Irradiation test of diagnostic components for ITER application in a fission reactor, Japan Materials Testing Reactor

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abstract. Radiation effects on components and materials will be one of the most serious technological issues in fusion systems realizing burning plasmas. Especially, diagnostic components, which should play crucial roles to control plasmas and to understand physics of burning plasmas, will be exposed to high-flux neutrons and gamma-rays. Dynamic radiation effects will affects performance of components substantially from beginning of exposure to radiation environments, and accumulated radiation effects will gradually degrade their functioning abilities in the course of their services. High-power-density fission reactors will be only realistic tools to simulate the irradiation environments expected in burning-plasma fusion machines such as the ITER, at present. Some key diagnostic components, namely magnetic coils, bolometers, and optical fibers, were irradiation-tested in a fission reactor, JMTR, to evaluate their performances under heavy irradiation environments. Results indicate that the ITER-relevant diagnostic components could be developed in time, though there are still some technological problems to overcome.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) is the first theater, where diagnostic components will be exposed to intense irradiation environments associated with high-flux high-energy-neutrons. Radiation effects will influence performance of diagnostic components substantially at the onset of fusion nuclear reactions, and successful control and operation of burning plasmas will strongly depend on development of radiation-hardened diagnostic components, and quantitative and qualitative understandings of radiation effects there. Radiation effects in diagnostics-related materials have been extensively studied in the course of ITER-EDA (Engineering Design Activity), effectively coordinated by the corresponding ITER central team [1]. Succeeding to the successful compilation of materials database on radiation effects [1], studies of radiation effects in diagnostic components were launched under international collaborations. Especially for fission reactor irradiation tests, which are time- and resource-consuming, and demanding sophisticated-technologies but are indispensable for development of radiation resistant diagnostic components, several international collaborations were set up. There, the Japanese ITER home team played crucial roles, utilizing Japan Materials Testing Reactor (JMTR) in the Oarai Research Establishment of Japan Atomic Energy Research Institute (JAERI), under close collaborations among universities, JAERI and industries.

The JMTR has neutron fluxes and gamma-ray dose rates, similar to those expected near burning plasma regions in ITER. Also, its structure is suitable for in-situ measurements, namely real-time studies of performance of materials and components under a reactor operation. Examples of international collaborations executed in the JMTR are a JUPITER-TRIST-ER (Japan/USA Project on Irradiation Tests Utilizing Reactors, Temperature Regulated In-Situ Test of Electrical Resistivity) project in Japan/USA collaboration for study of radiation effects in electrical insulators [2-4], international round robin tests of radiation resistant optical fibers [5-7], and irradiation tests of magnetic coils under Japan/USA collaboration [8-11] and of bolometers under Japan/EU collaboration [8,12,13]. In the present paper, recent results on performance of key diagnostic components, namely the magnetic coil, the bolometer, and the optical fibers, under the ITER-relevant irradiation conditions, are reported.

2. Irradiation tests of diagnostic components

2.1 Magnetic coil and bolometer

These two components are expected to play crucial roles for controlling plasma with a long burning duration in ITER. The magnetic coil is an essential tool to monitor a magnetic field in the ohmic-heating scenario with long-duration plasma discharges. In the meantime, the strong radiation distribution at the divertor must be known in fine details to control long-duration plasma-discharges free from disruption. The bolometer is the tool to realize this indispensable monitoring.

Several irradiation effects, such as radiation induced electrical conductivity (RIC) and radiation induced electromotive force (RIEMF) will introduce serious disturbances[10,14]. In-situ studies of performance of the magnetic coils revealed that the RIC is not a problem when a coil is made of a mineral insulating cable (MI-cable) [8]. Magnetic measurements could be carried out up to a few M Hz under the ITER relevant irradiation conditions in JMTR and the coil survived neutron fluence comparable to that expected in the whole life of ITER. In the meantime, some results showed that effects of the RIEMF may cause serious problems in magnetic-field measurements for a long plasma discharge duration, because it will generate a substantial drift voltage in some occasions [11]. Fig. 1 shows drift voltage in magnetic coils made of 1.5mm outer diameter MI-cable, measured by an advanced digital integrator, during JMTR power-up period. Here, the maximum fast (E>1MeV) and thermal (E<0.683eV) neutron fluxes were $5x10^{17}n/m^2s$, and $2.5x10^{18}n/m^2s$, respectively, at a reactor full power of 50MW. A gamma-ray dose rate was estimated 3.5kGy/s for iron at a reactor full power at the peak position in the irradiation rig. The neutron fluxes and the gamma dose rate are nearly proportional to the reactor power when the reactor power changed. Irradiation temperature changed 300K with 0 power of the reactor to above 900K with 50MW reactor power. Drift voltages showed complicated dependence on the reactor power, namely intensity of radiations and their magnitudes were far larger than those expected from electrical circuit analysis with the RIEMF values in simple-configuration MI-cables.
Extensive discussions were made among concerned research groups in the ITER-EDA and also stimulated experiments were carried out to check effects of the RIEMF on the drift

voltage, quantitatively. Recent results showed that the drift voltage generated by the ITER-relevant radiation environment was less than 1μV and a magnetic coil, satisfying the ITER design criteria, could be developed in time, with selection of appropriate materials and coil configurations and dimensions [10,11]. Concerning materials, aluminum (Al) and copper (Cu) should be excluded from the systems as possible as can be, as they generate short-life beta-emitters. Here, it should be noted that the copper and the aluminum are one of the best electrical conductors and aluminum oxide (Al_2O_3) is the most popular electrical insulator. Materials composing a sheath in MI-cables will be a major player in generating the RIEMF and heating-up the coil through nuclear heating. Several designs are under consideration, but a coil made of a small diameter (for example 0.5mm outer diameter) MI-cable, which is composed of a stainless steel or nickel-base super alloy sheath, a nickel center lead and a magnesia (MgO) electrical insulator layer, will be one which will decrease the RIEMF as well as decrease the internal impedance of the coil which will resultantly decrease the drift voltage. Also, the fine MI-cable will decrease a nuclear heating rate and improve technical uncertainty caused by localized heating of the coil system. The usage of finer MI-cables will make numbers of turns more and improve sensitivity of the coil. In the meantime, the detailed analysis indicated that the stability of the voltage integrator is another issue to be improved [11].

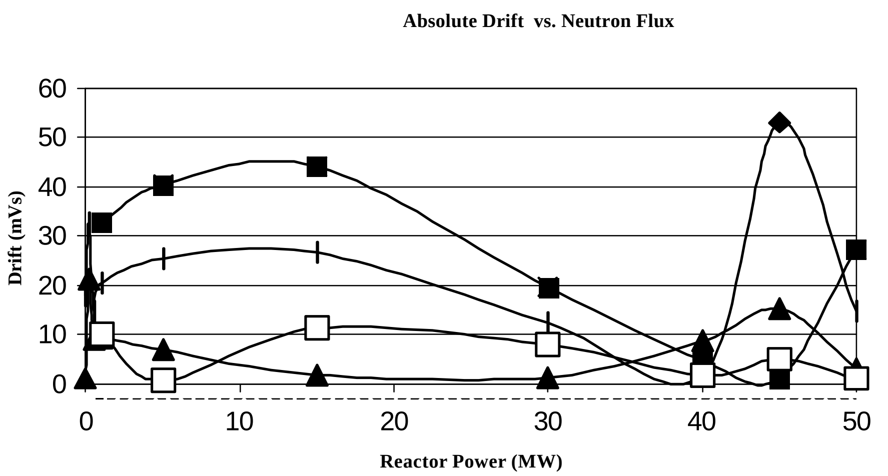


Figure 1 Drift voltage extrapolated to those for 1000 seconds measurements.
Closed rhombus; alumina insulator 0.25mm diameter copper center lead, closed square; magnesia insulator, 0.25mm diameter copper center lead, closed triangle; magnesia insulator 0.5mm diameter copper center lead, open square; magnesia insulator, 0.75mm diameter copper center lead.

The radiation-hardened bolometer, whose structures were shown in Fig. 2, was developed by modifying a JET-bolometer and was irradiation-tested in the JMTR. There, gold meanders were vapor deposited onto a muscovite ($KAl_2(Si_3Al)O_{10}(OH,F)_2$) thin plate. Its performance under ITER relevant irradiation conditions was qualified and quantified as shown in Fig. 3. The resistance of gold meander responded linearly to the input power under JMTR full power operation. An input power on the bolometer could be quantified with a suitable response time under the JMTR irradiation. A structure of the bolometer could withstand the 3 irradiation cycles, corresponding to the expected irradiation dose in the ITER. A few technical problems were found, such as increase of electrical conductivity of a gold meander due to nuclear transmutation of gold into mercury, and poor performance of electrical contacts between the gold meanders and measuring wires. Dimensional stability and mechanical integrity of a mica substrate is another concern. Alternative thin ceramic substrates were under development in the EU [15]. However, it was concluded that these technical problems could be overcome by conventional techniques easily and the ITER-relevant bolometer could be developed in time.

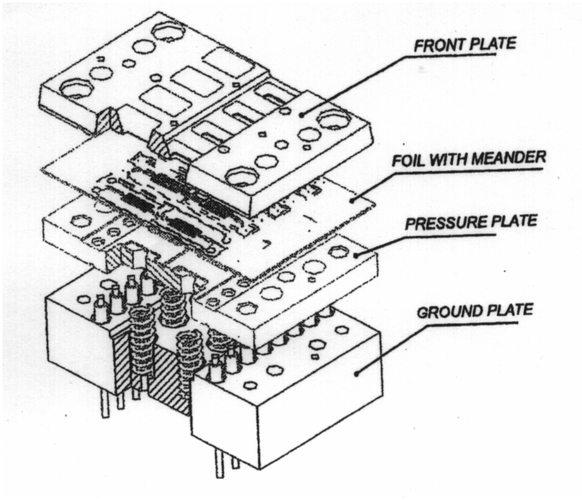


Figure 2 Structures of a developed bolometer. A front plate and a ground plate were made of copper. A pressure plate was made of aluminum nitride (AlN). A gold meander was on a mica substrate.

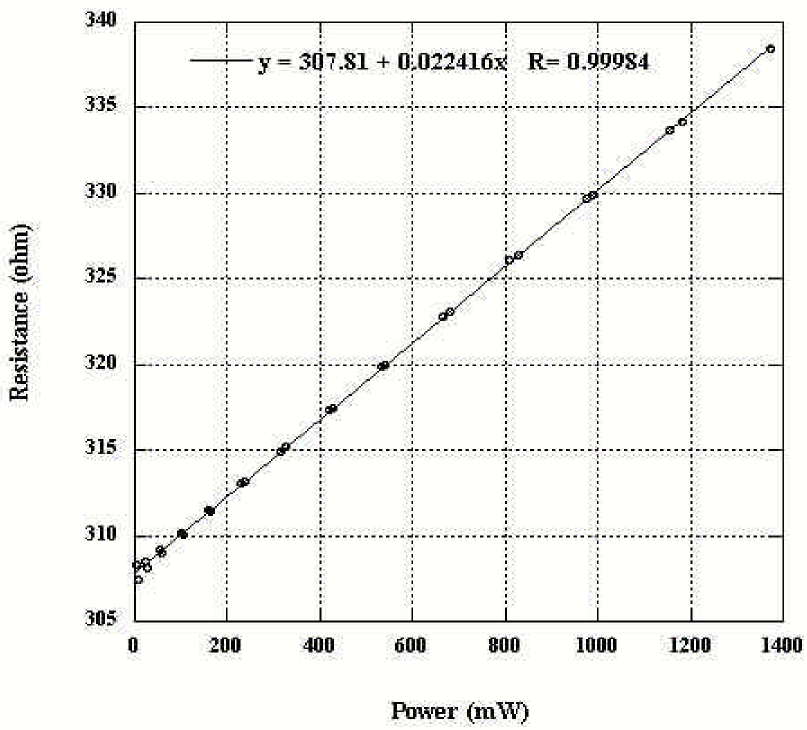
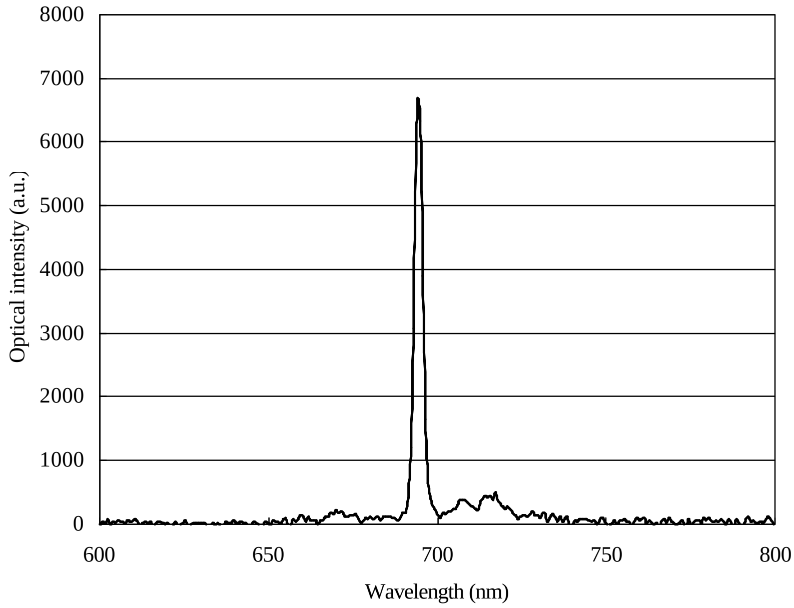


Figure 3 Resistance change as a function of input power under JMTR irradiation

2.2 Optical fibers

Improvement of radiation resistance of the optical fibers, made of fused silica (SiO_2), is remarkable in the course of ITER-EDA. At the beginning of ITER-EDA, it was a general consensus that the optical fibers were too vulnerable to radiation effects to use them near burning plasma. Then, the design criteria claimed that optical fibers would be used out of the bio-shield. However, recent results obtained under the international round robin experiments [5-7] are yielding promising results and some optical fibers, such as Russia-made hydrogen loaded KU-1, could be used even for visible application near burning plasma with a limited life. Fluorine doped fibers showed good radiation resistance in visible regions but recent reactor irradiation tests revealed that they had higher sensitivity to the micro bending loss. For infrared applications, several optical fibers could be found with a life-time far beyond the ITER whole operation period. Fig. 4 shows examples of application of optical fibers for optical diagnostics in irradiation environments. Radiation induced luminescence of Cr^{3+} in alumina was measured through an optical fiber under a Co-60 gamma ray irradiation. Realization of application of optical fibers near burning plasmas will give large technological impacts on reduction of cost and on resolving technological problems associated with limited space near the plasma, in ITER.



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