Active Radiation Monitoring Sensors for the High-Energy Physics Experiments of the CERN LHC

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On behalf of RADMON Working Group
Outline

- CERN, LHC, Accelerator & Experiments Radiation Field;
- Radiation Monitoring issues at the LHC;
- Active Dosimeters: RadFET and $p-i-n$ diode;
- Validation test in “LHC-like” environment;
- Integration issues at the LHC Experiments;
- Conclusions;

Development of OSL-based dosimeters → D. Benoit talk
**Large Hadron Collider**

- proton-proton collider;
- superconducting magnets;
- Starting up for physics in **May 2008**;
- Commissioning the LHC to full energy in one go.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dipole magnets</td>
<td>1232</td>
</tr>
<tr>
<td>Dipole field at 7 TeV</td>
<td>8.3 T</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Protons/bunch</td>
<td>$1.1 \times 10^{11}$</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>2808</td>
</tr>
<tr>
<td>Nominal bunch spacing</td>
<td>25 ns</td>
</tr>
<tr>
<td>Typical beam size in arcs</td>
<td>200-300 μm</td>
</tr>
</tbody>
</table>
LHC Radiation Field

RF Cavities & Beam Cleaning (collimation)

CMS / TOTEM

LHCb

ATLAS

ALICE

Injection beam-line

ATLAS

Injection beam-line

ARCs ~ 10 Gy/yr, $\Phi_{E>20\text{MeV}}$ ~ $3 \times 10^{10}$ cm$^{-2}$ yr$^{-1}$

DSs & LSSs ~ 0.1 - 1 kGy/yr

Beam-dump

Beam Cleaning (collimation)

Proton - residual gas

Proton - point losses

ARC (90% electronics)

DSs & LSSs

LHCb
LHC Radiation Field

Particle spectrum expected just outside the magnet cryostats [C. Fynbo, 2001]
Experiments Radiation Field

- Example: CMS radiation field
- MC simulation predictions:
  - gammas, protons, neutrons, pions, ...
  - different energies and intensities;
  - $f(r, \theta, z)$ with respect to IP;

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>2x10$^{-2}$</td>
<td>1x10$^5$</td>
<td>2x10$^{14}$</td>
<td>2x10$^{13}$</td>
</tr>
<tr>
<td>HCAL</td>
<td>2x10$^{-6}$</td>
<td>10</td>
<td>10$^{12}$</td>
<td>10$^{13}$</td>
</tr>
<tr>
<td>Muon</td>
<td>2x10$^{-9}$</td>
<td>0.01</td>
<td>10$^8$</td>
<td>10$^{10}$</td>
</tr>
</tbody>
</table>

- Dose and fluence in sub-detectors differ up to 7 orders of magnitude.

F.Ravotti
DESY - Hamburg - 07 August 2007
Radiation Monitoring

Purposes

LHC Experiments are designed for 10 years of physics operation
Equipment failures due to radiation damage are not expected, but

• Some components might be not well qualified in radiation hardness;

• Some long-term effects in complex radiation field are not predictable;

⇒ Radiation level survey needed for damage and failure analysis

• Radiation field simulations accuracy within factor 2-3;

⇒ Verification and improvement of simulations

• Layers of shielding materials are installed to reduce internal/external irradiation;

⇒ Improvement of shielding
Radiation Monitoring at LHC

The complexity of the LHC radiation field make its monitoring **challenging**;

**Ideally measure full spectrum** (particle type, energy and intensity at all location);

**In reality** the effects of this radiation field on specific materials are measured;

To cover the **broad ranges/spectra** expected **several sensors are needed**:

→ Passive Sensors (TLDs, Alanine, RPL, ...);

→ **Active Sensors**;

→ Fast Beam Condition Monitors (CVD diamond);

→ Specific Monitoring Devices (scintillators, metal foils, ...);
What can/should be measured?

- **TID – Total Ionizing Dose** (energy deposited by ionization)
  - represents the Ionizing Energy Loss (IEL) measured in $\text{Gy} = 1 \text{ J/Kg}$;
  - causing *e.g.* accumulation of charge in $\text{SiO}_2$ $\Rightarrow$ damage to microelectronic components
    - aging of gas detectors, scintillators, optical fibers, ...

- **$\Phi_{eq}$ – 1-MeV Equivalent Fluence** (displacement damage)
  - represents the energy imparted in displacing collisions in crystals (NIEL);
  - causing *e.g.* defects in semiconductor crystals $\Rightarrow$ silicon detector damage, optical devices, CCDs, ...
  - damage normalized to the one induced in Si from 1-MeV neutrons measured in $\text{cm}^2$;
Radiation Monitoring Sensors

ACTIVE DOSI METERS ("on-line")

- Radiation-sensing Field Effect Transistors (RadFETs) - $\text{TID}$ - ;
- Forward biased $p-i-n$ silicon diodes - $\Phi_{eq}$ - ;
- Optically Stimulated Luminescent Materials (OSL) - dose-rate, $\text{TID}$ - ;

See following talk by D. Benoit
RadFET Sensors (TID)

(1) e⁻/h⁺ pair generation;
(2) e⁻/h⁺ pair recombination;
(3) e⁻/h⁺ transport;
(4) hole trapping;
(5) Interface states buildup.

• Devices grounded during exposure
  ("simple" readout as required for LHC)
• $I_D$ const. $\Rightarrow V_{th} \propto \text{TID}$.
RadFET selection & characterization

Evaluation of packaging effects

Radiation response to $\gamma$, $n$, $p$, $\pi^\pm$.

$\Delta V_{th}$ stability evaluation with experimental Isochronal Annealing method

Recommended Devices

Measurement of key parameters ($T_c$, ...)

Studies on the long-term Isothermal annealing behaviours

Response in Low Dose-Rate (LDR) mixed hadron radiation environment

“Accelerated” Procedures

- Temperature coefficients;
- Readout currents;
- Signal drift-up;
- ...

9 RadFET devices from 4 producers (REM, NMRC, LAAS, T&N)

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RadFETs for the LHC

- **Thick-Oxide RadFET dies (1.6 \( \mu \)m):**
  - Producer: CNRS-LAAS, France;
  - \( \sim 500 \text{ mV/Gy} \div \sim 1 \text{ mGy to } 10 \text{ Gy}; \)
  - Suited for outer-detector regions;

- **Thin-Oxide RadFET dies (0.25 \( \mu \)m):**
  - Producer: REM Oxford Ltd, UK;
  - \( \sim 20 \text{ mV/Gy} \div 0.1 \text{ Gy to } \sim 10 \text{ kGy}; \)
  - Suited inner-detector regions.

\[ \Delta V_{th} = a \times D^b \]
\( p-i-n \) diodes (\( \Phi_{eq} \))

Displacement damage in high \( \rho \) Si-base

\[ \rightarrow \text{Macroscopic effect linear with } \Phi_{eq} \]

FORWARD BIAS

Fixed \( i_F \) \( \rightarrow \) \( V_F \propto \Phi_{eq} \)

Dosimetric effect at \textbf{intermediate/ high injection levels};

Devices \textbf{grounded} during exposure; Readout by \textbf{current pulses}

\[ V_F = f(\text{material parameters } [\tau, \rho, L], \text{geometry } [W], \text{readout current } [J], \text{pulse length}) \]

\textbf{CUSTOM MADE, High-Sensitivity (CMRP, LBSD)}
High-Sensitivity $p$-$i$-$n$ diodes are devices developed mainly for medical and military applications. Extensive characterization done for LHC (sensitivities, dynamic range, annealing, temperature effects ...);

The High-Sensitivity ($10^7$-$10^8$ mV/cm$^2$) imply a low dynamic range ($\Phi_{eq} \leq 10^{12}$ cm$^{-2}$)

$\Rightarrow$ These devices alone cannot satisfy all LHC requirements;

These devices need to be complemented by diodes with higher range

$(10^{12}$ cm$^{-2} < \Phi_{eq} < 10^{14}$-$10^{15}$ cm$^{-2}$);

$\Rightarrow$ Study of the Commercial $p$-$i$-$n$ diodes BPW34F
p-i-n diodes for the LHC

High-Sensitivity p-i-n diodes:
- Producer: CMRP, Australia;
- \( S = 5.9 \text{ mV}/10^9 \text{ cm}^{-2} \pm 13 \% \);
- \( \Phi_{\text{eq,max}} = 2 \times 10^{12} \text{ cm}^{-2} \);
- Suited for outer-detector regions;

Commercial p-i-n diodes:
- BPW34 from OSRAM
- \( S = 0.1 \text{ mV}/10^9 \text{ cm}^{-2} \pm 20 \% \);
- \( \Phi_{\text{eq,max}} = 4 \times 10^{14} \text{ cm}^{-2} \);
- Suited for inner-detector regions;
Validation Test

From the “accelerated” characterization to the “real” LHC conditions!

- MIXED RADIATION FIELD;
- DIFFERENT INTENSITIES $f(r,Z)$
  $\rightarrow$ Low Dose Rate (LDR);
- SEVERAL MONTHS IRRADIATION.

[ UdeM-GPP-EXP-98-03, 1998]
Comparison $\Phi_{eq}$ measurements against MC simulations

- Sim-A $f(r,Z)$ and Sim-B $f(r)$
  - Different Composition;
  - Different area layout.

Variations in the $\Phi_{eq}$ successfully monitored on-line!

Comm. $p$-$i$-$n$ diode (BPW)

High Sensitivity $p$-$i$-$n$ diode (CMRP)

$\varepsilon$ fluence = ± 16.2 %
RadFET Packaging

Development by External Company

- high integration level;
- modular, customizable;
- standard connectivity;
- satisfactory radiation transport proprieties.

Commercial Packaging (i.e. TO-5, DIL) cannot satisfy all Experiment Requirements (dimensions/materials)

Development / study in-house at CERN

~ 10 mm² 36-pin Ceramic carrier

Simulated model [Geant4 Team, INFN Genova]

– validate packaging and calculations;
– optimize packaging lid.

REM

LAAS
Integrated sensor carrier

INTEGRATED SENSOR CARRIER
(4 sensors, same readout method)

- CMRP diode
- RadFET package
- Temperature probe
- Soldering pads
- Selection pads
- Connector plug 12 ways (11 channels + common GND)
- BPW34 diode
- 250 μm PCB
Integration in the ATLAS Experiment

**ATLAS RADMON**
(IEL, NIEL, *thermal neutrons*)
> 200 sensors at LHC startup;

[I. Mandic, JSI]

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Sensors Readout scheme

Readout (I/V) that can be easily implemented in the LHC experiments ...
Sensors Readout at the LHC experiments

Schematic view of the readout for the ATLAS ID monitor

- CAN BUS
  - 4 ELMBs connected to one CAN branch
  - DAC to enforce I (V)

- Radiation Monitor Sensor Board
- RMSB

- PP1 board
- FCI connector
- twisted pairs ~ 1 m
- Type II cable ~ 12 m

- ELMB (ADC) board
- PP2 board

- PC-PVSSII DAC power supply
- USA15

- [I. Mandic, JSI]
RADMON in LHC tunnel

RADMON Box
(IEL, NIEL, SEU)
LHC tunnel, alcoves, caverns
integrated readout, robust.
The dosimeter design uses COTS components
and can operate up to a 200 Gy total dose.

~300 monitors at LHC startup.
255 junction boxes distributed by
15×WorldFIP Field bus segments.
Total segment length: 19Km

[C. Pignard, T. Wijnands, CERN]
# Radiation Monitoring at LHC experiments: Overview

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHCb</th>
<th>TOTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RADMON active sensors on integrated carriers</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td><strong>RADMON box (LHC) in experimental areas</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Passive Dosimeters</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>BCM fast (bunch by bunch)</td>
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<td>Yes</td>
<td>Yes</td>
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<td>Thermal neutron sensors</td>
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<td>Relative luminosity monitoring</td>
<td>Yes</td>
<td>?</td>
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<td>Thin aluminum foil dosimeters</td>
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<td>Scintillator panels for halo</td>
<td>Yes</td>
<td>?</td>
<td>Yes</td>
<td>?</td>
<td>No</td>
</tr>
</tbody>
</table>
Conclusions

- RADMON at the LHC Experiments is a **challenge** for semiconductor sensors to be used for **Radiation Monitoring**;

- **Selection** and **characterization** of **ACTIVE sensors** brought **to recommend** a set of **two RadFET devices** (LAAS 1600 & REM TOT501C) and **two p-i-n diodes** (CMRP & BPW34F) that fulfill the LHC experiments need;

- The devices **operation has been validated** in condition similar to the ones expected at the LHC (LDR test at CERN-IRRAD6);

- **Packaging** studies and **devices integration** have been carried out in function of the experiments need;

- Use of **different sensors** and measure of **different quantities** in **several locations** is the adopted Radiation Monitoring strategy at the LHC Experiments.