IRRADIATION EFFECTS ON PLASMA DIAGNOSTIC COMPONENTS (II)

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Irradiation Effects on Plasma Diagnostic Components (II)

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Irradiation tests on a number of diagnostic components under fission neutrons, gamma-rays and 14 MeV neutrons have been carried out as a part of the ITER technology R&D program. UV range transmission losses of a KU-1 quartz were measured during 14 MeV neutron and 60Co gamma-ray irradiation. Significant transmission losses were observed in the wavelength of 200-300 nm. Five kinds of ITER round robin fibers were irradiated in JMTR and the 60Co gamma-ray irradiation facility. KS-4V, KU-H2G and F-doped fibers have a rather good radiation hardness, which might be available just outside of the vacuum vessel in ITER. Mica substrate bolometer was irradiated in JMTR up to 0.1 dpa. During the cool down phase of the first cycle all connections went open circuit. The use of gold meanders in the bolometer might be problematic in ITER. The magnetic probes were irradiated in JMTR. Drift of 10 - 40 mVs for 1000s was observed with a digital longterm integrator, however, which might be induced not only by RIEMF but also drift inside the integrator itself. ITER-relevant magnetic coil could be made with MI-cables, whose electric drift for 1000-s integration is less than 0.5 mVs.

This work is conducted as an ITER Engineering Design Activities and this report corresponds to ITER Technology R&D Task Agreement on "Irradiation Effects Phase (II)" (G55TT05 FJ).

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+4 Department of Material Development, Takasaki Radiation Chemistry Research Establishment
+5 Department of ITER Project
*1 Tohoku University
*2 Osaka Institute of Technology
*3 Radiation Application Development Association
*4 CEA Cadarache
*5 General Atomics
*6 Hitachi, Ltd.
The sensitivity and linearity of the jxB magnetic sensor was investigated during the JMTR irradiation. The sensitivity was decreased by \( \sim 30 \% \) at a neutron fluence of \((1.8 \sim 2.8) \times 10^{23} \text{ n/m}^2\) in the high magnetic field compared with that before irradiation. Up to the dose of \( \sim 100 \text{ MGy} \), vacuum leak in the V-shaped windows seal assemblies with quartz and ZnSe was not observed. Those window assemblies are applicable to ITER in terms of radiation hardness. The multi-core optical fiber feedthrough was also tested under \(^{60}\text{Co}\) gamma-ray irradiation. Mainly vacuum tightness was examined. A vacuum leak occurred at the solder between fibers and the metal flange within the irradiation dose less than 1 MGy. A solvent for optical fibers with radiation hardness should be developed. The sensitivity of the sensing fiber for the optical-fiber current transformer was decreased dramatically by gamma-ray irradiation within only 1-2 kGy of gamma-ray dose. The development of a low birefringence fiber with radiation hardness is required for the ITER application.

Keywords: Irradiation Effect, ITER, Diagnostics, Windows, Optical Fibers, Bolometer, Magnetic Probe, JMTR, FNS
プラズマ計測機器要素に対する照射効果（II）

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（2002年2月5日受理）

ITER工学R&Dの一環として計測機器要素の照射試験を核分裂中性子、γ線、14-MeV中性子を用いて実施した。14-MeV中性子及び$^{60}$Co γ線照射下におけるKU-1溶融石英の紫外域透過率を測定したところ、200-300 nmの波長域に著しい透過損失が生じることが分った。5種類のITER共通資料の光ファイバーをJMR及び$^{60}$Co γ線で照射試験を行った。KS-4V、KU-H2G及びフッ素添加ファイバーは極めて高い耐放射線性を示し、ITERの真空容器外側付近まで導入できる見通しを得た。マイカ薄膜ボロメータを0.1dpaまでJMRで照射した。第1照射サイクルの停止時にボロメータの断線が発生し、金を蒸着した抵抗体は、ITERにおいて問題であることを示した。磁気プローブもJMRで照射試験を行った。磁気プローブと長時間デジタル積分器を接続したところ、100sの積分時間に対し、10〜40 mVsのドリフトが観測されたが、照射起電力で0で、積分器自体のドリフトにより発生したと考えられる。1000sの積分時間に対し、ドリフトを0.5 mVs以下に抑えうる、ITER仕様の磁気プローブをMIケーブルを用いて製作できる見通しが得られた。JMRで照射下のxB型磁気センサーの感度及び直線性を測定した結果、(1.8〜2.8)×10$^{20}$ n/m$^2$ の中性子フルエンスにおいて、高磁場に対する感度が約30%低下することが分った。

本研究はITER工学設計活動の一環として実施したもので、本報告は工学R&Dタスク協定「照射効果フェーズII」(G55TT05FJ)に基づくものである。

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V型リングによる窓シールを用いた石英およびZnSe窓を約100MGyのγ線照射試験を行ったが、真空リークは観測されなかった。よってこの方式の窓シールは耐放射線の観点に関してはITERに適用可能と考えられる。開発した多芯光ファイバーフィードスルーのγ線照射試験を実施したが、1 MGy以下で真空リークが発生し、ファイバーを接着する半田の材質に問題があることが分かり、改良する必要性を示した。γ線照射下におけるサニヤック型の光ファイバー電流計の動作試験を行ったが、1〜2 kGyで感度が著しく低下し、ITERに適用するためには耐放射線性を有する低屈折光ファイバーの開発が必要である。
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1. Introductions

1.1 Introduction

In the development of the diagnostics for the experimental thermonuclear reactor, radiation damage of diagnostic components is one of the most important issues. In ITER-FEAT, which is the reduced technical objectives/reduced cost ITER, a fast neutron fluence of typical diagnostic components is $2-3 \times 10^{23}$ n/m$^2$ on the inner surface of the vacuum vessel. Some diagnostics sensors and transmission components still have to be operated in such radiation conditions. As a part of the R&D program of the ITER Engineering Design Activities (EDA), we have carried out irradiation tests on a number of diagnostic components since 1992.

Ceramics are used as general insulating materials. For ceramics, the radiation induced conductivity (RIC) [1.1.1] is the most important issue as an insulation material. We investigated RIC effects of Al$_2$O$_3$ for 14 MeV neutrons. By extrapolating our results, the conductivity is estimated to be less than $10^{-6}$ S m$^{-1}$ in the ITER-FEAT first wall condition, which shows the availability of ceramics as an electrical insulator even in the vacuum vessel [1.1.2,1.1.3]. Optical elements are the most sensitive to radiation damages among the transmission components. The light emission efficiency of window materials was measured for 14 MeV neutrons and $^{60}$Co gamma-rays. We found that the light emission efficiency for 14 MeV neutrons was less than 1/10 of that for gamma-rays [1.1.4]. The transmission loss of a sapphire window was measured after irradiation at the Japan Material Testing Reactor JMTR. The transmittance decreased in the wavelength range of 200-800 nm. We found that there was no significant loss of transmission in the wavelength range of 800-5000 nm [1.1.5]. We have developed a radiation hardened fiber with fluorine doping in the core of the fibers. The fibers were irradiated by $^{60}$Co gamma-rays, 14 MeV neutrons and JMTR. Fluorine doping was effective to reduce the irradiation-induced losses not only for gamma-rays but also neutrons. Solid metal mirrors of molybdenum and aluminum were irradiated at JMTR. Significant change of the reflectivity was not observed for the Aluminum mirror [1.1.3].
References


1.2 Task description

In this original task agreement the following items should be carried out.

a) Materials:
   a-1) Window materials:
      i) Optical properties: Tests on radioluminescence from fused silica in UV regions with the FNS 14 MeV neutron source
   a-2) Optical fibers:
      i) Optical properties: Tests on radioluminescence and absorption of KS-4V optical fibers in the JMTR

b) Prototypical assemblies:
   b-1) Bolometers:
      i) Tests on EU bolometers with the mica substrate in the JMTR under the JA/EU collaboration.
   b-2) Magnetic coils:
      i) Tests on US magnetic coils in the JMTR under the JA/US collaboration (US joins the tests on a voluntary base.)
   b-3) jxB Magnetic Sensors (Mechanical probes for stationary magnetic fields):
      i) jxB magnetic sensors will be developed under the T496 task.
      ii) Tests in the JMTR. This sensor will be made considering to reduce temperature drift (including choice of strain gauge materials, etc.) and sensor size and to improve neutron radiation hardened properties.
   b-4) Optical fiber feedthrough:
      i) Tests on optical fiber feedthroughs in the $^{60}$Co gamma source. (The multi-channels feedthrough was made in the EDA phase.)
   b-5) V-shaped windows seal:
      i) Tests on V-shaped windows seal in the $^{60}$Co gamma source. Mainly SCCG (Sub-Critical Crack Growth) on mechanical properties of the window assemblies
will be examined. (the V-shaped windows seal was developed in the EDA phase and more improvement will be performed under the task T482.)

As an amendment, the following work items are added to the original Task Agreement

a-2) Optical fibers:
   ii) Optical properties: Test on radioluminesence and absorption of F-doped optical fibers in the JMTR.
   iii) Supply of a round robin material: Supply the F-doped optical fibers to EU and RF home teams as a round robin material.
   iv) Supply of an extension fiber: Supply the fused quartz core fiber to extend the round robin material in the irradiation experiment.

a-3) MI cables:
   i) RIEMF: Irradiation test of some kind of MI cables in JMTR or other irradiation facility in order to identify the RIEMF mechanism.

b-6) Optical current meter:
   i) Test of an optical current meter based on Faraday rotation in $^{60}$Co gamma source. Performance of the optical current meter will be examined under the radiation environment.
2. Windows

2.1 UV Range Absorption of KU-1 Quartz Window by 14 MeV Neutrons

Tatsuo Sugie, Takeo Nishitani, Satoshi Kasai and Junichi Kaneko

2.1.1 Objective

UV range spectroscopy is one of the most important diagnostics for monitoring impurities in ITER-FEAT. There is few data of in-situ neutron irradiation effects on the window material in UV range. We have carried out irradiation tests on the KU-1 quartz [2.1.1], which is a radiation-hardened fused quartz with a high OH concentration of 800 ppm and a candidate of the window material for UV and visible spectroscopy in ITER-FEAT, using the 14 MeV neutron facility FNS [2.1.2] in JAERI Tokai.

The objective of this irradiation test is to measure the transmission loss of KU-1 quartz during neutron irradiation and to compare the data with that during the break between irradiations or with that after the irradiation in the wavelength range from 200 nm to 400 nm.

2.1.2 Specimen

KU-1 quartz is a radiation-hardened fused quartz with a high OH concentration of 800 ppm [2.1.1]. The sizes of the KU-1 sample used in the irradiation test are shown below.

Diameter: 16 mm
Thickness: 8 mm

2.1.3 Experimental condition

The KU-1 sample was mounted in a sample changer arm and was located in front of the rotating tritium target of Fusion Neutronics Source (FNS) as shown in Fig. 2.1.1. A distance between the center of the sample and the tritium target was 22 mm. The energy of the
neutron was 14 MeV. UV light from a D₂ lamp was collimated by a quartz lens and illuminated the sample. The transmitted light was focused on the end of the optical fiber by a quartz lens and guided to a spectrometer located behind a heavy concrete shielding wall with 1.8 m thickness. The spectral distribution of the transmitted light was measured with the spectrometer. We calibrated the intensity of the D₂ lamp, transmission losses of the lenses and fiber optics by removing the sample from the optical beam line at each measurement. The radiation-induced loss of the fiber optics was so significant in the UV range that we replaced it every week during the experiment, which took three weeks. The total fluence was measured to be $7.4 \times 10^{19}$ n/m² by activation foils of niobium attached to the target and back side of the sample. In this measurement, the $^{93}\text{Nb}(n,2n)^{92}\text{mNb}$ reaction with a half lifetime of 10.15 days was used. The ionization dose rate was evaluated by calculations using the neutron Monte Carlo code MCNP-4B [2.1.3] to be 0.66 Gy/s by neutrons and 0.034 Gy/s by photons for quartz. The gamma-ray contribution is less than 5% of the total ionization dose.

2.1.4 Experimental results

The measured transmissivities are shown in Fig. 2.1.2 as a function of wavelength from 200 nm to 400 nm. The optical densities OD calculated by the following equation are shown in Fig. 2.1.3.

$$OD = \log_{10} \left( \frac{1}{T} \right) / 0.8$$

(2.1.1)

Here, T is a transmissivity and 0.8 is the thickness of the KU-1 sample. The reflection effect on the surfaces of the sample was not subtracted.

There was almost no reduction of the transmissivity in the wavelength range of longer than 350 nm. Significant transmission losses were observed in the wavelength range of 200-300 nm. Two absorption peaks were identified; one was E’-center at 215 nm and the other is from Si (III) defects at 245 nm. The E’-center absorption is much larger than the Si (III) defect’s one. The optical density at 235 nm and 260 nm plotted against the neutron fluence is
shown in Fig. 2.1.4. The absorption increased monotonically with the neutron fluence up to $3.8 \times 10^{19} \text{ n/m}^2$, and decreased 20% during the irradiation breaks. The absorption returned to almost the same level as before when the irradiation resumed.

2.1.5 Discussion

As described above, the absorption decreased during the irradiation breaks and returned to almost the same level as before. This phenomenon indicates that an absorption induced by the neutron irradiation is caused by stable scattering and short lifetime centers. The first contribution is proportional to the neutron fluence and the latter is almost proportional to the neutron flux.

2.1.6 Conclusion

The transmission losses of KU-1 quartz were measured during the 14 MeV neutron irradiation with the fluence up to $7.4 \times 10^{19} \text{ n/m}^2$ and were compared with that during the breaks between irradiations in the wavelength range of 200 - 400 nm. The data will be useful for designing the diagnostics windows in ITER especially for UV range spectroscopy. It seems that the spectroscopic measurements can be carried out with the KU-1 quartz windows in the wavelength range longer than 300 nm in ITER, but it will be necessary to prevent the neutron fluence below $5 \times 10^{18} \text{ n/m}^2$ in the wavelength range shorter than 250 nm. The absorption decreased during the breaks between irradiations and returned to the almost same level as before when the irradiation resumed. Therefore, calibration of the optical diagnostic systems will be necessary during the plasma discharges (during neutron irradiation) or to estimate the transmissivity of the window during neutron irradiation from the data measured during the breaks between the plasma discharges.
2.1.7 Remaining issues

The data has been measured at room temperature. It will be necessary to confirm the absorption of KU-1 quartz in the temperature range of 100 - 200 °C, which is expected during ITER operation.

References


Fig. 2.1.1 Experimental setup in the target rooms and enlarged view of the optics for transmissivity measurement.
Fig. 2.1.2 Measured transmissivities of KU-1 quartz glass as a function of wavelength from 200 nm to 400 nm. The transmissivities were measured at different fluence during the neutron (14 MeV) irradiation.
Fig. 2.1.3 Optical transmission loss in KU-1 quartz glass due to 14 MeV neutrons in the wavelength range of 200-400 nm.

Fig. 2.1.4 Optical density at 235 nm and 260 nm as a function of the neutron fluence.
2. 2 UV Range Absorption of KU-1 Quartz Window by $^{60}$Co Gamma-rays

Tatsuo Sugie, Satoshi Kasai, Takeo Nishitani, Shigeru Tanaka, Toshiaki Yagi and Noriko Yokoo

2.2.1 Objective

UV range spectroscopy is one of the most important diagnostics for monitoring impurities in ITER-FEAT. There is few data of in-situ gamma-ray irradiation effects on the window material in the UV range. We have carried out irradiation tests on the KU-1 quartz [2.2.1], which is a candidate for the window material for UV and visible spectroscopy in ITER-FEAT, using the $^{60}$Co gamma-ray irradiation facility in JAERI Takasaki.

The objective of this irradiation test is to measure the transmissivities of KU-1 quartz during gamma-ray irradiation and to compare the data with that during the break between irradiations or with that after the irradiation in the wavelength range from 200 nm to 400 nm.

2.2.2 Specimen

KU-1 quartz is a radiation-hardened fused quartz with a high OH concentration of 800 ppm [2.2.1]. The sizes of KU-1 used in the irradiation test are shown below.

Diameter: 16 mm
Thickness: 8 mm

2.2.3 Experimental condition

The KU-1 sample was mounted in a sample changer arm and was located in front of the gamma-ray source of the $^{60}$Co gamma-ray irradiation facility in JAERI Takasaki as shown in Fig. 2.2.1. UV light from a D$_2$ lamp was collimated by a quartz lens and illuminated the sample. The transmitted light was focused on the end of the optical fiber by a quartz lens and
guided to a spectrometer located outside the irradiation room. The spectral distribution of the transmitted light was measured with the spectrometer. We calibrated the intensity of the D₂ lamp, transmission losses of the lenses and fiber optics by removing the sample from the optical beam line for each measurement. We shielded the lenses and the optical fibers by lead-blocks against gamma-rays. The radiation-induced loss of the fiber optics was so significant in the UV range that we could not measure transmission losses below 250 nm with a good S/N ratios. The flux of gamma-rays was measured to be $1.33 \times 10^6$ R/hr ($1.16 \times 10^4$ Gy/hr) at the center of the sample.

### 2.2.4 Experimental results

The measured transmissivities during the irradiation are shown in Fig. 2.2.2 as a function of wavelength from 200 nm to 400 nm. The optical densities OD calculated by the following equation are shown in Fig. 2.2.3.

$$\text{OD} = \log_{10} \left( \frac{1}{T} \right) / 0.8$$  \hspace{1cm} (2.1.1)

Here, $T$ is a trasmissivity and 0.8 is the thickness of the KU-1 sample. The reflection effect on the surfaces of the sample was not subtracted.

There was no reduction of the transmissivity in the wavelength range longer than 350 nm. Significant transmission losses were observed in the wavelength range of 250-300 nm. No clear absorption peaks were observed in this wavelength range. The optical density at 250 nm and 300 nm plotted against the gamma-ray fluence is shown in Fig. 2.2.4. The absorption (optical density) increased rapidly with the fluence up to around $3 \times 10^4$ Gy. After that the increased rate of the absorption became moderate with the fluence up to $2.5 \times 10^5$ Gy. In the figure, open circles and open diamonds indicate the optical densities during the irradiation and closed ones are the optical densities during the breaks. Clear relaxation of the absorption during the breaks between irradiations was not observed in this experiment as shown in Fig. 2.2.4. For information, the optical densities measured after the irradiation with the fluence of $1.1 \times 10^6$ Gy are shown in Fig 2.2.5. In this figure, the absorption peak of the E⁺-center was observed at 215 nm.
2.2.5 Discussion

Clear relaxation of the absorption during the breaks between irradiations was not observed in the condition of room temperature and constant flux of $1.16 \times 10^4$ Gy/hr. It will be necessary to carry out the same experiment at higher temperature and under different fluxes.

2.2.6 Conclusion

The transmission losses of KU-1 quartz in the wavelength range of 250 - 400 nm were measured during the $^{60}$Co gamma-ray irradiation with a fluence up to $2.5 \times 10^5$ Gy and were compared with that during the breaks between irradiations. The data will be useful for designing the diagnostics windows in ITER especially for UV range spectroscopy. It seems that the spectroscopic measurements can be carried out with the KU-1 quartz windows in the wavelength range longer than 300 nm in ITER gamma-ray conditions, but it will be necessary to prevent the gamma-ray fluence below $1 \times 10^4$ Gy in the wavelength range shorter than 300 nm. The clear relaxation of the absorption during the breaks between irradiations was not observed in this experimental condition.

2.2.7 Remaining issues

The data has been measured at room temperature. It will be necessary to confirm the absorption of KU-1 quartz in the temperature range of 100 - 200 °C during irradiation, which is expected during under ITER operation. The absorption during the irradiation should be measured at different fluxes.

References

Fig. 2.2.1 Experimental setup in the irradiation room and enlarged view of the optics for transmissivity measurement.
Fig.2.2.2 Measured transmissivities of KU-1 quartz glass as a function of wavelength from 250 nm to 400 nm. The transmissivities were measured at different fluence during the $^{60}$Co gamma-ray irradiation.
Fig. 2.2.3 Optical transmission loss in KU-1 quartz glass due to $^{60}$Co gamma-ray in the wavelength range of 250 - 400 nm.
Fig. 2.2.4 Optical density at 250 nm and 300 nm as a function of the $^{60}$Co gamma-ray fluence during irradiations and the breaks.
Fig. 2.2.5  Optical densities measured after the irradiation with the fluence of $1.1 \times 10^6$ Gy.
3. Optical Fibers

3.1 $^{60}$Co-gamma irradiation tests on round robin fibers

Tsunemi Kakuta, Tatsuo Shikama and Takeo Nishitani

3.1.1. Objective

Optical fibers are playing important role on the present fusion diagnostics for not only spectroscopic measurements but also on the optics diagnostics such as the Thomson scattering measurement. Though we could not use fiber optics around the vacuum vessel due to the irradiation damage in ITER, we have to know the limit of the radiation to use them, which gives an impact on the diagnostics design.

We selected the candidate of optical fibers for the ITER diagnostics as the ITER round robin material from the results of the previous R&D task T246. The object of this irradiation test is to investigate gamma irradiation effects and radiation-resistance characteristics of the ITER round robin optical fibers.

3.1.2. Specimen

Optical fibers used the gamma-ray irradiation tests are listed in Table 3.1.1. Three Russian fibers [3.1.1-3.1.3] and two Japanese fibers [3.1.4-3.1.6] are tested. KU-H2G fiber is hydrogen treated and gamma pre-irradiated KU-1 fiber. All fibers are polymer jacketed.

3.1.3. Experimental Condition and Measurements

1) Irradiation facility

$^{60}$Co irradiation facility at JAERI Takasaki was used for this irradiation test. The picture of the sample and the irradiation facility is shown in Fig. 3.1.1.

2) Irradiation condition
The fiber was irradiated up to $1.9 \times 10^5$ Gy under the dose-rate of $1.2 \times 10^4$ Gy/hr = 3.3 Gy/s. Temperature of optical fiber during irradiation was about 20 °C.

(3) Measurements

The experimental setup is shown in Fig. 3.1.2. In-situ measurement for transmissivity at the wavelength region from 350 nm to 1750 nm was conducted by means of white light source and optical spectrum analyzer. One end of fiber was connected to AQ-4303B xenon-lamp white light source and other end was connected to AQ-6315A optical spectrum analyzer. The picture of the instrument is shown in Fig. 3.1.3.

3.1.4. Results

Initial transmission characteristics of the fibers before the irradiation are shown in Fig. 3.1.4. Large absorption peaks by OH were observed in KU-1 and KU-H2G. The peaks around 1400 nm are saturated. The initial loss of KU-H2G is the smallest in visible region.

Observed optical absorption spectra during gamma-ray irradiation are shown in Fig.s 3.1.5-3.1.9. The absorption band in all kinds of fibers were distributed to the wavelength ranged from UV to 800 nm by means of E'-center and NBOHC. The comparison of the absorption spectra of five fibers at the irradiated dose of 1.9 MGy is shown in Fig. 3.1.10. Induced transmission loss of the all kind of fibers are much smaller than that of pure SiO$_2$ core fiber obtained in previous work [3.1.4-3.1.6]. Increases in transmission loss were localized in the range of wavelength from 350 - 700 nm, except KU-1 fiber. Especially, the increase in transmission loss of MF fiber is quite small. The increase in transmission loss in the range of wavelength longer than 800 nm was observed for KU-1 fiber.

3.1.6. Conclusion

In the gamma-ray irradiation, induce transmission loss of the all kind of ITER round robin fibers are much smaller than that of pure SiO$_2$ core fiber. Especially, KS-4V, KU-H2G and F-doped fibers have rather good radiation hardness even in the visible range.
References


Table 3.1.1  List of optical fibers for the gamma-ray irradiation tests.

<table>
<thead>
<tr>
<th>Team</th>
<th>Fiber Type</th>
<th>Supplier</th>
<th>Diameter (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>core</td>
<td>clad.</td>
</tr>
<tr>
<td>RF</td>
<td>KS-4V</td>
<td>FORC</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>KU-1</td>
<td>FORC</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>KU-H2G</td>
<td>FORC</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>JPN</td>
<td>F F</td>
<td>Fujikura Ltd.</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>M F</td>
<td>Mitsubishi Cable</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>

FORC: Fiber Optics Research Center, Moscow
Fig. 3.1.1 Picture of the sample and the $^{60}$Co irradiation facility in JAERI Takasaki.
Fig. 3.1.2 Experimental setup of the gamma-ray irradiation test for optical fibers at the $^{60}$Co irradiation facility in JAERI Takasaki.
Fig. 3.1.3 Picture of the instrument for the gamma-ray irradiation test of optical fibers.
Fig. 3.1.4  Initial transmission characteristics of optical fibers.
Fig. 3.1.5  Observed optical absorption spectra of KS-4V fiber during gamma-ray irradiation.
Fig. 3.1.6 Observed optical absorption spectra of KU-1 fiber during gamma-ray irradiation.
Fig. 3.1.7 Observed optical absorption spectra of KU-H2G fiber during gamma-ray irradiation.
Fig. 3.1.8 Observed optical absorption spectra of a F-doped fiber produced by Fujikura during gamma-ray irradiation.
Fig. 3.1.9 Observed optical absorption spectra of a F-doped fiber produced by Mitsubishi during gamma-ray irradiation.
Fig. 3.1.10  Comparison of absorption spectra for five fibers at the irradiation dose of $1.9 \times 10^6$ Gy.
3.2 Irradiation tests on round robin fibers in JMTR

Tsunemi Kakuta, and Tatsuo Shikama

3.2.1. Objective

Irradiation effects by gamma-rays are mainly caused by ionization. On the other hand, fast neutrons make atomic displacements in the irradiated material. The objective of this irradiation test is to investigate neutron irradiation effects and radiation-resistance characteristics of the ITER round robin optical fibers using a fission reactor. Here we used the JMTR reactor.

3.2.2. Specimen

The optical fibers used in the JMTR irradiation tests are the same as those used in the gamma-ray irradiation test (see Table 3.1.1).

3.2.3. Experimental Condition and Measurements

(1) Irradiation facility

The JMTR reactor at JAERI Oarai was used for this irradiation test.

(2) Irradiation condition

- Fast neutron flux : $2.4 \times 10^{17}$ n/m$^2$·s
- Thermal flux : $1.9 \times 10^{18}$ n/m$^2$·s
- Gamma-ray heating : 1.4 W/g (for Si)
- Temperature : 135 °C

(3) Measurements

The experimental setup is shown in Fig. 3.2.1. A special capsule was used in the core region of reactor to irradiate the optical fibers as shown in Fig. 3.2.2. The total length of the optical fibers was 50 meters. The center with the length of 50 cm was inserted into the core region of JMTR.
The in-situ measurement for transmissivity in the wavelength region from 350 nm to 1750 nm was conducted by means of a white light source and an optical spectrum analyzer. One end of the fiber was connected to a white light source AQ-4303B xenon-lamp and the other end was connected to AQ-6315A optical spectrum analyzer. Also radio-luminescence spectra were also measured with the AQ-6315A optical spectrum analyzer by turning off the xenon-lamp.

3.2.4. Results

Observed optical absorption spectra during the JMTR irradiation are shown in Figs 3.2.3-3.2.7. The absorption band in all kinds of fibers except MF fiber was distributed to the wavelength range from UV to 700 nm by means of E’-center and NBOHCC. Increases in transmission loss were found in the range of wavelength from 350 - 700 nm in the all kind of fibers. The induced transmission loss of those fibers is much smaller than that of pure SiO₂ core fiber obtained in previous work [3.1.4-3.1.6]. An increase in the OH absorption peak at a wavelength of 1390 nm was observed in the fast neutron fluence larger than $1.5 \times 10^{23}$ n/m² in KS-4V, KU-1, KU-H2G and FF fibers. For the fast neutron fluence larger than $10^{23}$ n/m², the transmission loss increased in the wavelength region from 700 to 1700 nm in FF fiber due to the micro-rack of the core and cladding.

The behavior of the MF fiber is very curious. The induced loss increased dramatically in the wavelength range of 450 - 1700 nm, which also may be caused by the micro-rack of the core and cladding.

Another significant optical phenomenon is the optical emission in the fibers through a fluorescence process [3.2.1-3.2.5]. The radio-luminescence spectra of KS-4V and FF fibers are shown in Fig. 3.2.8. The optical emission wavelength ranged from 400 to 1700 nm with a sharp peak intensity at about 1270 nm was observed. The optical intensity distribution is approximately inversely proportional to the cube of the wavelength in the range from 700 to 1700 nm. This optical distribution was considered to be Cerenkov radiation by gamma-ray [4.1.1].
3.2.5. Conclusion

During fission reactor irradiation, induced transmission loss of the all kind of ITER round robin fibers except MF fiber are much smaller than that of pure SiO₂ core fiber. Especially, KS-4V, KU-H2G and F-doped fibers have a rather good radiation hardness even in the visible range. Those fibers might be available just outside the vacuum vessel in ITER, where the expected fast neutron fluence is \(\sim 10^{21} \text{ n/m}^2\).

References


Fig. 3.2.1 Experimental setup of the optical fiber irradiation test at JMTR.

Fig. 3.2.2 Accommodation of optical fibers in a special capsule for the JMTR irradiation tests.
Fig. 3.2.3 Optical absorption spectra of the KS-4V fiber observed during JMTR irradiation.
Fig. 3.2.4 Optical absorption spectra of the KU-1 fiber observed during JMTR irradiation.
Fig. 3.2.5 Optical absorption spectra of the KU-H2G fiber observed during JMTR irradiation.
Fig. 3.2.6 Optical absorption spectra of the F-doped fiber produced by Fujikura observed during JMTR irradiation.
Fig. 3.2.7 Optical absorption spectra of the F-doped fiber produced by Mitsubishi observed during JMTR irradiation.
Fig. 3.2.8  Radiation induced luminescence spectra of the KS-4V and FF fibers during JMTR irradiation.
4. Bolometer

4.1 Offline Irradiation Tests of Mica Substrate in JMTR

Takeo Nishitani, Tatsuo Shikama, M. Narui and Roger Reichel

4.1.1. Objective

Bolometers should be installed inside the vacuum vessel to measure the whole radiation losses. The JET type bolometer with mica substrate is widely used on magnetic fusion devices, and a candidate of the ITER bolometer [4.1.1]. They are made of gold meander-like resistors deposited on thin mica foils. However, it was worried that mica will suffer from a swelling under neutron irradiation because it has a laminar structure. There are few data of swelling for mica. The EU home team reported appreciable distortion after a fission reactor irradiation. It is guessed that the mica substrate was contaminated with humidity. Literature shows that humidity may distort mica under neutron irradiation [4.1.2].

The object of this irradiation test is to investigate the neutron irradiation effects such as the swelling rate of the mica substrate itself before the bolometer performance tests in a fission reactor.

4.1.2. Specimen

Mica substrates with a size of $10 \times 20 \times 0.02$ mm$^3$. Those substrates were provided by the EU home team. The chemical components are as follows;

<table>
<thead>
<tr>
<th>Element</th>
<th>SiO$_2$</th>
<th>Na$_2$O</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>K$_2$O</th>
<th>CaO</th>
<th>Li$_2$O</th>
<th>MgO</th>
<th>H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>45</td>
<td>0.9</td>
<td>37</td>
<td>1</td>
<td>1.3</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
<td>5.4</td>
</tr>
</tbody>
</table>
4.1.3. Experimental Condition and Measurements

The samples mounted in aluminum capsules were transferred into the core of the reactor using "water rabbit". Irradiated neutron fluences were \(1 \times 10^{22} \text{n/m}^2\), \(5 \times 10^{22} \text{n/m}^2\) and \(2 \times 10^{23} \text{n/m}^2\), which are equivalent to \(1 \times 10^3\), \(5 \times 10^3\) and \(2 \times 10^2\) dpa, respectively. The temperature during irradiation was \(60^\circ\text{C}\) and \(150^\circ\text{C}\) for each neutron fluence case. At the bolometer location on ITER-FEAT, the neutron fluence is expected to be about \(10^1\) dpa during the machine lifetime. So the maximum fluence irradiated on the substrate is one tenth of the fluence during ITER lifetime. The temperature of the water coolant is designed to be \(150^\circ\text{C}\) for shielding blankets and the vacuum vessel. If the bolometers have good heat conduction with such components, the temperature of the bolometers would be around \(150^\circ\text{C}\).

4.1.4. Results

The expansion rate of the mica substrates as a function of the neutron fluence is shown in Fig. 4.1.1. The change of the thickness is below the measurement uncertainty. The expansion increase linearly with the neutron fluence at \(60^\circ\text{C}\). On the other hand, it is proportional to the square root of the neutron fluence, which indicates that defects generated by irradiation are annealed at high temperatures [4.1.3]. It is remarkable that the size expansion is only 0.13% for the ITER relevant condition of \(150^\circ\text{C}\) and \(10^2\) dpa.

4.1.5. Conclusion

Form the bolometer design point of view, the size expansion of the bolometer substrate should be less than 2%. The size expansion of only 0.13% for \(150^\circ\text{C}\) and \(10^2\) dpa gives us the good prospect of the mica substrate bolometer in the ITER application.

In the real bolometer, the mica substrate has a gold meander on the surface. The mechanical and electrical robustness of the meander is another issue under the ITER-relevant radiation conditions. An irradiation test of the bolometer itself was carried out at JMTR from November 2000 to March 2001 in order to evaluate the bolometer performance under neutron irradiation.
References


Fig. 4.1.1. Expansion rate of the mica substrates as a function of the neutron fluence.
4.2 Online Irradiation Tests of JET Type Bolometer in JMTR

Takeo Nishitani, Tatsuo Shikama, Etsuo Ishitsuka and Roger Reichel

4.2.1. Objective

In Section 4.1, the neutron irradiation effects on mica substrates were investigated, where we obtained a good prospect of the mica substrate up to the neutron fluence of ~0.01 dpa. In the present design of the bolometer system, bolometers will be installed on the inner surface of the vacuum vessel and will measure whole radiation losses from the plasma through the gap between blanket modules as shown in Fig. 4.2.1. In those locations, the total neutron fluence is expected to be ~0.1 dpa during the ITER lifetime. Here we investigated the bolometer performance under the neutron irradiation up to the neutron fluence of ~0.1 dpa.

4.2.2. Specimen

The picture of the bolometer with mica substrate [4.2.1,4.2.2] is shown in Fig. 4.2.2. Also the structure is shown in Fig. 4.2.3. This bolometer consists of four bolometer units. Each bolometer unit consists of four meanders on the mica substrate foil as shown in Fig. 4.2.4. Two meanders are under the open window of the front plate made of copper to measure the radiation from the plasma. The others are under the reference window, which is closed for the plasma radiation, to compensate a change of the temperature and also the nuclear heating. The mica substrate foil with gold meanders is put between the front plate and the pressure plate made of aluminum nitride. Four electrodes are plated on the backside of the pressure plate for each bolometer unit as shown in Fig. 4.2.5. Both ends of four meanders are connected to the electrode by thin gold wires though small holes of the pressure plate, which forms a bridge circuit. The schematic diagram of the electrical contact pin and a crimp is
shown in Fig. 4.2.6. The electrical contact pin touches to the electrode on the backside of the pressure plate by a thick gold wire and a crimp.

4.2.3. Experimental Condition

The bolometer was irradiated in JMTR of JAERI Oarai with three irradiation cycles from November 2000 to March 2001. The fast neutron fluence higher than 1 MeV for one irradiation cycle of 25 operation is 0.03 dpa. So the fast neutron fluence is about 0.1 dpa for three irradiation cycles. The fast neutron flux was $1.41 \times 10^{17}$ n/m$^2$/s and the thermal neutron flux was $1.5 \times 10^{18}$ n/m$^2$/s. The gamma heating rate was 1.54 W/g for iron. The bolometer was inserted in an irradiation capsule with He of 2 atm pressure in order to cool the bolometer. The temperature of the bolometer was not actively controlled, but about 100 °C during the 50 MW operation of JMTR.

The irradiation periods were as follows;

- First cycle: 17th November, 2000 - 12th December, 2000
- Second cycle: 12th January, 2001 - 6th February, 2001
- Third cycle: 26th February, 2001 - 23rd March, 2001

4.2.4. Measurements

The electrode pins were connected to the twisted pair MI cables which lead to the electronics outside of the reactor. Resistance of the meander, sensitivity of the bolometer and the time constant were measured during irradiation.

(1) Measurement of the resistance

The cable connection of the bolometer for the resistance measurement is shown in Fig. 4.2.7. The resistance was measured with a digital multimeter and stored to the computer automatically. The resistance between cable BM3-white and BM3-gray is,
\[ R(BM3) = \frac{(R_{m1} + R_{m2})(R_{m3} + R_{m4})}{(R_{m1} + R_{m2} + R_{m3} + R_{m4})} \]  \hspace{1cm} (4.2.1)

Because, the resistance of each meander is almost the same, \( R(BM3) \) is the average of \( R_{m1}, \)
\( R_{m2}, R_{m3}, \) and \( R_{m4}. \)

(2) Sensitivity and response time measurements by the AC technique

Figure 4.2.8 shows a block diagram of the sensitivity and the response time measurements by an AC technique. The bolometer unit is connected to the external bridge circuit. The response of the bridge, \( U_{\text{out}} \), is measured with a lock-in amplifier for the AC input to the bridge, \( U_{\text{in}} \). Before the measurement, resistances of the external bridge are set to be,

\[ R_1 = R_2 = R_3 = R_{\text{ex}} \]  \hspace{1cm} (4.2.2)

The measurement is done by switching from \( U_{\text{in}1} \) to \( U_{\text{in}2} \), where \( U_{\text{in}2} > 10 \times U_{\text{in}1} \). The typical response of the bolometer for the switching input AC voltage is shown in Fig. 4.2.9. The resistance of the bolometer, \( R_m \), is derived from the bridge output as,

\[ R_m = \frac{R_m}{\frac{U_{\text{out}}}{U_{\text{n}}} + 0.5} - R_m \]  \hspace{1cm} (4.2.3)

We defined \( R_1, R_2 \) and \( R_3 \) to be the bolometer resistance before the switch, at the moment of switch and 2 sec after the switch. The input power to the bolometer, \( P_{\text{in}} \), is

\[ P_{\text{in}} = \frac{U_{\text{in}}^2}{R} \]  \hspace{1cm} (4.2.4)

where \( R = (R_2 + R_3)/2. \)

The gain of the bolometer is defined by the change in the output voltage per input power as,
Gain = \frac{(\Delta R/R)}{P_{in}} \quad (4.2.5)

where \( \Delta R = R_3 - R_2 \).

The response time \( \tau \) of the bolometer is derived from the fitting function for \( U_{out} \) from the moment of switch to 2 sec after the switch.

(3) Sensitivity measurements by the DC technique

Figure 4.2.10 shows a block diagram of the sensitivity measurements by the DC technique. The input current, \( I_{in} \), is measured by the voltage of a standard resistance of 1\( \Omega \). The input voltage for the bolometer, \( V_{in} \), is directly measured with a digital voltmeter. The bolometer resistance, \( R_m = \frac{V_{in}}{I_{in}} \), will be represented by a function of the input power, \( P_m = V_{in} \cdot I_{in} \), as,

\[ R_m = R_{m0} + \Delta R \cdot P_m \quad (4.2.6) \]

The gain of the bolometer is derived from the increase rate of the resistance for the input power as,

\[ Gain = \frac{(\Delta R/R_{m0})}{P_{in}} \quad (4.2.7) \]

(4) Response time measurements by the DC technique

Figure 4.2.11 shows a block diagram of the response time measurements by a DC technique. Before the measurement, the resistances of the external bridge are set to be,

\[ R_1 = R_2 = R_3 = R_{m0} \quad (4.2.8) \]
The response of the external bridge is measured directly for the step input with a digital oscilloscope. The response time $\tau$ of the bolometer is derived from the fitting function for the response waveform.

4.2.5. Results

(1) Bolometer resistance

The bolometer resistances at the reactor start-up as a function of the reactor power are shown in Fig. 4.2.12. It seems that the bolometer resistances increased with the reactor power. However, the temperature of the bolometer increased with the reactor power due to the gamma heating. The bolometer resistances plotted against the temperature are shown in Fig. 4.2.13. The bolometer resistances increase with the temperature linearly. If we fit the relation with the following function,

$$R = R_{RT} \{1 + \alpha (T-20)\}$$

(4.2.9)

where $R_{RT}$ is the bolometer resistance at room temperature (20 °C) and $T$ is the temperature in °C. From Fig. 4.2.13, $\alpha = 0.0037$ is obtained, which is almost consistent with the value before the irradiation, $\alpha = 0.0035$, however, a little bit larger than it. We have a couple of possible explanations; one is the irradiation effect and another is a difference in the temperature for the bolometer itself and the thermocouple.

Figure 4.2.14 shows the bolometer resistance plotted against the fast neutron fluence up to $6 \times 10^{23}$ n/m$^2$ at the reactor power of 50 MW with a temperature of $\sim$100 °C. The bolometer resistance increased with the neutron fluence at almost constant temperature, which may be caused by transmutation from gold to mercury. The increase in the bolometer resistance is not linear to the neutron fluence. The fitting function in Fig. 4.2.14 is,
\[ R = R_0 \{1 - \exp(-cF)\} \]  \hspace{1cm} (4.2.10)

where, \( F \) is the fast neutron fluence in \( \text{n/m}^2 \), \( R_0 = 286.8 \ \Omega \) and \( c = 1.87 \times 10^{-24} \ \text{m}^2 \).

During the reactor shutdown of the first irradiation cycle with a rate of 0.5 MW/min from 10 a.m. of 12th December, 2000, the resistance of BM4 increased to be twice at about 25.1MW, at 68 °C, about 10:50 am as shown in Fig. 4.2.15, which indicated that one resistor was broken. We confirmed that the resistance between BM3(white) and BM4(gray) (see Fig. 4.2.7) was open, which suggested that meander 3 or the connecting wires were broken. When the reactor power became zero at 11.40 am, resistances between wires were as follows:

- BM3(white)-BM4(white) : 326.19 \( \Omega \)
- BM3(gray)-BM4(white) : 315.68 \( \Omega \)
- BM3(gray)-BM4(gray) : 328.29 \( \Omega \)

We confirmed the large permanent increase in resistance for the room temperature, which might be caused by the nuclear transmutation of gold into mercury. At about 15.00 of the day, all electrical contact was lost.

During the reactor startup of the second irradiation cycle on 12 January, 2001, the resistance of BM3(gray)-BM4(white) revived. Resistances of BM3(white)-BM4(white) and BM3(white)-BM4(gray) revived in 17 or 18 January. The resistance of BM3(Gray)-BM4(Gray) was still broken. Those resistances were lost during the shutdown of the second irradiation cycle. In the third irradiation cycle, no resistance did revive anymore.

(2) Sensitivity and response time by the AC technique measurements

A typical waveform of the external bridge output measured with the lock-in amplifier is shown in Fig. 4.2.16. We derived the sensitivity and the response time from this response curve. The sensitivity defined by Eq. 4.2.5 decreased to about half of the initial value at the reactor start up as shown in Fig. 4.2.17, which can be partly explained by normal loss of sensitivity with temperature. After the 10 MW lump up, the sensitivity stayed almost constant.
at 0.1 $W^{-1}$. The response time plotted versus the reactor power during the reactor start up is shown in Fig. 4.2.18. The response time increased from 25 ms to 30 ms at the reactor start up. After the 10 MW lump up, the sensitivity also kept constant at 30 ms. The measured response time is much smaller than the typical response time of 160 ms in vacuum, which is due to the thermal conductivity of the He.

We found some difficulty in the AC measurements. The measured sensitivity and the response time depend on the phasing angle in the lock-in amplifier, which means that the inductive components in this bolometer including MI lead wires are not negligible. We found the optimum phasing angle to maximize the sensitivity and the response time by scanning the phasing angle in the lock-in amplifier. However, the optimum phasing angle changed during the irradiation. Because it takes long time to fine the optimum phasing angle, we gave up the AC measurement.

(3) Sensitivity by DC measurements

The bolometer resistance plotted against the DC input current is shown in Fig. 4.2.19. The increase in the resistance is proportional to the square of the input current, which indicates that the increase is proportional to the input power. Figure 4.2.20 shows the bolometer resistance plotted against the DC input power, which indicates a good linearity for the input power. The coefficient $\Delta R$ for the input power (see Eq.4.2.6) at the reactor power of 50MW is plotted versus the fast neutron fluence in Fig. 4.2.21. $\Delta R$ was almost constant during the first irradiation cycle. During the first irradiation cycle, the external power was input to four meanders via wires BM4(white) and BM4(Gray). On the other hand, the power was input to only one meander (meander 1) via wires BM4(white) and BM3(Gray). $\Delta R/P_{in}$ in the second cycle was expected to be 4 times larger than that in the first cycle. However, $\Delta R/P_{in}$ in the second cycle was about twice of that in the first cycle, which indicates that thermal diffusion from the heated meander to the other meanders and the mica substrate is not negligible. There is no fluence effect on $\Delta R/P_{in}$ during each irradiation cycle. The bolometer
sensitivity defined by \((\Delta R/R)/P_m\) is shown in Fig. 4.2.22. The sensitivity in the second cycle is also about twice of that in the first cycle. The sensitivity decreased with the neutron fluence, which is due to the increase in the resistance with the neutron fluence. It seems that the difference between the sensitivity with the AC measurement and those with DC measurements is not so large in the first cycle from the history of the sensitivity in the second cycle.

(4) Response time by the DC measurements

The typical response of the external bridge for the step input is shown in Fig. 4.2.23. The waveform is rather noisy compared with that of the AC measurement. We obtained the response time from the exponential fitting function. The response time at a reactor power of 50MW is plotted versus the fast neutron fluence in Fig. 4.2.24. There was not significant change in the bolometer response time during irradiation.

4.2.6. Discussion

In this experiment, significant increase in the bolometer resistance was observed. Transmutation rate, \(R_{\text{Au-Hg}}\) of gold to mercury is represented by

\[
R_{\text{Au-Hg}} = \sigma \phi t
\]

(4.2.11)

where \(\sigma\) is the absorption cross section, \(\phi\) is the neutron flux and \(t\) is the irradiation time in sec. Gold has a large absorption cross section for low energy neutrons [4.2.3]. Preliminary, we estimated the transmutation rate only for thermal neutrons during one irradiation cycle.

\[
R_{\text{Au-Hg}} = (88.60 \times 10^{-28} \text{ m}^2) (1.5 \times 10^{18} \text{ m}^{-2} \text{ s}^{-1}) (2.16 \times 10^6 \text{ s})
\]
So about 3% of gold is transmuted to mercury for one irradiation cycle. Because the absorption has a large resonant region in the keV range, the transmutation rate might be larger than 3%. Produced mercury would make amalgam with gold. A change from gold to platinum may be advantageous.

Due to the thermal conductivity of the He, the response time of the bolometer was significantly reduced from 160 ms in vacuum to about 30 ms under the conditions of the irradiation. The atmosphere dependence of the bolometer response time was investigated with laboratory measurements at Tore Supra and JET. The observed reduction agrees with the results shown in Fig. 4.2.25. The response time varied somewhat during the transient phases of the ramp-up of the reactor power. This may be due to small changes in the conductivity of the surrounding atmosphere caused by out-gassing of the surrounding tube on heating up.

4.2.7. Conclusion

An irradiation test of the bolometer was carried out at JMTR from November 2000 to March 2001, in order to evaluate the bolometer performance under irradiation, where the total neutron fluence is planned to be 0.1 dpa. The bolometer was inserted in an irradiation capsule with He of 2 atm pressure in order to cool the bolometer. Significant increase of the meander resistance from 275 Ω to 446 Ω was observed during 45 days at constant reactor power, which might be caused by the nuclear transmutation of gold into mercury. The sensitivity of the bolometer decreased slightly at constant reactor power. The response time was much smaller than that in vacuum, which is due to the thermal conductivity of He. There was not significant change in the response time during irradiation. During the cool down phase of the first cycle all connections went open circuit. Some recovered on start-up of the second cycle, however, all connections went open circuit again near the end of the second cycle. They did not recover any more during the third cycle. The preliminary conclusion is that the use of thin gold films in ITER may be problematic and that mica merits more interest. This points the
way to further developments and investigations and strengthens hope to use this type of bolometers in ITER.

References


Fig. 4.2.1 Schematic view of the bolometer installed on ITER.

Fig. 4.2.2 Picture of the bolometer with mica substrate.
Fig. 4.2.3 Schematic structure of the bolometer with mica substrate.

Fig. 4.2.4 Meander arrangement on the mica substrate foil.
Fig. 4.2.5  Picture of the four electrodes plated on the backside of the pressure plat.
Fig. 4.2.6 Schematic diagram of the electrical contact pin and a crimp.

Fig. 4.2.7 Cable connection of the bolometer.
Fig. 4.2.8  Block diagram of the sensitivity and the response time measurements by an AC technique.

Fig. 4.2.9  Response of the external bridge for stepped up of AC input.
Fig. 4.2.10  Block diagram of the sensitivity measurements by an DC technique.

Fig. 4.2.11  Block diagram of the response time measurements by an DC technique.
Fig. 4.2.12  Resistances of the bolometer plotted against the reactor power at the reactor start-up.

Fig. 4.2.13  Resistances of the bolometer plotted against the temperature at the reactor start-up.
Fig. 4.2.14 Bolometer resistance plotted against the fast neutron fluence at the reactor power of 50 MW at the temperature of $\sim$100 °C.

Fig. 4.2.15 Time history of the bolometer resistance BM4 during the reactor shutdown of the first irradiation cycle.
Fig. 4.2.16 Typical waveform of the external bridge output measured with the lock-in amplifier for 1 kHz input.

Fig. 4.2.17 Sensitivity of the bolometer plotted against the reactor power at the reactor startup measured by AC technique.
Fig. 4.2.18  Response time of the bolometer plotted against the reactor power at the reactor startup measured by AC technique.

Fig. 4.2.19  Bolometer resistance plotted against the input current measured by DC technique.
Fig. 4.2.20  Bolometer resistance plotted against the input power measured with DC technique during the first irradiation cycle.

Fig. 4.2.21  Coefficient of the bolometer resistance for the input power as a function of the fast neutron fluence.
Fig. 4.2.22 Bolometer sensitivity as a function of the fast neutron fluence.

Fig. 4.2.23 Typical response of the external bridge for the step input.
Fig. 4.2.24  Response time at a reactor power of 50MW plotted against the fast neutron fluence.

Fig. 4.2.25  Bolometer sensitivity and response time in different atmosphere.
5. Magnetic probe

5.1 Analysis of electric properties of a magnetic probe under JMTR irradiation

Takeo Nishitani, Masayuki Fukao, Tatsuo Shikama and Shin Yamamoto

5.1.1. Objective

Magnetic probes have to be installed inside the vacuum vessel to measure the magnetic field in order to control the plasma position [5.1.1,5.1.2]. The radiation condition for the magnetic probe is expected to be fast neutron flux and fluence of $\sim 1 \times 10^{12}$ n cm$^{-2}$ s$^{-1}$ and $\sim 3 \times 10^{19}$ n cm$^{-2}$, respectively, in ITER-FEAT. The magnetic probe has to have high reliability, because the replacement is very difficult in fusion reactors. The magnetic probe made of ceramics coated cable is popular in present tokamaks [5.1.3]. However, the ceramics coating may be peeled out or cracked due to mechanical and thermal shocks. The magnetic probe made of Mineral Insulated (MI) cable is regarded as the most reliable magnetic sensor, and proposed to ITER. We irradiated it in the Japan Material Testing Reactor (JMTR) with in-situ measurements. MI cable has metal sheath, so that we have to take account of the electro-magnetic shielding effect of the sheath to evaluate the electric characteristics of the probe. In the previous report [5.1.4], the analysis model of the magnetic coils did not take account of the sheath effects. We established the analysis method of the electric properties of the magnetic coil and applied it to the irradiation data obtained at JMTR.

5.1.2. Specimen

The coil of the magnetic probe was made of 1.6 mm MI cable, which has 280 turns (10 layers $\times$ 28 turns) around a ceramic bobbin with 9 mm diameter. The length of the solenoid is 50 mm and the total cable length in the coil is 24 m. The sheath and core materials of the MI-cable were Stainless Steel 316 and oxygen free copper, respectively. The insulation material of MI cable was MgO.
5.1.3. Experimental Condition

The probe was mounted in an irradiation capsule which was filled with Helium gas to exhaust the γ-ray heat of the probe and to avoid oxidation. The irradiation capsule was inserted into the core region of the JMTR reactor.

The magnetic probe was irradiated in JMTR with three irradiation cycles. The duration of one irradiation cycle was 25 days. The fast neutron flux (>1 MeV) and thermal neutron flux (<0.63 eV) were $9.3 \times 10^{12}$ n cm$^{-2}$ s$^{-1}$ and $1.2 \times 10^{14}$ n cm$^{-2}$ s$^{-1}$, respectively, at the 40 MW operation. The fast neutron fluence and thermal neutron fluence were $3.9 \times 10^{19}$ n cm$^{-2}$ and $5.0 \times 10^{20}$ n cm$^{-2}$, respectively. The γ-ray heating rate of the probe was 1.5 W/g. The base irradiation temperature was about 400°C at 40 MW operation. The temperature of the probe was monitored by a chromel-constantan (CRC) thermocouple inserted between the ceramic bobbin and the coil. The magnetic probe was connected to leading wires of 25 m MI cable. The electrical characteristics were measured with an impedance analyzer (HEWLETT PACKARD 4194A). The current and voltage between the sheath and the center conductor were measured with an electrometer (KEITHLEY 614) to investigate the radiation induced electrical motive force (RIEMF).

5.1.4. Analysis

The sheath of the MI cable shows an electro-magnetic shielding effect for the center conductor. The sheath is modeled by the secondary coil which is assumed to be single-tune, because the sheath is a short-circuited winding. The equivalent circuit is shown in Fig.5.1.1 (a), which can be simplified to Fig.5.1.1 (b). According to the circuit in Fig.5.1.1 (b), the impedance $Z(\omega)$ across the terminals is represented by

$$Z(\omega) = R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} + i\omega\left(L_1 - \frac{\omega^2 M}{R_2^2 + \omega^2 L_2^2}\right)$$  (5.1.1)

where, $L_1$ and $L_2$ are inductance for the probe and the sheath, respectively, and $R_1$ and $R_2$ are
resistance for the probe and the sheath, respectively. $M$ is the mutual inductance between the probe and the sheath. By introducing the coupling coefficient $K= M/(L_1 L_2)^{1/2}$ between probe and sheath, $Z(\omega)$ is expressed by

$$Z(\omega) = R_1 \left( 1 + \frac{K^2 \omega^2 \tau_1 \tau_2}{1 + \omega^2 \tau_2^2} \right) + i \omega L_1 \left( 1 - \frac{K^2 \omega^2 \tau_2^2}{1 + \omega^2 \tau_2^2} \right)$$ (5.1.2)

where $\tau_1 = L_1/R_1$ and $\tau_2 = L_2/R_2$ [5.1.5].

We measured the impedance $|Z(\omega)|$ and phase $\theta(\omega)$ for 400 points of frequency $\omega$ between 100 Hz and 100 KHz with the impedance analyzer. We determined four free parameters of $R_i$, $L_i$, $K$ and $\tau_2$ by minimizing the deviation of the real part and imaginary part of $Z(\omega)$ as follows;

$$\sum \left\{ R_i \left[ 1 + \frac{K^2 \omega_i^2 \tau_1 \tau_2}{1 + \omega_i^2 \tau_2^2} \right] - |Z(\omega_i)| \cos \theta(\omega_i) \right\}^2$$

$$+ \left\{ \omega_i L_i \left[ 1 - \frac{K^2 \omega_i^2 \tau_2^2}{1 + \omega_i^2 \tau_2^2} \right] - |Z(\omega_i)| \sin \theta(\omega_i) \right\}^2$$ (5.1.3)

where, $|Z(\omega)|$ and $\theta(\omega)$ are the measured impedance and phase, respectively. Figure 5.1.2 shows the typical measured impedance compared with the fitting based on Eq. (5.1.3). Measured and calculated values of $|Z|$ and $\theta$ agree very well. Here $R_i = 7.27 \Omega$, $L_i = 3.50 \text{ H}$, $K = 0.952$ and $\tau_2 = 1.91 \times 10^{-5} \text{ s}$ are obtained. Nearly unity of $K = 0.952$ shows rather strong coupling between coil and sheath.

5.1.5. Results

For a magnetic probe, the inductance is the most important property. Figure 5.1.3 shows the inductance of the probe plotted against the reactor power. A very weak increase in the inductance, only 0.17% for the reactor power from 0 to 40 MW, was observed. There is
not significant difference among the three irradiation cycles. The temperature of the probe was proportional to the reactor power during the reactor start-up phase. In the stationary phase of the reactor with 40 MW power, we controlled the temperature to be 400, 500 and 600 °C. We re-plotted the inductance against the temperature as shown in Fig.5.1.4. The inductance increases with the temperature. The temperature coefficient of the inductance is derived to be $3.4 \times 10^{-5}^{\circ}C$. Figure 5.1.5 shows the inductance at 400 °C plotted against the fast neutron fluence. We confirmed that the inductance did not change up to a fast neutron fluence of $6 \times 10^{19}$ n cm$^{-2}$, which is twice of the expected value at the magnetic probe location in ITER.

Figure 5.1.6 shows the resistance of the probe plotted against the temperature. Those data include three irradiation cycles. The resistance increases monotonically with the temperature. The increase is 4.0 Ω for the temperature from 20 to 600 °C. Figure 5.1.7 shows the resistance at 400 °C plotted against the fast neutron fluence. There is no significant change in the probe resistance up to the fast neutron fluence of $6 \times 10^{19}$ n cm$^{-2}$, which indicates that there is no irradiation effect on the electrical characteristics of the copper conductor.

5.1.6. Discussion

Assuming the magnetic probe to be simple solenoid coil, the inductance of the probe is represented by,

$$L = \frac{\mu_0 \pi a^2 N^2}{b}$$  \hspace{1cm} (5.1.5)

where $\mu_0$ is the permeability of vacuum, $a$ is the coil radius, $N$ is the number of turns, and $b$ is the solenoid length. The thermal expansion of the coil is assumed to be only the diameter $a$, because that of the coil bobbin made of Alumina ceramics is negligible. The temperature coefficient of the inductance is given by $\Delta L/L = 2 \Delta a/a$. We do not know which of the sheath and center conductor is more important for the thermal expansion of the coil, however, temperature coefficients of linear expansion for stainless steel which is the sheath material and copper which is the center conductor material are not so different. The former is $1.64 \times$
$10^{-5}/\degree C$, the later is $1.72 \times 10^{-5}/\degree C$. So we can estimate the temperature coefficient of the probe to be $3.3-3.4 \times 10^{-5}/\degree C$, which is in good agreement with the measurement. So the weak dependence of the inductance on the reactor power can be explained by the thermal expansion of the coils due to the $\gamma$-ray heating which is proportional to the reactor power.

The resistivity of copper is $1.72 \times 10^{-8}$ $\Omega$m at 20$\degree$C, and $5.2 \times 10^{-8}$ $\Omega$m at 600$\degree$C. The increase in the resistance of the 24 m copper cable with 0.5 mm diameter is calculated to be 4.2 $\Omega$ for the temperature from 20 to 600 $\degree$C, where we take into account of the thermal expansion of the center conductor. The measured increase in the resistance of 4.0 $\Omega$ is almost consistent with this calculation. The difference may be caused by non-uniformity of the temperature in the coil.

5.1.7. Conclusion

We irradiated a magnetic probe made of Mineral Insulated cable in the JMTR Reactor. We analyzed the probe inductance with the equivalent circuit modeling the sheath as a secondary coil to eliminate the shielding effect of the sheath. We found the weak dependence of the inductance on the reactor power, which can be explained by the thermal expansion of the coil due to the $\gamma$-ray heating. The probe inductance did not change up to the fast neutron fluence of $6 \times 10^{19}$ n cm$^{-2}$. Also we observed the increase in the resistance of the coil with the temperature, which is consistent with the thermal coefficient of copper resistivity. There is no significant change in the resistance up to a fast neutron fluence of $6 \times 10^{19}$ n cm$^{-2}$. Thus, there is no irradiation effect on the electrical characteristics of the magnetic probe made of MI cable. However, the issue of RIEFM is still open, which is discussed in the next section.
References


Fig. 5.1.1 Equivalent circuit diagram of the magnetic probe made of MI cable. The sheath of MI cable is modeled by the secondary coil.

Reactor Power: 10 MW
Temperature: 149°C

Fig. 5.1.2. Calculated and measured impedance and phase of the magnetic probe in the range of frequency 100 Hz to 100 kHz.
Fig. 5.1.3. Inductance of the magnetic probe plotted against the reactor power. Very weak increase in the inductance, only 0.17% for the reactor power from 0 to 40 MW, was observed.

Fig. 5.1.4. Inductance of the magnetic probe plotted against the temperature. The temperature coefficient of the inductance is derived to be $3.4 \times 10^{-5}/^\circ C$. 
Fig.5.1.5. Inductance at 400 °C plotted against the fast neutron fluence. The inductance was constant up to the fast neutron fluence of $6 \times 10^{19}$ n cm$^{-2}$.

Fig.5.1.6. Resistance of the magnetic probe plotted against the temperature. The resistance increases monotonically with the temperature. The increase is 4.0 Ω for the temperature from 20 to 600 °C.
Fig. 5.1.7. Resistance at 400 °C plotted against the fast neutron fluence. The resistance was constant up to the fast neutron fluence of $6 \times 10^{19} \text{ n cm}^{-2}$.
5.2 RIEMF on magnetic probes under JMTR irradiation

Tatsuo Shikama, Takeo Nishitani, Robin Snider, Masayuki Fukao and Shin Yamamoto

5.2.1. Objective

A magnetic probe will be one of the important plasma-diagnostic tools to be used in the heavy radiation environment of ITER. In the case of ITER, a magnetic probe is expected to endure a total ionizing dose of \(\sim 10^{8-9}\) Gy and a neutron fluence of \(\sim 10^{24}\) n/m². In the beginning of ITER Engineering Design Activity (EDA), the degradation of electrical insulation among coiling wires was a major concern. A design criterion suggested a critical electrical conductivity lower than \(10^{-6}\) S/m at \(10^4\) Gy/s [5.2.1]. Extensive studies of radiation effects in ceramic insulators have shown that candidate ceramic insulators such as alumina (Al₂O₃) and magnesia (MgO) will satisfy this condition [5.2.2 and 5.2.3].

However, the established materials-radiation-effects databases are not sophisticated enough for developing reliable components and systems used in nuclear fusion systems with burning plasmas. Interactions among various radiation effects may result in unexpected technical problems and may cause malfunctions of components and systems. Behavior of components and systems under irradiation should be studied and analyzed in the light of existing knowledge about radiation effects in each constituent material, and unexpected phenomena should be identified and their influence on the total performance of components and systems should be evaluated.

An irradiation test of components and systems is a resource-consuming research enterprise and international collaboration is essential. The USA and Japan have been carrying out irradiation tests of magnetic probe in fission reactors independently. Obtained results have shown that a coil being made of mineral-insulating cables (MI-cables) will be a primary candidate for ITER. International collaborative radiation tests of MI-cables and magnetic coils for plasma diagnostics were carried out in JMTR under Japanese/US collaboration.
5.2.2. Specimen

MI-cables have been used in many applications in heavy radiation environments and their reliability is far better than ceramic-coated wires as electrical cables. So, the ITER-EDA is evaluating that the MI-coil will be the primary candidate. There will be several choices involved for MI-cables, namely, materials for a center lead, an insulator, and an outer sheath. Copper and nickel are conventional choices for a center lead, and magnesia (MgO) is the most popular choice as an insulator. SS316/304 and Inconel would be conventional outer-sheath material. The ITER-EDA is considering these choices and its primary choice is copper for a center lead, and alumina (Al₂O₃) for an electrical insulator. Copper is a highly electrically conductive and paramagnetic material, and alumina is thought to be reliable under heavy radiation especially at elevated temperatures. In the meantime, magnesia is known to be susceptible to humidity-contamination and its electrical conductivity increases substantially with increase of contained humidity.

The MI-cables listed in Table 5.2.1 were manufactured in the USA and in Japan, and magnetic coils were made by winding these cables on alumina-made bobbins in the USA as shown in Fig. 5.2.1. Two MI-cables were wound on one bobbin to study magnetic interactions between two coils. The previous results indicated that the parasitic voltage, which was induced in a center lead by radiation environments, would be the most hazardous for a magnetic probe. The parasitic voltage induced by radiation is called radiation induced electromotive force (RIEMF) and its cause and detailed behavior are not yet well understood [5.2.6]. Some proposed mechanisms suggested that RIEMF might depend on the geometry of MI-cables. Thus, MI-cables having three different center-lead diameters were chosen in the present experiment.

5.2.3. Experimental Condition

Four magnetic coils were accommodated in an instrumented radiation rig in Japan and their behavior was examined in-situ under JMTR irradiation. Schematic structures of an instrumented irradiation rig are shown in Fig. 5.2.2. An X-ray photograph of two coils wound on one alumina-made bobbin is shown in Fig. 5.2.3. The position of two bobbins wound with two coils in a reactor core is shown in Fig. 5.2.4. The position was chosen so that two bobbins
have nearly the same radiation flux. However, the resultant coils had substantial flux gradient along their axis as shown in Fig. 5.2.4.

Studies of dynamic irradiation effects were carried out as a function of reactor powers, namely as a function of the intensity of the radiation, at reactor start-up and shut down. The neutron flux ranged from nearly zero to $\sim 5 \times 10^{17}$ n/m²s and the gamma-ray dose rate ranged from less than 0.1 Gy:s to 5 kGy:s for iron. Accumulated radiation effects were studied for 25 days at a JMTR with full power of 50 MW. So the total neutron fluence was $1.1 \times 10^{24}$ n/m² or 0.1 dpa for iron.

Three N-type thermocouples were attached to the outer surface of the outer coil on each bobbin, at two edges and the middle. No active temperature control using an electric heater was carried out. The irradiation rig was designed so that the coil temperature would be in the range of 600-700 K.

5.2.4. Measurements

Four research groups from Japan and the USA participated in in-situ measurements. The performance of the coils as a magnetic coil was studied using long-time integrators developed in the USA and in Japan. For the ITER application, an integration period of 1000 s is needed and a USA-made integrator satisfies this condition. The electrical behavior was studied with an a.c. impedance analyzer. Fundamental radiation effects, namely radiation induced conductivity (RIC) in ceramic insulators in MI-cables and radiation induced electromotive force (RIEMF) were measured between a center lead and a sheath of MI-cables as well as along a center lead by standard d.c. methods and a.c. impedance measurements. The outer sheath and the d.c. instruments had a common ground potential and a current caused by the RIEMF was measured directly by an electrometer, a Keithley 6517. Also, the current caused by the RIEMF was measured by measuring the induced d.c. voltage through 1 k-100 M standard resistors by a Keithley 2001 voltmeter.

The a.c. impedance measurements confirmed that the equivalent electrical circuit model described in the previous section was valid and the circuit parameters were not strongly affected by the radiation, except for the electrical insulation between the center lead and the outer sheath, and for the electrical conductance of a center lead. In the meantime,
measurements using long-time integrators were found to be substantially disturbed by electrical drifts. In the case of an integrator designed for operation for a relatively short integration period, measurements were actually unsuccessful. The long-term integrator developed by the USA showed better performance, though it was also affected by a small electrical drift which was thought to be caused by the RIEMF.

5.2.5. Results

Electrical currents induced by RIEMF were plotted against the reactor power as shown in Fig. 5.2.5(a). The coils 3 and 4 showed negative electrical currents, namely current from the sheath to the center conductor. In the previous experiments [5.2.4], we had understood that the RIEMF currents were almost proportional to the reactor power as in coils 1 or 3. However, the RIEMF currents in coils 2 and 4 showed a complicated behavior. The mechanism of the RIEMF behavior is under discussion. The RIEMF voltage is shown in Fig. 5.2.5 (b). The magnitude of the RIEMF voltages in coils 2 and 4 decreased with increase in the reactor power. The RIEMF voltage in coil 3 was negative and was rolled over above the reactor power of 30 MW. That in coil 1 increased once with increase in the reactor power and decreased above 30 MW. The RIEMF voltage is represented by $I_{RIEMF} \cdot \Omega_{int}$, here $\Omega_{int}$ is an internal resistance. The internal resistance decreased with the reactor power not only due to the RIC of the insulator material but also a residual gas in the powder of the insulator material between the center conductor and the sheath.

During the magnetic measurement, a differential voltage between both side of the center conductor is integrated by an integration circuit. If the RIEMF is really symmetric along the MI cable, the RIEMF effect on the differential voltage should be canceled. If an asymmetry exists, it may cause a drift of the integrated signal. We measured the drift with the long-term integration circuit for 1000 s duration time. We observed a drift of 10 - 40 mVs as shown in Fig. 5.2.6. If the permitted error of the magnetic filed measurement is 1 % for the
flat-top phase of the ITER-FEAT operation, the drift of the integrator output has to be less than 0.6 mV. So the observed drift is a very severe problem for the ITER-FEAT operation.

5.2.6. Discussion

If the coils have strict symmetry along their axes, the RIEMF generated between the center lead and sheath would not cause an electric drift which disturbed the above-mentioned long-term integration. However, as shown in Fig. 5.2.4, coils were found to have asymmetry along their axes, such as a radiation flux gradient and a temperature gradient. The observed drift of a magnitude of a few V in a long-term integrator indicates that there will be asymmetry of the electrical resistance of the order of 0.1-1 Ω, ~10% of the total electrical conductance of the center lead, along the center lead. Results of temperature monitoring and measurements of radiation induced conductivity of ceramic insulators strongly suggested that there will be a substantial temperature gradient along the MI-cable. A thermal analysis suggested that one leg of MI-cable, which went through a center bore of a bobbin, would have been heated up ~100 - 150 K higher than average coil temperature.

However, the coil made with the MI-cable having the fattest center lead, 0.75 mm in diameter, showed relatively good performance and its electrical drift was not much larger than the permissible drift of 0.5 V. The MI-cable with the 0.75-mm diameter center lead showed the lowest RIEMF as well as the highest electrical conductance along the lead. Both contributed to the lowest electrical drift. By improving geometrical asymmetry, a magnetic coil whose electrical drift is less than 0.5 μV will be possible following the present results.

5.2.7. Summary

An international joint venture was undertaken in the ITER-EDA for radiation-testing of magnetic probes in a fission reactor. The USA and Japan carried out the experiment, collaboratively designing coils, selecting materials, fabricating MI-cables, manufacturing coils, making an irradiation rig, and measuring the performance of coils. Obtained results are still under analysis, but preliminary results suggest that the ITER-relevant magnetic coil could be made with MI-cables, whose electric drift for 1000-s integration is less than 0.5 mV
under ITER relevant radiation environments.

References


Table 5.2.1 Details of the MI-cables used for magnetic coil

<table>
<thead>
<tr>
<th></th>
<th>First(A)/Upper</th>
<th>Second (B)/lower</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coil No.</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Position</strong></td>
<td>inside</td>
<td>outside</td>
</tr>
<tr>
<td><strong>Sheath material</strong></td>
<td>SS304</td>
<td>SS316</td>
</tr>
<tr>
<td><strong>Sheath diameter</strong></td>
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<td>1.6 mm</td>
</tr>
<tr>
<td><strong>Insulator</strong></td>
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<td>MgO</td>
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<tr>
<td><strong>Center lead material</strong></td>
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<td>Cu</td>
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<tr>
<td><strong>Center lead diameter</strong></td>
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<td>0.75 mm</td>
</tr>
<tr>
<td><strong>Providing party</strong></td>
<td>Japan</td>
<td>USA</td>
</tr>
</tbody>
</table>
Fig. 5.2.1 Cross-sectional structure of the magnetic coils.
Fig. 5.2.2 Schematic cross-section of the radiation rig for the magnetic coils.
Fig. 5.2.3 X-ray transmission view of magnetic coils accommodated in the radiation rig.

Fig. 5.2.4 Position of magnetic coils in the fission reactor with gamma-ray intensity profile.
Fig. 5.2.5 RIEMF (a) currents and (b) voltages as a function of the reactor power
Fig. 5.2.6 Drift of the long term integrator output after 1000 sec integration.
5.3 RIEMF on magnetic probes under gamma-ray irradiation

Takeo Nishitani, Satoshi Kasai, Tatsuo Shikama, Noriko Yokoo, Toshiaki Yagi and Shigeru Tanaka

5.3.1. Objective

In the previous experiment at JMTR (see Section 5.2), we measured the RIEMF between the center conductor and the sheath. The differential voltage between both ends of the center conductor of the magnetic probe is important in the real magnetic measurements. We observed the drift to be 10 - 40 mVs for 1000 sec integration time with a digital long term integrator connected to both ends of the center conductor. However, we could not confirm that the observed drift was caused by RIEMF.

The objective of this test is to try the direct measurement of the differential voltage between both ends of the center conductor of the magnetic probe under gamma-ray irradiation, and to investigate the effect of the center core diameter of the MI cable on the RIEMF.

5.3.2. Specimen

Two magnetic probes were used in this irradiation test. Parameters of those magnetic probes are listed in Table 5.3.1. We used two kind of MI cables; one with a center core diameter of 0.5 mm and another with 0.8 mm. The other parameters are the same. A drawing of the magnetic probe is shown in Fig. 5.3.1. One MI-cable was wound on an alumina bobbin. Both ends of the MI cable are used as lead wires with a length of 20 m.

5.3.3. Experimental Condition

(1) Irradiation facility

The magnetic probes were irradiated in the $^{60}$Co irradiation facility in JAERI Takasaki. The arrangement of the gamma-ray source, magnetic probes and measurement instruments are shown in Fig. 5.3.2. The $^{60}$Co source with an intensity of 115 kCi (4286 TBq)
is stored in a water pool. The source is lifted into the irradiation room. The irradiation room is shielded with 1.3 m thick heavy concrete walls.

(2) Irradiation condition

The magnetic probes were mounted on the cylindrical metal-mesh-fence which located outside the $^{60}$Co source lifted from the water pool as shown in Fig. 5.3.3. The diameter of the fence is $\sim 0.76$ m. In ITER-FEAT, magnetic probes will be installed in a gap of the shielding blanket modules, where the ionization dose rate is estimated to be $\sim 1 \times 10^2$ Gy/s. In this experiments, the gamma dose rate at the magnetic probes was calibrated to be $\sim 15$ kGy/h or 4.2 Gy/s, which is about 1/20 of ITER-FEAT. We irradiated magnetic probes for 20 hours, so the total dose was 300 kGy. The temperature changed from room temperature to 280 °C. The irradiation history is shown in Fig. 5.3.4.

5.3.4. Measurements

The measurement instruments for the magnetic probe irradiation test are shown in Fig. 5.3.5. The temperature of the probe was controlled by a heater. The differential voltage between both ends of the center lead was measured with a sensitive digital voltmeter, a Keithley 182 whose sensitivity is 1 nV, as shown in Fig. 5.3.5 (a). The sheaths of the MI cables were grounded. Also the RIEMF between the sheath and the center leads was measured with a digital voltmeter, a Keithley 2000, as shown in Fig. 5.3.5 (b). Both center leads and sheaths were short-circuited.

5.3.5. Results

In the magnetic measurement, a differential voltage between both ends of the center lead is integrated by an integration circuit. Here we measured the differential voltage between both ends of the center lead directly. The differential voltage between both ends of the center lead, which was of the order of 0.1 $\mu$V, was affected by the contact electricity. The reconnection of the cables disturbed the voltage. We measured the voltage with and without gamma-ray irradiation during an identical measurement. Measured voltages at the lump down
of the 2nd irradiation were shown in Fig. 5.3.6. The voltage of the magnetic probe with φ 0.8 mm cable had a rather large fluctuation, which was due to the intrinsic characteristics of the sensitive voltmeter. For the magnetic probe with φ 0.5 mm cable, the fluctuation level was less than 50 nV. We could not recognized significant change of the voltage during and after irradiation. In other word, the RIEMF between both ends of the center lead is less than which is the fluctuation level of the measurement, 50 - 100 nV.

The time histories of the RIEMF voltage between the center conductor and the sheath are shown in Figs. 5.3.7 - 5.3.11. During the first irradiation, the RIEMF voltage of the φ 0.5 mm cable decreased exponentially. That of the φ 0.8 mm cable increased once at the beginning of the irradiation, and decreased monotonically about 1 hour later. The polarity changed from positive to negative at 9.5 hours. The absolute value of the RIEMF voltage of the φ 0.5 mm cable was much larger than that of the φ 0.8 mm one. The connection of the measurement was open once in order to measure the resistance between the center conductor and the sheath. After that the voltage of the φ 0.5 mm cable recovered to be +0.18 V, and decreased gradually as shown in Fig. 5.3.8. After the termination of the irradiation, the voltage of the φ 0.5 mm cable became almost constant. On the other hand, the voltage of the φ 0.8 mm cable was constant at -0.035 V during the 1st irradiation and increased after the termination. The voltage decreased to be -0.06 V immediately at the turn of the 2nd irradiation as shown in Fig. 5.3.9. The voltage of the φ 0.5 mm cable decreased gradually.

During the second irradiation, the temperature lumped up from 50 to 280 °C by turning on the heater as shown in Fig. 5.3.10. The voltage of the φ 0.8 mm cable increased for temperatures lower than ~150°C, however, decreased to 0V for temperatures higher than ~150°C. During the third irradiation, the temperature lumped down as shown in Fig. 5.3.11. The voltage of the φ 0.8 mm cable was kept to be ~0V during a temperature of ~270°C, however, increased with increase in temperature, which suggested that a high temperature might suppress the RIEMF. Though the temperature effect was not clear for the φ 0.8 mm
cable, it seems that the decrease rate of the voltage increased a little bit during the temperature lumping down.

5.2.6. Discussion

We could not recognize a RIEMF in the differential voltage between both ends of the center lead during gamma-ray irradiation. The voltage might be less than $\sim$50nV in the dose rate of $\sim$4 Gy/s. If the RIEMF voltage is assumed to be proportional to the dose rate, the voltage is estimated to be $\sim$0.1 µV or $\sim$ 0.1 mVs for the 1000 sec integration at ITER-FEAT condition, which is within an acceptable level of the magnetic measurement.

The behaviors of the RIEMF voltage between the center lead and the sheath are not understood well. The response time of the RIEMF was $\sim$2 hour and $\sim$2 min for the $\phi$ 0.5 mm and $\phi$ 0.8 mm cables, respectively. It seems that such a long response time is caused by a charge-up of the cable. High temperature might suppress the RIEMF due to the decrease in the resistance between the center lead and the sheath, which were 11 MΩ and 0.7 MΩ at 50 and 280 °C, respectively under irradiation.

5.2.7. Conclusion

The behaviors of the RIEMF voltage between the center lead and the sheath are still mysterious. However, the RIEMF in the differential voltage between both ends of the center lead might be negligible for the magnetic measurement on ITER-FEAT.
Table 5.3.1 Parameters of the magnetic probes used in the gamma-ray irradiation test.

<table>
<thead>
<tr>
<th></th>
<th>Probe A</th>
<th>Probe B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe diameter (mm)</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Probe length (mm)/Coil length (mm)</td>
<td>130/80</td>
<td>130/80</td>
</tr>
<tr>
<td>Number of turns</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>MI Cable: Sheath diameter (mm)</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>: Sheath material</td>
<td>SS316</td>
<td>SS316</td>
</tr>
<tr>
<td>: Center lead diameter (mm)</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>: Center lead material</td>
<td>Copper</td>
<td>Copper</td>
</tr>
<tr>
<td>Insulator material</td>
<td>MgO</td>
<td>MgO</td>
</tr>
<tr>
<td>Resistance between both end of center lead including pig tails (Ω)</td>
<td>4.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Fig. 5.3.1 Drawing of the magnetic probe used in the gamma-ray irradiation test.
Fig. 5.3.2. Arrangement of the gamma-ray source, magnetic probes and measurement instruments.
Fig. 5.3.3 Schematic view of the magnetic probes at the $^{60}$Co irradiation facility. The magnetic probes were mounted on the cylindrical metal-mesh-fence which is located outside the $^{60}$Co source lifted from the water pool.
Fig. 5.3.4  Irradiation history of the magnetic probes.
Fig. 5.3.5 Measurement instruments for the magnetic probes irradiation tests.
Fig. 5.3.6  Voltage between both ends of the center lead measured at the lump down of the 2nd irradiation.
Fig. 5.3.7 RIEMF voltage between the center conductor and the sheath in the first irradiation.

Fig. 5.3.8 RIEMF voltage between the center conductor and the sheath at the lump down of the first irradiation.
Fig. 5.3.9 RIEMF voltage between the center conductor and the sheath in the second irradiation.

Fig. 5.3.10 RIEMF voltage between the center conductor and the sheath, and the temperature in the second irradiation.
Fig. 5.3.11 RIEMF voltage between the center conductor and the sheath, and the temperature in the third irradiation.
6. jxB Magnetic Sensor

6.1 On-line Irradiation Tests of jxB Magnetic Sensor in JMTR

Satoshi Kasai, Takahide Nakayama and Etsuo Ishitsuka

6.1.1 Objective

The measurement of the magnetic field under quasi-steady state conditions is important for long pulse operation of ITER[6.1.1~6.1.6]. Present inductive methods using a conventional magnetic probe have a limit of time integration in the range of several thousand seconds. A new concept of a hybrid magnetic sensor consists of a conventional magnetic probe and a mechanical sensor (jxB magnetic sensor). The objective is to investigate the jxB magnetic sensor performance such as sensitivity for magnetic field by the in-situ measurement under the neutron irradiation in the fission reactor of JMTR at JAERI Oarai.

6.1.2 Specimen

The jxB magnetic sensor i.e. mechanical sensor, consists of a load cell, sensing coil/frame, sensing coil support, joint mechanism, mechanical sensor support and lead wires. Figure 6.1.1 shows the top view and side view of the newly designed mechanical sensor. The material of the strain gauge is nickel-chromium (model of strain gauge : Kyowa Co. Ltd., KG-873-NiCr). The size of the resistance pattern of the strain gauge is $3.5 \times 5$ mm. The resistance patterns are made of the same rod. The four active gauges are located on the stainless steel (SS 316) sensor beam. A couple of strain gauges are bonded on one side of the beam by ceramic ($\text{Al}_2\text{O}_3$) plasma spray coating and another couple of strain gauges are bonded on the other side, which form an electrical bridge circuit as shown in Fig. 6.1.2. The thickness of the ceramic ($\text{Al}_2\text{O}_3$) plasma spray coating is about 250 μm and the sensor beam is 0.5 mm thickness. The sensor beam is mounted on the mechanical sensor support (Al 5052) which is mounted on the inner wall of the capsule in JMTR. A mineral insulated cable (MI-cable : sheath material is SS316L, core is copper, insulator is MgO) with 0.5 mm in diameter is used.
as a lead wire for the signal. The bulk of the sensor-beam is made of stainless steel (SS316L) and the part of the beam connected with the sensing coil is made of aluminum (Al 5052) to conduct the excessive heat of the sensing coil generated by nuclear heating during irradiation in JMTR to a heat sink (mechanical sensor support) through the sensor beam.

The frame of the sensing coil is aluminum (Al 5052). The coil is made of MI-cable with 0.5 mm in outer diameter (inner conductor : Cu, 0.2 mmØ) and the number of turns is more than 100. The sensing coil/frame is supported by the pivot mechanism, which is mounted on the mechanical sensor support. A flexible link between the sensing coil/frame and the sensor beam (load cell) is adopted to eliminate the noise caused by the thermal expansion stress of the sensing coil frame. The material of this link is inconel.

The main size of the sensor is 126 mm in length and 42 mm in width over the size of the previous sensor.

6.1.3 Experimental condition

(1) Irradiation facility
JMTR in JAERI Oarai

(2) Irradiation condition
Irradiation period : Nov. 2000 ~ March 2001
Irradiation hole : H12
Irradiation environment : He gas (2 atm.)
Neutron Flux (E > 1 MeV) : 1.7×10¹⁷ n/m²/s

(3) Experimental devices

Figure 6.1.3 shows a diagram of the experimental set-up. The j×B sensor is installed in a capsule of JMTR. The position of the sensor in the capsule is about 0.235 m lower than the center of the reactor-core. The capsule is filled with He gas (about 2 atm.) and its pressure is regulated to keep the temperature of ~ 200 °C at the strain gauge. The temperature near the strain gauge is monitored by a thermocouple (K-type). Two solenoid coils generate the magnetic field from 0 to 250 Gauss near the sensing coil. The current of solenoid coils is supplied by a constant current power supply. The current of the sensing coil is 1 A, which is supplied by the constant current power supply. This coil is slightly tilted when the magnetic
field is applied by the solenoid coils. A torque acting on the sensing coil is detected by the load cell. The output of the load cell is shown on the display of strain-gauge amplifier. The bridge voltage of load cell is kept at 5 V, which is supplied by a constant voltage power supply with amplifier and display. In all measurements, the commercially available strain gauge amplifier (WGA-710A-4 : Kyowa Electric Instruments Ltd.) was used. The zero-level drift was subtracted from the output of the load cell.

(4) Measurements

Before the irradiation experiment, the zero-level drift of the output of the load cell, the temperature dependence of the output of the load cell, linearity of the output of the load cell against the weight and sensitivity of the sensor versus magnetic field in different temperature were measured [6.1.7]. Also, just before irradiation, linearity of the sensitivity and the magnetic dependence of the sensitivity were measured in the capsule filled with He gas at room temperature.

6.1.4 Experimental results

The sensitivity and linearity of the sensor were obtained in gradual power-up phase and in full-power phase. The current of the sensing coil is fixed to 1A in all tests. This current was chosen so that the maximum movement of the edge of the sensing coil frame by tilting is about 0.2mm, i.e. ~ 1/5 of the 1mm gap between the edge of the sensing coil frame and the heat sink in Fig.6.1.1 in the external magnetic field of 250 Gauss. An external magnetic field was applied by two solenoid coils. A standard gauss meter was used to calibrate the magnetic field generated by the solenoid coils and a calibration curve of the magnetic field was obtained against the current of solenoid coils. During the test, the solenoid coils was excited first and after that the sensing coil was excited for a short time (a few second). This process (ramp-up and ramp-down of the current of the coils) was repeated at each magnetic field. Two constant power supplies were used to keep the currents of the solenoid coils and the sensing coil. The externally applied magnetic field was discretely changed from 0 to 250 Gauss. Figure 6.1.4 shows the sensitivity of the sensor versus the external magnetic field at different neutron fluences. The sensitivity was obtained by using the output of the sensor subtracted zero-level drift. A non-linearity was observed as in pre-irradiation tests. In this figure, the
deviation of the sensitivity from the fitting line is less than 6 %. After reactor operation start, the change of the sensitivity was small up to a fluence of about $8.1 \times 10^{20}$ n/m$^2$ as shown in Fig.6.1.5 (a) (sensitivity of the sensor as a function of neutron fluence in different magnetic fields). In this phase, the temperature near the strain gauge which was measured with a thermocouple was gradually increased. At full power, its temperature was kept constant, but its value was 110–117 °C because that the temperature could not be raised to 200 °C due to trouble in the temperature regulation system of the JMTR capsule. In the full power region, the sensitivity indicates a gradual decrease with a fluence up to the fluence of about $2.8 \times 10^{23}$ n/m$^2$ as shown in Fig.6.1.5 (b). The maximum decrease rate compared with that of pre-irradiation is about 30 % at a neutron fluence of (1.8– 2.8)×10$^{23}$ n/m$^2$ in the high magnetic field. Beyond this fluence, the sensitivity was increased gradually in the high magnetic field or kept constant in low magnetic field. Resistances of strain gauges were increased up to a fluence of about $7.3 \times 10^{22}$n/m$^2$ after keeping constant temperature (110–117 °C ) in full power operation of JMTR. After that, resistances were decreased with a neutron fluence as shown in Fig.6.1.6. In this figure, an initial increase of resistances is due to temperature rise by reactor power-up (up to a fluence of about $9.5 \times 10^{21}$ n/m$^2$). The resistances of strain gauges are included the resistance of lead wires (MI-cables). The resistance of the Al$_2$O$_3$ insulator between strain gauges and sensor beam (SS316L), which includes the resistance of MgO insulator of MI-cable, was kept at more than 10 MΩ during irradiation. The irradiation test has been completed on March 23 in 2001. The total fluence in 3 cycles of irradiation tests was $\sim 1 \times 10^{24}$ n/m$^2$.

6.1.5 Discussion

Influence of the neutron fluence on the sensitivity and linearity of the j×B magnetic sensor was investigated. The linearity of the sensor appears to be slightly improved with increasing fluence due to decreasing sensitivity as shown in Fig.6.1.4. The reason of the behavior of the sensitivity as shown in Fig.6.1.5 is not clear yet, but the decrease of the sensor sensitivity may be due to the change in resistance of the strain gauges and/or the increase of the Young's Modulus of the stainless steel which is used in the sensor beam by some effect of neutron irradiation. The Young's Modulus of the stain-less steel increases with neutron
fluence and its increasing saturates in Ref. 6.1.8.

6.1.6 Conclusion

A non-linearity was observed against weight and magnetic field in neutron irradiation tests as well as in pre-irradiation tests. The deviation of the sensitivity from the fitted line was less than 7 % in the present \( j \times B \) magnetic sensor. The sensitivity was decreased by \( \sim 30 \% \) compared with that before irradiation at a neutron fluence of \( (1.8 \sim 2.8) \times 10^{21} \text{ n/m}^2 \) in the high magnetic field.

6.1.7 Remaining issues

It is necessary to make a further improvement for the prototype sensor, for example, improvement of linearity, reproducibility, decrease of sensitivity, etc. The \( j \times B \) magnetic sensor may be able to be used in the radiation environment of ITER-FEAT although its sensitivity was decreased by neutron irradiation in the present work. In the actual application, it may be necessary to execute an in-situ calibration of the sensitivity by using externally applied magnetic fields.
References


Fig. 6.1.1 Schematic diagram of the jxB magnetic sensor.

Fig. 6.1.2 Strain gauges bonded on the sensor beam and the electrical bridge formed by the 4 strain gauges.
Fig. 6.1.3 Diagram of the experimental set-up of the $j \times B$ magnetic sensor in the neutron irradiation test in JMTR.

Fig.6.1.4 Dependence of the sensitivity of the $j \times B$ magnetic sensor on the magnetic field in different neutron fluences.
Fig. 6.1.5 (a) Sensitivity of the $j \times B$ magnetic sensor versus neutron fluence in different magnetic fields. The horizontal axis is logarithmic scale.
Fig. 6.1.5 (b) Sensitivity of the j×B magnetic sensor versus neutron fluence in different magnetic field. The horizontal axis is linear scale, and the expanded graph in full power region in Fig.6.1.5 (a).
Fig.6.1.6 Resistance of strain gauges between each terminal versus neutron fluence.
7. Window Seal

7.1 Gamma-ray Irradiation Test on Window Seal

Tatsuo Sugie, Satoshi Kasai, Takeo Nishitani, Shigeru Tanaka, Toshiaki Yagi and Noriko Yokoo

7.1.1 Objective

A vacuum window seal with a mechanical seal method has been developed by Japan Atomic Energy Research Institute for ITER diagnostics [7.1.1]. The window seal realize the vacuum seal by pressing the metallic ring plate on the window materials such as quartz, ZnSe, etc. instead of welding. The non-welding seal has many advantages to the conventional welding seal; e.g. preference potential of non-radioactive material, neglect of thermal stress caused by difference in the thermal expansion properties.

The objective of this irradiation test is to confirm that the window seal maintains the vacuum seal under gamma-ray irradiation. Here, we carried out the irradiation test with a vacuum window seal for ZnSe.

7.1.2 Specimen

The structure of the vacuum window seal for ZnSe (hereafter ZnSe-window) is shown in Fig. 7.1.1 schematically. The vacuum seal is realized by pressing the ring plate on the edge of the window material. The plate is composed of a titanium plate with a thickness of 0.8 mm put between copper plates with a thickness of 0.1 mm. A detailed drawing of the ZnSe window is shown in Fig. 7.1.2.

The specifications of the ZnSe window are as follows.

- Material of ZnSe window: ZnSe
- Effective diameter of window: 100 mm
- Diameter: 203 mm
- Vacuum Seal Method: mechanical seal with ring plate
- Vacuum Seal: He Leak < $1 \times 10^{-10}$ Pa m$^3$/s  
- Capacity to Resist Inner Pressure Rise: 5 atm  
- Mechanical acceleration of structure: > 15g, duration 10 ms, 1000 cycles  
- Temperature: 20 - 200 °C  
- Temperature ramp rate: > 20 °C /hr,

7.1.3 Experimental condition

The ZnSe-window was installed in front of the gamma-ray source of the $^{60}$Co gamma ray irradiation facility in JAERI Takasaki as shown in Fig. 7.1.3. The inside of the ZnSe-window was evacuated by a turbo-molecular pump located outside the irradiation room. In order to carry out vacuum leak tests during the irradiation, He-gas was blown on the ZnSe-window by using a pipe from the outside of the irradiation room. The picture of the ZnSe-window installed in the irradiation room is shown in Fig. 7.1.4. The leak tests were carried out by using a He-leak detector as shown in Fig. 7.1.3. The gamma-ray flux was measured to be $1.01 \times 10^6$ R/hr at the ZnSe-window.

7.1.4 Experimental results

There were no vacuum leak during ten month of gamma ray irradiation with a flux of $1.01 \times 10^6$ R/hr. There were some irradiation breaks because of maintenance of the facility. Unfortunately, a He-leak of $2 \times 10^{-5}$ Pa m$^3$/s was detected at a dose of about $6.3 \times 10^9$ R.

7.1.5 Discussion

The ZnSe-window had maintained the vacuum seal up to a dose of $6.3 \times 10^9$ R with a flux of $1.01 \times 10^6$ R/hr. It will be sufficient for the requirements of ITER. But, it is very difficult to identify whether the vacuum leak was caused by the effect of the gamma ray irradiation.
7.1.6 Conclusion

Gamma-ray irradiation tests of the vacuum window seal for ZnSe had been carried out at the $^{60}$Co gamma ray irradiation facility in JAERI Takasaki. The window seal maintains the vacuum seal up to the sufficient fluence for ITER’s requirement. But it is not clear if the vacuum leak was caused by the gamma-ray irradiation. More tests will be necessary.

7.1.7 Remaining issues

It will be necessary to identify the origin of the vacuum leak. It will be useful to compare this result with the lifetime test of the window.

Here, we carried out the irradiation test for the ZnSe-window. Irradiation tests for the other window with different window materials such as quartz will be necessary.

References

Fig. 7.1.1 Schematic cross section of the vacuum window seal for ZnSe.

Fig. 7.1.2 Detailed drawing of the vacuum window seal for ZnSe.
Fig. 7.1.3 Experimental setup of the $^{60}\text{Co}$ gamma-ray irradiation test for the ZnSe-window seal.
Fig. 7.1.4 Vacuum window seal of the ZnSe set in front of the $^{60}$Co gamma-ray source.
8. Optical Feed-through

8.1 Gamma-ray Irradiation Test on Optical Feed-through

Tatsuo Sugie, Satoshi Kasai, Takeo Nishitani, Shigeru Tanaka, Toshiaki Yagi and Noriko Yokoo

8.1.1. Objective

In order to relay optical images from just outside the diagnostics port to the diagnostic equipment through the cryostat vacuum boundary, it will be favorable to use an optical fiber bundle in the visible and IR region in ITER. There are two advantages as follows.

i) The optical fiber bundle relays optical images through the narrow labyrinth, which is provided to prevent neutron stream, without a relay optics composed of lenses and mirrors.

ii) The problem of the displacement of the optical axis that is caused by the thermal distortion and the electromagnetic force of the diagnostic port will be evaded by using the optical fiber bundle easily.

In this situation, it is necessary to use an image transmission system through the vacuum boundary. As one of the image transmission systems, a multi-channel optical fiber feed-through has been developed for visible and IR light transmission lines through the vacuum boundary [8.1.1].

The objective of this irradiation test is to confirm that the optical fiber feed-through maintains the vacuum seal under the gamma ray irradiation.

8.1.2. Specimen

The optical fiber feed-through has transmission lines of 57 channels on a vacuum flange. The transmission lines were improved in order to achieve a good transmission and uniformity among the channels by using a fiber rod of a diameter of 2.5 mm. Each fiber rod, which is composed of a core, clad and jacket, was made by the same method as the optical fiber. The
structure is shown in Fig. 8.1.1. The rod is soldered on the vacuum flange by a high temperature solder (sp-27) as shown in Fig. 8.1.2. A schematic view of the partial cross section of the optical fiber feed through and the connector is shown in Fig. 8.1.3.

The specification of the optical fiber feed-through is summarized as follows.

- Material of fiber core: Fused quartz
  - Diameter of fiber core: 200 μm
  - Number of transmission channel: 57
  - Vacuum Seal Method: Nickel/Gold plated fiber rod+
    - Vacuum Seal: High temperature solder (sp-27)
    - Capacity to Resist Inner Pressure Rise: He Leak < 1 x 10^{-10} Pa m^3/s
    - Mechanical acceleration of structure: 5 atm
    - Temperature: > 15g, duration 10 ms, 1000 cycles
    - Uniformity among each channel: 20 - 200 °C
    - Maximum connecting loss per channel: 60 % (target)
    - Connector: 3 dB (target)
    - For remote handling

8.1.3 Experimental condition

The optical fiber feed-through was installed in front of the gamma-ray source of the 60Co gamma-ray irradiation facility in JAERI Takasaki as shown in Fig. 8.1.4. Inside the optical fiber feed-through was evacuated by a turbo-molecular pump located outside the irradiation room. In order to carry out vacuum leak tests during the irradiation, He-gas was blown on the optical fiber feed-through by using a pipe from the outside of the irradiation room. The leak tests were carried out by using a He-leak detector as shown in Fig. 8.1.4. The dose rate of was measured to be 1.23 x 10^6 R/hr at the center of the optical fiber feed-through.

8.1.4 Experimental results

A He-leak of 8 x 10^{-7} Pa m^3 / s was detected after 15 hours and 36 minutes from the start of the irradiation. Unfortunately, we could not identify the time when the leak occurred,
because the leak test had not been carried out before the time of the first leak test. It is clear
only that the leak was occurred at the dose of less than $2 \times 10^7$ R.

8.1.5 Discussion

Before the irradiation test, a green deposit was observed on the solder connecting the
vacuum flange and the fiber rod as shown in Fig. 8.1.5. But, we could not detect a He-leak
before the irradiation. After the irradiation test and detecting the He-leak, we found the
deposit had grown a little. The main ingredients of the deposition were measured to be Ni, Cl,
Zn, Al and Si by an x-ray analyzer. From this result, the deposition is assumed to be the
chloride of nickel. It is supposed that nickel plated on the fiber rod became nickel chloride by
reacting with the chloride, which is one of the components of the flux for soldering, since the
flux had remained on the solder. The reaction and the oxidation of nickel seem to be assisted
by the gamma ray irradiation.

8.1.6 Conclusion

The vacuum seal of the optical fiber feed-through was tested under $^{60}$Co gamma-ray
irradiation. A vacuum leak was detected. The leak seems to be caused by the chemical
reaction of nickel plated on the fiber rod to chloride contained in the flux under the gamma
ray irradiation.

8.1.7 Remaining issues

It will be necessary to remove the flux completely after soldering or to develop
another connecting and vacuum sealing method between the fiber rod and the flange made of
stainless steel.

References
[8.1.1] T. Sugie, T. Toriya and S. Kasai, “Development of Multi-channel Optical Fiber Feed-
Fig. 8.1.1 Fiber rod. (Core: Fused quartz, Clad: F-doped fused quartz, Jacket: Fused quartz) Fiber rod made by the same method as the optical fiber. The rod is plated with Ni and Au.

Fig. 8.1.2 Schematic view of the part of the optical fiber feed-through. There are 57 transmission lines on the vacuum flange.
Fig. 8.1.3  Partial cross section of the optical fiber feed-through and the connector.
Fig. 8.1.4 Experimental setup of the $^{60}$Co gamma-ray irradiation test for the optical fiber feed-through.

Fig. 8.1.5 Green deposition observed on the solder gluing the vacuum flange and the fiber rod.
9. Optical-fiber Current Transformer using Sagnac Interferometer

9.1 On-line Irradiation Tests on Sensing Fiber of Optical-fiber Current Transformer

Satoshi Kasai, Isamu Sone, Mitsushi Abe, Takeo Nishitani, Shigeru Tanaka, Toshiaki Yagi, Noriko Yokoo and Shin Yamamoto

9.1.1 Object

Measurements of magnetic field and plasma current are very important issues for long-pulse or steady state operation in ITER-FEAT. It is difficult to measure the field or current with high accuracy due to a zero-level drift of an integrator and/or radiation induced electromotive force (RIEMF) using conventional methods, i.e. magnetic pick-up coil, Rogowski coils with the integrator. The objective of this irradiation test is to investigate the possibility of a new type of current measurement method using an optical-fiber current transformer in a gamma-ray irradiation field.

9.1.2 Specimen

Specifications of an optical fiber, i.e. sensing fiber are shown in Table 9.1.1. The materials of core and clad of the optical fiber are pure silica. This fiber is a commercially available fiber (Oxford Electronics Ltd.). It is a low birefringence fiber, which can propagate optical radiation preserving the state of polarization for long distances. Ideally this means that the fiber must have perfect geometry and be completely symmetrical along the optical axis. It must also be homogeneous along the axis. Any linear polarization can be represented by two linear polarizing modes orthogonal to each other. An ideal low birefringence fiber will propagate these two modes with ideal velocity. In a real fiber, there are a number of imperfections such as ellipticity, eccentricity, microbending, bending etc. Such imperfections lead to a difference in velocities between the two polarization modes of the fiber and hence a
phase-difference between them. The low birefringence fiber has very low phase-difference, which is not a linear function of length. This type fiber can be used as a Faraday rotation sensor.

As shown in Fig. 9.1.1 (a), the fiber (type: LB800) for short wavelengths ($\lambda = 850$ nm) has an acrylate coating layer 220 $\mu$m thick outside the clad. The jacket has an inner plastic tube surrounded by kevlar strands and an outer low smoke zero halogen jacket. The diameter of the optical fiber core is 3 mm. The maximum temperature is 100 °C. Another fiber (type: LB1500) for long wavelengths ($\lambda = 1550$ nm) is shown in Fig. 9.1.1 (b). This fiber cord with an inner plastic tube outside the coating layer is installed in a stainless-steel tube (SS 304) with 1 mm in inner diameter and 1.4 mm of outer diameter. The transmission fibers except the sensing fiber are polarization preserving fibers.

9.1.3 Experimental condition

(1) Irradiation facility

The sensing fiber for the optical-fiber current transformer was irradiated in the $^{60}$Co irradiation facility in JAERI Takasaki. The arrangement of the gamma-ray source, optical fiber current transformer and measurement apparatus are shown in Fig. 9.1.2. The $^{60}$Co source with an intensity of 115 kCi (4286 TBq) is stored in a water pool. The source is lifted into the irradiation room. The irradiation room is shielded with 1.3 m thick heavy concrete walls.

(2) Irradiation condition

The optical fiber was wound in two turns on the cylindrical metal-mesh-fence which is located outside the $^{60}$Co source lifted from the water pool as shown in Fig. 9.1.3. The diameter of the fence is $\sim 0.76$ m. The length of the irradiated fiber is $\sim 4.8$ m. The dose rate at the optical fiber position is evaluated to be $\sim 17$ kGy/h. A solenoid coil (No.1) is put near the gamma-ray source to generate a magnetic field around the sensing fiber in the irradiation region. The sensing fiber crosses the solenoid coil. The No.2 solenoid coil is put outside the irradiation region, and also the finer crosses the coil.

(3) Experimental devices

The principle of the current measurement using the optical-fiber current transformer is based on the magnetic–optical effect, i.e. Faraday effect in the magnetic optical materials.
The plane of the linear polarization propagating into the magnetic optical materials put in the magnetic field is rotated. In a conventional optical current transformer, a rotating angle measurement of the linear polarized light was used. The new type is based on the measurement of the phase difference between circular polarized lights propagating in the optical fiber in the clockwise direction and in the counterclockwise direction using the Sagnac interferometer. The details of the principle and system are described in Refs. [9.1.1-9.1.6]. In order to demonstrate the optical-fiber current transformer, performance tests were carried out using the Hitachi tokamak (HT-2) discharges [9.1.1].

Brock diagram of the optical-fiber current transformer and experimental set-up are shown in Fig. 9.1.4. This system consists of the sensing fiber, the solenoid coil that generates the magnetic field around the sensing fiber and the Sagnac interferometer. The light source of the interferometer is a super luminescent diode (SLD) with 780 nm, and an auto power controller (APC) is used to keep the detected light-intensity constant. Light from the light source becomes linear polarized light by a fiber polarizer. At a fiber coupler, the linear polarization light is separated into two linear-polarized beams. One is propagated in the clockwise direction and another is propagated in the counterclockwise direction. These lights are converted into the circular polarized light through the $\lambda/4$ phase-plate and are propagated in the sensing fiber. The two propagating light are coupled at the fiber coupler. The intensity of the interference light was detected by a photo diode and the phase difference between two lights was evaluated from the intensity. A phase modulator, that is a piezoelectric transducer (PZT) with a wound fiber on it and is driven by a PZT-driver with 22 kHz, modulates the phase of transmitted light. This is used to improve the sensitivity and resolution for small phase differences. A dummy fiber makes up for a deficiency of modulating intensity. The sensing fiber is a pure silica fiber with low birefringence. The other fibers are a polarization-preserving fiber. The solenoid coil along the sensing fiber as shown in Fig.9.1.3 generates the magnetic field. The number of turns is 4000 and the current is 1 A. A polyimide-coated wire was used.

(4) Measurements

The measurement system in the irradiation test is shown in Fig.9 1.4. The photo detector detected the intensity of the interference light from the optical-fiber current transformer and the intensity of the light was monitored using an optical power meter (Ando
Electric Co. Ltd., AQ-2105B). These outputs and the current of the solenoid coil were put in a digital multi-meter (Keithley Ltd., 2000 Multimeter), which was used as a data logger. All data were acquired by a personal computer. Two sensing fibers (model: LB800) for λ = 850 nm were irradiated. Sensing fiber No. 1 was irradiated for a long time (about 1230.4 hrs.). Total dose was about 20.9 MGy. In this test, solenoid coil No. 1 in the irradiation region was excited. Sensing fiber No. 2 was irradiated for about 424.9 hrs, and the total dose was about 7.2 MGy. Solenoid coil No.1 in the irradiation region and solenoid coil No.2 outside irradiation region were excited to investigate the polarization properties of light propagating in the fiber. The model LB1500 sensing fiber for λ = 1550 nm was irradiated for about 424.9 hrs, and the total dose is about 7.2 MGy. In this fiber, a transmission loss of a light was observed.

9.1.4 Experimental results

(1) Sensing fiber: Model LB800 (λ = 850 nm)

(a) Sensing fiber No.1

The No.1 sensing fiber of the model LB800 was irradiated during exciting the solenoid coil No.1 with 1989 AT coil current. The transmission loss of the polarized light, i.e. the output of the optical-fiber current transformer (CT) was obtained by an in-situ measurement. The output of the optical-fiber CT began to decrease just after about 5 minutes from irradiation start. Figure 9.1.5 shows decreasing of the output with time for 600 minutes after about 7 hrs irradiation (The solenoid coil No.1 current is 1989 AT). The output was gradually decreased with time and its reduction rate was about 1/22 of the non-irradiation fiber.

(b) No.2 sensing fiber

In tests of the sensing fiber No.2 of the model LB800, irradiation and non-irradiation were repeated as shown in Fig. 9.1.6. The current of the No.1 and No.2 solenoid coils is 2000 AT, respectively. Figure 9.1.7 shows the change of the output of the optical-fiber CT using the No.2 sensing fiber (model LB800) before irradiation. It was nearly constant within 10 mV peak-to-peak, i.e. the sensitivity of the optical-fiber CT was constant. During 10 minutes irradiation (total dose ≡ 2.8 kGy), the output of the optical-fiber CT was monitored in the
cases the No.1 coil and No.2 coil excited alternately. The output of the optical-fiber CT decreased during irradiation but its reduction was stopped without irradiation in the case of the No.1 coil excitation as shown in Fig. 9.1.8. In the case of the No.2 coil excitation, the output kept the level before irradiation, i.e. there was no reduction of the sensitivity of the non-irradiation part of the sensing-fiber. There may be no change of the polarization-light-transmission property of the sensing fiber located in the irradiation region at low dose. During 20 and 60 minutes irradiations, the output of the optical-fiber CT in the case of the No.1 coil excited approached a zero level described by the dotted line as well as 10 minutes irradiation as shown in Fig. 9.1.9. On the other hand, the output was gradually increased with increase of the gamma dose in the case of the No.2 coil excitation. This may be due to a change of the polarization of the light propagating along the sensing fiber installed in the irradiation region.

(2) Sensing fiber Model LB1500 ($\lambda = 1550$ nm).

The optical-fiber current transformer for the sensing fiber (model LB1500) for long wavelengths ($\lambda = 1550$ nm) is under development. So, only the sensing fiber was irradiated to investigate the transmission loss of the non-polarized light. The optical transmission at a wavelength of $\lambda = 1550$ nm was decreased with time by gamma irradiation. After about 30 minutes irradiation, it was reduced to about 66 % of the initial level (~5.1 $\mu$W) before irradiation. When the irradiation was stopped, the reduction of the optical transmission was stopped and it was slightly increased. Figure 9.1.10 shows the time dependence of the optical transmission after ~ 19 hrs of irradiation. The optical transmission was decreasing with time. The spikes in this figure indicate the data during irradiation stop. The level of the optical transmission after 49 hrs from irradiation start (in this figure, after 30 hrs) is ~ 45 % of the initial level (~ 5.1 $\mu$W). At this point, the total dose is about 1 MGy. In this measurement, the light source was operated in the constant current mode to check the optical transmission of the sensing fiber. However, the light source should be used to keep the light intensity constant for the actual optical-fiber CT. The commercially available sensing fiber (model LB1500) may be used in the gamma irradiation environment up to 1 MGy.
9.1.5 Discussion

The present sensing fiber is a low birefringence fiber in which circular polarized light can propagate preserving the state of polarization. However, in the real sensing fiber, an ellipsoidal polarized light propagates. For this fiber, the sensitivity of the optical-fiber CT may be decreased by generating dispersion of the polarization mode in the fiber as a result of the local birefringence of the sensing fiber caused by gamma-ray irradiation.

9.1.5 Conclusion

(1) The sensitivity of the sensing fiber (model LB800) for the optical-fiber current transformer, Sagnac interferometer, was decreased by the gamma-ray irradiation.

(2) It may be possible to measure the current by a Sagnac interferometer using the sensing fiber (model LB1500) for long wavelength.

9.1.6 Remaining issues

It is necessary to develop a radiation-resistive optical-fiber for the Sagnac interferometer. The transmission properties of the polarized light in the sensing fiber, for example Verdet constant that indicate the coefficient of the Faraday effect should be investigated in detail.

References

Table 9.1.1 Specification of optical fibers for the optical current transformer.

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<td>5.0μm/125μm</td>
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Fig.9.1.1 The sensing fibers of the optical-fiber current transformer, for short wavelengths ($\lambda=850$ nm) (a) and for long wavelengths ($\lambda=1550$ nm) (b).
Fig.9.1.2 Gamma-ray irradiation facility in JAERI Takasaki.
Fig. 9.1.3 Set-up of the sensing-fiber irradiation test.
Fig. 9.1.4 (a) A diagram of the optical-fiber current transformer.
Fig.9.1.4 (b) A detailed diagram of the data processor of the current transformer.
No.1 coil current = 1989 AT

Sensing Fiber (λ=850 nm) No.1

Output of Optical CT (V)

Excited Coil: No.1

Output = 0

Time (min.)

Fig.9.1.5 Time dependence of the output of optical-fiber CT for 600 minutes after 7 hrs irradiation.
Fig. 9.1.6 Gamma-ray irradiation scheme of the sensing fiber (model LB800) for short wavelengths.

Fig. 9.1.7 Change of the output of the optical-fiber CT using the sensing fiber No.2 (model LB800, $\lambda$=850 nm) before irradiation.
Fig. 9.1.8 Time dependence of the output of the optical-fiber CT in the cases of coil No.1 excited and of coil No.2 excited during gamma-ray irradiation for 10 minutes and irradiation stop. The sensing fiber is No.2 (model LB800, λ=850 nm).
Fig.9.1.9 The output of the optical-fiber CT in the cases of coil No.1 excited and of coil No.2 excited during 60 minutes irradiation. The sensing fiber is No. 2 (model LB800, λ=850 nm). Coil current is 2000 AT.
Fig.9.1.10 Time dependence of the optical transmission of the sensing fiber (model LB 1500, \(\lambda=1550\) nm) during irradiation. The spikes on the graph indicate the transmission during irradiation stop. The optical transmission at 30 hrs is about 45% of the initial level. At this point, the gamma-ray dose is about 1 MGy.
10. Conclusion

In the development of the diagnostics for ITER, radiation damage of diagnostic components is one of the most important issues. We have carried out irradiation tests on a number of diagnostic components under fission neutrons, gamma-rays and 14 MeV neutrons.

UV range transmission losses of a KU-1 quartz were measured during 14 MeV neutron irradiation at FNS with neutron fluences of up to $7.4 \times 10^{19}$ n/m$^2$ and also during $^{60}$Co gamma-ray irradiation up to ~1MGy. Significant transmission losses were observed in the wavelength range of 200-300 nm. In the ITER, the transmission loss should be calibrated frequently by in-situ technique.

Five kinds of ITER round robin fibers were irradiated in JMTR and the $^{60}$Co gamma-ray irradiation facility. The induced transmission losses of those fibers are much smaller those that of pure SiO$_2$ core fibers. Especially, KS-4V, KU-H2G and F-doped fibers have rather good radiation hardness even in the visible range. Those fibers might be available just outside of the vacuum vessel in ITER, where the fast neutron fluence is expected to be ~$10^{21}$ n/m$^2$.

The mica substrate bolometer was irradiated in JMTR up to 0.1 dpa. Significant increase in the meander resistance from 275 Ω to 446 Ω was observed during 45 days at constant reactor power, which might be caused by the nuclear transmutation of gold into mercury. During the cool down phase of the first cycle all connections went open circuit. The use of gold meanders might be problematic in ITER.

The USA and Japan carried out the experiments, collaboratively designing coils, selecting materials, fabricating MI-cables, manufacturing coils, making an irradiation rig, and measuring the performance of coils. A drift of 10 - 40 mVs was observed with a digital long term integrator, however, which might be caused by not only RIEMF but also drift inside the integrator itself. ITER-relevant magnetic coils could be made with MI-cables, whose electric drift for 1000-s integration is less than 0.5 mVs. From the results of the gamma-ray irradiation
tests for the magnetic probes, the RIEMF in the differential voltage between both ends of the center lead might be negligible for the magnetic measurement on ITER-FEAT.

The dependences of sensitivity and linearity of the jxB magnetic sensor on neutron fluence was investigated during the JMTR irradiation. A non-linearity was observed against weight and magnetic field in neutron irradiation tests as well as in pre-irradiation tests. The deviation of the sensitivity from the fitted line was less than 7 % in the present jxB magnetic sensor. The sensitivity was decreased by ~30 % compared with that in before irradiation at a neutron fluence of (1.8– 2.8)×10^{23} n/m\(^2\) in the high magnetic field. It is necessary to make a further improvement for the prototype sensor.

A V-shaped window seal was tested under \(^{60}\)Co gamma-ray irradiation. Mainly SCCG (Sub-Critical Crack Growth) on mechanical properties of the window assemblies with quartz and ZnSe were examined. Up to the dose of ~100MGy, no vacuum leak of the window assemblies was observed. Those window assemblies are applicable to ITER in terms of radiation hardness.

A multi-core optical fiber feedthrough was also tested under \(^{60}\)Co gamma-ray irradiation. Mainly vacuum tightness was examined. A vacuum leak occurred at the solvent between fibers and the metal flange within the irradiation dose less than 1 MGy. A solvent for optical fibers with a radiation hardness should be developed.

The characteristics of the optical-fiber current transformer were investigated during \(^{60}\)Co gamma-ray irradiation. The sensitivity of the optical-fiber current transformer was decreased by gamma-ray irradiation dramatically within only 1- 2 kGy. The development of a low birefringence fiber with radiation hardness is required for the ITER application.
Acknowledgment

The authors would like to express their gratitude to the operating staff of JMTR, FNS and $^{60}$Co irradiation facility for their operation of those facilities. This report has been prepared as an account of work assigned to the Japanese Home Team under Task Agreement number G55TT05 FJ within the Agreement among the European Atomic Energy Community, the Government of Japan, the Government of the Russian Federation, and the Government of the United States of America on Cooperation in the Engineering Design Activities for the International Thermonuclear Experimental Reactor ("ITER EDA Agreement") under the auspices of the International Atomic Energy Agency (IAEA).
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国際単位系 (SI) と換算表

### 表1 SI基本単位および補助単位

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<td>ボルト</td>
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原子質量単位 u

### 表3 固有の名称をもつSI組立単位

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(86年12月26日現在)