The ATLAS Radiation Dose Measurement System

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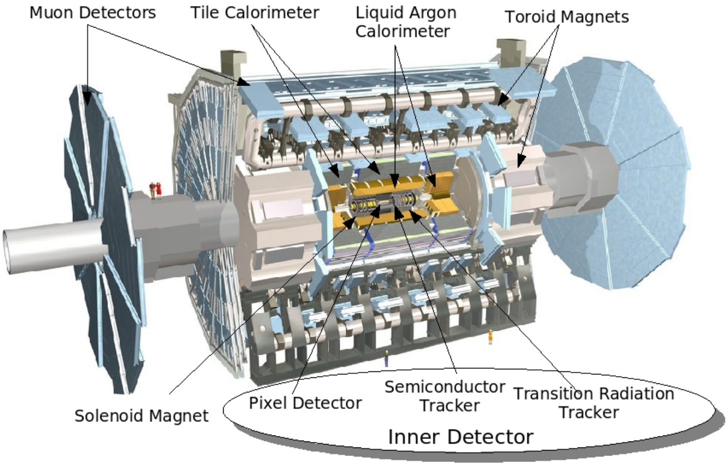
The ATLAS Experiment

Proton-proton collisisions at $\sqrt{s} = 14\,\text{TeV}$ and $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



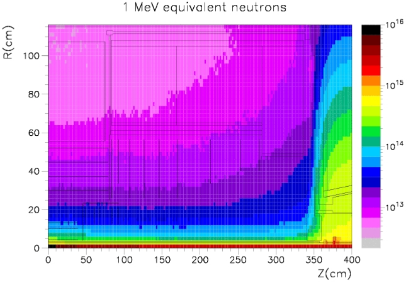
Motivation and Measured Quantities

- 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), $1\,\mathrm{Gy} = 1\,\mathrm{J/kg}$
     - Problem to MOS and bipolar devices
  2. Non Ionizing Energy Loss (NIEL) / equivalent fluence (Φ_{eq})
     - Hadrons cause displacement damage in silicon
     - Expressed in 1 MeV neutron equivalent fluence $(\mathrm{n/cm^2})$
     - $\Phi_{\mathrm{eq}} = \kappa\Phi = \frac{\int D(E)\phi(E)\,dE}{D(E_{\mathrm{n}}=1\,\mathrm{MeV})}$
  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: $\text{TID} > 100\,\text{kGy}$
  - Non Ionizing Energy Loss $\Phi_{eq} > 10^{15}\ 1\,\mathrm{MeV n/cm^{-2}}$
- 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



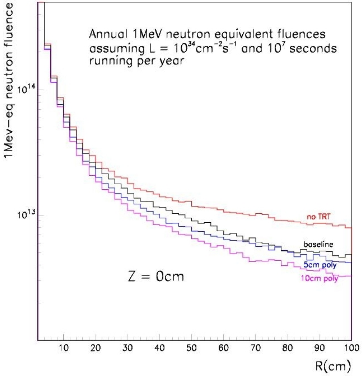
FLUKA simulation by Ian Dawson

Radiation Field at SLHC

- Luminosity: $\mathcal{L}(\text{SLHC}) \approx 10 \times \mathcal{L}(\text{LHC})$
- Ionizing dose scales with luminosity:

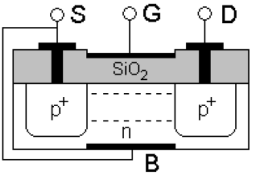
  $\mathrm{TID(SLHC)} \approx 10 \times \mathrm{TID(LHC)}$
- Upgrade of ATLAS tracker to full silicon
  $\rightarrow$ loss of moderating effect of the Transition Radiation Tracker
  $\rightarrow$ NIEL not expected to scale with luminosity
  $\rightarrow$ as compensation introduce a 5 cm thick moderator

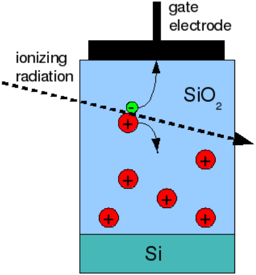
Non Ionising Energy Loss at the SLHC



Ian Dawson

Total Ionizing Dose (TID) Measurement - RadFETs

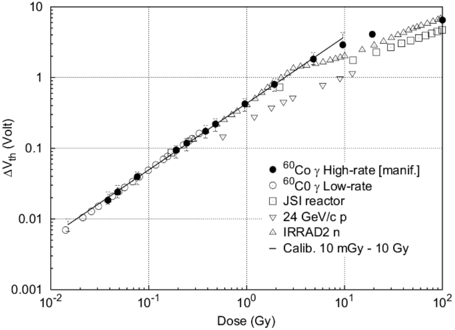


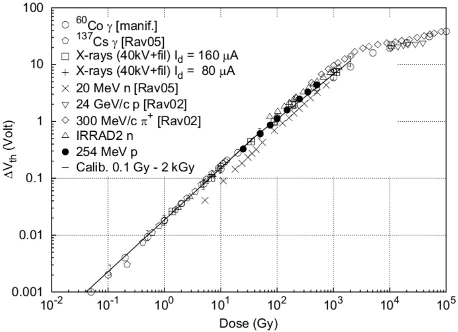


- RadFET: Radiation Field Effect Transistor
- Electrons escape, holes are trapped in SiO_2-Si boundary.
- Higher negative gate voltage needed to open transitor.
- Measure gate voltage increase at given drain current. $\Delta V = a \times (TID)^b$
- Sensitivity depends on oxide thickness
- Three RadFETs used in ATLAS to cover large range of doses:
  - 0.01 Gy to 10 Gy: 1.6 μm from CNRS LAAS, Toulouse, France
  - up to 10^4 Gy: 0.25 μm from REM, Oxford, UK
  - up to 10^5 Gy: 0.13 μm from REM, Oxord, UK

Response curves of RadFETs in use

1.6 μm LAAS RadFET	0.25 μm REM RadFET
0.01 Gy to 10 Gy	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

$\Rightarrow$ reduced minority carrier lifetime in a p-i-n diode

$\Rightarrow$ increase of resistance

$\Rightarrow$ measure voltage change at given forward current

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

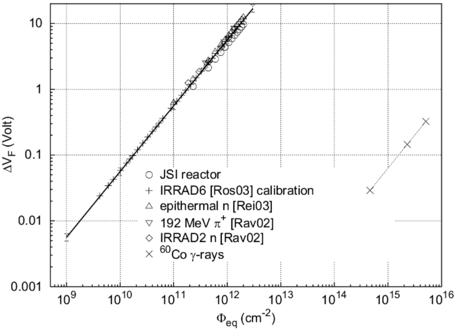
p-i-n diodes used in ATLAS:

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

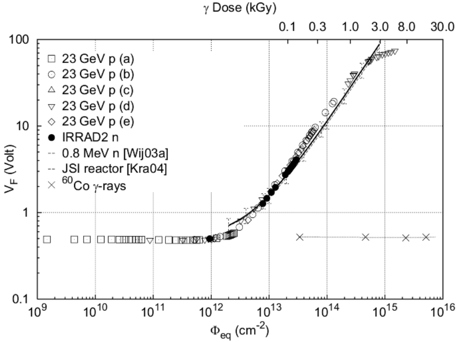
CMRP p-i-n diode

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 3×10^{12} n/cm^2

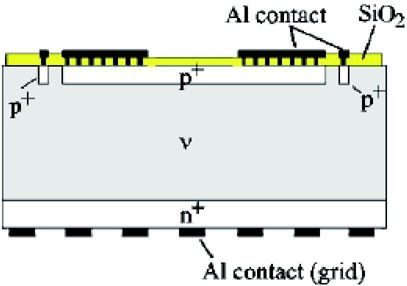
Non Ionising Energy Loss (NIEL) Measurement (2)

Second Method: Bulk damage in silicon

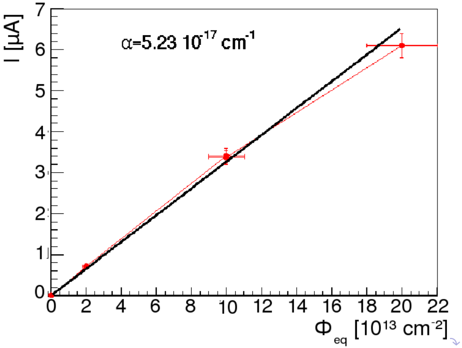
$\rightarrow$ Increase of leakage current (I_{leakage}) in reverse biased diode:

$$\Phi_{eq} = I_{\text{leakage}}/(\alpha V) \qquad \text{(V: sensitive (depleted) Volume)}$$

- 10^{11} to 10^{15} n/cm^2 higher fluences with higher voltage
  - Pad diode with guard ring structure on epitaxial silicon
  - 25 μm thin $\rightarrow$ fully depleted at voltages < 30 V also after irradiation



Federico Ravotti

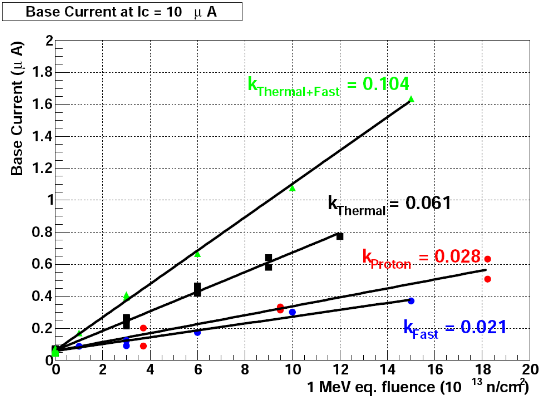


Thermal Neutron Fluence Measurements

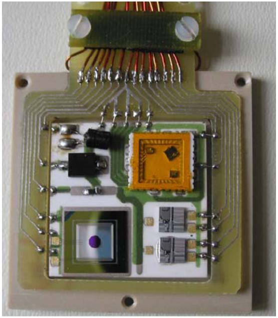
- DMILL transistors are used in readout electronics in parts of the Inner Detector (SCT).
- Base current at fixed collector current sensitive to fast and thermal neutrons:

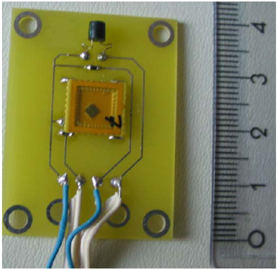
$$\frac{\Delta I_b}{I_c} = k_{eq}\Phi_{eq} + k_{th}\Phi_{th}$$

- k_{eq} and k_{th} known
  Φ_{eq} measured with diodes
  $\longrightarrow$ determine Φ_{th}



Radiation Monitoring Sensor Boards

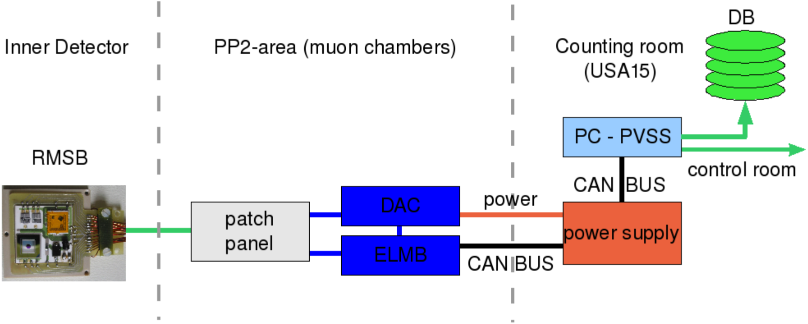


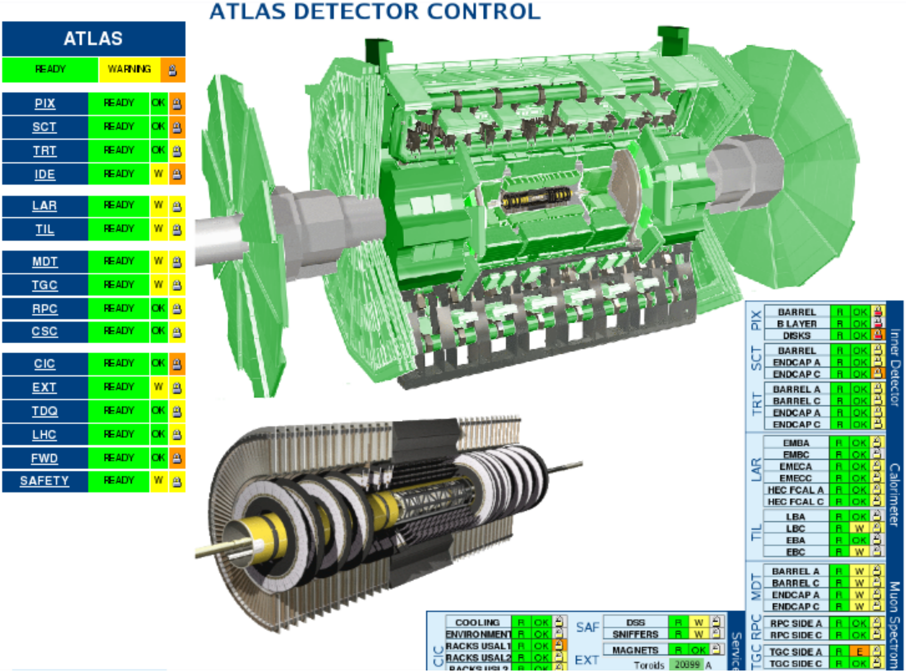


- Inner Detector: 14 Modules that contain:
  - 3 RadFETs for different dose ranges
  - 2 PIN diodes for low and high fluences
  - 1 Epitaxial (large fluence range)
  - 2 DMILL bipolar transistors
  - NTC temperature sensor
  - resistive pad for heating on the back side
- Outside the Inner Detector region: 48 modules
  - 1 high sensitivity PIN diode (CMRP)
  - 1 RadFET
  - NTC temperature sensor

Readout

- Usage of standard ATLAS components for straight forward 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




ATLAS DETECTOR CONTROL
ATLAS
READY WARNING
PIX READY OK
SCT READY OK
TRT READY OK
IDE READY W
LAR READY W
TIL READY W
MDT READY W
TGC READY W
RPC READY OK
CSC READY OK
CIC READY OK
EXT READY W
TDQ READY OK
LHC READY OK
FWD READY OK
SAFETY READY W
PIX BARREL R OK
B LAYER R OK
DISKS R OK
SCT BARREL R OK
ENDCAP A R OK
ENDCAP C R OK
TRT BARREL A R OK
BARREL C R OK
ENDCAP A R OK
ENDCAP C R OK
Inner Detector
LAR EMBA R OK
EMBC R OK
EMECA R OK
EMECC R OK
HEC FCAL A R OK
HEC FCAL C R OK
TIL LBA R OK
LBC R W
EBA R OK
EBC R W
Calorimeter
MDT BARREL A R W
BARREL C R W
ENDCAP A R W
ENDCAP C R W
RPC RPC SIDE A R OK
RPC SIDE C R OK
TGC TGC SIDE A R E
TGC SIDE C R OK
Muon Spectrom
CIC COOLING R OK
ENVIRONMENT R OK
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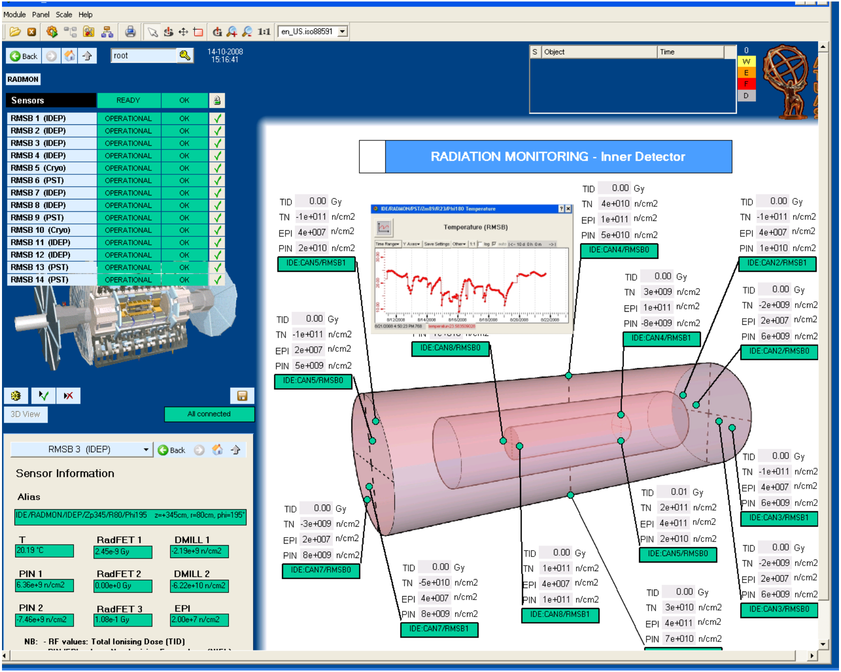
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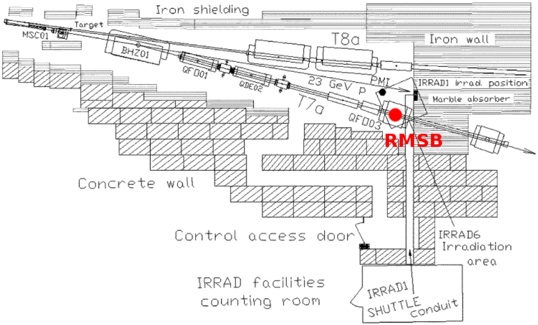
RMSB 3 (IDEP) OPERATIONAL OK
RMSB 4 (IDEP) OPERATIONAL OK
RMSB 5 (Cryo) OPERATIONAL OK
RMSB 6 (PST) OPERATIONAL OK
RMSB 7 (IDEP) OPERATIONAL OK
RMSB 8 (IDEP) OPERATIONAL OK
RMSB 9 (PST) OPERATIONAL OK
RMSB 10 (Cryo) OPERATIONAL OK
RMSB 11 (IDEP) OPERATIONAL OK
RMSB 12 (IDEP) OPERATIONAL OK
RMSB 13 (PST) OPERATIONAL OK
RMSB 14 (PST) OPERATIONAL OK
3D View
All connected
RMSB 3 (IDEP)
Sensor Information
Alias
IDE/RADMON/IDEP/Zp345/R80/Phi195 z=+345cm, r=80cm, phi=195°
T 20.19 °C
RadFET 1 2.45e-9 Gy
DMILL 1 2.19e+9 n/cm2
PIN 1 6.36e+9 n/cm2
RadFET 2 0.00e+0 Gy
DMILL 2 -6.22e+10 n/cm2
PIN 2 -7.46e+9 n/cm2
RadFET 3 1.08e-1 Gy
EPI 2.00e+7 n/cm2
NB: - RF values: Total Ionising Dose (TID)
RADIATION MONITORING - Inner Detector
Temperature (RMSB)
TID 0.00 Gy
TN -1e+011 n/cm2
EPI 4e+007 n/cm2
PIN 2e+010 n/cm2
IDE:CAN5/RMSB1
TID 0.00 Gy
TN -1e+011 n/cm2
EPI 2e+007 n/cm2
PIN 5e+009 n/cm2
IDE:CAN5/RMSB0
IDE:CAN8/RMSB0
TID 0.00 Gy
TN 4e+010 n/cm2
EPI 1e+011 n/cm2
PIN 5e+010 n/cm2
IDE:CAN4/RMSB0
TID 0.00 Gy
TN 3e+009 n/cm2
EPI 1e+011 n/cm2
PIN -8e+009 n/cm2
IDE:CAN4/RMSB1
TID 0.00 Gy
TN -1e+011 n/cm2
EPI 4e+007 n/cm2
PIN 1e+010 n/cm2
IDE:CAN2/RMSB1
TID 0.00 Gy
TN -2e+009 n/cm2
EPI 2e+007 n/cm2
PIN 6e+009 n/cm2
IDE:CAN2/RMSB0
TID 0.00 Gy
TN -1e+011 n/cm2
EPI 4e+007 n/cm2
PIN 6e+009 n/cm2
IDE:CAN3/RMSB1
TID 0.01 Gy
TN 2e+011 n/cm2
EPI 4e+011 n/cm2
PIN 2e+010 n/cm2
IDE:CAN5/RMSB0
TID 0.00 Gy
TN -2e+009 n/cm2
EPI 2e+007 n/cm2
PIN 6e+009 n/cm2
IDE:CAN3/RMSB0
TID 0.00 Gy
TN -3e+009 n/cm2
EPI 2e+007 n/cm2
PIN 8e+009 n/cm2
IDE:CAN7/RMSB0
TID 0.00 Gy
TN -5e+010 n/cm2
EPI 4e+007 n/cm2
PIN 8e+009 n/cm2
IDE:CAN7/RMSB1
TID 0.00 Gy
TN 1e+011 n/cm2
EPI 4e+007 n/cm2
PIN 1e+011 n/cm2
IDE:CAN8/RMSB1
TID 0.00 Gy
TN 3e+010 n/cm2
EPI 4e+011 n/cm2
PIN 7e+010 n/cm2

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.



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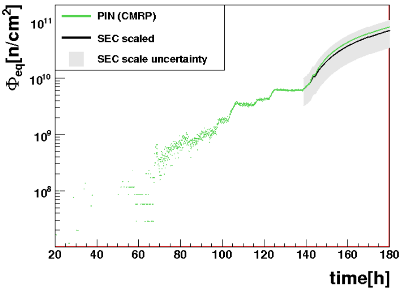
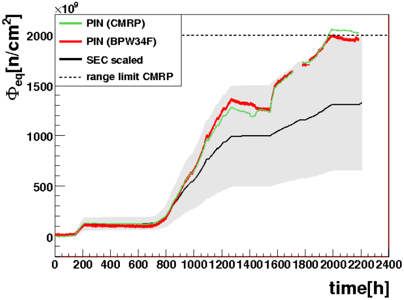
PIN diodes in Mixed Radiation Environment

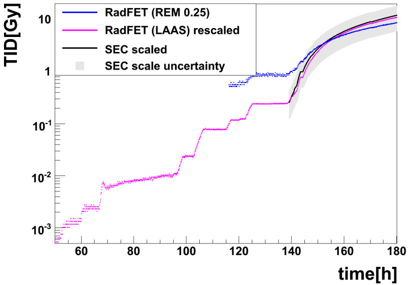




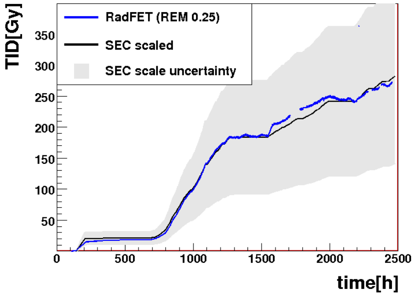
- Secondary Emission Counter (SEC) counts number of protons
    - conversion factors to TID and NIEL from previous measurements
    - not useful for very small doses (unstable beam conditions)
- CMRP PIN diode also sensitive to low fluences (10^9 1 MeV neq/cm^2).
- Good agreement between PIN diodes (20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

RadFETs in Mixed Radiation Environment

High sensitivity RadFET
(LAAS 1.6 μm)



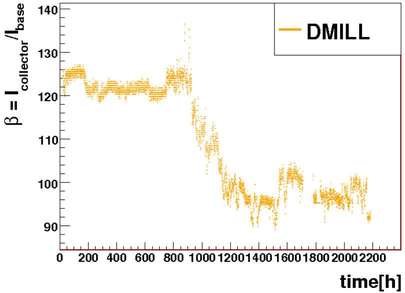
Medium sensitivity RadFET
(REM 0.25 μm)



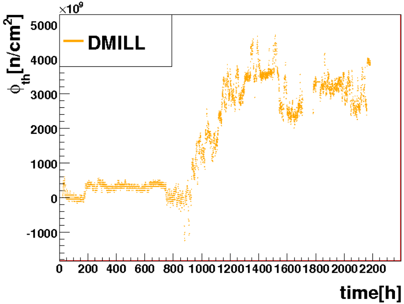
- LAAS RadFET sensitive already at doses 10^{-2} Gy
- But: reduced response of LAAS in proton rich environment
  $\rightarrow$ recalibration for this special case

DMILL Transistors in Mixed Radiation Environment

$$\beta = \frac{\text{collector current}}{\text{base current}}$$

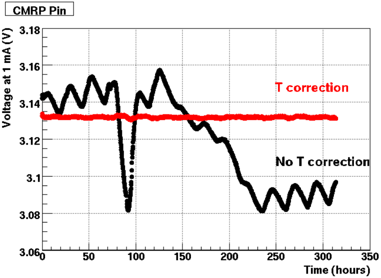


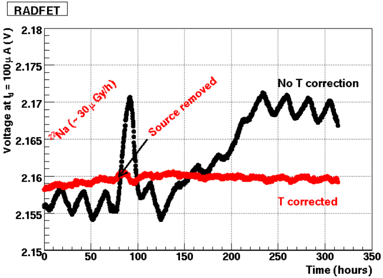
thermal neutron fluence

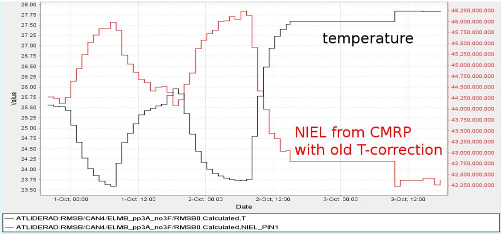


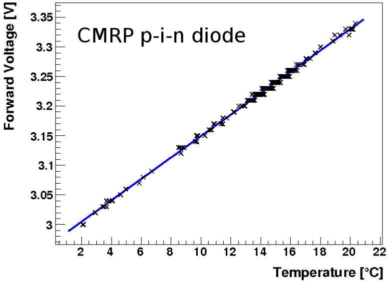
- Directly measure degradation of DMILL transistor performance.
- Determine neutron fluence (using Φ_{eq} from PIN diode as input).
- Improvement of the readout timing to avoid "noise"

ATLAS Baseline Measurements





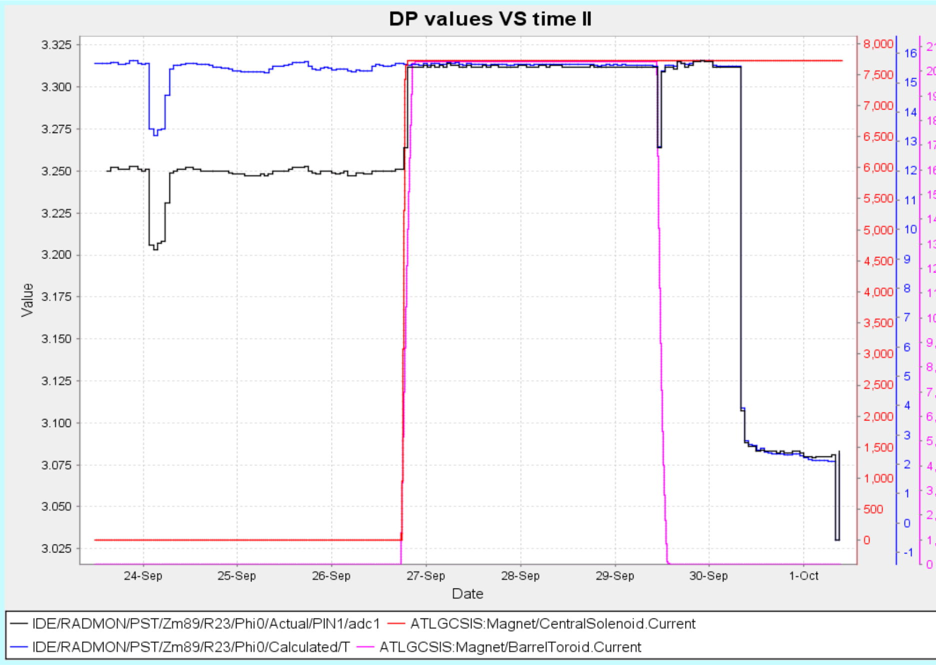




Summary

- 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 $10^8\,\mathrm{neq/cm^{-2}}$ up to $10^{15}\,\mathrm{neq/cm^{-2}}$
  - 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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ATLGCSIS:Magnet/CentralSolenoid.Current
IDE/RADMON/PST/Zm89/R23/Phi0/Calculated/T
ATLGCSIS:Magnet/BarrelToroid.Current