Performance of the
Online Radiation Dose Monitoring System
in ATLAS experiment

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on behalf of the ATLAS Collaboration

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The ATLAS experiment

- experiment at the Large Hadron Collider at CERN
- proton-proton collisions: $E_p = 13\text{ TeV}$, Luminosity $\sim 2 \cdot 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
Radiation Field in ATLAS

- secondary particles from p-p interaction point
- radiation from interaction of secondary particles with detector material

Expected radiation levels in the innermost layers (integrated luminosity ~ 500 fb⁻¹):

- Total Ionizing Dose (TID):
  \[ TID > 10^6 \text{ Gy} \]

- Displacement damage caused by Non Ionizing Energy Loss (NIEL):
  \[ \Phi_{eq} > 10^{15} \text{ n/cm}^2 \]
  (1 MeV neutron equivalent in Si)

  ➔ such radiation levels cause damage to detectors and readout electronics

Aim of radiation monitoring system:
  ➔ monitor doses to understand detector performance
  ➔ cross check radiation background simulations

Online (remote readout) system:
  ➔ difficult (if possible at all) access to replace passive dosimeters
  ➔ frequent measurements
TID measurements with RadFETs

- RadFETs: p-MOS transistor
- Holes caused by radiation get trapped in the gate oxide:
  
  \[ \Delta V = a \times (TID)^b \]
  
- Sensitivity and dynamic range depend on oxide thickness:

**Inner detector (high doses):**
- 3 RadFETs at each monitoring location:
  - LAAS 1.6 µm; REM 0.25 µm;
  - REM 0.13 µm

**Other locations (lower doses):**
- LAAS 1.6 µm

Displacement damage measurements with diodes

• displacement damage in silicon:
  increased resistance, reduction of carrier lifetime, increase of reverse current

⇒ forward bias: voltage at given forward current increases
⇒ reverse bias: reverse current increases

Forward bias

• linear response over wide range of fluences $\Delta V = k \cdot \Phi_{eq}$
• high sensitivity diode (CMRP, University of Wollongong, AU) $10^9$ to $10^{12}$ n/cm$^2$,
• commercial (Osram) silicon PIN photodiode BPW34F $10^{12}$ to $10^{15}$ n/cm$^2$

Displacement damage measurements with diodes

Reverse bias

Reverse current proportional to fluence \( \Delta I = \Phi_{eq}/\alpha V \)

- 25 \( \mu \)m x 0.5 cm x 0.5 cm pad diode with guard ring structure processed on epitaxial silicon
  - thin epitaxial diode can be depleted with \( V_{bias} < 30 \) V also after irradiation with \( 10^{15} \) n/cm\(^2\)
  - in this fluence and time range \( V_{bias} \) does not increase with annealing

- sensitive from \( 10^{11} \) n/cm\(^2\) to \( 10^{15} \) n/cm\(^2\)
- relatively large annealing corrections needed
• bipolar transistors of same type as in front end ASICs of the SCT
• measure base current at 10 µA collector current
  ➔ monitor status of front end electronics
  ➔ sensitive to fast and thermal neutrons

\[
\Delta I_b = k_{eq} \cdot \Phi_{eq} + k_{th} \cdot \Phi_{th};
\]

\[k_{eq}, k_{th}\text{ from calibration, } \Phi_{eq}\text{ measured with diodes } \rightarrow \Phi_{th}\text{ can be determined}\]

For more info see:

No significant effect of thermal neutrons seen ➔ not possible to estimate thermal neutron fluences
**Radiation Monitor Sensor Board (RMSB)**

**Inner Detector**

- for dose monitoring in the Inner Detector:
  - large range of doses
  - no access
  ➔ need many sensors

• large temperature variations (5 to 20°C) at some locations
  ➔ stabilize temperature to 20 ± 1 °C by heating back side of the ceramic hybrid

**CMRP diode**

**BPW34 diode**

**Thermistor**

**epi diode**

**Radfet package:**

- 0.25 µm SiO₂
- 1.6 µmSiO₂
- 0.13 µmSiO₂

**Bipolar transistors**

**Ceramic hybrid (Al₂O₃)**

**Thick film resistive layer** \( R = 320 \, \Omega \)

4 cm

Back side
Radiation Monitor Sensor Board (RMSB)

Monitors at larger radii

- lower dose ranges
  \(\text{mGy to 10 Gy, } 10^9 \text{ to } \sim 10^{12} \text{ n/cm}^2\)

- no temperature stabilization
  \(\Rightarrow\) correct read out values with known temperature dependences

![Image of a radiation monitor sensor board with components labeled CMRP diode, Thermistor, and LAAS radfet (1.6 µmSiO\(_2\)).]
Simulations

- dataset of 50000 events generated by Pythia 8, inelastic cross section of 78.42 mb at $\sqrt{s} = 13$ TeV
- events processed with FLUKA 2011 or Geant4
- simulations are based on 3D detector model but radiation maps used in this work are averaged in azimuthal angle

More info: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/RadiationSimulationPublicResults

Integrated luminosity $L_{int}$ is a measure of number of proton-proton collisions

$\Rightarrow$ Simulated dose (fluence): $D = D_{norm} \cdot L_{int}$

$I. Mandić, ANIMMA 2019, Portorož, Slovenia, June 17 - 21 2019$
### Monitoring Locations

- 14 monitors in the Inner Detector

| Location               | $r$ (cm) | $|z|$ (cm) |
|------------------------|----------|-----------|
| Pixel Support Tube (PST) | 23       | 90        |
| ID end plate small r   | 54       | 345       |
| ID end plate large r   | 80       | 345       |
| Cryostat Wall          | 110      | 0         |
Results Inner Detector (ID)

TID measured with 0.13 um RadFET

**ATLAS Preliminary**
Inner Detector, Run 2 (2015 - 2018)

Pixel Support Tube

Black: PYTHIA8+Geant4 simulation
\[ r = (23 \pm 1) \text{ cm} \]
\[ z = (90 \pm 4) \text{ cm} \]

\( \Phi_{eq} \) measured with BPW34 diodes (forward bias)

**ATLAS Preliminary**
Inner Detector, Run 2 (2015 - 2018)

Pixel Support Tube

Red: measurements, BPW34 diodes
Black: PYTHIA8+Geant4 simulation
\[ r = (23 \pm 1) \text{ cm} \]
\[ z = (90 \pm 4) \text{ cm} \]

**ATLAS Preliminary**
Inner Detector, Run 2 (2015 - 2018)

Pixel Support Tube

Blue: measurement, epitaxial diodes
Black: PYTHIA8+Geant4 simulation
\[ r = (54 \pm 2) \text{ cm} \]
\[ z = (345 \pm 3) \text{ cm} \]

\( \Phi_{eq} \) measured with epi diodes (reverse bias)

- averages of measurements with sensors at same \( r, z \) are shown
  - good agreement with simulations!
• dozes/fluence per integrated luminosity

→ integrated luminosity causing radiation exposure in Run 2 estimated to $160 \text{ fb}^{-1} \pm 3 \text{ fb}^{-1}$

• averages of measurements with sensors at same $r,z$ are shown

→ good agreement with Geant4 and Fluka simulations!
Monitoring at larger radii

**ATLAS** Preliminary

Muons, Run 2 (2015 - 2018)

Small Wheels \( r \sim 2.1 \text{ m}, z \sim 6.9 \text{ m} \)
Big Wheels \( r \sim 1.8 \text{ m}, z \sim 13 \text{ m} \)

Coloured bands: PYTHIA8 + Geant4
Red: \( r = (2.1 \pm 0.1) \text{ m}, z = (6.9 \pm 0.1) \text{ m} \)
Blue: \( r = (1.8 \pm 0.1) \text{ m}, z = (13.0 \pm 0.1) \text{ m} \)

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Monitoring at larger radii

- 22 monitors near readout electronic equipment of LAr and Tile calorimeters
- monitors at several azimuth angles

⇒ average over monitors at same \( r, z \) but different \( \phi \)

- simulation in 3D but dose maps averaged over phi
- uncertainties of material distribution large in this region ⇒ not included in the error bars of simulation points
Sensors with different sensitivity at each monitoring location in the ID enabled dose/fluence measurements and comparison with simulation from the start of LHC operation!
Summary

• system for remote measurements of integrated total ionizing doses (TID) and non-ionizing energy loss (NIEL) in silicon

  ➔ RadFETs for TID, diodes for NIEL

• usage of sensors with different sensitivities enabled measurements over wide range of doses and fluences

• measurements compared to simulations of radiation background in the ATLAS detector

  ➔ good agreement with simulation in the Inner Detector

  ➔ agreement found also at larger radii where the detector geometry is very complex

• measurements of radiation background and comparisons with simulation are important to understand and predict detector performance and to cross check simulation which sets the requirements for radiation tolerance for parts to be installed during ATLAS upgrade