Investigation of radiation damage effects in the CMS pixel detector

Danyyl Brzhechko on behalf of the CMS collaboration

TIPP 2021
Introduction
CMS Pixel detector

- CMS Pixel detector is the innermost part of CMS
- Two main parts: Barrel Pixel and Forward Pixel detectors
- An upgraded Pixel detector was installed in the beginning of 2017
- Leakage current and depletion voltage studies are done for 2017-2018 years of operation for full CMS pixel detector
Leakage current studies
Leakage current simulation

- Change in leakage current due to irradiation:
  \[ \Delta I_{\text{leak}}(t, T; \Phi_{\text{eq}}) = \alpha(t, T) \Phi_{\text{eq}}(r, z) V \]

- Fluence distribution: \( \Phi_{\text{eq}} \sim r^{-1.5} \) and almost flat vs \( z \)

- In FPix, modules cover wide range of \( r \):
  \[ \Delta I_{\text{leak}}(t, T; \Phi_{\text{eq}}) = \alpha(t, T) \int \Phi_{\text{eq}}(r, z) dV = \alpha \langle \Phi_{\text{eq}} \rangle_V V, \]
  \( \langle \Phi_{\text{eq}} \rangle_V \) is the average fluence over a module volume.

- Leakage current at the end is scaled to a reference temperature \( T_{\text{ref}} \) using:
  \[ I_{\text{leak}}(T_{\text{ref}}) = I_{\text{leak}}(T) \cdot \left( \frac{T_{\text{ref}}}{T} \right)^2 \exp \left( - \frac{E_g^*}{2k_B} \left( \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right) \right) \]

Leakage current results: Layer 1

- Leakage current data and simulation per module, scaled to $T_{\text{ref}} = T_{\text{module}}$

- $T_{\text{module}} = \text{temperature reading during operation} + 3\, ^{\circ}\text{C}$ (from mock-up studies, T-sensors not on the modules, near CO$_2$ cooling pipe)

- Good agreement for Layer 1
Leakage current results: Layers 2-4

- Leakage current data and simulation per module, scaled to $T_{ref} = T_{module}$
- $T_{module}$ = temperature reading during operation + 3°C (from mock-up studies, T-sensors not on the modules, near CO$_2$ cooling pipe)
- Underestimation by about a factor of 2. Scale factor is needed.
- Discrepancy in Layer 2, 3 and 4 might be caused by temperature mismodeling

CERN Yellow Report: https://doi.org/10.23731/CYRM-2021-001
Leakage current results: Forward Pixel, Ring 1

- Leakage current data and simulation per volume, scaled to $T_{ref} = 0^\circ C$
- T-sensors on-top of the HDI, much better temperature data than for BPix
- Good agreement between data and simulation for Ring 1. No scale factor required
- FLUKA prediction reliable in full z range of FPix ($|z|$ from 32 to 50 cm)
- Discrepancy at the start of run periods in 2017 and 2018 probably due to temperature underestimation

<table>
<thead>
<tr>
<th>$\Phi_{eq}$ Disk</th>
<th>Disk 1</th>
<th>Disk 2</th>
<th>Disk 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final fluence ($L_{int}=120$ fb$^{-1}$)</td>
<td>$1.71 \cdot 10^{14} n_{eq}/cm^3$</td>
<td>$1.62 \cdot 10^{14} n_{eq}/cm^3$</td>
<td>$1.56 \cdot 10^{14} n_{eq}/cm^3$</td>
</tr>
</tbody>
</table>

CERN Yellow Report: https://doi.org/10.23731/CYRM-2021-001
Leakage current results: Forward Pixel, Ring 2

- Leakage current data and simulation per volume, scaled to $T_{ref} = 0^\circ C$
- $T$-sensors on-top of the HDI, much better temperature data than for BPix
- Good agreement between data and simulation for Ring 2. No scale factor required
- FLUKA prediction reliable in full z range of FPix ($|z|$ from 32 to 50 cm)
- Discrepancy at the start of run periods in 2017 and 2018 probably due to temperature underestimation

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Phase-1 Forward Pixel - Leakage current vs day

Leakage current results:

- Forward Pixel, Ring 2
- Leakage current data and simulation per volume, scaled to $T_{eq} = 0^\circ C$
- $T$-sensors on top of the HDI, much better temperature data than for BPix
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Final fluence ($L_{int} = 120$ fb$^{-1}$)

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<tr>
<th>$\Phi_{eq}$</th>
<th>Disk 1</th>
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<tbody>
<tr>
<td>$n_{eq}/cm^3$</td>
<td>$0.81 \cdot 10^{14}$</td>
<td>$0.78 \cdot 10^{14}$</td>
<td>$0.76 \cdot 10^{14}$</td>
</tr>
</tbody>
</table>

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CERN Yellow Report: https://doi.org/10.23731/CYRM-2021-001
Depletion voltage studies
Depletion voltage

- Depletion voltage $V_{\text{depl}}$:

$$V_{\text{depl}} = \frac{ed^2}{2\varepsilon\varepsilon_0 |N_{\text{eff}}|}$$

- $N_{\text{eff}}$ - effective doping concentration, $d$ - module thickness

- $N_{\text{eff}} = N_{\text{eff}}(\Phi_{eq}, t, T; g_C, g_A, g_Y; \ldots) = N_C + N_A + N_Y + N_{dr}$

- $g_C, g_A, g_Y$ are the parameter sets

- Two parameter sets are considered: RD48-oxy and CB-oxy

- Fit of $g_C$ for FPix ($g_A$ and $g_Y$ fixed)

- Non-linear dependence of the constant damage rate was tested for FPix and Layer 1 BPix using $N_C(\Phi_{eq}) = g_C \log \ln(\Phi_{eq})$ as an empiric model

- In order to fully deplete a sensor of FPix, the fluence of the innermost part ($r \sim 4.5$ for ring 1, $r \sim 9.5$ cm for ring 2) is taken in the depletion voltage simulation

- Depletion voltage data is determined from the cluster charge (for BPix also from cluster size) vs bias voltage

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$V_{\text{dep}}$ [V] (d = 300,um) vs $\Phi_{eq}$ [10^{12} cm^{-2}] for n-type and p-type

$N_{\text{eff}}$ [10^{11} cm^{-2}] vs $\Phi_{eq}$ [10^{12} cm^{-2}]

CMS Preliminary 2018 $\sqrt{s} = 13$ TeV

Increasing $L_{\text{int}}$

Avg. Norm. On-Tri Clu. Charge (ke)

Layer 2 (four modules)

$L_{\text{int}} = 0.5$ pb^{-1}

$L_{\text{int}} = 4.6$fb^{-1}

$L_{\text{int}} = 8.7$fb^{-1}

$L_{\text{int}} = 14.9$fb^{-1}

$L_{\text{int}} = 21.8$fb^{-1}

$L_{\text{int}} = 25.4$fb^{-1}

$L_{\text{int}} = 31.5$fb^{-1}

$L_{\text{int}} = 40.5$fb^{-1}

$L_{\text{int}} = 48.5$fb^{-1}

$L_{\text{int}} = 53$fb^{-1}

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Depletion voltage results. BPix

- CB-oxy parameter set is considered for the simulation
- The full depletion voltage is estimated from the fit of the cluster charge
- Layer 1 to be replaced during LS2. Layer 2 depletion voltage to be expected at 650 V at the end of Run 3

**Barrel pixel detector**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Formula</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 4</td>
<td>$n=0 \Rightarrow r=16.0 \text{ cm}, 0.5 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
<td></td>
</tr>
<tr>
<td>Layer 3</td>
<td>$n=0.5 \Rightarrow r=10.9 \text{ cm}, 0.9 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
<td></td>
</tr>
<tr>
<td>Layer 2</td>
<td>$n=1.0 \Rightarrow r=6.6 \text{ cm}, 1.8 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td>$n=2.9 \Rightarrow r=2.9 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
<td></td>
</tr>
</tbody>
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**Forward pixel detector**

<table>
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<tr>
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<th>Density</th>
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<tr>
<td>Disk 1</td>
<td>$n=1.5 \Rightarrow r=50.0 \text{ cm}, 0.5 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
</tr>
<tr>
<td>Disk 2</td>
<td>$n=2.0 \Rightarrow r=50.0 \text{ cm}, 0.5 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
</tr>
<tr>
<td>Disk 3</td>
<td>$n=2.5 \Rightarrow r=50.0 \text{ cm}, 0.5 \cdot 10^{14} \text{n}_{\text{cm}}/\text{cm}^2$</td>
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</table>
Depletion voltage Layer 1: non-linear model

- Depletion voltage data and simulation using linear and non-linear models for constant damage rate:
  - Fit of $g_C$ parameter was done to depletion voltage data for Layer 1
  - Logarithm dependence shows much better agreement than linear ($\chi^2_{\text{lin}} \gg \chi^2_{\text{log}}$)

Phase-1 Barrel Pixel - Full depletion voltage vs day

The depletion voltage value and uncertainty was estimated from the cluster charge distributions (top plot) as the intercept of two regimes: under-depleted (green) and fully depleted (red) sensors.

CERN Yellow Report: https://doi.org/10.23731/CYRM-2021-001
Depletion voltage: Ring 1, Disk 1

- Fit of $g_C$ parameter, assuming linear model, with $g_A=1.4 \times 10^{-2} \text{ cm}^{-1}$, and $g_Y=7 \times 10^{-2} \text{ cm}^{-1}$ fixed
- Data is obtained from the average cluster charge distribution vs. bias voltage - kink of the distribution
- Fit is done only for 2018 data points
- Logarithmic model for $N_C$ tested - try to find an effective empiric model
- Final fluence assumed for the innermost slice of Ring 1, Disk 1: $3.32 \times 10^{14} n_{eq}/cm^2$

Final fluence of the innermost slice of the module for Run 2 ($10^{14} n_{eq}/cm^2$), $L_{int}=120 \text{ fb}^{-1}$

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<td>3.32</td>
<td>2.99</td>
<td>2.92</td>
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<tr>
<td>Ring 2</td>
<td>1.15</td>
<td>1.11</td>
<td>1.09</td>
</tr>
</tbody>
</table>

CERN Yellow Report: https://doi.org/10.23731/CYRM-2021-001
Depletion voltage: Ring 1, Disk 3

- Fit of $g_C$ parameter, assuming linear model, with $g_A = 1.4 \times 10^{-2}$ cm$^{-1}$, and $g_Y = 7 \times 10^{-2}$ cm$^{-1}$ fixed
- Data is obtained from the average cluster charge distribution vs. bias voltage - kink of the distribution
- Fit is done only for 2018 data points
- Logarithmic model for $N_C$ tested - try to find an effective empiric model
- Final fluence assumed for the innermost slice of Ring 1, Disk 3: $2.92 \cdot 10^{14}$ $n_{eq}/cm^2$

Final fluence of the innermost slice of the module for Run 2 ($10^{14}$ $n_{eq}/cm^2$), $L_{int} = 120$ fb$^{-1}$

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Conclusions
Conclusions

- Leakage current studies:
  - Good agreement for Layer 1, scale factor of -2 is needed for Layer 2-4
  - Good agreement for FPix (no need for scale factors, better knowledge of the temperature)

- Depletion voltage studies:
  - BPix: underestimation for Layers 2-4, underestimation in 2017 and overestimation at the end of 2018 for Layer 1
  - FPix: fit results for $g_c$ parameter is close to “-oxy” models.
  - Logarithmic dependence of $N_C$ on fluence was tested on Layer 1: much better agreement ($\chi^2/\text{ndof} = 1.1$) than for linear dependence ($\chi^2/\text{ndof} = 19.3$)
  - Plans: studies of logarithmic dependence for Layers 2-4
Thank you!
Back up
## Functions and constants

<table>
<thead>
<tr>
<th>Function, relation or constant</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time/temperature scaling function</strong></td>
<td>( \Theta(T; T_{ref}) = \exp \left( -\frac{E_l^*}{k_B \left( \frac{1}{T} - \frac{1}{T_{ref}} \right)} \right) )</td>
</tr>
<tr>
<td><strong>Arrhenius law</strong></td>
<td>( \frac{1}{\tau_l} = k_{0l} \cdot \exp \left( -\frac{E_l}{k_B T} \right) )</td>
</tr>
<tr>
<td>( \alpha_l )</td>
<td>((1.23 \pm 0.06) \cdot 10^{-17} \ [A \ cm^{-1}])</td>
</tr>
<tr>
<td>( k_{0l} )</td>
<td>((1.23^{+5.3}_{-1.0}) \cdot 10^{13} \ [s^{-1}])</td>
</tr>
<tr>
<td>( E_l )</td>
<td>(1.11 \pm 0.05 \ [eV])</td>
</tr>
<tr>
<td>( \alpha_0^* )</td>
<td>(7.07 \cdot 10^{-17} \ [A \ cm^{-1}])</td>
</tr>
<tr>
<td>( \xi )</td>
<td>(3.07 \cdot 10^{-18} \ [A \ cm^{-1}])</td>
</tr>
<tr>
<td>( E_l^* )</td>
<td>(1.30 \pm 0.14 \ [eV])</td>
</tr>
<tr>
<td>( E_g^* )</td>
<td>(1.21 \ [eV])</td>
</tr>
<tr>
<td>( k_B )</td>
<td>(8.6173303 \cdot 10^{-5} \ [eV \ K^{-1}])</td>
</tr>
</tbody>
</table>
## Parameter sets

<table>
<thead>
<tr>
<th>Parameter set name</th>
<th>Constants ($10^{-2} \text{ cm}^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutrons</td>
<td>Protons</td>
</tr>
<tr>
<td></td>
<td>$g_A$</td>
<td>$g_Y$</td>
</tr>
<tr>
<td>CB-oxy</td>
<td>1.4</td>
<td>5.7</td>
</tr>
</tbody>
</table>