Thermal neutron induces Single-Event Upsets in the FPGA used in particle physics experiments

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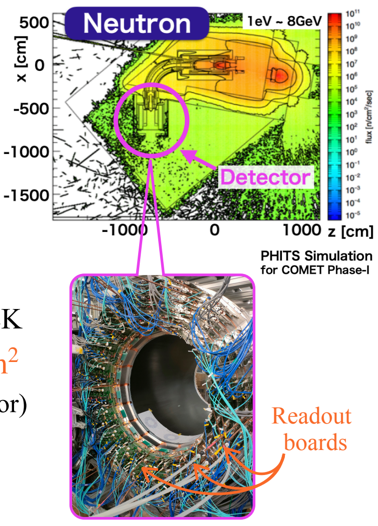
Introduction

Radiation on Particle Physics Experiments

To explore beyond the Standard Model, beams generated by accelerators are becoming higher intensity, higher luminosity and higher energy.
→ **increase background radiations** (neutron, gamma, proton, etc.)
→ **affects electronics**.

e.g.) COMET [1] @ J-PARC, SuperKEKB/Belle II [2] @ KEK
Estimated cumulative neutron dose $\sim 10^{12}\ n_{1-MeVeq}/cm^2$ (Including safety factor)

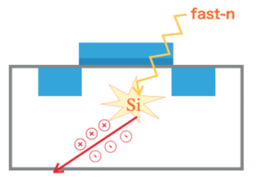
There is a large amount of **thermal neutrons** around the detector readout electronics.

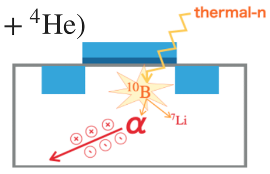


Neutron effect

- Fast neutron (> 0.1 MeV): nuclear reaction with Si
  → emit Ion particle
- Thermal neutron (< 1 eV): capture reaction with ^{10}B
  → emit α particle ($^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$)

→ Induce electron-hole pairs
→ Change the logic state (**Single-Event Upset, SEU**)
Counterplan : neutron sheild, error-correcting code, etc.





Semiconductor designe & SEU occured by thermal neutron

Trend : ^{10}B less oxide film is used ・・・SEUs by thermal neutron decreased…?
→ Some studies reported SEUs induced by thermal neutrons [3], [4] .
It might still contain ^{10}B ? / SEU trends vary depending on the product type.

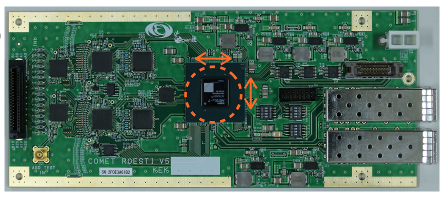
Motivation of this study

To estimate SEUs caused by thermal neutrons in an FPGA
(For fast neutrons, it has been studied in [5].)

Measurement

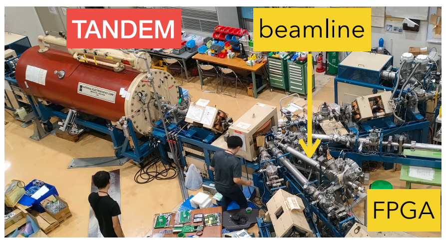
We measured SEU counts on FPGA and fluences of thermal and fast neutrons by irradiating neutron (n) beams in several different setups.

FPGA Artix-7 on the COMET readout board ROESTI [6]
28-nm CMOS process FPGA (AMD Inc.)



Facility Tandem accelerator at Kobe Univ.

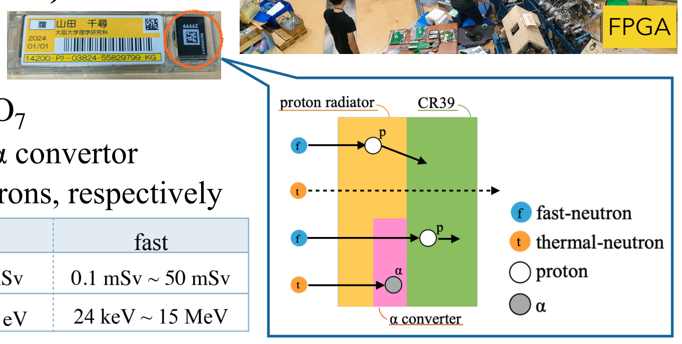
- Beam : 3 MeV deuteron (d)
- Reaction : $^{9}Be + d(3\ MeV) \rightarrow {}^{10}B + n$
- Neutron energy : 2 MeV (< 7 MeV)
- Neutron flux : $4.8 \times 10^{6}\ Hz/cm^2/\mu A$ at 10 cm from a target



Neutron measurement (CR39)

CR39 (Nagase Landauer Ltd.)

- Solid-state track detector
- Plastic consisting of $C_{12}H_{18}O_7$
- Contain protonradiator, and α convertor
- Measure fast or thermal neutrons, respectively

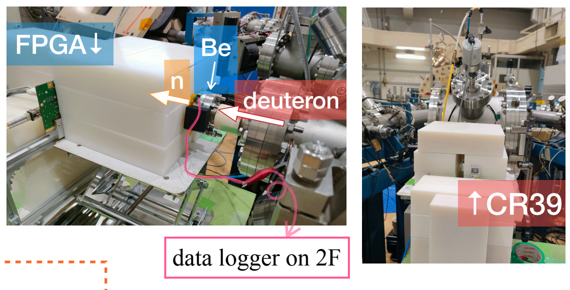


specification [7]	thermal	fast
Dose range	0.1 mSv ~ 6 mSv	0.1 mSv ~ 50 mSv
Energy range	0.025 eV ~ 0.5 eV	24 keV ~ 15 MeV

+ Record the deuteron beam current in a data logger (GRAPHTEC GL840)
(To normalize SEU rate by beam charge) chrarge ∝ irradiated neutrons

Setup & SEU Measurement

- ✦ Put some blocks around the beam
- ✦ Irradiated FPGA and CR39
- ✦ Detected and corrected SEUs by Soft Error Mitigation (SEM) IP core [8]
- ✦ Recorded deuteron beam current



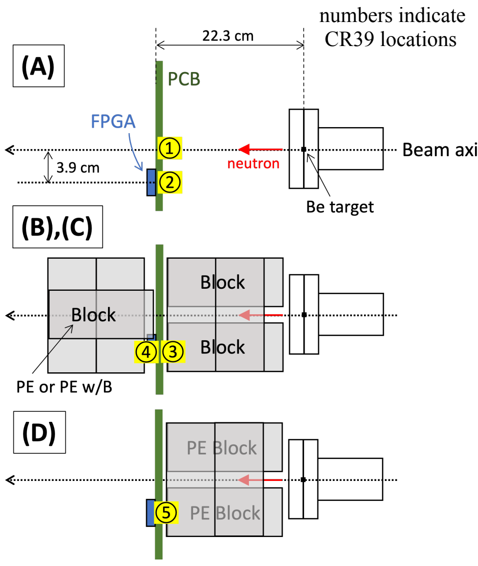
(A) : Without blocks (reference)
CR39 - ① On-axis, ② FPGA surface

(B) : With Polyethylene (PE) blocks
(degrade or reflect fast neutrons)
CR39 - ③ FPGA surface

(C) : With PE blocks containing B_2O_3
(shield both fast and thermal neutrons)
CR39 - ④ FPGA surface

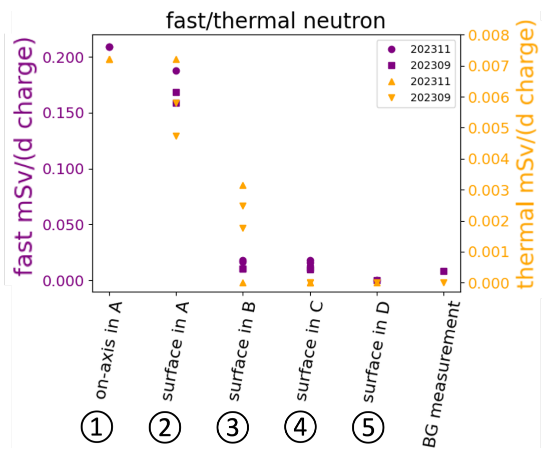
(D) : Remove blocks behind FPGA from (B)
(investigate the impact of behind block = reflected-derived thermal neutrons)
CR39 - ⑤ FPGA surface

Background (BG) CR39 - no irradiation



Result & Disscusion

Neutron measurement

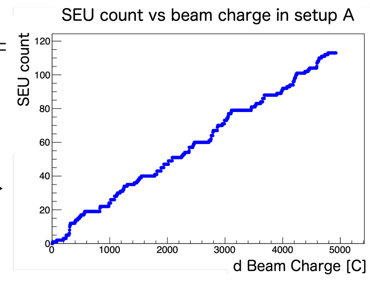


- Without blocks, both fast and thermal neutrons were irradiated. (①, ②)
- The one-minute measurement in 202309-thermal (▲) was too short to detect in ③.
- Thermal and fast neutrons are successfully shielded in ④ due to B_2O_3-containing blocks.
- Most thermal neutrons came from the reflection of the behind block in ⑤ compare to ③.

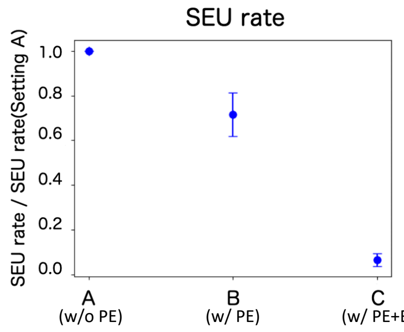
→ Confirmed neutron energy trend
A : fast,thermal
B : thermal
C : neither fast nor thermal

SEU measurement

Setup	SEU count	deutron charge[C]	SEU / (d charge)
A	113	4.9×10^{3}	2.3×10^{-2}
B	104	6.2×10^{3}	1.7×10^{-2}
C	6	4.0×10^{3}	1.5×10^{-3}



SEU counts increased in propotion to the beam charge →



← The SEU rate on each setups relative to the result of A

★It was found that SEUs occured due to thermal neutrons.
★Shielding of B_2O_3-containing blocks greatly contributes to reducing the SEUs.

Conclusion & Future

- Particle physics experiments using the beam of high-intensity, luminosity, and energy require consideration of radiation effects on electronics.
- Fast neutrons and thermal neutrons can induce charged particles inside transistors through different processes, which can cause SEUs.
- We investigated SEUs induced by thermal neutrons using an FPGA employed in a particle experiment.
- By placing polyethylene blocks, we succeeded in producing thermal neutrons from a tandem accelerator and observed SEUs caused by thermal neutrons.
- We showed that it is necessary to consider the influence of thermal neutrons in the experiments and the usefulness of countermeasures such as shielding.

Future work

- To better understand the rate of SEU
  ★Simulating a detailed neutron energy distribution ★Measuring the energy
- Investigate where and how much ^{10}B is contained by elemental analysis

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