The ATLAS Radiation Dose Measurement System

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The ATLAS Experiment

Proton-proton collisions at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$
Motivation and Measured Quantities

Why care about radiation dose levels?

- Irradiation changes the performance of detectors and electronics!

Measured quantities:

1. **Total Ionizing Dose (TID)**
   - Mainly due to photons, electrons and positrons
   - Measured in Gray (Gy), \( 1 \text{ Gy} = 1 \text{ J/kg} \)
   - Problem to MOS and bipolar devices

2. **Non Ionizing Energy Loss (NIEL) / equivalent fluence (\( \Phi_{eq} \))**
   - Hadrons cause displacement damage in silicon
   - Expressed in 1 MeV neutron equivalent fluence \( (n/\text{cm}^2) \)
   - \( \Phi_{eq} = \kappa \Phi = \int \frac{D(E)\phi(E)\,dE}{D(E_n=1 \text{ MeV})} \)

3. **Thermal neutron fluence**
Radiation Field in ATLAS

- Exposure of electronics to:
  - radiation from pp-collisions (mainly pions)
  - neutrons from interactions of hadrons with detector material

- After 10 years of LHC operation electronics irradiated up to:
  - Total Ionizing Dose: TID > 100 kGy
  - Non Ionizing Energy Loss $\Phi_{eq} > 10^{15}$ 1 MeVn/cm$^{-2}$

- Monitoring of radiation levels needed in order to:
  - cross check simulations
  - understand change in detector performance
  - and as independent measurement

Non Ionising Energy Loss in the ATLAS Inner Detector

FLUKA simulation by Ian Dawson
Radiation Field at SLHC

- Luminosity: $\mathcal{L}(\text{SLHC}) \approx 10 \times \mathcal{L}(\text{LHC})$
- Ionizing dose scales with luminosity: $\text{TID}(\text{SLHC}) \approx 10 \times \text{TID}(\text{LHC})$
- Upgrade of ATLAS tracker to full silicon → loss of moderating effect of the Transition Radiation Tracker → NIEL not expected to scale with luminosity → as compensation introduce a 5 cm thick moderator
Total Ionizing Dose (TID) Measurement - RadFETs

- **RadFET**: Radiation Field Effect Transistor
- Electrons escape, holes are trapped in SiO$_2$-Si boundary.
- Higher negative gate voltage needed to open transistor.
- Measure gate voltage increase at given drain current. $\Delta V = a \times (TID)^b$
- Sensitivity depends on oxide thickness
- Three RadFETs used in ATLAS to cover large range of doses:
  - 0.01 Gy to 10 Gy: 1.6 $\mu$m from CNRS LAAS, Toulouse, France
  - up to $10^4$ Gy: 0.25 $\mu$m from REM, Oxford, UK
  - up to $10^5$ Gy: 0.13 $\mu$m from REM, Oxford, UK
Response curves of RadFETs in use

1.6 µm LAAS RadFET
0.01 Gy to 10 Gy

0.25 µm REM RadFET
up to $10^4$ Gy
Non Ionising Energy Loss (NIEL) Measurement (1)

**First Method:** Bulk damage in forward biased p-i-n diode

- NIEL causes bulk damage in silicon
- ⇒ reduced minority carrier lifetime in a p-i-n diode
- ⇒ increase of resistance
- ⇒ measure voltage change at given forward current

\[ \Phi_{eq} = k \times (V - V_0) \]

p-i-n diodes used in ATLAS:
1. \(10^8\) to \(10^{12}\) n/cm\(^2\): CMRP from University of Wollongong, Australia
2. \(10^{12}\) to \(10^{15}\) n/cm\(^2\): OSRAM BPW34 Silicon PIN photodiode
Response curves of p-i-n diodes in use

CMRP p-i-n diode
$10^8$ to $10^{12}$ n/cm$^2$

BPW34 p-i-n diode
up to $10^{15}$ n/cm$^2$

The BPW34 diodes that are used in ATLAS were pre-irradiated with
$3 \times 10^{12}$ n/cm$^2$
Second Method: Bulk damage in silicon
→ Increase of leakage current \( (I_{\text{leakage}}) \) in reverse biased diode:
\[
\Phi_{\text{eq}} = \frac{I_{\text{leakage}}}{(\alpha V)} \quad (V: \text{sensitive (depleted) Volume})
\]
- \( 10^{11} \) to \( 10^{15} \) n/cm\(^2\) higher fluences with higher voltage
- Pad diode with guard ring structure on epitaxial silicon
- 25 \( \mu \)m thin \( \rightarrow \) fully depleted at voltages \(< 30 \) V also after irradiation
DMILL transistors are used in readout electronics in parts of the Inner Detector (SCT).

Base current at fixed collector current sensitive to fast and thermal neutrons:

\[
\frac{\Delta I_b}{I_c} = k_{eq} \Phi_{eq} + k_{th} \Phi_{th}
\]

\(k_{eq}\) and \(k_{th}\) known
\(\Phi_{eq}\) measured with diodes
→ determine \(\Phi_{th}\)
Radiation Monitoring Sensor Boards

- **Inner Detector:** 14 Modules that contain:
  - 3 RadFETs for different dose ranges
  - 2 PIN diodes for low and high fluences
  - 1 Epitaxial (large fluence range)
  - 2 DMILL bipolar transistors
  - NTC temperature sensor
  - Resistive pad for heating on the back side

- **Outside the Inner Detector region:** 48 modules
  - 1 high sensitivity PIN diode (CMRP)
  - 1 RadFET
  - NTC temperature sensor
Readout

- Usage of standard ATLAS components for straightforward integration:
  - ELMB: 64 adc channels, CAN bus communication
  - ELMB-DAC: current source, 16 channels
- Sensors are only biased during readout
- PVSS based detector control system (DCS)
- Integration in ATLAS DCS and data base archiving
Readout and Online Monitoring

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The ATLAS Radiation Dose Measurement System
Tests in Mixed Radiation Environment at CERN PS

- Mixed high energy particles in IRRAD6 environment at CERN PS.
- Two modules (Inner Detector style) are irradiated since mid May.
- Test of readout setup/procedure and calibration constants.

F. Ravotti, M. Glaser et. al
PIN diodes in Mixed Radiation Environment

- Secondary Emission Counter (SEC) counts number of protons
  - conversion factors to TID and NIEL from previous measurements
  - not useful for very small doses (unstable beam conditions)
- CMRP PIN diode also sensitive to low fluences ($10^9$ 1 MeV neq/cm$^2$).
- Good agreement between PIN diodes (20% uncertainty).
Tests in Mixed Radiation Field

RadFETs in Mixed Radiation Environment

- High sensitivity RadFET (LAAS 1.6 $\mu$m)
- Medium sensitivity RadFET (REM 0.25 $\mu$m)

LAAS RadFET sensitive already at doses $10^{-2}$ Gy

But: reduced response of LAAS in proton rich environment
→ recalibration for this special case
DMILL Transistors in Mixed Radiation Environment

\[ \beta = \frac{\text{collector current}}{\text{base current}} \]

Directly measure degradation of DMILL transistor performance.

Determine neutron fluence (using \( \Phi_{eq} \) from PIN diode as input).

Improvement of the readout timing to avoid “noise”
ATLAS Baseline Measurements

Tests in Mixed Radiation Field

The ATLAS Radiation Dose Measurement System

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CMRP Pin

RADFET

CMRP p-i-n diode
Radiation monitoring important
- to cross check simulations
- determine the correlation between dose levels and luminosity
- monitor electronics performance changes - particularly in the inner detector

The system in ATLAS allows online monitoring of radiation levels:
- TID in SiO$_2$ from cGy up to 100 kGy
- NIEL in Si from $10^8$ neq/cm$^{-2}$ up to $10^{15}$ neq/cm$^{-2}$
- thermal neutron fluence and degradation of DMILL bipolar transistors

Integration in ATLAS Detector Control System

Test and optimization in mixed radiation field at low dose rates
Backup