Investigation of irradiation effects on highly integrated leading edge electronic components of diagnostics and control systems for the LHD deuterium operation

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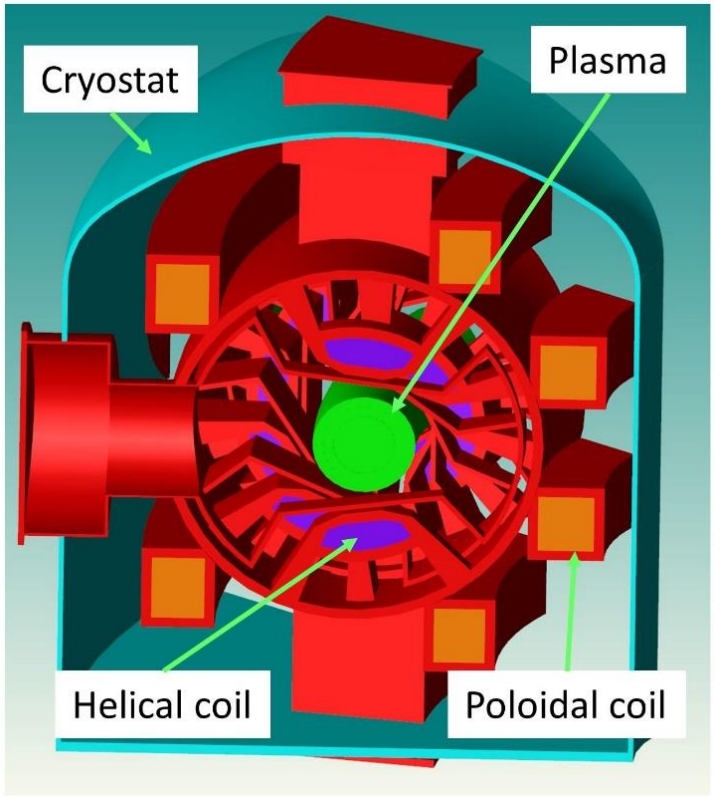
Introduction

- **Large Helical Device is controlled by means of many semiconductor integrated circuits placed around LHD in the torus hall with remote control capability.**
- **However, the radiation damage due to neutron and/or gamma-ray may lead to serious impact on those systems in deuterium campaign started from March 2017 and continues for nine years.**
- **Irradiation tests on semiconductor integrated circuits were intensively performed in the 1990s in irradiation facilities for ITER. It is reported that a programmable logic controller (PLC) was broken by 1000 Gy gamma-ray irradiation.**
- **At present, the radiation resistance of electronic components might change because of higher integration of integrated circuits compared with integrated circuits of more than 20 years ago.**
- **Therefore, the effects due to irradiation on electronic components being used currently should be investigated for control and measurement of LHD deuterium plasmas.**

MCNP calculation

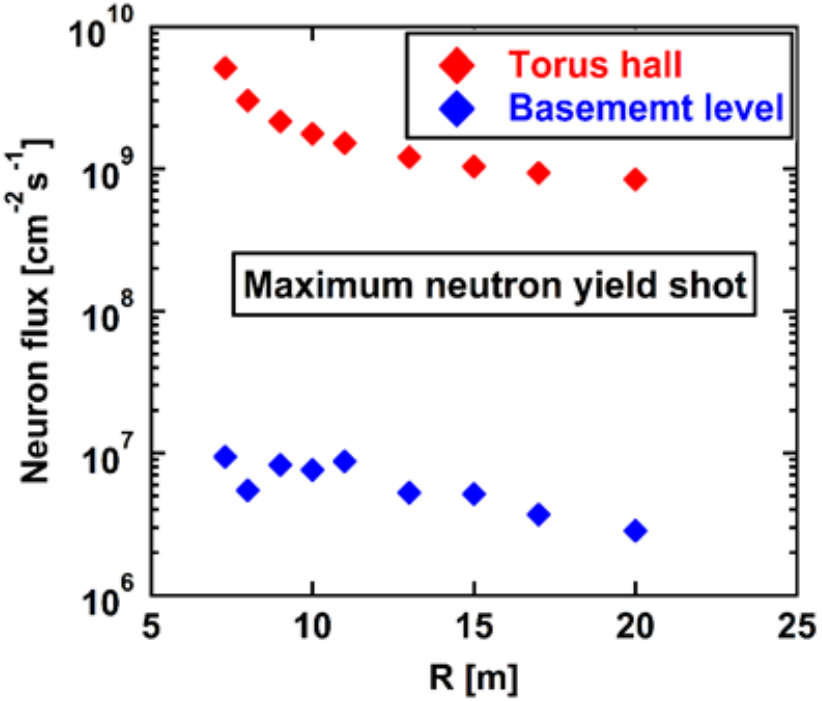
- **For precise estimation of the radiation field in the LHD torus hall, MCNP6 is used with ENDF B-VI.**
- **The geometry in one toroidal pitch angle is modelled based on the CAD drawing with some simplification.**
- **The neutron source is isotropic and homogeneous in the torus with the energy of 2.45 MeV.**

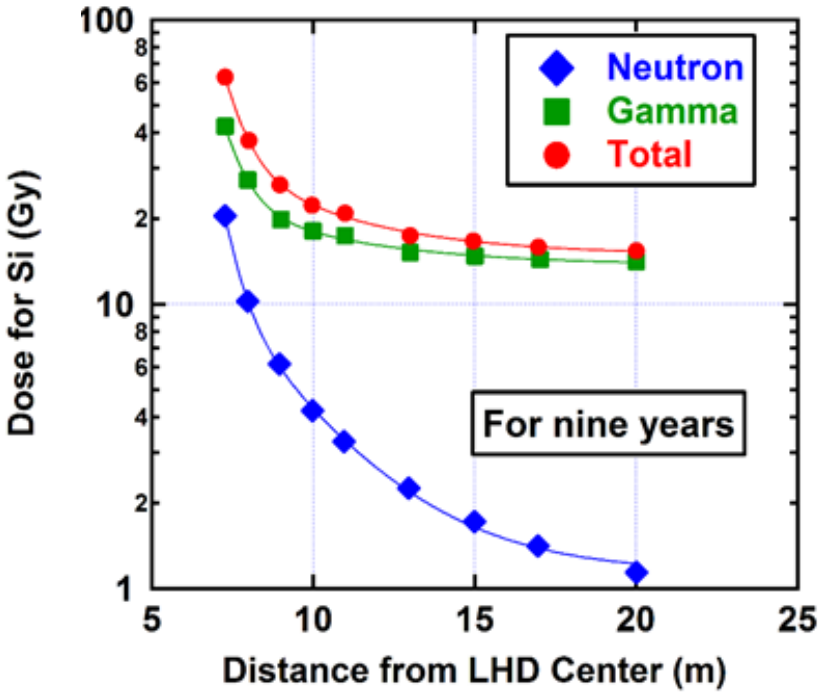
MCNP Model of LHD.



The figure is made with SuperMC

Neutron flux and Dose profile

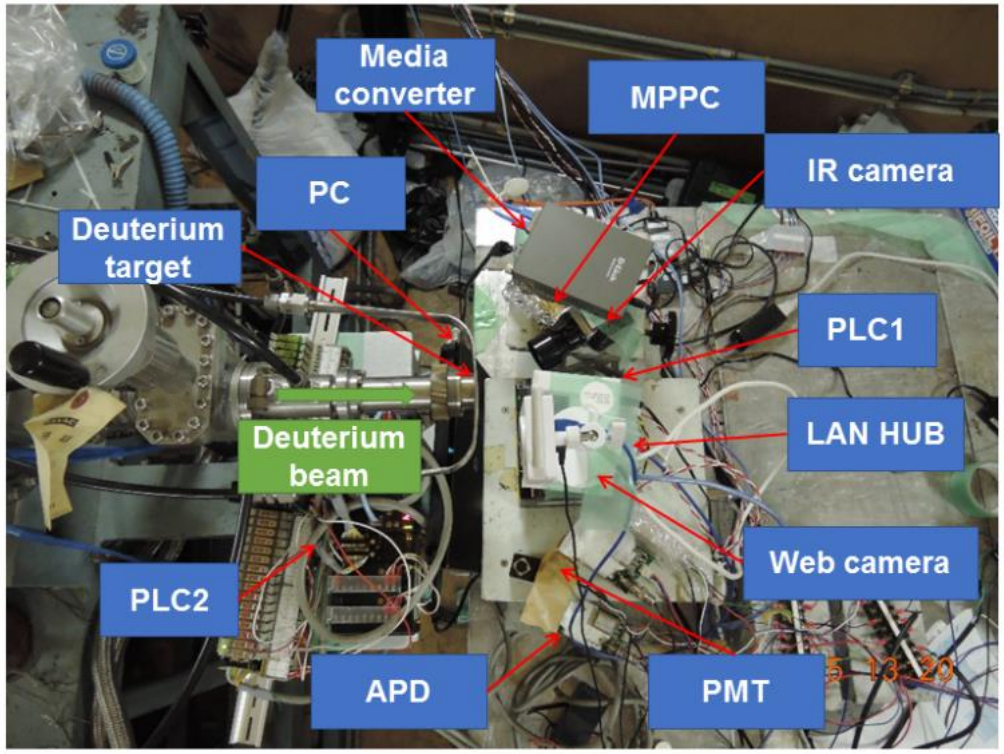




- **Neutron flux profile in the LHD torus hall at maximum neutron emission discharge (total neutron emission rate of 1.9×10^{16} s^{-1})**
  - **The flux in the torus hall and basement level are around 10^9 $cm^{-2}s^{-1}$ and around 10^6 $cm^{-2}s^{-1}$, respectively.**
- **The profile of the dose on silicon during the nine years of the LHD deuterium operation period.**
  - **Dose for silicon is about 70 Gy. The gamma-ray contributions are dominant in dose.**

DD Neutron irradiation test

DD neutron irradiation test in OKTAVIAN



- **DD Neutron irradiation tests are performed in OKTAVIAN at Osaka University and Fast Neutron Laboratory at Tohoku University for 11.5 hours.**
- **Neutron rate from source is around 9×10^{8} n/s (measured with activation foil).**
- **The neutron flux at 5 cm away from the target is up to 3×10^{6} $cm^{-2}s^{-1}$.**
- **The neutron flux at 10 cm away from the target 7×10^{5} $cm^{-2}s^{-1}$.**

Summary neutron irradiation experiment on electronic equipment of LHD (1)

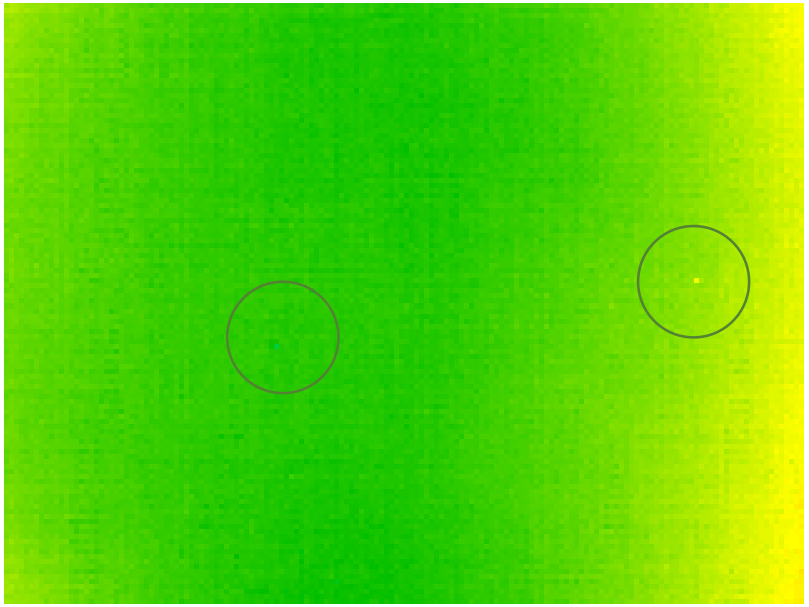
Component	Manufacturer	Model number	Neutron flux [$cm^{-2}s^{-1}$]	Transient effect	Neutron fluence [cm^{-2}]	Permanent effect
PC	Hewlett-Packard	HP Mini 5103	3×10^{5}	Network disconnection (Once)	4×10^{9}	Not observed
Media converter	D-Link	DMC-700SC	7×10^{5}	Not observed	8×10^{9}	Not observed
IR camera	Indigo	Omega	7×10^{5}	Dots appeared	8×10^{9}	Not observed
MPPC	Hamamatsu photonics	C13366-1350GA	7×10^{5}	Not observed	8×10^{9}	Not observed
Web camera	I-O DATA	TS-WLCAM	3×10^{6}	Dots appeared (< 1 Hz)	3×10^{10}	Not observed
APD	Hamamatsu photonics	C12703-01	2×10^{5}	Pulse (1.5 Hz)	2×10^{9}	Not observed
PMT	Hamamatsu photonics	H10723-210	2×10^{5}	Pulse (23 Hz)	2×10^{9}	Not observed

Summary neutron irradiation experiment on electronic equipment of LHD (2)

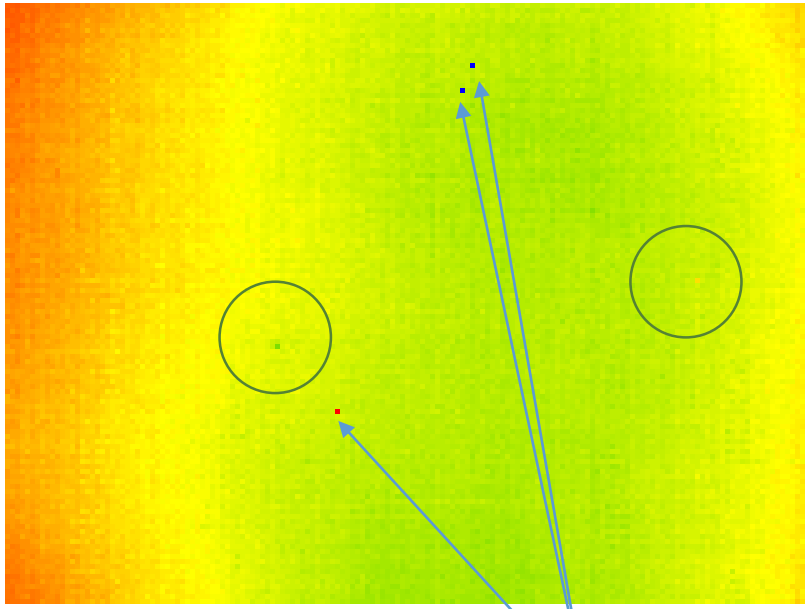
Component		Manufacturer	Model number	Neutron flux [$cm^{-2}s^{-1}$]	Transient effect	Neutron fluence [cm^{-2}]	Permanent effect
PLC1	CPU	YOKOGAWA	PU10-0S	3×10^{6}	Network disconnection (three times)	3×10^{10}	Not observed
	Power		SP71-4S		Not observed		Not observed
	Analog input		AD04-0V		Not observed		Not observed
	Analog output		DA04-1N		Various effects		Not observed
PLC2	CPU	OMRON	CJ2M-CPU31	3×10^{5}	Not observed	4×10^{9}	Not observed
	Power		CJ1W-PA205C		Not observed		Not observed
	Analog output		CJ1W-DA021		Not observed		Not observed
	Analog input		CJ1W-AD041-V1		Not observed		Not observed

Neutron induced dots on IR camera

Before irradiation



After irradiation

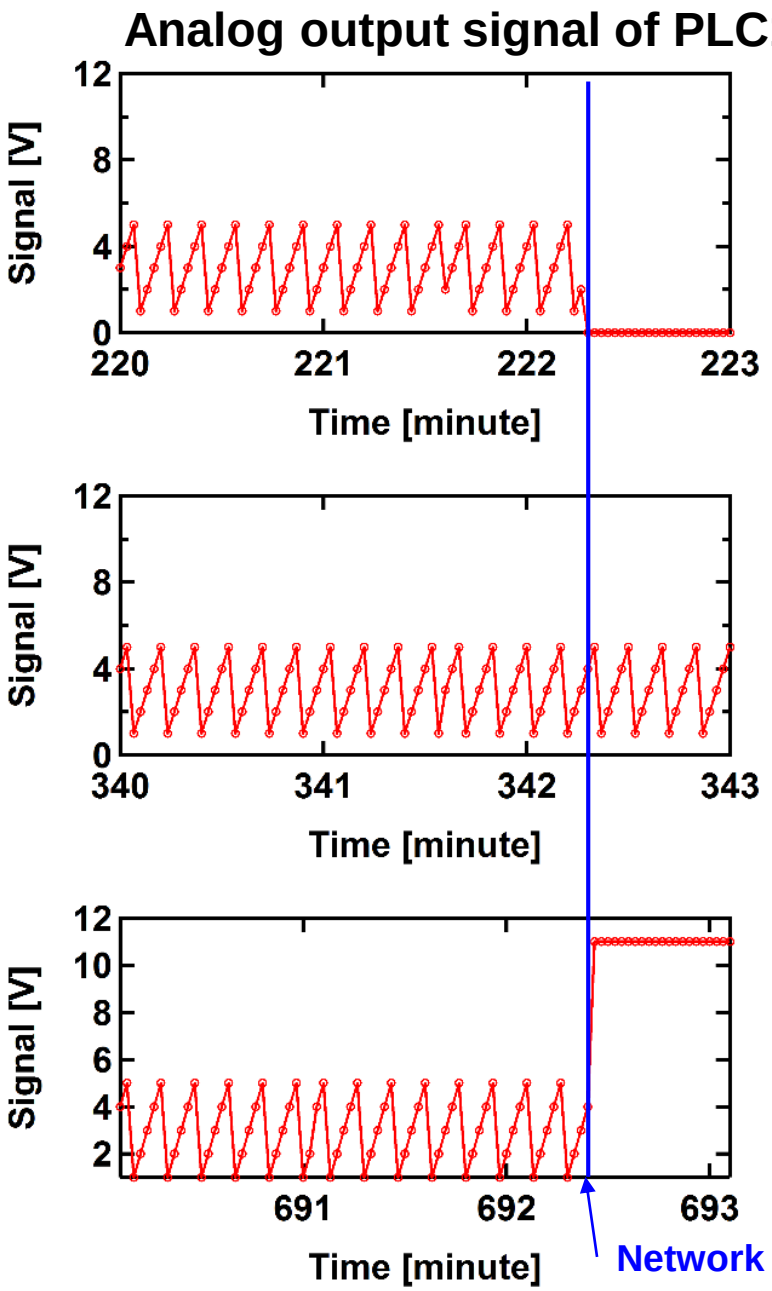


Dots appeared before irradiation

Neutron induced dots
(disappear after reboot)

- We observed four dots per 3 hours at neutron flux of 7×10^5 $cm^{-2}s^{-1}$.
- The IR camera will be installed on the upper port of LHD where expected maximum neutron flux is 10^{10} $cm^{-2}s^{-1}$.
  - If the number of dots linearly grows as neutron flux, the number of dead pixels due to neutrons will reach 43,000 dots per shot.

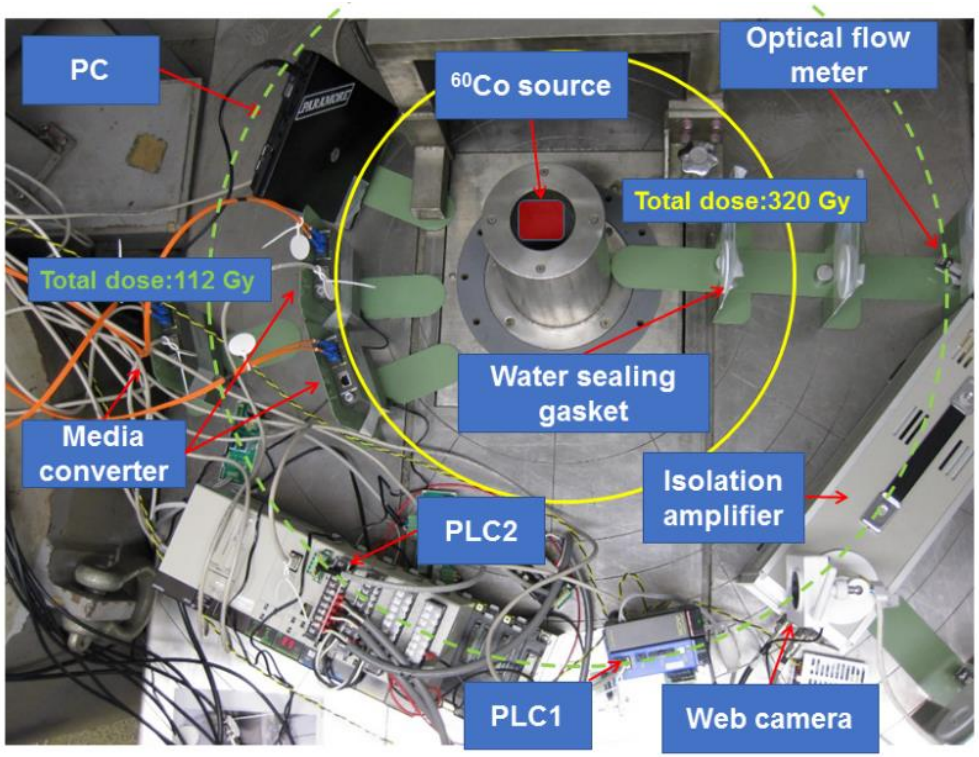
Transient effect on PLC1



- We observed disconnection of network of PLC1 three times during neutron irradiation test.
  - The behavior of output signal module is different in each case.
- Case A: output signal goes to zero
- Case B: no change (though PLC connection failed)
- Case C: output signal goes to 11 V (maximum output voltage)
- These disconnection of the network recovers due to the reboot.

- No error is observed on PLC2 when neutron flux of 3×10^5 $cm^{-2}s^{-1}$

^{60}Co gamma-ray irradiation test



- **Gamma-ray irradiation tests are performed in the Nagoya University Cobalt-60 irradiation facility for 3.7 hours.**
- **The dose rate on silicon (2015/7/14) is 86 Gy/h at 30 cm from the source and 30 Gy/h at 50 cm from the source.**

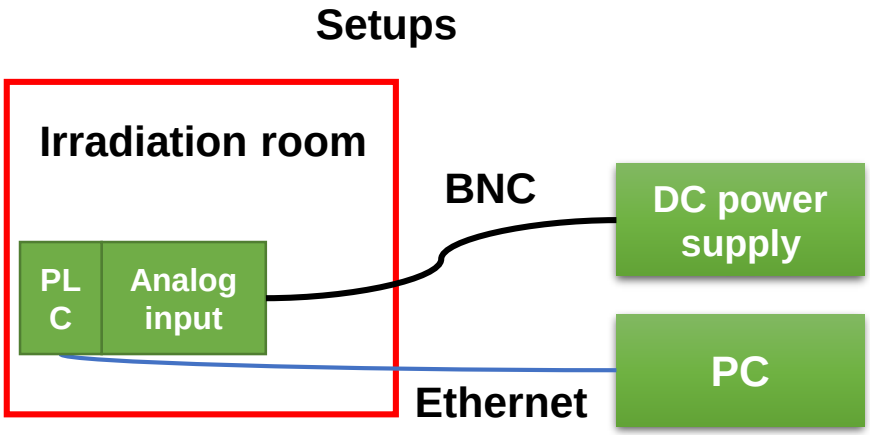
Summary gamma-ray irradiation experiment on electronic equipment of LHD (1)

Component	Manufacturer	Model number	Maximum dose (Gy)	Transient effect	Permanent effect
PC	Hewlett-Packard	HP Mini 5101	320	Not observed	Broken (224 Gy)
Media converter	D-Link	DMC-700SC	320	Not observed	Not observed
Optical flow meter	TOKYO KEISO	R-760-E	240	Not observed	Not observed
Isolation amplifier	NF corporation	P62-A	112	Not observed	Not observed
Web camera	I-O DATA	TS-WLCAM	112	Dots appeared	Not observed

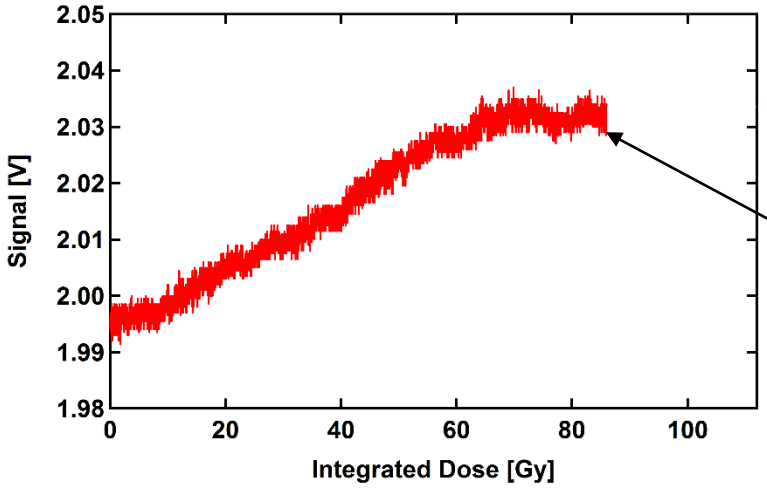
Summary gamma-ray irradiation experiment on electronic equipment of LHD (1)

Component		Manufacturer	Model number	Maximum dose (Gy)	Transient effect	Permanent effect
PLC1	CPU	YOKOGAWA	PU10-0S	112	Dots appeared	Broken (86 Gy)
	Power		SP71-4S		Not observed	Broken (86 Gy)
	Analog input		AD04-0V		Not observed	Not observed
	Analog output		DA04-1N		Not observed	Offset increase Broken (86 Gy)
PLC2	CPU	OMRON	CS1G-CPU42H	112	Not observed	Not observed
	Power		C200HW-PA204S		Not observed	Broken (112 Gy)
	Analog output		CS1W-DA08V		Not observed	Not observed
	Analog input		CS1W-AD08-V1		Not observed	Broken (95 Gy)

Offset increase due to gamma-ray on PLC1

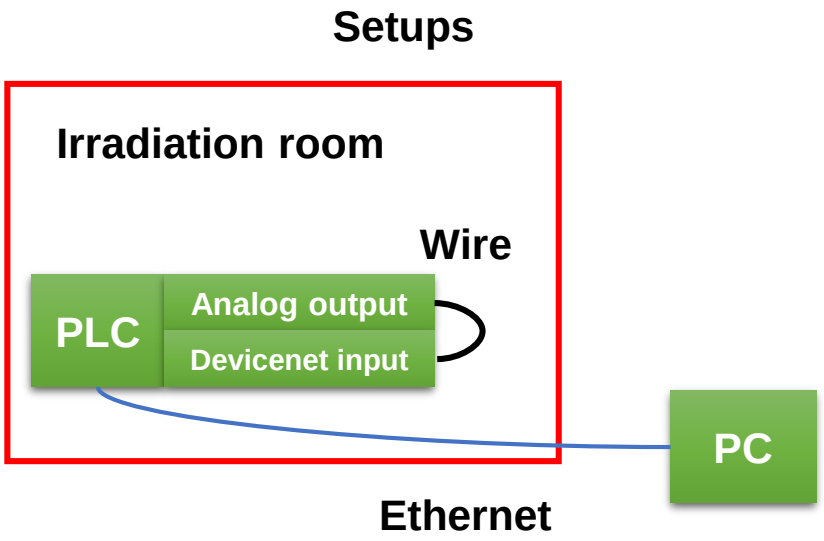


- MODEL:FA-M3, YOKOGAWA
- DC voltage (2 V) is inputted to analog input module on a PLC.
- The input signal is monitored by a PC.
- Offset due to gamma-ray is gradually increased.
- Analog input module is broken at 86 Gy.

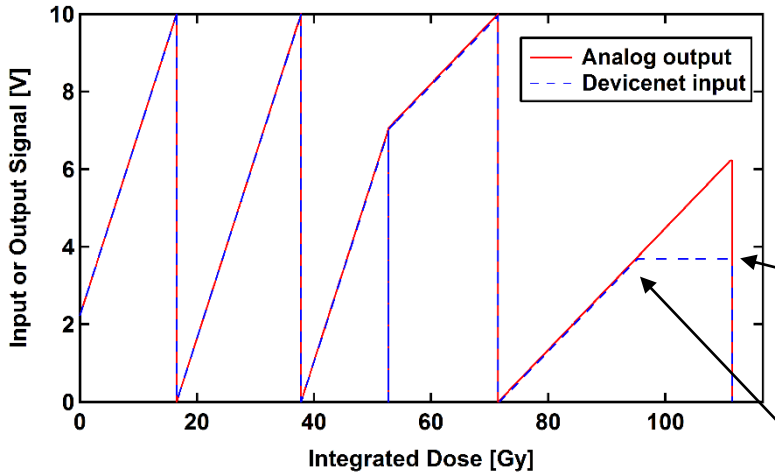


analog input module is broken

Permanent effect on PLC2



- MODEL: CS1G,OMRON
- Time-varying voltage is applied from analog output module to Devicenet input on the PLC.
- The input/output voltage is monitored through a PC.
- Devicenet input is broken at 95 Gy.
- Ethernet module and power module of PLC are broken at 112 Gy.



Ethernet and power module are broken

Devicenet input module is broken

Summary

- **Effects of neutron and gamma-ray irradiation on electronic equipment currently used in the LHD torus hall are studied in OKTAVIAN, Fast Neutron Laboratory, and Nagoya University Cobalt-60 irradiation facility.**
- **The irradiation on PCs, media converters, the IR camera, an MPPC, web cameras, APDs, PMTs, PLCs, optical flow meters, and isolation amplifiers are performed.**
- **In neutron irradiation test, the disconnection of the network is observed on the PC at neutron flux of 3×10^5 $cm^{-2}s^{-1}$, and on PLCs at neutron flux of 3×10^6 $cm^{-2}s^{-1}$. This neutron flux is comparable with the flux at the basement level of the LHD torus hall. The experiment also shows that there is no effect on the PLC on the neutron flux below 3×10^5 $cm^{-2}s^{-1}$.**
- **Neutron-induced dead pixels are observed on the IR camera. These dots disappear due to reboot. Neutron-induced signal is observed on APDs and PMTs. No effect is observed on the media converter and the MPPC at neutron flux of 3×10^5 $cm^{-2}s^{-1}$ and neutron fluence of 8×10^9 cm^{-2}.**
- **This neutron and gamma-ray irradiation test shows that highly integrated electronic components such as PLCs and PCs will have a trouble in the torus hall without neutron shield, and equipment used in this experiment can survive nine years of deuterium operation in the torus hall if we consider the gamma-ray dose only.**
- **Hence, we designed the neutron shield for the IR camera, and we moved PCs and PLCs as far as possible to the basement level of the torus hall and put several neutron shields made by the borated polyethylene for the safe operation of LHD deuterium experiments.**