Online Radiation Dose Measurement System for ATLAS experiment

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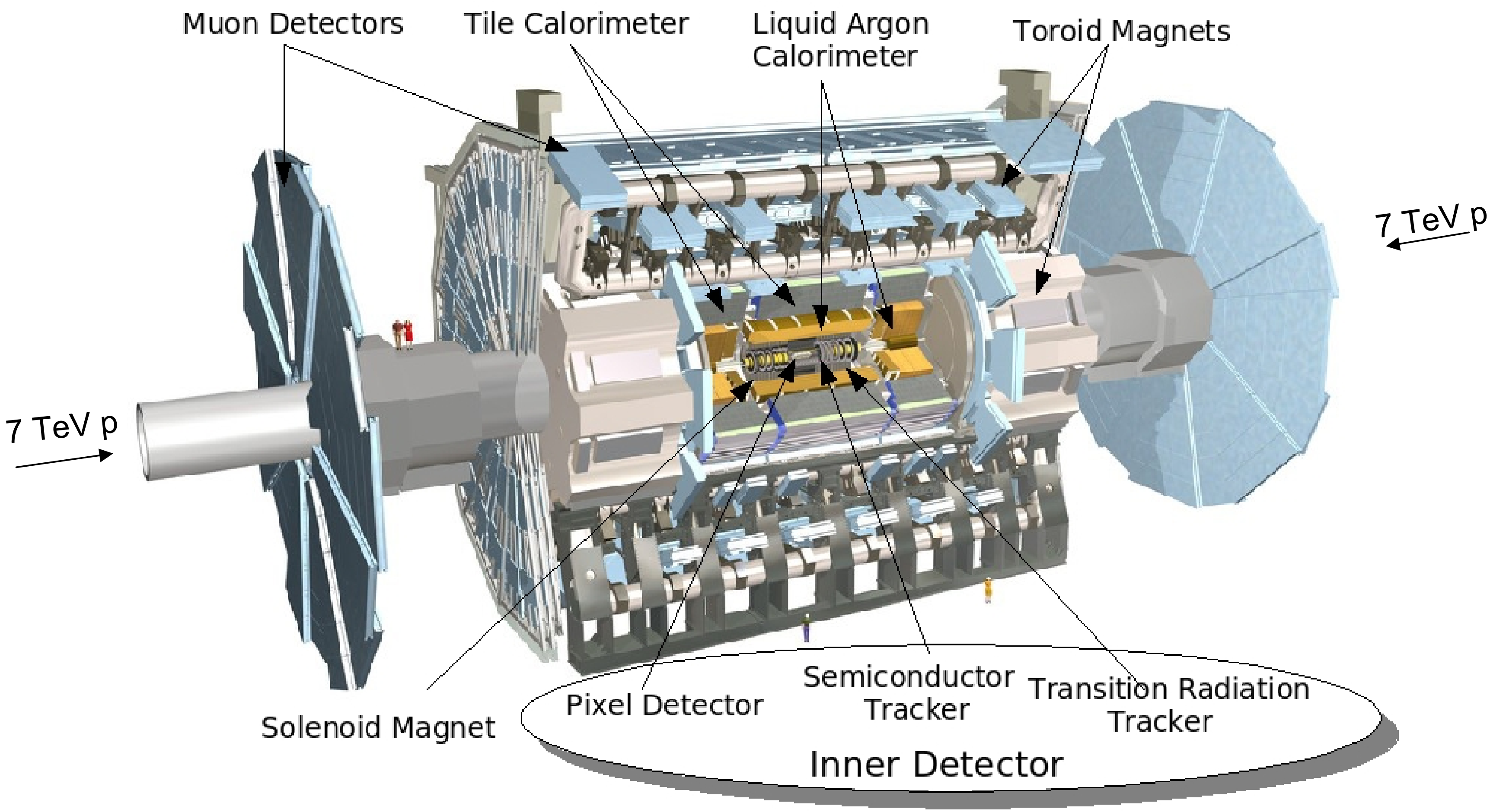
Lot of work with radiation sensors (characterization, selection, calibration, annealing studies etc...) was done by F. Ravotti, M. Glaser, M. Moll et al. from the CERN RADMON team
http://lhc-expt-radmon.web.cern.ch/lhc-expt-radmon/

The ATLAS experiment

- experiment at the Large Hadron Collider at CERN
- proton-proton collisions, E_p = 7 TeV, Luminosity = 10^{34} $cm^{-2}s^{-1}$

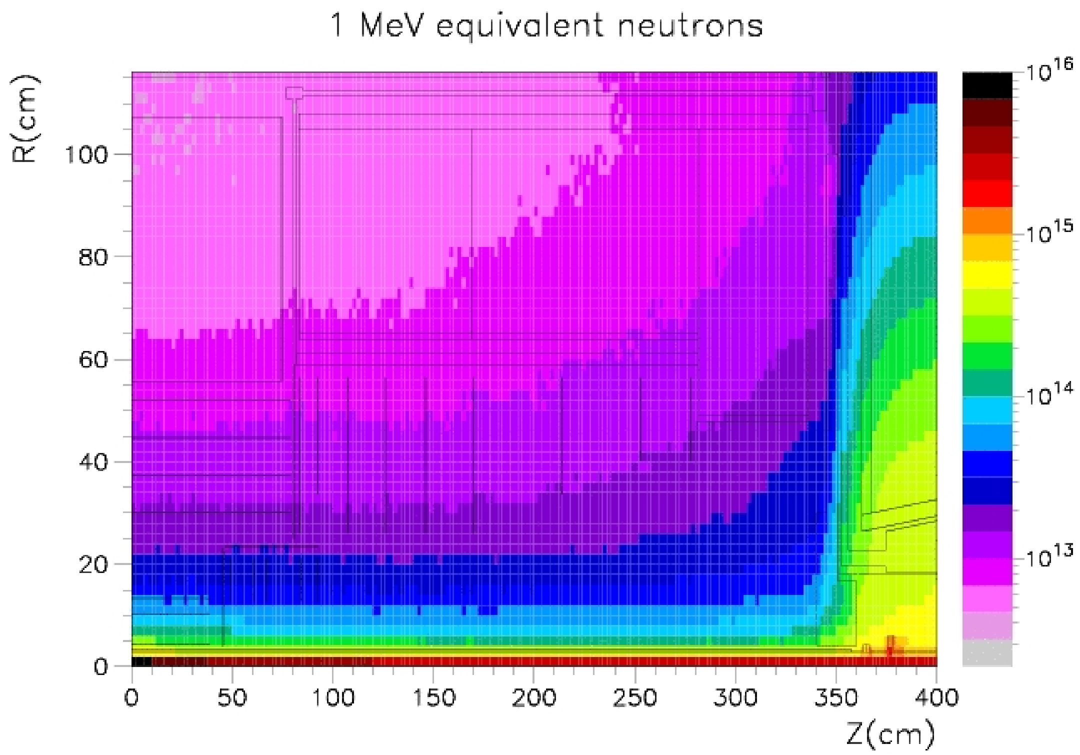


Radiation Field in ATLAS

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

Radiation levels after 10 years of LHC operation:

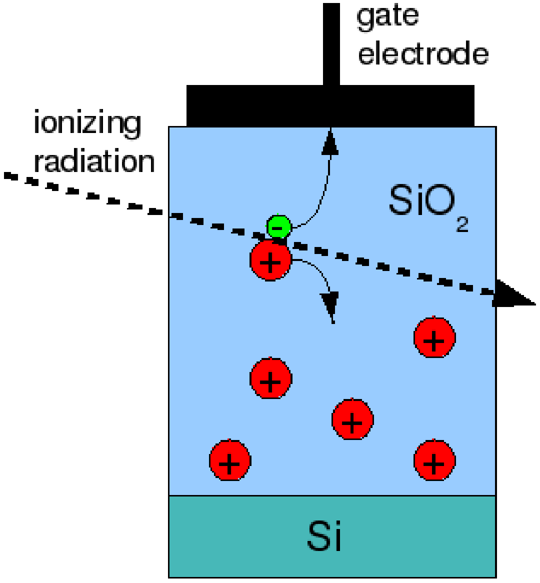
- Total Ionizing Dose (TID): TID > 100 kGy
- Non Ionizing Energy Loss (NIEL): $\Phi_{eq} \sim 10^{15}$ n/cm^2 (1 MeV equivalent neutrons in Si)
- Thermal neutrons $\Phi \sim 10^{15}$ n/cm^2

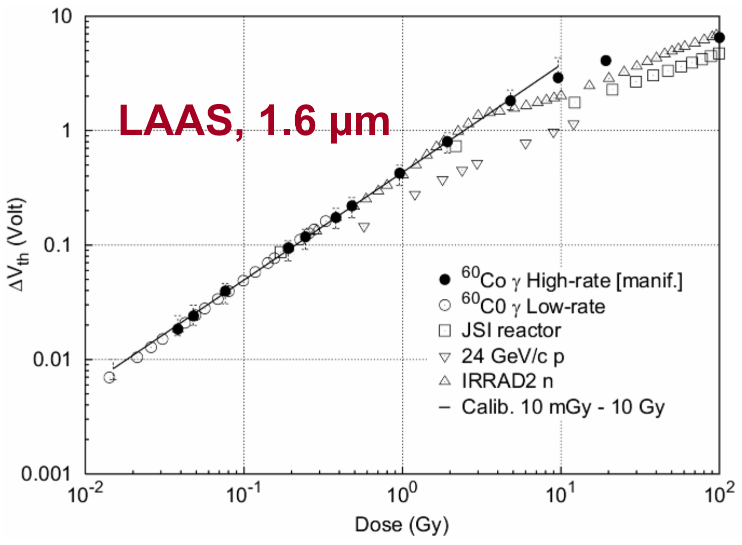


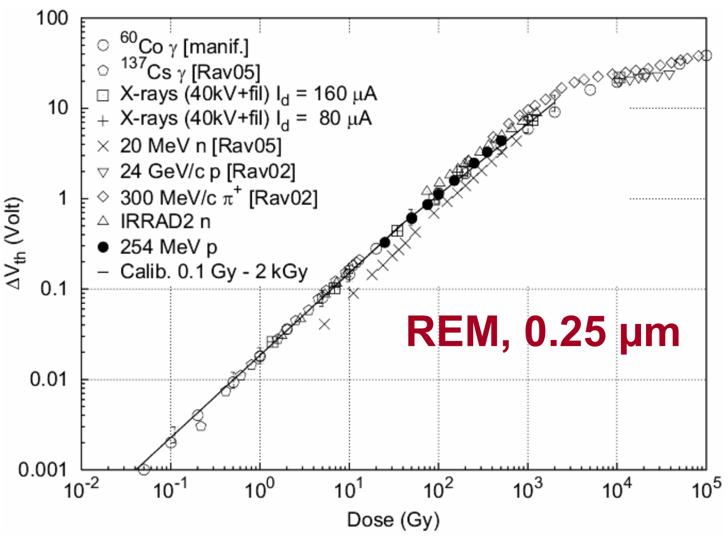
- such radiation levels cause damage to detectors and readout electronics
  - ➔ dose monitoring necessary to understand detector performance
  - ➔ cross check of simulations and make predictions

TID measurements with RadFETs

- RadFETs: p-MOS transistor
- holes created by radiation get trapped in the gate oxide:
  ➔ increase of threshold voltage with dose:
  DV = a x (TID)^{b}
- sensitivity and dynamic range depends on oxide thickness:







- characterizations, selection, calibrations done by CERN RADMON team: F. Ravotti, M. Glaser, M. Moll....

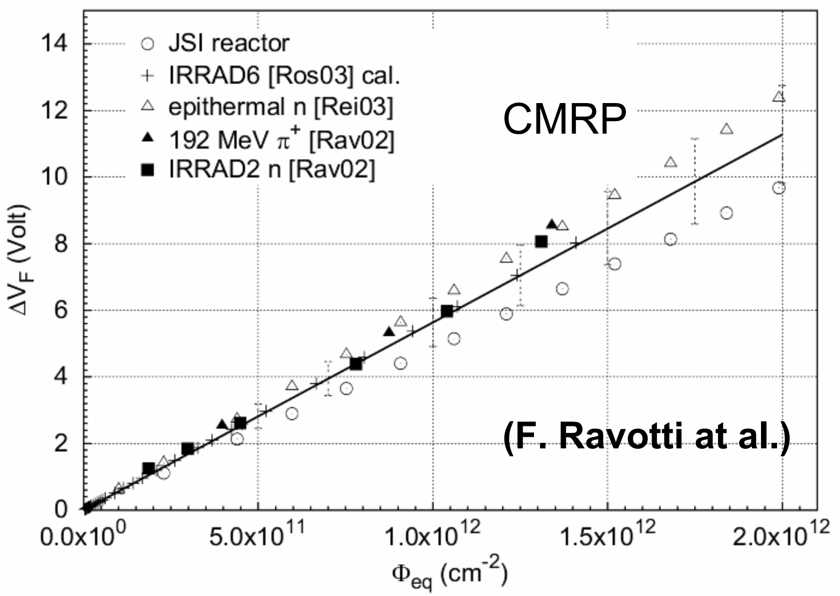
NIEL measurements with diodes

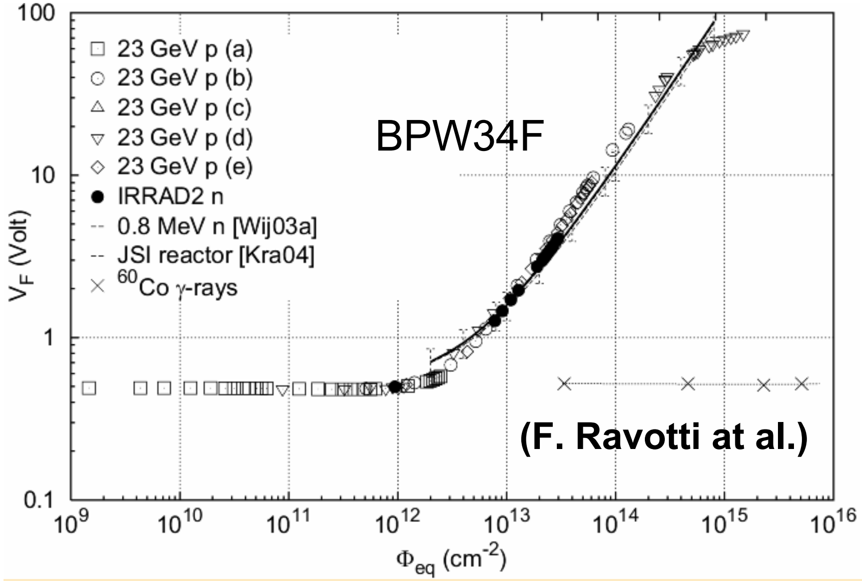
- bulk damage in silicon consequence:
  increased resistance, increase of reverse current....

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

<u>Forward bias</u>

- linear response **$DV = k \cdot \Phi_{eq}$** (***V*** measured at ***I*** **= 1 mA**)
- 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





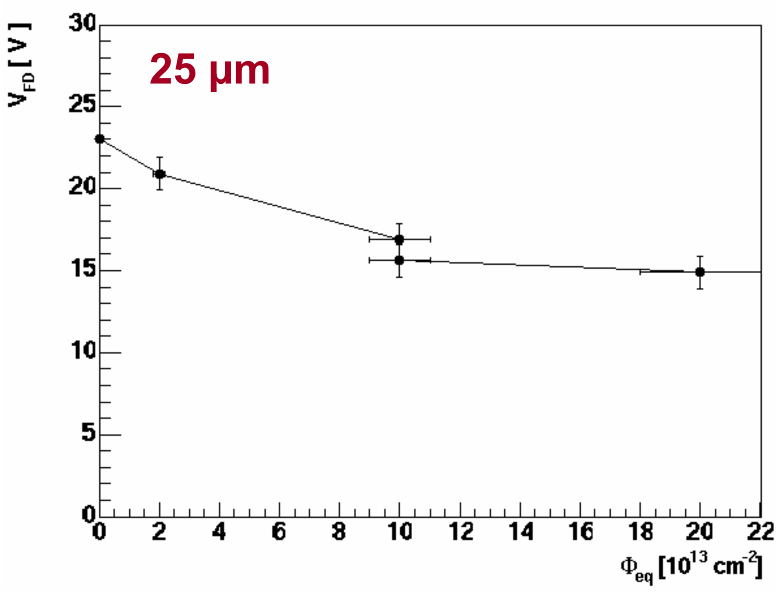
➔ sensitivity can be shifted to lower Φ if diode is pre-irradiated with ~ $3 \cdot 10^{12}$ n/cm^2

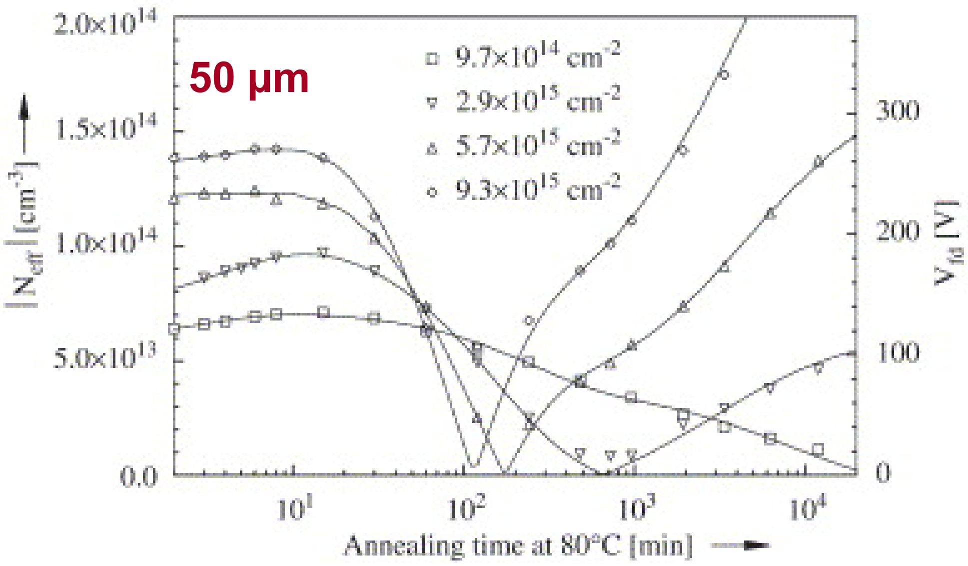
NIEL measurements with diodes

Reverse bias

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

- **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 to measure fluences from 10^{11} n/cm^2 to 10^{15} n/cm^2





G. Lindstrőm et al., NIMA 568 (2006)

Thermal neutrons

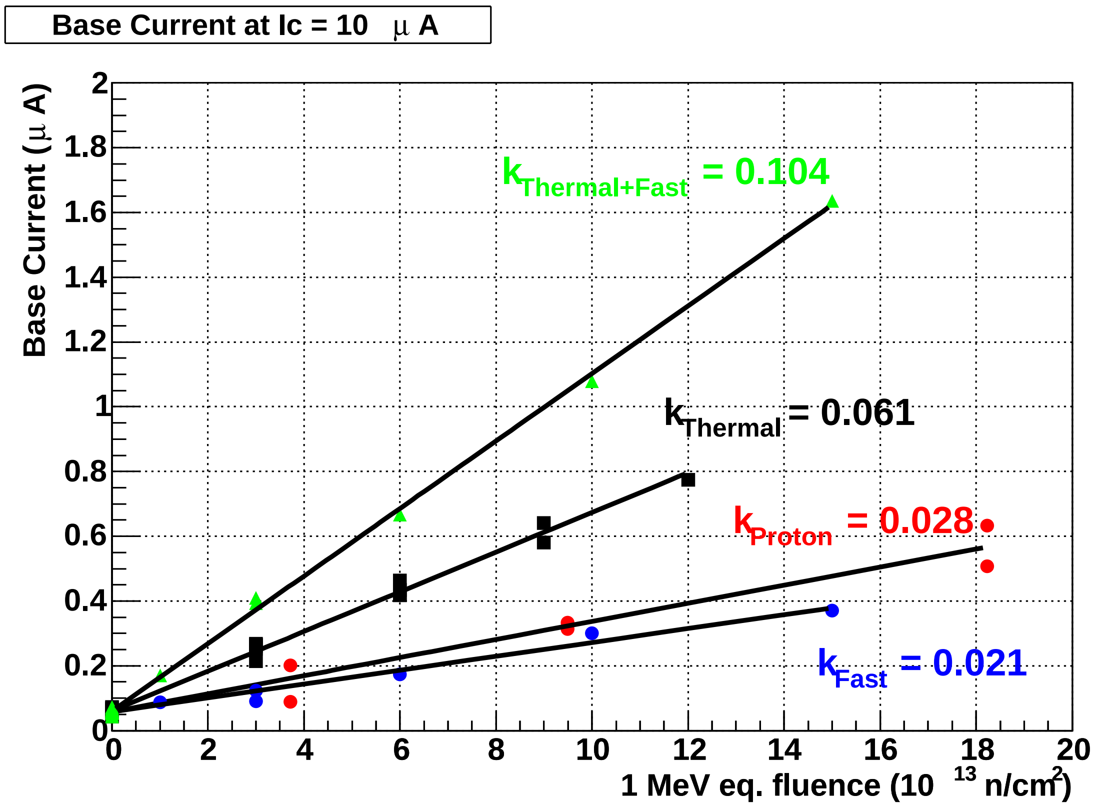
- bipolar transistors (DMILL) used in front end ASICs
- measure current gain: base current at given collector current

  ➔ sensitive to fast and thermal neutrons

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

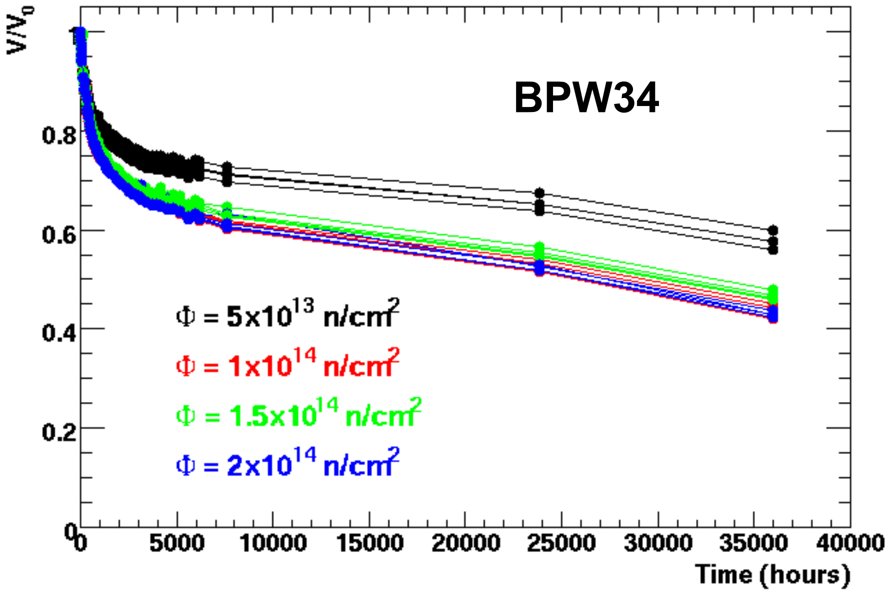
k_{eq}, k_{th} and Φ_{eq} known

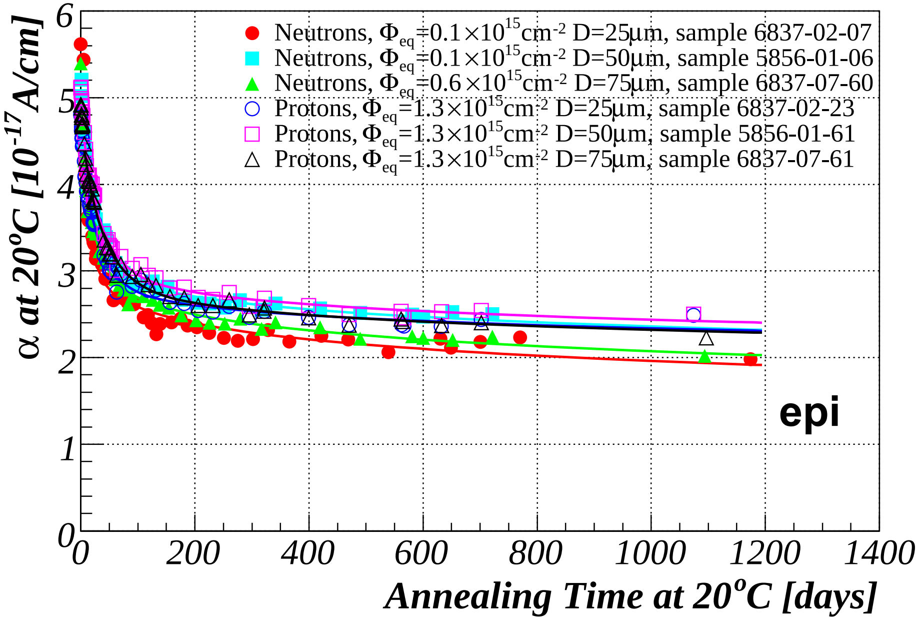
➔ Φ_{th} can be determined



Annealing

- not significant (~ 15% or less in 1 year at RT): RadFETs, DMILL transistors, CMRP diodes
- larger: BPW34, epi





Radiation Monitor Sensor Board (RMSB)

Inner Detector

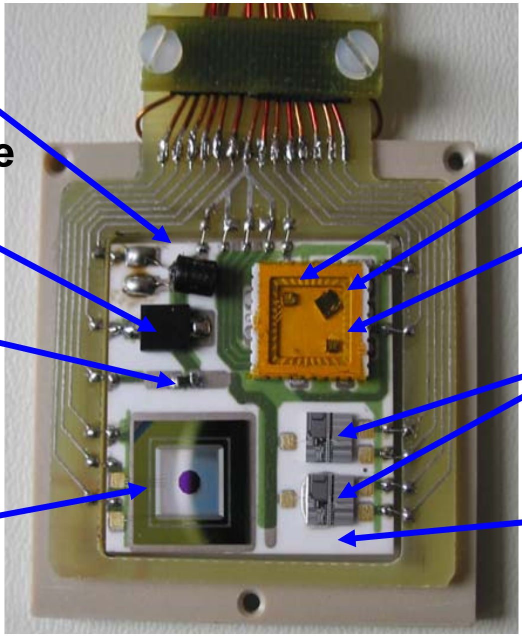
- for dose monitoring in the Inner Detector:

  - large range of doses
  - no access in 10 years

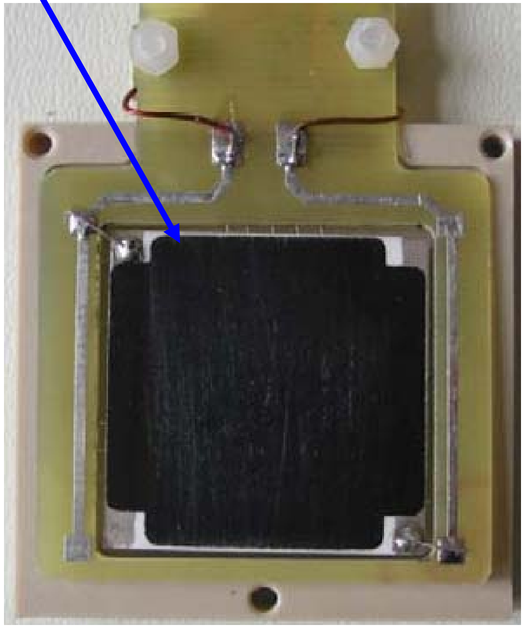
  ➔ **need many sensors**

- large temperature variations (-10 to 20°C) at some locations

  ➔ stabilize temperature to 20 ± 1°C by heating back side of the ceramic hybrid



Thick film resistive layer R = 320 Ω



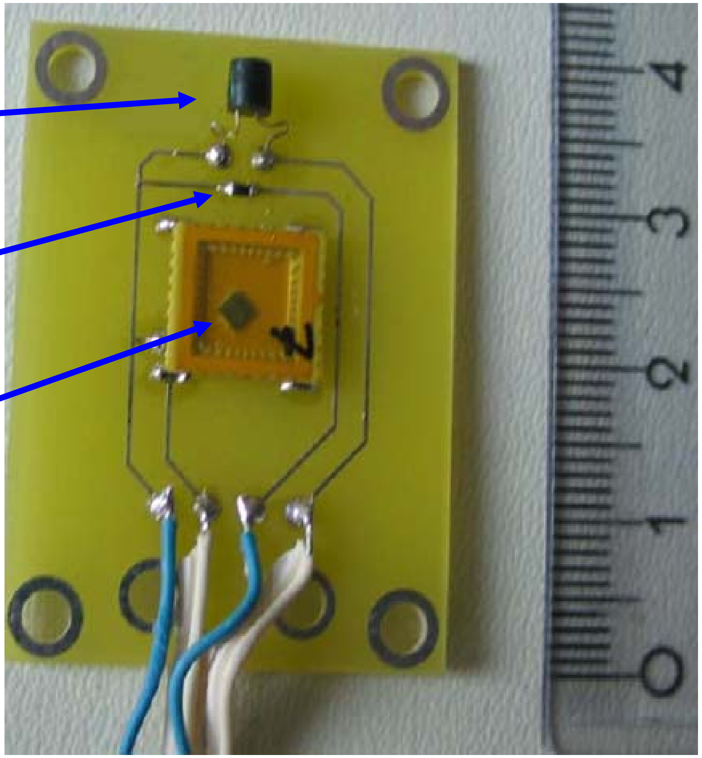
Back side

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



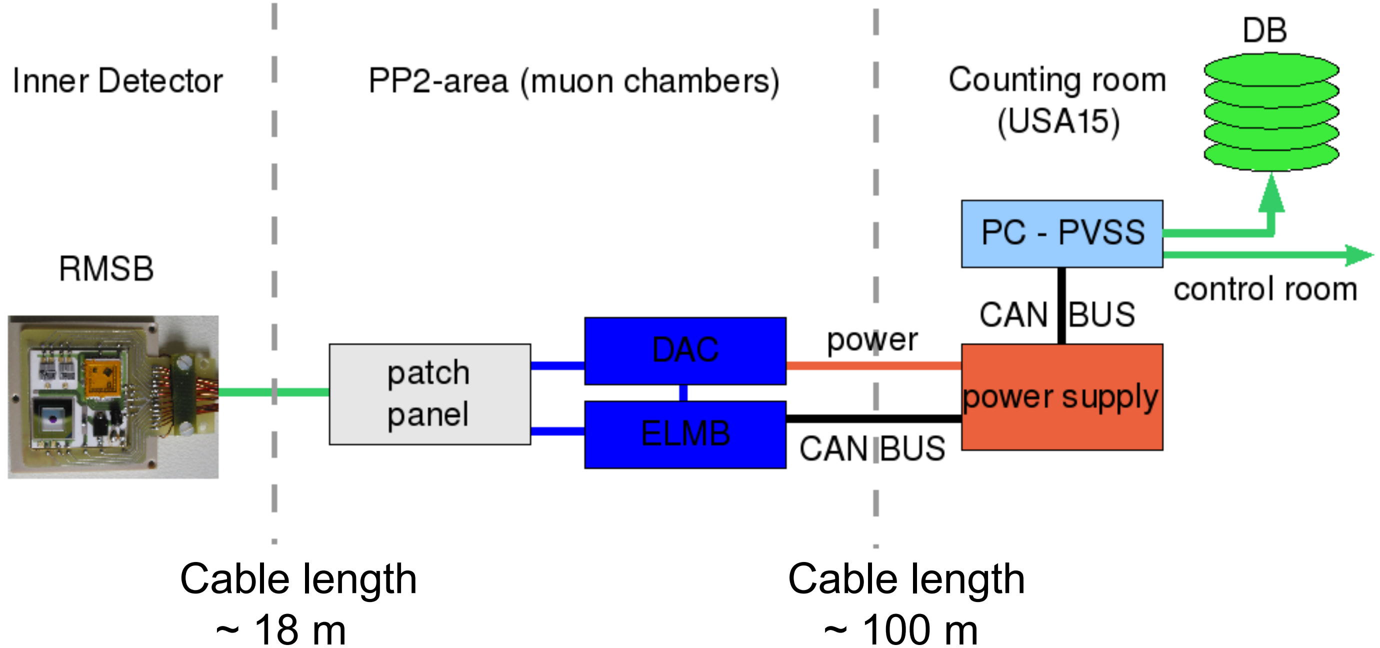
CMRP diode

Thermistor

LAAS radfet
(1.6 µmSiO_2)

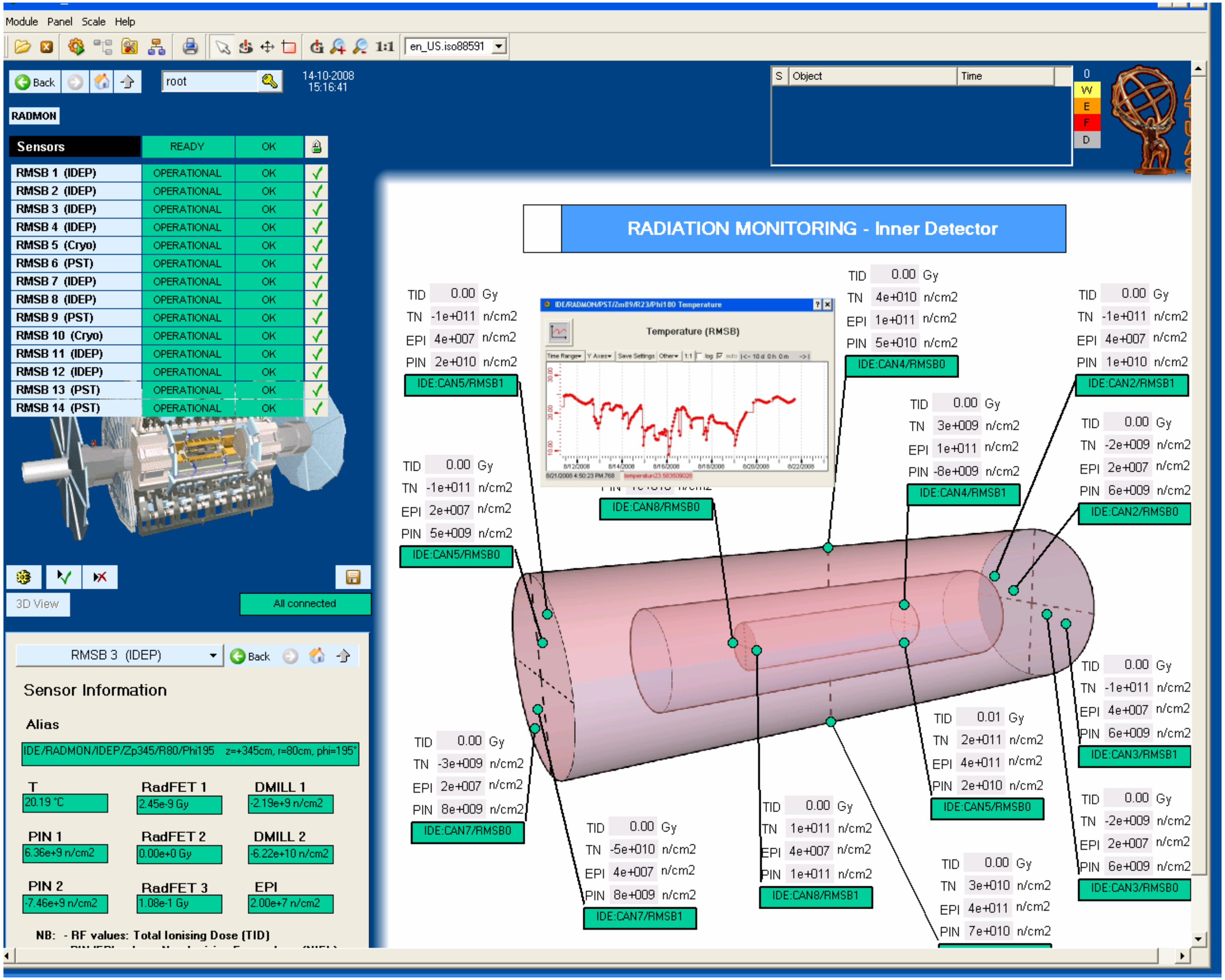
Readout

- 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
- readout values available in the ATLAS control room and archived for offline analysis



Monitoring locations

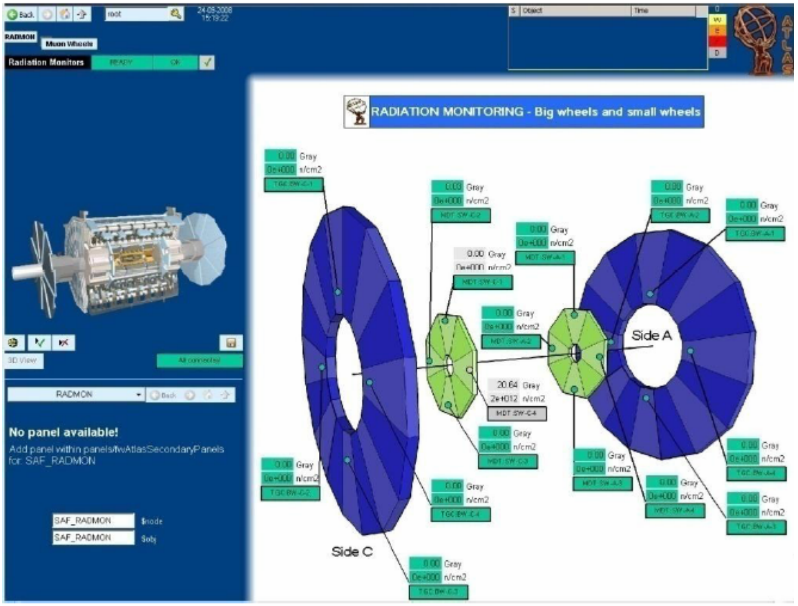
- 14 monitors in the Inner Detector



Monitoring locations

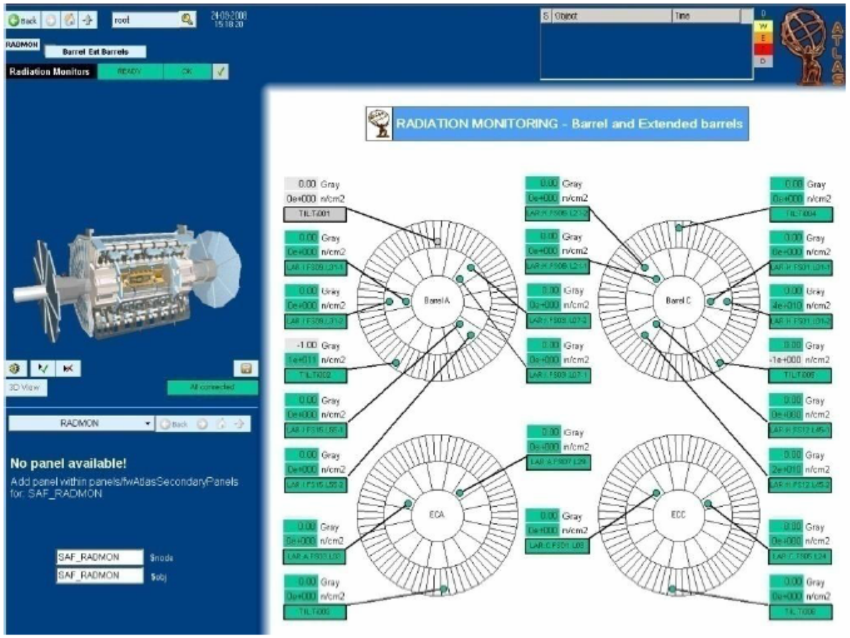
- 48 locations outside of the Inner Detector

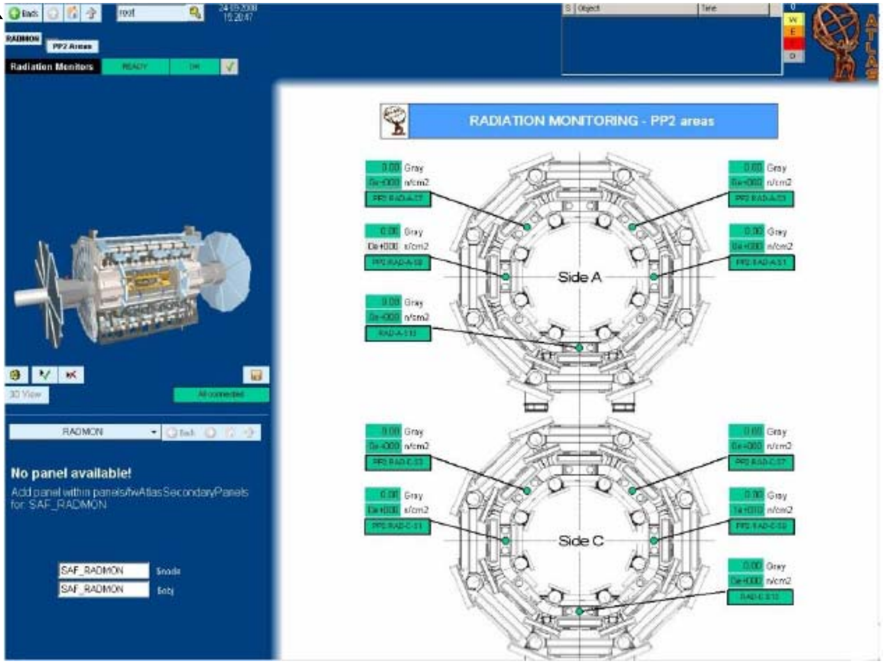
Muon detectors



Calorimeters

TRT electronics

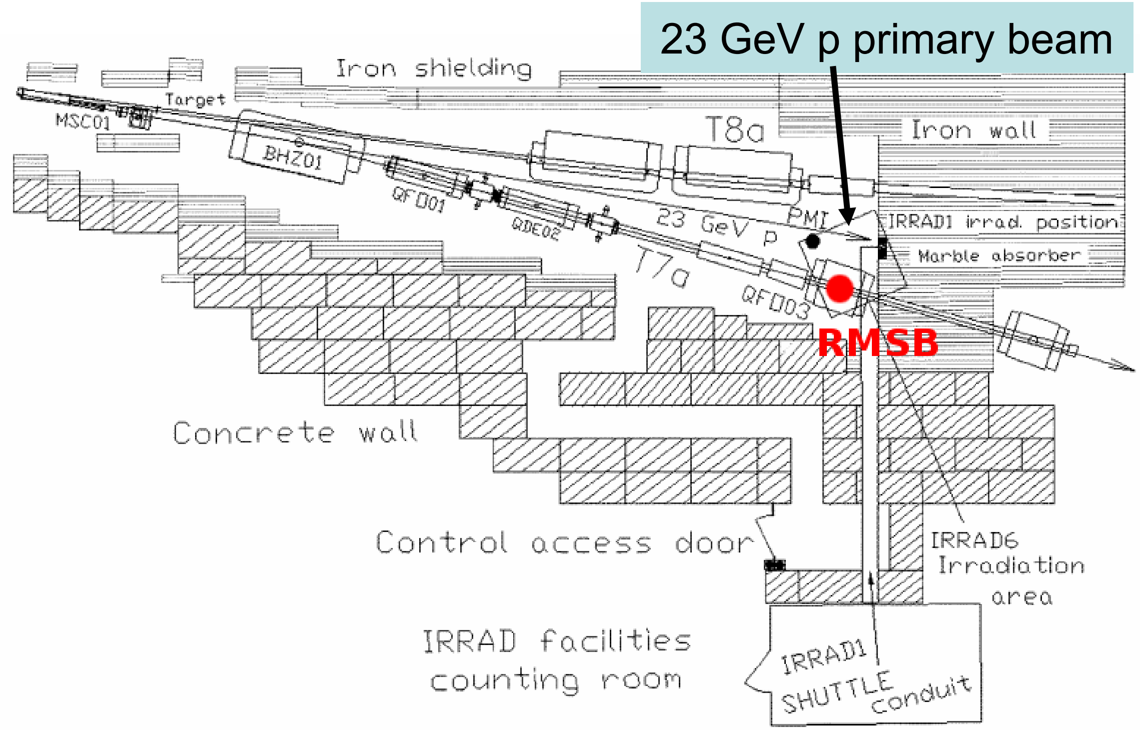




Tests in Mixed Radiation Environment

- 2 ID-type RMSBs with readout installed in the IRRAD6 irradiation facility at CERN in 2008
- mixture of pions, protons, neutrons, photons
- low dose rates, beam on-off
  ➔ similar conditions as in ATLAS

- SEC counter Secondary Emission Counter (SEC): counts number of protons in primary beam
  ➔this number is proportional to the dose at RMSB location



F. Ravotti, M. Glaser et al., *IEEE TNS Vol. 54 (4), pp. 1170-1177, 2007.*

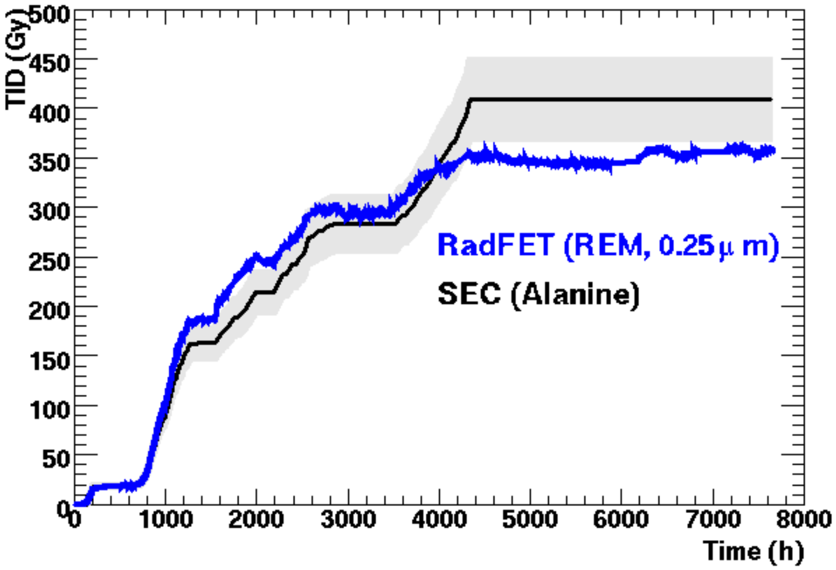
Tests in Mixed Radiation Environment

TID

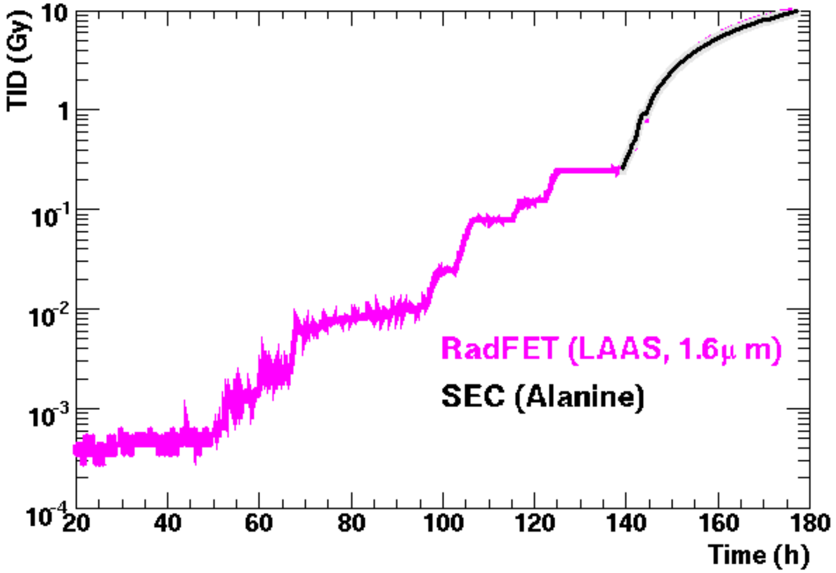
- SEC counts converted to dose (Gy) with alanine dosimeter

➔ dose 410 ± 20 Gy measured with alanine at the end of beam period (at 4000 h)

Medium Sensitivity
➔ good agreement with SEC
➔ no significant annealing



High Sensitivity RadFET
➔ mGy sensitivity

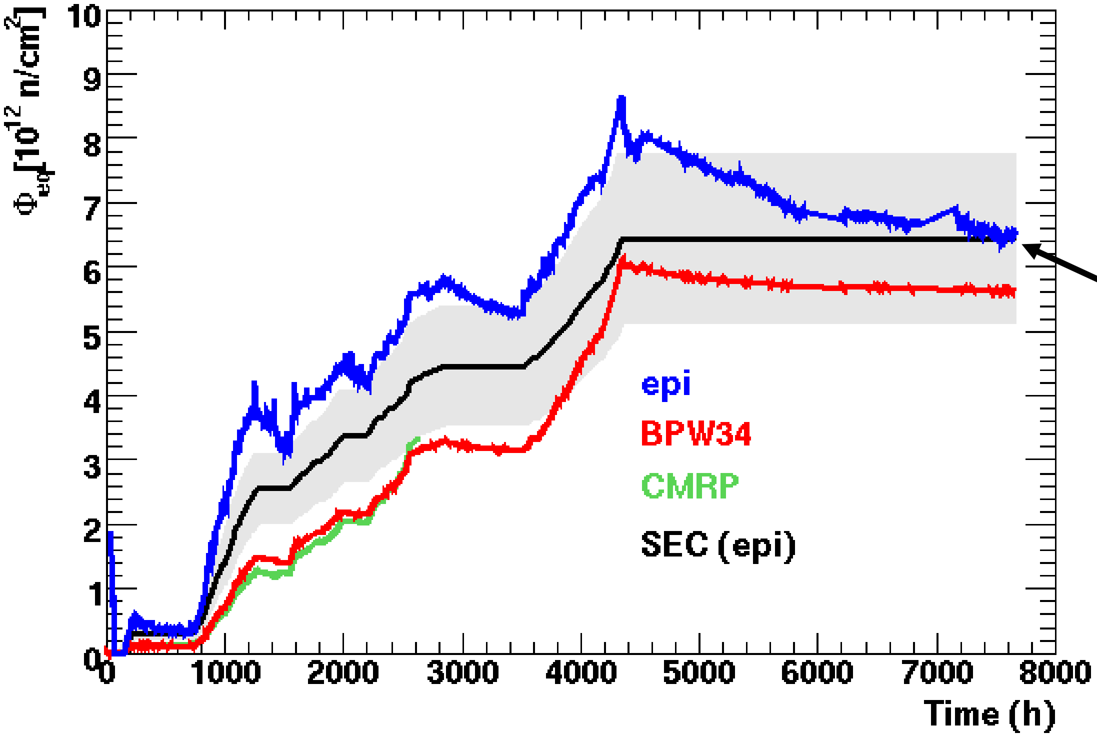


Tests in Mixed Radiation Environment

NIEL

- SEC counts converted to 1 MeV equivalent neutron fluence with epitaxial diode on RMSB

➔ current ***I* = 0.11 μA** measured at **Time ~ 8000 h**
➔ with **α = 2.7 ·10^{-17} Acm** we get fluence **Φ_{eq}= 6.5·10^{12} n/cm^2**



SEC normalized at this point

- raw measurements (no corrections for annealing)

Tests in Mixed Radiation Environment

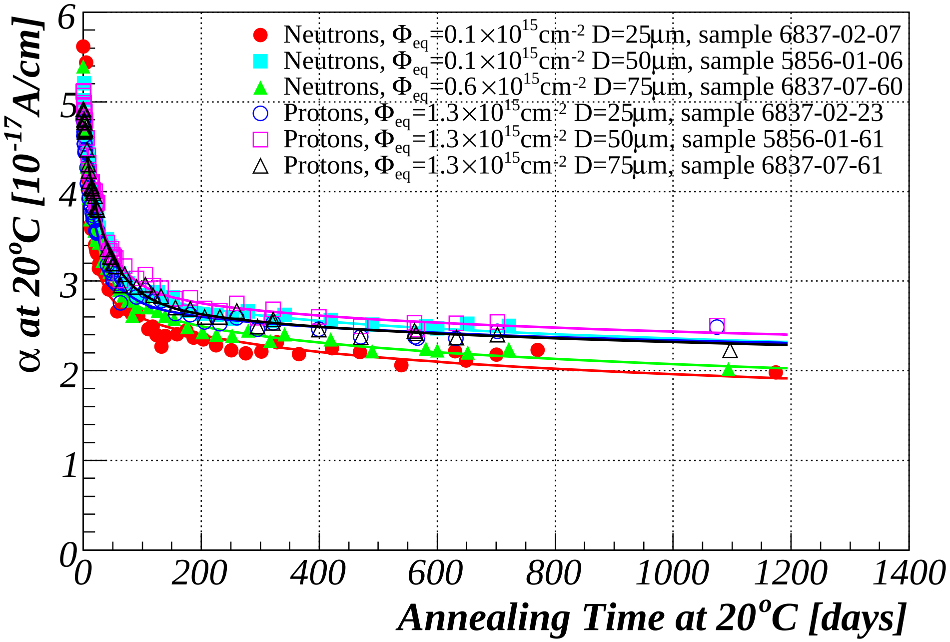
Annealing:

• approximation:

$$I(t) = I_1(t) + I_0$$

$$I_1(t) = V\Phi\alpha_1 \cdot e^{-\frac{t}{\tau}}; \quad I_0 = V\Phi\alpha_0$$

$$dI(t) = -\frac{I_1(t)}{\tau}dt$$



• change of current **D*I*** measured at time ***t*** in IRRAD6 after time interval **D*t***:

$$\Delta I = \alpha V \Delta\Phi - \frac{dI(t)}{dt} \cdot \Delta t$$

$$\Delta I = \alpha V \Delta\Phi - \frac{I_1(t)}{\tau} \cdot \Delta t$$

$$I_1(t) = I(t) - V\alpha_0\Phi(t)$$

$$\alpha = \alpha_1 + \alpha_0$$

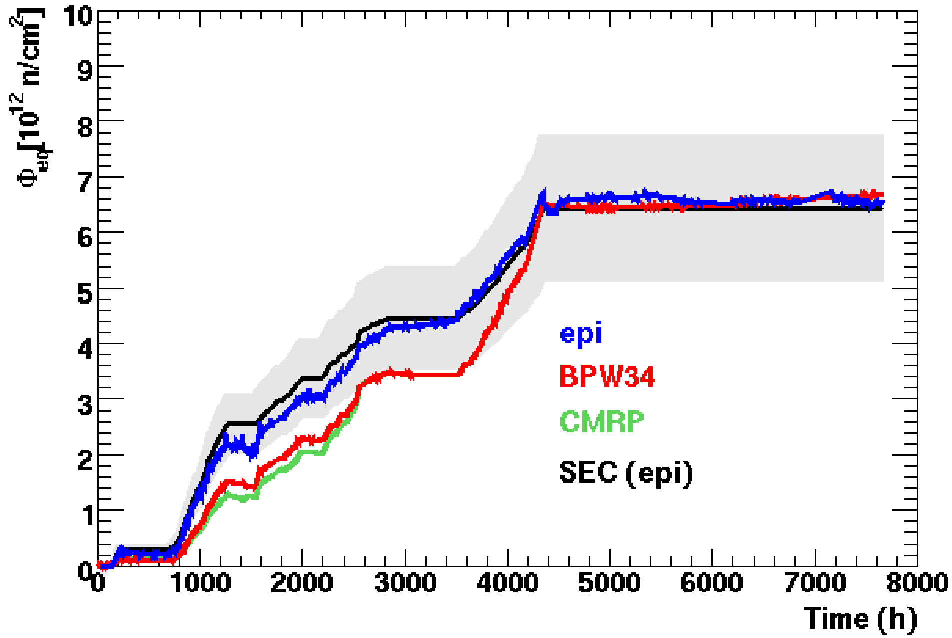
$$\Rightarrow \quad \Delta\Phi = \frac{1}{\alpha V}\left(\Delta I + \frac{I_1(t)}{\tau} \cdot \Delta t\right).$$

Tests in Mixed Radiation Environment

NIEL

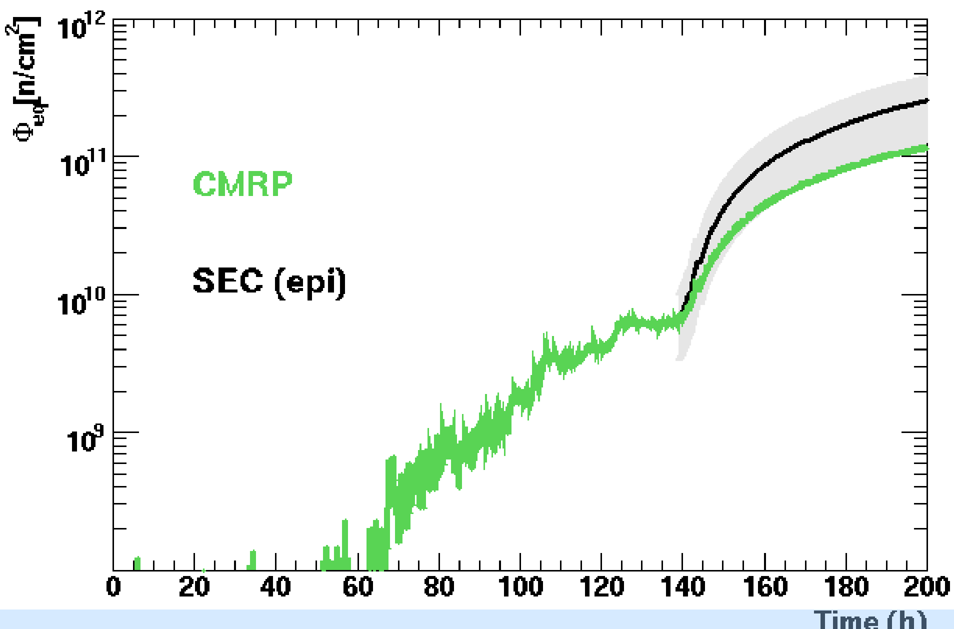
All diodes:
- epi → reverse bias
- BPW34 → forward bias
- CMRP → forward bias

➔ epi and BPW34 corrected for annealing



High Sensitivty PiN diode (CMRP)
- measure forward bias @ I = 1 mA

➔ sensitivity ~ 10^9 n/cm^2



Tests in Mixed Radiation Environment

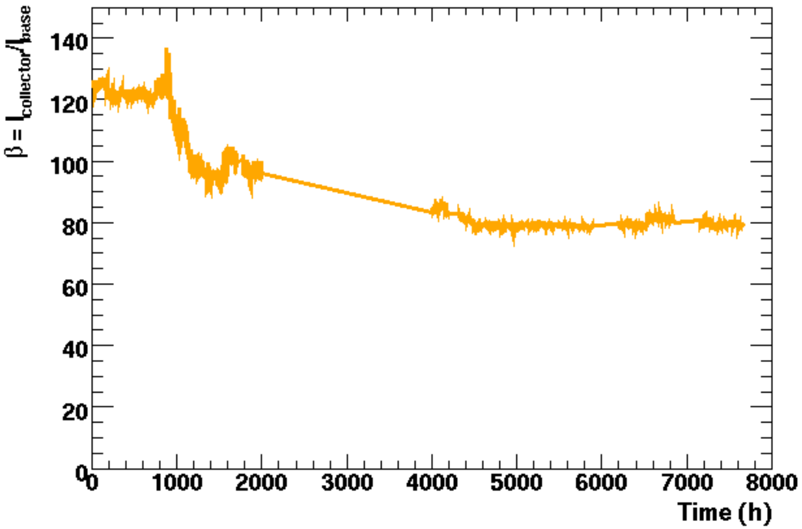
Thermal neutrons

- base current I_b measured at collector current I_c = 10 µA

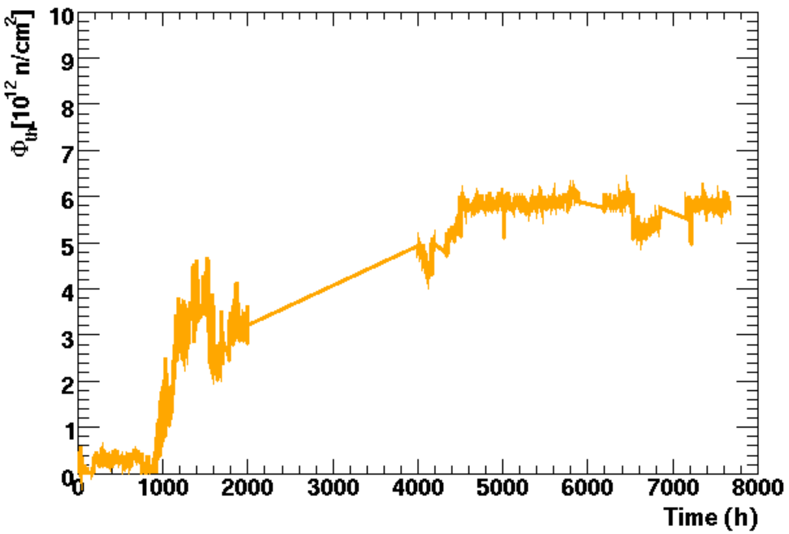
1. monitor current gain $\beta = I_c/I_b$
2. measure fluence of thermal neutrons:

➔ $\Phi_{th} = 1/k_{th}\,(DI_b/I_c - k_{eq}\cdot\Phi_{eq})$, Φ_{eq}: measured with BPW34

β degradation



Thermal neutron fluence



Experience from ATLAS

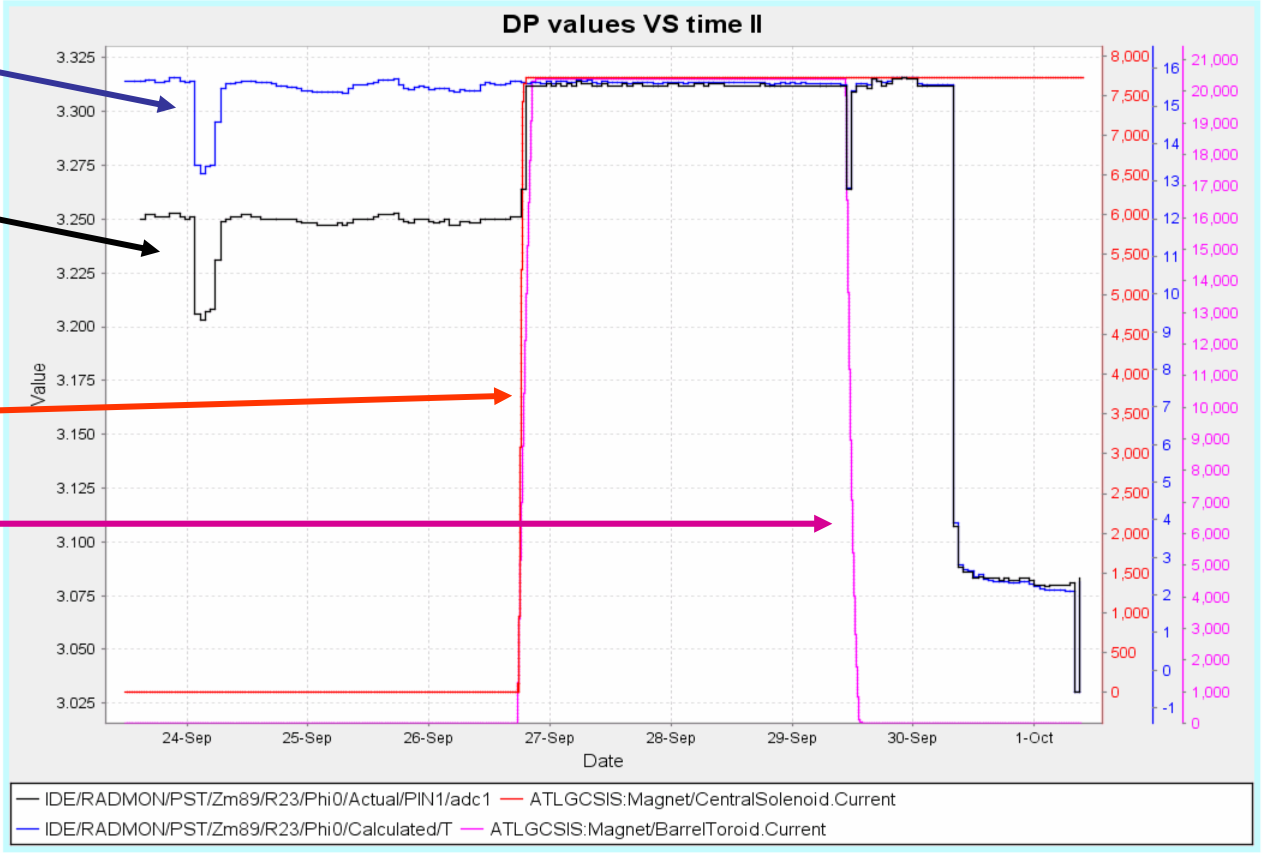
- complete system was installed and integrated in ATLAS DCS in 2008
- stability checked, temperature dependences measured
  ➔ surprise: response of diodes operated in forward bias influenced by magentic field

Temperature

Diode Voltage

Solenoid field

Toroid field



- later tests showed that the effect doesn't change with fluence ➔ can be subtracted

Summary

• system for online radiation monitoring in ATLAS Inner Detector:

➔ total ionization dose in $Si0_2$
➔ bulk damage in silicon in terms of 1 MeV equivalent neutron fluence
➔ fluence of thermal neutrons (Inner Detector only)
➔ readout compatible with ATLAS Detector Control System

• tests in mixed radiation environment

➔ sufficient sensitivity: TID ~ mGy, $\Phi_{eq} \sim 10^9\ n/cm^2$
➔ sufficient accuracy: ~ 20%
➔ annealing effect can be controlled

• complete system was installed and integrated in ATLAS DCS in 2008

➔ few months of data taking in 2008
➔ good stability

Ready to measure doses!