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Radiation Tolerance of the MUX64 for the High Granularity Timing Detector of ATLAS

Wang Chuanye[1] , XU Zifeng[1], ZHANG Li[3], HUANG Xing[2], SHA Qiyu[3,4], GE Zhenwu[1], CHE Yimin[1], HOU Suen[5], ZHANG Jie[3,4], LIU Tiankuan[2], LIANG Zhijun[3,4], ZHANG Lei[1], YE Jingbo[3], QI Ming[1]

[1]Nanjing University(CN), [2]Southern Methodist University(US), [3]Institute of High Energy Physics, Chinese Academy of Sciences(CN), [4]University of Chinese Academy of Sciences(CN), [5]Institute of Physics, Academia Sinica(TW)

chuanye.wang@cern.ch

Introduction

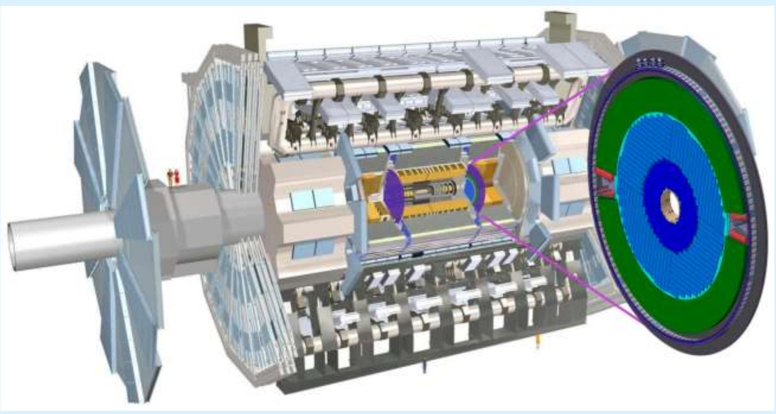


Figure1. Schematic of the ATLAS detector and the HGTD vessel

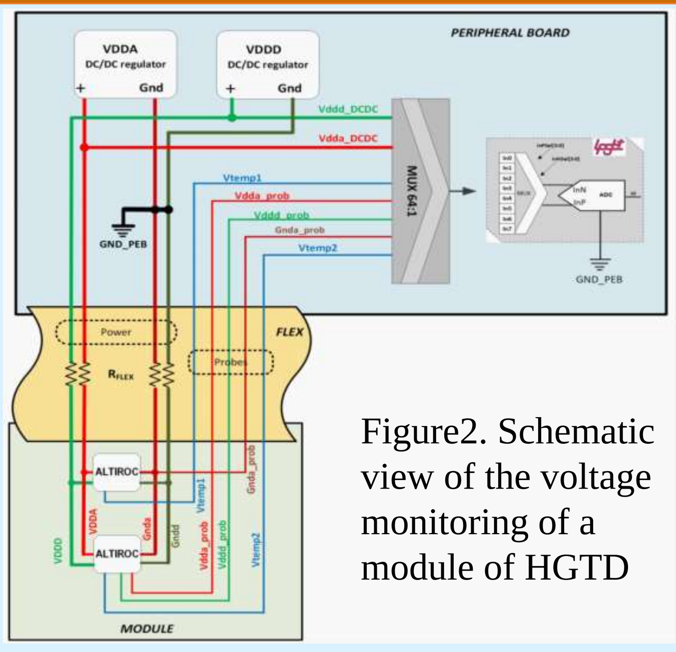


Figure2. Schematic view of the voltage monitoring of a module of HGTD

- The MUX64 ASIC is a 64-to-1 analog multiplexer developed for multiplexing of ADC input channels in the peripheral electronics of High Granularity Timing Detector (HGTD) for the ATLAS Phase-II upgrade.
- On-resistance (R_{on}) of MUX64 is required to be lower than 900 Ω for matching the precision of the ADC, while off-resistance (R_{off}) of MUX64 is required to be larger than 60 MΩ.[4]
- The MUX64 chips will be used in the radiation field of high-luminosity pp collisions at LHC to an integrated luminosity of 4000 fb^{-1} [2] . To verify the radiation tolerance of the MUX64, Non Ionizing Energy Loss (NIEL) and Total Ionizing Dose (TID) tests have been performed.
- The NIEL test was conducted with 80 MeV protons beam at APEP of CSNS[3] , two chips was irradiated to a fluence of 3.21×10^{15} (Si 1 MeV neq)/cm^2. The TID test was carried out in a MultiRad160 X-ray machine, five chips were irradiated to 0.746 MGy (Si) at a dose rate of 5.98 Gy/s (Si).

Radiation tolerance requirements

Radiation tolerance requirement

	Requirement (Ave of Genta and Fluka)	Requirement (Max of Genta and Fluka)	Test Dose
Total Ionizing Dose [Gy]	4.71×10^5	4.97×10^5	7.46×10^5
1 MeV neutron equivalent [cm^{-2}]	2.18×10^{15}	2.18×10^{15}	3.21×10^{15}

Table 1. TID and NIEL requirement and test results

- The R_{on} of MUX64 was measured to characterize the radiation damage.

NIEL test setup

Parameters of the CSNS Proton Experiment Platform:

- Energy: 10-80 MeV; Beam Injection rate: $10^5 - 10^{10}$ pps/cm^2.
- Beam spot size: $10\times10\ mm^2 - 50\times50\ mm^2$ (continuously adjustable uniformity > 95%).

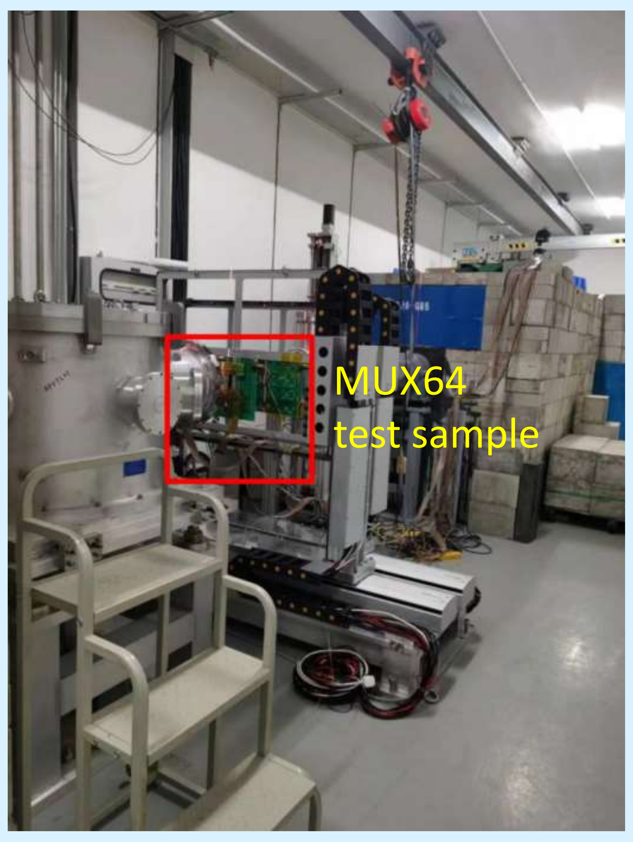


Figure 3. Photo of MUX64 at APEP

NIEL test conditions

- Average injection proton rate: 1.86×10^9 pps/cm^2 (14.48 days in total).
- NIEL scale factor: 1.378 (for 80MeV proton to 1MeV neutron).
- Total equivalent fluence: 3.21×10^{15} (Si 1 MeV neq)/cm^2.

TID test setup

Basic Parameters of MultiRad160 X-ray machine:

- Max voltage: 160 kV, Max current: 25 mA , max dose rate = 5 Gy/s (at positioned in air, 14.5 cm from the source).
- The MultiRad160 used in this test has been calibrated (in Si) by the ATLAS ITK strip group at 40 kV, 20 mA.[1]

TID test conditions

- Dose rate: 5.98 Gy/s (in Si, 10 cm from source, 40kV, 20mA).
- Total irradiation dose: (35 h per chip) 7.46×10^5 Gy.

Figure 4. MultiRad160 configuration

NIEL and TID test results

Technical procedure

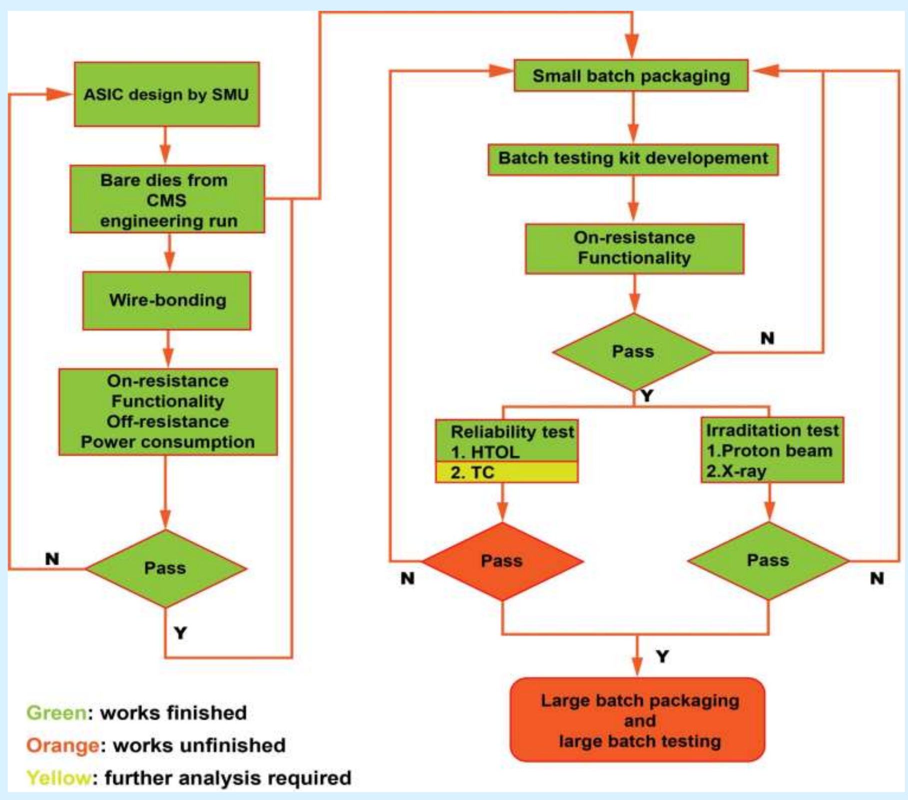
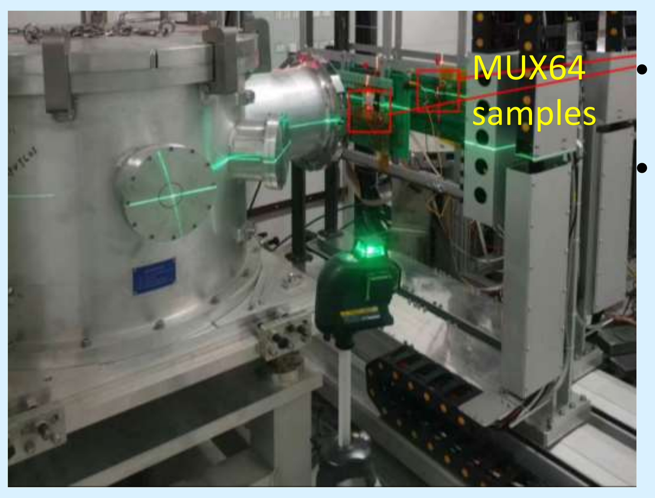


Figure4. Test procedure of MUX64. High Temperature Operating Life(HTOL). Temperature Cycling(TC).

Result of NIEL test



- Two MUX64 are tested simultaneously.
- Both chips are irradiated in the proton beam, positioned in sequence.

Figure5. MUX64s in NIEL test.

- A thin aluminum foil is attached to the front of the first MUX64 to measure the flux of proton.
- No accurate measurement for the flux nor the proton beam energy of the second MUX64.

MUX64 before NIEL irradiation

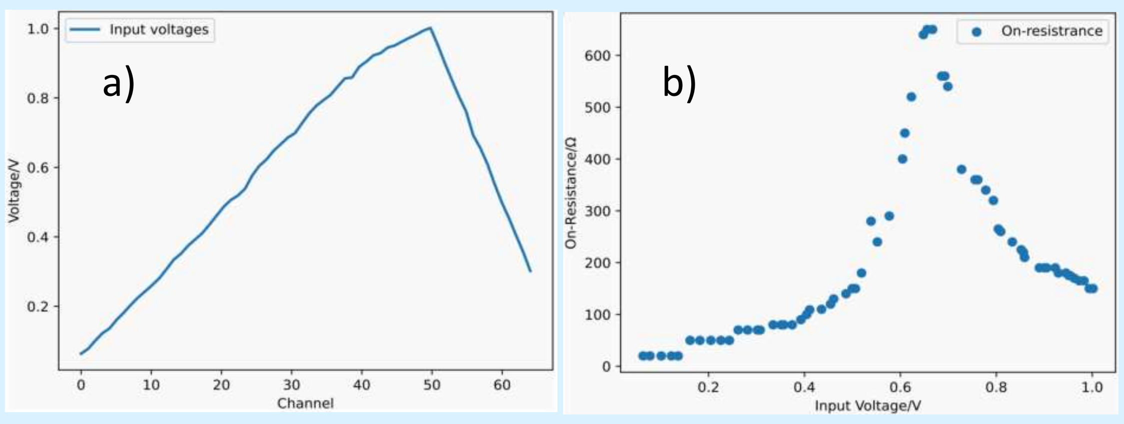
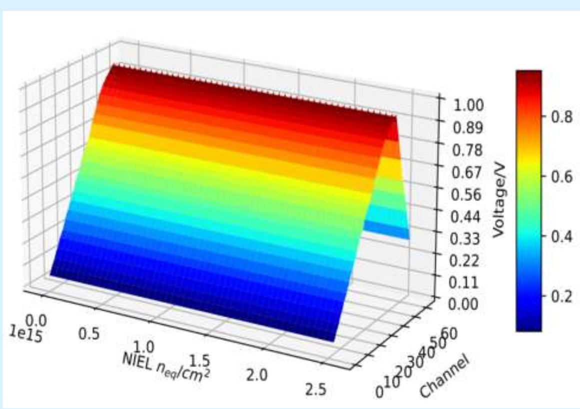


Figure 6. (a) Input voltage (V_{in}) curve; (b) R_{on} versus V_{in} before irradiation.

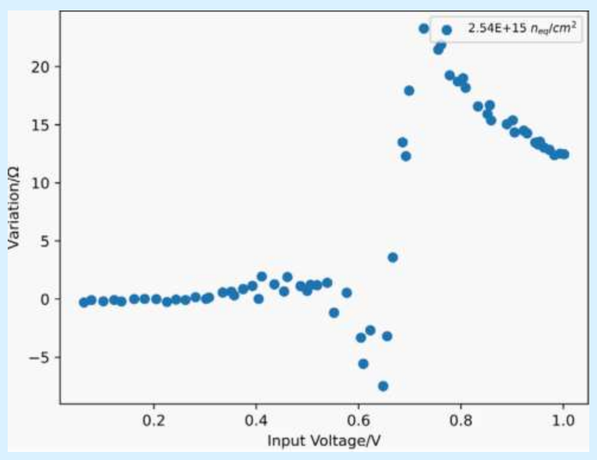
- The spike near 0.65V in figure 6 (b) is because both MOSFETs of transmission gate in MUX64 are in partially conducting state.
- The R_{on} over 0-1V input voltage ($\mathbf{V_{in}}$) is required to be lower than 900 Ω. (Same as TID test)

MUX64 performance after NIEL irradiation



- The smooth surface shown in Figure 7 indicates no channel misalignment during irradiation.

Figure7. V_{in} to each channel under irradiation



- Figure 8 shows the R_{on} variation ($\mathbf{\Delta R_{on}}$) versus V_{in} after the fluence of 2.54×10^{15} (1 MeV neq)/cm^2.
- The ΔR_{on} after irradiation is less than 25 Ω.
- Two tested MUX64s show compatible performance.

Figure8. ΔR_{on} versus V_{in} after irradiation.

Result of TID test

- The MUX64s were irradiated one by one in the X-ray machine. In total five samples were tested.
- The MUX64 sample in X-ray cavity was supported 10 cm from the source.
- A 0.15 mm Al foil was applied to absorb low energy photons.
- Dose rate calibration had included the Al filter.
- The temperature in the X-ray chamber was not controlled.

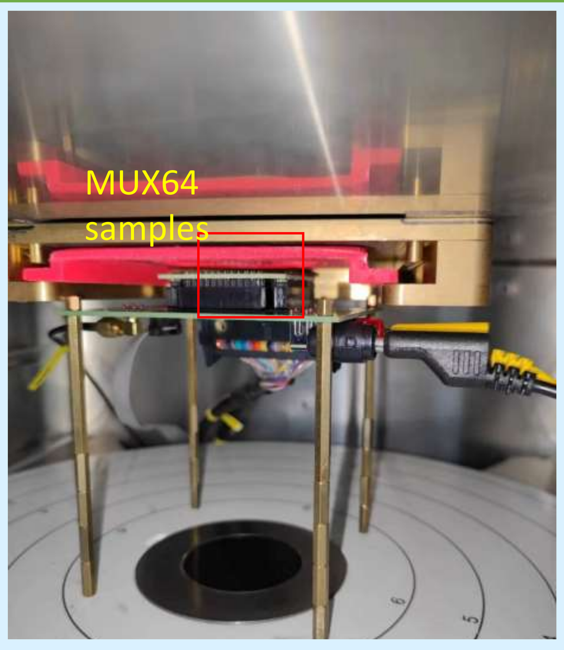


Figure9. MUX64 position in the X-ray cavity.

MUX64 before TID irradiation

- R_{on} of each channel were measured with V_{in} ranging from 0.05V to 1.20V (step 0.05V).
- Figure 10. shows the expected R_{on}-V_{in} Curve.

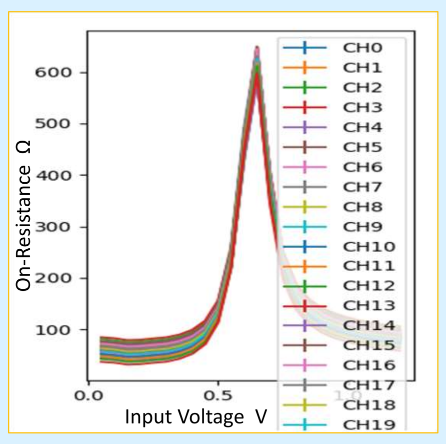


Figure10. R_{on} versus V_{in} before irradiation.

MUX64 performance after TID

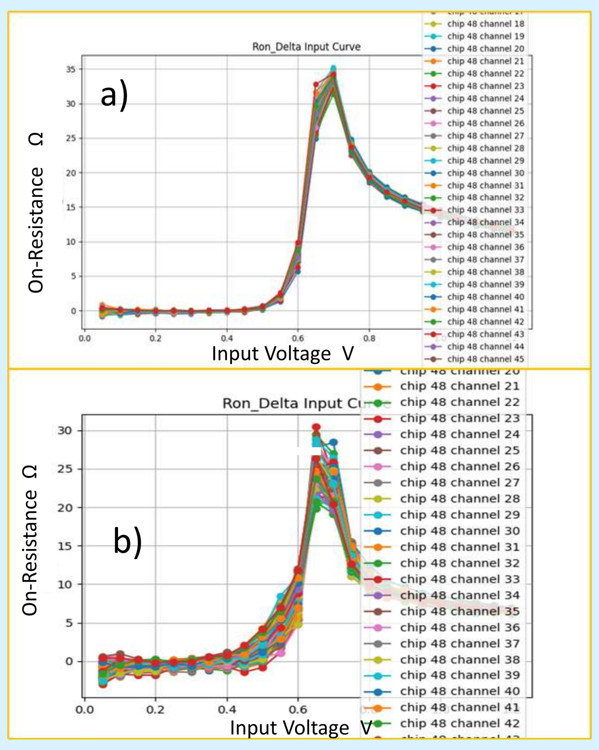


Figure11 :
(a) ΔR_{on} after irradiation; (b) ΔR_{on} after annealing.

The R_{on} were measured for a typical (Chip-48) before irradiation at 28.2℃, after irradiation at 26.5℃, and after annealing at 25.0℃.

- The ΔR_{on} after irradiation is less than 35 Ω.
- The ΔR_{on} after annealing is less than 30 Ω.
- The other 4 chips have compatible performance after TID.

Conclusion

- The radiation tolerance of MUX64 is verified. It is expected to function effectively in the high-luminosity environment of the HGTD for a service period corresponding to the accumulated luminosity of 4000 fb^{-1}.
- The MUX64 samples were irradiated by 80 MeV protons for NIEL effect equivalent 3.21×10^{15} (Si 1MeV neq)/cm^2, and X-ray for TID to 0.746 MGy (in Silicon). The multiplexing functionality shows negligible degradation for the radiation tolerance requirements of HGTD.

Reference

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[2] P. Moreira et al. The lpGBT: a radiation tolerant ASIC for Data, Timing, Trigger and Control Applications in HL-LHC, presented at TWEPP 2019.

[3] Chen, H., Wang, XL. China's first pulsed neutron source. *Nature Mater* **15**, 689–691 (2016). https://doi.org/10.1038/nmat4655

[4] Z. Xu et al., MUX64, an analogue 64-to-1 multiplexer ASIC for the ATLAS high granularity timing detector, 2023 JINST 18 C03012