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IRRADIATION TESTS OF A CAVITY CORE MATERIAL AND GaN DEVICES IN J-PARC MAIN RING

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Abstract

Magnetic-alloy cavities have been used in several accelerators [1]. Small magnetic alloy rings were irradiated in J-PARC to evaluate the effects of radiation on the magnetic properties. Complex permeability and hysteresis curves were measured before and after irradiation. No significant variation was observed by the total ionization dose of 18 kGy and a neutron flux of $2.3{\times}10^{14}$ n/cm^2. The doses were measured using RadMon ver.6 developed by CERN. High neutron irradiation caused radio activity and radioactive nuclei in the cores were identified in this study. An attempt was also made to use RadMon in the low gain mode. This suggested that RadMon can be used at dose beyond 16 kGy. Gallium nitride devices have also been tested for future applications in accelerator tunnels. They exhibit excellent radiation hardness.

IRRADIATION TEST AT J-PARC MR

The J-PARC Main Ring (MR) delivers a 535 kW proton beam to the T2K neutrino experiment. Beam loss in the ring mainly occurs around the injection energy of 3 GeV and is localized at the beam collimators. The beam hits the collimator jaws which are surrounded by a thick iron shield. The scattered and secondary particles travel downstream through the beam pipe. A very high dose rate of about 500 Gy/week is expected near the beam pipe during high intensity beam operations [2]. The downstream of the collimator was used for irradiation experiments.

Since 2020, we have irradiated magnetic alloy materials used for RF cavities in J-PARC and CERN [3,4]. A magnetic alloy, Finemet®, material contains nano-crystals of 10 nm size. There has been interest in whether radiation in accelerators affects the properties of magnetic alloy-loaded cavities. In the CERN PS, it has been used for an instability damper cavity since 2014 under high radiation levels (~kGy). The J-PARC irradiation area received a dose several times higher. Another aim is to test GaN solid-state amplifiers for future use in improving PS RF cavity feedback [3–5]. GaN amplifier was tested under operational condition of about 300 W output power.

Radiation monitors, RadMon, have been used to measure total ionization dose, TID, and neutron flux density [6,7]. Downstream of the collimator section in the ring is shown in Fig. 1. A small magnetic alloy core was located below the RadMon1 radiation monitor in front of the solid-state amplifier and another core was located below the RadMon2 monitor. The expected dose of the experiment was higher than 10 kGy (1Mrad) which is in the range of 100 nm RadFET in a deported module of RadMon ver.6. The range of the neutron monitor was also insufficient. To estimate accurately, we used the third RadMON located outside the irradiation test area.

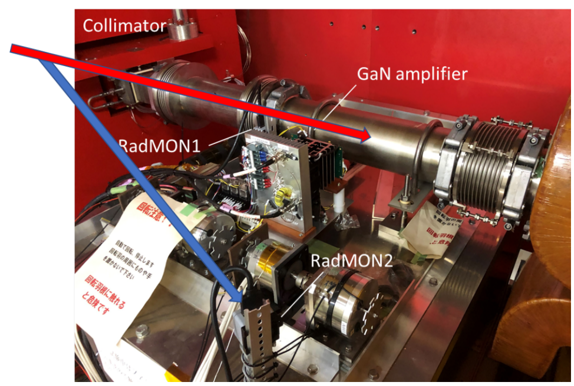

Figure 1: Irradiation test area in J-PARC Main Ring

RADIATION MONITORS

The measurement began in December, 2020. Figure 2 shows the correlation between the TID and neutron flux densities for RadMon1 and 2 [8]. RadMon1 reached the measurement range of the neutron flux density of $3{\times}10^{13}$n/cm^2 in March, 2021. Although RadMon2 was located away from the beam pipe and its TID was 4.5 times less than that of RadMON1, the neutron flux density was only half. Subsequently, the neutron flux densities were estimated from the TIDs of other RadMONs. Figure 3 shows the TID of RadMON1 and 2 until June, 2021. TID increased rapidly during high-intensity beam operation for the T2K long-baseline neutrino experiment. This increased slowly in the slow extraction mode. Long shut downs are also observed between the runs. Table 1 summarized the TID and neutron flux densities irradiated during the experiment.

Table 1: Dose Summary of Material Irradiation Test

Location	TID	Neutron Flux Density
RadMon1	18 kGy	$2.3{\times}10^{14}$n/cm^2
RadMon2	4 kGy	$1.1{\times}10^{14}$n/cm^2

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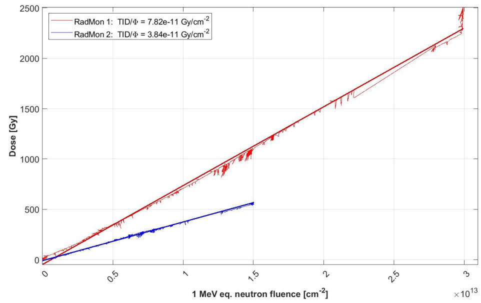

Figure 2: TID vs. neutron flux density for different locations, RadMon1 (Red) and 2 (Blue).

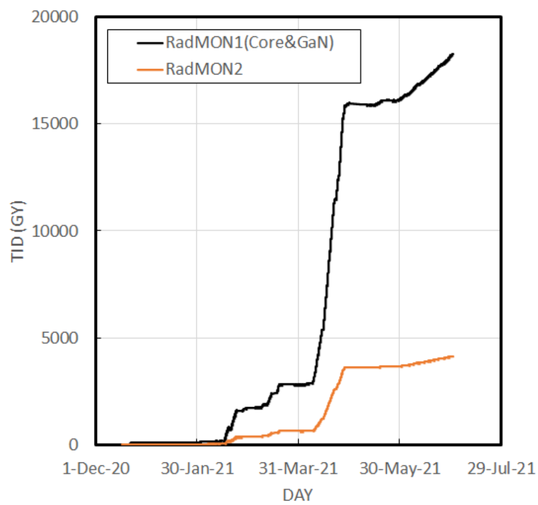

Figure 3: TIDs during irradiation test between 2020-2021.

MAGNETIC ALLOY CORES

Magnetically annealed magnetic alloy cores (Finemet® FT3L) were prepared for irradiation experiments. Cores were located below the RadMon monitors. Hysteresis and permeability were measured before and after irradiation.

Hysteresis Curve Measurements

Hysteresis curves were measured at different frequencies before and after 4 kGy and 1.0×10^{14}n/cm^2 irradiation as shown in Fig. 4. No changes were observed by the irradiation.

Permeability Measurements

The electrical properties of the cores before and after irradiation are shown in Fig. 5. The left and right figures show the inductance and resistance, respectively, before and after irradiation at 18 kGy. The permeabilities of the cores are shown in Fig. 6. The properties also showed no variation with irradiation. A TID of 18 kGy corresponds to several years of operation of the CERN PS damper cavity. The irradiation tests are going to be conducted to confirm higher radiation hardness of the material.

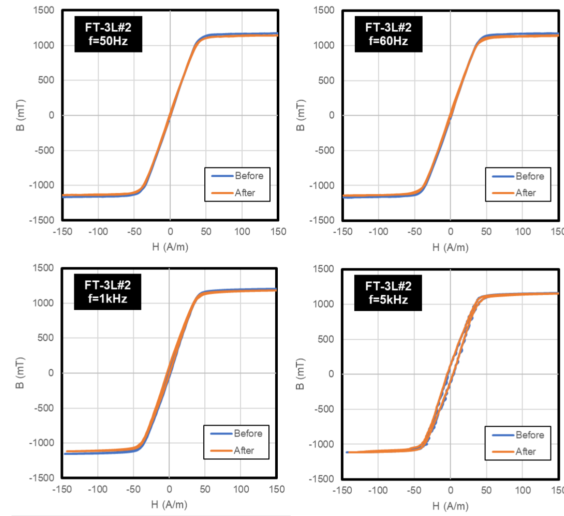

Figure 4: Hysteresis Curves of FT3L core for 50 Hz, 60 Hz, 1 kHz and 5 kHz before and after 4 kGy irradiation.

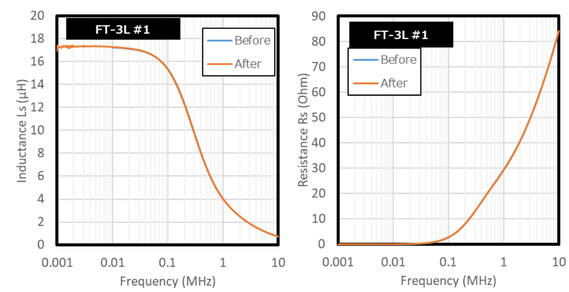

Figure 5: Inductance (Left) and resistance (Right) before and after irradiations of 18 kGy (Top).

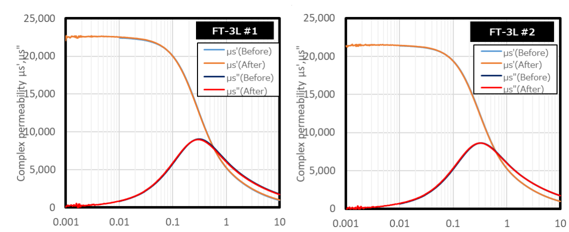

Figure 6: Permeabilities of core before and after irradiation of 18 kGy (Left) and 4 kGy (Right).

Evaluation of Radioactivity

The radioactivity of the cores was also measured using a portable radiation detector, Cambera InSpector1000. Figure 7 shows the energy spectra of gamma rays from irradiated cores and the background. It shows Mn-54 (834.85 keV) around 834.6 keV which was produced from Fe-54 in the core. The material contains small amount of Cu and Nb. The peaks around 1118 keV and 1845 keV might correspond to Zn-65 (1115.54 keV) and Y-88 (1836.06 keV) produced from Cu-65 and Nb-93, respectively. A peak at approximately 1465 keV exists in the background measurement. This is

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consistent with K-40. More precise measurements will be performed after ongoing irradiation tests.

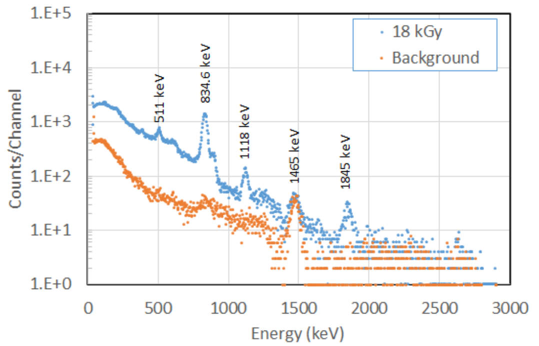

Figure 7: Energy spectra of irradiated core (Blue) and background (Red).

GALIUM NITRIDE DEVICES

Another purpose of the irradiation test was to see the stability of Galium Nitride solid-state device under heavy radiation. An amplifier using GaN, QPD1016, was located near RadMon1 as shown in Fig. 1. The output power of the amplifier was approximately 300 W with 30 % duty cycle. The amplifier gain was monitored as shown in Fig. 8. The gain was stable during the irradiation.

We also tested another GaN device, QPD1013 in 2019-2020 under idling conditions to observe the variations of biasing characteristics. No changes were observed at the TID of 30 kGy.

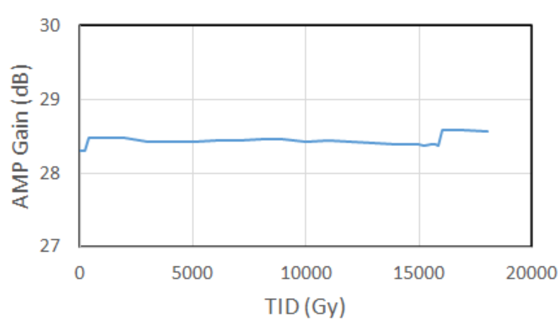

Figure 8: Amplifier gain during 18 kGy irradiation. Manual gain adjustments were seen around 0 kGy and 16 kGy.

LOW GAIN MODE OF RADMON

RadMon ver.6 has the options to measure higher and lower TIDs. One option is to apply bias to increase sensitivity. Another option is to reduce the gain. Owing to the two RadFETs on RadMON, one was used to obtain TID as shown in Fig. 2 and the other was used in the low gain mode. Figure 9 shows the response of the 100 nm RadFET with the low gain of 0.1. This suggests that RadMon ver.6 is applicable for measuring high TID beyond 10 kGy although the response was not continuous while turning off.

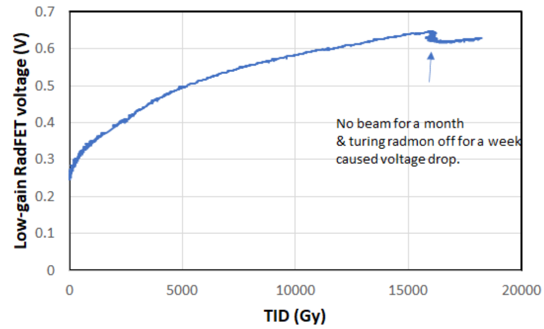

Figure 9: Response of low gain RadFET.

CONCLUSION

Irradiation tests of magnetic alloy cores and GaN amplifier were performed at J-PARC Main Ring collimator section. TID of 18 kGy and neutron flux of $2.3{\times}10^{14}$n/cm^2 were irradiated. No changes were observed in the electrical characteristics of the cores. The amplifier gain was also stable. The irradiation test of the cores is continuing.

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