INTRODUCTION TO RADIATION DAMAGE: BASIC PHYSICS AND CONCEPTS
Overview

- Introduction
- Radiation environments
  - Space environment
  - Ground environment
  - High Energy Physics
- Radiation concepts
  - Overview of radiation quantities
  - Particle interactions
- Radiation damage
  - Damage on electronics
  - Damage on Silicon Detectors
Overview

Radiation is ubiquitous

<table>
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<th>Natural human environment</th>
<th>Extended natural environment</th>
<th>Artificial environment</th>
</tr>
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<td>• Natural radioactivity of material</td>
<td>• High altitude avionic</td>
<td>• Nuclear reactors</td>
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<tr>
<td>• Sea level cosmics</td>
<td>• Satellites (various orbits)</td>
<td>• HEP experiments (collider halls), synchrotron facilities</td>
</tr>
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<td></td>
<td>• Space station</td>
<td>• Radiation therapy facilities</td>
</tr>
<tr>
<td></td>
<td>• Deep space missions</td>
<td>• Industrial accelerators and sources</td>
</tr>
</tbody>
</table>

Radiation can be a tool, but also an hazard!
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The space radiation environment

Galactic and extra-galactic cosmic rays
Protons and HZE (high Z and Energy) ions:
Flux maximum at ~ 300 MeV/n

Solar flares
- Protons: keV ÷ 500 MeV
- Ions: 1 ÷ few 10 MeV/n

Particles trapped by magnetic fields
- Protons: keV ÷ 500 MeV
- Electrons: eV ÷ 10 MeV
Galactic cosmic rays (1)

- Diffuse galactic background
  - Composition: ~85% protons, ~14% $\alpha$, ~1% heavy nuclei
  - Likely formed by explosive events such as supernova
  - Most up to 10GeV/amu. Rarely up to $10^{20}$ eV ($10^{11}$ GeV)
  - They are fully ionized and hence interact with and are influenced by magnetic fields
    - Anti-correlated with solar activity: solar flux scatters incoming charged particles
    - Interaction with Earth magnetic field
Galactic cosmic rays (2)

**GCR components**

**Energy spectrum**

![Graph showing the energy spectrum of cosmic rays with different components like He, C, H, and Fe.](image1)

![Graph showing differential flux vs. kinetic energy for cosmic rays.](image2)
Solar particle events (1)

- Solar activity: 11-year cycle
  - 7 years of high activity (solar maximum)
  - 4 years of low activity (solar minimum)

- Events such as solar flares and coronal mass ejections, which increase during solar maximum give rise to solar cosmic rays

- Composition: mostly protons, $\alpha$, heavy nuclei

- Flares: at Earth surface fluxes up to $10^6p/(cm^2 s)$ [1972], spectra high variable
Solar particle events (2)

- Between the Apollo 16 and 17 manned space missions, one of the largest solar proton events ever recorded arrived at Earth.

- Computer simulations were done of the radiation levels an astronaut inside a spacecraft would have experienced during this event.

- The astronauts would have absorbed lethal doses of radiation within 10 hrs after the start of the event.

- As NASA ponders the feasibility of sending manned spaceflight missions back to the Moon or to other planets, radiation protection for crew members remains one of the key technological issues which must be resolved.

4000 mSv is an average fatal single dose
Solar wind and magnetic field

- The interaction of the particles and the magnetic field forms a shock front around which the particles are deflected like water around the bow of a ship.
- The solar wind compresses and confines the magnetic field on the side toward the Sun and stretches it out into a long tail on the night side.
- Magnetosphere shelters the surface of the Earth from the constant bombardment by charged particles.
Trapped radiation belts

- Van Allen radiation belts
  - Inner (1000-6000 km): mainly protons (> 10 MeV)
  - Outer (13000-60000 km): electrons (0.1 – 10 MeV)
South Atlantic Anomaly

- Magnetic and rotation axis do not coincide
- Above South America, the Inner Van Allen Belt extends only to about 200 - 300 kilometers (off the coast of Brazil and extending over much of South America)
- This is what is called the South Atlantic Anomaly
- Satellite failures are much more common in this stronger radiation zone
Air showers (1)
Air showers (2)

- Under 20 km altitude neutrons dominate as cause of radiation-induced failures in avionic systems.
- In mountains and at sea level there are enough of them to be a real concern for ground-based electronics that play vital roles (e.g. in computers, pacemakers, cars, power devices in locomotives, …)
“Radiation induced single events could be happening on everyone’s PC, but instead everybody curses Microsoft.”

Paul Dodd, Sandia National Laboratories
Accelerator environment

- Instantaneous effects (due to the presence of beam)
  - Damage induced by the passage of a single particle

- Cumulative effects (due to long duration of exposure)
  - bulk damage to Silicon-detectors:
  - surface damage to electronics (degrade of S/N,…)
  - Light loss in scintillators/fibers
  - activation of detectors and materials (problems for maintenance)
  - damage to materials (insulators)

After 10 years of operation will have produced just a few thousand of rare hard events at the very high price of producing about $10^{16}$ busy “events”.

VERY RADIATION HOSTILE ENVIRONMENT!
Radiation environments of HEP experiments at accelerators are very hostile! A very large number of particles is generated at every beam interaction. Charged particles ionize, contributing to total dose. But they can also damage the material properties of detectors (silicon, crystals, etc).
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Source
• What kind is it (natural, reactor, accelerator)
• Activity
• Luminosity of accelerator

Radiation Field
• Where are you with respect to the source
• Exposure: what are you exposed to (types of particle at your location)
• Flux
• Fluence

Exposed material
• What are you made of (silicon, oxide, etc)
• Dose, dose rate
• Stopping power of particles (LET, NIEL)
• Various effects (cumulative, sudden)
Radiation damage quantities (1)

- **Activity**
  - 1 Bequerel (Bq): 1 disintegration/s
  - 1 Curie (Ci): $3.7 \cdot 10^{10}$ Bq
    - Typical activity of 60Co source for radiotherapy: ~ 1 kCi
    - Geological sample activity: ~ 0.1 Bq

- **Luminosity**: (of an accelerator) is how many particles we are able to squeeze through a given space in a given time
  - $N_1, N_2$: number of particles
  - $A$: interaction area (size of the beam)
  - $\nu$: collision frequency

\[
L = \frac{N_1 N_2}{A} \times \nu
\]

- $R$: particle production rate
- $\sigma_i$: cross section of $i^{th}$ channel

\[
R = \sum_i R_i = L \cdot \sum_i \sigma_i = L \cdot \sigma_{TOT}
\]
Radiation damage quantities (2)

- **Flux** ($\phi$) is the number of particles per unit of area and per unit of time
  
  $\phi = \text{particles}/(\text{Area} \times \text{Time})$
  
  Measurement Unit: $\text{particles}/(\text{cm}^2 \times \text{s})$

- **Fluence** ($\Phi$) is the number of particles per unit of area (time integral of the flux)
  
  $\Phi = \int \phi \cdot dt = \text{particles/Area}$
  
  Measurement Unit: $\text{particles/cm}^2$
Radiation damage quantities (3)

- **Dose** \((D)\) is the energy deposited by radiation per unit of mass

- **Absorbed Dose**: is the energy delivered to irradiated matter per unit mass by ionizing radiation
  - 1 rad = 100 erg/g
  - 1 Gray (Gy) = 1 J/kg
  - 1 Gy = 100 rad
  - 1 rad = 0.01 Gy

- **Displacement Damage Dose**
  - The fraction of the total energy absorption (per unit of mass) that results in damage to the lattice structure of solids through displacement of atoms

- **Dose equivalent**
  - It refers to a quantity applied to biological effects. It includes scaling factors to account for the more severe effects of certain kinds of radiation
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Radioactivity</th>
<th>Absorbed Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Rate of radiation emission (transformation or disintegration)</td>
<td>Energy delivered by radiation per unit of mass of irradiated material</td>
</tr>
<tr>
<td><strong>Common Unit Symbol</strong></td>
<td><strong>Curie (Ci)</strong>&lt;br&gt;1 Ci = 37 GBq (a large amount)</td>
<td><strong>Rad</strong>&lt;br&gt;1 rad = 100 erg/g&lt;br&gt;1 rad = 0.01 Gy</td>
</tr>
<tr>
<td><strong>International Units (SI) symbol</strong></td>
<td><strong>Bequerel (Bq)</strong>&lt;br&gt;1 Bq = 1 event of disintegration per second (a very small amount)</td>
<td><strong>Gray (Gy)</strong>&lt;br&gt;1 Gy = 1 J/kg&lt;br&gt;1 Gy = 100 rad</td>
</tr>
</tbody>
</table>
Typical Ionizing Radiation Doses

- **radiobiological doses**
  - < 5 mGy: typical annual dose of human in civilized culture
  - 50 mGy: allowable annual dose for radiation worker
  - 1 Gy: common dose of a single X-ray treatment
  - 2.5 Gy: total-body lethal dose for humans and many mammals
  - 60 Gy: localized dose for full cancer therapy

- **technological/industrial doses**
  - < 1 kGy: Teflon structurally unstable
  - 15-35 kGy: sterilization
  - 20 kGy (2 Mrad): curing of polyester resins
  - 100-200 kGy (10-20 Mrad): curing of epoxy resins
  - 200 kGy: natural rubber unusable
  - 1000 kGy (100 Mrad): polyvinylchloride (PVC) unusable
  - 50-100 MGy: polyimide degraded significantly
Flux representation (1)

- The amount of radiation crossing a surface per unit of time

- “Integral flux”: particles per unit area per unit of time (e.g. particles cm\(^{-2}\) s\(^{-1}\)) above a certain threshold

- “Differential flux”: the differential with respect to energy (e.g. particles MeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\))

- “Directional flux”: the differential flux with respect to the solid angle (e.g. particles cm\(^{-2}\) steradian\(^{-1}\) s\(^{-1}\))
Flux representation (2)

- Directional integral flux of ions with LET $> \text{LET}_0$ in space
Flux representation (3)

- Differential Energy spectra of air shower neutrons at sea level

![Graph showing differential flux vs. neutron energy]

- Neutrons with $E > 1$ MeV is $\sim 21$ cm$^{-2}$ h$^{-1}$
- Neutron with $1$ MeV $< E < 10$ MeV is $\sim 8$ cm$^{-2}$ h$^{-1}$
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Particle interactions

- **Ionizing energy loss**
  - Ionizing radiation, such as x-rays, gammas, and all charged particles create free charge in materials, which affects properties and performance.

- **Non-ionizing energy loss**
  - Particles (neutrons, pions, protons, ions, even electrons) can displace atoms from their usual lattice sites and produce “bulk” damage effects.
Basic particle interactions with matter

- **Charged particles** (protons, ions, electrons, muons, charged pions, kaons,...)
  - Coulomb Interactions with electrons (ionization) and nuclei (atomic displacement)
  - Nuclear Interactions (mainly for energetic hadrons, such as protons, pions, kaons)
  - Deceleration of charged particles causes photon emission (Bremsstrahlung) with continuous spectra (mainly for electrons)

- **Neutrons**
  - Neutron capture/spallation/inelastic scattering: formation of excited composite nucleus followed by de-excitation and emission of $\gamma$-rays, particles ($\alpha$, $\beta^+/-$, n, p) and nuclear fragments
  - Elastic scattering with nuclei (atomic displacement)
  - Ionization can be induced by secondary charged particles

- **Photons**
  - Photoelectric effect
  - Compton effect
  - Pair production
Ionization

- It is ultimately associated with transfer of kinetic energy from incident particle to the bound electrons of the material substance.

- In the case of charged particles (electrons, protons, alfa, ions, muons, pions, ...), ionization is caused ***DIRECTLY*** through the coulomb interaction with the electrons of the substance.

- In the case of neutral particles (photons, neutrons,...), ionization is mainly ***INDIRECT*** by the release of an energetic charged particle within the substance.
  
  - **Photons**: ionization is mainly the result of the transfer of photon energy to a bound electron providing sufficient kinetic energy to detach the electron from the atom. If the electron is energetic enough, it too can further ionize.
  
  - **Neutrons**: ionization is through a nuclear interaction event in which nuclear reaction products are agents of ionization.
Dose for particles

Dose \((\text{energy/mass})\) = \textit{proportionality} \((\text{energy} \times \text{length}^2/\text{mass})\) \times \textit{fluence} \((\text{length}^2)\)

\[
\text{Total Ionising DOSE (TID)} = \frac{\text{energy to ionisation}}{\text{mass}} = \text{LET} \times \Phi
\]

\[
\text{Displacement Damage DOSE (DDD)} = \frac{\text{energy to displacements}}{\text{mass}} = \text{NIEL} \times \Phi
\]

- Typically Linear Energy Transfer (LET) and Non Ionizing Energy Loss (NIEL) expressed in MeV-cm\(^2\)/mg
- Energy deposited in a block of matter:
  - energy to ionization = LET(energy-length\(^2\)/mass) \times \text{fluence} (length\(^{-2}\)) \times \text{mass}
  - energy to displacements = NIEL(energy-length\(^2\)/mass) \times \text{fluence} (length\(^{-2}\)) \times \text{mass}
Stopping power

For a charged particle, the “average energy loss” is characterized by

- **STOPPING POWER** $S = \frac{dE}{dx}$ (keV/$\mu$m): it is the average energy loss per unit of path length of a particle in traversing a material.
  - It results from Coulomb interactions
    - With electrons $S_{\text{ele}} = \frac{dE}{dx}_{\text{ele}}$
    - With atomic nuclei $S_{\text{nuc}} = \frac{dE}{dx}_{\text{nuc}}$

- **MASS STOPPING POWER**
  - $(1/\rho)S = \text{LET} + \text{NIEL}_{\text{coulomb}}$ [MeV-cm$^2$/mg]

(*) Note: rare nuclear (non-coulomb) interactions are not considered.
Charged particle travelling through a medium

- Coulomb interaction with atomic electrons or with the nucleus:

\[ \text{Ratio of effective areas (cross-sections) gives relative probability of interactions to occur.} \]

\[ \frac{\text{number of interactions with electrons}}{\text{number of interactions with nuclei}} = \frac{R_{\text{atom}}^2}{R_{\text{nucleus}}^2} \approx 10^8 \]

Conclusion: regards energy transfers, **coulomb collisions with electrons are much more important than with nuclei (except when very SLOW at end of range!)**
The Linear Energy Transfer (LET) is the amount of energy that an ionizing particle transfers to the material traversed per unit of distance.

Normally used to describe the ionization track caused by passage of an ion. **LET is material-dependent and is also a function of particle energy.**

For ions of concern in space radiation effects, it increases with decreasing energy (it also increases at high energies, beyond the minimum ionizing energy).
Range of heavy charged particles (1)

- Will lose small amounts of energy per coulomb collision:
  - are hardly deflected by atomic electrons
  - do get slightly deflected by interactions with nuclei (multiple scattering)
  - important deflections are very rare (Rutherford-like hard interactions)

- The overall trajectory is almost a straight line!!!

\[
\text{range} = \int \left[ \frac{dE}{dx} \right]^{-1}_{\text{total}} dE
\]

TOTAL stopping power \(\frac{dE}{dx}\)

\[
\frac{dE}{dx} = \frac{dE}{d\xi}_{\text{ionization}} + \frac{dE}{d\xi}_{\text{nuclear coulomb}}
\]

NOTE: both change along track as particle slows down till the ion is so slow as to be “harmless”
Range of heavy charged particles (2)

- Even in the case of a perfectly collimated monoenergetic beam of particles, the stopping process will introduce a finite divergence in the propagating beam. This is what is called the **lateral straggling** of the beam.

- At the same rate, there is a stochastic indetermination on the penetration depth into the target (**longitudinal straggling**)
What about electrons?

- An electron (positron) projectile will behave quite differently:
  - an incident electron may collide with an atomic electron and lose ALL its energy in a single collision (billiard ball effect)!
  - IN GENERAL: incident electrons and positrons may lose a large fraction of their kinetic energy in any one collision
  - They are easily scattered to large angles hence their trajectories are VERY ZIG-ZAG

1 MeV electron in copper

http://www.slac.stanford.edu/~rfc/egs/basicsimtool.html
Range

100 protons (1 MeV) in Al

100 electrons (1 MeV) in Al

The range is not well defined for electrons
Bremsstrahlung

- An accelerated charge will radiate

\[
\text{Intensity } \propto a^2 \sim \left( \frac{Z_{\text{proj}} Z_{\text{targ}} e^2}{M_{\text{proj}}} \right)^2 \sim \frac{Z_{\text{proj}}^2 Z_{\text{targ}}^2}{M_{\text{proj}}^2}
\]

- High-energy electromagnetic radiation in the X and gamma energy range is emitted by charged particles as they slow down when they scatter off atomic nuclei.

- Although the primary particle might ultimately be absorbed, the bremsstrahlung radiation can be highly penetrating.

- The most common source of bremsstrahlung is electron scattering.
Electromagnetic (Coulomb) interaction of Particles with matter

Heavy charged particle: many interactions with the atomic electrons. The incoming "continuously" particle losses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is significantly deflected by numerous soft scatterings (multiple scattering) or and occasional rare single hard Rutherford scatterings.

If the incident particle is an electron then the electron can lose a lot of energy in just one collision with an atomic electron or by emitting Bremsstrahlung photons.
Heavy particles

- Not electrons
- Especially Ions

I will introduce a few concepts:
  - Bethe-Bloch electronic stopping power for heavy ions
  - LET versus depth
  - Surface LET
  - Bragg peak
  - Range
The SRIM tool

- A simple tool to simulate the interactions of heavy ions with matter is SRIM (Stopping and Range of Ions in Matter)
- SRIM is a group of programs which calculate the stopping power and the range of ions (up to 2 GeV/amu) into matter using a quantum mechanical treatment of ion-atom collisions
- SRIM can be downloaded from http://www.srim.org/
- TRIM (the Transport of Ions in Matter) is the most comprehensive program included.
  - TRIM will accept complex targets made of compound materials with up to eight layers, each of different materials. It will calculate both the final 3D distribution of the ions and also all kinetic phenomena associated with the ion's energy loss: target damage, sputtering, ionization, and phonon production. All target atom cascades in the target are followed in detail. The programs are made so they can be interrupted at any time, and then resumed later. Plots of the calculation may be saved, and displayed when needed
Bethe-Bloch for heavy ions

\[
\left( \frac{dE}{dx} \right)_{\text{ele}} = \left( \frac{Z_{eff}^2}{V^2} \right)_{\text{particle}} \times \left( \frac{zp}{A} \right)_{\text{material}} \times \left\{ \ln \left( \frac{2me^2\beta^2}{I} \right) - \ln(1 - \beta^2) - \beta^2 - \delta \right\}
\]

where \( I = \text{mean excitation potential of target material; for Silicon } I \approx 170 \text{ eV} \)

- for velocity of ion \( V >> v_{\text{Bethe}} = v_0 Z^{2/3} \) where \( v_0 = c/137 = v_{\text{Bohr}} \)
  - ion completely stripped of electrons, full nuclear charge, \( Z_{\text{eff}} \sim Z \)
- for velocity of ion \( V \approx v_{\text{Bethe}} \) and slower
  - ion retains/picks-up electrons and charge decreases(!) as ion slows

\[
Z_{\text{eff}}(V) = \eta(V) \times Z
\]

\[
\eta(V) = 1 - A \exp(-B V/v_{\text{Bethe}})
\]

\( Z_{\text{eff}}(V) = \eta(V) \times Z \) good to a few percent

\( \eta(V) = 1 - A \exp(-B V/v_{\text{Bethe}}) \)

\( A = 1 \)

\( B = 0.95 \)

\[
\left( \frac{dE}{dx} \right)_{\text{ele}} \approx \rho \times Z^2 \times F(V) = \rho \times \frac{Z^2}{\beta^2} \times f(V)
\]

\[
\text{LET} = \frac{\left( \frac{dE}{dx} \right)_{\text{ele}}}{\rho} \approx \frac{Z^2}{\beta^2} \times f(V)
\]

Silicon: \( \rho = 2.33 \text{g/cm}^3 \)
The diagram illustrates the stopping power of a muon ($\mu^+$) on Cu as a function of the muon momentum. The plot shows the contributions from nuclear losses, Anderson-Ziegler, Bethe-Bloch, and radiative effects. The y-axis represents the stopping power in MeV cm$^2$ g$^{-1}$, while the x-axis represents the momentum of the muon in MeV/c, GeV/c, and TeV/c. The Bethe-Bloch region is indicated where radiative effects reach 1%. The diagram also highlights the radiative losses and the parameter $E_{\mu c}$ without the correction factor $\delta$.
LET vs depth of material

100MeV $^{18}$O ions in Silicon

Bragg peak $\text{LET}_{\max} \approx 170 \text{ eV/Å}$

Surface value $(dE/dx)_0$

average RANGE

$\text{LET}_{\min} \approx 2.5 \text{ eV/Å}$
The importance of range

- Ions must have sufficient energy to penetrate overlayers
- Need to evaluate LET at the correct depth

Sensitive volume is down here!
Range

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Range (microns)</th>
<th>LET₀ (eV/Å)</th>
<th>LET₀ (MeV-cm²/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>37.65</td>
<td>108.16</td>
<td>4.66</td>
</tr>
<tr>
<td>100</td>
<td>95.23</td>
<td>72.12</td>
<td>3.107</td>
</tr>
<tr>
<td>150</td>
<td>176.23</td>
<td>53.97</td>
<td>2.325</td>
</tr>
</tbody>
</table>

N.B. \((dE/dx)_0\) decreases monotonically with E!
Range in Silicon

![Graph showing the range in silicon for different elements (Li, O, Si, Br, Au) as a function of energy (E in MeV). The graph plots range in microns on the y-axis and energy in MeV on the x-axis.]
Surface LET

<table>
<thead>
<tr>
<th>energy (MeV)</th>
<th>energy (MeV/amu)</th>
<th>LET(0) (eV/Å)</th>
<th>LET(0) (MeV-cm²/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>79</td>
<td>1</td>
<td>809</td>
<td>35.0</td>
</tr>
<tr>
<td>158</td>
<td>2</td>
<td>961</td>
<td>41.6</td>
</tr>
<tr>
<td>237</td>
<td>3</td>
<td>968</td>
<td>41.9</td>
</tr>
<tr>
<td>316</td>
<td>4</td>
<td>936</td>
<td>40.5</td>
</tr>
</tbody>
</table>

Br⁷⁹

- broad maximum
- decrease! beyond maximum
When performing heavy ion experiments you need to know:
1. RANGE
2. where you are on these LET vs Energy/amu curves!

Note: ions with same energy/amu have the same velocity
Ionization

- Ionization energy loss = energy deposited per unit path length due to ionization resulting from the coulomb interaction of the impinging particle with the electrons of the material
- However: caution!
- Depth dose profile of photons and heavy ions:
Track structure

- As ion slows the spatial extent of ionisation decreases (not enough energy to extract energetic deltas).
- The height of ionisation decreases as effective charge $Z_{\text{eff}}$ of ion decreases.

50 GeV Fe in emulsion

Nuclear emulsion tracks of a single cosmic Fe nucleus at various stages in its deceleration from relativistic velocities to REST. The distances are the residual ranges at which the ion track is observed.

Displacement damage

- **Caused by:** p, n, ions, electrons, \( \gamma \)-rays
- **Result of:** transfer of non-ionizing energy (NIEL) to lattice NUCLEI causing structural damage to lattice (defects).
- **Basic mechanism:** collision between incoming particle and a lattice nucleus (called Primary Knock-on Atom, i.e. PKA) displaces atom from original lattice position generating point defects (vacancies and interstitials).
- **Pejorative mechanism:** energetic PKA generates other point defects or even highly damaged regions (cascades, clusters), depending on energy transferred during the primary collision.

\[
\text{NIEL} = (dE/dx)_{\text{displacement}}
\]
Elastic collisions

Initial (before)

Final (after)

In elastic collisions kinetic energy is conserved hence the maximum transferable energy for a given incident energy is

\[ E_{2,\text{max}}^{\text{final}} = E_{1}^{\text{initial}} \times \frac{4M_1M_2}{(M_1 + M_2)^2} \]

Non-relativistic

Minimum energy of incident particle to give target particle a minimum (Threshold) energy

\[ E_{\text{incident}}^{\text{min}} = E_{\text{threshold}} \times \frac{(M_{\text{inc}} + M_{\text{tar}})^2}{4M_{\text{inv}}M_{\text{tar}}} \]

Non-relativistic
## Vacancies in Silicon

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>Germanium</th>
<th>Silicon</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>$35\pm5$ eV</td>
<td>$27.5$ eV</td>
<td>$25$ eV</td>
<td>$7$-11 eV</td>
</tr>
<tr>
<td>damage threshold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **$^{60}$Co-gammas**
  - Max $E_\gamma \approx 1$ MeV
  - Effective particles are *Compton* electrons.
  - Point defects only. (No clusters!)

- **Electrons**
  - $E_e > 255$ keV for displacement
  - $E_e > 8$ MeV for cluster

- **Neutrons** (elastic scattering)
  - $E_n > 186$ eV for displacement
  - $E_n > 35$ keV for cluster

---

**Displacement damage threshold energies**

- Diamond
- Germanium
- Silicon
- GaAs

- $35\pm5$ eV
- $27.5$ eV
- $25$ eV
- $7$-11 eV

---

**More isolated defects**

---

**More clusters**
NIEL scaling hypothesis (1)

- Bulk damage has been widely verified to be strictly proportional to the Non Ionizing Energy Loss (NIEL scaling hypothesis)

\[ \text{Displacement Damage Dose} \; \text{DDD} = \text{NIEL} \times \Phi \]

units: \( \text{NIEL(MeV-cm}^2/\text{mg}) = \text{NIEL(keV-cm}^2/\text{g}) \times 10^3 \)

- An equivalent expression for NIEL is the so called Damage Function or Displacement Damage cross section \( D(E) \)
  - \( 100 \; \text{MeV-mb} = 100 \; \text{MeV-mb} \times (10^3 \; \text{keV/MeV}) \times (10^{-27} \; \text{cm}^2/\text{mb}) \times (\text{mole Silicon}/28.086 \; \text{g}) \times (6.022 \times 10^{23}/\text{mole}) = 2.144 \; \text{keV-cm}^2/\text{g} \)

- The D or NIEL value is depending on the particle type and energy.
According to an ASTM standard, the displacement damage cross section for 1 MeV neutrons is set as a normalizing value.

In Silicon the reference values are:

- \( D \) (1 MeV neutrons) = 95 MeV-mb
- \( \text{NIEL} \) (1 MeV neutrons) = 2.037 keV-cm²/g

A particle fluence \( \Phi \) can be reduced to an equivalent 1 MeV neutron fluence \( \Phi_{\text{eq}} \) to produce the nearly the same bulk damage.

These are chosen as STANDARD reference values when calculating the equivalent 1 MeV neutron fluence values for irradiations using:

- neutrons of another energy;
- other particle types (electrons, protons, pions, ions...)

NIEL scaling hypothesis (2)
Hardness factor

- On the basis of the NIEL scaling, the damage efficiency of any flux of particle with a given kinetic energy $E$ can then be described by the **hardness factor** $k$, defined as
  
  $$ k_{\text{particle}}(E) = \frac{D_{\text{particle}}}{D_n(1\text{MeVn})} \quad \text{(ratio of damage functions)} $$

- e.g. for $k=2$, $\Phi_{eq} = 2 \times \Phi$, hence $5 \times 10^{13}$ particles/cm$^2$ make a bulk damage equivalent to $10^{14}$ standard-ones/cm$^2$

- A generic damage parameter $\alpha$ (e.g. leakage current) measured with one type of radiation $(X)$, compared with the same parameter measured using another type of radiation $(Y)$, scale according to:
  
  $$ \frac{\alpha(X)}{\alpha(Y)} = \frac{k(X)}{k(Y)} $$

  - $\alpha(X)$ and $\alpha(Y)$ are the generic damage parameters using radiations $X$ and $Y$,
  - $K(X)$ and $K(X)$ are the hardness factors of radiation $X$ and $Y$, respectively.
Displacement damage functions
### Particles and damages

<table>
<thead>
<tr>
<th>Radiation</th>
<th>TID</th>
<th>Displacement (NIEL)</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays (^{60}\text{Co})</td>
<td>Expressed in (\text{SiO}_2)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Almost identical in Si or (\text{SiO}_2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(p)</td>
<td>Equivalences in (\text{Si}^8)</td>
<td>Equivalences in (\text{Si}^8)^*</td>
<td>Only via nuclear interaction. Max LET of recoil in Silicon = 15MeVcm²mg⁻¹</td>
</tr>
<tr>
<td></td>
<td>(\text{at } 60\text{MeV} \quad 10^{11}\text{p/cm}^2 = 13.8\text{krd})</td>
<td>(\text{at } 53\text{MeV} \quad 1\text{p/cm}^2 = 1.25\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{at } 100\text{MeV} \quad 10^{11}\text{p/cm}^2 = 9.4\text{krd})</td>
<td>(\text{at } 98\text{MeV} \quad 1\text{p/cm}^2 = 0.92\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{at } 150\text{MeV} \quad 10^{11}\text{p/cm}^2 = 7.0\text{krd})</td>
<td>(\text{at } 154\text{MeV} \quad 1\text{p/cm}^2 = 0.74\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{at } 200\text{MeV} \quad 10^{11}\text{p/cm}^2 = 5.8\text{krd})</td>
<td>(\text{at } 197\text{MeV} \quad 1\text{p/cm}^2 = 0.66\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{at } 250\text{MeV} \quad 10^{11}\text{p/cm}^2 = 5.1\text{krd})</td>
<td>(\text{at } 244\text{MeV} \quad 1\text{p/cm}^2 = 0.63\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{at } 300\text{MeV} \quad 10^{11}\text{p/cm}^2 = 4.6\text{krd})</td>
<td>(\text{at } 294\text{MeV} \quad 1\text{p/cm}^2 = 0.61\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{at } 23\text{GeV} \quad 10^{11}\text{p/cm}^2 = 3.2\text{krd})</td>
<td>(\text{at } 23\text{GeV} \quad 1\text{p/cm}^2 = 0.50\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td>(n)</td>
<td>Negligible</td>
<td>Equivalences in (\text{Si}^8)^*</td>
<td>As for protons, actually above 20MeV (p) and (n) can roughly be considered to have the same effect for SEEs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{at } 1\text{MeV} \quad 1\text{n/cm}^2 = 0.81\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{at } 2\text{MeV} \quad 1\text{n/cm}^2 = 0.74\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{at } 14\text{MeV} \quad 1\text{n/cm}^2 = 1.50\text{n/cm}^2)</td>
<td></td>
</tr>
<tr>
<td>Heavy Ions</td>
<td>Negligible for practical purposes (example: (10^6) HI with LET=50MeVcm²mg⁻¹ deposit about 800 rd)</td>
<td>Negligible</td>
<td>Yes</td>
</tr>
</tbody>
</table>

---

\(^*\) Energy here is only kinetic (for total particle energy, add the rest energy \(mc^2\)).

\(^{**}\) The equivalence is referred to “equivalent 1MeV neutrons”, where the NIEL of “1MeV neutrons” is DEFINED to be 95 MeVmb. This explains why for 1MeV neutrons the equivalence is different than 1.
Overview

- Introduction
- Radiation environments
  - Space environment
  - Ground environment
  - High Energy Physics
- Radiation concepts
  - Overview of radiation quantities
- Radiation damage
  - Damage on electronics
  - Damage on Silicon Detectors
Radiation damage

- When a particle strikes a microelectronics device, it can transfer energy to the medium both by atomic displacement and/or by ionization:

  - **Single Event Effects (SEE):** damage induced by the passage of a single energetic ionizing particle which releases enough ionization in a sensitive volume to induce a device/system malfunction (threshold effect)
  - **Total Ionizing Dose (TID):** degradation of performances of irradiated devices due to the homogeneous accumulation of charge in oxide layers and Si-SiO2 interfaces in microelectronics circuits exposed to ionizing radiation.
  - **Bulk Damage (DDD):** damage caused by the displacement of crystal atoms by the interaction of the incident particles with the nuclei of the lattice atoms.
Single Event Effect mechanism

- When a single high LET particle interacts with a device it leaves an ionization trail that may perturb the device.
- If (some of) the charge generated by is collected by a sensitive node of the device/circuit, and this charge is larger than the critical charge required to start an anomalous behavior, an effect (Single Event Effect) may be seen, affecting the electrical performance of the device/circuit.
Single Event Effects (SEE) (1)

- In space applications electronic devices may receive direct impacts of galactic and extra-galactic heavy energetic ions (HZE) cosmic rays during operational lifetime of a spaceflight.

- **Energetic neutrons and protons** may produce secondary highly ionizing ions in nuclear interactions.

- Highly ionizing ions are produced indirectly (secondaries) in the experimental halls of High Energy Physics experiments such as LHC where huge quantities of hadrons are produced.

- **Neutrons** are a problem in avionics and at sea level.
Single Event Effects (SEE) (2)

- Rewriting data
- Software or hardware mitigation
- Power cycling

**destructive**
- SEB
- SEGR
- SESB
- SEDR

**soft**
- SEL
- SEU
- MBU
- SEFI

**transient**
- SET
- DSET
- ASET

**Power**

**Digital**

**Analog**
<table>
<thead>
<tr>
<th>Type of Single Event</th>
<th>Description</th>
<th>Affected devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEU upset</td>
<td>Corruption of information</td>
<td>Memories, latches in logic devices</td>
</tr>
<tr>
<td>MBU multiple bit upset</td>
<td>Several memory elements corrupted by single ion</td>
<td>Memories, latches in logic devices</td>
</tr>
<tr>
<td>SEFI functional interrupt</td>
<td>Loss of normal operation</td>
<td>Complex devices with built-in state/control sections</td>
</tr>
<tr>
<td>SET transient</td>
<td>Pulse response of certain amplitude and duration</td>
<td>Analog, mixed signal devices</td>
</tr>
<tr>
<td>SED disturb</td>
<td>Momentary corruption of info in a but</td>
<td>Combinatorial logic, latches in logic devices</td>
</tr>
<tr>
<td>SHE hard error</td>
<td>Unalterable change of state of a memory cell</td>
<td>Memories, latched in logic devices</td>
</tr>
<tr>
<td>SEL latchup</td>
<td>Generation of unexpected high current</td>
<td>CMOS, BiCMOS</td>
</tr>
<tr>
<td>SESB snap back</td>
<td>Generation of unexpected high current</td>
<td>N-channel power MOSFETs, SOI</td>
</tr>
<tr>
<td>SEB burnout</td>
<td>Destructive burn-out</td>
<td>BJT, etc.</td>
</tr>
<tr>
<td>SEGR gate rupture</td>
<td>Rupture of gate dielectric</td>
<td>Power MOSFETs</td>
</tr>
<tr>
<td>SEDR dielectric rupture</td>
<td>Rupture of dielectric layer</td>
<td>Non-volatile NMOS, FPGA, linear devices</td>
</tr>
</tbody>
</table>
SEE testing

- SEE testing is necessary to
  - determine the presence and characteristics of single events
  - calculate the SEE rate for a radiation environment
- SEE testing is usually done at accelerators, (cyclotrons or tandem Van der Graaff machines) that irradiate the whole device with ions. Some in air and some in vacuum.
- The sensitivity of a device to SEE is expressed in terms of SEE cross section
- Proton testing
SEE experimental cross section

The fraction of incident particles that cause SEE \( \frac{N_{\text{SEE}}}{N_{\text{inc}}} \) is equal to the fraction of exposed area this is sensitive

\[
\frac{N_{\text{SEE}}}{N_{\text{inc}}} = \frac{N_S \cdot \sigma_{\text{bit}}}{A} = \frac{\sigma_{\text{device}}}{A}
\]

\[
N_{\text{SEE}} = N_S \frac{N_{\text{inc}}}{A} \sigma_{\text{bit}} = N_S \cdot \Phi_{\text{inc}} \cdot \sigma_{\text{bit}}
\]

\[\sigma_{\text{bit}} = \frac{N_{\text{SEE}}}{N_S \cdot \Phi_{\text{inc}}} \quad \sigma_{\text{device}} = N_S \cdot \sigma_{\text{bit}} = \frac{N_{\text{SEE}}}{\Phi_{\text{inc}}} \]

\( A \): area of device exposed to beam

\( \sigma_{\text{bit}} \): Cross-section of each sensitive volume

\( N_s \): number of sensitive volumes in area \( A \)

\( \sigma_{\text{device}} = \sigma_{\text{bit}} \times N_s \): Total sensitive area exposed to beam
The cross section ($\sigma$) for Single Event Effects is $\sigma = \frac{N_{\text{SEE}}}{\Phi}$

- practical flux set by dead-time of DUT (typical few $10^{-1}$ to $10^{4}$ ions cm$^{-2}$s$^{-1}$)
- Statistical Error improves with fluence
- however fluence is limited by Total Dose
- $\sigma$(LET) deviates from ideal curve
  - Charge collection efficiency varies across sensitive area,
  - Diffusion of charge from ion strikes near sensitive volume,
  - Multiple junctions with different sensitivities and areas,
  - MBU, etc

WEIBULL FIT of threshold curve

$$\sigma = \sigma_{\text{sat}} \times \{1 - \exp[-(L - L_{\text{th}})/W]^s\}$$

$\sigma_{\text{sat}}$: saturation value
$L_{\text{th}}$: threshold LET value
$W$ and $s$ are fitting parameters
Testing at Non-normal incidence

Testing is done at non-normal incidence to:

- Increase LET (effective LET) without changing beam species
- Determine sensitive volume depth (d)
- Look for multiple bit upsets (MBUs)
- Check SEU hardening that requires multiple nodes to upset for the cell to upset

\[ \theta = 0^\circ \text{ (normal)} \]

SRIM simulation (http://www.srim.org).

Shallower depths are reached!

\[ \theta = 60^\circ \]

\[ \text{LET}_0(\theta) = \frac{\text{LET}_0}{\cos(\theta)} \]

\[ \text{depth} = \text{range} \times \cos(\theta) \]
Proton testing

- Devices sensitive should be tested for proton SEE sensitivity especially for devices with heavy ion \( \text{LET}_{th} < 20 \text{ MeV} \cdot \text{cm}^2/\text{mg} \)
- Mission proton exposure is significant
- Since LET is not a well-defined number for the group of secondary particles emitted by the silicon nucleus, a better metric is proton energy.
- Cross-section is calculated in the same way as for heavy ions.
- SEUs are measured as a function of proton energy.
To sum up...

- Single ionizing particle deposits enough ionization in a sensitive volume to cause spontaneous damage in live device. Note: it requires a minimum amount of ionization!
- SEE are due to:
  - heavy ions (e.g. primary galactic high charge and energy cosmic rays)
  - neutrons
  - protons, pions
- Effects in live electronics depend greatly on technology and design:
  - permanent HARD SEE (may be destructive)
    - SEL (CMOS, CPUs, PLC,...)
    - SEB (MOSFETs, power devices,...)
    - SEGR (power MOSFETS)
    - ...
  - static SOFT SEE (data corruption)
    - SEU (RAM, PLC,...)
    - SEFI
  - transient SEE (spurious signal)
    - combinatorial logic
    - operational amplifiers
- Rate of effects scale with particle flux
- Tolerance of devices expressed in cross-section (cm$^2$) = $N_{\text{SEE}}$/fluence
- Depends on specific ionization power of culprit LET > $\text{LET}_{\text{threshold}}$
- In hadron environment SEE rates proportional to hadron flux $E > 20 \text{ MeV}$ $E_n > 2 \text{ MeV}$
Total Ionizing Dose effects in MOS structures

- Cumulative effect due to charge trapping in oxides
- Effects of TID in MOS devices
  - Parasitic leakage current paths
  - Threshold voltage
  - Mobility degradation

Trapped charge in the SiO$_2$ bulk is always positive

Interface traps can trap both e and h
Basic mechanisms in oxide layers

- **Electron-Hole Pair Generation** in SiO$_2$: $\sim$ 17 eV/pair
- **Pair Recombination**. N.B. “fractional yield” depends on type of radiation and on the electric field (MV/cm) across the oxide (see figure)
- Electron and hole **pair transport**: e$^-$ $\sim$ in picosec, h$^+$ in millisecond
- Hole Trapping
- Interface Trap Formation
- Dependence on bias

![Graph](image-url)
Threshold voltage shift

- Oxide trapping
  - $N_{OT}$: number of trapped charges

- Interface trapping (+ for PMOS, - for NMOS)
  - $N_{IT}$: number of trapped charges

\[
\Delta V_{IT} = -\frac{Q_{IT}}{C_{OX}} = \pm \frac{q \cdot N_{IT}}{C_{OX}} \quad \Delta V_{OT} = -\frac{Q_{OT}}{C_{OX}} = -\frac{q \cdot N_{OT}}{C_{OX}}
\]
Leakage current increase

- Charge trapped in the isolation acts as lateral parasitic transistor
- Transistor is ON when it should be OFF
TID tolerant layout

- TID-induced leakage in NMOS, and between n+ diffusions, has been considered the main limiting factor in the radiation tolerance of CMOS.
To sum up...

- **Cumulative damage**
  - Insulators: wherein electrons and holes produced by ionization are fixed and charged regions are induced; i.e. material does not return to its initial state.
  - In context of silicon devices (wherein there are oxide layers and Si-SiO2 interfaces) also called surface damage.

- **Due to energy deposition in form of ionization:**
  - electrons
  - gamma and X-rays (⇒ electrons via photoelectric, Compton and pair-production)
  - pions, protons, ions

- **Damages all types of semiconductor electronics (CMOS and bipolar)**
  - Threshold Shifts (transistors)
  - Leakage Current
  - Timing Changes
  - Startup Transient Current
  - Functional Failures

- **Effects scale with total dose**

- **Tolerance of devices expressed in TID (Gray or Rad; 1 Gy = 100 rd = 1 J/kg)**

- **Modern CMOS COTS usually can withstand 10-20 krad (good for low -below Van Allen belts - orbits)**

- **Shielding may partially mitigate**
  - Low energy protons
  - Electrons
Silicon Detectors (1)

- Reverse biased P-N junction
- High resistivity silicon (low doping)
- Charged particles crossing the device will produce electron-hole pairs
- The moving electrons and holes will create a signal in the electric circuit.
Silicon Detectors (2)

- If the detector is under-depleted:
  - Charge loss $\rightarrow$ inefficiency
  - Charge spread $\rightarrow$ loss resolution

- Full depletion is important:

![Diagram](image-url)
Radiation Damage in Silicon Detectors

- The two types of radiation damage to detector materials:
  - **TID ("surface damage")** due to ionization energy loss and trapping of charges in oxide layers and interfaces. It affects
    - interstrip capacitance (noise factor), breakdown behavior
  - **DDD ("bulk damage")** due to non-ionizing energy loss and build up of crystal defects. It leads to
    - changes in effective doping concentration (higher depletion voltage)
    - Increase of leakage current (increase of shot noise, thermal runaway!)
    - Increase of charge carrier trapping and hence loss of collected charge.
Charge collection decrease

- Figure of Merit of detectors: Signal-to-Noise Ratio S/N
- High fluence proton irradiation causes so severe bulk damage that S/N degrades too much.
- Irradiation creates defects with energy levels deep inside the band gap. These defects act as trapping centers. Charge carriers are trapped in these levels and released after some time (depending on the depth of the energy level). \( \rightarrow \) charges released with delay are no longer measured within the integration time of the electronics.

What is signal and what is noise?
Leakage current increase

- Defects can act as **recombination-generation centers**: an increase in overall leakage current with fluence is an almost universal effect.
- The leakage current per unit volume grows linearly with equivalent fluence $\Phi_{eq}$.

- The $\alpha$ damage parameter is constant over several orders of equivalent fluence and independent of impurity concentrations in Si.
Change of effective doping concentration

- The irradiation produces mainly acceptor like defects and removes donor type defects. In a n type silicon the effective doping concentration $N_{eff}$ decreases and after a point called type inversion (n type Si becomes p type Si) increases again.

$$V_{depletion} = \frac{eN_{eff}d^2}{2\varepsilon_0\varepsilon_{Si}}$$

- The voltage needed to fully deplete the detector $V_{FD}$ is directly related to the effective doping concentration:

- The depletion voltage and consequently the minimum operation voltage decreases, and after the inversion point increases again.
**Type inversion and depletion voltage**

**Before type inversion:**

- For a non-irradiated diode and before type inversion, the depletion region grows from the p-n junction side; i.e. from the p+ implant for p-intrinsic-n detectors.

**After type inversion:**

- With Type-Inversion, the n-type bulk starts to behave like p-type bulk and the depletion grows from the backside of the diode.

- If the detector is under-depleted:
  - Charge spread
  - Charge loss
HL-LHC requirements

<table>
<thead>
<tr>
<th>Parameter or Feature</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>layout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel</td>
<td>layers 4 (option 5)</td>
<td>4</td>
</tr>
<tr>
<td>length</td>
<td>91 cm - 140 cm</td>
<td>55 cm</td>
</tr>
<tr>
<td>radii (mm)</td>
<td>38, 78, 155, 250</td>
<td>30, 68, 109, 160</td>
</tr>
<tr>
<td>Endcap</td>
<td>Disks 2 × 6 (option 2 × 5)</td>
<td>2 × 3 (option 2 × 5)</td>
</tr>
<tr>
<td>radial range</td>
<td>150–315 mm</td>
<td>45–161 mm</td>
</tr>
<tr>
<td>Z range</td>
<td>877–1675 mm</td>
<td>391–516 mm</td>
</tr>
<tr>
<td>Pseudorapidity coverage</td>
<td>2.7</td>
<td>2.5 (option higher)</td>
</tr>
<tr>
<td>Active area</td>
<td>8–12 m²</td>
<td>3–4 m²</td>
</tr>
<tr>
<td>ASIC size</td>
<td>≈ 4 cm²</td>
<td></td>
</tr>
<tr>
<td>Number of readout chips</td>
<td>15k–25k</td>
<td></td>
</tr>
<tr>
<td>Module size</td>
<td>inner barrel 1 × 2 chips</td>
<td></td>
</tr>
<tr>
<td></td>
<td>other barrel 2 × 2 chips</td>
<td></td>
</tr>
<tr>
<td></td>
<td>disks 2 × 2 chips (3 × 2)</td>
<td></td>
</tr>
<tr>
<td>Hit rates and radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interactions /25 ns</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Particle flux inner barrel</td>
<td>&lt;</td>
<td></td>
</tr>
</tbody>
</table>

**Parameter or Feature**

<table>
<thead>
<tr>
<th>Parameter or Feature</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pixel hit rate inner barrel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>≈ 1 GHz/cm² (30 KHz/pixel 25 × 150 μm²)</td>
<td>≈ 2 GHz/cm² (50 KHz/pixel 25×100 μm²)</td>
</tr>
</tbody>
</table>

**10yr, 3 ab⁻¹ TID**

1 MeV n. eq.

- 10 MGy
- 2×10¹⁶

**SEU tolerance**

- Re-configure <1 module/yr/hr
- <0.1% hit data loss

**Sensor**

<table>
<thead>
<tr>
<th>Signal</th>
<th>Polarity</th>
<th>MIP charge</th>
<th>Max. charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>negative</td>
<td>10 Ke⁻</td>
<td>TBD</td>
</tr>
<tr>
<td></td>
<td>negative (TBC)</td>
<td>5-10 Ke⁻</td>
<td>linear up to 2 (4) MIP</td>
</tr>
</tbody>
</table>

**Pixel max. capacitance**

- 200 fF (<400 fF)
- 200 fF TBC

**Pixel max. leakage current**

- 20 nA (<100 nA)
- 20 nA TBC

**Readout Chip**

<table>
<thead>
<tr>
<th>Hit loss at max rate</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

**Threshold**

<table>
<thead>
<tr>
<th>dispersion (tuned)</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;100 e⁻</td>
<td>&lt;200 e⁻ (100 e⁻)</td>
</tr>
</tbody>
</table>

**variation w/time**

<table>
<thead>
<tr>
<th>Min. thr. noise occupancy</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 10⁻⁶</td>
<td>&lt; 10⁻⁶</td>
</tr>
</tbody>
</table>
To sum up

- Cumulative bulk damage; e.g. a less ordered lattice produces long term effects on semiconductor properties
- Due to energy deposition in non-ionizing interactions:
  - neutrons
  - protons, ions (especially slow ones near end of range)
  - energetic electrons
- Sensitive devices (NOTE: CMOS, not bulk sensitive, is practically unaffected)
  - silicon detectors
  - laser diodes, LED, opto-couplers
  - solar cells
  - CCDs
  - linear bipolar devices
- effects scale with particle fluence
- tolerance of devices expressed in fluence of 1-MeV neutron equivalents; risk begins at fluence $\Phi \sim 10^{11-12}$ 1-MeV neutrons/cm$^2$