On line radiation monitoring in the LHC tunnel and underground areas with SEU counters, RADFETs and PIN diodes

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Acknowledgements :

RADWG members, ESA, JPL, Radiation community

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CERN Radioprotection group

Monte Carlo experts (FLUKA, MARS, GEANT4) at CERN and Protvino

Outline

- Introduction
- Motivation
- Radiation fields around the ring
- Monitoring system
- Radiation Monitoring Board
- Radiation Sensors
- Results from 2004 campaign

Radiation Hazards for the LHC machine :

- ➔ Large amount of electronic systems in the LHC tunnel (~12.000 crates) and underground areas under irradiation
- ➔ All designs are based on COTS components with variable radiation tolerances
- ➔ Prediction of radiation along the ring is based on theoretical models and Monte Carlo codes
- ➔ Shielding will be installed in some areas but predicted shielding efficiency may not be achieved

— EXAMPLE —

QUENCH PROTECTION SYSTEM :

- **Quench Detectors (2100 Units)**
- **Acquisition and monitoring**
- **Quench Heater Power converters (6200 Units)**

REQUIRED MINIMUM RADIATION TOLERANCE :

- **TID : 200 Gy**
- **NIEL : 1×10^{12} 1 MeV equivalent neutrons/cm^2**
- **Single Event Upset free at 1×10^{11} hadrons/cm^2**

Courtesy : R. Denz (LHC/ICP)

Radiation Monitoring - Motivation

There is a considerable uncertainty on the radiation environment in the tunnel and on the radiation tolerance of equipment.

The radiation monitoring system will help to reduce this uncertainty by providing an early warning as the radiation levels at the location of the equipment increase.

During circulating beam in LHC :

➔ Monitor degradation of electronics due to radiation when beam “on”

➔ Detect instantaneous failures caused by radiation (SEEs) instead of by normal MTBF :

- Propose appropriate radiation tolerant components in case of radiation induced failures
- Propose appropriate radiation test for upgraded electronics designs before installation in the machine

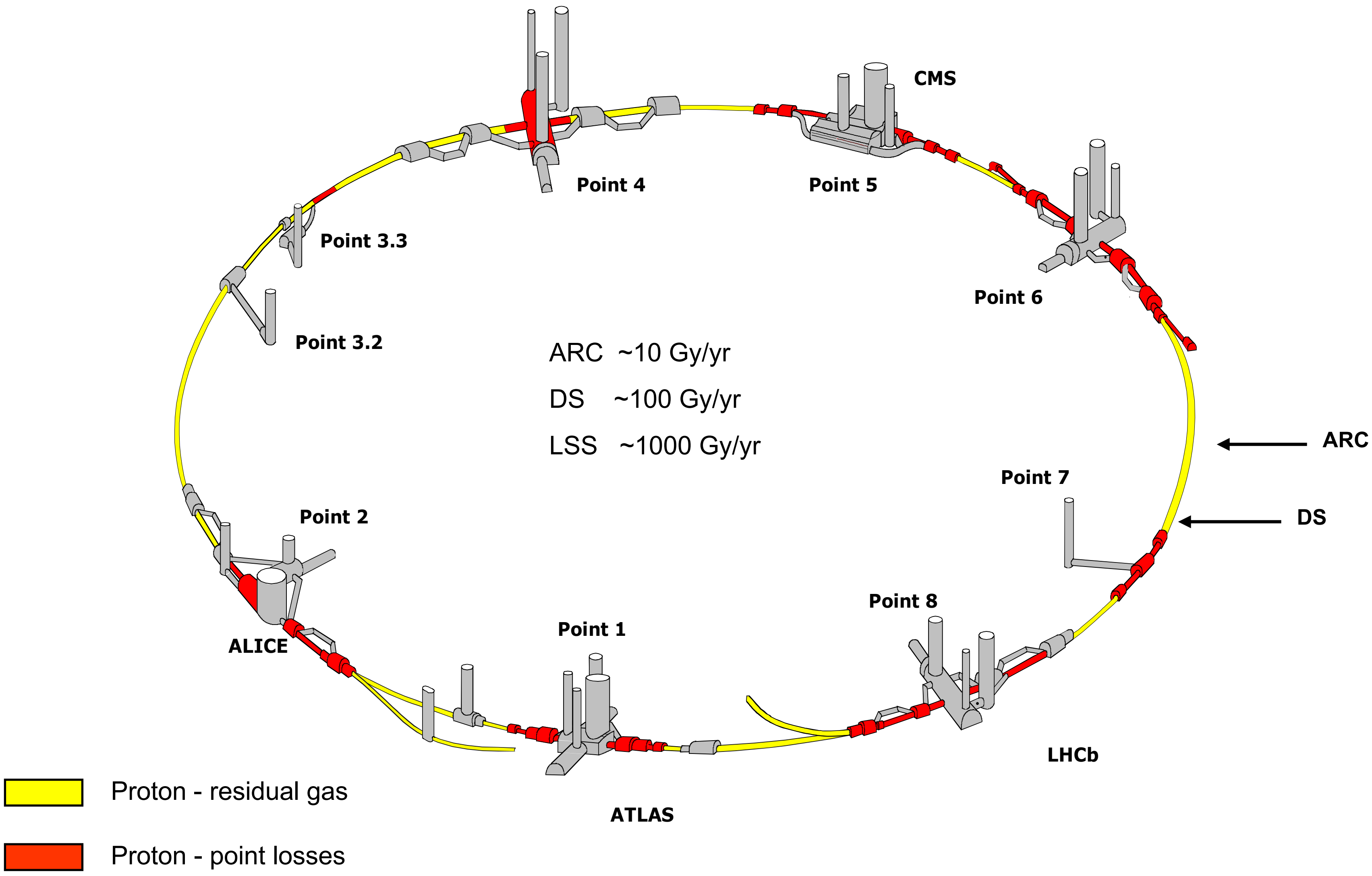
➔ Anticipate replacement of electronics that degraded due to cumulative radiation damage effects

➔ Cross check FLUKA/MARS/GEANT4 simulation results

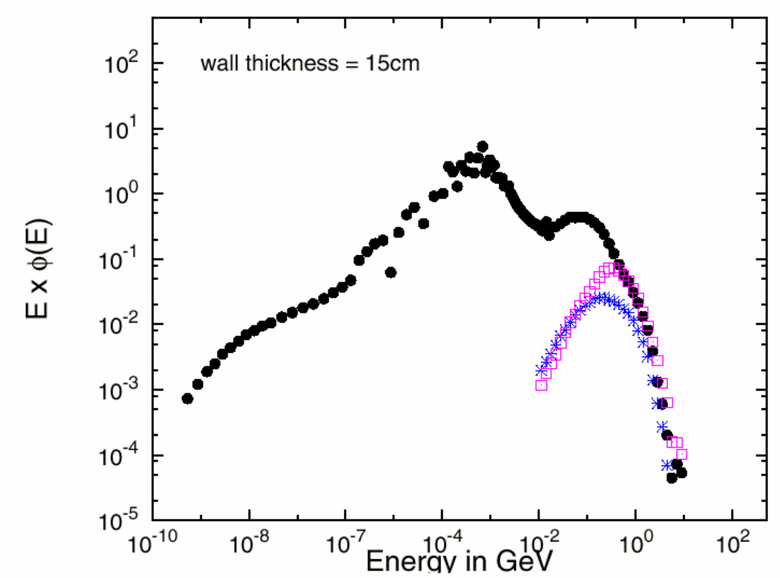
- Dynamic pressure in ARCs in coast, after quench, …
- “Radiation flash”, collimation, radiation in RRs due to collision products, …

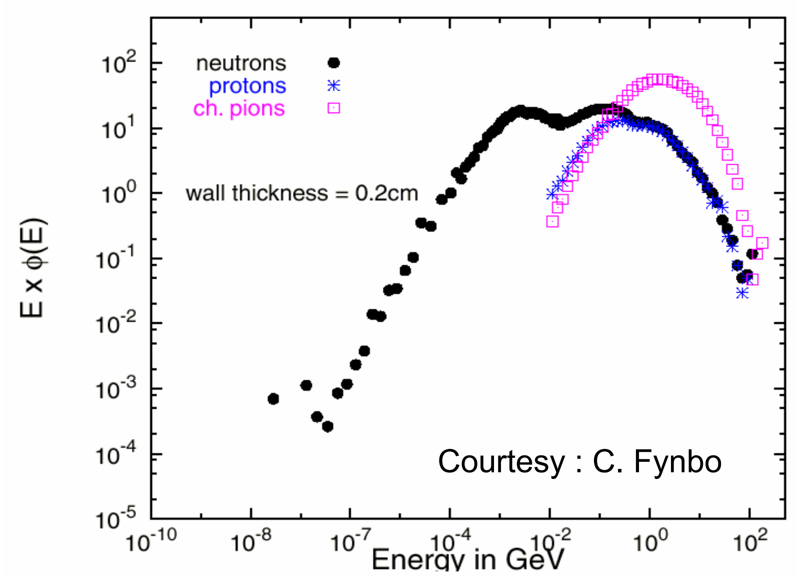
➔ Measure shielding efficiency – confirm staged implementation

Radiation levels - global distribution



Radiation Levels : fluence to dose ratios





1 year in ARC :

Dose : 10 Gy

1 MeV eq. neutrons : 5×10^{10} $cm^{-2}Gy^{-1}$

Hadrons (E>20 MeV) : 3×10^{9} $cm^{-2}Gy^{-1}$

1 year in DS :

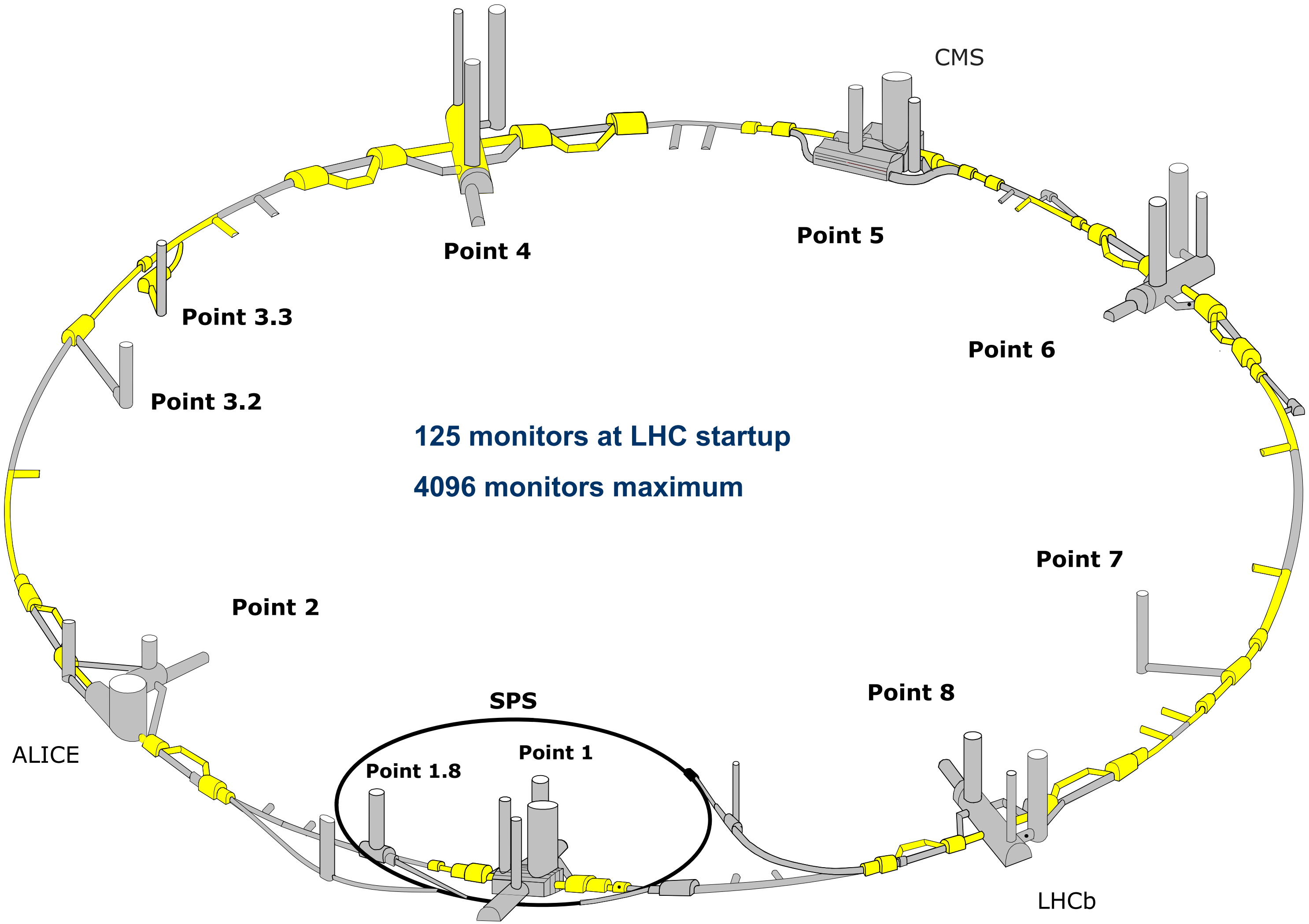
Dose : 100 Gy

1 MeV eq. neutrons : 6×10^{10} $cm^{-2}Gy^{-1}$

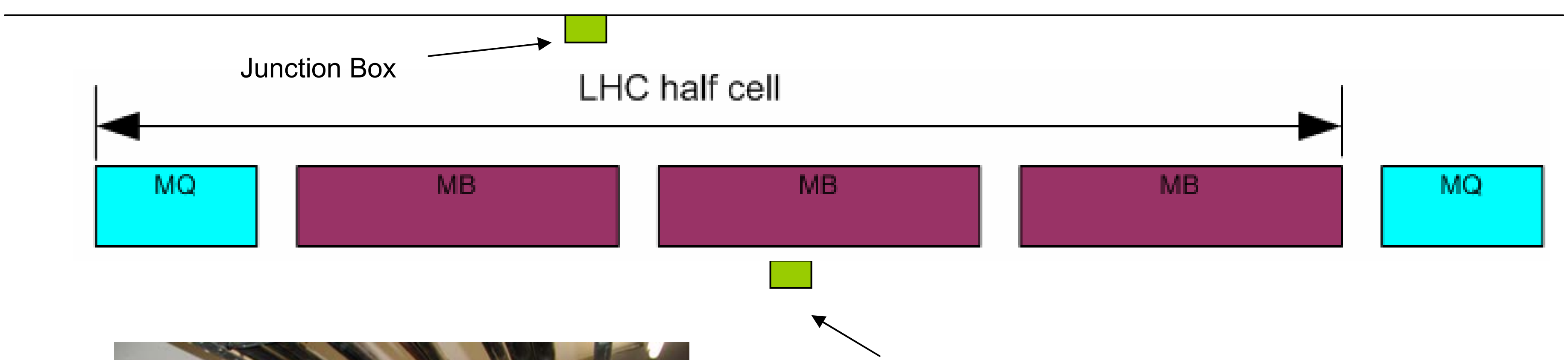
Hadrons (E>20 MeV) : 4×10^{9} $cm^{-2}Gy^{-1}$

Fluence to dose ratios are similar !

Radiation monitoring system



Location of Junction box and monitors - ARC



Radiation Monitor

Can be placed at max 25 meters from junction box

Any location within half cell (max 32 per half cell)

Junction box with signal cabling in ARC

CBWS Version 3.0

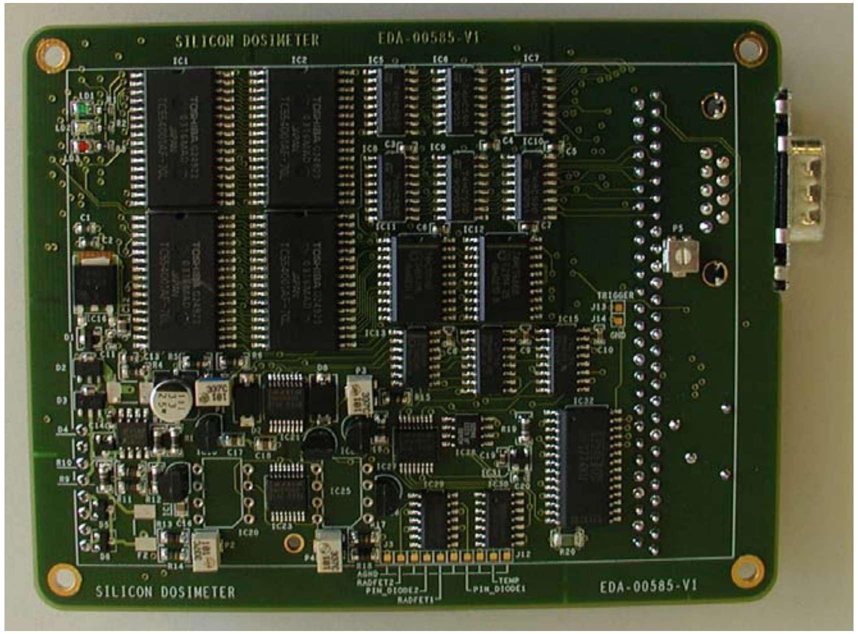
Aluminum casing with cover and sides partially removed

Size : 11 x 9 x 5 cm

(i.e medium sized cigar box)

Radiation Monitoring board

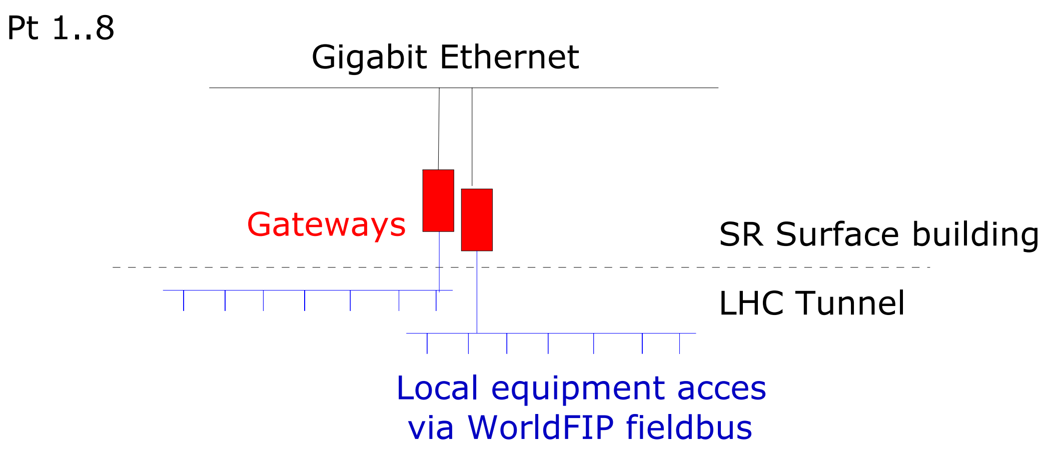
- Radiation tolerant design (200 Gy)
- Remote readout via WorldFIP at 1 Mbit/s
- Up to 100 Hz Measurements of
  - Dose, Dose rate
  - 1 Mev Eq. Neutrons fluence
  - Hadron (E>20 MeV) flux and fluence

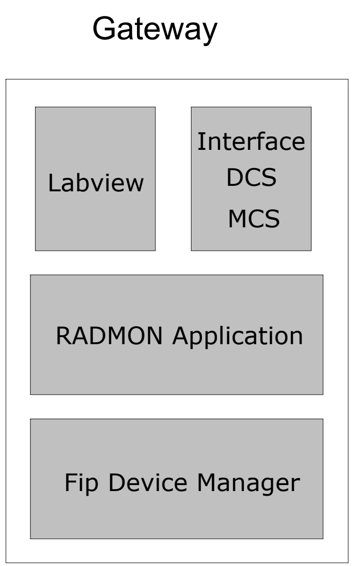


V3.1 Prototype Radiation Monitor

Development time : 3 years - first pre-series expected Q3 2005

Radiation Monitoring board - architecture

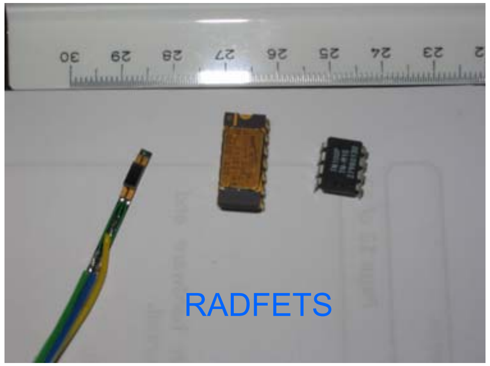




- Gateways are standard Industrial PCs
- 1 Gateway - 1 Fip segment
- 2 Gateways per point – 16 in total for LHC tunnel
- Linux or LynxOS Operating system
- Fip Designer and Labview for equipment tests
- Interface DCS/MCS to be provided by user group

Radiation Sensors

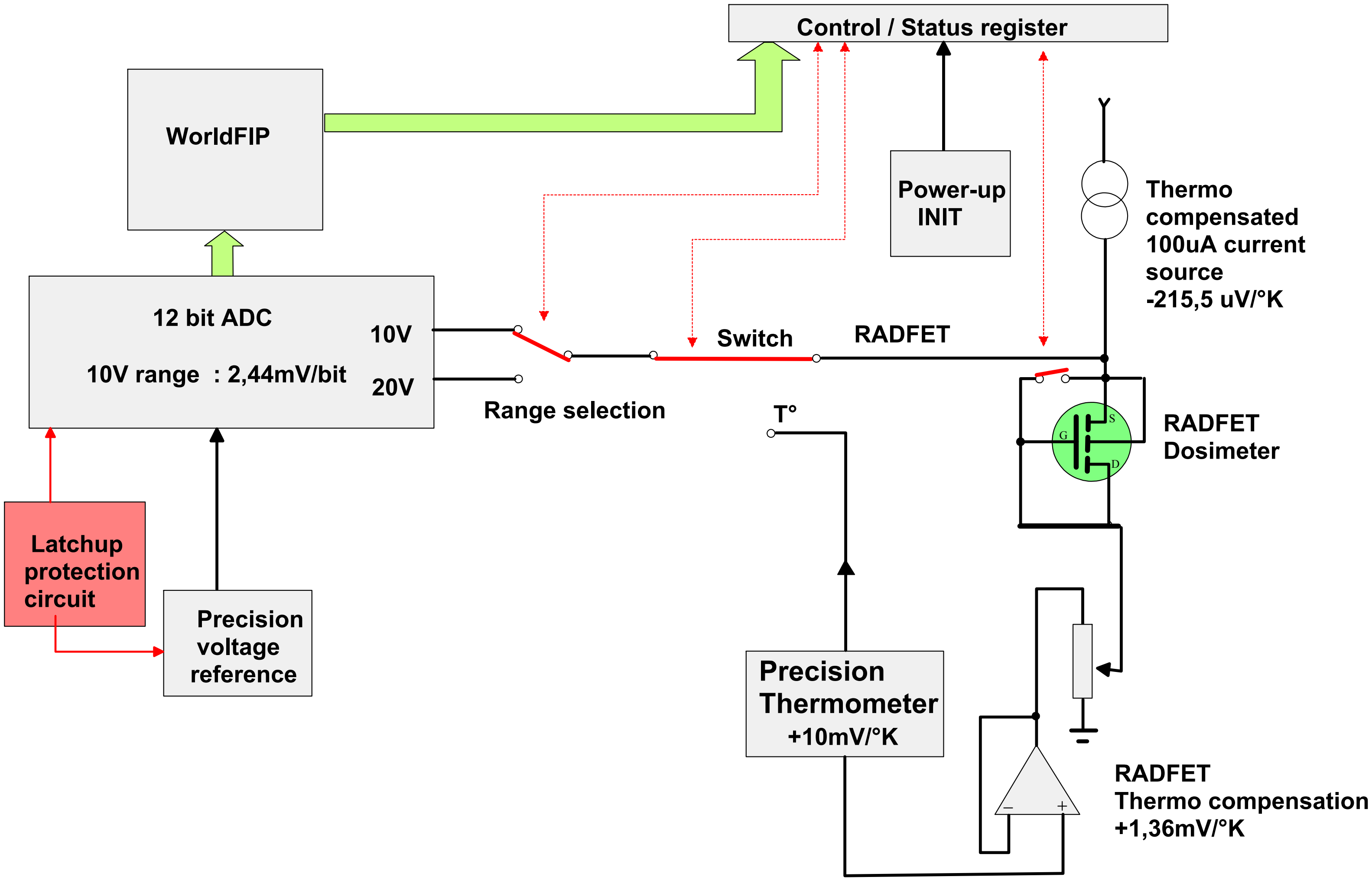
- Dose sensor : RADFET
  - Measure trapped charge in gate oxide
  - ΔV at constant current proportional to Dose
  - Insensitive to neutrons, high energy hadrons
- Hadron sensor : Toshiba TC554001AF
  - Measure radiation induced voltage spikes over a reversed biased p-n junction
  - Number of “0-1 or 1-0” in SRAM direct proportional to the hadron fluence (E> 20 MeV)
  - Insensitive to dose, low energy hadrons
- Neutron sensor : SIEMENS BPW34
  - Measure conductivity variation at high forward injection
  - ΔV at constant current proportional to 1 MeV eq. n
  - Insensitive to dose, high energy hadrons


RADFETS


TOSHIBA TC554001AF-70L

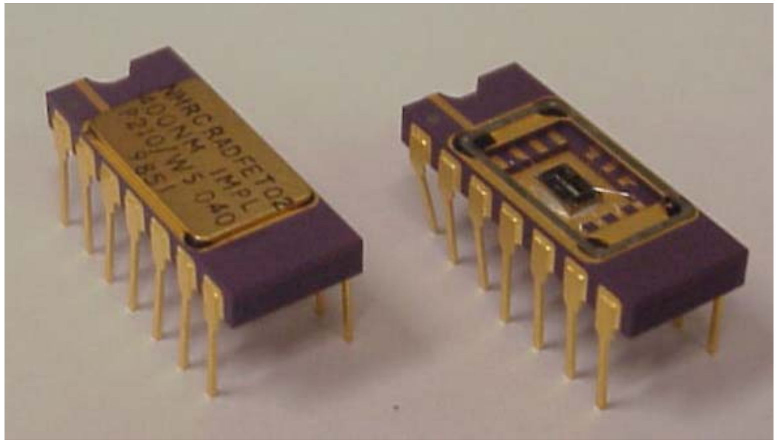

SIEMENS BPW34

RADFET – bloc diagram



RADFET- manufactures and types

3 manufacturers – 7 different types



Manufacturer A :

- 100 nm, 400 nm Implanted, 1 μm Implanted
- Four Radfets per chip
  - two 300/50 devices
  - two 690/15 devices
- Die size 1 mm x 1 mm
- 250 mm Kovar lid (Ni, Co, Fe)

Manufacturer B :

- 100 nm, 250 nm, 500 nm
- Two Radfets per chip
- Epoxy plastic lid

Manufacturer C :

- 940 nm
- Die size 1 mm x 1 mm
- Opaque epoxy resin lid

RADFET- readout protocols

Readout protocols are not unique :

Manufacturer A :

- Readout 30 s after power switching
- Readout current 10 or 100 µA
- Recommends several AD conversions

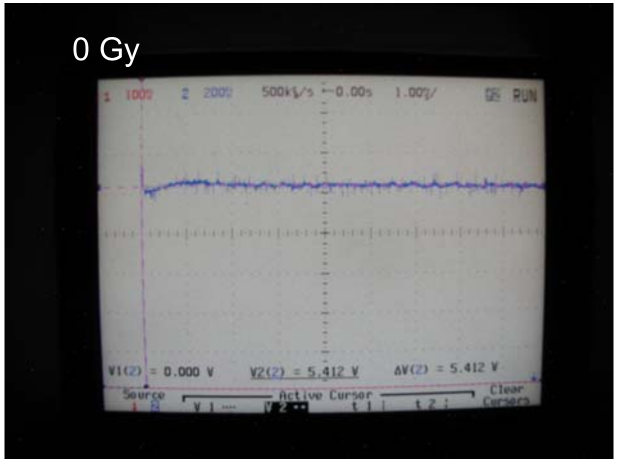
Manufacturer B :

- Readout after 'several seconds'
- Readout current 10, 50 or 100 µA

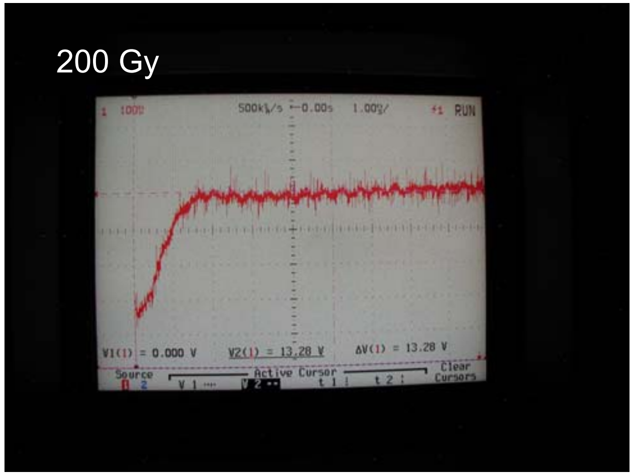
Manufacturer C :

- Readout after 2 or 4 seconds
- Readout after 10 or 20 seconds is identical
- Readout current 40, 90 or 160 µA

Current rise time increases with dose !



500 nm Radfets from manufacturer B



RADFET- variations in temperature

Temperature coefficients

(for non irradiated devices)

Manufacturer A :

- 100 nm : -1.2 mV per °C
- 400 nm : -1.0 mV per °C
- 1 μm : -1.6 mV per °C

Manufacturer B :

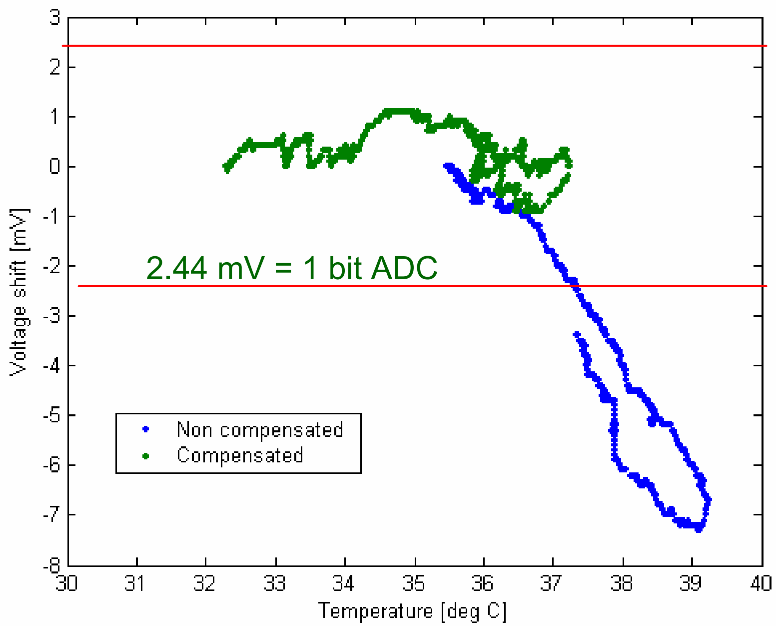
- 100 nm : -0.66 mV per °C
- 250 nm : -1.13 mV per °C
- 500 nm : -1.34 mV per °C

Manufacturer C :

- 940 nm : -3.32 mv per °C

Manufacturer A – RADFET 1000 nm

(non irradiated device)



In practice :

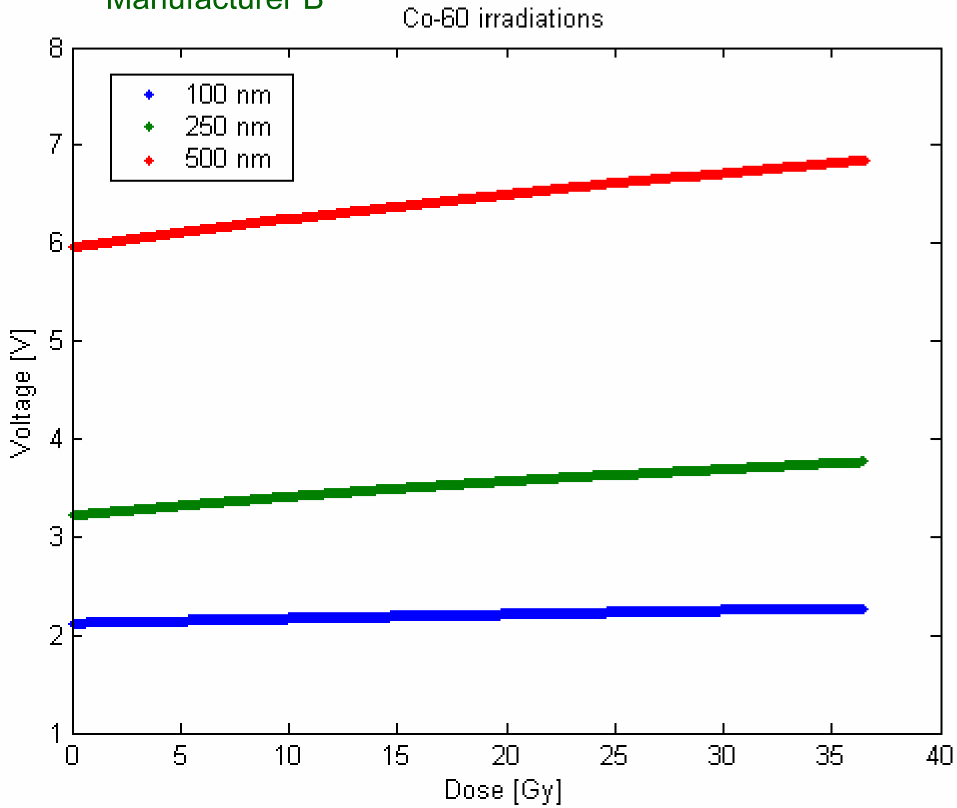
ΔT is very small (self heating of transformers dominates)

RADFET- Co-60 irradiation

PAGURE Irradiator

CEA Saclay

Manufacturer B



Sensitivity :

Manufacturer A :

- 100 nm : ?
- 400 nm : 80 mV per Gy
- 1 μm : ?

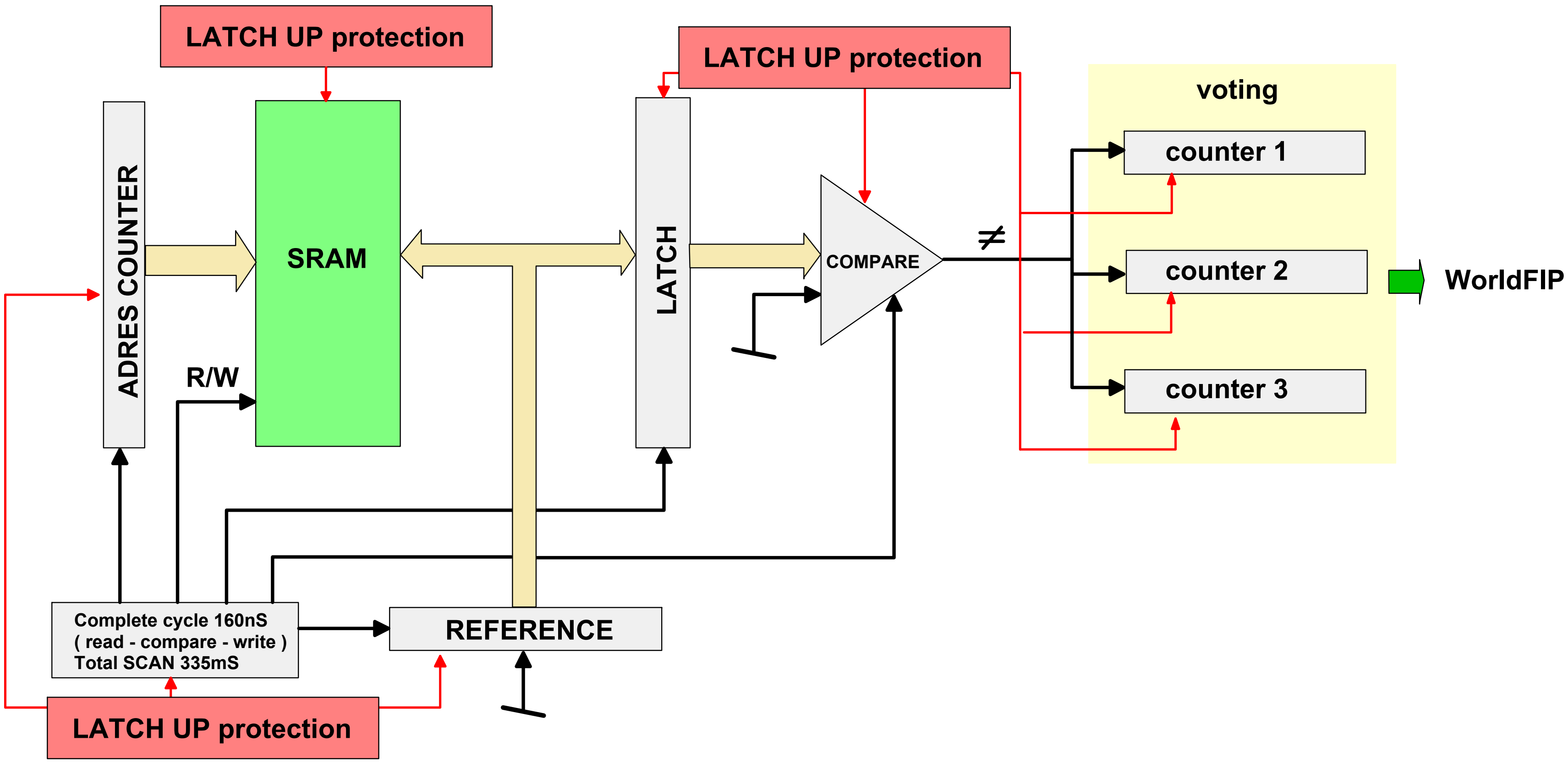
Manufacturer B :

- 100 nm : 5 mV per Gy
- 250 nm : 15 mV per Gy
- 500 nm : 25 mV per Gy

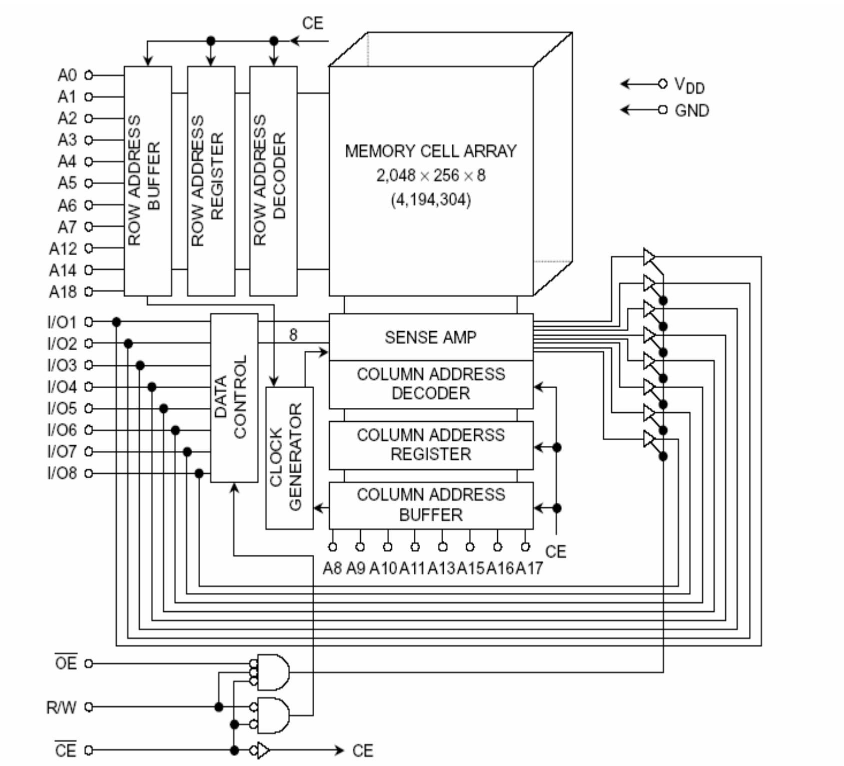
Manufacturer C :

- 940 nm : 120 mV per Gy

SEU counter – bloc diagram



SEU counter - Toshiba TC554001AF-70L



Toshiba TC554001AF-70L

Characteristics :

- 0.4 µm technology
- 3 – 5 V operation
- 4 Mbit (524288 words x 8 bits)
- grid arrangement 8192 x 512
- min cycle time 70 ns

Heavy Ion Radiation tolerance (0.5 µm):

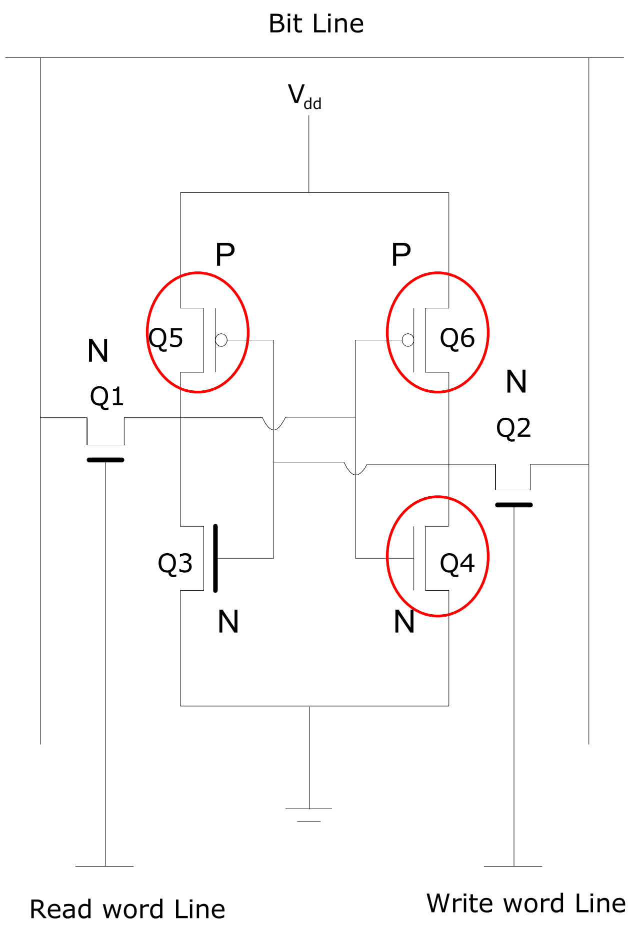
- Latch up threshold < 37 Mev.cm^2/mg
- SEU threshold < 1.7 MeV.cm^2/mg
- No Multiple Bit Upsets
- Cross section 0->1 equal to 1->0
- No frequency effect at 1.25 MHz

Neutron Radiation tolerance :

- 0.4 µm identical to 0.5 µm
- no latch up at E_n= 180 MeV

Ref. : Esa/Estec QCQ9956S-C
C. Sanderson, RADECS 2000

SEU counter - SEUs in a 6 T SRAM cell 0.4 μm



Asymmetric SRAM cell :

- 3 – 5 V operation
- 3 TFTs, 3 bulk transistors
- Read at 3 V if β(Q3)/β(Q1) > 3.0
- Write at 3 V if β(Q4)/β(Q2) < 0.1

Effect of lowering the bias V_{dd}

- SEU sensitivity increased
- TID is increased (writing becomes more difficult because β(Q4)/β(Q2) increased)

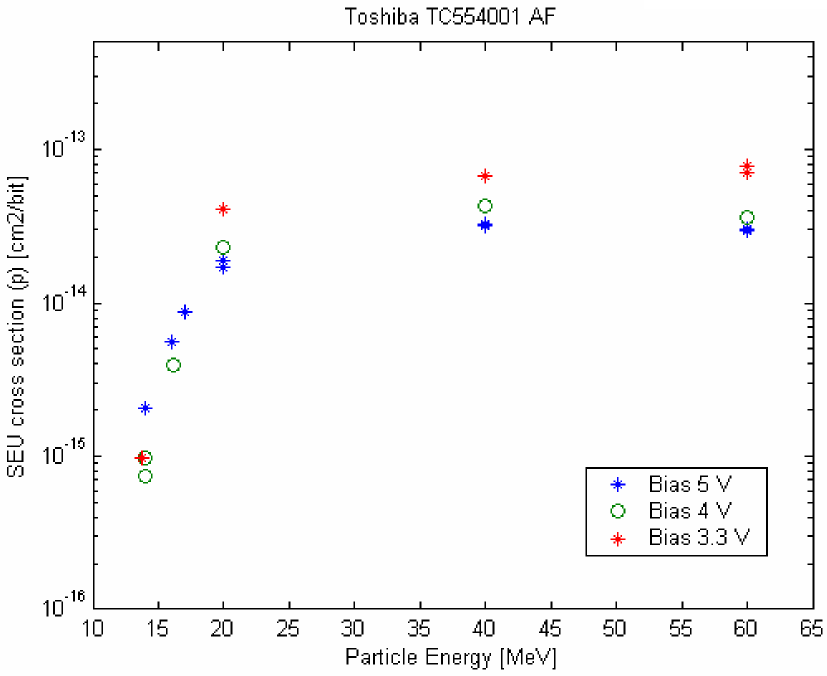
$Q_{crit} = C_{node} V_{dd} + I_{restore}/f$

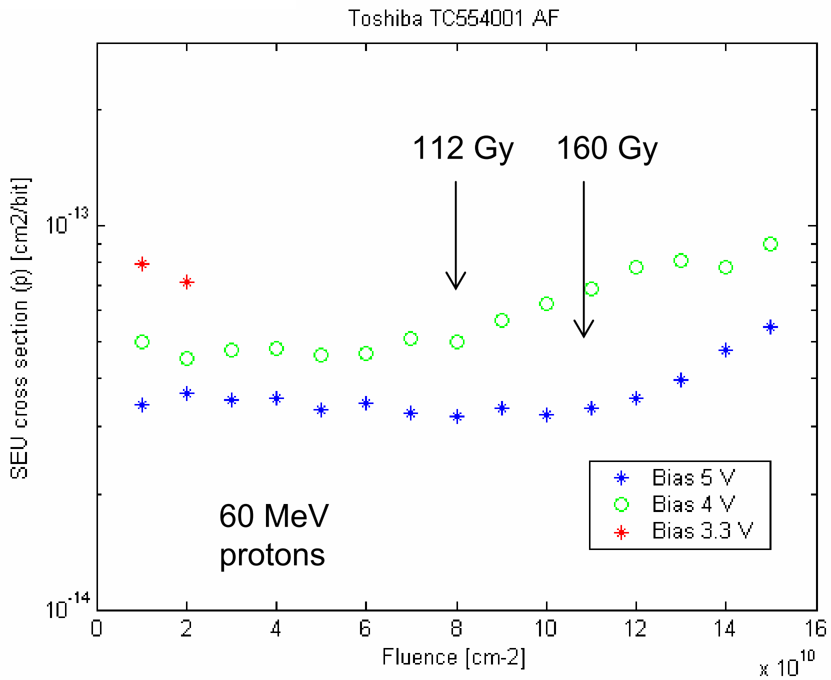
Q_{crit} = radiation induced charge
C_{node} = capacity of the node
$I_{restore}$ = current restoring transistor
f = frequency of event

SEU counter - proton cross sections

CYCLONE - UCL Louvain la Neuve

OPTIS Facility - PSI Villingen





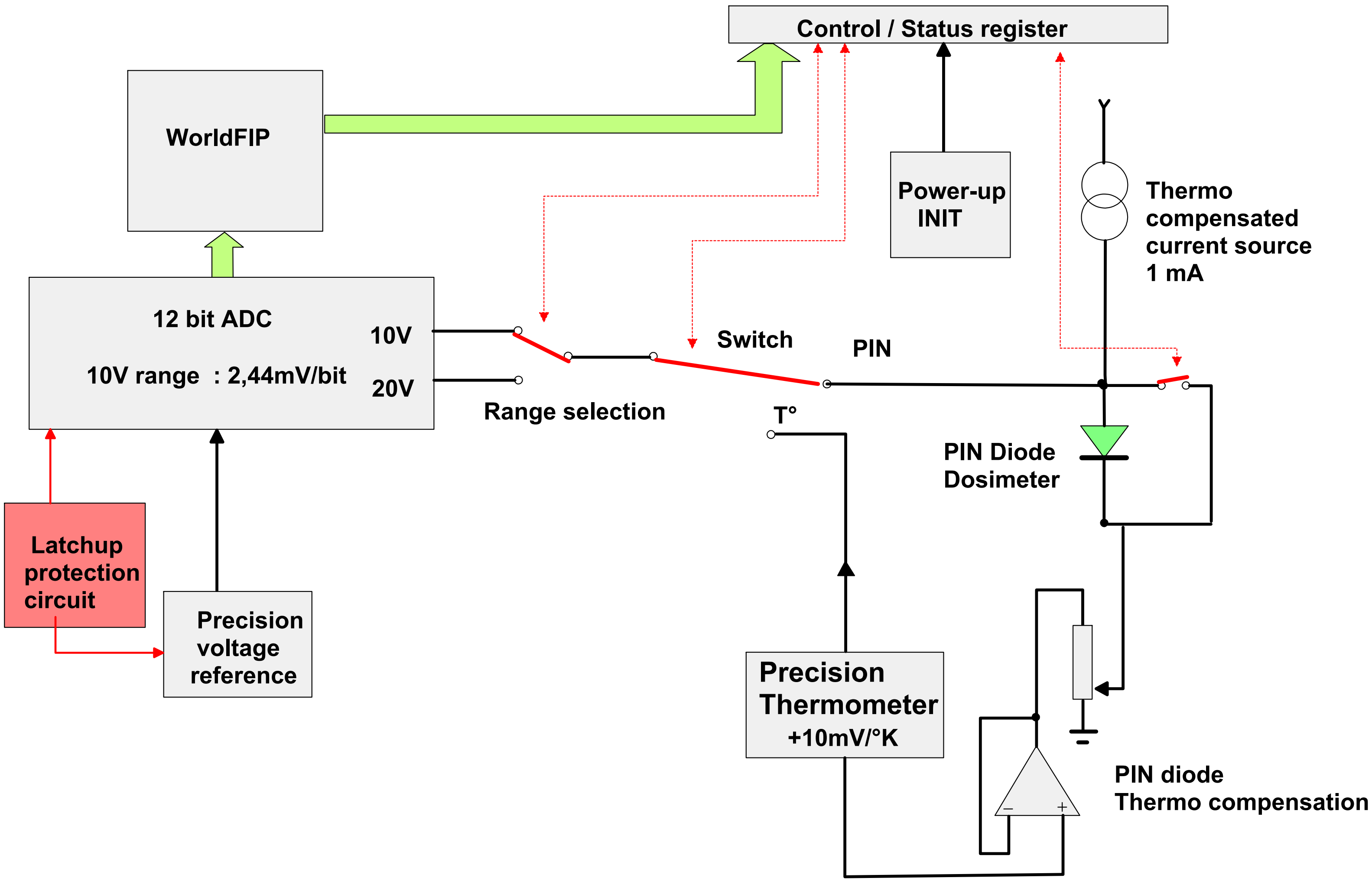
SEU cross section :

- 3 - 8 x 10^{-14} cm^{-2}/bit depending on bias
- Identical to neutron cross sections
- No latch up

Cumulative effects :

- Sensitivity increased at higher dose (but can be used up to 200 Gy)
- Certain bits stuck at “0” after ~160 Gy (but can be annealed out at 100 ºC – 4hrs)

Pin Diode – bloc diagram



PIN diode – Siemens BPW34 FS

Characteristics :

- Silicon PIN Photodiode
- Standard off-the-shelf
- Die size 2.65 x 2.65 mm
- Thickness 0.3 mm
- Temperature coef. : 2.4 mV per °C

Readout protocol :

- Readout current 1 mA
- Measure ΔV after 5 ms
- Zero Temperature Coefficient

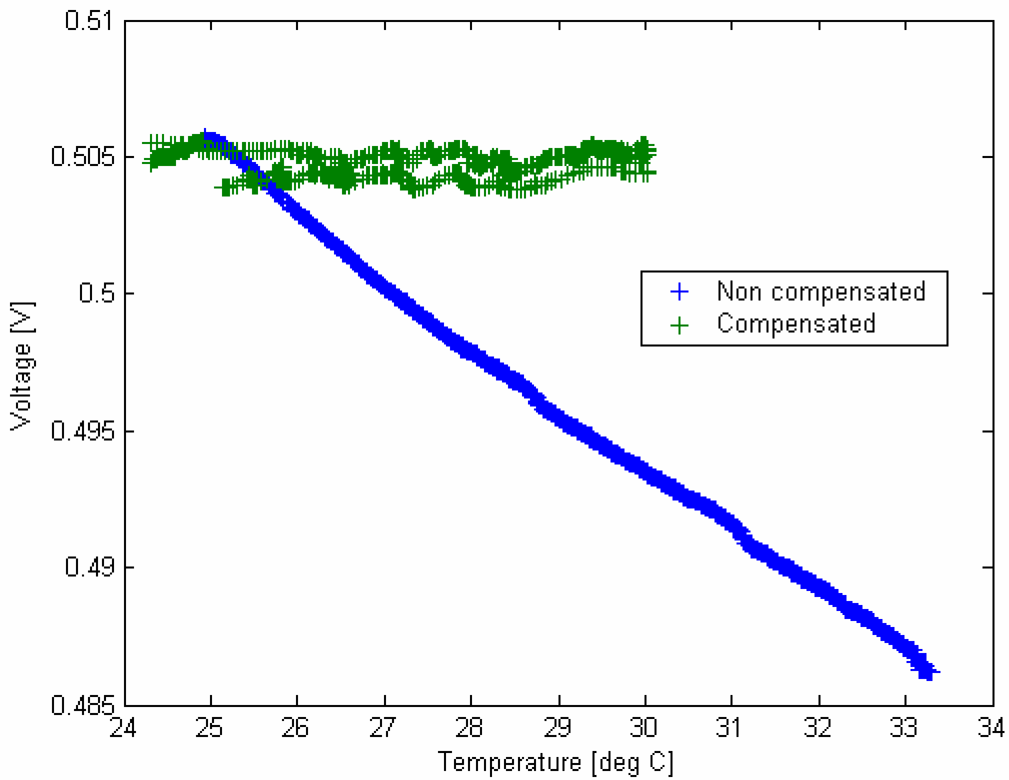
Neutron response :

- Linear response 10^8-10^{12} neutrons/cm^2

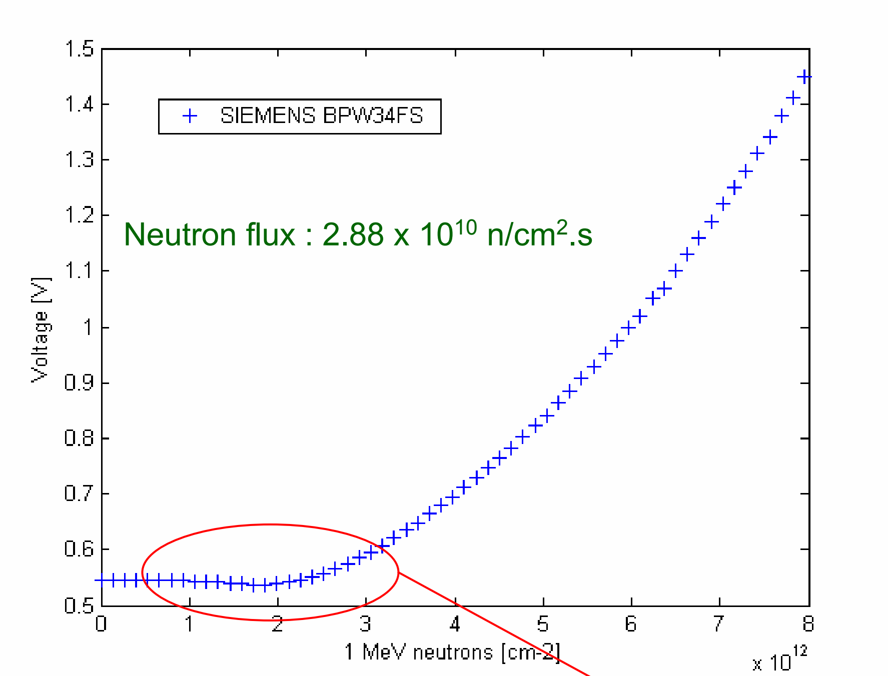
Ref. : CERN-TIS-CFM/IR/92-09 September 1992

SIEMEMS BPW34FS

(non irradiated device)



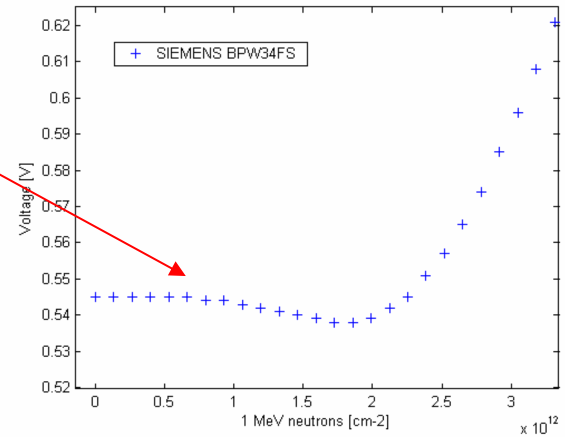
PIN diode – 1 MeV neutron response



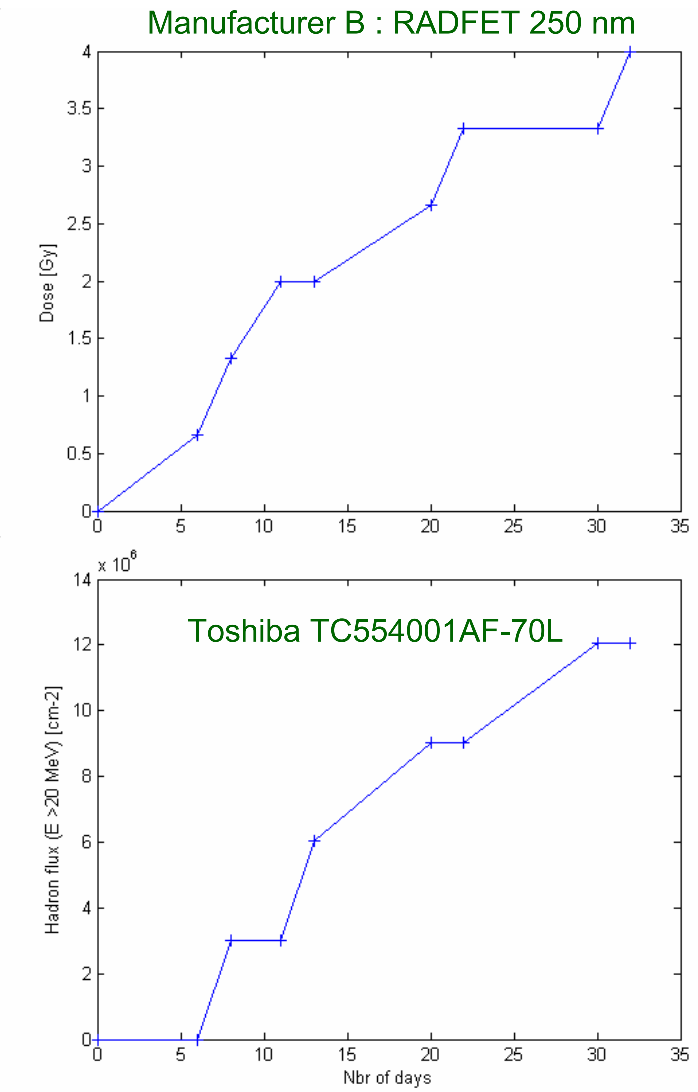
Calibration run with 1 MeV neutrons :

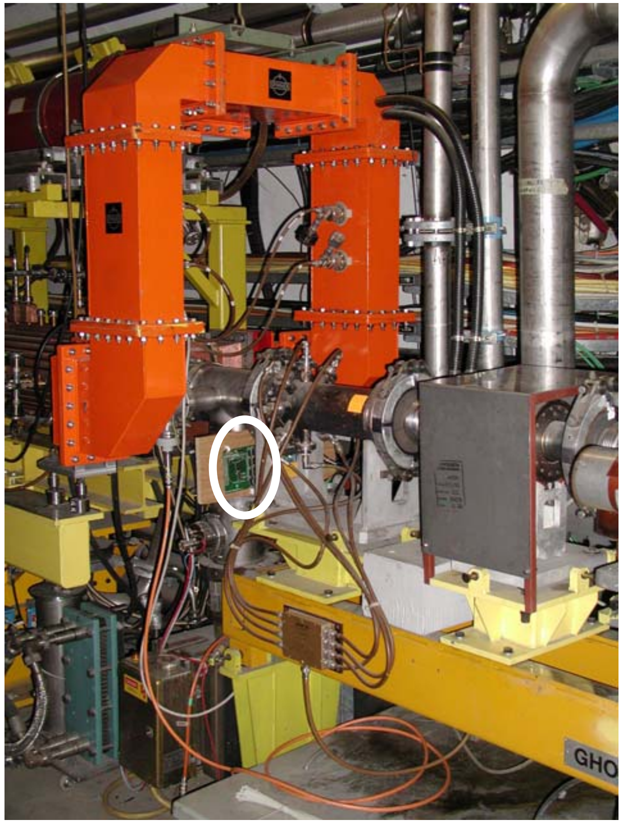
- High flux operation
- Calibration : 9.1×10^{10} neutrons per mV
- No data available below 1×10^{10} n/cm^2
- Annealing at room temperature small

Delicate experiment
Requires additional study to increase sensitivity



Results SPS campaign 2004 – SPS ring BA3



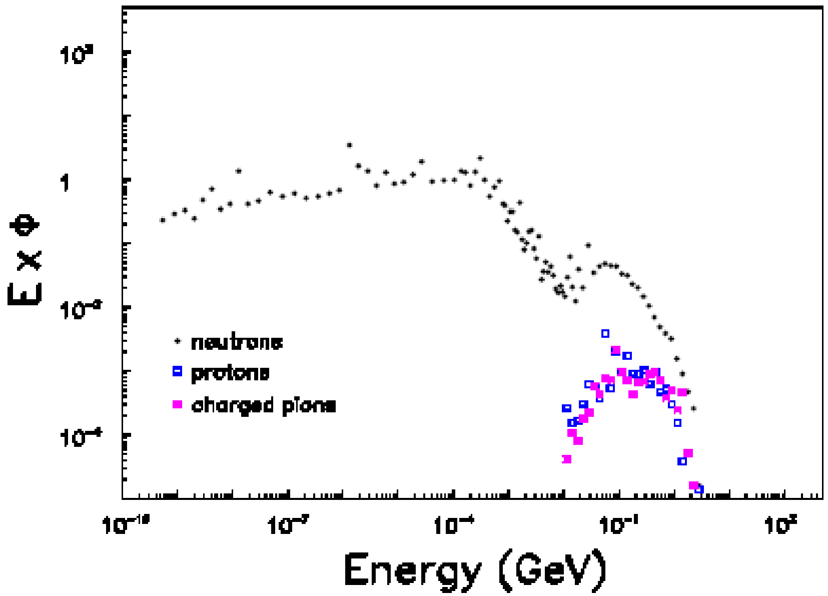


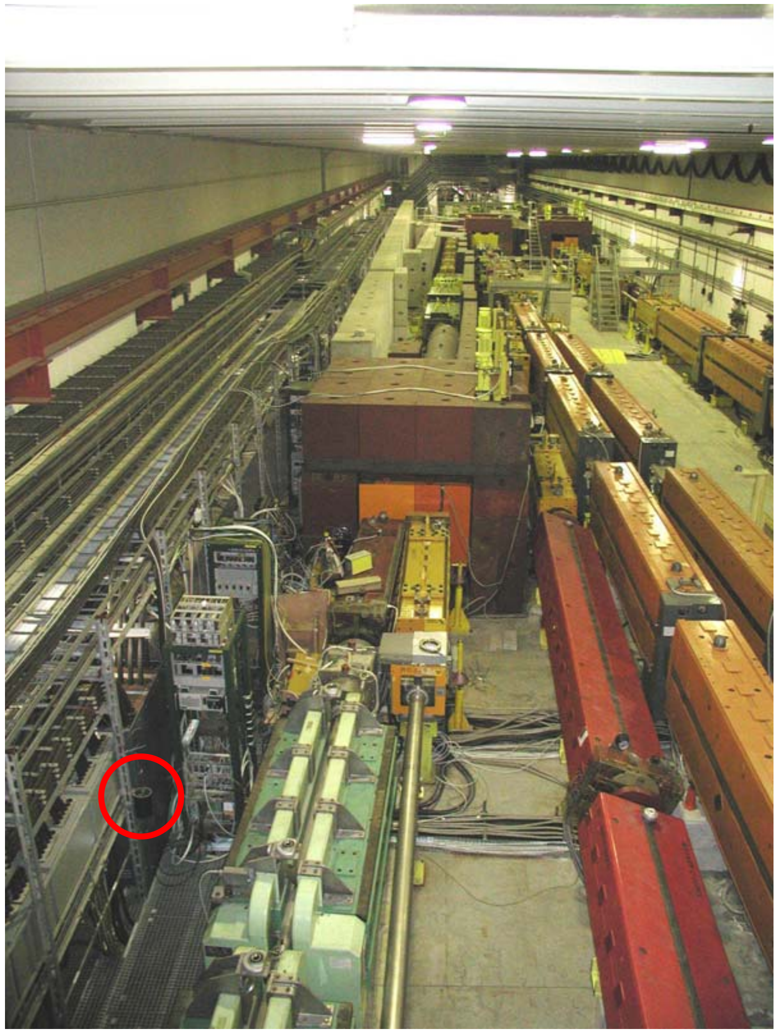
Radiation Field in SPS –BA3 close to RF :

- Dominated by e- and γ
- Fluence : dose ratio = 3.5 x 10^6 h/Gy·cm^{-2}
- ~1000 times less compared to LHC

Acknowledgements : U. Wehrle, T. Boll

Results SPS campaign 2004 - LHC Test Facility (TCC2)





LHC Radiation Test Facility (TCC2)

Dose rate	1 to 20 Gy per day
1 MeV neutrons	8 x 10^{10} $cm^{-2}Gy^{-1}$
20 MeV hadrons	4 x 10^{9} $cm^{-2}Gy^{-1}$

LHC ARCs

Dose rate	10 Gy per year
1 MeV neutrons	5 x 10^{10} $cm^{-2}Gy^{-1}$
20 MeV hadrons	3 x 10^{9} $cm^{-2}Gy^{-1}$

Results SPS campaign 2004 – LHC test facility (TCC2)

Dosimeters available :

- Ionisation chambers (2 different types)
- Scintillator probe
- Alanine passive dosimeter

Alanine ($C_3H_7NO_2$) & RPL (passive dosimeters)

- Measures only during beam on

Eberline FHT191 N Ionisation chamber

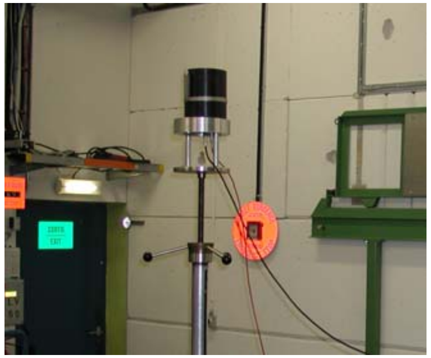
- Energy range 35 keV ... 7 MeV
- Pressurized chamber with N_2
- Dose rate measurement from 10 nSv/h up to 10 Sv/h
- Suited for pulsed radiation fields (short response time)

Automess Dose Rate Meter 6150AD6

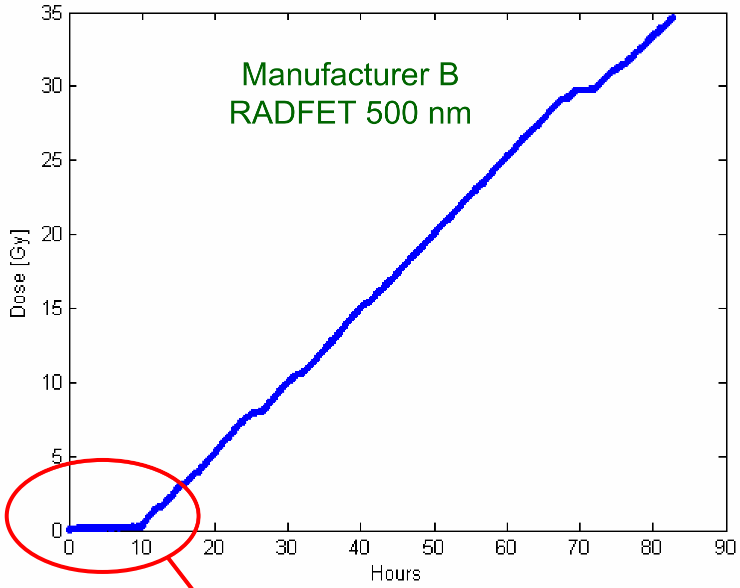
- Energy range: 60 keV - 1.3 MeV
- Dose rate measurement from 0.01 µSv/h - 9.99 mSv/h
- Only for RP purposes (beam off)

PMI – Ionisation chamber

- Calibrated with ^{137}Cs
- Dose rate measurement from 1 µSv/h
- Not designed for pulsed radiation fields (long response time)

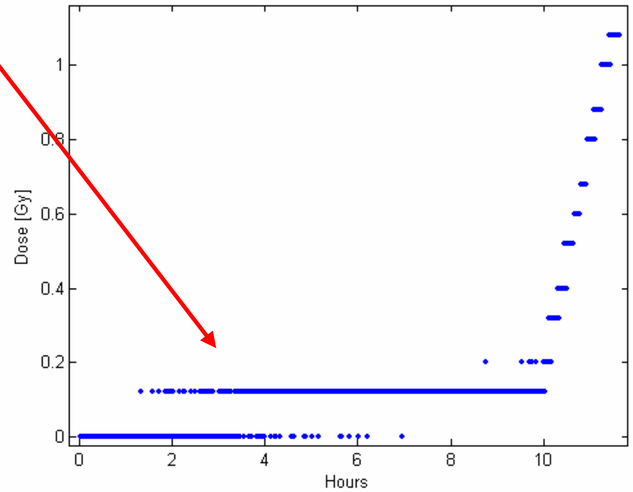


Results SPS campaign 2004 – Dose in TCC2



Dose measurements :

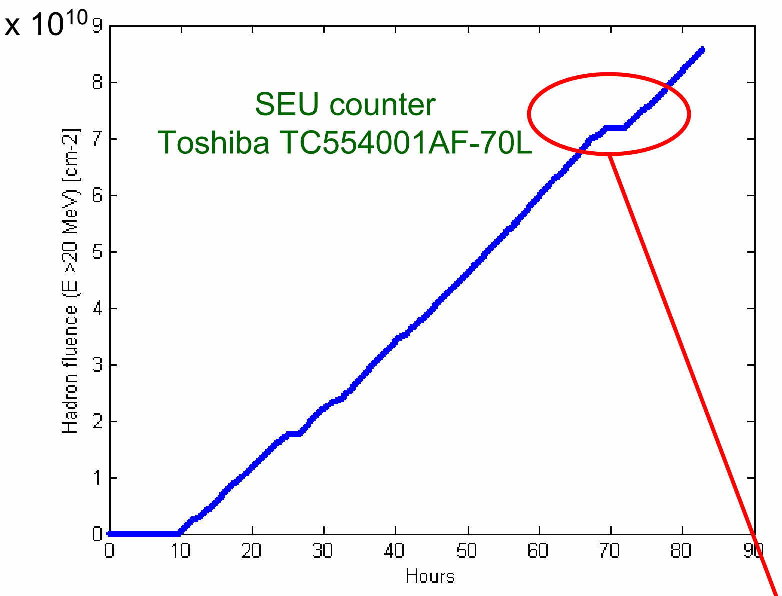
- 137 Gy [Si] : RADFET
- 93 Gy [$C_3H_7NO_2$] : Alanine
- 80 Gy [Air] : PMI Ionisation Chamber
- 102 Gy [Air] : FHT191N Ionisation Chamber



Remnant dose Rate :

~1000 times less compared to 'beam on'

Results SPS campaign 2004 – Hadrons in TCC2

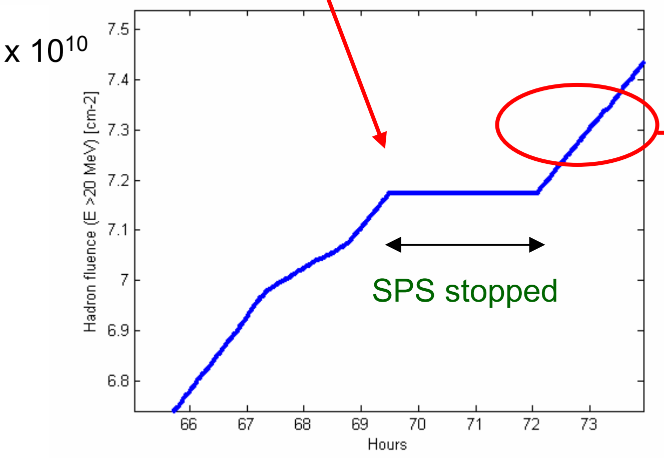


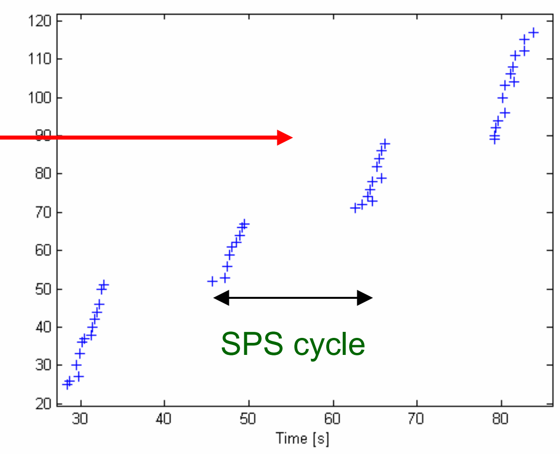
Radiation Monitor Fluence measurements:

20 MeV hadrons 3.1×10^{11} cm^{-2} (SEU Counter)

Compare Fluence : Dose ratio with simulations

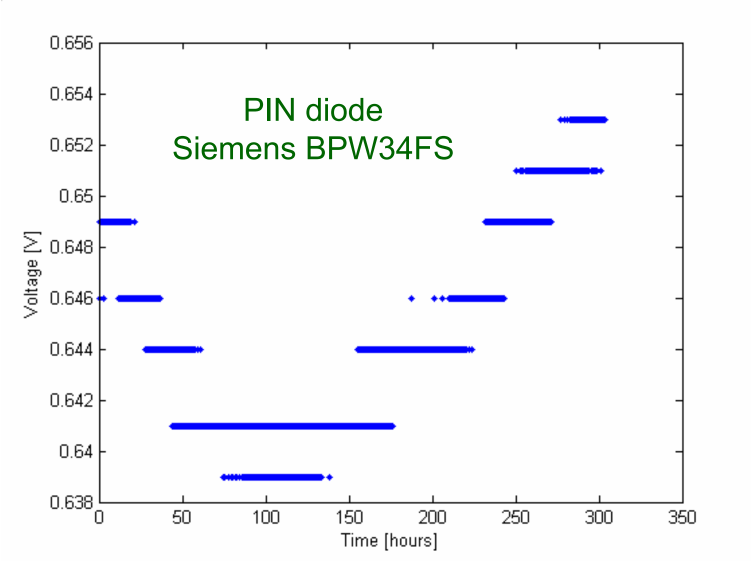
20 MeV hadrons 1×10^{9} $cm^{-2}Gy^{-1}$ (FLUKA)
20 MeV hadrons 2.3×10^{9} $cm^{-2}Gy^{-1}$ (Radiation Monitor)





100 Hz data acquisition !

Results SPS campaign 2004 – 1 MeV neutrons in TCC2



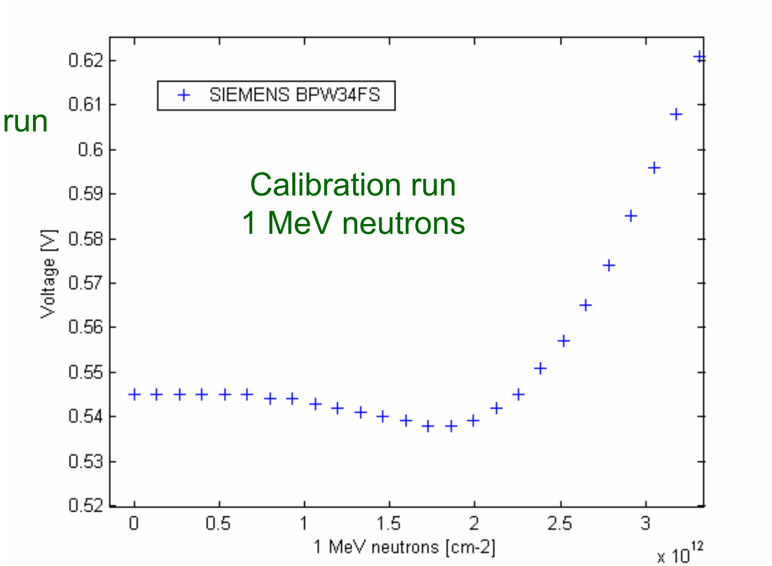
Radiation Monitor Fluence measurements:

1 MeV neutrons 2.5×10^{12} cm^{-2} (PIN diode)

Compare measurements with simulation :

1 MeV eq. Neutrons 2×10^{10} $cm^{-2}Gy^{-1}$ (FLUKA)
1 MeV eq. Neutrons 1.8×10^{10} $cm^{-2}Gy^{-1}$ (Radiation Monitor)

Compare to Calibration run with nuclear reactor



Remarkable performance !

Conclusions

What we learned in the last 5 years :

- ➔ Radiation measurements in a complex field such as that of the LHC are difficult – up to 20% error is possible
- ➔ Good understanding of radiation damage can only be achieved by measuring several components of the radiation field simultaneously (not just dose)
- ➔ For the monitoring of LHC tunnel electronics : on-line measurements with sub second time resolution is required
- ➔ Cross check on a regular basis with passive dosimeters recommended
- ➔ Cross check with simulated (Monte Carlo) predictions recommended (spectra)

Specific to electronics :

- ➔ Damage from Single Events caused by fast neutrons will be our first concern in the LHC
- ➔ A radiation tolerant design for the tunnel based on COTS takes 3 years (including final tests)
- ➔ Don't take anything for granted