma rays on the pulse counting mode and Campbell mode, respectively. Output signals from the preamplifier were compared with the input signals to calculate the gain change by the irradiation. The result suggests that the change in the gain in pulse counting mode is small enough to withstand use during the operation period of ITER. This experiment is still on-going, the details of which will be published elsewhere.

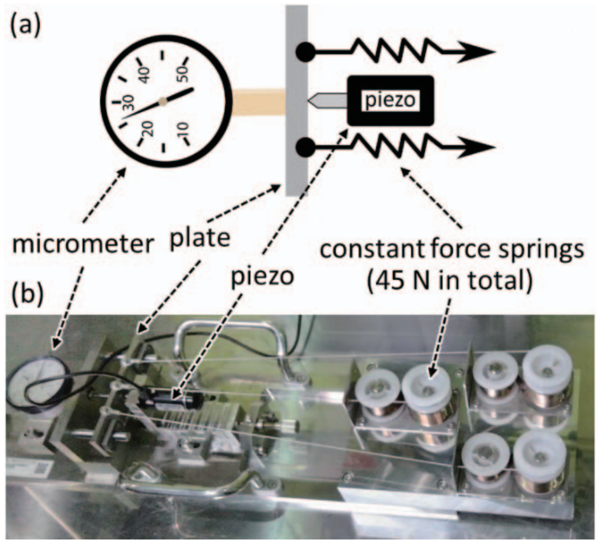

Fig. 4 Schematics and photograph of the functional test.

3.2 PoPola

PoPola is a laser-aided diagnostic system to measure the polarization change of a probing far-infrared laser beam passing through plasma [12]. The design uses piezo actuators to adjust mirror angles in the PC and IS. A candidate piezo actuator (Newport PZA 12) was tested by using neutron and gamma irradiation. A functional test of the piezo actuators was performed to confirm the requirements of the mechanical design for the steering mirror holder. That is, whether the stroke force of the piezo actuator is over 25 N and to confirm whether the maximum stroke length of the piezo actuator is over 7.4 mm after irradiation. Figure 4 shows the schematics and a photograph of this functional test. The testing device applies a constant axial load of 45 N to the piezo actuator during the test by using constant force springs (Sunco NWS 1.5-1). The axial load can be changed by exchanging the constant force springs. The motion of the piezo actuators is monitored by a micrometer (Mitsutoyo 2050S, minimum scale division of 10 μm).

The gamma ray irradiation was carried out at a dose

Table 2 Results of the functional test. The error ranges were standard deviations that were calculated from the results of seven measurements in total.

Motion of piezo actuator	Before irradiation (nm/step)	Dosed 1 MGy (nm/step)
Extension	6.6 ± 0.45	5.9 ± 0.07
Contraction	9.1 ± 0.62	9.2 ± 0.12

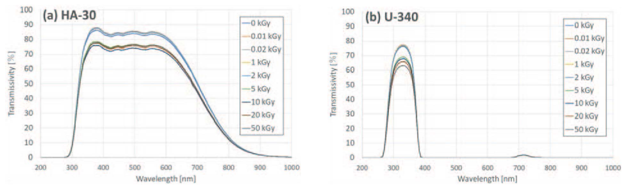

Fig. 5 Transmission spectra of optical filters (a) HA-30, (b) U-340.

rate of 1.7 kGy/h up to 1 MGy at the 6th cell in the No. 2 Co-60 irradiation facility. The shaft of the piezo actuator moves in discrete steps as the driver sends polyphase voltage signals to the actuator. The stroke distance after 10,000 discrete steps under an axial load of 45 N to the actuator was observed. The results are summarized in Table 2. The stroke distance per step changed slightly after gamma ray irradiation. The change of the stroke distance is smaller than the measurement variation, which may be caused by variations in friction of the linear bushes of the testing device. The piezo actuator continued functioning after the gamma ray irradiation test. Thus, this piezo actuator can be used in a radiological environment where the gamma dose is 1 MGy or less.

3.3 ETS

The ETS is one of the primary optical diagnostic systems for measuring electron temperature Te and electron density ne profiles, employing high power Nd: YAG lasers 1064 nm in wavelength for probing beams and 694.3 nm in wavelength for calibration [13]. High-power pulsed laser beams are irradiated in-vessel through the ITER vacuum windows, which function as the confinement boundary for tritium, beryllium, etc., and is crucial to ensure safety. Standard vacuum window assemblies in ITER have reflection-reducing dielectric multilayer coating, however, it was unclear if dielectric coating had enough laser durability after gamma ray irradiation. Therefore, gamma ray irradiation tests on optically coated glass for vacuum windows and dielectric mirrors were performed.

For vacuum windows, UV grade high-OH content fused silica (UF-WP, Lattice Electro Optics) having a thickness of 5 mm was irradiated at a dose rate of 9 kGy/h up to 10 MGy at the 6th cell in the No. 2 Co-60 irradiation facility. After irradiation, the laser-induced damage threshold (LIDT) was investigated at NFI. The LIDT did not deteriorate, rather it increased due to irradiation. The details of the experiments are reported in [14].

Polarizers are used in the ETS to detect scattered light at a high signal to noise ratio, since background light is non-polarized while scattered light is linearly polarized. The irradiation conditions were the same as that of the windows, and the transmittance was observed at both wavelengths (632.8 nm and 1064 nm). Since neither the transmission nor the extinction ratios degraded up to 10 MGy, a wire-grid polarizer sandwiched by two fused silica substrates can be used to control the polarization of visible and near-infrared wavelengths in gamma ray environments outside an ITER diagnostic port [14].

3.4 DIM

The DIM is a spectroscopic diagnostic tool that observes light emissions of fuels and impurities from plasmas at wavelengths of 200 - 1000 nm [15]. For the optical elements for UV, even relatively low doses of gamma rays produce color centers and result in optical transmittance degradation. Several different devices need to be verified. Here, the progress of experiments for the glass materials, polka-dot beam splitters, optical filters, optical fibers, and metal mirrors are described.

The glass materials are used for lenses on the optical path and the spectroscopes [16]. Gamma ray irradiation effects on silica, CaF_2, and $LiCaAlF_6$ demonstrated the feasibility of using silica and CaF_2 in the IS. The feasibility of using polka-dot beam splitters in the IS was also confirmed. The details of these are reported in [8].

Several radiation-hard optical fibers have been used in previous experiments [8], the results of which indicate DIM measurement performance. Subsequent irradiation experiments will facilitate the selection of the optimal materials having high radiation resistance.

There are three types of DIM spectrograph: filter spectrographs (FS), survey spectrographs (SS) and high-dispersion spectrographs (HDS). FSs have narrow band filters, dichroic mirrors, and focusing lenses. A characteristic of a band-pass filter using a dielectric multilayer film is that it allows light having a wavelength λ/n of the transmitting center wavelength λ to pass through. Optical filters (Hoya HA-30 (50 × 50 × 3.1 mm) and U-340 (50 × 50 × 2.6 mm)) were irradiated at dose rates of 100 Gy/h and 0.5 - 10 kGy/h (at the 1st cell in the food irradiation building and the 6th cell in the No. 2 Co-60 irradiation facility, respectively). Figure 5 shows the change of transmission spectra due to gamma ray irradiations. Irradiation up to 50 kGy reduced transmittance by 10% for HA-30 and 20% for U-340 due to formations of color centers. The transmittances were observed to slightly recover by decreasing the color centers at room temperature. This information provides valuable insight into filter design.

During the ITER maintenance phase, humid air will

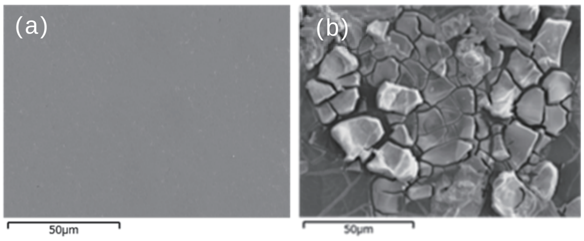

Fig. 6 SEM images of Mo surfaces: (a) without irradiation (b) with irradiation.

be introduced to prevent tritium from adhering to the equipment inside the vacuum vessel during the vacuum break. We observed decreases in reflectance due to corrosion of the plasma-facing metal mirror caused by gamma ray irradiation in several humid environments. Mo specimens were irradiated with gamma rays under various humidity environments to evaluate the deterioration of the reflectance. Figure 6 shows SEM images of Mo specimens, where (a) is a mirror polished surface without irradiation and (b) is gamma irradiated at a dose rate of 2.5 kGy/h up to 6 MGy with a relative humidity of 75%. Reflectance measurements were not possible because the surface was flaky and crumbled away. This corrosion was most likely caused by the generation of radicals; however, we plan to investigate this in detail elsewhere. None of the Mo specimens could maintain their reflectance under any humid conditions. It has become apparent that the effects of corrosion on different mirror materials need to be investigated to optimize optical performance.

3.5 IRTh

The IRTh is a thermographic system that measures the divertor surface temperature profile of 200 - 3600°C to an accuracy of 10% from mid-infrared radiance. IRTh has passive IR observation optics which has been called the dual two-color method [17].

Gamma ray irradiation experiments to confirm the health of an electronic device, the OE/EO converting unit, and to evaluate changes of transmittance by the irradiations for optical elements have been performed. Figure 7 shows the experimental setup for the health check of the converting unit. In the health test of the OE/EO converting to link a camera into the Opt-C:Link unit (AVAL DATA AOC-162), we measured changes in appearance, changes in the current from the DC power supply due to insulation, the link display of the optical line, and images from the IR camera. A chart was attached in front of the blackbody source, and the images from the IR camera were observed before and after irradiation using the image acquisition software AIPTool. We also acquired image data collected without the converting unit by using the software Altair for camera control and image acquisition. The temperature of the blackbody source was 75°C, and the distance between the blackbody source and the tip of the IR camera lens was 50 cm.

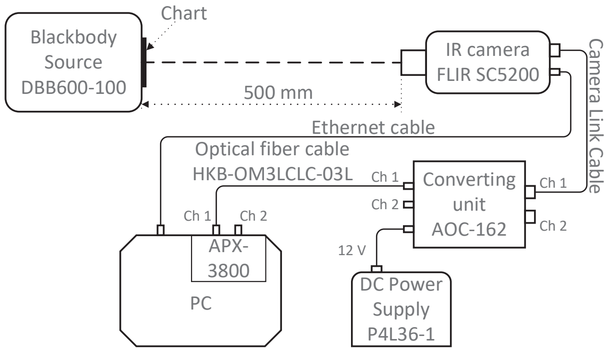

Fig. 7 Experimental setup for health check of the converting unit with IR camera equipment.

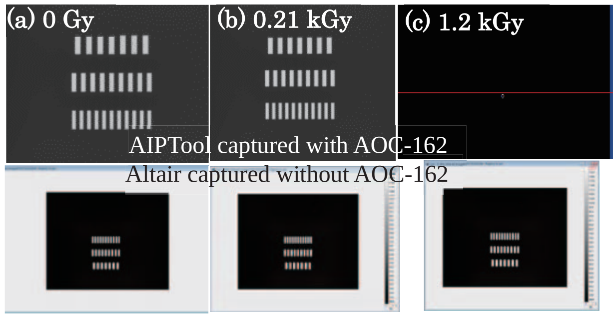

Fig. 8 IR camera images.

The OE/EO converting unit was irradiated at a dose rate of 1 Gy/h up to 2 Gy; 2 Gy/h up to 5 Gy; 3 Gy/h up to 8 Gy; 6 Gy/h up to 11 Gy; 5 Gy/h up to 21 Gy; 10 Gy/h up to 46 Gy and 6 Gy/h up to 145 Gy at the 1st cell in the food irradiation building, and at a dose rate of 0.13 kGy/h up to 0.21 kGy and 1 kGy/h up to 1.2 kGy at the 6th cell in the No. 2 Co-60 irradiation facility. The unit's appearance did not change after irradiation. The unit was removed from the cell several times to test the current from the DC power supply, the link display, and that images from the IR camera were captured. Figure 8 shows the images from the IR camera before and after 0.21 kGy and 1.2 kGy irradiations. The upper images were captured via the camera link cable, OE/EO converter, and optical fiber cable, and the lower images were captured via ethernet cable. The patterns were captured at 0.21 kGy, but not at 1.2 kGy. The cause of failure was radiation damage in a module of the converting unit.

For the IR optical elements, several specimens have been tested and qualified, such as optical fibers, band-pass filters, parallel beam splitters, window and lens materials (glass, sapphire, Ge, Si, ZnS, ZnSe and CaF_2). The details will be published elsewhere. Here, the window materials are described. The materials for IR windows, CaF_2, ZnSe (not coated and anti-reflection (AR) coated), ZnS (not coated and AR coated), Si (not coated and AR coated)) were irradiated up to 10 MGy at the 6th cell in the No. 2 Co-60 irradiation facility. No significant changes were observed in transmittance of the CaF_2 and Si up to around 5.9 MGy. ZnSe and ZnS, however, degraded several % points in transmittance in the wavelength range of 1.2 μm to 20 μm before 5.9 MGy of irradiation. SEM and X-ray photoelectron spectroscopy (XPS) analyses revealed that this degradation was not due to absorption, but due to either surface oxidation or hydration. The AR coating on ZnSe or ZnS mitigated the degradation in transmittance, except for around 3.0 μm.

Future studies must be conducted to finalize the design of the IRTh system. Each electronic device to be implemented must be tested for gamma ray resistance. Potential uses of CaF_2 in the mid-infrared range, such as AR coatings on optics, should be explored. In addition, individual differences in production lots for use in ITER equipment must be clarified.

4. Summary

The JADA Diagnostics Group has been conducting gamma ray irradiation experiments at TARRI since 2018. In these experiments, we measured changes in surface morphologies, transmittance, and reflectance caused by irradiation, inspected durability by using irradiating lasers, and observed the effects of irradiation on electronic equipment. Based on the results of the experiments, some devices were qualified to be used in ITER, while others must be redesigned. These experiments not only for confirmed durability, but also led to some novel scientific findings. Subsequent gamma ray irradiation experiments are planned to be conducted to finalize the design of each system and manufacture the actual equipment.

Acknowledgments

We appreciate the members of the JADA Plasma Diagnostic Group for their valuable advice in carrying out this study. We would like to thank Naotsugu Nagasawa and Hajime Seito for the implementation of the gamma ray irradiation experiments, and Shunya Yamamoto, Hiroshi Koshikawa, Hiroyuki Okazaki, and Masaki Sugimoto for their cooperation during observations. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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