Serena Mattiazzo

Dipartimento di Fisica e Astronomia

Università di Padova

and INFN Padova

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 ubiquituos

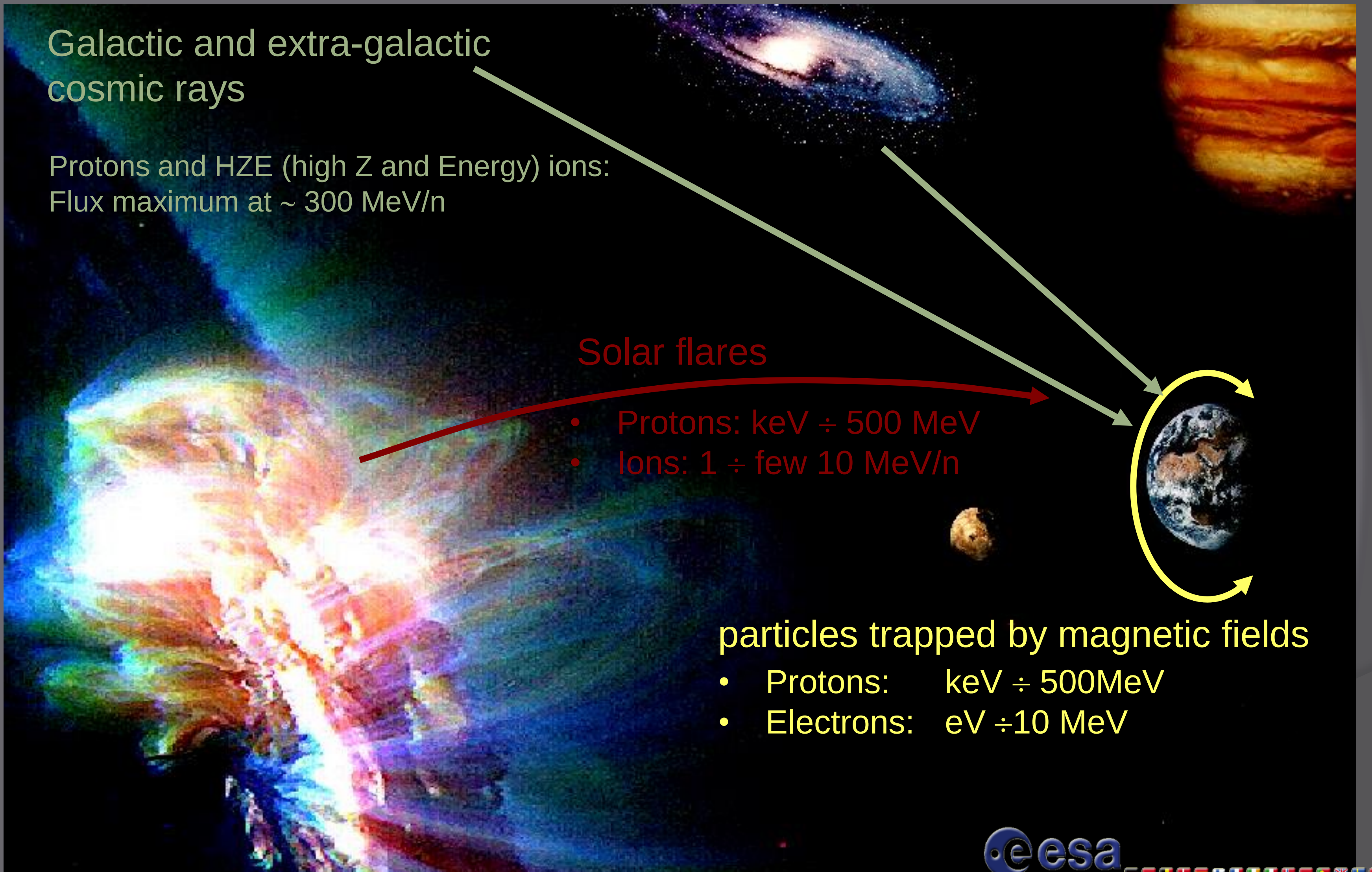
Natural human environment	**Extended natural environment**	**Artificial environment**
• Natural radioactivity of material • Sea level cosmics	• High altitude avionic • Satellites (various orbits) • Space station • Deep space missions	• Nuclear reactors • HEP experiments (collider halls), synchrotron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

Radiation can be a tool, but also an hazard!

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

The space radiation environment

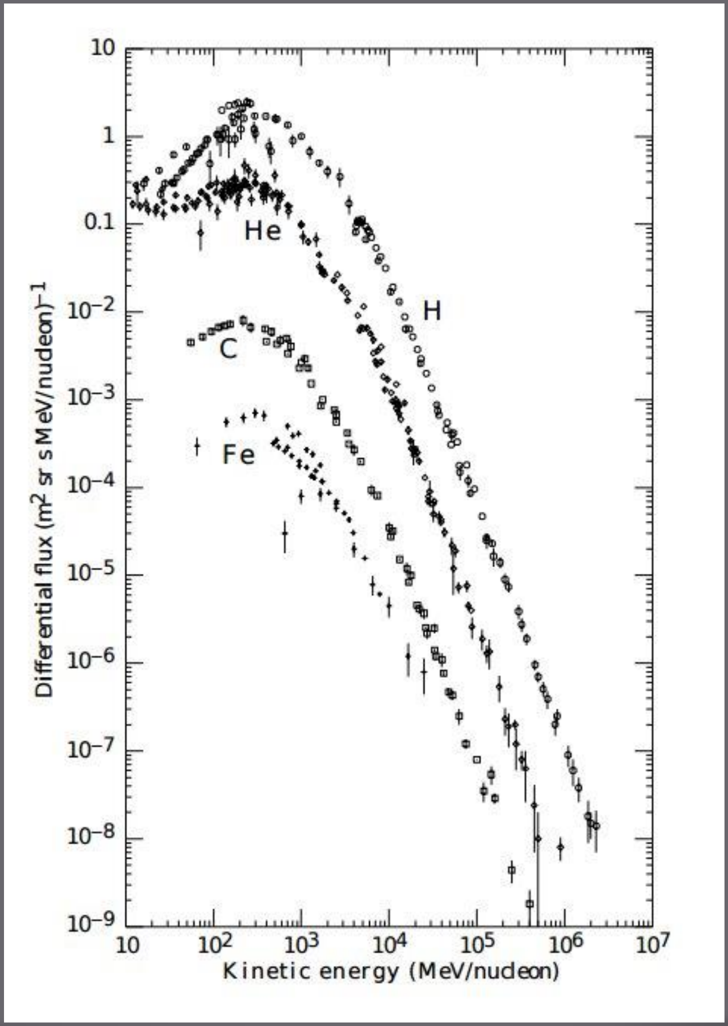


Galactic cosmic rays (1)

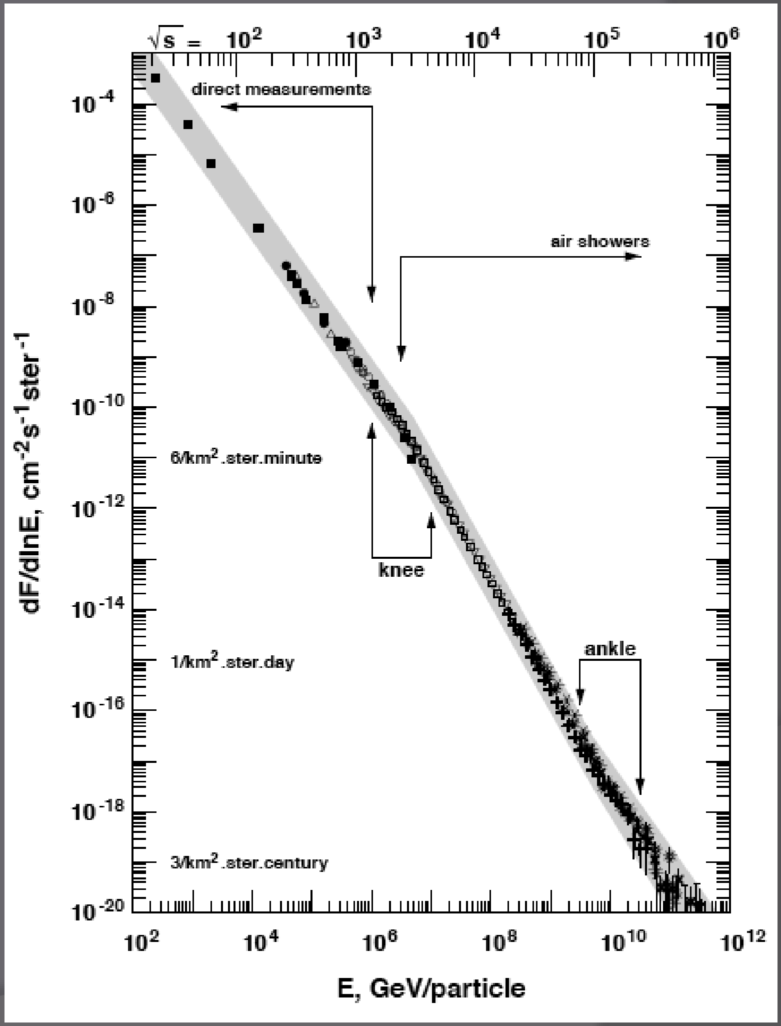
- Diffuse galactic background
  - Composition: ~85% protons, ~14% α, ~1% heavy nuclei
  - likely formed by explosive events such as supernova
  - Most up to 10GeV/amu. Rarely up to 10^{20} eV (10^{11} GeV)
  - They are fully ionized and hence interact with and are influenced by magnetic fields
    -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

Galactic cosmic rays (2)

GCR components



Energy spectrum



Solar particle events (1)

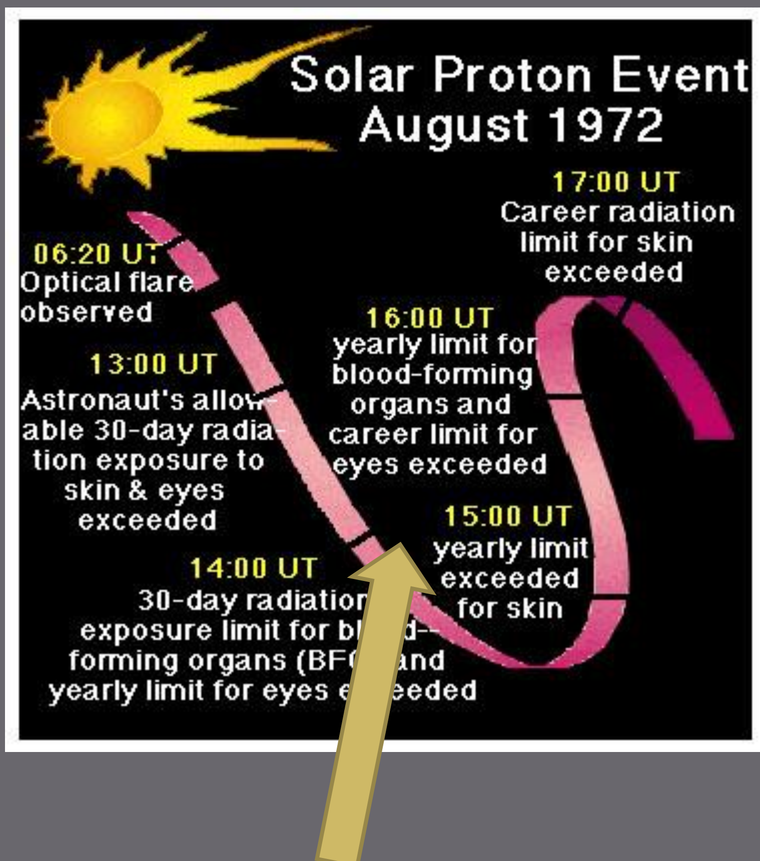
- Solar activity: 11-year cycle
  - 7 years of high activity (solar maximum)
  - 4 years of low activity (solar minimum)

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

- Composition: mostly protons, α, heavy nuclei

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

Solar particle events (2)

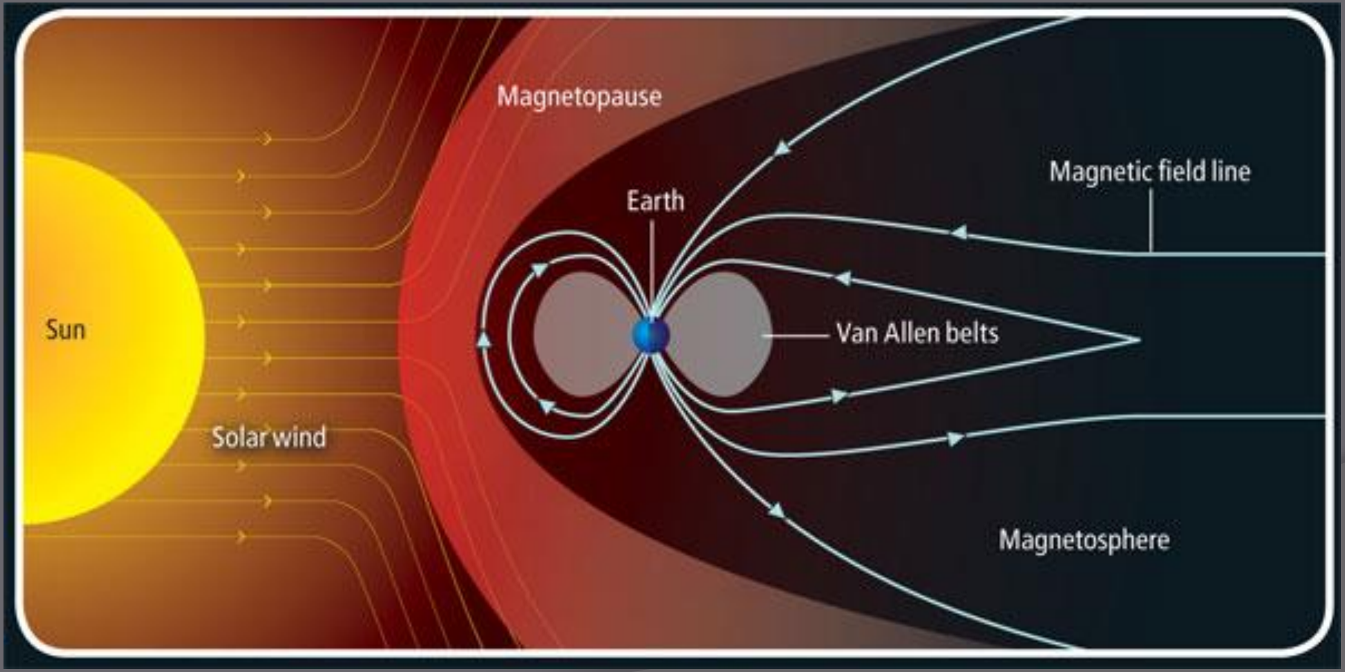


4000 mSv is an average fatal single dose

- 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.

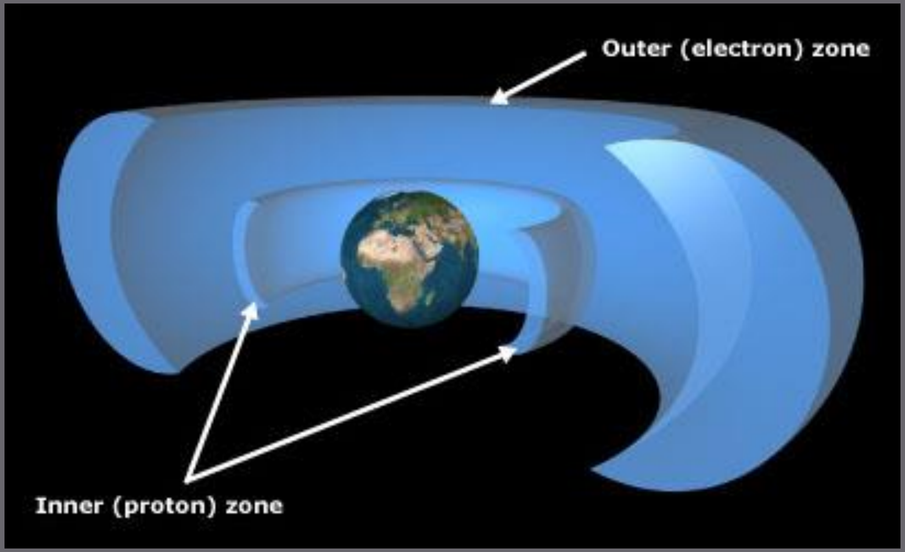
Solar wind and magnetic field

- 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 (1000-6000km): mainly protons (> 10 MeV)
  - Outer (13000-60000km): electrons (0.1 – 10 MeV)



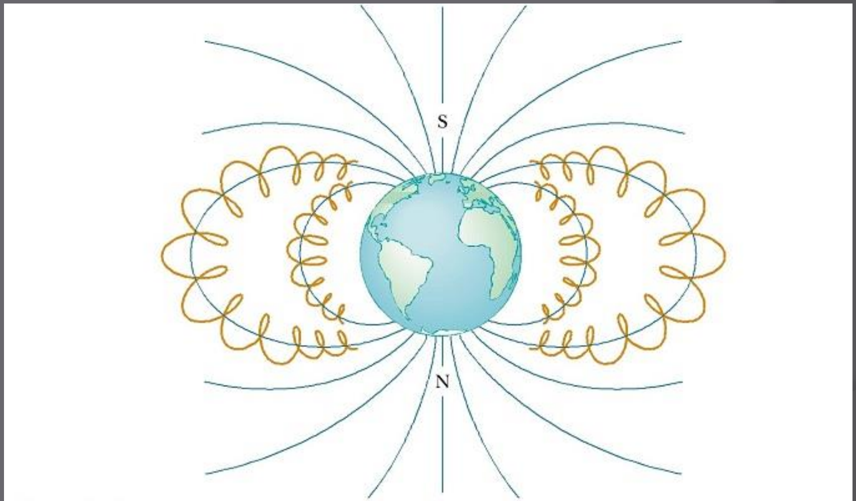
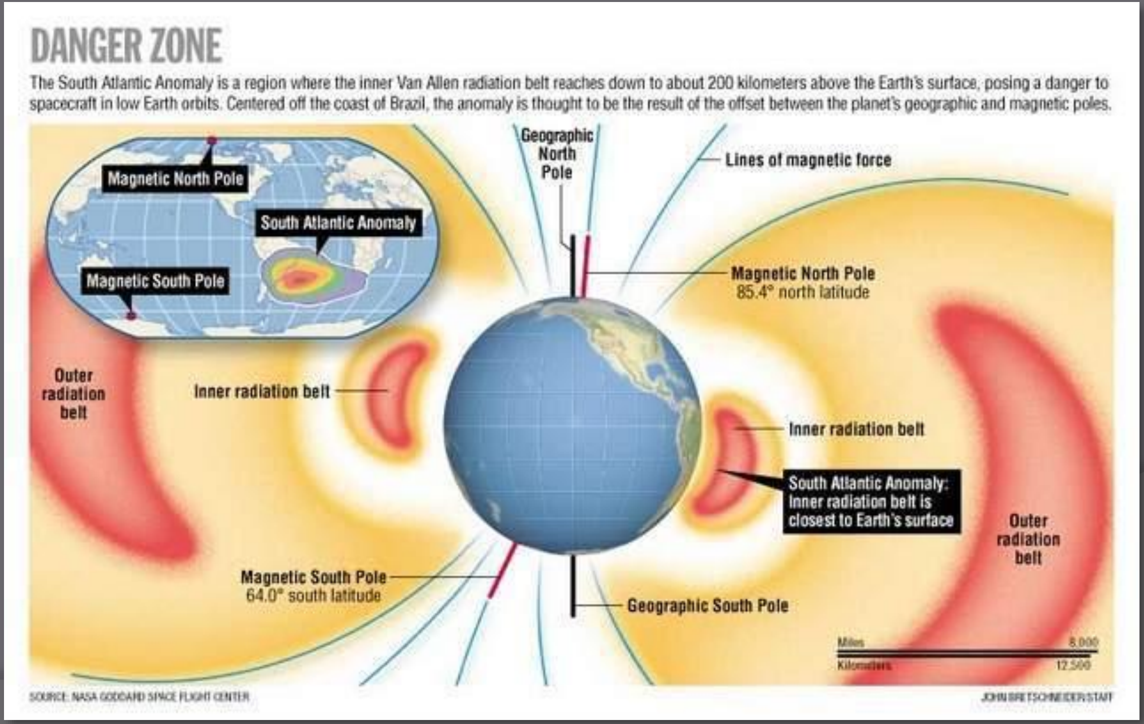


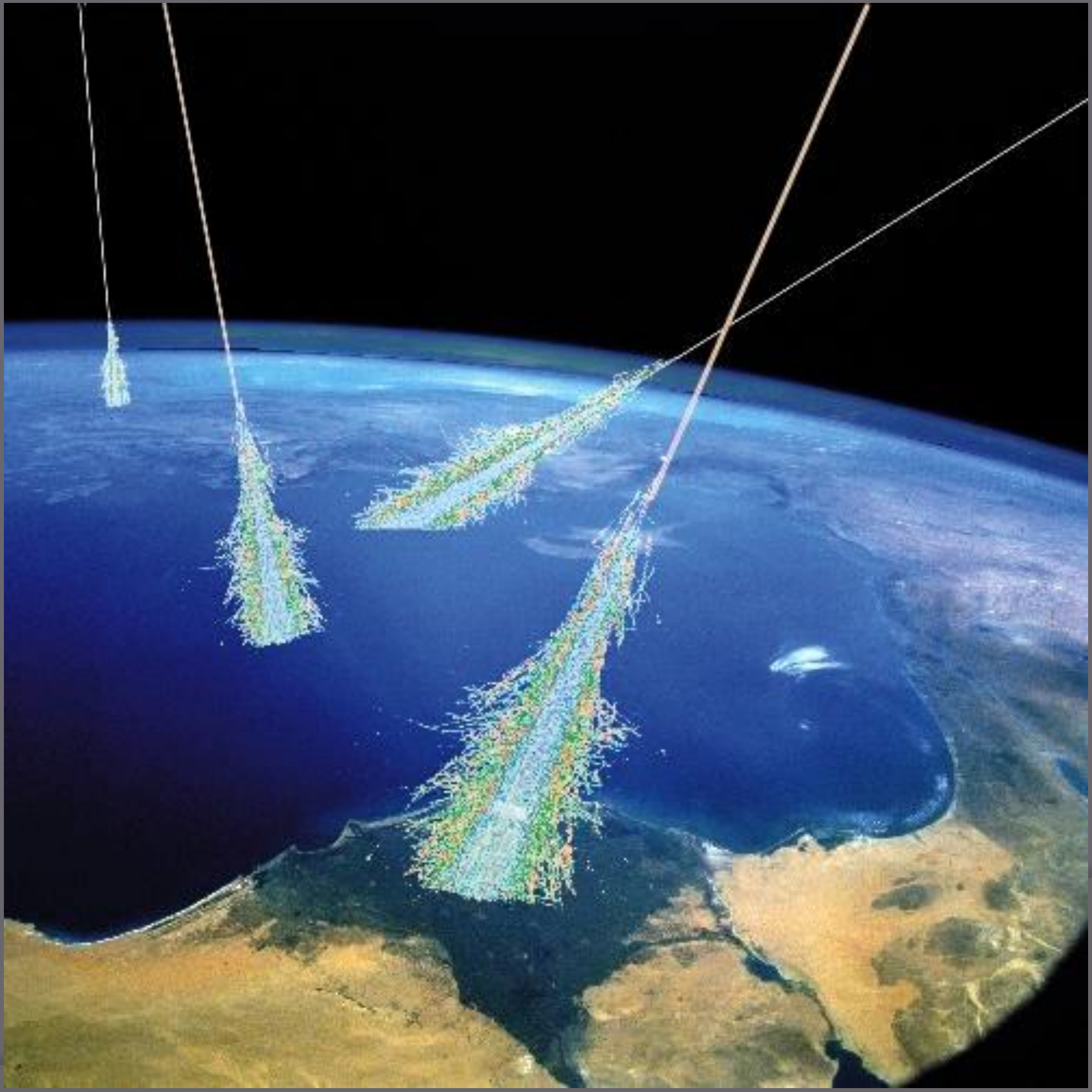
Figure 29.21 The Van Allen belts are made up of charged particles trapped by the Earth's nonuniform magnetic field. The magnetic field lines are in blue and the particle paths in red.

South Atlantic Anomaly

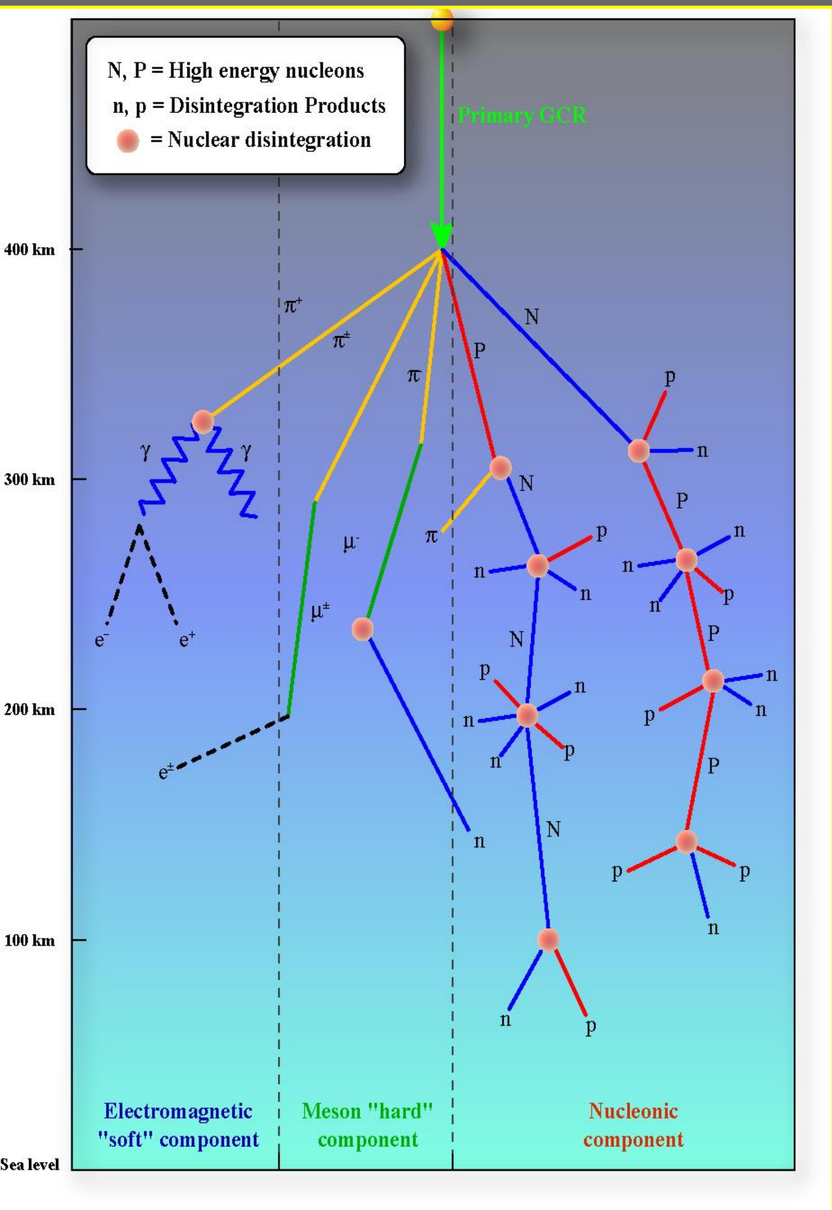
- Magnetic and rotation axis do not coincide
- Above South America, the Inner Van Allen Belt extends only to about 200 - 300 kilometers (off the coast of Brazil and extending over much of South America)
- This is what is called the South Atlantic Anomaly
- Satellite failures are much more common in this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



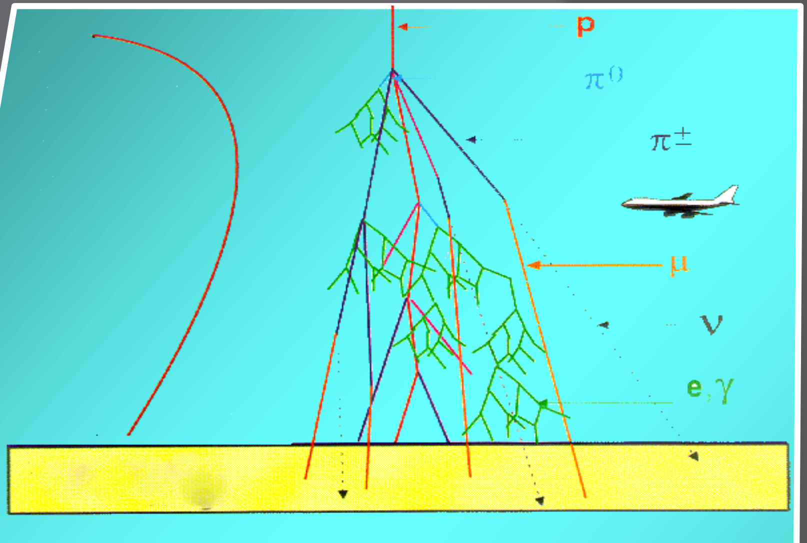
Air showers (1)



Air showers (2)



Shower maximum at ~18 km



- Under 20 km altitude neutrons dominate as cause of radiation-induced failures in avionic systems.
- In mountains and <u>at sea level</u> there are enough of them to be a real concern for ground-based electronics that play vital roles (e.g. in computers, pace makers, cars, power devices in locomotives,…)

Ground level

Aviation

Automotive

Trains

Infrastructure

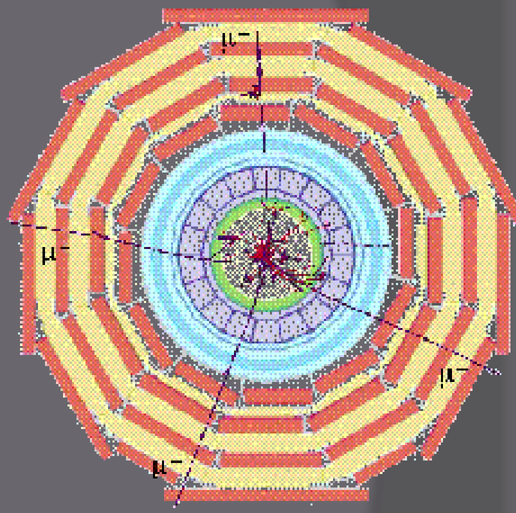
"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."
Paul Dodd, Sandia National Laboratories

Medical

Accelerator environment

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

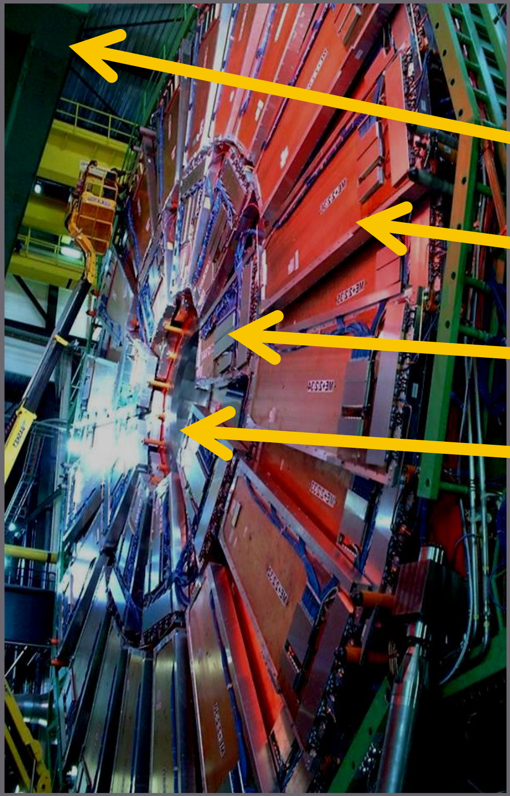
- Cumulative effects (due to long duration of exposure)
  - bulk damage to Silicon-detectors:
  - surface damage to electronics (degrade of S/N,…)
  - Light loss in scintillators/fibers
  - activation of detectors and materials (problems for maintenance)
  - damage to materials (insulators)

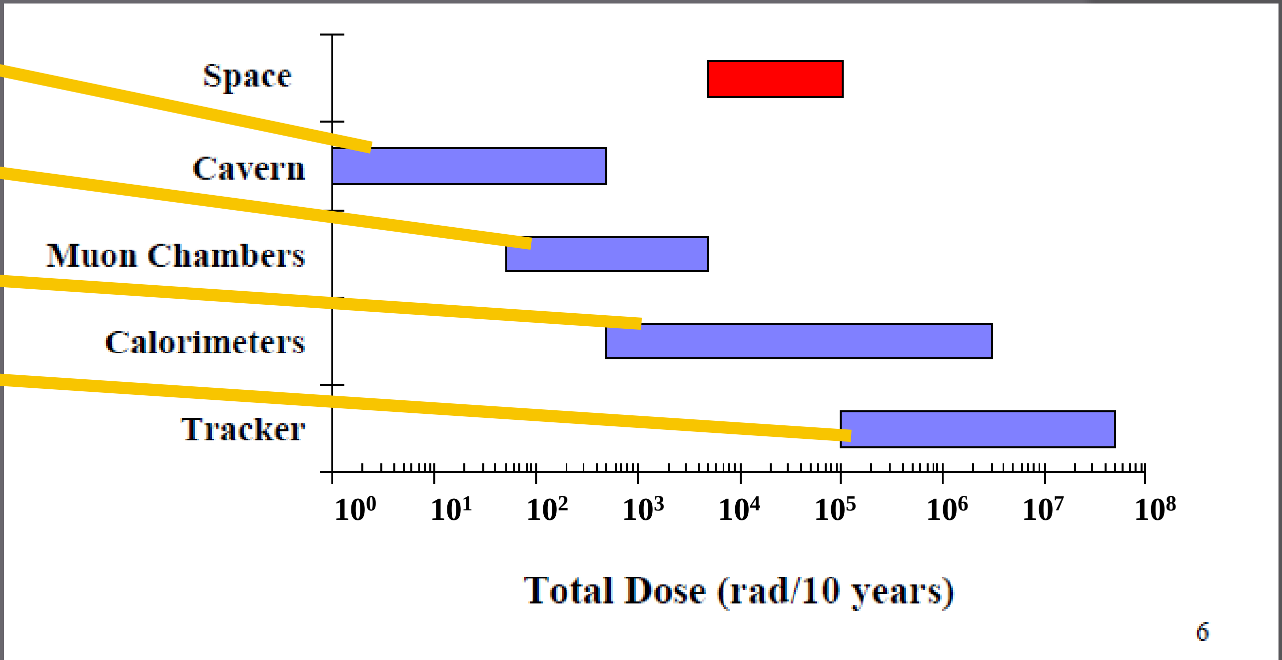


After 10 years of operation will have produced just a few thousand of rare hard events at *the very high price of producing about 10^{16} busy "events".*

VERY RADIATION HOSTILE ENVIRONMNENT!

Total Dose in space and LHC environments





J. Gasiot
CERN Training Radiation effects on electronic components and systems for LHC

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).

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

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)
  - ν collision frequency

$$L = \frac{N_1 N_2}{A} \times \nu$$

  - R: particle production rate
  - σ_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** (ϕ) is the number of particles per unit of area and per unit of time

formula

$$\phi = \text{particles}/(\text{Area} \times \text{Time})$$

Measurement Unit

particles/(cm^2 $\times$ s)

- **Fluence** (Φ) is the number of particles per unit of area (time integral of the flux)

formula

$$\Phi = \int \phi \cdot dt = \text{particles}/\text{Area}$$

Measurement Unit

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

Glossary

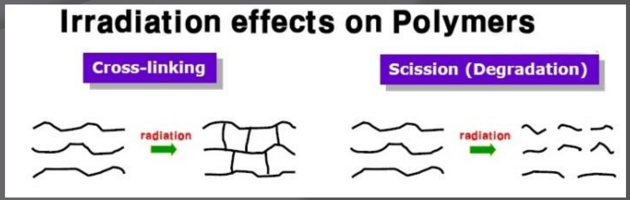
Parameter	Radioactivity	Absorbed Dose
Definition	**Rate of radiation emission (transformation or disintegration)**	**Energy delivered by radiation per unit of mass of irradiated material**
Common Unit Symbol	**Curie (Ci)** 1 Ci = 37 GBq (a large amount)	**Rad** 1 rad = 100erg/g 1 rad = 0.01 Gy
International Units (SI) symbol	**Bequerel (Bq)** 1 Bq = 1 event of disintegration per second (a very small amount)	**Gray** (Gy) 1 Gy = 1J/kg 1 Gy = 100 rad

Typical Ionizing Radiation Doses

Skip

- **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

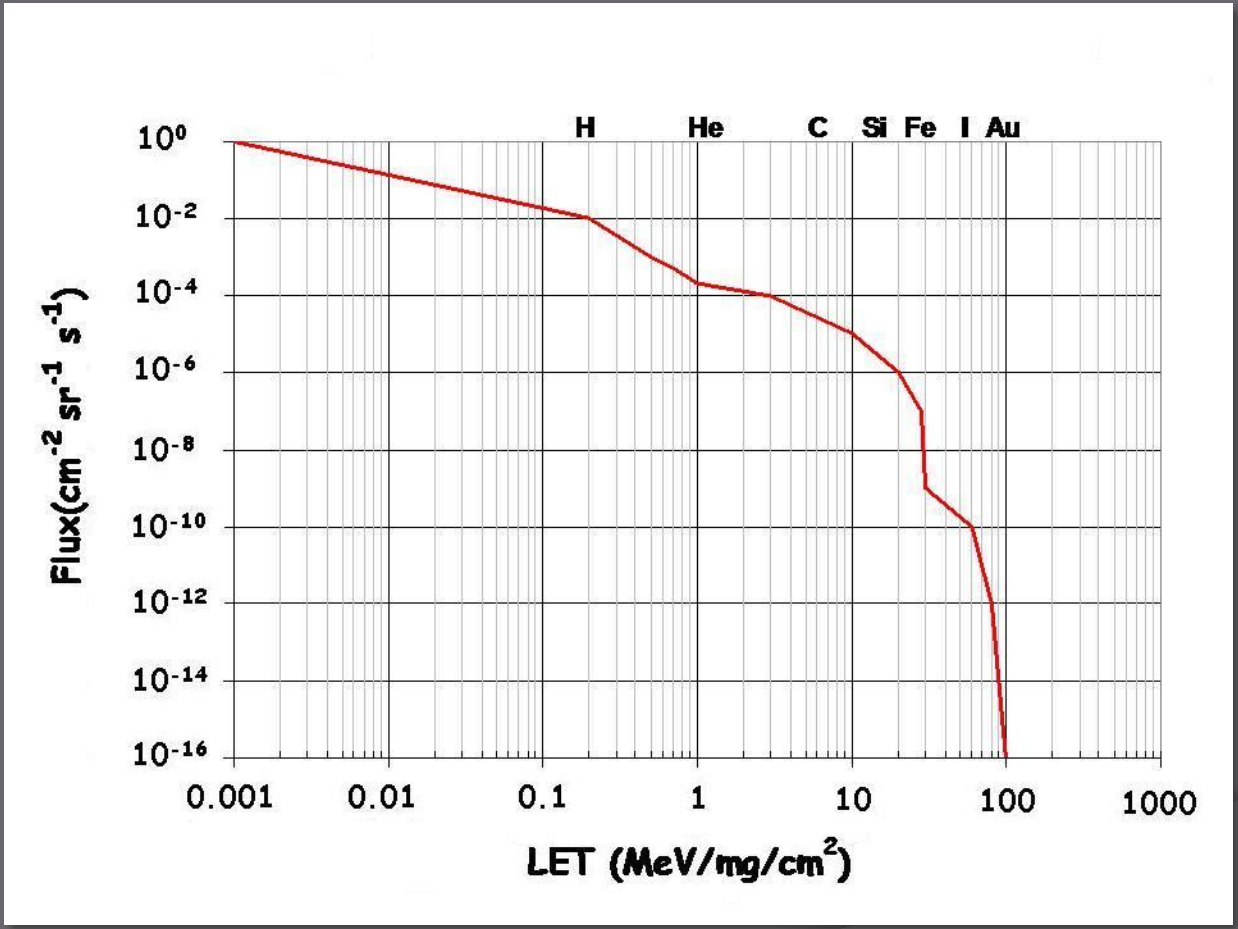


Flux representation (1)

- 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})

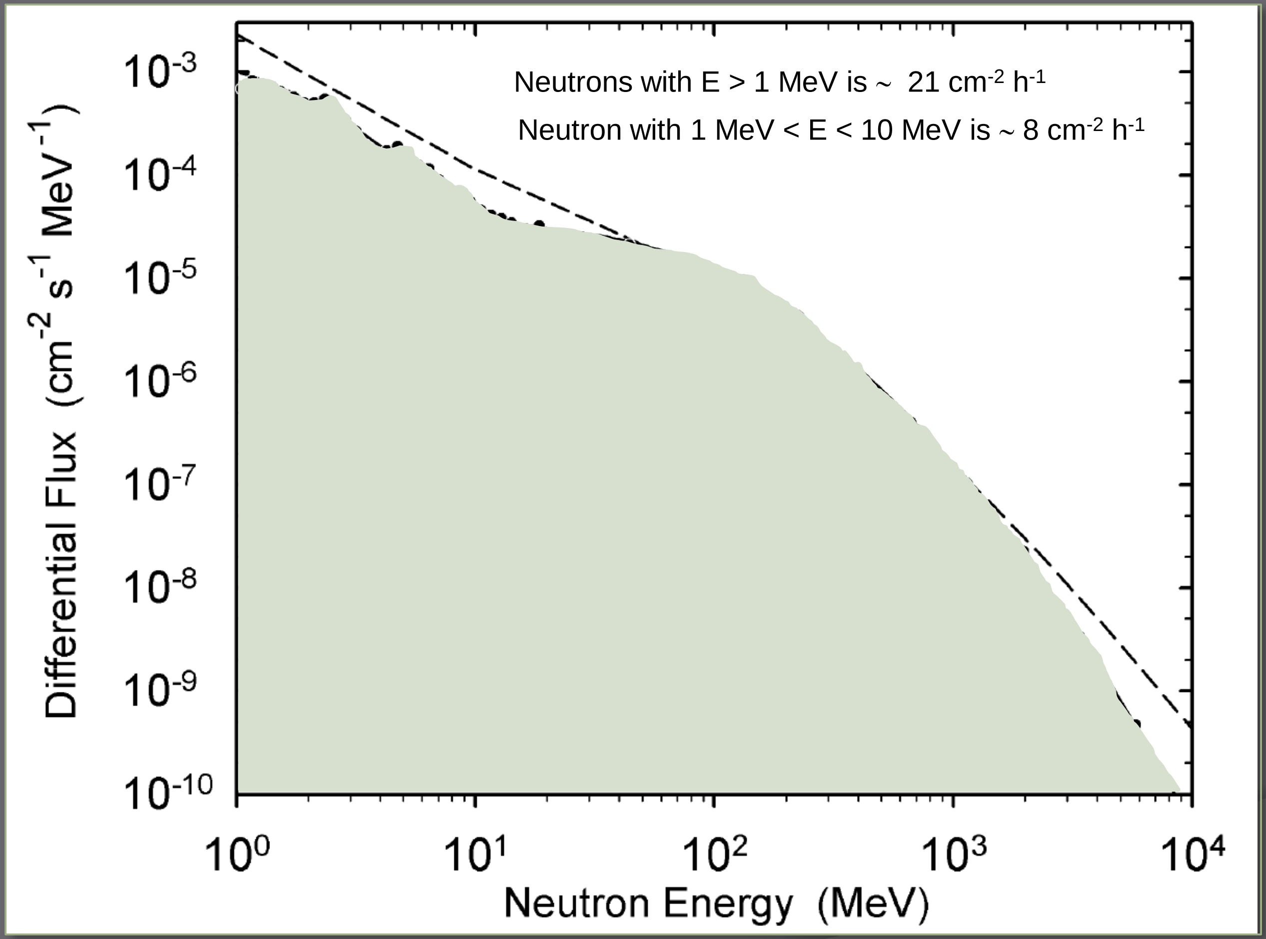
Flux representation (2)

- Directional integral flux of ions with LET> LET_0 in space



Flux representation (3)

- Differential Energy spectra of air shower neutrons at sea level



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

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 γ-rays, particles (α, $\beta^{+/-}$, 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 (energy/mass) = **proportionality factor** (energy×length²/mass) × **fluence** (length⁻²)

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

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

- 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) × fluence (length^{-2}) × mass
  - energy to displacements = NIEL(energy-length^2/mass) × fluence (length^{-2}) × mass

Stopping power

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

- **STOPPING POWER** S = dE/dx (keV/μm): 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 $S_{ele} = (dE/dx)_{ele}$
    - With atomic nuclei $S_{nuc} = (dE/dx)_{nuc}$
- **MASS STOPPING POWER**
  - $(1/\rho)S$ = LET + $NIEL_{coulomb}$ [$MeV\text{-}cm^2/mg$]

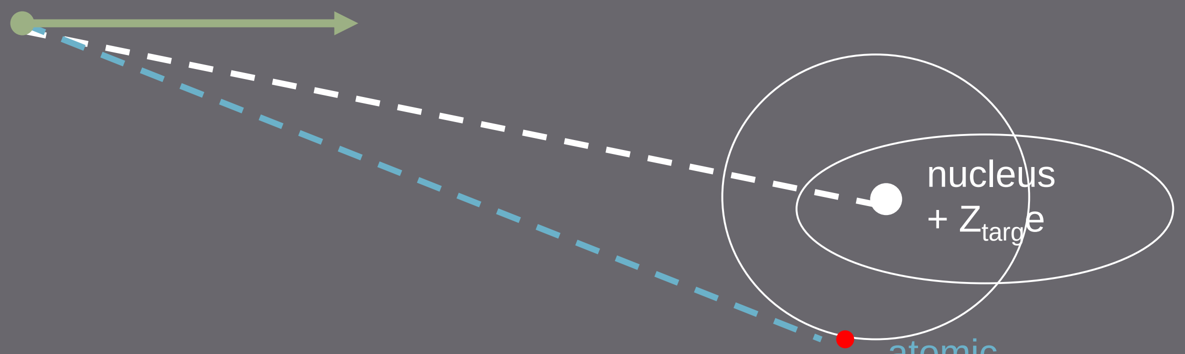
density

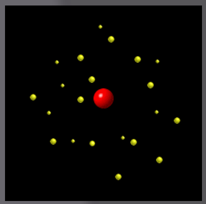
Warning! Electrons also radiate photons!

(*) Note: rare nuclear (non-coulomb) interactions are not considered.

Charged particle travelling through a medium

- Coulomb interaction with atomic electrons or with the nucleus:





Ratio of effective areas (cross-sections) gives relative probability of interactions to occur.

the radius of nucleus $R_{nucleus} \sim 10^{-14}$ m

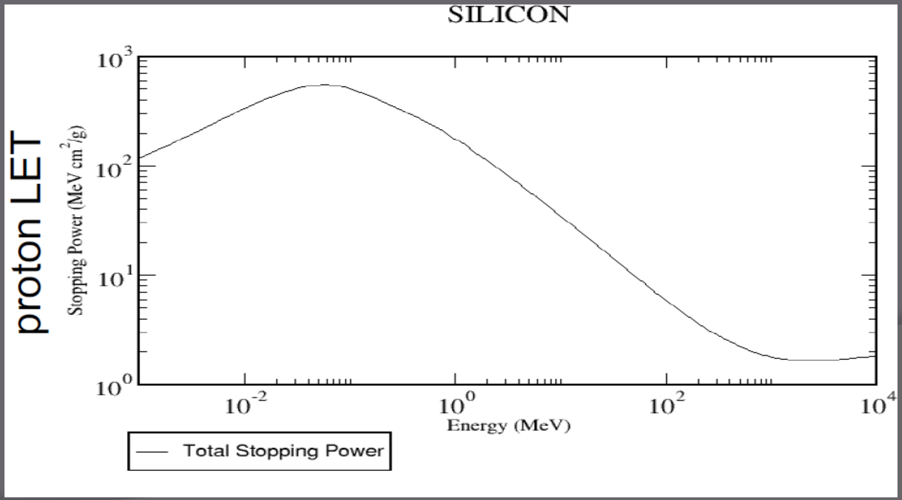
the radius of atom $R_{atom} \sim 10^{-10}$ m

$$\frac{\text{number of interactions with electrons}}{\text{number of interactions with nuclei}} = \frac{R_{atom}^2}{R_{nucleus}^2} \sim 10^8$$

Conclusion: regards energy transfers, **coulomb collisions with electrons are much more important than with nuclei** **<u>(except when very SLOW at end of range!)</u>**

Linear Energy Transfer (LET)

- 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!!!

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

thickness of medium
for which kinetic energy of
incident particle is spent
WELL DEFINED

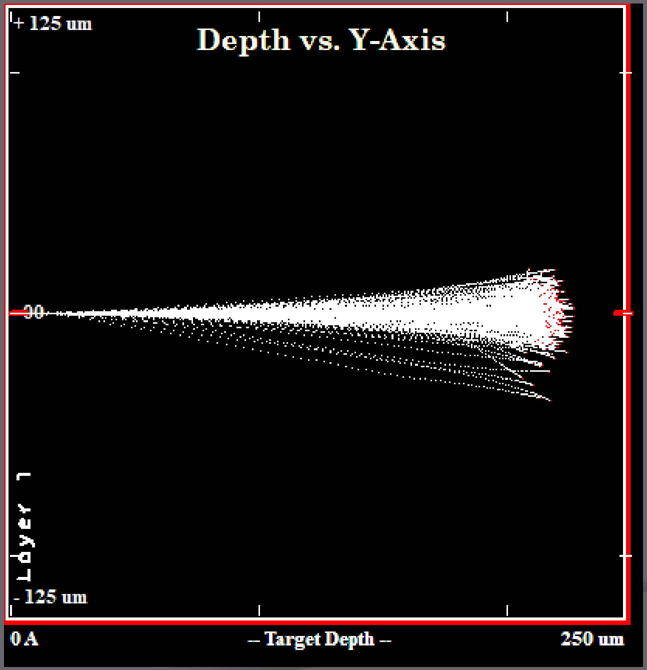
TOTAL stopping power dE/dx

$dE/dx = dE/dxi_{onization} + dE/dx_{nuclear\ coulomb}$

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)

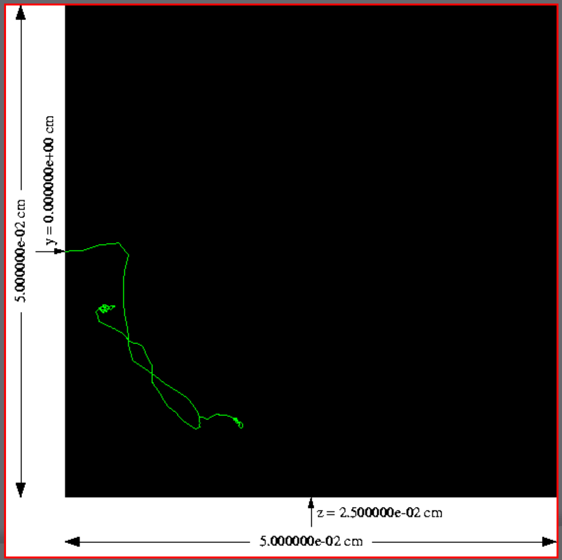
- Even in the case of a perfectly collimated monoenergetic beam of particles, the stopping process will introduce a finite divergence in the propagating beam. This is what is called the **lateral straggling** of the beam.
- At the same rate, there is a stochastic indetermination on the penetration depth 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



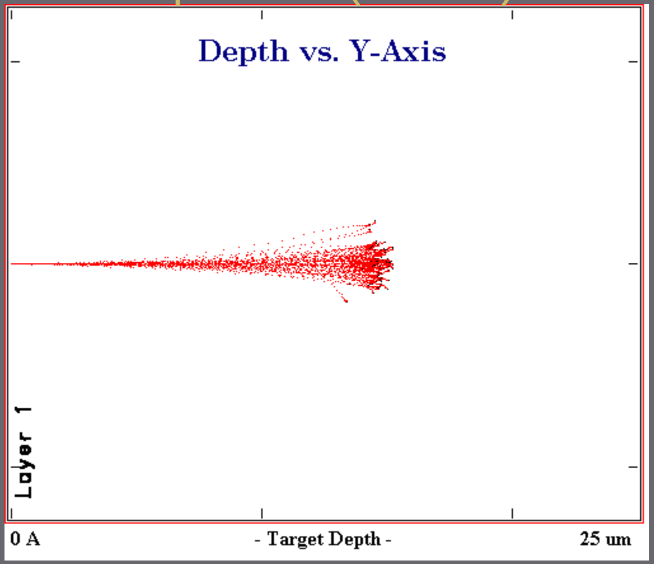
path very zig-zag!

0.5 mm
by
0.5 mm

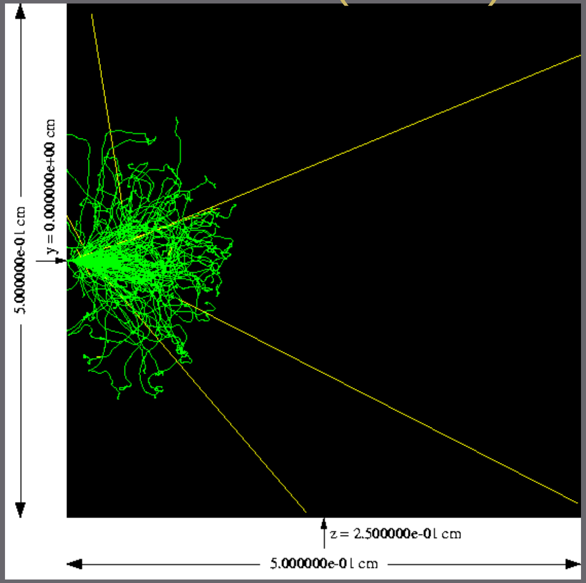
http://www.slac.stanford.edu/~rfc/egs/basicsimtool.html

Range

100 protons (1 MeV) in Al



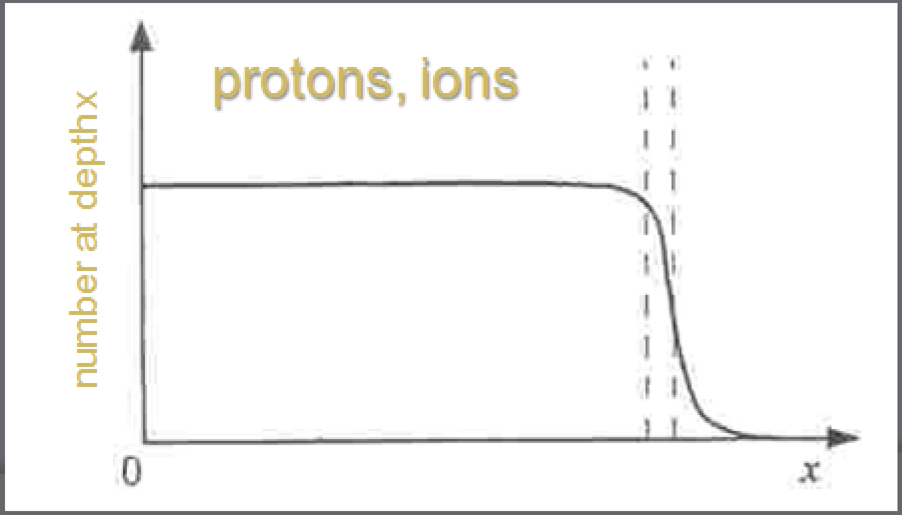
100 electrons (1 MeV) in Al

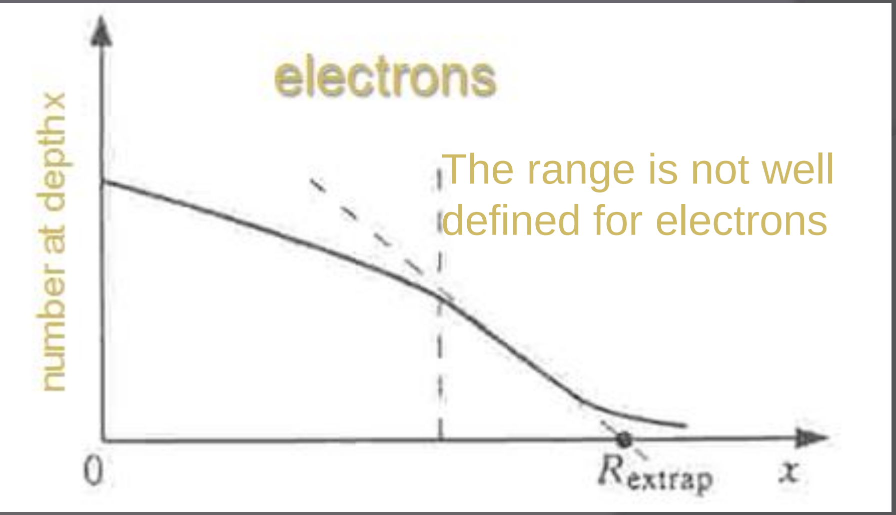


electrons in green

photons in yellow

5 mm by 5 mm





Bremsstrahlung

- An accelerated charge will radiate

$$\text{Intensity} \propto a^2 \sim \left\{ \frac{Z_{proj} Z_{targ} e^2}{M_{proj}} \right\}^2 \sim \frac{Z_{proj}^{\;2} Z_{targ}^{\;2}}{M_{proj}^{\;2}}$$

- 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.

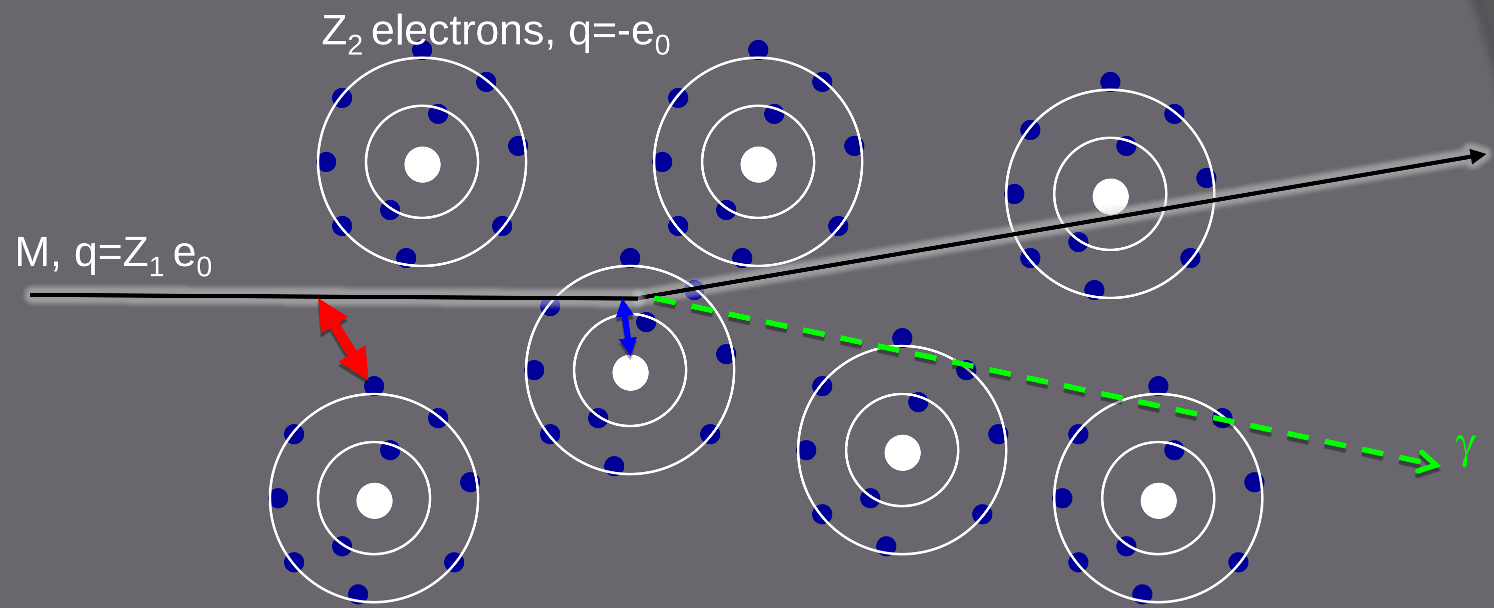
- Although the primary particle might ultimately be absorbed, the bremsstrahlung radiation can be highly penetrating.

- The most common source of bremsstrahlung is electron scattering.

Summary slide

Skip

- Electromagnetic (Coulomb) interaction of Particles with matter



- Heavy charged particle: many interactions with the atomic electrons. The incoming "continuously" particle looses 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 o 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

$$\left(\frac{dE}{dx}\right)_{ele} = \left(\frac{Z_{eff}^2}{V^2}\right)_{particle} \times \left(\frac{z\rho}{A}\right)_{material} \times \left\{ln\left(\frac{2m_e c^2 \beta^2}{I}\right) - ln(1-\beta^2) - \beta^2 - \delta\right\}$$

I = mean excitation potential of target material; for Silicon I ~ 170 eV

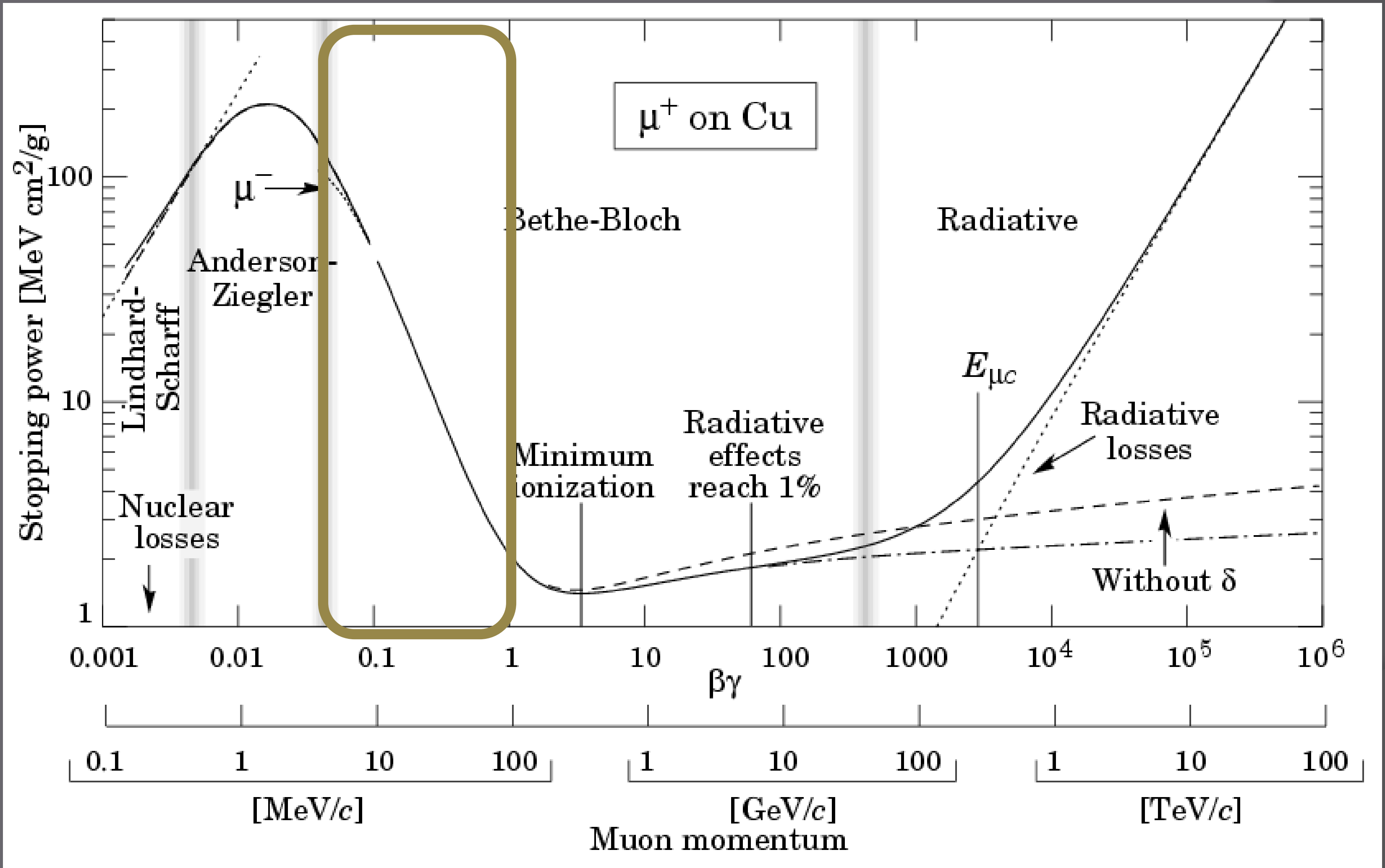
- for velocity of ion $V >> v_{Bethe} = v_0 Z^{2/3}$ where $v_0 = c/137 = v_{Bohr}$
  - ion completely stripped of electrons, full nuclear charge, $Z_{eff} \sim Z$
- for velocity of ion $V \approx v_{Bethe}$ and slower
  - ion retains/picks-up electrons and charge decreases(!) as ion slows

$Z_{eff}(V) = \eta(V) \times Z$	good to a few percent
$\eta(V) = 1 - A \exp(-B\ V/v_{Bethe})$	A =1
	B = 0.95

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

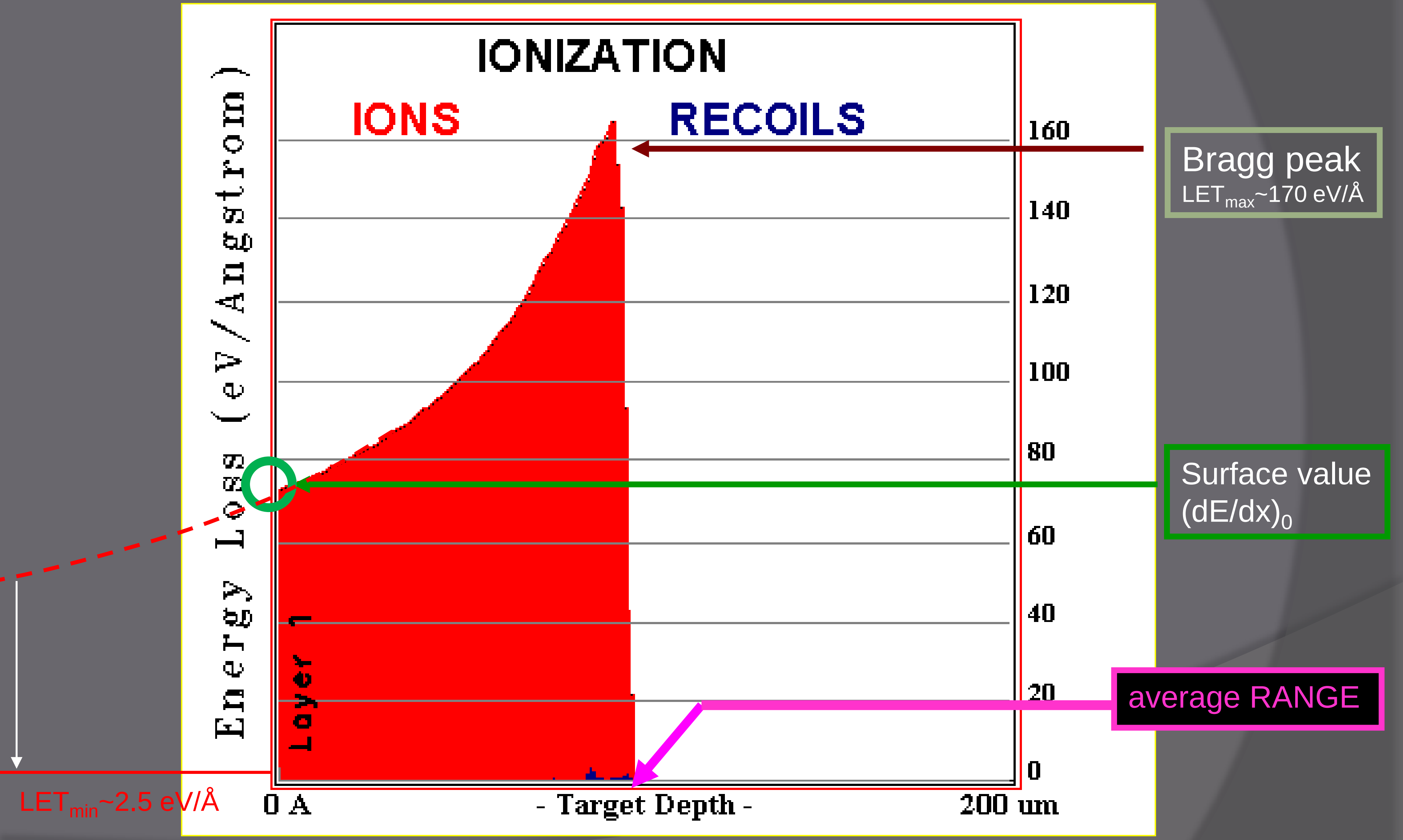
$$LET = \frac{\left(dE/dx\right)_{ele}}{\rho} \approx \frac{Z^2}{\beta^2} \times f(V)$$

Silicon: $\rho = 2.33 g/cm^3$



μ+ on Cu
μ−
Bethe-Bloch
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
Stopping power [MeV cm2/g]
1
10
100
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

LET vs depth of material

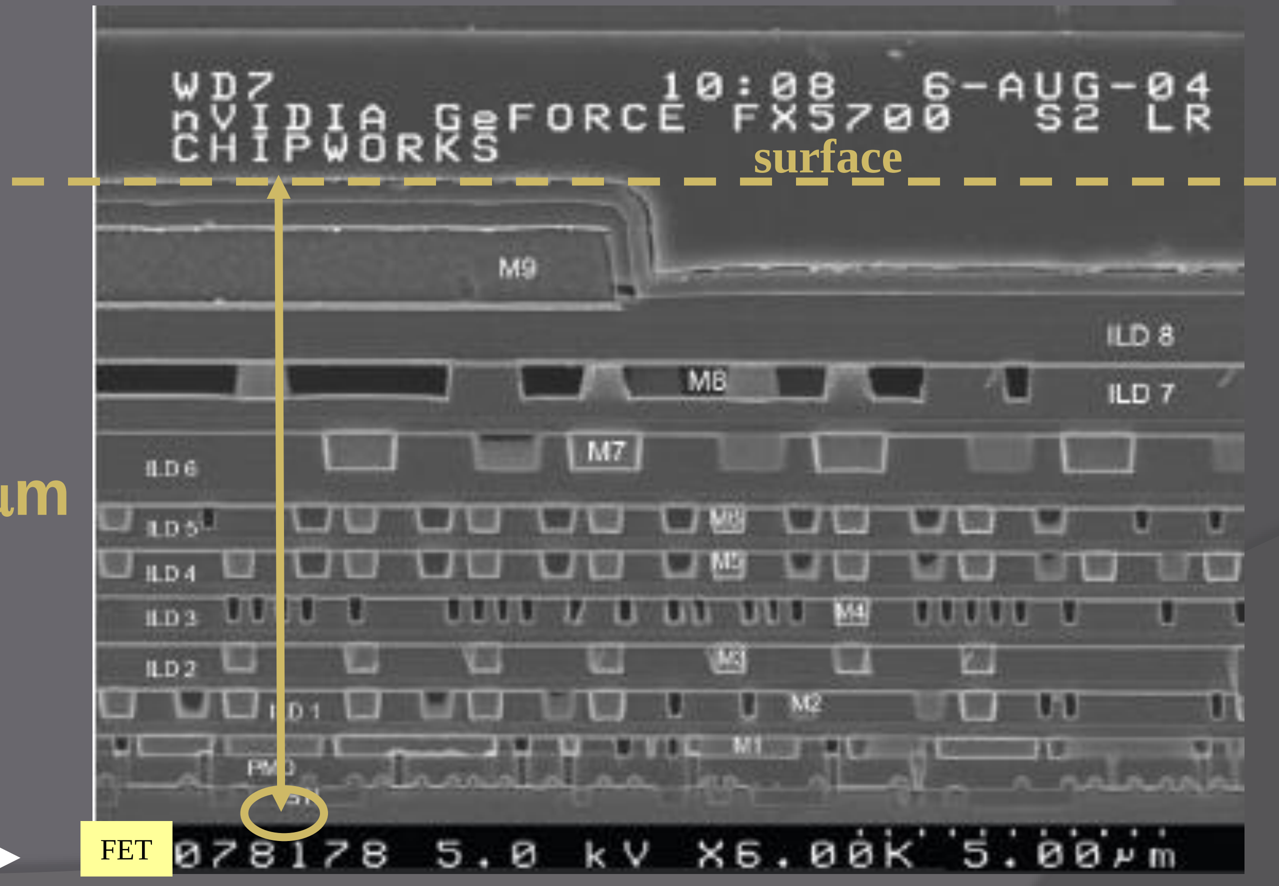


100MeV ^{18}O ions in Silicon

The importance of range

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

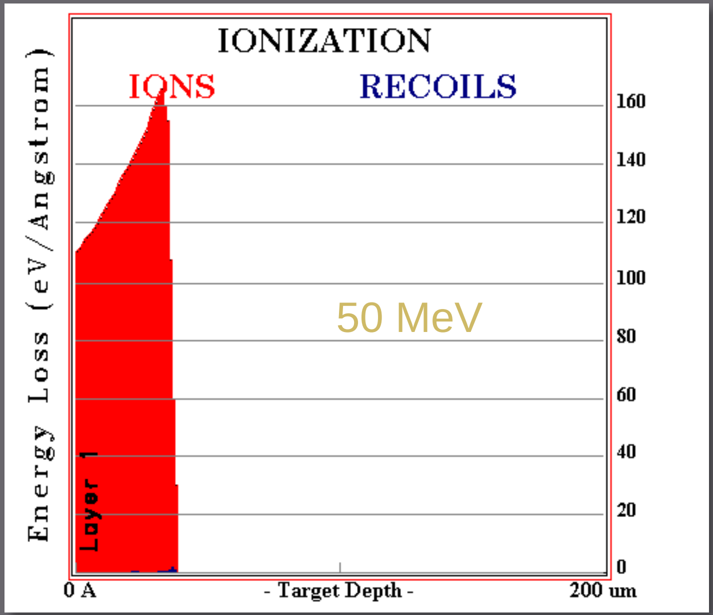
16 μm

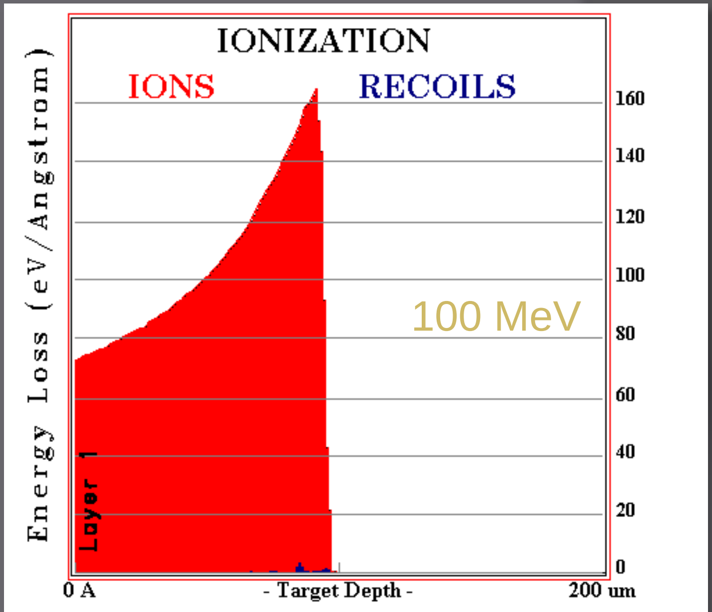


Sensitive volume is down here!

Range

O^{16}

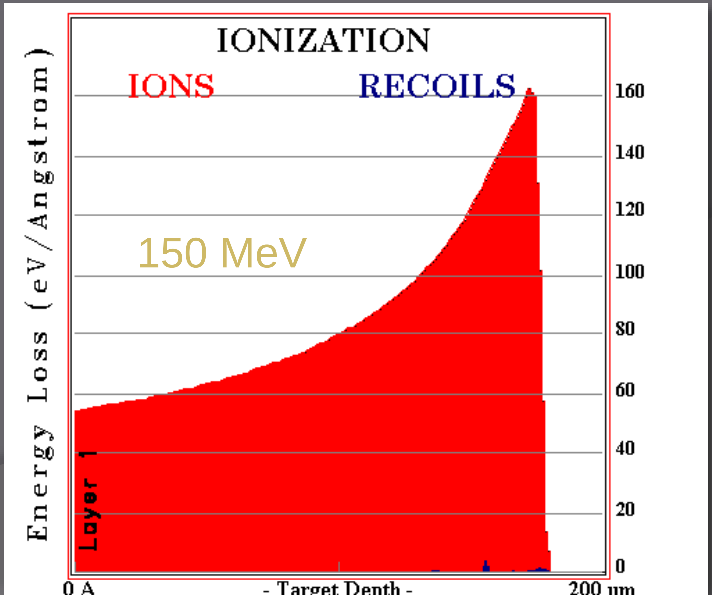




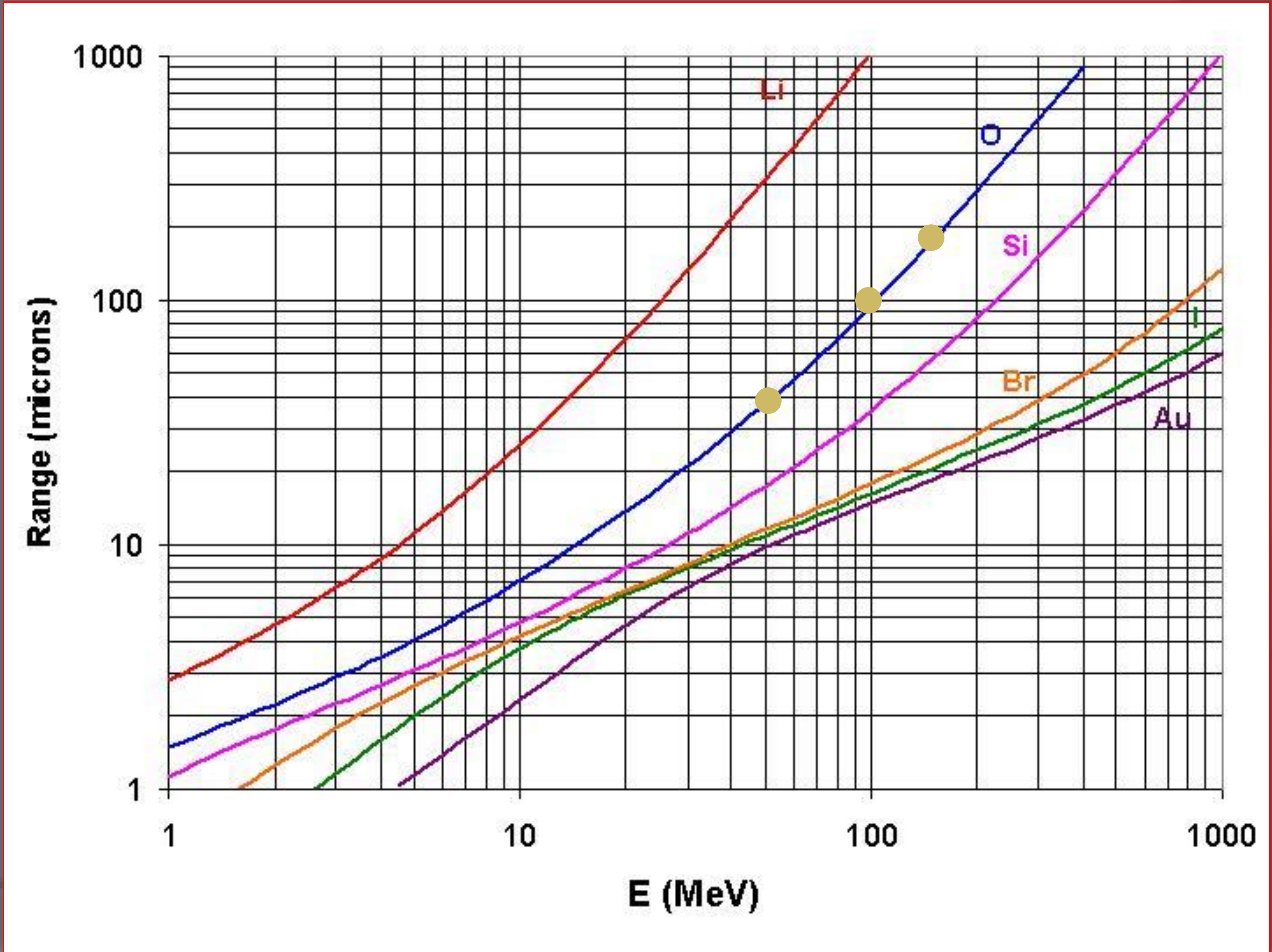
surface value of $(dEdx)_{ele}$ in silicon

energy (MeV)	range (microns)	LET_0 (eV/Å)	LET_0 (MeV-cm²/mg)
50	37.65	108.16	4.66
100	95.23	72.12	3.107
150	176.23	53.97	2.325

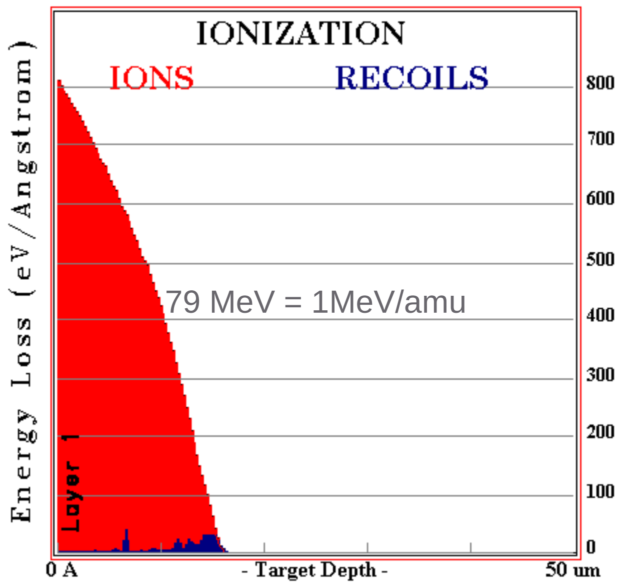
N.B. $(dE/dx)_0$ decreases monotonically with E!

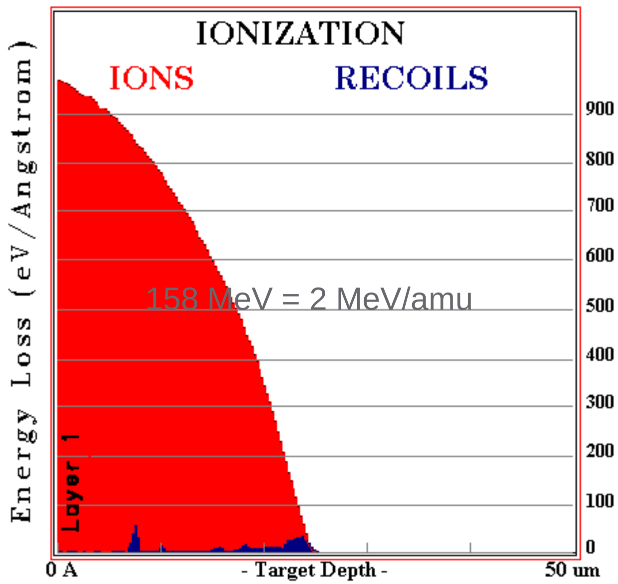


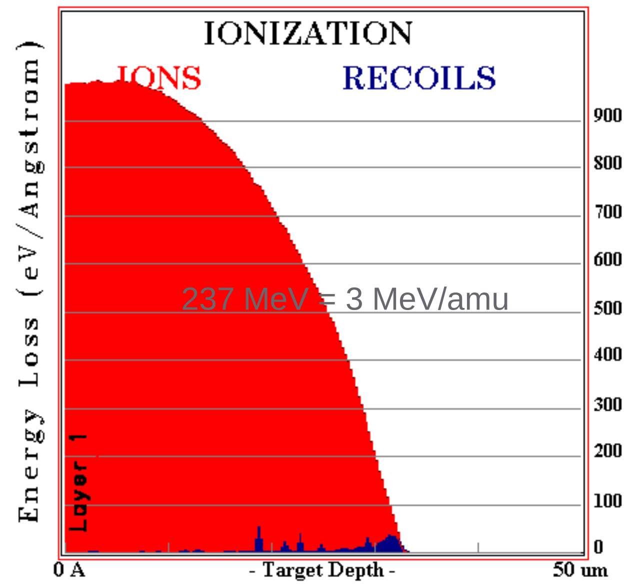
Range in Silicon



Surface LET





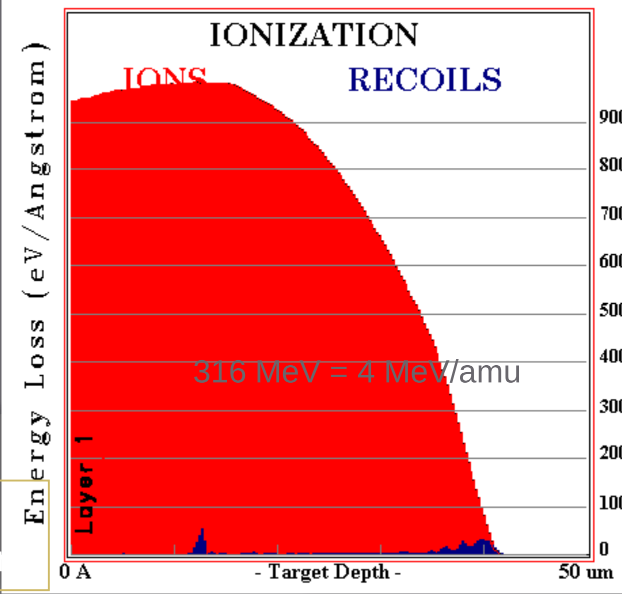


energy (MeV)	energy (MeV/amu)	LET(0) (eV/Å)	LET(0) (MeV-cm²/mg)
79	1	809	35.0
158	2	961	41.6
237	3	968	41.9
316	4	936	40.5

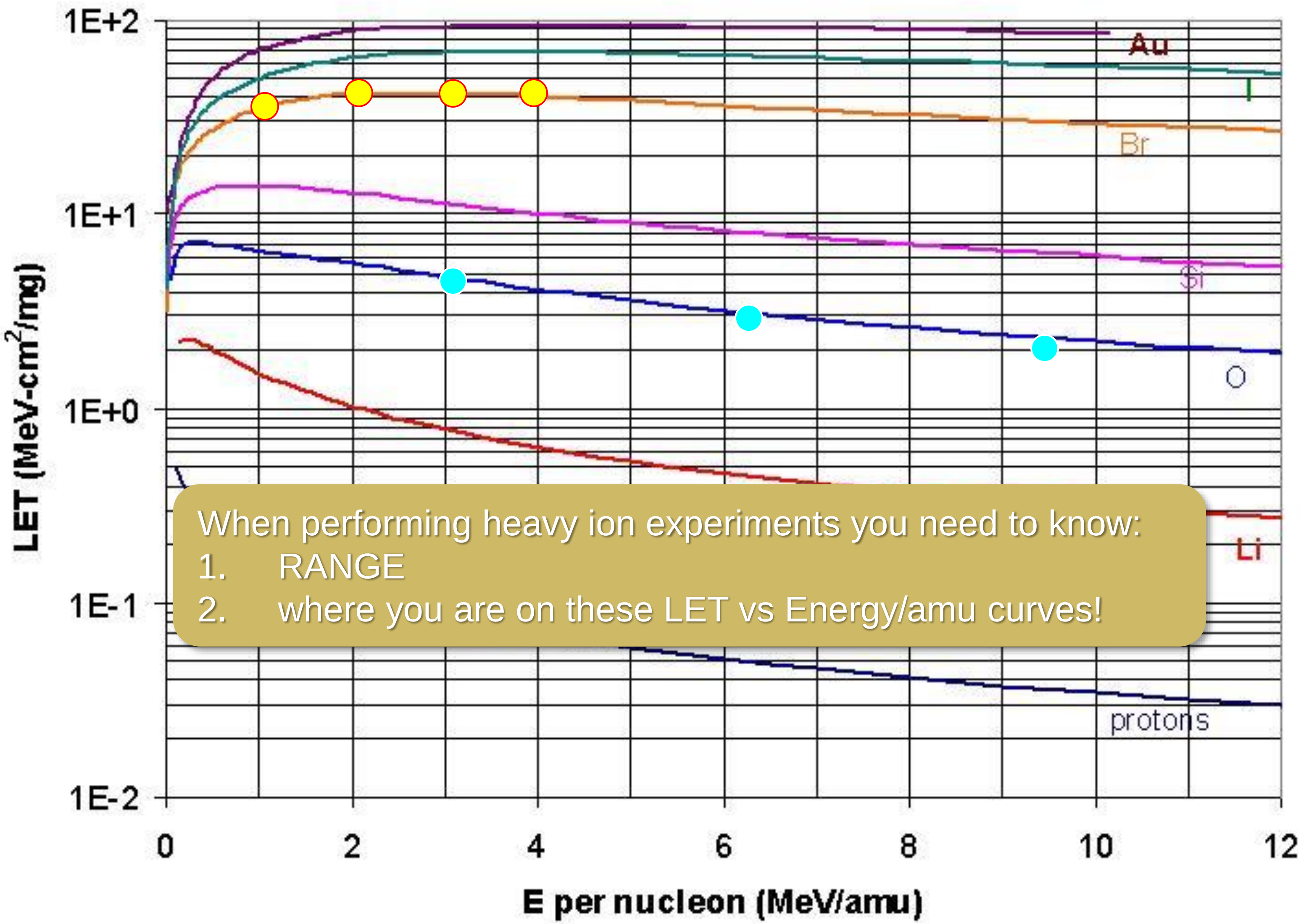
Br^{79}

broad maximum

decrease! beyond maximu



Surface LET in Silicon



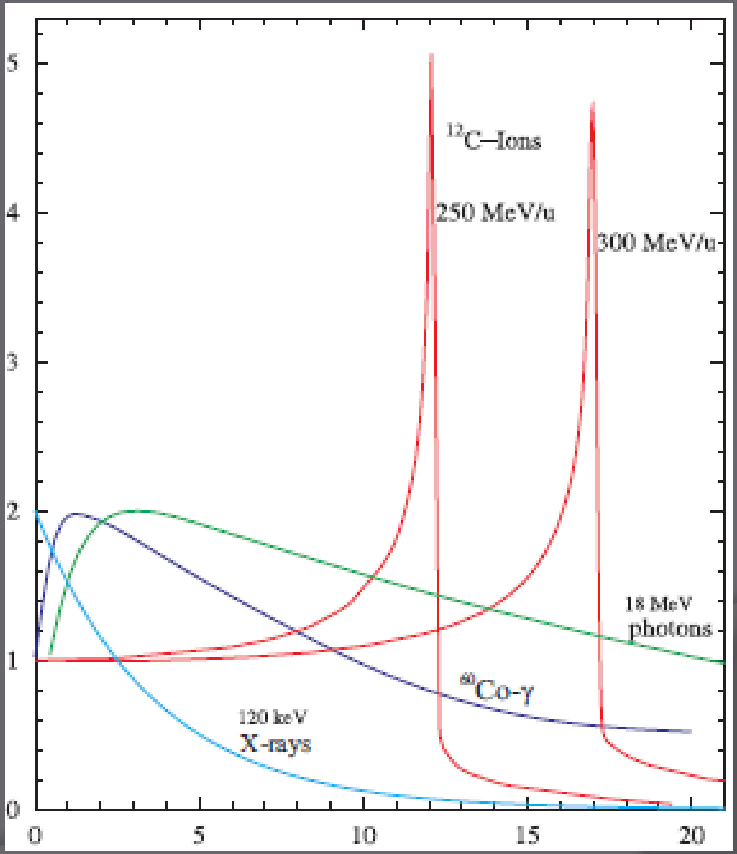
When performing heavy ion experiments you need to know:

1. RANGE
2. where you are on these LET vs Energy/amu curves!

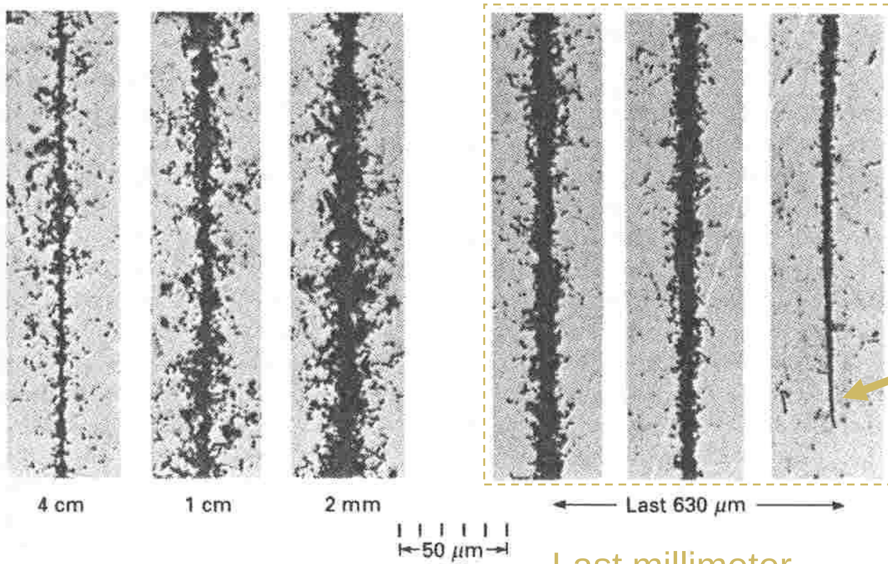
Note: ions with same energy/amu have the same velocity

Ionization

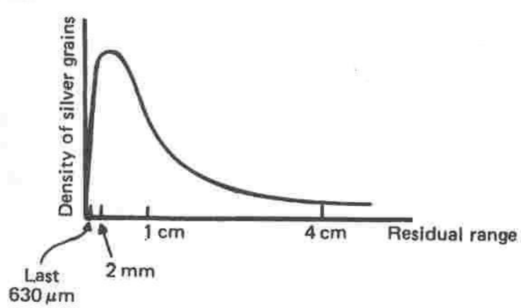
- Ionization energy loss = energy deposited per unit path length due to ionization resulting from the coulomb interaction of the impinging particle with the electrons of the material
- However: caution!
- Depth dose profile of photons and heavy ions:



Track structure



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.

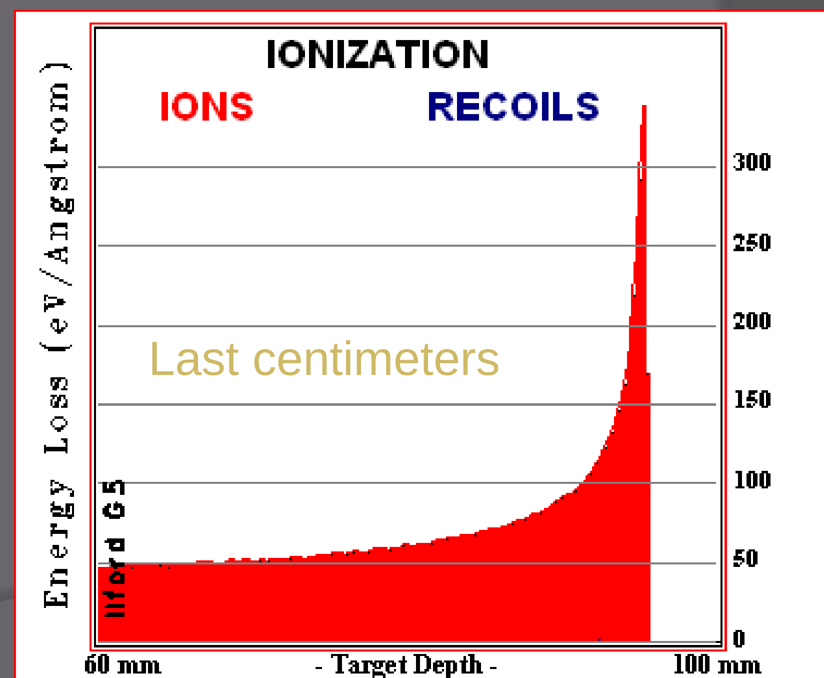


M. M. Shapiro, R. Silberberg (1970). *Ann. Rev. Nucl. Sci.*, 20, 328

- 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_{eff} of ion decreases.

Ion stopped!

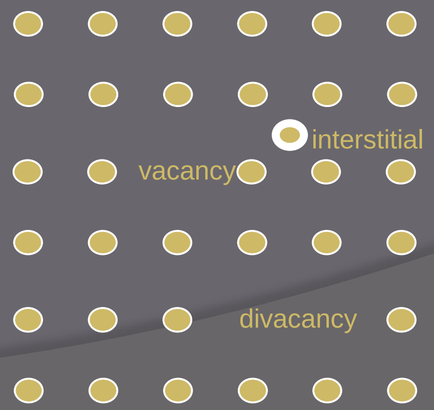
50 GeV Fe in emulsion



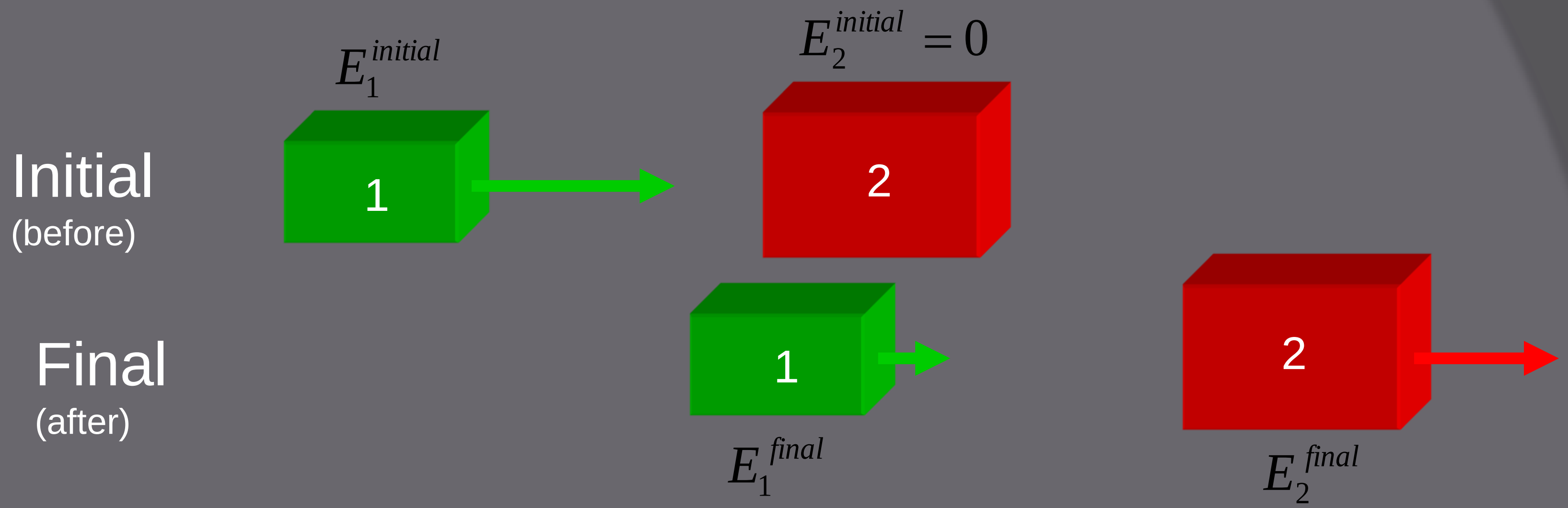
Displacement damage

- Caused by: p, n, ions, electrons, γ-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.

$NIEL = (dE/dx)_{displacement}$



Elastic collisions



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

$$E_{2,max}^{finale} = E_1^{initial} \times \frac{4M_1M_2}{(M_1+M_2)^2}$$

Non-relativistic

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

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

Non-relativistic

Vacancies in Silicon

Displacement damage threshold energies			
Diamond	Germanium	**Silicon**	GaAs
35±5 eV	27.5eV	**25eV**	7-11eV

^{60}**Co-gammas**	**Electrons**	**Neutrons** (elastic scattering)
Max $E_{\gamma} \approx 1$ MeV Effective particles are *Compton* electrons. Point defects only. (No clusters!)	$E_e > 255$ keV for displacement	$E_n > 186$ eV for displacement
	$E_e > 8$ MeV for cluster	$E_n > 35$ keV for cluster

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)

Displacement Damage Dose DDD = NIEL $\times$ Φ

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

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

- The D or NIEL value is depending on the particle type and energy.

NIEL scaling hypothesis (2)

- 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**
  - **NIEL (1 MeV neutrons) = 2.037 keV-cm2/g**

- A particle fluence Φ can be reduced to an equivalent 1 MeV neutron fluence Φ_{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...)

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
  - $k_{particle}$ (E)=$D_{particle}/D_{n(1MeVn)}$ (ratio of damage functions)

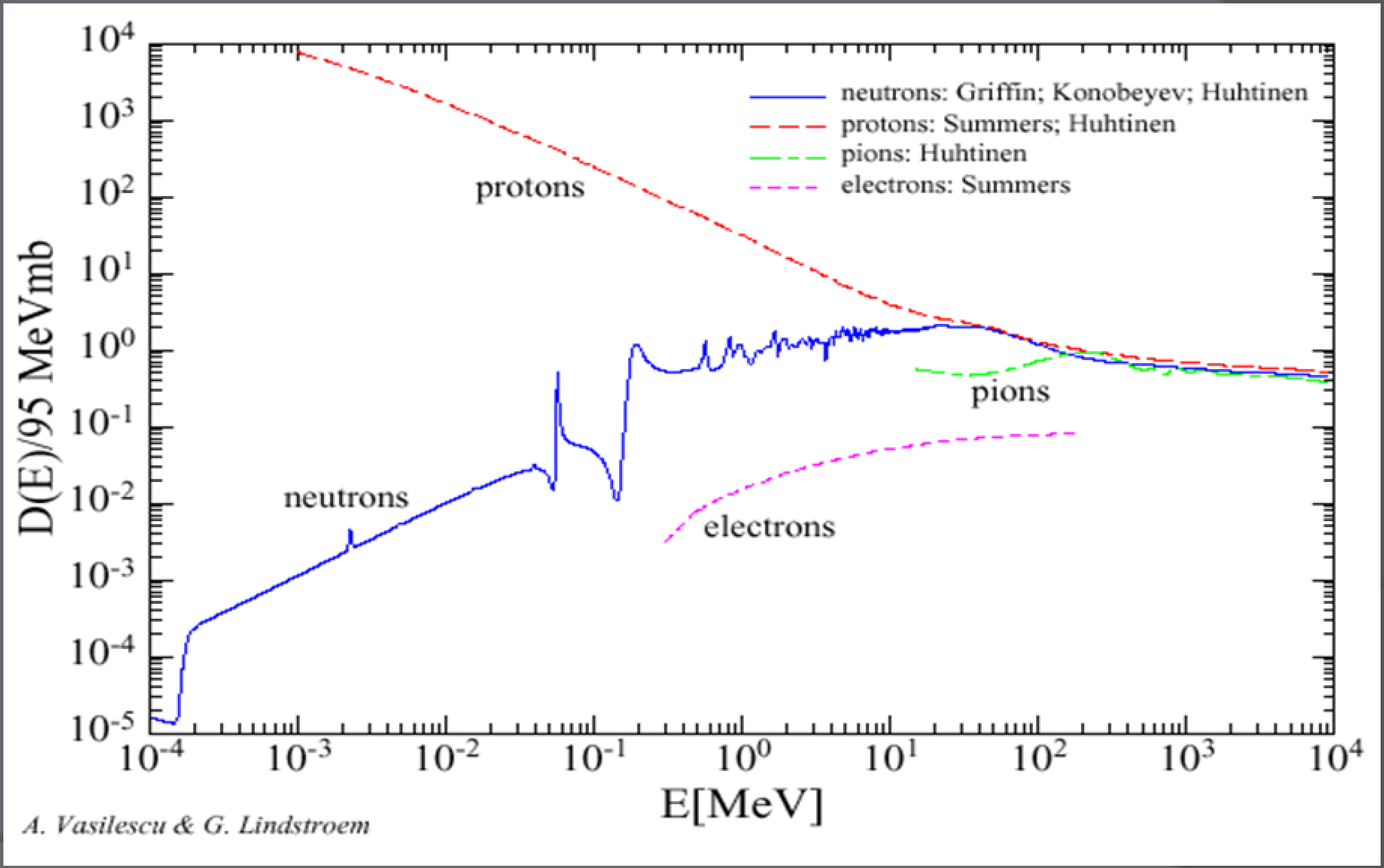
- e.g. for k=2, $\Phi_{eq} = 2\times\Phi$, hence 5×10^{13} particles/cm^2 make a bulk damage equivalent to 10^{14} standard-ones/cm^2

- A generic damage parameter α (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:

$$\frac{\alpha(X)}{\alpha(Y)} = \frac{k(X)}{k(Y)}$$

  - α(X) and α(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

Radiation	TID	Displacement (NIEL)	SEE
X-rays ^{60}Co γ	Expressed in SiO_2 Almost identical in Si or SiO_2	No	No
p	Equivalences in Si[$] @60MeV 10^{11}p/cm^2=13.8krd @100MeV 10^{11}p/cm^2=9.4krd @150MeV 10^{11}p/cm^2=7.0krd @200MeV 10^{11}p/cm^2=5.8krd @250MeV 10^{11}p/cm^2=5.1krd @300MeV 10^{11}p/cm^2=4.6krd @23GeV 10^{11}p/cm^2=3.2krd	Equivalences in Si[$,*] @53MeV 1 p/cm^2 = 1.25 n/cm^2 @98MeV 1 p/cm^2 = 0.92 n/cm^2 @154MeV 1 p/cm^2 = 0.74 n/cm^2 @197MeV 1 p/cm^2 = 0.66 n/cm^2 @244MeV 1 p/cm^2 = 0.63 n/cm^2 @294MeV 1 p/cm^2 = 0.61 n/cm^2 @23GeV 1 p/cm^2 = 0.50 n/cm^2	Only via nuclear interaction. Max LET of recoil in Silicon = 15MeVcm^{2}mg^{-1}
n	Negligible	Equivalences in Si[$,*] @1MeV 1 n/cm^2 = 0.81 n/cm^2 @2MeV 1 n/cm^2 = 0.74 n/cm^2 @14MeV 1 n/cm^2 = 1.50 n/cm^2	As for protons, actually above 20MeV p and n can roughly be considered to have the same effect for SEEs
Heavy Ions	Negligible for practical purposes (example: 10^6 HI with LET=50MeVcm^{2}mg^{-1} deposit about 800 rd)	Negligible	Yes

[$] 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

Federico Faccio, this school, 2009

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 particle
✓ Ionizing radiation

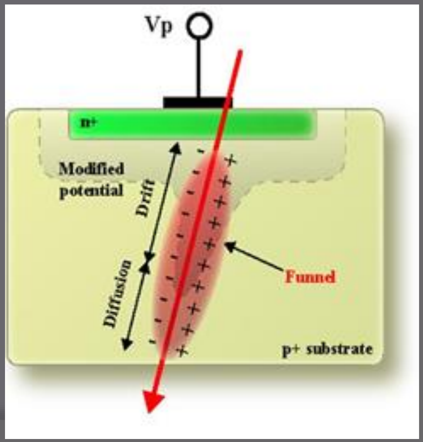
✓ Cumulative effect
✓ Ionizing radiation

✓ Cumulative effect
✓ Non-Ionizing radiation

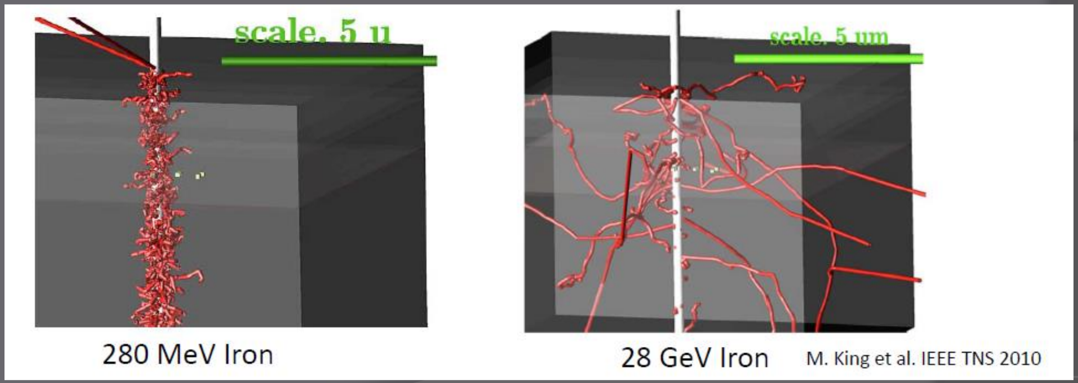
Single Event Effect mechanism

- 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

Charge collection at a sensitive junction



Track structure



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.

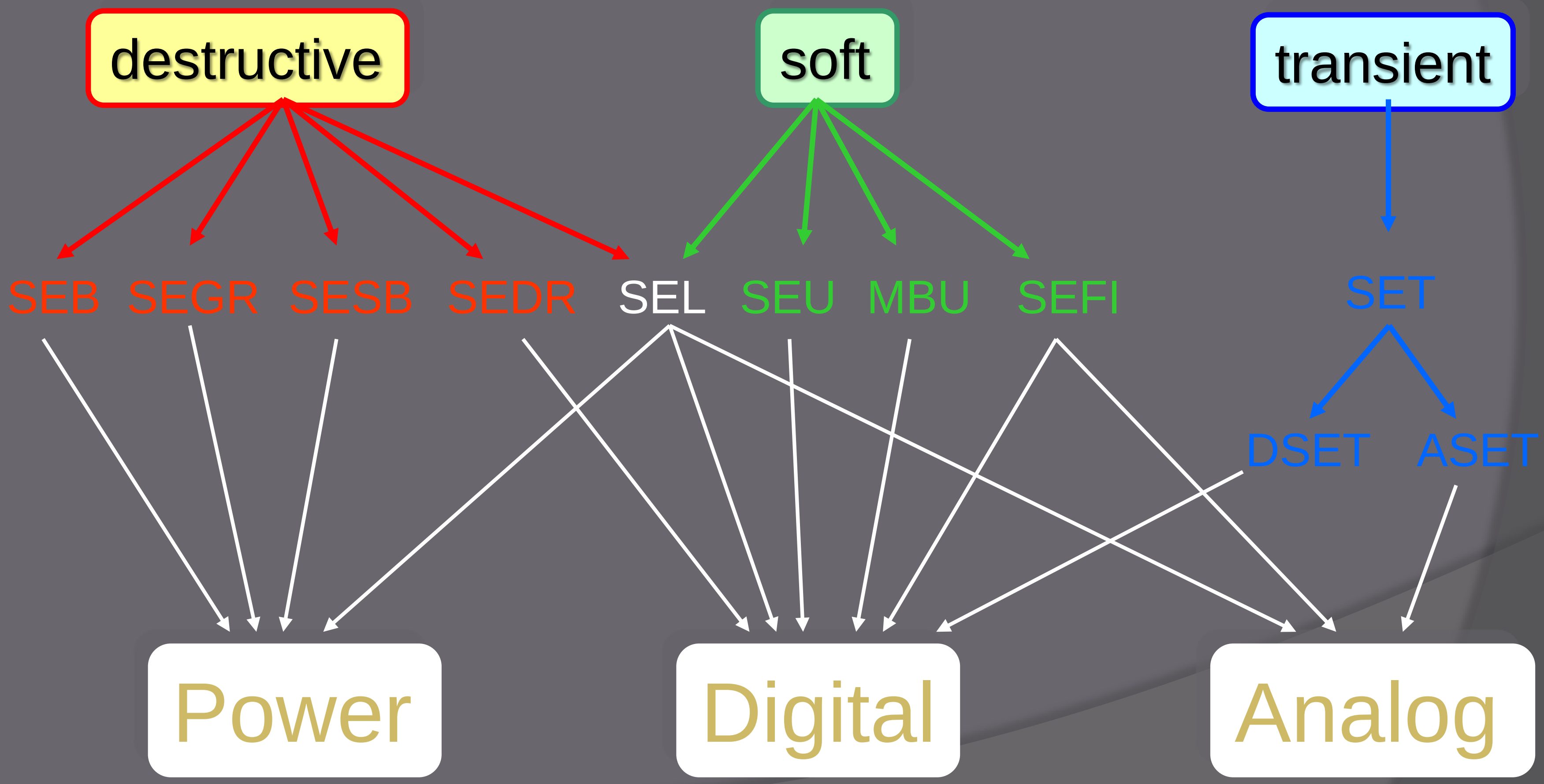
- **Energetic neutrons and protons** may produce secondary highly ionizing ions in nuclear interactions.

- 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*



Glossary

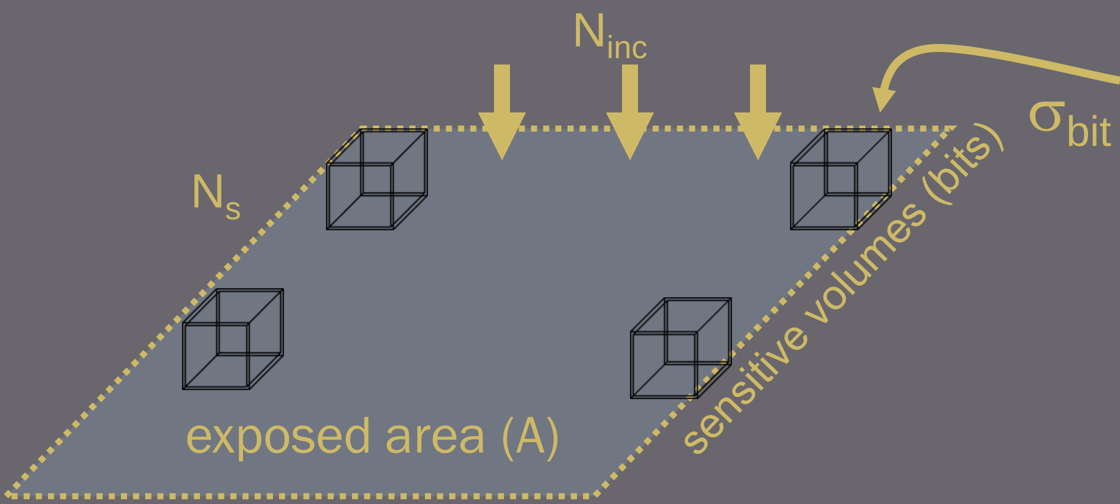
Skip

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

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



A : area of device exposed to beam

σ_{bit} : Cross-section of each sensitive volume

N_s : number of sensitive volumes in area A

$\sigma_{device} = \sigma_{bit} \times N_s$: Total sensitive area exposed to beam

The fraction of incident particles that cause SEE N_{SEE}/N_{inc}
is equal to the
fraction of exposed area this is sensitive

$$\frac{N_{SEE}}{N_{inc}} = \frac{N_S \cdot \sigma_{bit}}{A} = \frac{\sigma_{device}}{A} \Rightarrow N_{SEE} = N_S \frac{N_{inc}}{A} \sigma_{bit} = N_S \cdot \Phi_{inc} \cdot \sigma_{bit}$$

Experimentally

$$\sigma_{bit} = \frac{N_{SEE}}{N_S \cdot \Phi_{inc}} \qquad \sigma_{device} = N_S \cdot \sigma_{bit} = \frac{N_{SEE}}{\Phi_{inc}}$$

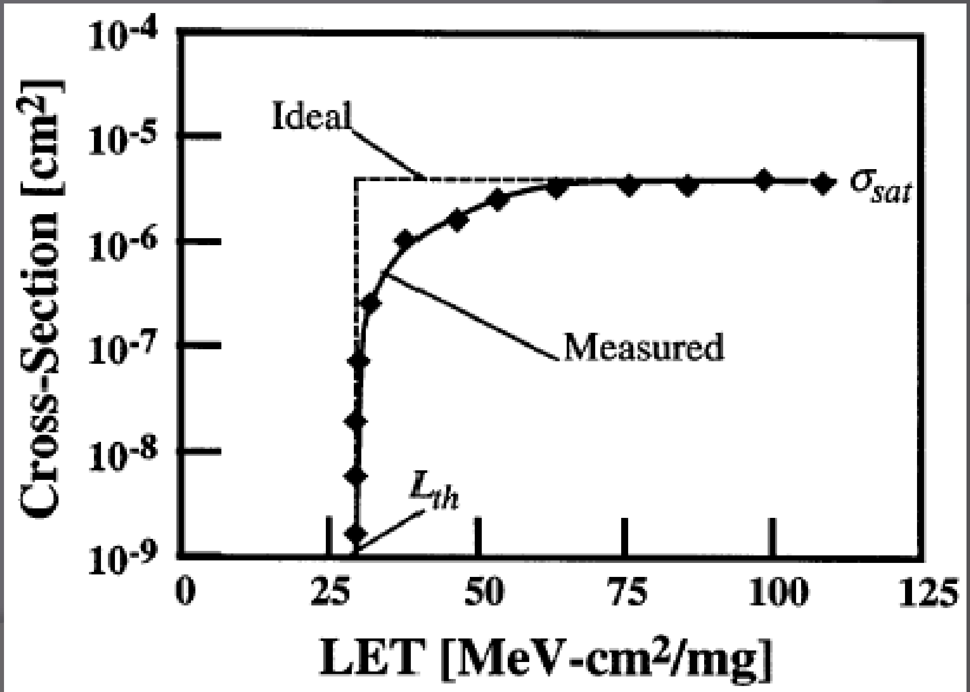
Broad beam SEE experiment

- The cross section (σ) for Single Event Effects is $\sigma = N_{SEE} / \Phi$
  - practical flux set by dead-time of DUT (typical few 10-10^4 ions $cm^{-2}s^{-1}$)
  - Statistical Error improves with fluence
  - however fluence is limited by Total Dose
  - σ(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

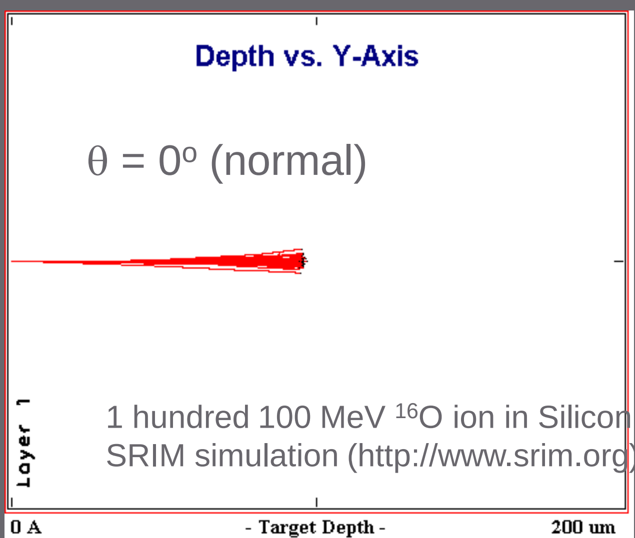
$$\sigma = \sigma_{sat} \times \{1-\exp[-(L-L_{th})/W]^{S}\}$$

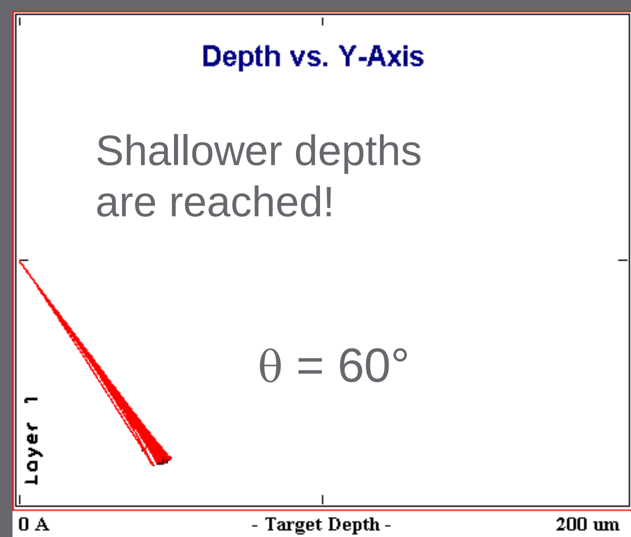
σ_{sat}: saturation value
L_{th}: threshold LET value
W and s are fitting parameters

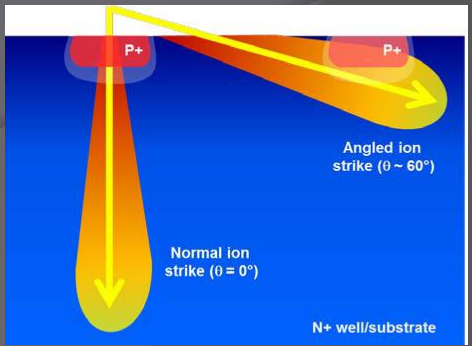


Testing at Non-normal incidence

- 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







$LET_0(\theta) = LET_0/\cos(\theta)$ $\quad$ $depth = range \times \cos(\theta)$

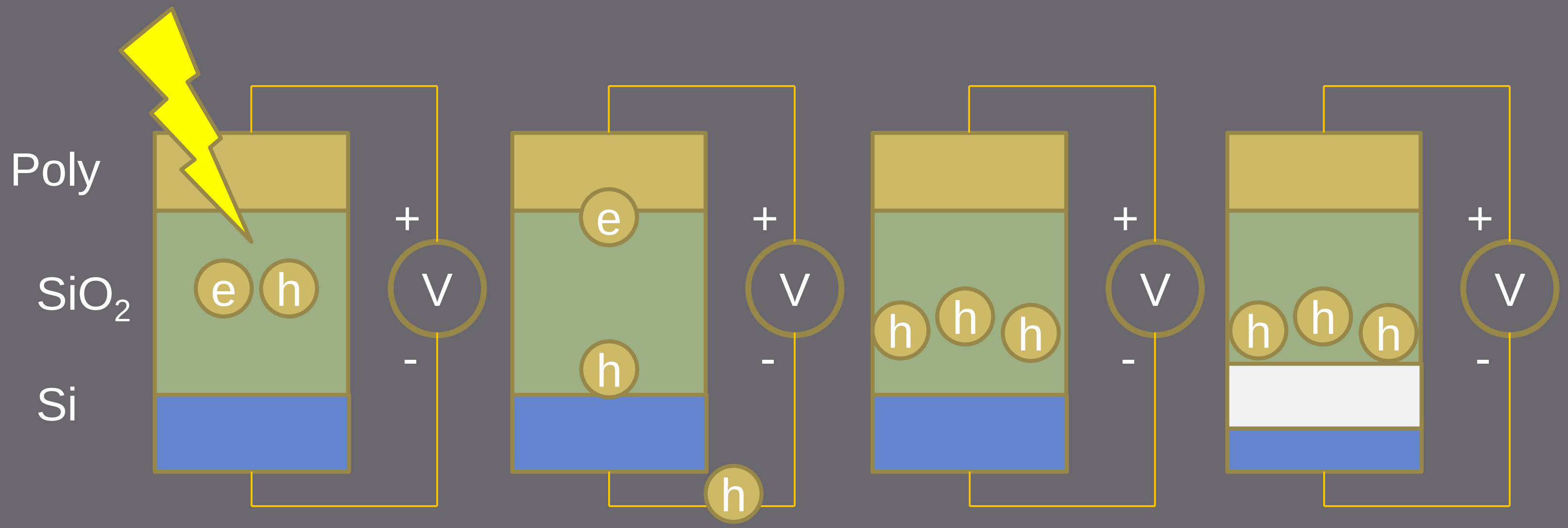
Proton testing

- Devices sensitive should be tested for **proton SEE sensitivity** especially for
  - devices with heavy ion $LET_{th} < 20$ MeV·cm^2/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_{SEE}/fluence
- depends on specific ionization power of culprit LET > $LET_{threshold}$
- in hadron environment SEE rates proportional to hadron flux E > 20 MeV E_n> 2 MeV

Total Ionizing Dose effects in MOS structures



Trapped charge in the SiO_2 bulk is always positive

Interface traps can trap both e and h

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

Basic mechanisms in oxide layers

- Electron-Hole **Pair Generation** in SiO_2: ~ 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- ~ in picosec, h+ in millisecond
- Hole Trapping
- Interface Trap Formation
- Dependence on bias

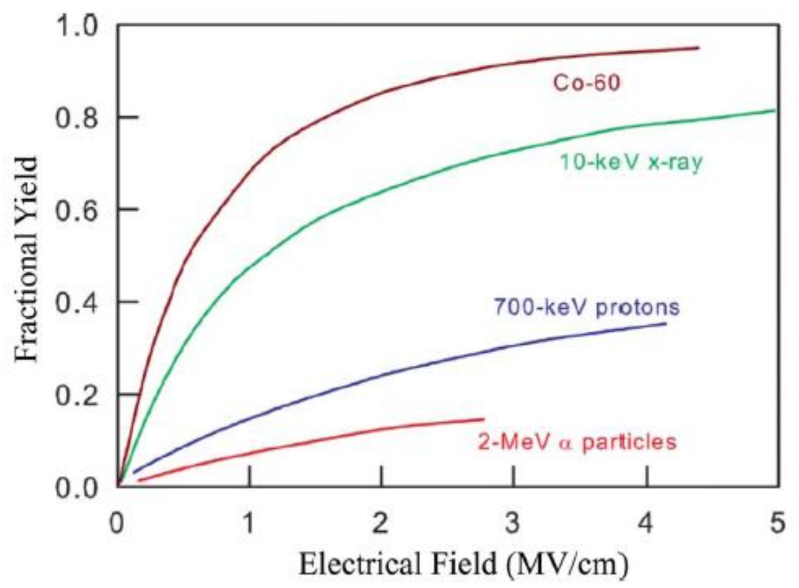
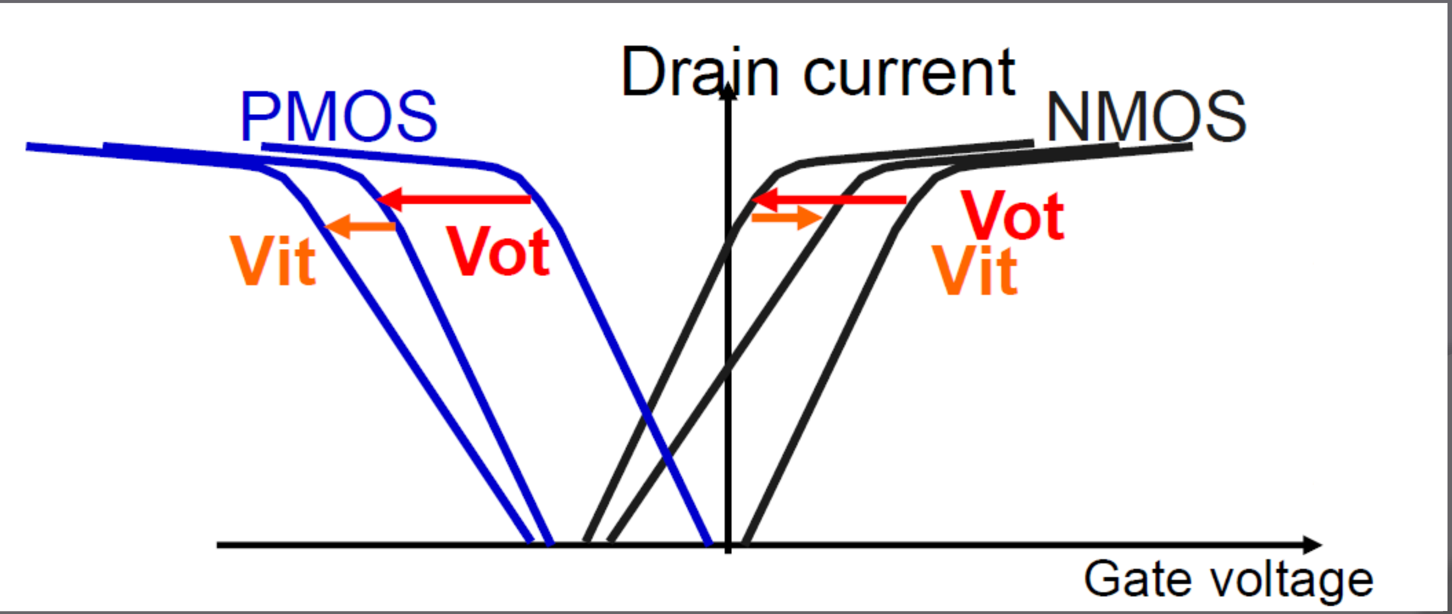


Fig. 1. Fractional yield as a function of the electrical field applied throughout the oxide and for different incident particles [1], [2].

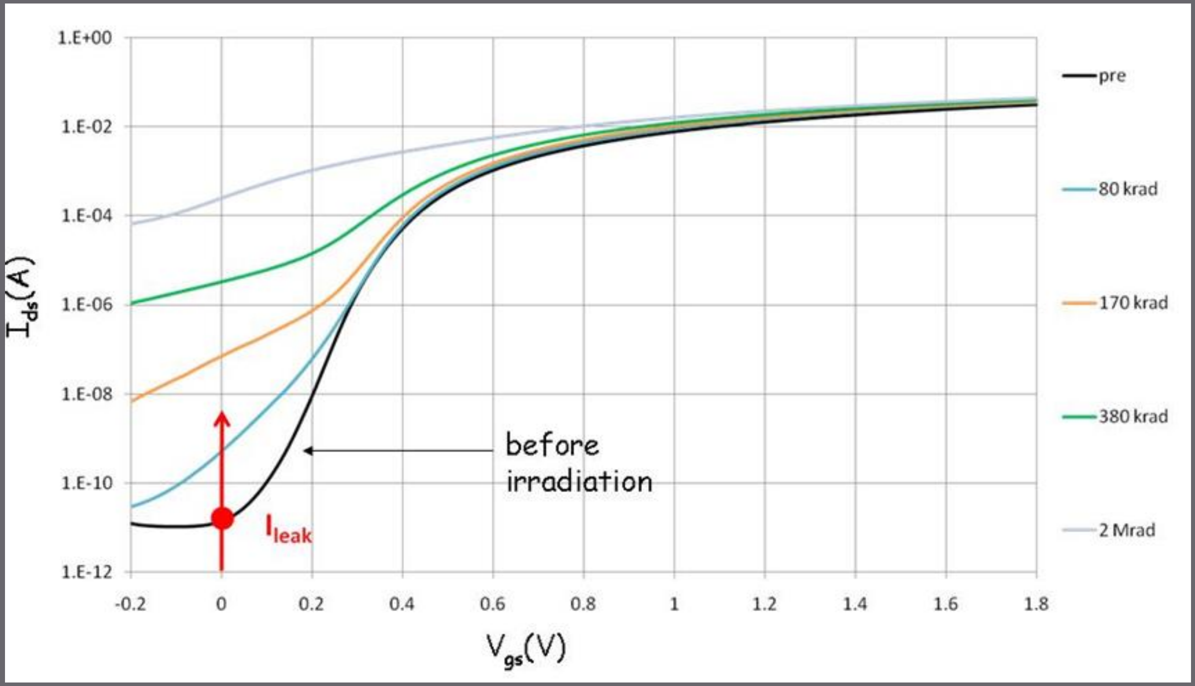
Threshold voltage shift

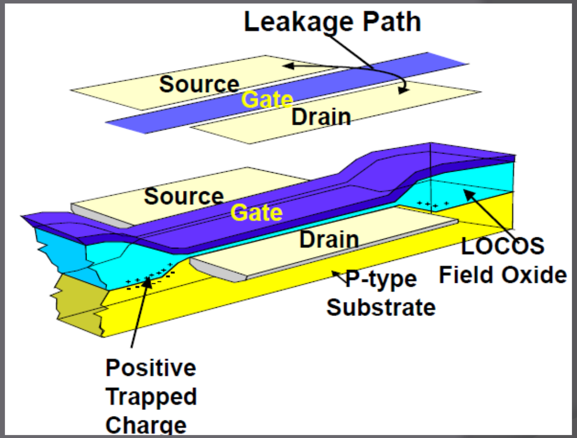
- Oxide trapping
  - N_{OT}: number of trapped charges
- Interface trapping (+ for PMOS, - for NMOS)
  - N_{IT}: number of trapped charges
- $\Delta V_{IT} = -\frac{Q_{IT}}{C_{OX}} = \pm\frac{q \cdot N_{IT}}{C_{OX}}$ $\Delta V_{OT} = -\frac{Q_{OT}}{C_{OX}} = -\frac{q \cdot N_{OT}}{C_{OX}}$



Leakage current increase

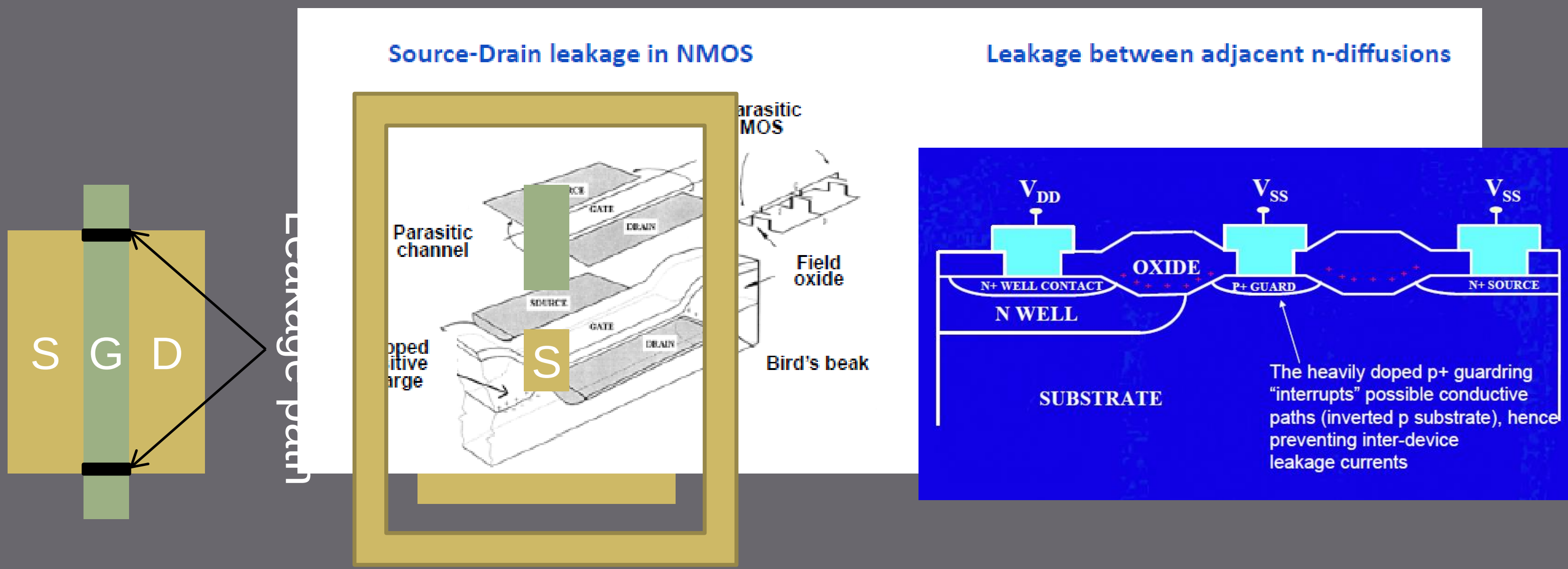
- Charge trapped in the isolation acts as lateral parasitic transistor
- Transistor is ON when it should ne OFF





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



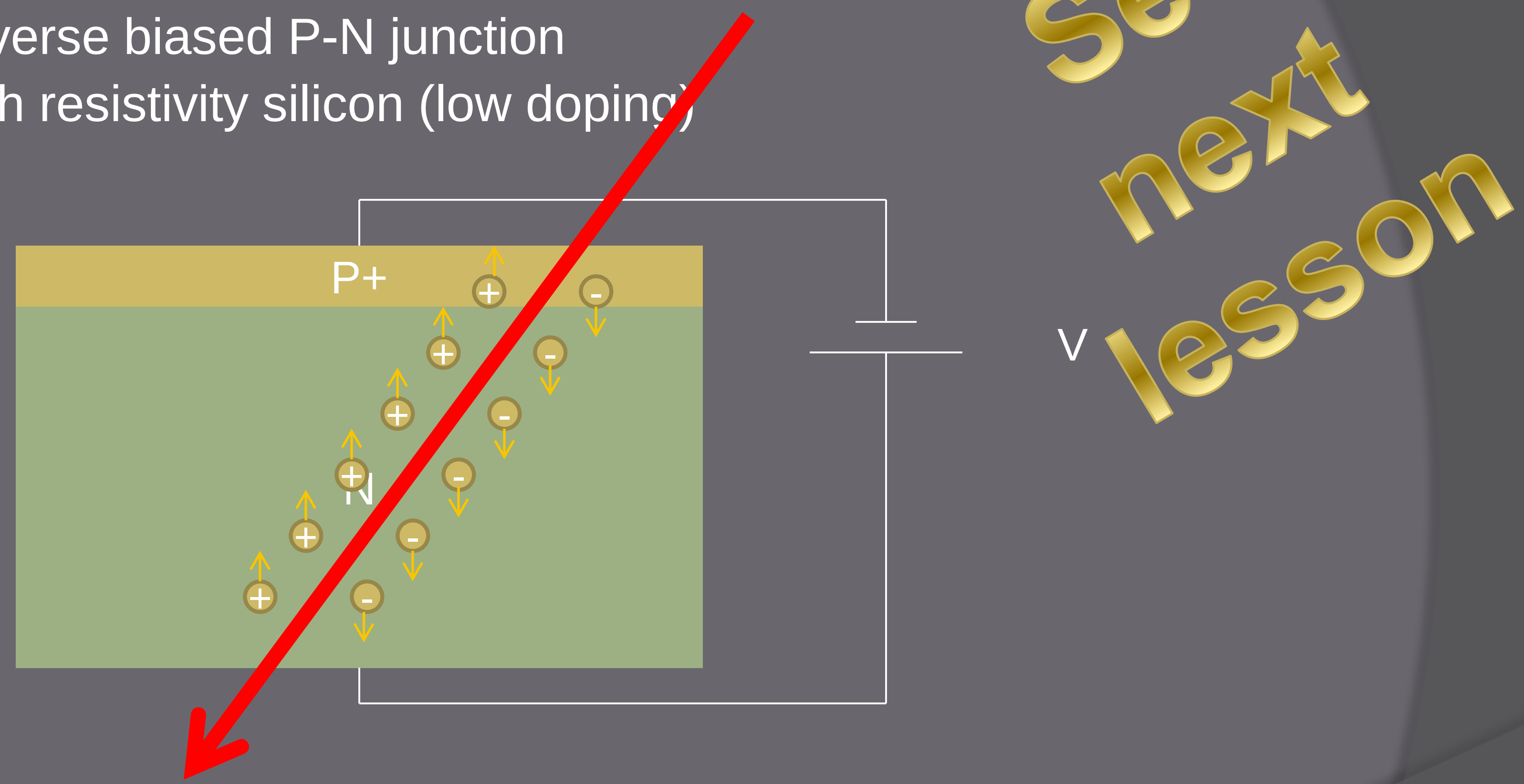
Enclosed layout transistors **Guardrings**

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

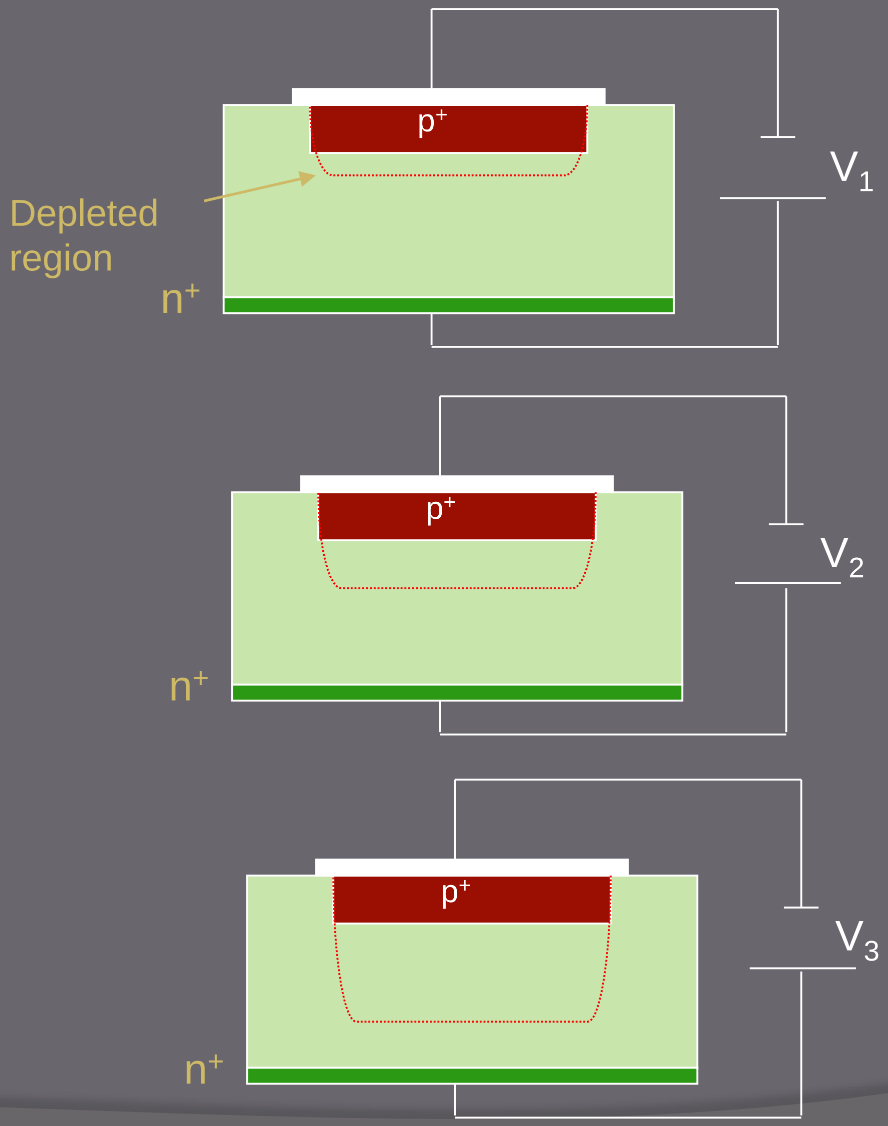
Silicon Detectors (1)

- Reverse biased P-N junction
- High resistivity silicon (low doping)

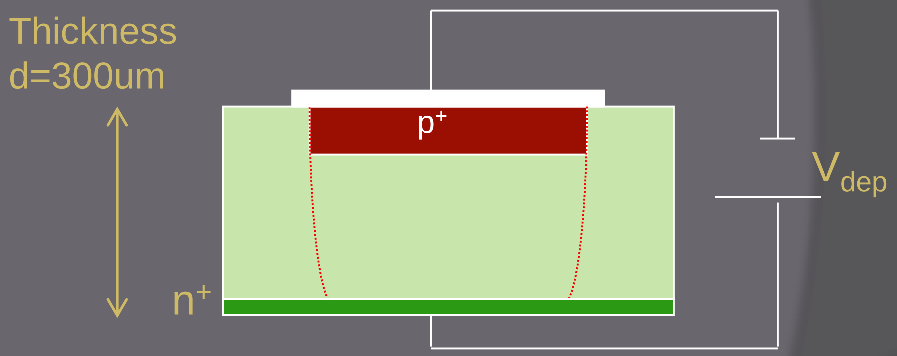


- Charged particles crossing the device will produce electron-hole pairs
- The moving electrons and holes will create a signal in the electric circuit.

Silicon Detectors (2)

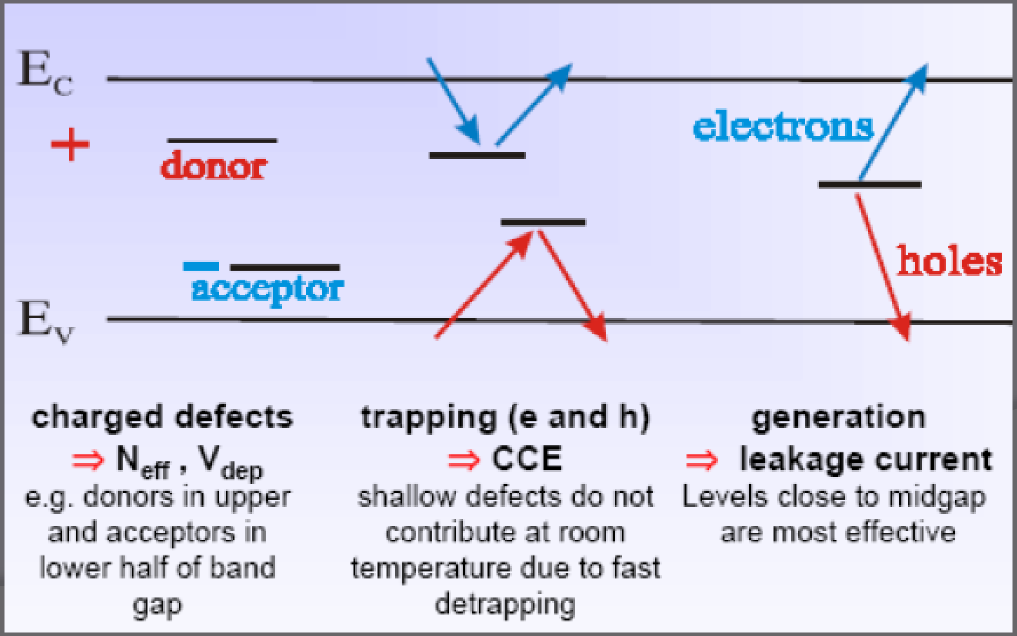


- If the detector is under-depleted:
  - Charge loss → inefficiency
  - Charge spread → loss resolution
- Full depletion is important:



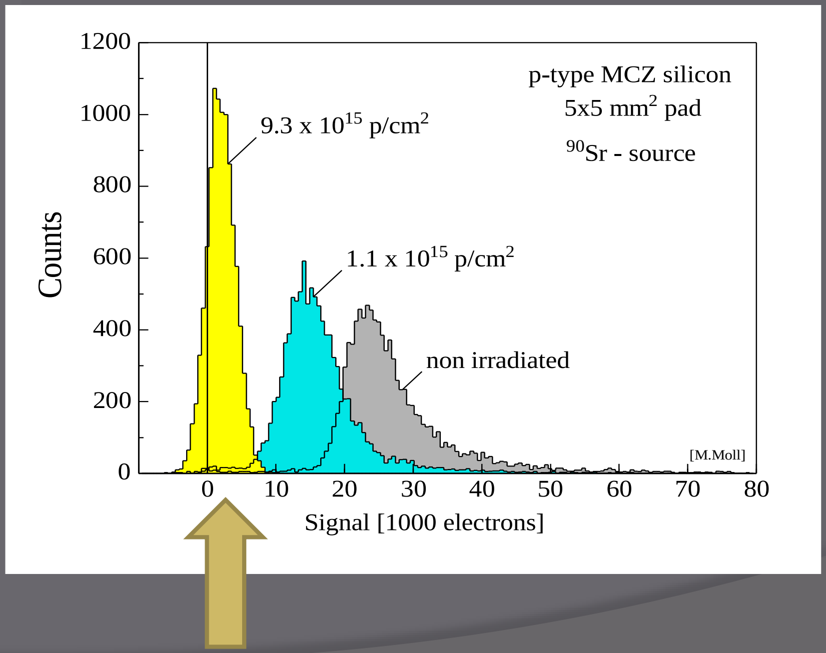
Radiation Damage in Silicon Detectors

- 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). ➔ charges released with delay are no longer measured within the integration time of the electronics

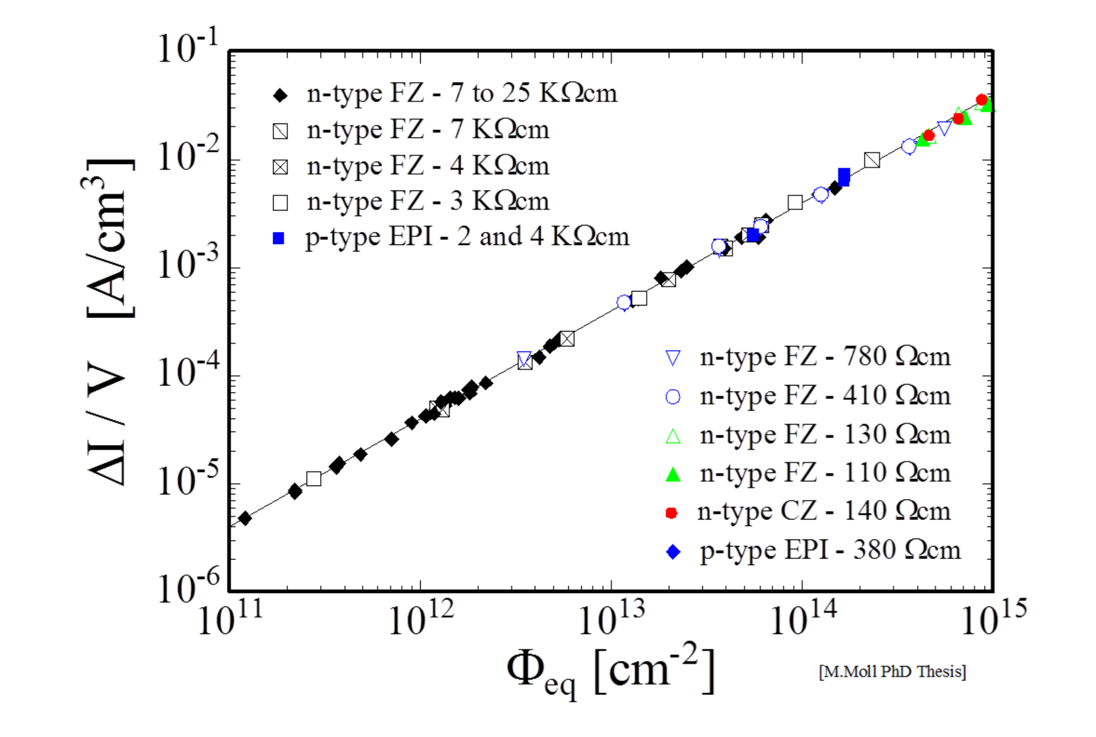


Michael Moll (CERN – PH-DT2-SD)

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 Φ_{eq}.

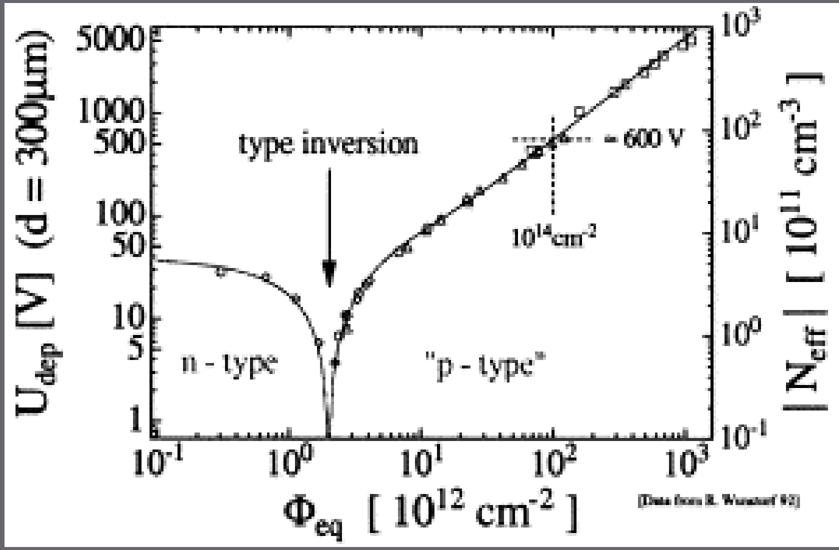


- The α **damage parameter is constant** over several orders of equivalent fluence and independent of impurity concentrations in Si.

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 Neff decreases and after a point called type inversion (n type Si becomes p type Si) increases again.

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

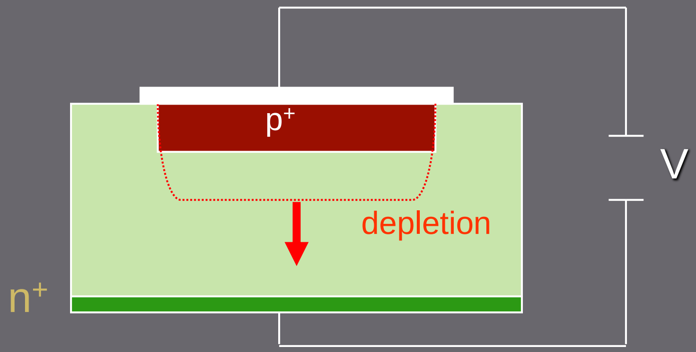


- The voltage needed to fully deplete the detector V_{FD} is directly related to the effective doping concentration:

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

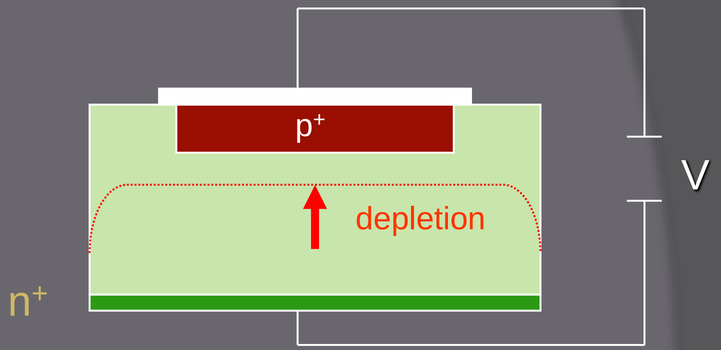
Type inversion and depletion voltage

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

Skip

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

Parameter or Feature		ATLAS	CMS
Pixel hit rate inner barrel		$\approx 1\,GHz/cm^2$ (30 KHz/pixel $25 \times 150\,\mu m^2$)	$\approx 2\,GHz/cm^2$ (50 KHz/pixel $25 \times 100\,\mu m^2$) (100 KHz/pixel $50 \times 100\,\mu m^2$)
10yr, 3 ab^{-1}	TID	10 MGy	
	1 MeV n. eq.	2×10^{16}	
SEU tolerance		Re-configure <1 module/lyr/hr <0.1% hit data loss	
Sensor			
Signal	Polarity	negative	negative (TBC)
	MIP charge	10 Ke^-	5-10 Ke^-
	Max. charge	TBD	linear up to 2 (4) MIP
Pixel max. capacitance		200 fF (<400 fF)	200 fF TBC
Pixel max. leakage current		20 nA (<100nA)	20 nA TBC
Readout Chip			
Hit loss at max rate		<1%	<1%
Threshold	minimum	$\approx 1000\,e^-$	$\approx 1000\,e^-$
	dispersion (tuned)	$< 100\,e^-$	$< 200\,e^-$ ($100\,e^-$)
	variation w/time	$< 100\,e^-$	$< 200\,e^-$ ($100\,e^-$)
Min. thr. noise occupancy		$< 10^{-6}$	$< 10^{-6}$

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 $\Phi \sim 10^{11\text{-}12}$ 1-MeV neutrons/cm^2