Radiation Hardness of Electronics for Phase-2 Upgrade of RPC Muon System

Behzad Boghrati
Institute for Research in Fundamental Science (IPM)
on behalf of CMS Muon Group
11 November 2020
Outline

• General Perspective of CMS experiment
• LHC upgrade timeline
• Radiation Effects on Electronics
• Tests Standards and Guidelines
• Electronics Validation Strategy
• Goals
• How measure the Single Event Effects
• Which type of beam?
• Neutron beam or Proton beam or Both?
CERN Experiments (CMS and ATLAS)

Behzad Boghrati, Radiation Tolerant Electronics for Phase-2 Upgrade of RPC Muon System, 2nd International Workshop on Experimental Particle Physics, 11 Nov 2020
CMS Experiment at LHC (UXC)
LHC / HL-LHC Plan

Behzad Boghrati, Radiation Tolerant Electronics for Phase-2 Upgrade of RPC Muon System, 2nd International Workshop on Experimental Particle Physics, 11 Nov 2020
• **Expected fluence and dose (RE34/1 FEBs)**
  - at R=303 cm for RE3/1 is \(\sim 4.3 (5.8) \times 10^{11} \text{ n/cm}^2\), and
  - at R=304 cm for RE4/1 it is about \(6.2 (8.2) \times 10^{11} \text{ n/cm}^2\),
  - at R=303 cm for RE3/1 is \(\sim 10 (13.6) \text{ Gy}\)
  - at R=304 cm for RE4/1 it is about \(18 (24) \text{ Gy}\)
  - where R=303 (304) cm are the expected FEB positions

• **Expected fluence and dose (Balcony)**
  - The total irradiation fluence \(800 \times 10^9 \text{ cm}^{-2}\)
  - Maximum integrated dose is about \(10 \text{ Gy}\)
Radiation Effects in Electronics

Radiation Effects

Cumulative Effects
- Ionization (TID)
- Displacement (Fluence)

Single Event Effects
- Permanent
  - Single Event Burn out
  - Single Event Gate Rupture
  - Single Event Latchup
- Transient
  - Single Event Transient
- Static
  - Single Event Functional Interrupt
  - Single Event Upset

Non-Recoverable Errors
- Single Event Functional Interrupt

Recoverable Errors
- Single Bit Upset
- Multi Bit / Cell Upset

Behzad Boghrati, Radiation Tolerant Electronics for Phase-2 Upgrade of RPC Muon System, 2nd International Workshop on Experimental Particle Physics, 11 Nov 2020
Electronics Radiation Hardening for Phase-2 Upgrade

- **Simulation of the CMS Radiation environment**
  - Maximum expected Fluence after collecting 3000 fb⁻¹
  - The expected absorbed dose after collecting 3000 (4000)fb⁻¹
  - NO Safety Factor

- **Radiation could cause**
  - Permanent damage
  - Temporary effects such as data corruption induced by SEU

- **Electronics**
  - Digital Components: TID/displacement damage, SEU, Latchup $E_n < 20$ MeV
  - Analog Components: TID/displacement damage, $E_n < 1$ MeV [1]

- **Goals:**
  - Obtain the SEU cross section of FPGA resources (Configuration Memory, BRAM, MGTs, FFs)
  - Estimate of the Upset rate within the CMS radiation environment
  - Digital/Analog Components : Check the fault resilience of the other ASICs
  - Evaluation of the rad-hard techniques adopted during the experiments must prevent build up of errors in different FPGA parts

<table>
<thead>
<tr>
<th>Fluence [particles cm⁻²]</th>
<th>Dose [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEB for RE3/1 (R = 304 cm) near to the border at higher radii</td>
<td>Max = $4.3 \times 10^{11}$ 1-MeV NE in SI</td>
</tr>
<tr>
<td>FEB for RE4/1 (R = 304 cm) near to the border at higher radii</td>
<td>Max = $6.2 \times 10^{11}$ 1-MeV NE in SI</td>
</tr>
<tr>
<td>Link board for Barrel (Z &lt; 600 cm)</td>
<td>Max = $350 \times 10^9$ Neutrons with $E_n &lt; 20$ MeV</td>
</tr>
<tr>
<td>Link board for Endcap (Z &gt; 600 cm)</td>
<td>Max = $800 \times 10^9$ Neutrons with $E_n &lt; 20$ MeV</td>
</tr>
</tbody>
</table>
Response of devices to radiation

### Cumulative Effects

**Table 1. Non destructive SEE phenomena.**

<table>
<thead>
<tr>
<th>Device</th>
<th>Degradation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upset - SEU*</td>
<td>corruption of the information stored in a memory element</td>
</tr>
<tr>
<td>Multiple Bit Upset - MBU</td>
<td>several memory elements corrupted by a single strike</td>
</tr>
<tr>
<td>Functional Interrupt - SEFI</td>
<td>loss of normal operation</td>
</tr>
<tr>
<td>Transient - SET</td>
<td>impulse response of certain amplitude and duration</td>
</tr>
<tr>
<td>Disturb - SED</td>
<td>momentary corruption of the information stored in a bit</td>
</tr>
<tr>
<td>Hard Error - SHE</td>
<td>unalterable change of state in a memory element</td>
</tr>
</tbody>
</table>

**Memories, latches in logic devices**

### Single Event Effects

**Table 3. Typical TID degradation modes in devices.**

<table>
<thead>
<tr>
<th>Device</th>
<th>Degradation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOS</td>
<td>Shifting of threshold voltage</td>
</tr>
<tr>
<td>BJT</td>
<td>Current gain degradation</td>
</tr>
<tr>
<td>Digital circuits</td>
<td>Increased leakage current (Iccep, Icc-sb), reduced retention time (DRAMs and SDRAMs)</td>
</tr>
<tr>
<td>Linear devices</td>
<td>Increased Offset voltage and bias current</td>
</tr>
</tbody>
</table>


### Destructive SEE phenomena.

**Table 2.**

<table>
<thead>
<tr>
<th>Device</th>
<th>Degradation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latchup - SEL</td>
<td>high-current conditions</td>
</tr>
<tr>
<td>Snapback - SESB</td>
<td>high-current conditions</td>
</tr>
<tr>
<td>Burnout - SEB</td>
<td>destructive burnout</td>
</tr>
<tr>
<td>Gate Rupture - SEGR</td>
<td>rupture of gate dielectric</td>
</tr>
<tr>
<td>Dielectric Rupture - SEDR</td>
<td>rupture of dielectric</td>
</tr>
</tbody>
</table>

**CMOS, BiCMOS devices**

**N- MOSFET, SOI devices**

**BJT, N-channel Power MOSFET**

**Power MOSFETs**

**Non-volatile NMOS struct., FPGA, linear devices...**

### Table 4. Typical DD degradation modes in circuits.

<table>
<thead>
<tr>
<th>Device</th>
<th>Degradation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD/APS</td>
<td>Reduced responsivity (Increase of dark current, RTS occurrence...)</td>
</tr>
<tr>
<td>Bipolar Linear devices</td>
<td>Gain degradation</td>
</tr>
<tr>
<td>Solar cells</td>
<td>Reduced efficiency (output power, short circuit current)</td>
</tr>
<tr>
<td>Laser diode</td>
<td>Threshold current increase</td>
</tr>
</tbody>
</table>

Two main standards are widely used within the framework of SEE testing:

1) **ESA/SCC 25100**: Single Event effects test methods and guidelines

2) **JEDEC JESD57**: Test procedures for the measurement of Single-Event Effects in semiconductor devices from heavy ion irradiation

The SCC standard applies to proton and heavy ion testing whereas the JEDEC standard only addresses heavy ion testing.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>ESA/SCC 25100</th>
<th>JEDEC JESD57</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>Single Event effects test method and guidelines</td>
<td>Test procedures for the measurement of Single-Event Effects in semiconductor devices from heavy ion irradiation</td>
</tr>
<tr>
<td>Radiation sources and characteristics</td>
<td>HI : range $\geq 30 \mu m$, $10^2 \geq \text{Flux} \geq 10^5 \text{ions/cm}^2\cdot\text{s}$</td>
<td>range large compared to the depth of the collection region, $10^2 \geq \text{Flux} \geq 10^5 \text{ions/cm}^2\cdot\text{s}$</td>
</tr>
<tr>
<td></td>
<td>p+ : 20-300 MeV</td>
<td>LET up to $120 \text{MeV/\mu g cm}^2$</td>
</tr>
<tr>
<td></td>
<td>$10^5 \geq \text{Flux} \geq 10^4 \text{ions/cm}^2\cdot\text{s}$</td>
<td></td>
</tr>
</tbody>
</table>
| Dosimetry    | Uniformity $\pm 10\%$ over the device area | Energy $\pm 10\%$
| | Flux $\pm 10\%$ | Uniformity $\pm 10\%$ over the device area |
| | | Flux $\pm 10\%$ |
| Testing requirements | Sample size $\geq 3$ (same dtr) 5 measurements at different effective LETs (HI) or Energies (p+, normal incidence) Max fluence of resp. $10^7$ and $10^6$ part./cm$^2$·s for HI and p+ or a meaningful number of events | Measurements at onset threshold, 10%, 25%, 50% and 75-80% of the saturated $\sigma$, Max fluence of $10^7$ ions/cm$^2$·s for “hard” devices, $10^6$ ions/cm$^2$·s or 100 events whichever comes first for “soft” devices Tilt angles limited to $60^\circ$ |
Main features of TID radiation types.

- Radioactive Cs137 and Co60 sources deliver gamma rays, two strong advantages:
  - the very wide range of dose rates available
  - the fact that the total dose is well controlled in the device thickness.

- As photons delivered by Co60 have a large energy, 1.17 and 1.33 MeV, dose uniformity is ensured.

- This advantage can be lost if the irradiation facility is not correctly filtered and delivers a sizeable ratio of low energy scattered photons inducing dose enhancements. Consequently, it is necessary to take care to correctly assess accurate dosimetry and use adequate filtering methods.

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>Main advantages</th>
<th>Main drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons (accelerator)</td>
<td>High dose rate available</td>
<td>Costly</td>
</tr>
<tr>
<td></td>
<td>Representative of some orbits</td>
<td>Not adequate for low dose rates</td>
</tr>
<tr>
<td>Protons (accelerator)</td>
<td>High dose rate available</td>
<td>DD contribution</td>
</tr>
<tr>
<td></td>
<td>Representative of some orbits</td>
<td>Costly</td>
</tr>
<tr>
<td>X rays (photons)</td>
<td>High dose rates available</td>
<td>Dose enhancement effect</td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td>Not adequate for low dose rates</td>
</tr>
<tr>
<td>Cs$^{137}$ &amp; Co$^{60}$ sources</td>
<td>Very large dose rate range</td>
<td>Heavy shielding necessary</td>
</tr>
<tr>
<td>(gamma rays)</td>
<td>Dose uniformity</td>
<td>Non-dominant in orbit</td>
</tr>
</tbody>
</table>
## Electronics Radiation Tolerance validation Strategy

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>FPGA</th>
<th>ASIC</th>
<th>Goals</th>
</tr>
</thead>
</table>
| 1    | Obtain the SEU cross section of FPGA resources (Configuration Memory, BRAM, MGTs, FFs) | ✓ $\sigma_{\text{CRAM}}$: $6.89 \times 10^{-15}$ (cm$^2$/bit) \[1\]  
✓ $\sigma_{\text{BRAM}}$: $6.15 \times 10^{-15}$ (cm$^2$/bit)  
✓ $\sigma_{\text{GTX}}$: $7.27 \times 10^{-12}$ (errors/lane/cm$^2$/bit) | - | ❑ Measurement the Single event effects rate on the FPGA |
| 2    | Estimate of the Upset rate within the CMS radiation environment | ✓ 1 SEU every 413 seconds in Configuration  
✓ 1 SEU every 1694 seconds in Logics | - | ❑ Estimate of the SEU rate, by using the result of simulation |
| 3    | Cold-Test, Fault injection in Lab | ✓ Firmware mitigation will be started after completion of the firmware integration | - | ❑ Evaluation of the rad-hard techniques  
❑ Internal Scrubbing |
| 4    | Hot-Test, (SEE) | ✓ Proton beam / Heavy Ion cocktail | - | ❑ Evaluation of the rad-hard techniques adopted during the experiments must prevent build up of errors in different FPGA parts  
❑ Irradiations are done in vacuum and for most of the ions naked chips are needed. |
| 5    | Full Electronics Test (TID) | ✓ 300 krad  
✓ $1.3 \times 10^{13}$ (proton/cm$^2$) without TIFR | ✓ Cobalt -60 or X-Ray | ❑ Check the fault resilience of all electronics active devices such as FPGA, Digital and Analog ASICs, under X-Ray at 1 MeV Neutron Equivalent energy. Exactly similar to Medical irradiation treatment. |

\[1\] Radiation testing campaign results for understanding the suitability of FPGAs in detector electronics, 10.1016/j.nima.2015.11.033, 2015.
Goals of the SEE Experiment

A SEE experiment aims
- evaluating in real-time the device’s response under consecutive exposures with several beam characteristics.

The final objective
- is to obtain a good description of the device behavior and an accurate measurement of its radiation response ($\sigma(E)$ or $\sigma(LET)$ for each error mode) to enable the calculation of reliable in-flight SEE rates.
How to measure the SEE

\[
\delta (\text{LET}) = \frac{\text{Number of SEE}}{\text{Fluence}} \quad (\text{units in cm}^2)
\]

\[
\text{LET} (\theta) = \text{LET} (0^\circ) / \cos \theta
\]

\[
\text{Number of SEUs} = \text{Fluence} \times \delta (\text{LET})
\]

\[
\delta (\text{LET}) \text{ Correlated with LET}
\]

\[
\text{LET} \text{ Correlated with Particle or Ion beam Energy and Atomic mass of target material}
\]
Linear Energy Transfer (LET)

\[ \rho (LET) = \frac{N \cdot E}{F \cdot N \cdot E} \cdot \frac{cm^2}{mg} \]

\[ LET(\theta) = \frac{LET(0^\circ)}{\cos \theta} \]

30 MeV proton beam \( \rightarrow \) LET \( 1.469 \times 10^{-2} \) MeV \( cm^2 \) mg\(^{-1}\)

\[ t_{HL-LHC} = \frac{3000 \times 10^{39} \ cm^{-2}}{1.5 \times 10^{34} \ cm^{-2} \ s^{-1}} = 2.0 \times 10^8 \ s \]

\[ \sigma_{sat} \]

SEE Cross Section

\[ \sigma (LET) = \frac{\text{Number of Events}}{\text{Fluence}} \ (\text{units in cm}^2) \]

\[ LET(\theta) = LET(0^\circ) / \cos \theta \]
Mitigation Technique:
Scrubbing

Mitigation Technique:
TMR

Mitigation Technique:
ECC
Mitigation Technique:
RESET, Flash-reloading,
Power recycling

Fig. 6. Current strip chart taken during a SEL test run at TAMU, April 2014. Seven or eight SEL current-anomaly steps are clearly visible. Nominal current for this rail is 210±16 [mA].

Fig. 7. Weibull curve for current-step events observed during SEL testing. $L_a=1.9$ [MeV-cm$^2$/mg], $\sigma_w=3.16\times10^{-4}$ [cm$^2$/bit], $W=53.4$ [MeV-cm$^2$/mg], $S=3.8$. 
**Test facilities and domain of application**

- **SEE characterization** of devices requires real-time testing under exposure (functional testing mainly), and the use of particle accelerators,

- **TID assessment** implies the full parametrical characterization at different step of dose levels received (sequence of irradiation/testing phases). Mostly, 60Co sources are used for irradiating

- **DD testing** is quite similar to TID characterization as parametrical measurements and functional checking occurs at different received fluence levels (leading to an equivalent displacement damage dose - DDD6). However, DD testing requires the use of particle accelerators

<table>
<thead>
<tr>
<th>Standards</th>
<th>Effect</th>
<th>Parameters of concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA-SCC 22900.4</td>
<td>TID</td>
<td>Total dose, dose rate</td>
</tr>
<tr>
<td>MIL-STD 883E Method 1019.6</td>
<td>TID</td>
<td>Total dose, dose rate</td>
</tr>
<tr>
<td>ESA-SCC 25100.1</td>
<td>SEE</td>
<td>LET/range (heavy ions), Energy (protons)</td>
</tr>
<tr>
<td>JESD57</td>
<td>SEE</td>
<td>LET/range (heavy ions)</td>
</tr>
<tr>
<td>ESA-SCC 22900.4</td>
<td>DD</td>
<td>Energy</td>
</tr>
</tbody>
</table>
CRC facilities at Louvain-la-Neuve
Located at Louvain-la-Neuve (~20 km from Brussels)

Institut de Recherche en Mathématique et Physique (IRMP)
Center for Cosmology, Particle Physics and Phenomenology (CP3)
Centre de Ressources du Cyclotron (CRC)

Three irradiation facilities

- **NIF**: Neutron Irradiation Facility
  - Fast Neutrons (0-50 MeV)
  - Flux: $10^{11}$ n/(cm$^2$ s)

- **LIF**: Proton Irradiation Facility
  - Protons 10-60 MeV
  - Flux: $5 \times 10^8$ p/(cm$^2$ s)

- **HIF**: Heavy-Ion Irradiation Facility
  - Heavy Ion "cocktails"
  - Electronic failures induced by radiation
    (Single Event Effects)
HIF characteristics

- Two heavy ions "cocktails" covering a wide range of LET and ranges.
  - Fully characterisation of SEE response of electronic components.
  - Fast ion changing within the same cocktail (few minutes)
- Beam flux is variable between a few ions/s.cm² and \( \sim 10^4 \) ions/s.cm²
  - Can be modified from user station
  - Online monitoring \( \rightarrow \) high precision in fluence delivered
- Redundant metrology
  - Fluence and energy
  - Moving frame, alignment system
  - ESA SEU monitor: 4x4 Mbit SRAM (Atmel AT60142F) arranged in a square region of 24mm x 24mm
- Beam homogeneity of 10% on a 25 mm diameter.
- Standard mechanical interface and feedthroughs
- Irradiations are done in vacuum and for most of the ions naked chips are needed.
## HIF "cocktails"

<table>
<thead>
<tr>
<th>M/Q</th>
<th>Ion</th>
<th>DUT energy [MeV]</th>
<th>Range [µm Si]</th>
<th>LET [MeV/mg/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$^{15}$N$^{3+}$</td>
<td>60</td>
<td>59</td>
<td>3.3</td>
</tr>
<tr>
<td>5</td>
<td>$^{20}$Ne$^{4+}$</td>
<td>78</td>
<td>45</td>
<td>6.4</td>
</tr>
<tr>
<td>5</td>
<td>$^{40}$Ar$^{8+}$</td>
<td>151</td>
<td>40</td>
<td>15.9</td>
</tr>
<tr>
<td>4.94</td>
<td>$^{84}$Kr$^{17+}$</td>
<td>305</td>
<td>39</td>
<td>40.4</td>
</tr>
<tr>
<td>4.96</td>
<td>$^{124}$Xe$^{25+}$</td>
<td>420</td>
<td>37</td>
<td>67.7</td>
</tr>
</tbody>
</table>

### Cocktail 1
**High LET**

<table>
<thead>
<tr>
<th>M/Q</th>
<th>Ion</th>
<th>DUT energy [MeV]</th>
<th>Range [µm Si]</th>
<th>LET [MeV/mg/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.25</td>
<td>$^{13}$C$^{4+}$</td>
<td>131</td>
<td>292</td>
<td>1.1</td>
</tr>
<tr>
<td>3.14</td>
<td>$^{22}$Ne$^{7+}$</td>
<td>235</td>
<td>216</td>
<td>3</td>
</tr>
<tr>
<td>3.33</td>
<td>$^{40}$Ar$^{12+}$</td>
<td>372</td>
<td>117</td>
<td>10.2</td>
</tr>
<tr>
<td>3.22</td>
<td>$^{58}$Ni$^{19+}$</td>
<td>567</td>
<td>100</td>
<td>20.4</td>
</tr>
<tr>
<td>3.32</td>
<td>$^{83}$Kr$^{25+}$</td>
<td>756</td>
<td>92</td>
<td>32.6</td>
</tr>
<tr>
<td>3.54</td>
<td>$^{124}$Xe$^{35+}$</td>
<td>995</td>
<td>73</td>
<td>62.5</td>
</tr>
</tbody>
</table>

### Cocktail 2
**High penetration**

<table>
<thead>
<tr>
<th>M/Q</th>
<th>Ion</th>
<th>DUT energy [MeV]</th>
<th>Range [µm Si]</th>
<th>LET [MeV/mg/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>84Kr</td>
<td>12C</td>
<td>1H</td>
<td>1H</td>
<td>1H</td>
</tr>
<tr>
<td>56Fe</td>
<td>28Si</td>
<td>UCL</td>
<td>UCL</td>
<td>UCL</td>
</tr>
<tr>
<td>12C</td>
<td>PSI</td>
<td>IPN</td>
<td>IPN</td>
<td>IPN</td>
</tr>
<tr>
<td>1H</td>
<td>JYFL</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CMS-FLUKA Simulation**

- **Preliminary**
- **Phase-2 geometry**

$L = 3000$ fb$^{-1}$

750 cm $< R < 800$ cm
HIF: Heavy Ion Facility
UCLouvain Irradiation Test Facility

Feedthroughs

Small Flange:
- 8x BNC + 2x SHV (F/F)
- 9x BNC (F/F)
- 2x USB
- 10x SMA (F/F)
- 2x Sub D 25 (M/M)
- 2x HE 10 40 pin (M/M)
- 2x H80A2CO 40 (M/M)
- Water cooling 4-6mm hose with rack connectors input/output + Thermocouple connector

Large Flange:
- 10x BNC (F/F)
- 10x BNC (Ground isolated) (F/F)
- 10x SMA (Ground isolated) (F/F)
- 6x Sub D 25 (Cannot be dismounted) (M outside/F inside)

Transition available on request:
- Sub-D25 transition to Ethernet (M/Eth, F/Eth)
- USB transition

Behzad Boghrati, Radiation Tolerant Electronics for Phase-2 Upgrade of RPC Muon System, 2nd International Workshop on Experimental Particle Physics, 11 Nov 2020
• We measured the impact of the scrubbing core on the reliability of the benchmark design implementations in its different versions (plain and distributed TMR), corresponding to a total of five different firmwares.

• The total irradiation fluence $800 \times 10^9 \text{ cm}^{-2}$

• Average fluxes per run ranged from $2.2 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ to $3.5 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$

• Each test run consisted of the following steps
  1. power on FPGA
  2. configure the FPGA with the redundant bitstream
  3. read back configuration
  4. activate the scrubber
  5. start irradiation
  6. wait until the benchmark circuit fails permanently and log if the scrubber fails in the meanwhile
  7. stop irradiation
  8. verify FPGA configuration against the read back of step 3
  9. power off FPGA.
We measured the impact of the scrubbing core on the reliability of the benchmark design implementations in its different versions (plain and distributed TMR), corresponding to a total of five different firmwares.

- The total irradiation fluence $800 \times 10^9 \text{ cm}^{-2}$
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3. read back configuration;
4. activate the scrubber;
5. start irradiation;
6. wait until the benchmark circuit fails permanently and log if the scrubber fails in the meanwhile;
7. stop irradiation;
8. verify FPGA configuration against the read back of step 3;
9. power off FPGA.

Different parameters were measured:

1. FPGA supply voltages and currents
2. Configuration RAM (CRAM) cross-section
3. Block RAM (BRAM) cross-section
4. Data link failure rates
5. Functional Interrupt

During the experiments, CRAM and BRAM data were continuously read through JTAG interface.

New data file were compared with the previous data file and the number of differences between the two files were recorded.
TID testing with X-Ray
Summary

✓ Radiation Effects on Electronics
✓ Tests Standards and Guidelines
✓ Electronics Validation Strategy
✓ Goals
✓ How measure the Single Event Effects
✓ Which type of beam?
   ✓ Proton beam or Heavy Ion
Thank you!
References

1. Single-Event Characterization of the 28 nm Xilinx Kintex-7 Field-Programmable Gate

2. Radiation testing campaign results for understanding the suitability of FPGAs in detector electronics, 10.1016/j.nima.2015.11.033, 2015.

3. Radiation testing of electronics for the CMS Endcap muon system,


5. Radiation Hardness Studies and Evaluation of SRAM-Based FPGAs for High Energy Physics Experiments Array under Heavy Ion Irradiation
Backup Slides
Expected Fluence in RPC system (3000 fb\(^{-1}\)) vs Ultimate (4000 fb\(^{-1}\)) HL-LHC scenario

• Expected fluence in terms of 1-MeV neutron equivalent in Si, after collected 3000 fb\(^{-1}\) (in blue) and 4000 fb\(^{-1}\) (in red) is shown on the plots.

• Plot represents the upgrade iRPC region – RE3/1 and RE4/1

• All values are averaged over \(\phi\).

• The average ratio between the ultimate and base HL-LHC scenario is 1.33.

• Expected fluence
  • at R=303 cm for RE3/1 is \(\sim 4.3 (5.8) \times 10^{11} \text{ n/cm}^2\), and
  • at R=304 cm for RE4/1 it is about \(6.2 (8.2) \times 10^{11} \text{ n/cm}^2\),
  • where R=303 (304)cm are the expected FEB positions

• Safety factor of 3 is not included.

• The systematic uncertainty is yet to be fully qualified?
Expected Dose in RPC system (3000 fb⁻¹) vs Ultimate (4000 fb⁻¹) HL-LHC scenario

• Absorbed dose after collected 3000 fb⁻¹ (in blue) and 4000 fb⁻¹ (in red) is shown on the plots.

• All values are averaged over φ.

• The highest value at 165 cm is systematic and is caused by the geometry differences and larger Z bin (Z bin = 10 cm).

• Thus the value in the Z bin is averaged over RPC material and air.

• The average ratio between the values from the ultimate and base HL-LHC scenario is 1.33.

• Expected dose
  • at R=303 cm for RE3/1 is ~10 (13.6) Gy
  • at R=304 cm for RE4/1 it is about 18 (24) Gy
  • where R=303 (304)cm are the expected FEB positions

• Safety factor of 3 is not included
• The systematic uncertainty is yet to be fully qualified
• The **Link system** will be installed on the **Balcony of CMS**, where the rates are even lower than what we have at the periphery of the detector.

• **Total Irradiation Dose** is **0.001-10 Gy @ 3000fb⁻¹**

• **Neutron Flux** at the **CMS Balcony** is **1x10⁴ cm⁻²s⁻¹ @5 x 10³⁴ cm⁻²s⁻¹**

• **Neutron Fluence for 10 HL-LHC years** is **1x10¹² cm⁻²**

• The new Link board components have been chosen from COTS which are validated for radiation at the level of **300 Gy**

• The FPGA TID KINTEX-7 (XC7K160T) is **3400-4500 Gy**

• **Scrub Time of entire FPGA (Real time SEU detection and Correction) : 13ms**

• The Single Event upset (SEU) rate on **configuration memory** is **1 SEU every 413 sec.** and **1 SEU every 1695 sec. at Block RAM**

• **TMR** and **Configuration Scrubbing** will mitigate the SEUs
Device characterization with heavy ions

- The SEU sensitivity of a circuit is most conveniently tested with heavy-ion irradiations.

- The results of the heavy ion irradiation are most conveniently represented by a Weibull fit, which as a function of the deposited ionization energy $E_{\text{dep}}$ has the form

$$
\sigma = \sigma_0 \left(1 - \exp\left\{-\left[\frac{E_{\text{dep}} - E_0}{W}\right]^s\right\}\right)
$$

- Here $W$ and $S$ are shape parameters
- $\sigma_0$ is the saturation value of the SEU cross section
- $E_0$ the SEU threshold

- Thus there are four free parameters to be fitted.
- We can observe a very sharp threshold (red dots) below which the circuit does not upset.
- Above this threshold the upset rate first increases rapidly and then slowly saturates. This saturation corresponds to the situation where all sensitive regions of the device upset when hit by an ion so that a further increase of LET has no effect.

Weibull fit to experimental heavy ion data for the ASSC4008CW-35E, 4Mbit SRAM from Austin [7]. We have assumed a sensitive depth of 1 μm to convert from LET to Edep.
Electronics validation Strategy

1. **Obtain** the SEU cross section of FPGA resources (Configuration Memory, BRAM, MGTs, FFs)
2. **Estimate** of the Upset rate within the CMS radiation environment
3. **Cold-Test**, **Fault injection in Lab and Evaluation of the rad-hard techniques**
4. **Hot-Test**, **(SEE) Evaluation of the rad-hard techniques** adopted during the experiments must prevent build up of errors in different FPGA parts
5. **Full Electronics Test (TID)**, Check the fault resilience of all electronics active devices such as FPGA, Digital and Analog ASICs, under X-Ray at 1 MeV Neutron Equivalent energy. Exactly similar to Medical irradiation treatment.
SEU Mitigation on FPGA

- **SEU**: Ionizing radiation with enough energy is capable of altering the state of an integrated circuit causing a single event upset (SEU).

- Three main memory elements that are subject to SEUs:
  1. Configuration Memory (CRAM)
  2. Block Memory BRAM
  3. Flip-flops

✓ **SEU mitigation**

1. **SEU in the Configuration Memory (CRAM)** ->
   - Internal Scrubbing: SEM IP core
   - External Scrubbing: GBTx + GBT-SCA
   - Hybrid Scrubbing: SEM IP core + GBTx + GBT-SCA
   - Blink Scrubbing: Periodic Re-configuration at end of every orbit, (Legacy Link System)

2. Block Memory BRAM -> **built-in error correction (ECC; Hamming, Read-Solomon)**

3. Flip-flops -> **TMR**