Online Radiation Dose Measurement System for ATLAS experiment

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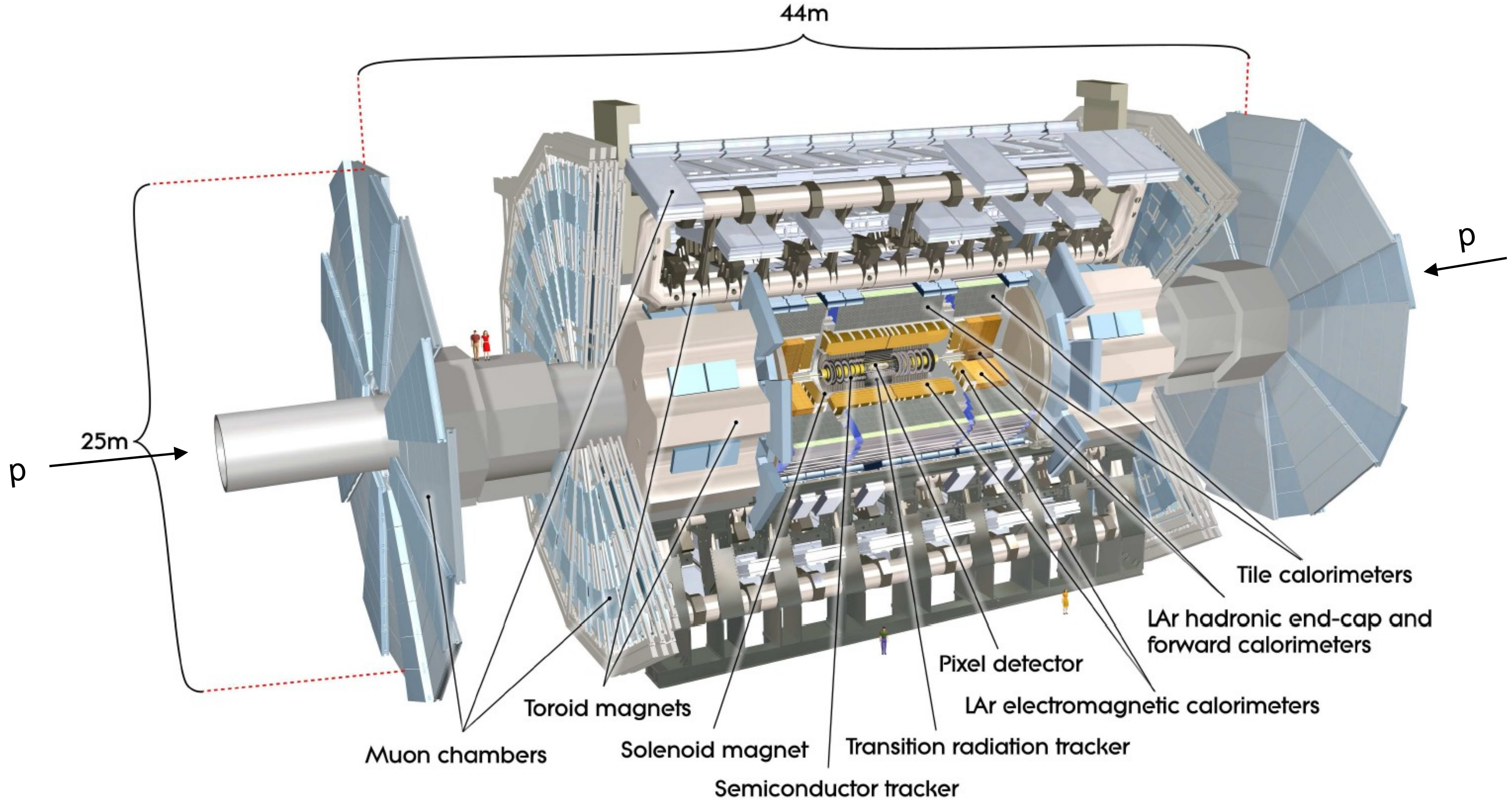
The ATLAS experiment

- experiment at the Large Hadron Collider at CERN
- proton-proton collisions:
  - → in 2011: E_p = 3.5 TeV, Peak Luminosity = 3.6×10^{33} $cm^{-2}s^{-1}$
  - → in 2012: E_p = 4 TeV, Peak Luminosity ~ 6×10^{33} $cm^{-2}s^{-1}$
  - → after 2014: E_p = 7 TeV, Luminosity ~ 10^{34} $cm^{-2}s^{-1}$



Radiation Field in ATLAS

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

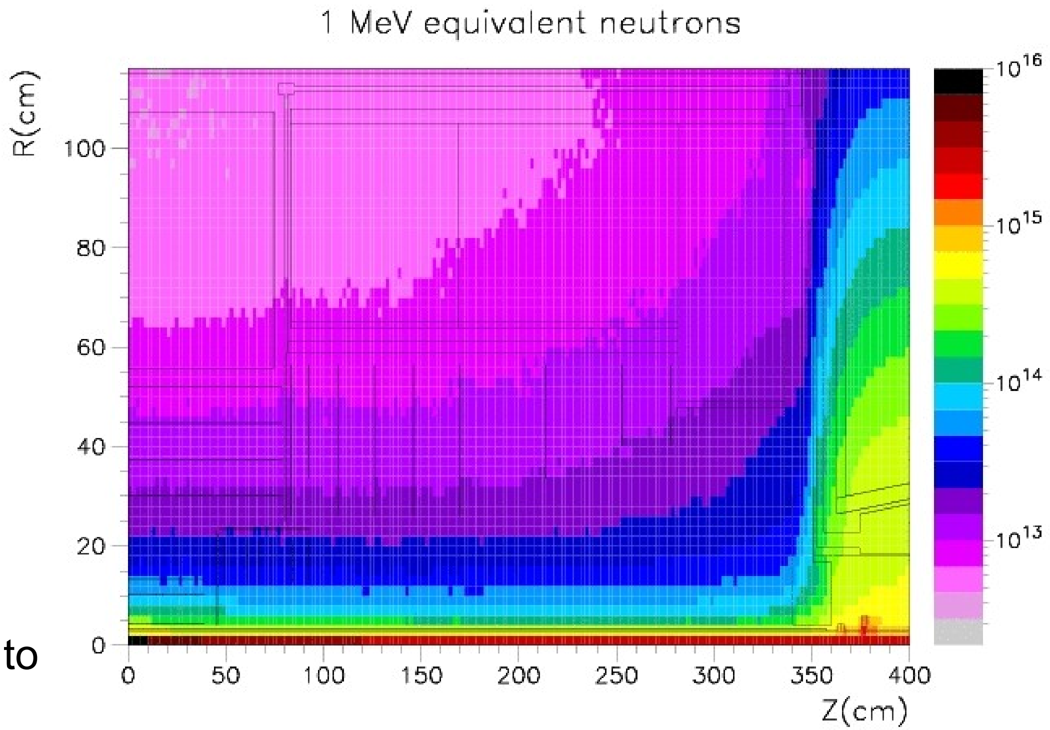
Expected radiation levels:

- Total Ionizing Dose (TID):
  TID > 100 kGy

- Non Ionizing Energy Loss (NIEL):
  $\Phi_{eq} > 10^{15}$ n/cm^2
  (1 MeV equivalent neutrons in Si)

- Thermal neutrons $\Phi \sim 10^{15}$ n/cm^2

➔ such radiation levels cause damage to detectors and readout electronics



Aim of radiation monitoring system:

➔ dose monitoring necessary to understand detector performance

➔ cross check of simulations and make predictions

Radiation damage in detectors and electronics

Main Total Ionising Dose (TID) effect:

→ radiation induced charge trapped in SiO_2 layer

→ consequences:

- change of threshold voltage in MOS transistors
- leakage current between transistors
- drop of gain in bipolar transistors
- many more (e.g. attenuation in optical fibres ….)

Main displacement damage (Non Ionising Energy Loss: NIEL) effect:

→ energetic hadrons damage crystal lattice

→ consequences:

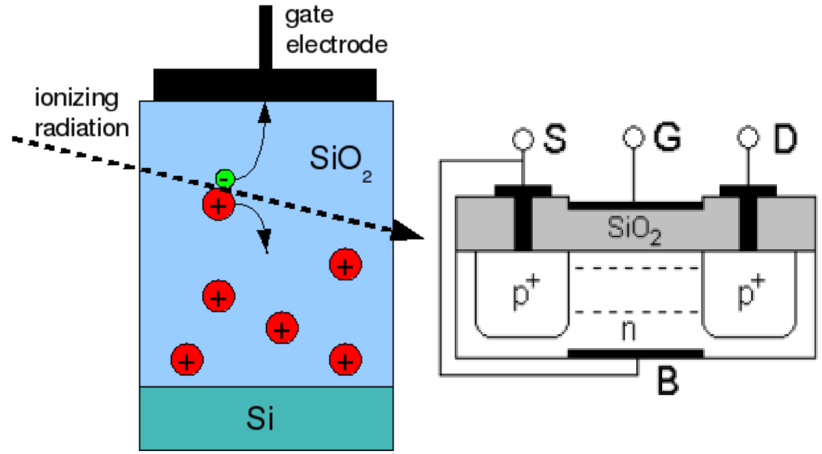
- increased reverse current in silicon detectors
- increased full depletion voltage in silicon detectors
- gain degradation in bipolar transistors
- many more (e.g. degradation of responsivity in photo-diodes …)

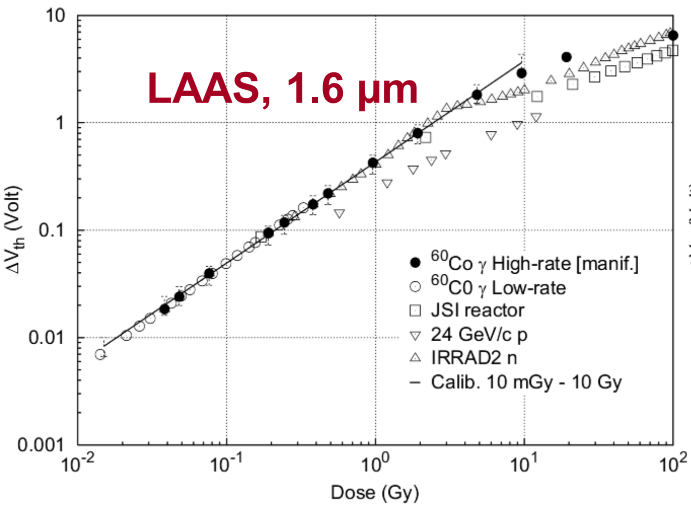
✓ detector components must be specially designed and selected for radiation environment

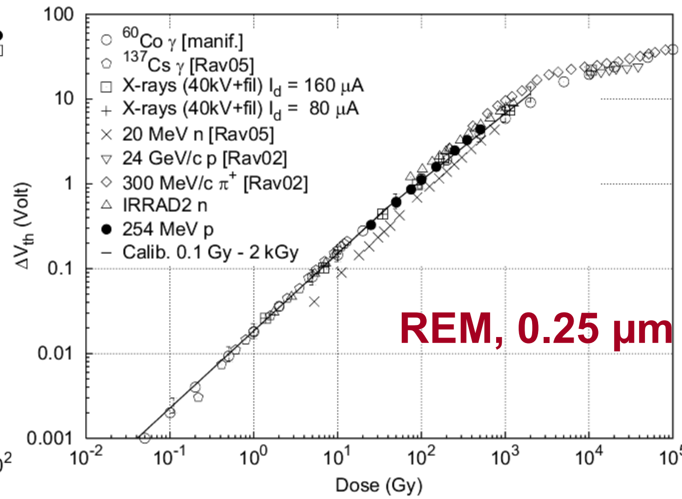
✓ accumulated doses must be monitored to understand detector performance

TID measurements with RadFETs

- RadFETs: p-MOS transistor
- holes caused by radiation get trapped in the gate oxide:
  ➔ increase of threshold voltage with dose:
  $\Delta V = a \times (TID)^b$
- 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

- characterizations, selection, calibrations done by CERN RADMON team:
  F. Ravotti, M. Glaser, M. Moll.... (F. Ravotti ,PhD thesis, CERN-THESIS-2007-013)

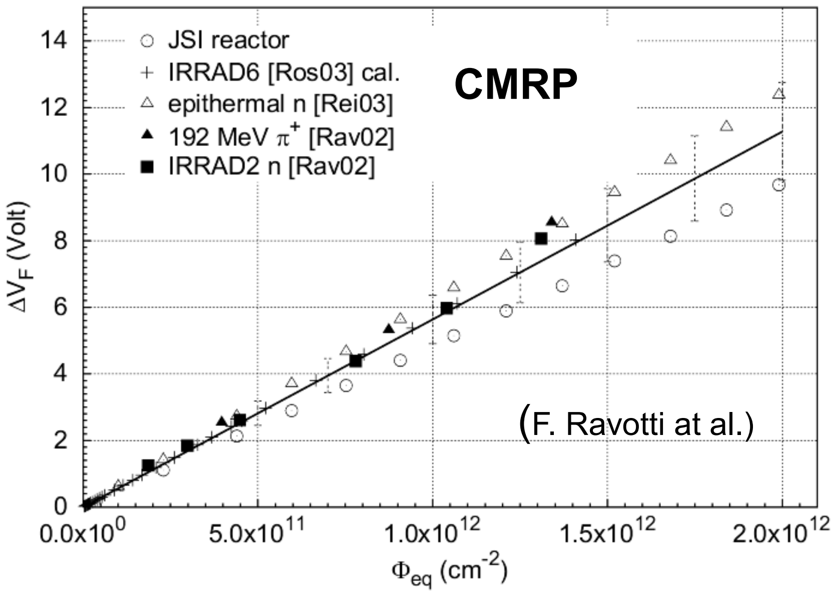
NIEL measurements with diodes

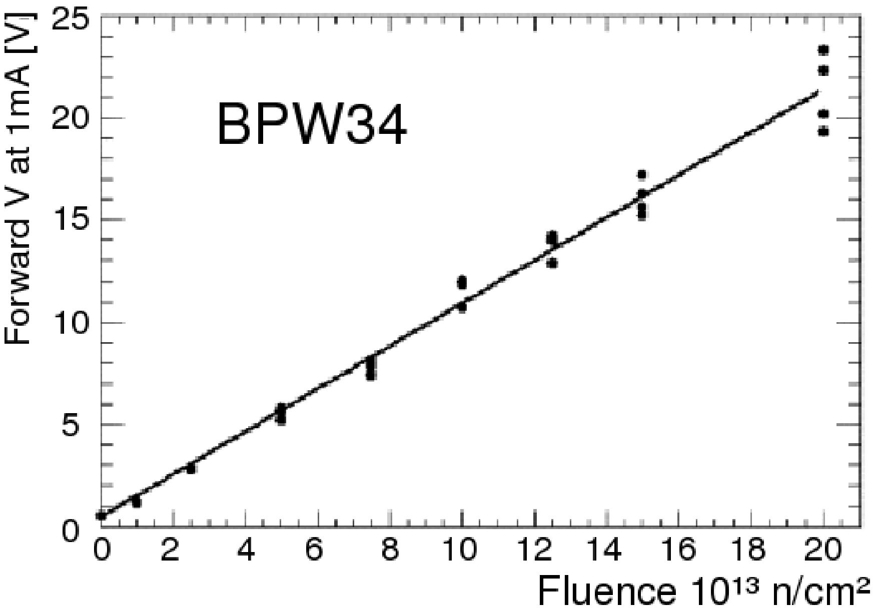
- displacement damage expressed in units of equivalent fluence of 1 MeV neutrons
- consequences of displacement damage (Non Ionising Energy Loss NIEL) in silicon:
  → increased resistance, reduced carrier lifetime, increased reverse current …

Two methods for measurements with diodes:
 ➔ forward bias: voltage at given forward current increases
 ➔ reverse bias: increase reverse current

Forward bias

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



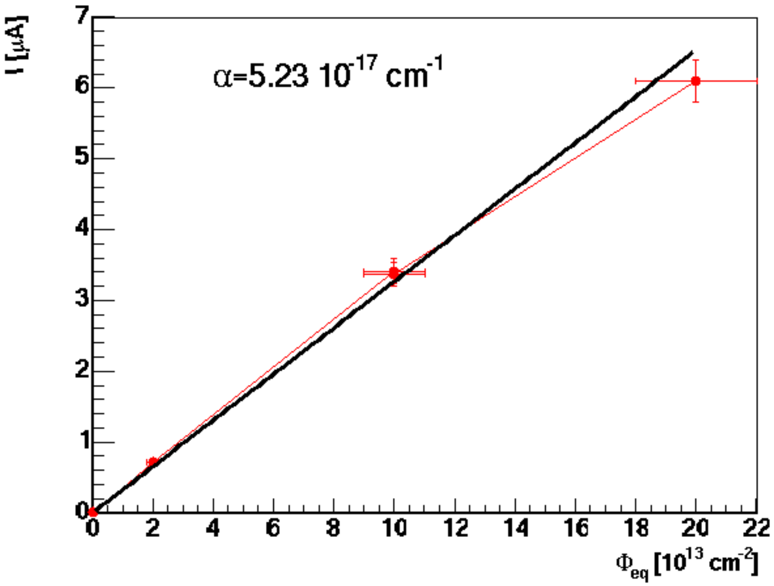


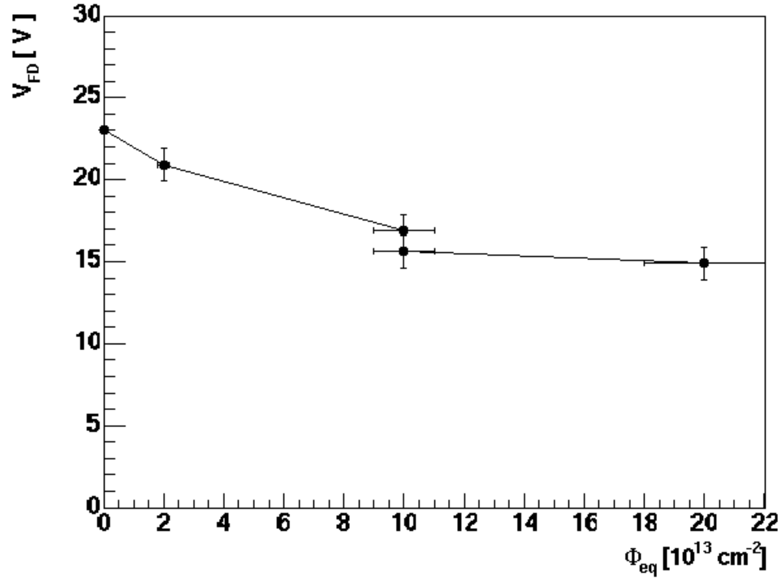
NIEL measurements with diodes

<u>Reverse bias</u>

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

- **25 µm** 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
- suitable for fluences from 10^{11} n/cm^2 to 10^{15} n/cm^2

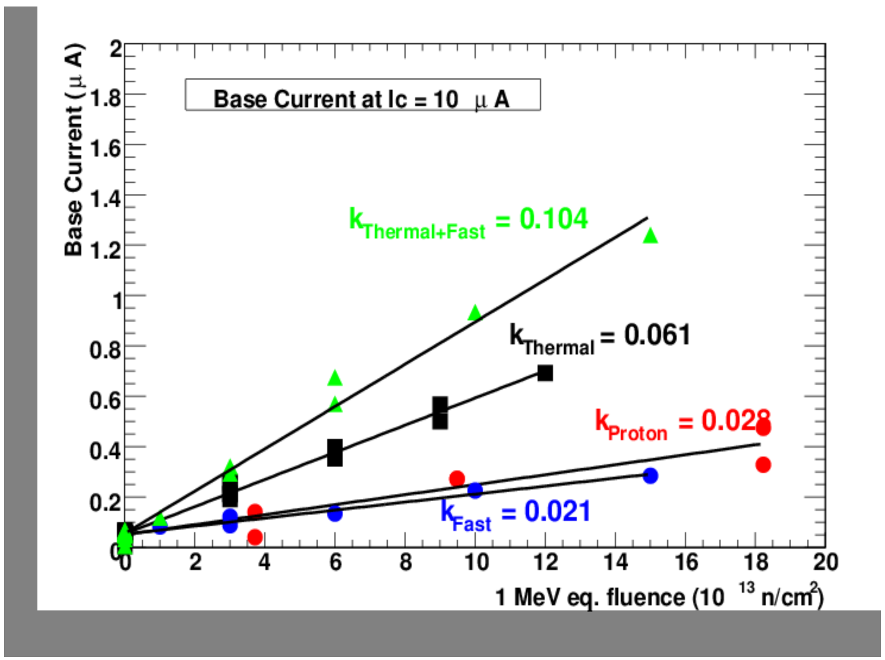


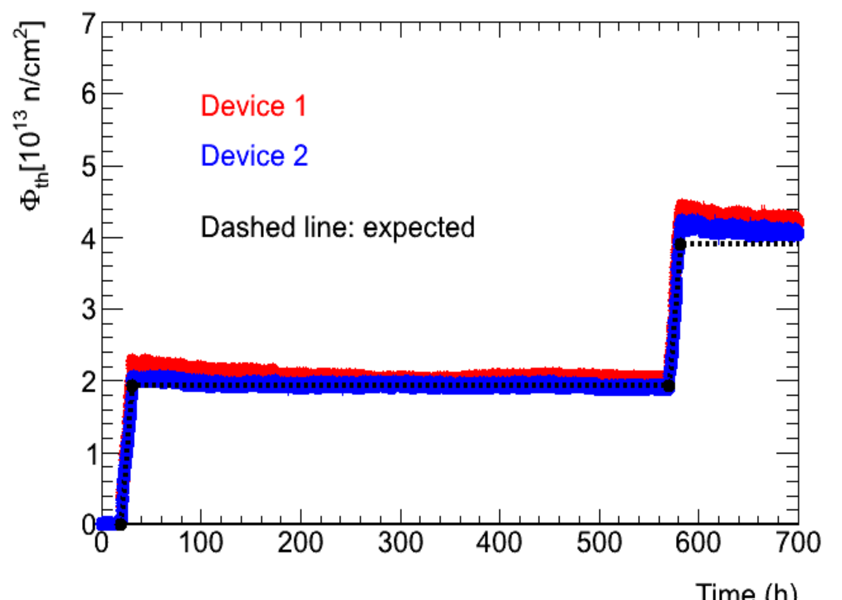


Thermal neutrons

- bipolar transistors (DMILL) used in front end ASICs
- measure base current at given collector current
  - ➔ monitor status of front end electronics
  - ➔ sensitive to fast and thermal neutrons

$\Delta I_b/I_c = k_{eq} \cdot \Phi_{eq} + k_{th} \cdot \Phi_{th}$; k_{eq}, k_{th} and Φ_{eq} known → Φ_{th} can be determined





Response to thermal neutrons (reactor)

Radiation Monitor Sensor Board (RMSB)

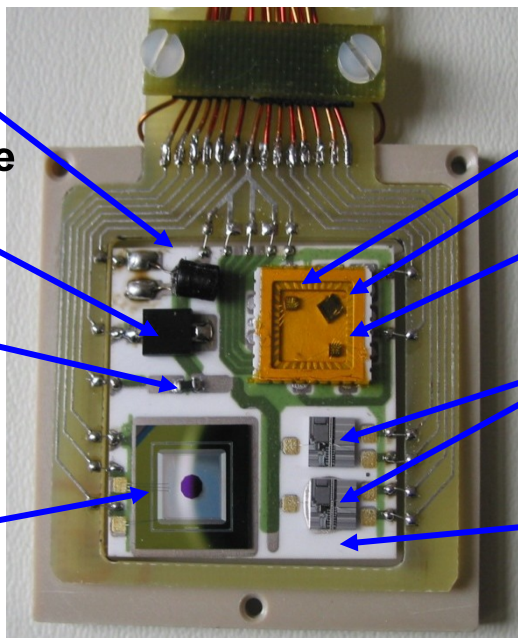
Inner Detector

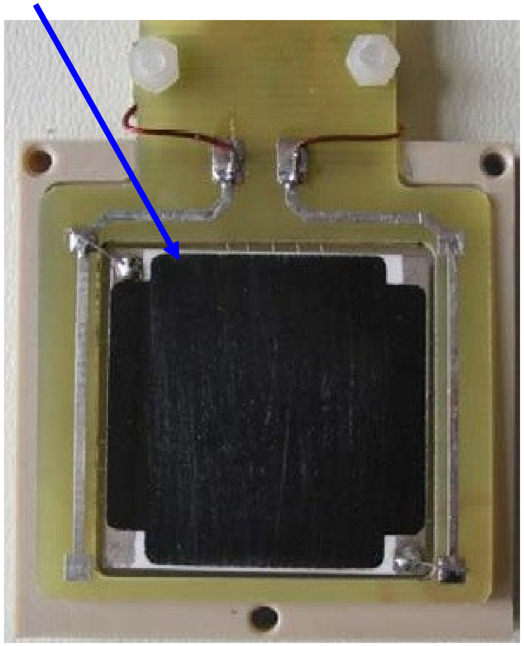
- for dose monitoring in the Inner Detector:
  - large range of doses
  - no access in 10 years

  ➔ **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





Back side

Radiation Monitor Sensor Board (RMSB)

Other locations

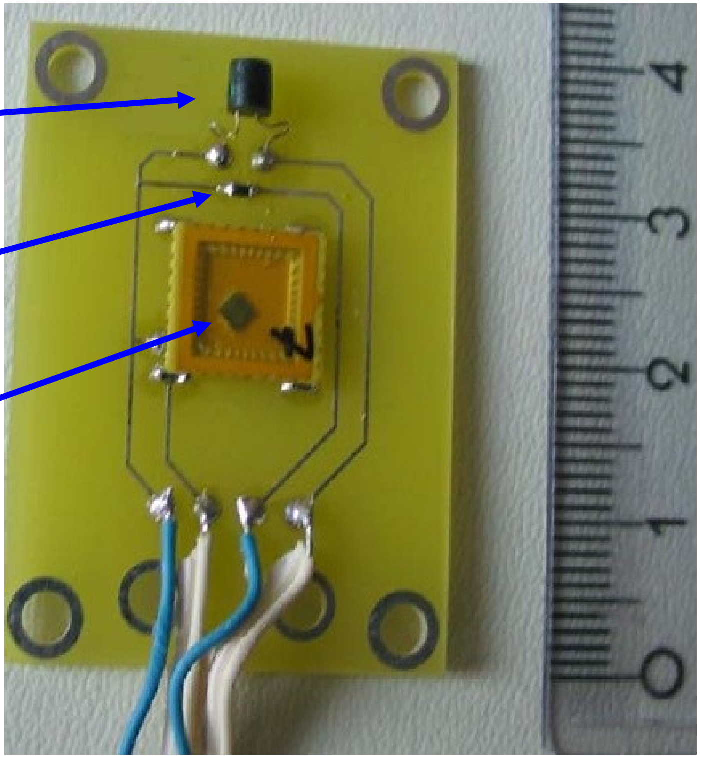
- lower dose ranges
  ➔ mGy to 10 Gy, 10^9 to ~10^{12} n/cm^2

- no temperature stabilization
  ➔ correct read out values with known temperature dependences

CMRP diode

Thermistor

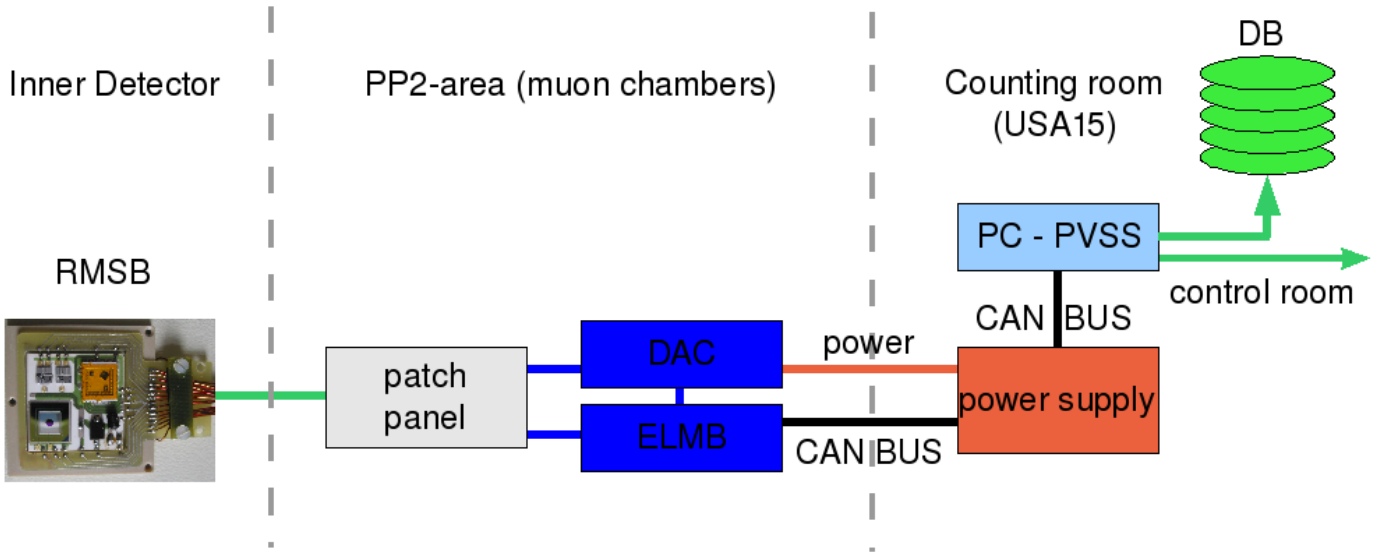
LAAS radfet
(1.6 μmSiO_2)



Readout

- use standard ATLAS Detector Control System components
  - **ELMB:**
    - 64 ADC channels
    - can bus communication
  - **ELMB-DAC:**
    - current source, 16 channels (I_{max} = 20 mA, U_{max} = 30 V)
- sensors are biased only during readout (~ few minutes every hour)

- software written in PVSS



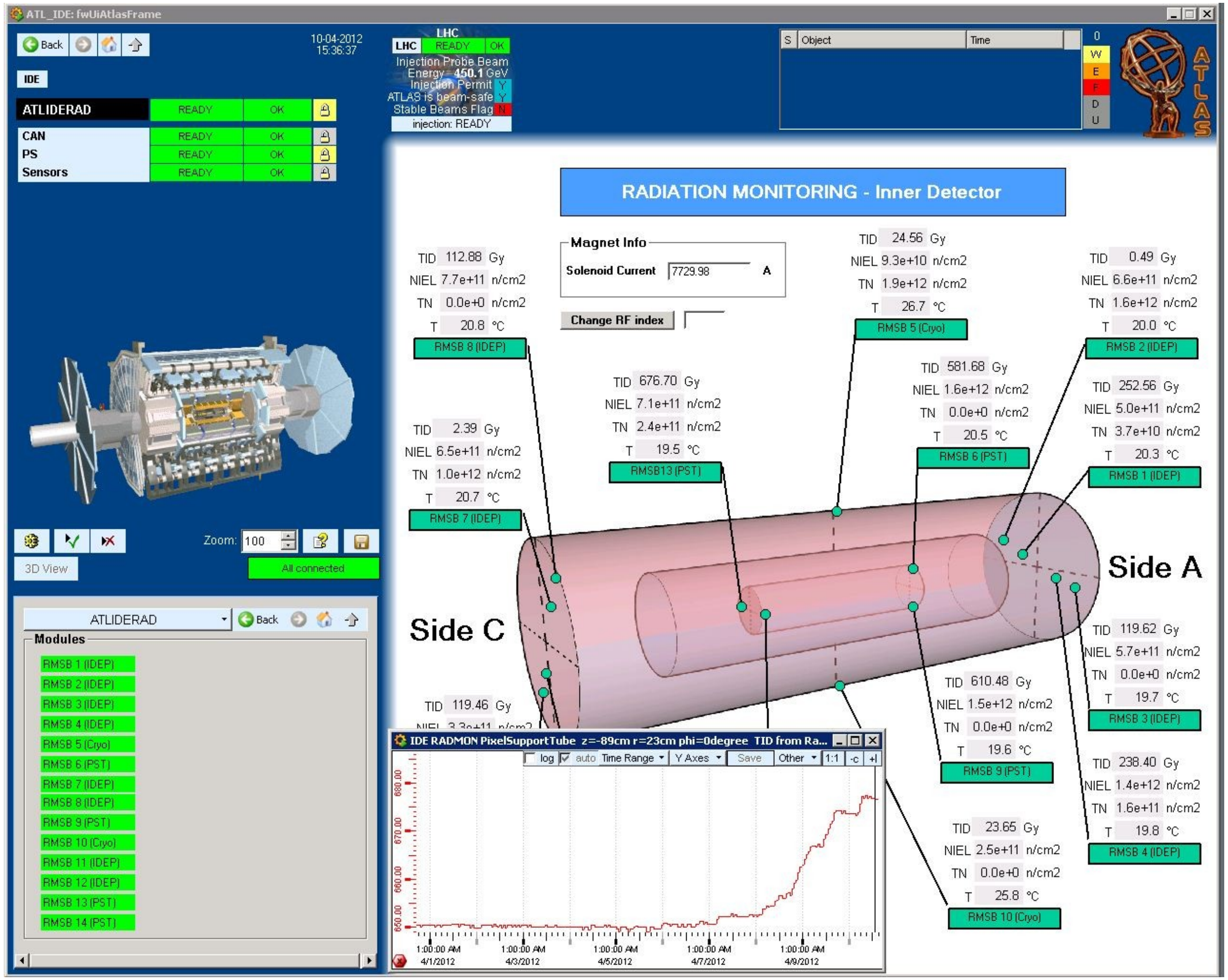
Cable length
~ 18 m

Cable length
~ 100 m

Readout

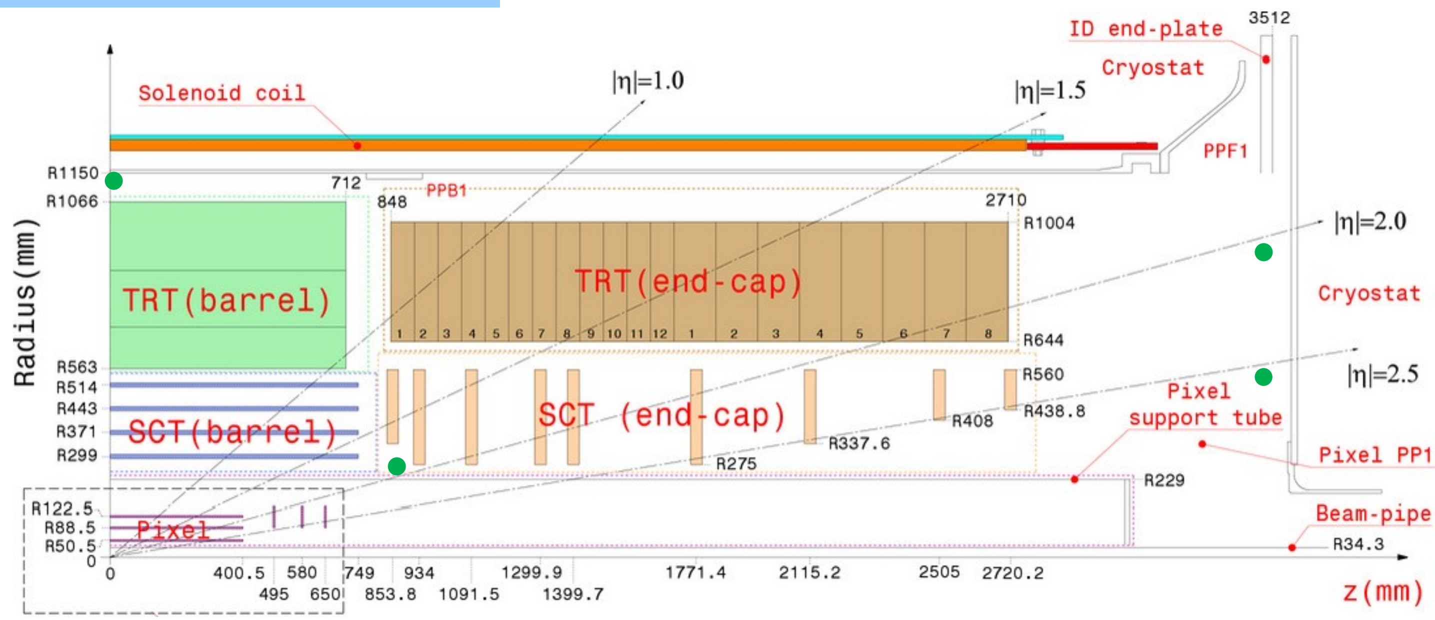
- Information about accumulated doses available online

Detector Control System Screen Shot:

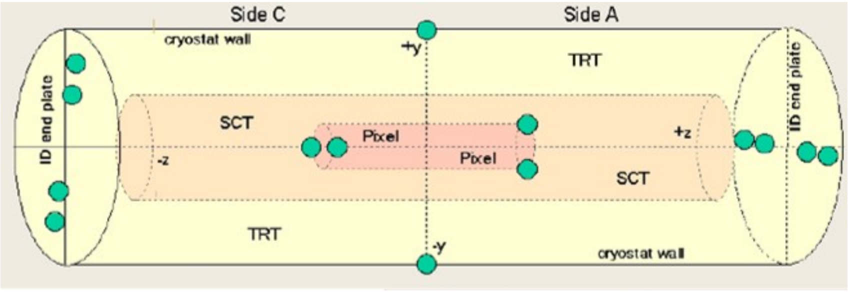


Monitoring Locations

- 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	90



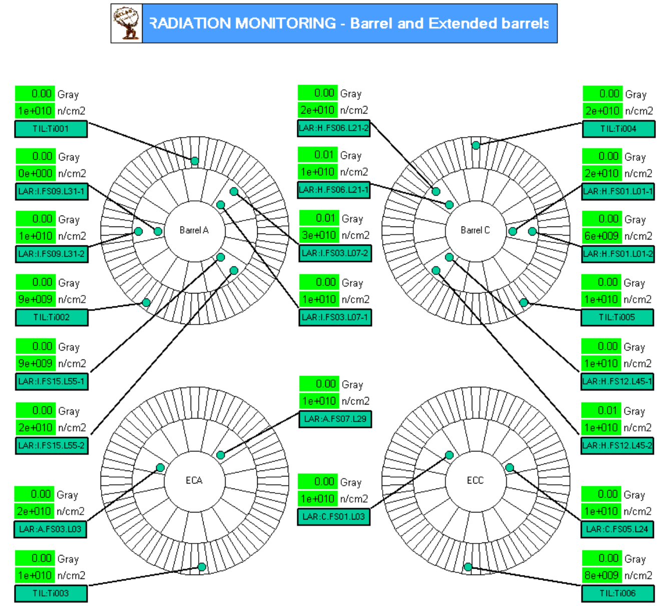
Monitoring locations

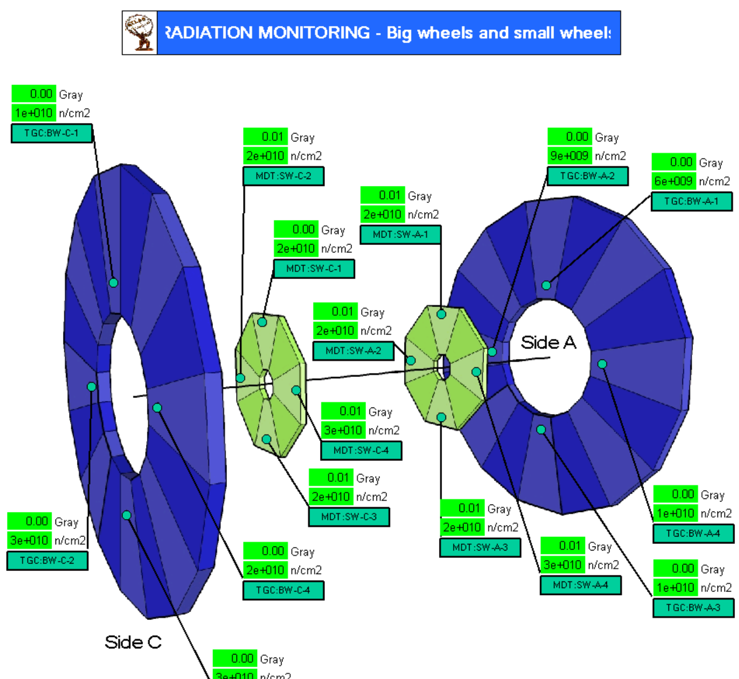
- 48 locations at larger radii
- 2 monitors very forward (z = 240 m, r = 0.2 m)

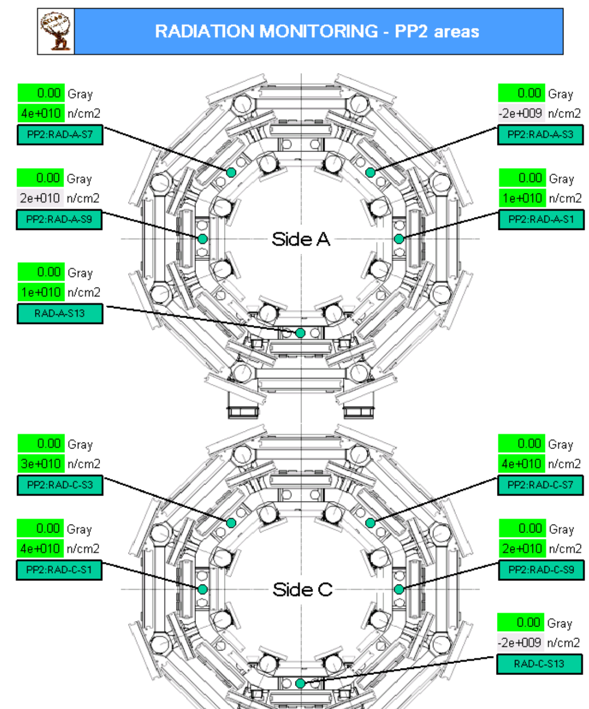
Calorimeters: 22

Muon detectors: 16

PP2: 10







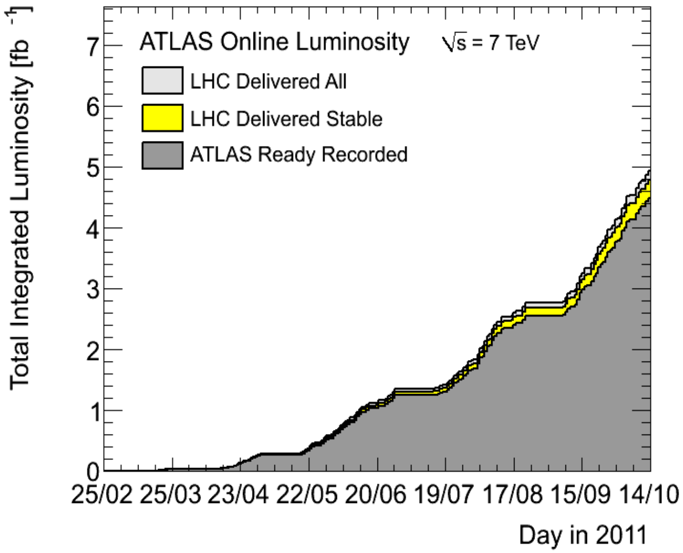
FLUKA Simulations

More in:

- I. Dawson and C. Buttar, "The radiation environment in the ATLAS inner detector", *Nucl. Inst. Meth. A453,*pp. 461-467, 2000.
- M. Bosman, I. Dawson, V. Hedberg, M. Shupe, "ATLAS Radiation Background Taskforce Final Summary Document", ATL-GEN-2005-001.
- I. Dawson et al., "*Fluence and dose measurements in the ATLAS inner detector and comparison with simulation*." ATL-COM INDET-2011-001

- FLUKA particle transport code
- PHOJET event generator
- simulations done for $\sqrt{s}$ = 7 TeV assuming a proton-proton inelastic cross section 77.5 mb as predicted by PHOJET

Doses and fluences per fb^{-1} of integrated luminosity			
RadMon Location	Coordinates	Dose (Gy)	1 MeV equivalent neutron fluence (10^{11} n/cm^{-2})
Pixel support tube	r= 23 cm |z| = 90 cm	110	2.22
Inner Detector End Plate – small radius	r = 54 cm |z| = 345 cm	55.4	2.24
Inner Detector End Plate - large radius	r = 80 cm |z| = 345 cm	27.0	1.35
Cryostat Wall	r = 110 cm |z| = 0 cm	4.9	0.45

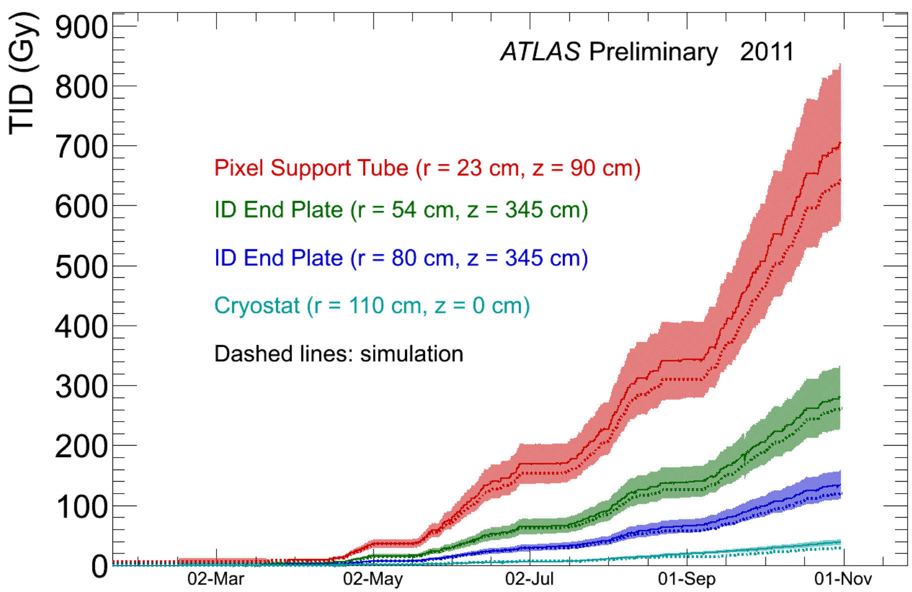


Integrated luminosity is a measure of number of proton-proton collisions

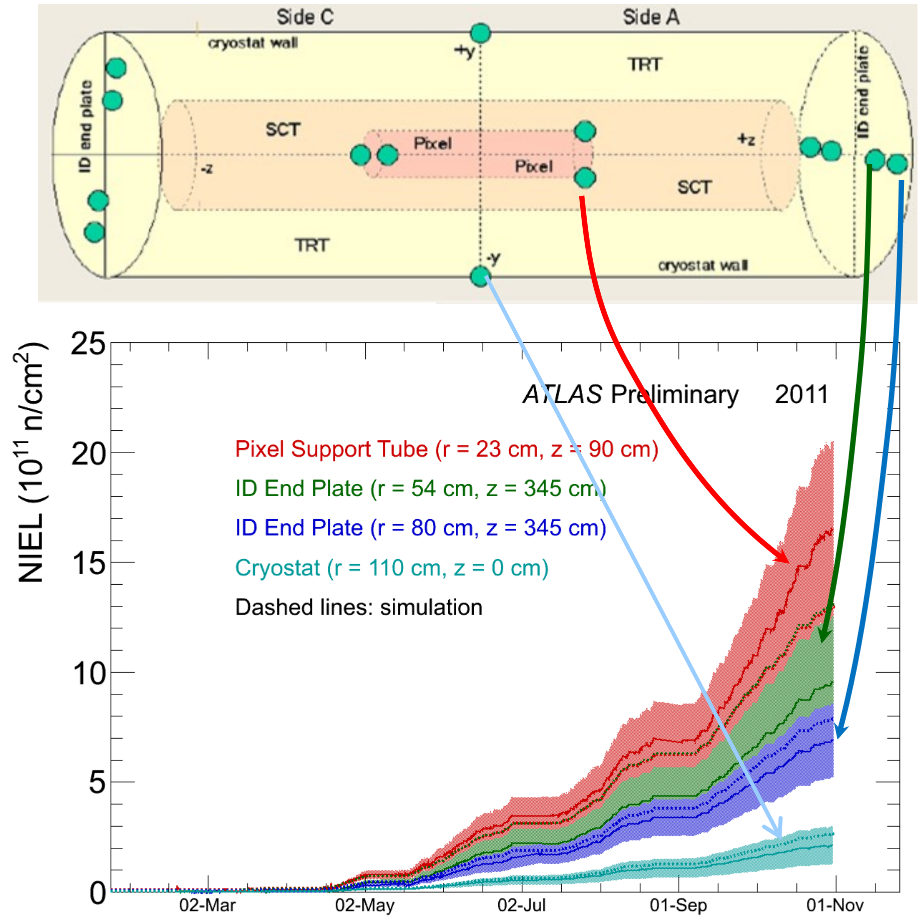
→ Simulated dose (fluence) = simulation factor × integrated luminosity

Results Inner Detector (ID)

- data up to 31st October 2011
  → Integrated luminosity ~ 5.6 fb^{-1}



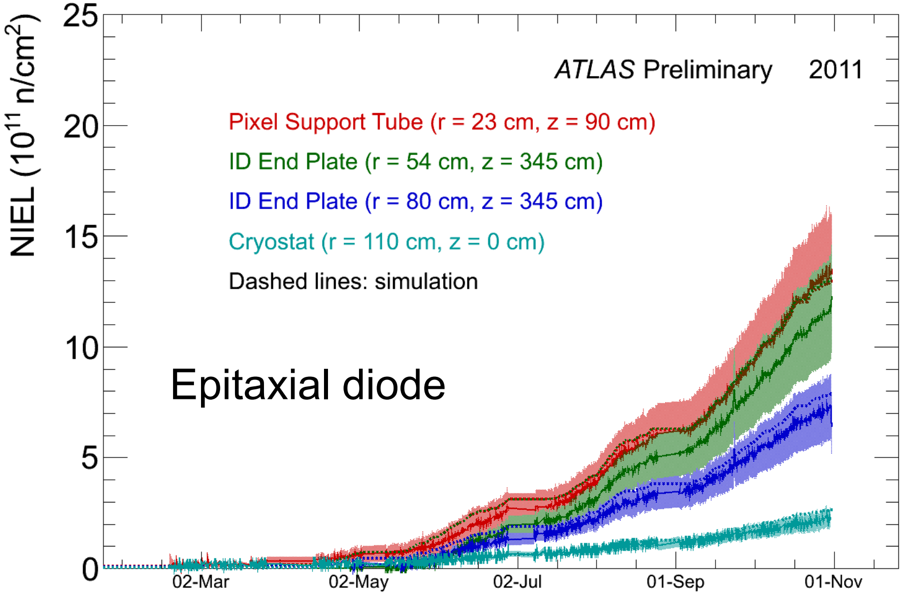
TID measured with 0.13 um RadFET (low sensitivity)



NIEL (1 MeV equivalent neutron fluence) measured with CMRP diodes (high sensitivity, forward bias)

- averages of measurements with sensors at similar locations are shown
  ➔ excellent agreement with predictions!

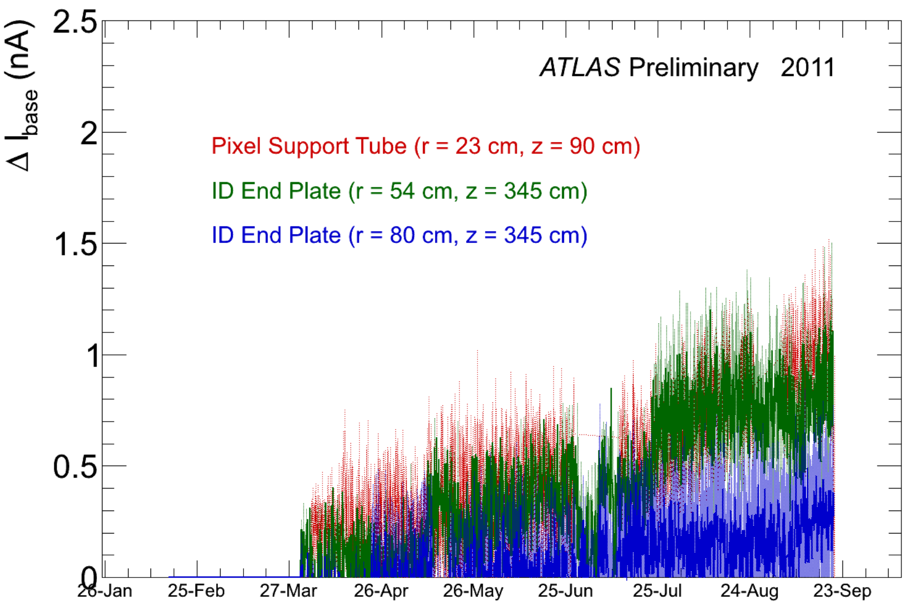
Results ID



Good agreement with reverse current measurements with thin epitaxial diode

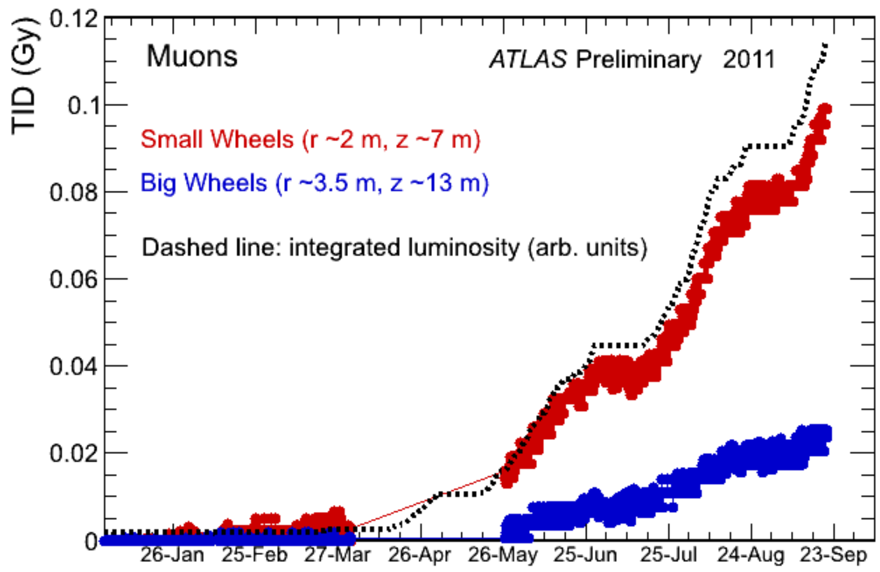
- first signs of base current increase in DMILL bipolar transistors
- current increase consistent with thermal neutron fluence of the order of 10^{11} n/cm^2

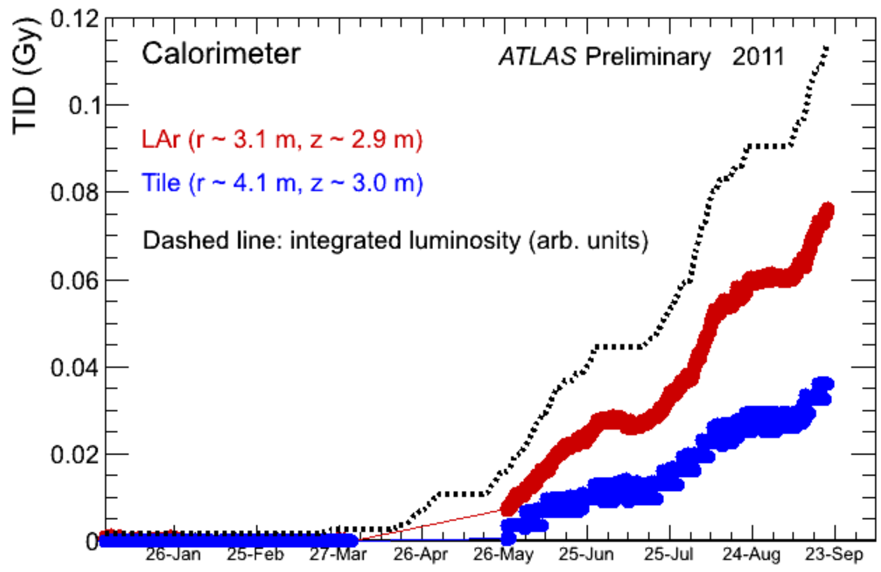
  → in agreement with FLUKA



Results out of ID

- outside of ID (radius > 2 m) doses still very low, on the limit of sensitivity
- accumulated dose proportional to integrated luminosity
- neutron fluences too low for reliable measurements





Conclusions

- measured doses and fluences proportional to integrated luminosity
- in the Inner Detector excellent agreement with predictions from FLUKA simulations

  → important for prediction of future detector performance

  → important for predictions for future High Luminosity LHC
- radiation damage already seen in detector components

  → increase of reverse current in silicon detectors

  → damage in agreement with FLUKA simulations