Silicon radiation damage at the LHC experiments

A brief overview

Many thanks to Ben Nachman and Marco Bomben
jory.sonneveld@cern.ch
LHC experiments

LHC Peak luminosity: $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

Inner detector systems:

**CMS** fluences up to $7.9 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$

**ATLAS**: IBL now has $> 1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$!

**LHCb**: 10 years with a delivered 10 fb$^{-1}$ and innermost region (VELO) $6.5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
**ATLAS**: 3.325 cm from beam line

**LHC Run 2**: inner detector systems December 2018

**ALICE**: 3.3 cm from beam line

**CMS**: 2.9 cm from beam line

**LHCb**: 0.7 cm from beam line

**Inner tracker upgrade in LS2**

**Velo upgrade in LS2**
**ATLAS**: 3.325 cm from beam line

**LHC Run 2**: Inner detector systems early 2021

**ALICE**: 2.2 cm from beam line, monolithic active pixel sensors 33 μm x 33 μm

**CMS**: 2.9 cm from beam line

**LHCb**: 0.51 cm from beam line, pixel sensors 55 μm x 55 μm in VELO

**VELO and trackers upgrade in LS2**
High particle rates

Will the inner detectors survive?

See radiation background monitoring and simulation session.
Effects from radiation damage

Effects from radiation damage can be challenging in operation of detectors as well as for physics:

- Increasing leakage currents
- Charge accumulation in silicon oxide layers
- Single event upsets, in readout only → see electronics session
- Decreasing signal-to-noise ratios
- Changing depletion voltages
- Radiation induced activation of components

From Michael Moll
Ideal signal detection with silicon sensors

- A minimum ionizing particle (MIP) traveling through a fully depleted region ($V_{FD}$) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, charges are collected at the readout

From Frank Hartmann
Microscopic defects

- **Bulk damage**: non-ionizing energy loss (NIEL), e.g.:
  - Frenkel pair: vacancy + interstitial

- **Surface damage**, or ionizing energy loss: not considered for silicon but important in silicon oxide
1 MeV neutron-equivalent:

- D(E): displacement damage function in
- NIEL cross section MeV mb
- Reference: 1 MeV neutron-equivalent at 95MeV mb

Michael Moll
Radiation damage

Effects from radiation damage:

- Leakage current increase
- Space charge distribution: bulk doping in undamaged sensors but contribution from defects after irradiation $\rightarrow$ change in operational voltage
  - Material dependent (oxygen-content) and particle-type-dependent
- Trapping $\rightarrow$ decreased charge collection efficiency

Annealing: recombination

From Michael Moll
Impact on data

Modeling radiation damage is important for performance (operational voltage) but also for physics: see afternoon session.

Average pixel charge

Significant decrease of dE/dx and cluster size for IBL

Pixel occupancy per average number of interactions per bunch crossing (μ)

Lorentz angle

Lorentz angle
Modeling radiation damage

Modeling of radiation damage is very important for data quality

- Hamburg model can serve to model leakage currents and depletion voltages
- To model signal: need to include defect parameters from trapping in Poisson and transport equations like in technology computer-aided design (TCAD).

From Michael Moll
Not so ideal signal detection: radiation damage

Charges induced by an incident particle are collected with reduced efficiency as a result of radiation damage that causes:

- **Deformation** of the electric field
- **Trapping** induces screening of charge
- Diffusion or annealing deflects the path:
  - **Annealing**
- Magnetic field, which changes with operational bias voltage and changing electric field, deflects the path:
  - **Lorentz angle**

From Ben Nachman
Modeling radiation damage:
the depletion voltage Hamburg model

Assumptions:

- Little trapping
- No double junction
- 1 MeV neutron equivalence

\[ V_{\text{dep.}} = |N_{\text{eff}}| \cdot \frac{ed^2}{2\varepsilon_0} \]

\[ \Delta N_{\text{eff}}(t) = N_{\text{beneficial a.}}(t) + N_{\text{stable damage}} + N_{\text{reverse a.}}(t) \]

Input:

- Fluence
- Temperature over time (in order to include annealing effects)
- Sensor thickness \( d \), sensor material

Output: effective space charge \( N_{\text{eff}} \) \( \rightarrow \) depletion voltage \( V_{\text{dep.}} \)

\[ dN_{\text{A stable}} / dt \propto \Phi(t) \]
Depletion voltage measurements vs prediction

Difficult to fit all data points -- up to where is the Hamburg model valid?
Leakage current measurements vs prediction

\[ I(T) \propto T^2 \exp(-E_{\text{eff}}/2k_B T) \]

\[ E_{\text{eff}} = 1.214 \pm 0.014 \text{ eV} \]

- 8-10% reduction of leakage current for 1 °C between 0 °C and -20 °C

See talk by Finn Feindt

ATLAS sees a z-dependence. Does CMS see this, too? → see talk by Finn Feindt

ATLAS radiation damage results from Vinicius Franco Lima
Assumption: no double junction

Homogeneous electric field in Hamburg model holds only for non-irradiated silicon: a double junction forms in irradiated silicon.

Pictured:
p-type microstrip detector made from float zone silicon: 5 kΩcm, 300μm, and \( V_{\text{dep}} = 180 \text{ V} \)
Assumption: neutron-equivalent

We always talk of ‘neutron-equivalent’: is this really applicable?
Most non-ionizing energy loss in inner tracking systems from pions.
In outer and forward tracking systems, most bulk damage comes from neutrons.

Kramberger, Cindro, Mandic, Mikuž, Milovanović, Zavrtanik 2014

Neutrons, 1e15/cm²

Pions, 1.6e15/cm²
Protons vs neutrons

- Smaller peak fields for neutrons
- Less pronounced double junction for neutrons
- Protons have flatter field at junction (less peaked)

From Marko Mikuž
Beyond the Hamburg model: simulation for data

Different ways of simulating bulk defects like trapping and altered electric fields, as well as annealing and Lorentz angles.

<table>
<thead>
<tr>
<th>Energy Deposition</th>
<th>Bichsel Model + G4 (δ-rays)</th>
<th>Pixelav (applied as correction to G4)</th>
<th>Geant4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy spreading</td>
<td>from Bichsel + chunking</td>
<td>from Bichsel + chunking</td>
<td>Uniform (space) + uniform/Gauss (E)</td>
</tr>
<tr>
<td>E-field/ Lorentz angle</td>
<td>TCAD (Chiochia et al.)</td>
<td>TCAD (tuned to data)</td>
<td>N/A</td>
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<tr>
<td>Diffusion</td>
<td>Einstein</td>
<td>Einstein</td>
<td>tuned</td>
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<td>Noise</td>
<td>capacitive coupling + noise</td>
<td>readout noise</td>
<td></td>
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<tr>
<td>Radiation damage</td>
<td>trapping + charge induction</td>
<td>trapping + charge induction</td>
<td></td>
</tr>
</tbody>
</table>

See afternoon session

From Ben Nachman
Simulation of radiation effects in LHCb

Charge is reduced and “diffusion length” increased to match data.

From Tomasz Szumlak
The ATLAS digitizer for simulation of radiation

- Double peak electric field
- Fluence from FLUKA + pythia

From Ben Nachman
CMS simulation

- Works up to $1.2 \times 10^{15} \text{n_{eq}/cm^2}$: good for predictions in run 3
- Perform detailed independent simulation and apply correction factors;
- Cluster reweighting to reflect fluctuations

From Jörn Schwandt

From Morris Swartz
Summary

Effects from radiation damage can be challenging in operations and for physics:

- Increasing leakage currents
- Charge accumulation in silicon oxide layers
- Single event upsets
- Decreasing signal-to-noise ratios
- Changing depletion voltages
- Radiation induced activation of components

Modeling these effects is important, but can be challenging:

- Do we need a nontrivial space charge distribution in the Hamburg model?
- Temperature modeling and dependence
- How do leakage currents depend on r and z?