Radiation effects in the CMS phase 1 pixel detector

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CMS phase 1 pixel detector

- 4 hit coverage and high-rate capability
- Turbine-like structure for endcap disks for optimal resolution
- CO₂ cooling for reduced material
- DCDC converters to keep same powering services → 9V supplied
- Uniform module design throughout

<table>
<thead>
<tr>
<th>Fluence</th>
<th>Inner Area</th>
<th>Outer Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8 Mrad</td>
<td>$5 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$</td>
<td>$\eta=0$</td>
</tr>
<tr>
<td>5.2 Mrad</td>
<td>$9 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$</td>
<td>$\eta=0.5$</td>
</tr>
<tr>
<td>8.5 Mrad</td>
<td>$1.8 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$</td>
<td>$\eta=1.0$</td>
</tr>
<tr>
<td>40.1 Mrad</td>
<td>$7.9 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$</td>
<td>$\eta=1.5$</td>
</tr>
</tbody>
</table>

- L1: r=29mm
- L2: r=66mm
- L3: r=109mm
- L4: r=160mm

- Beam pipe: r=22.5mm
- Optical links
- 2x3 endcap disks
- CO₂ cooling loop
- 2.4, 3V

Fluences as of today, from FLUKA 3.23.1.0
Module design

Readout chips (ROCs): 80x52 pixels, 250nm CMOS ASIC, pulse height digital readout

Endcap disks 1-3
- 672 modules
- 40-100 MHz/cm²
- PSI46dig: column drain
- 2 TBM readout channels
- Functions up to 150 Mrad

Barrel layer 1
- 96 modules
- 580 MHz/cm²
- PROC600: dynamic cluster column drain
- 8 TBM readout channels
- Functions up to 480 Mrad

Barrel layer 2-4
- 1088 modules
- 40-100 MHz/cm²
- PSI46dig: column drain
- 2 TBM readout channels (L3,L4) / 4 TBM readout channels (L2)
- Functions up to 150 Mrad
LHC: a challenging environment

Radiation effects are challenging for operations and performance:

- Damage and single event upsets (SEUs) in electronics
  - false signals, chip damage
- Bulk defects cause change of space charge distribution
  - bias voltage increase
- Increasing leakage currents and heat dissipation
- Charge trapping in sensor:
  - decreasing charge collection efficiency

Will the inner detectors survive?

2017+2018: 118 fb$^{-1}$
2018: 68 fb$^{-1}$
Impact on performance and data

- Radiation effects clearly seen in Lorentz angle evolution and pixel charge profile
- Effects can be reduced by increasing bias voltage and performing annealing
- Decrease in charge collection efficiency taken into account in simulation using PixelAV and TCAD.

Normalized average pixel charge vs sensor depth:
- flat for unirradiated sensors
- increase for 350 → 400V and annealing
- decrease with further irradiation

Thresholds:
Endcaps: 1500 e⁻
L2-4 12000e⁻
L1: 2100e⁻
Relatively constant over time
Radiation effects on depletion voltage

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

Regular sensor bias voltage scans on subset of representative modules
Simulation with effective space charge Hamburg model ($E_{\text{eff}}=1.21$ eV), fluence from DPMJet + FLUKA 3.23.1.0

Run 3 depletion voltages expected to be within power supply limit of 800V.

Operational voltages at end of run 2:
- L1: 450V
- L2: 300V
- L3-L4: 250V
- Ring 1: 350V
- Ring 2: 300V

CMS pixel operations
Leakage currents

- Leakage currents in L2-4 underestimated by about a factor of 2
- Main uncertainties from temperature modeling and particle generator + FLUKA → work on improvements in modeling foreseen
- Prediction for run 3: safely below the operational limit of the power supplies of 20mA.

CMS pixel operations
Leakage currents vs z

Leakage current seems consistently higher for lower z. ATLAS sees a similar effect.

No effect seen on layers other than innermost:

Preliminary: needs further studies.

See Sally Seidel’s talk
CO$_2$ cooling

Important to understand detector temperatures for radiation effects:

- ✓ -22°C, option to go lower
- ✓ 1.7mm ø stainless steel cooling loops
- ✓ wall thickness 50μm
- ✓ very lightweight
- ✖ gradient of 4-5K along cooling loop
- ✖ efficient cooling but no efficient heating which can be problematic for targeted annealing or safety

Increasing the flow did decrease some gradient but still a non-negligible pressure drop along cooling loop: under investigation

CMS-TDR-011

CMS pixel operations
Temperature studies with a mockup of layer 2

Realistic layer 2 half-shell mechanics and CO$_2$ cooling with adjustable heat load on pseudo-modules with temperature sensors

Thermal mockup indispensable:
- temperature modeling is a large uncertainty for simulation
- few temperature sensors in the detector

Mockup results agree well with detector results
Radiation effects in electronics

CCU misbehavior:
- 1/300pb\(^{-1}\) reset portcard → reprogram
- 1/month reset DCDCs

From Klaas Padeken

Front end controllers/drivers

TBM
- 30/fb\(^{-1}\) in L1 transistor in TBM flipflop sets TBM to ‘no readout’ mode: “stuck TBMs”
- recovery only with power cycle

From Benedikt Vormwald

Power supplies

Irradiated DCDCs stop functioning in disabled state (not an SEU)
- 63/1216 at end of 2017 stopped functioning
- 333/1216 in 2017 found to have high current

Compensation for chip radiation effects in offline reconstruction

ROC: solved by reprogramming
DCDCs

- SEU in transistor in TBM flipflop sets TBM to ‘no readout’ mode → powercycle TBM
- Powercycled with DCDCs (lowest amount of modules) in 2017
- Increased leakage current in DCDCs after irradiation causes charging up of capacitor in disabled state ← design mistake in layout around one transistor:
- High and low voltage group granularity not the same: damaged modules from HV on where DCDCs were broken → LV off.

Disconnected DCDCs: for safety switched off entire power supply (LV and HV). No DCDC broke in 2018!

From Federico Faccio
Radiation effects: on-track cluster charge

In long shutdown 2017-2018: replaced 6 of 8 layer 1 modules damaged by high voltage leakage current

No impact on hit efficiency!

Annealed

Operational voltage 450V

CMS pixel offline
Summary and lessons learned

- Successful commissioning of CMS pixel detector since start of 2017
- Despite many challenges, pixel detector performed very well in 2017 and 2018
- Good to have test setups to study:
  - CO$_2$ cooling with adjustable heat load for understanding
    - module temperatures
    - radiation effects
- HV and LV granularity: Ideally the same
- Monitoring temperatures, chip properties important for studying radiation effects
Spares
Inner layer chip: crosstalk, inefficiency, timing

- Layer 1 timing very different from layer 2
- High thresholds resulting from crosstalk and large timewalk
- Inefficiency at high and low rates
- Distribution of pedestals in analog pulse height large, \( \sim 80 \) ADC units

All solved/addressed in next L1 chip version.
**CO₂ cooling**

**A→B:** CO₂ pressure is increased for transfer to the experiment

**B→C:** temperature increases from heat exchange with returning CO₂

**C→D:** pressure inside the detector is reduced to reach onset of evaporation

**D→E:** heat from the detector is absorbed

**E→F:** CO₂ liquid/vapor mixture condensates on incoming colder CO₂ pipe

**F→G:** CO₂ is cooled with main chiller

**G:** temperature in detector is regulated with pressure in accumulator: 
D-G low impedance system with ~constant pressure back to D

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From KEK

Image: CMS-TDR-011
DCDC malfunctioning

- Probability of breaking DCDC in disabled state peaks at a certain dose and diminishes after.

Enclosed layout (ELT) vs linear transistors → can ‘cut’ leakage current path by adding ELT in series

- Capacitor charges up in disabled state and causes spikes beyond 3.3V.

From Federico Faccio
Cluster charge vs depth: grazing angle method

- Ionizing particles arriving at shallow angle create pixel “signal street”
- Each pixel in the street has a charge from part of the track from a certain depth segment
- Compute drift and depth from track and pixel position and $\alpha, \beta$
- Project 3D histogram of drift, depth, and charge along drift path to obtain charge vs depth.

$\alpha = \text{grazing angle}$
$\beta = \text{mean arrival position (mean surface charge deflection)}$
$\Theta_L = \arctan(\tan(\beta)/\tan(\alpha)) = \text{Lorentz angle}$

From Henrich and Kaufmann