Overview of Radiation Effects on Electronics and Impact on CERN Particle Accelerator Activities

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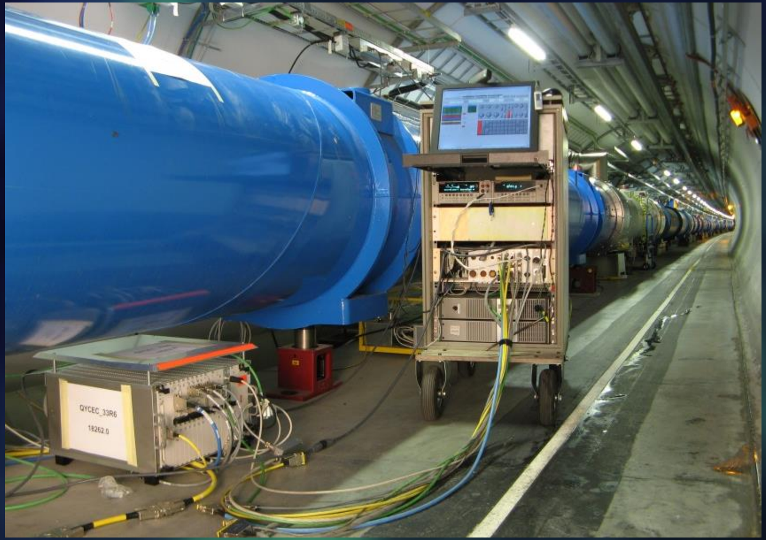
Controls
Electronics &
Mechatronics

R2E

Context

- The **reliability** is a main concern for the CERN electronic equipment
- The **criticality** of the equipment can be very high
- A large number of systems are exposed to the radiation environments induced by the LHC
- Radiation-induced failures on LHC electronics can lead to:
  - **Beam Dumps** → Lost time for physics
  - **LHC safety system failures** → Part of the machine can be destroyed



@ Courtesy of the TE/MPE Group

- Systems can be highly distributed (**up to thousand of units**):
  - Use of RadHard devices not affordable → Most of the systems are **COTS-based**

- The radiation qualification of these systems is then a major task in order to avoid failures in operation

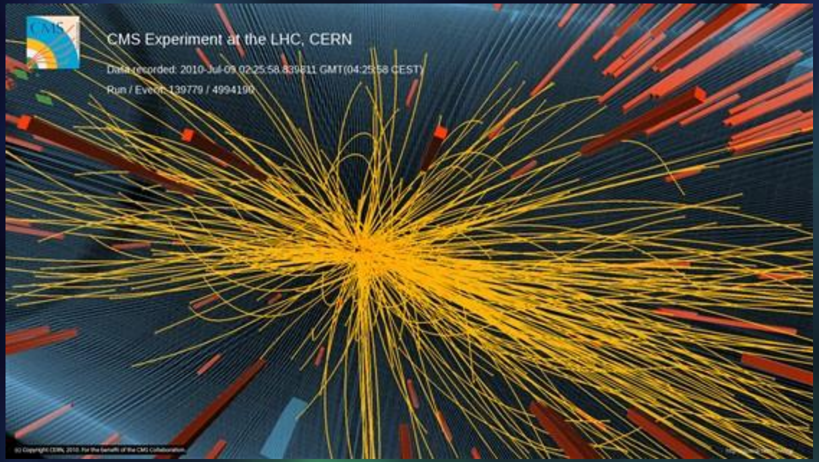
Radiation Sources at CERN

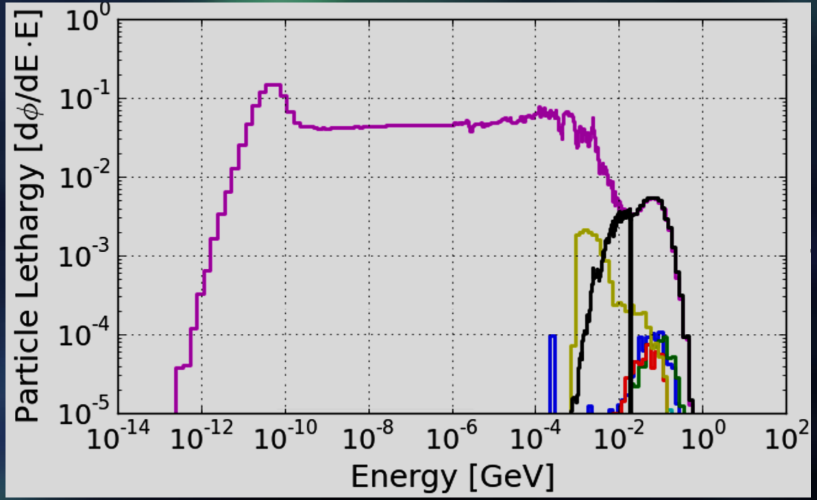
- **Collision debris**
    - Debris resulting of Beam/Beam and Beam/Target collisions
    - Scale with beam luminosity

- **Direct beam losses caused by beam operations**
    - Cleaning (collimation), Extraction, Injection, Dump etc…
    - Levels usually scale with beam intensity and energy

- **Beam-Residual Gas interactions**
    - Due to imperfect vacuum in the machine
    - Scale with residual gas density and beam intensity/energy

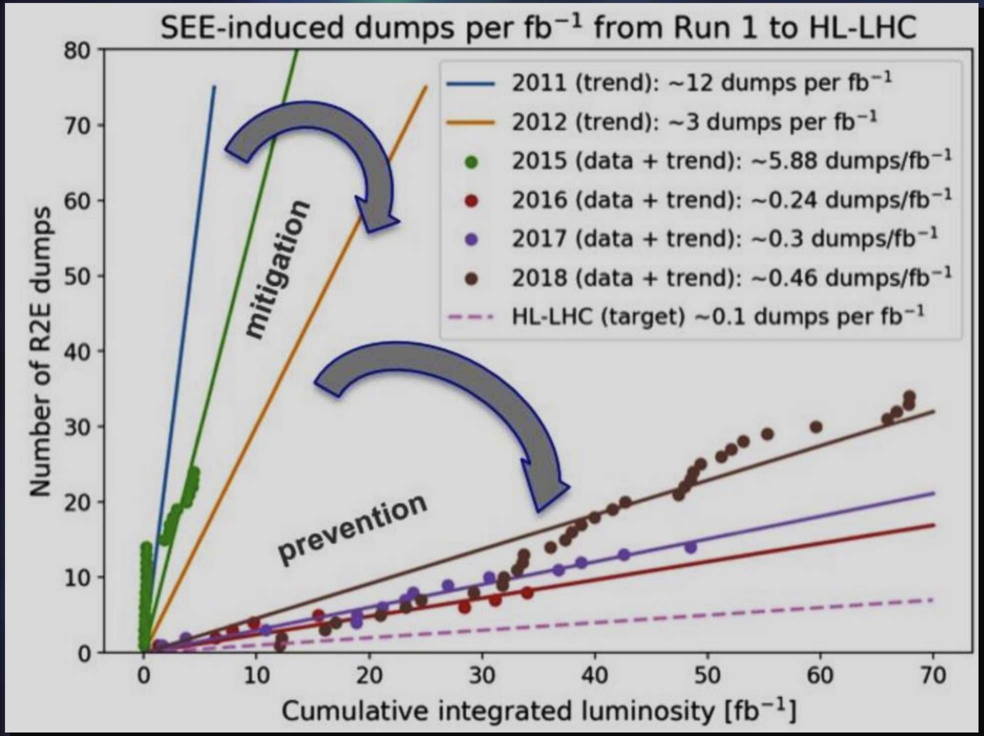
- Each interaction initiates particle showers generating a wide range of particles in terms of type (protons, pions, photons, muons, neutrons etc…) and energy (from meV up to GeV)





LHC Challenge

- Radiation to Electronics (R2E) project was created in 2010, following the LHC start to deal with LHC radiation-induced failures
- **Mitigation actions** (shielding and system relocating) and **preventive actions** (radiation monitoring, radiation qualification…) led to a very successful Run 2 of the LHC



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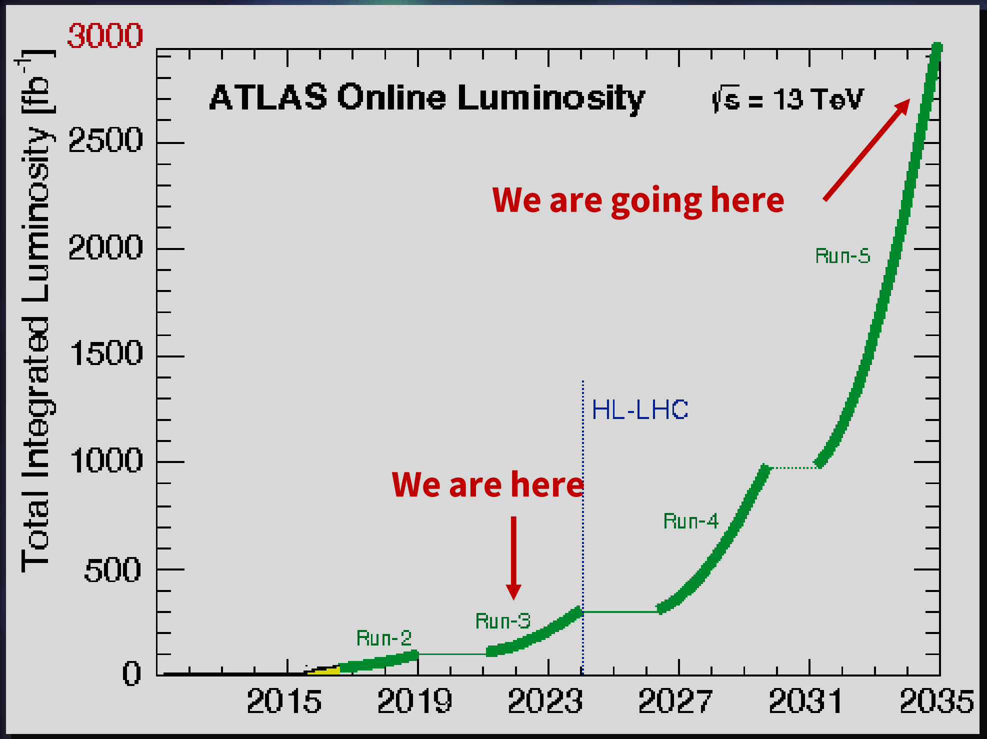
- **Mitigation actions** (shielding and system relocating) and **preventive actions** (radiation monitoring, radiation qualification…) led to a very successful Run 2 of the LHC
- The future upgrade of the LHC (High Luminosity LHC) will increase by a factor 4 the annual accelerator luminosity and radiation levels
- **In the next 12 years systems might be exposed to ~9 times more radiations than in the past 12 years**
- The LHC radiation-failure rate must be furthermore decrease
- **Radiation Hardness Assurance (RHA) is now more important than ever**



From: link

$$N_{SEE\_Failure} = \underset{\substack{\uparrow \\ \text{Number of systems}}}{N} * \sigma * fluence$$

Radiation to Electronic (R2E) Project Structure

The Radiation To Electronics (R2E) project covers many aspect of Radiation Hardness Assurance in the form of working packages/groups:

A. Operation

A-1: Project management

A-2: Radiation Working Group

A-3: Measurement and Calculation Working Group

A-4: Material Testing and External Facilities

A-5: Injector Chain

B. Infrastructure

B-1: CERN Facilities

B-2: RadMON Monitoring

B-3: Optical Fiber Dosimetry

B-4: Shielding & Relocation

C. Radiation Tolerant Developments

C-1: Common Building Blocks

C-2: Vacuum

C-3: Beam Instrumentation

C-4: Quench Protection System

C-5: Power Converters

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CERN Radiation Hardness Assurance (RHA)

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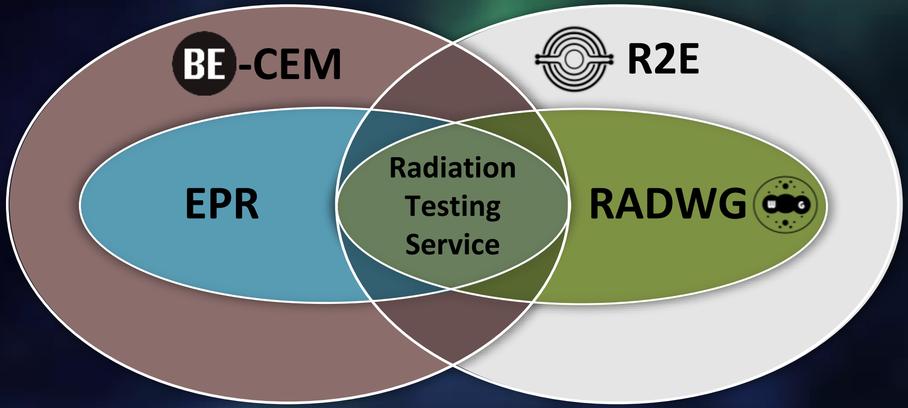
RadWG: Provides the crucial service of qualifying components of possible use in the accelerator and covering the full test chain: from the setup development, through the test execution, and up to the related analysis and reporting.

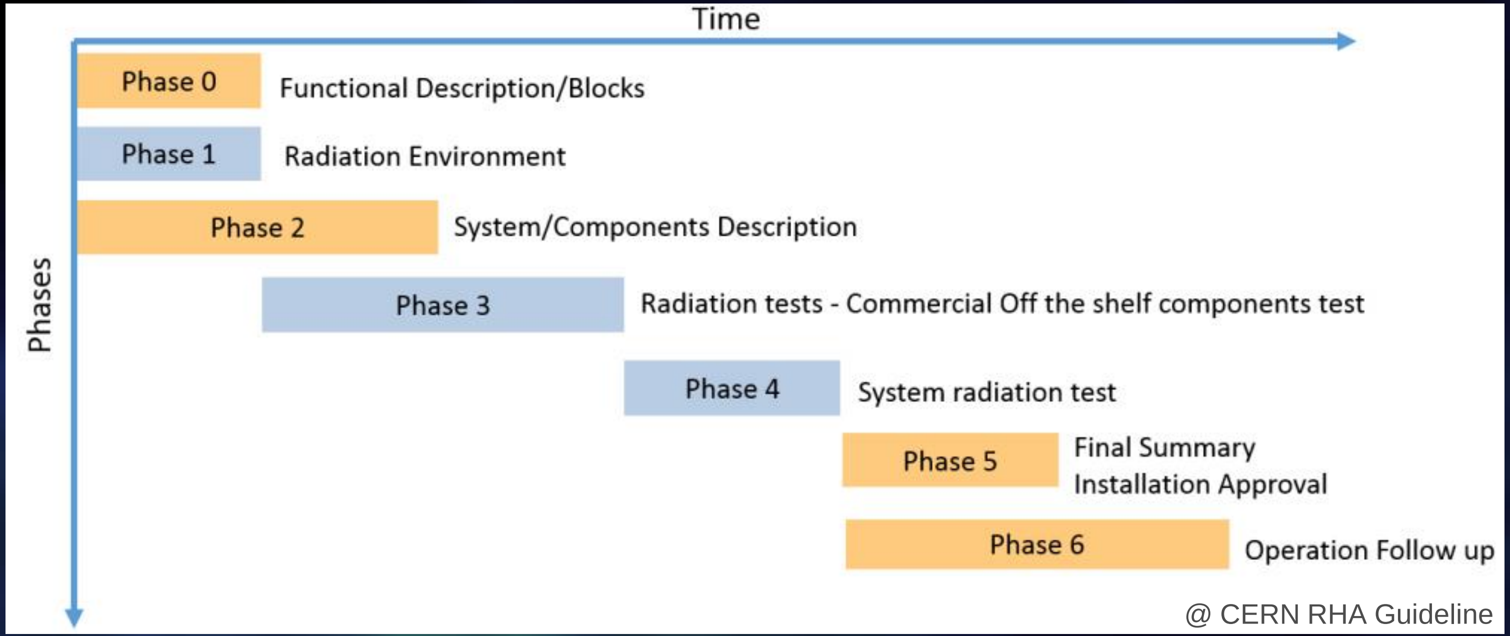
Radiation Test Service

- BE-CEM-EPR provides, through R2E resources, the service of radiation testing of electronic components supporting the Radiation Working Group (RadWG)
- The RadWG supports the accelerator sector equipment groups for the assessment of radiation tolerance of electronic equipment to be installed in radiation exposed areas.
- It is as a forum for electronic engineers to discuss
  - Design practices
  - Radiation tests
  - Radiation induced failures in the accelerators.
- The RadWG is one of the pillars of the R2E project



CERN RHA Guideline for COTS-based system

Within the R2E project the process for system qualification was defined:



@ CERN RHA Guideline

- Provide advices and support for component type & technology choice
- Collect Test request
- Test & Reporting
- Provide support on system failure analysis and mitigation

- Provide advices in early development stages for component choice
- Help analyzing system failure observed in operation or during system-level test and propose mitigation techniques or part replacement candidates

Radiation test service process

Request collection

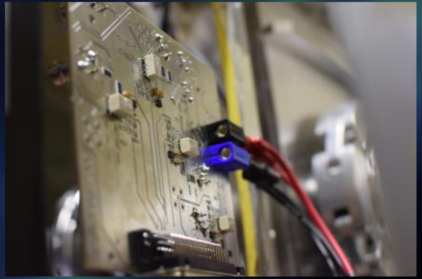
The requests for radiation testing are collected and processed selecting the most suitable methodology and facilities

Test planning and structure

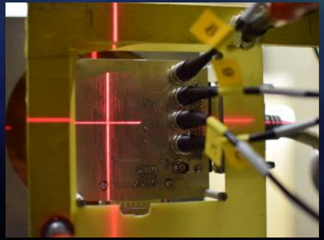
Each component/system is analyzed, and all the possible radiation effects are taken into account for planning the test and structure it

Board and instrumentation preparation

For each component a dedicated set of test board is prepared and the associated instrumentation is chosen to face the complexity of the radiation test



Testing



The test are carried out at CERN facilities such as CHARM or Co60 and in external facilities. The transport, personnel and instrumentation are selected considering the peculiar aspect of each facility

Result analysis

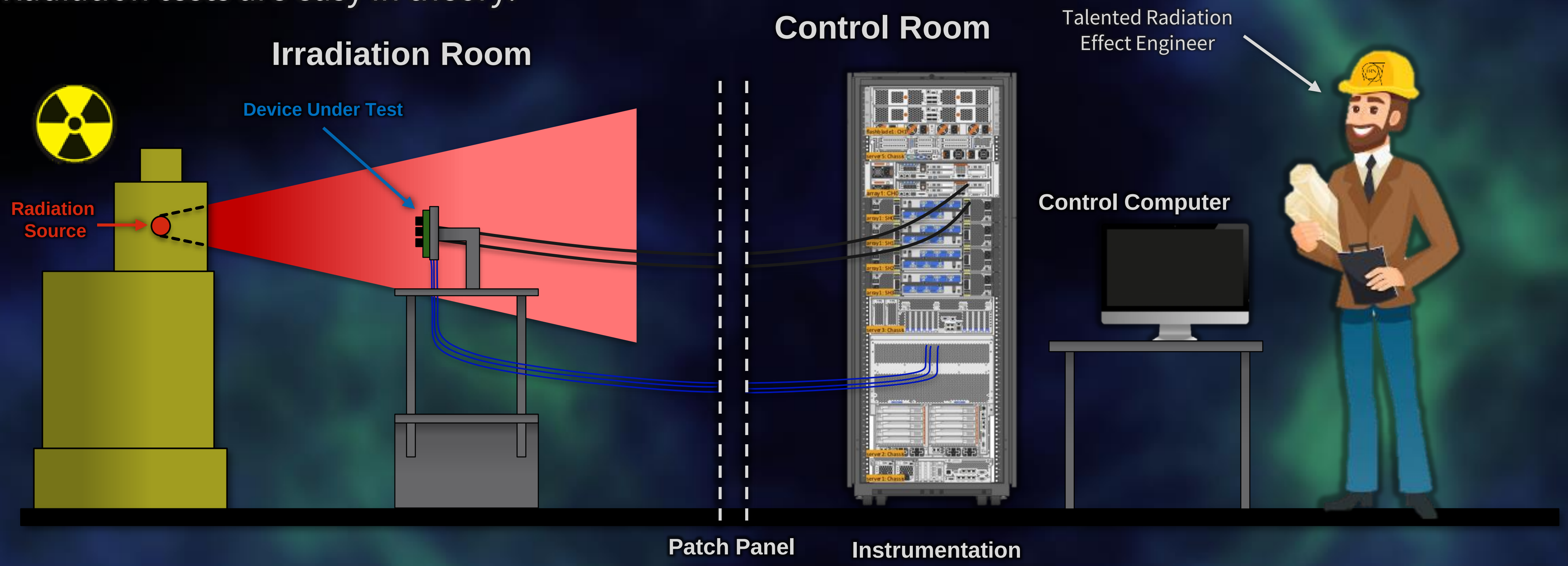
The results are analyzed during and after the tests for each component considering the end application and the possible operational issues

Database and Publication

The results are collected, stored and in EDMS and published in the RADWG database to allow an easy research of the best candidates for the new radiation tolerant designs

Radiation Tests in practice

Radiation tests are easy in theory:



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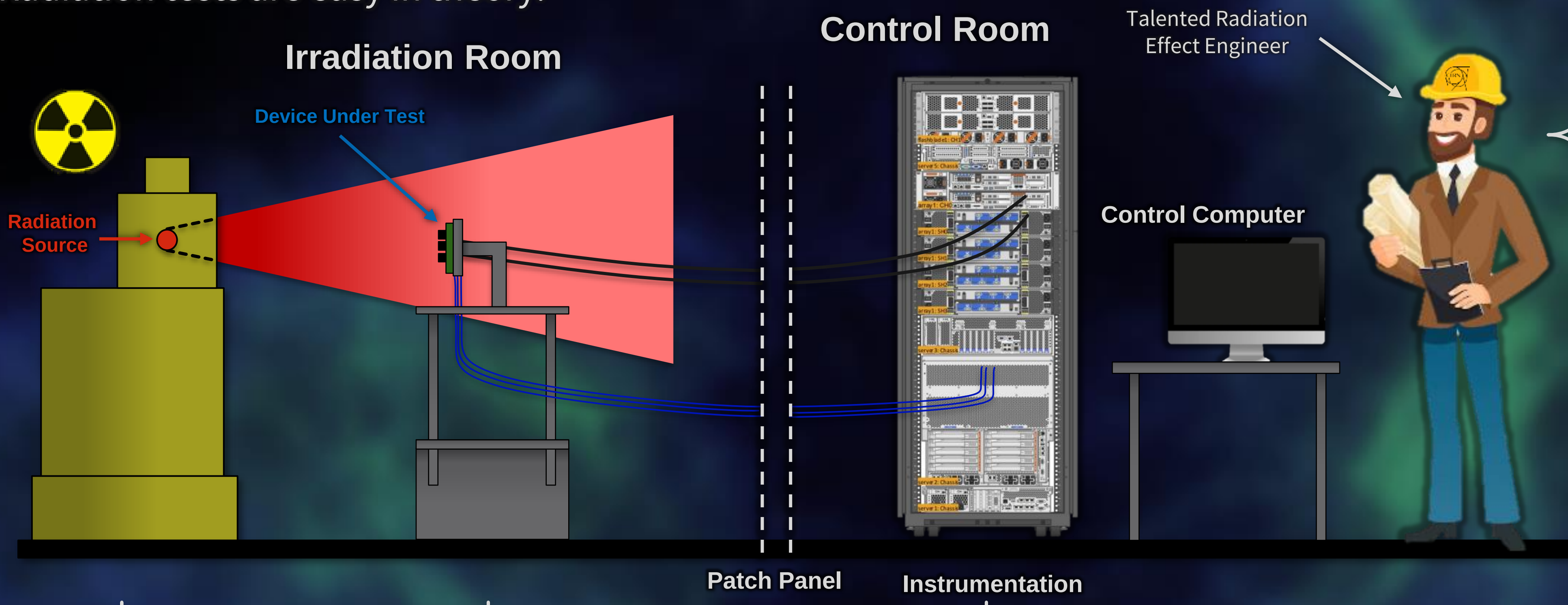


How to estimate damage in operation?

How the effects combine at system-level?

What failure rate uncertainty is satisfying?

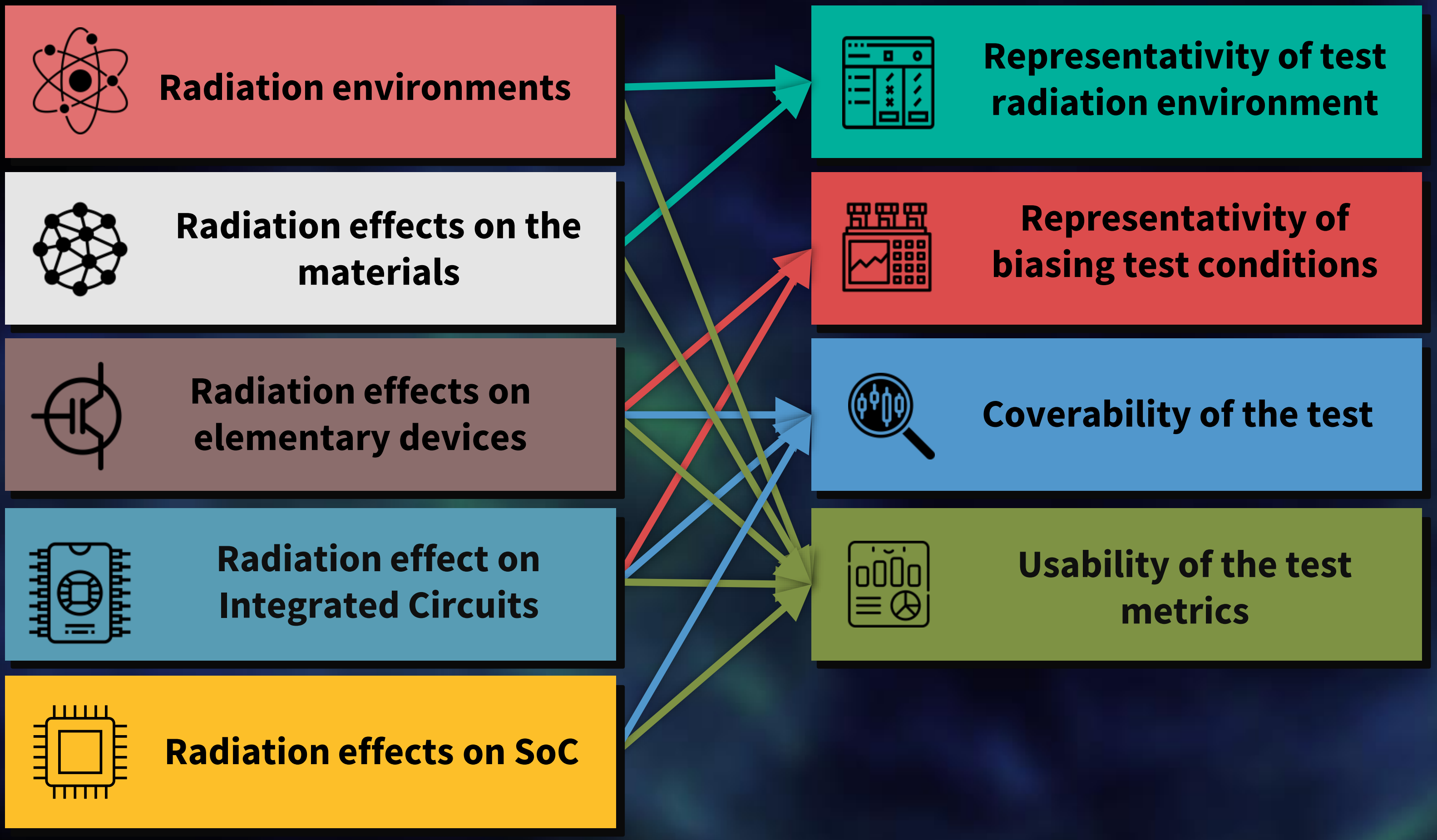
What Radiation source(s) to use?
What flux/dose rate?
Continuous flux?

What to test? What to measure?
What to expect?

How to test? Biased? Unbiased? Static? Dynamic?
Real time monitoring or step-by-step characterization?

Radiation Testing Challenges

Reliable component qualification is obtained through a wide variety of knowledges and activities:



Radiation environments

Radiation effects on the materials

Radiation effects on elementary devices

Radiation effect on Integrated Circuits

Radiation effects on SoC

Representativity of test radiation environment

- Type/Energy of test particle(s)
- Radiation Effect(s)
- Flux, Dose Rate

Representativity of biasing test conditions

- Passive or active irradiation?
- Dynamic or static biasing?

Coverability of the test

- Circuit-level degradation
- Knowledge of failure modes
- Error propagation

Usability of the test metrics

- Should allow a fine estimation in operation

CERN RHA & Testing Challenges

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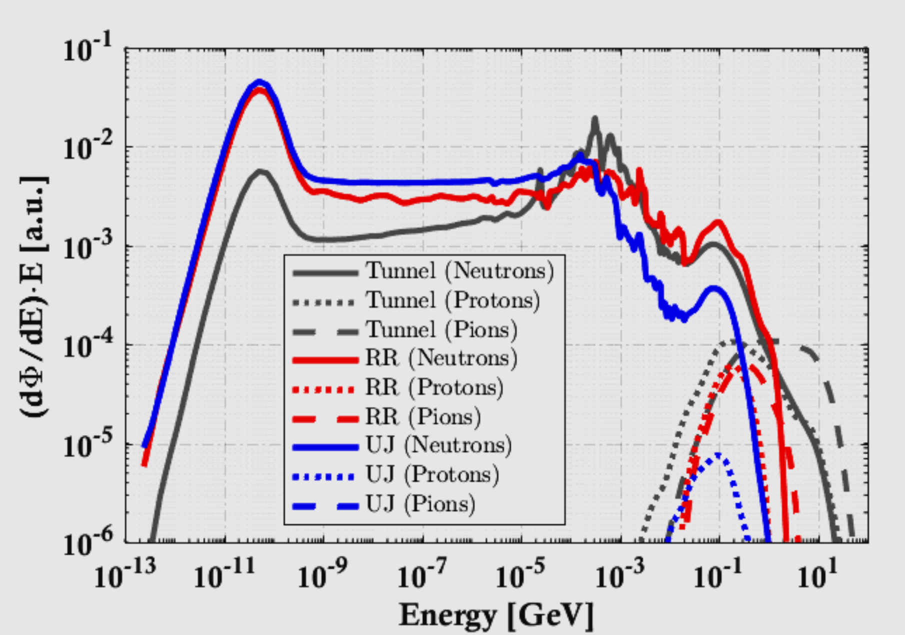
CERN Radiation Environments

- The radiation environment defines all the testing and qualification strategy
- The composition is obtained through FLUKA simulations benchmarked by different types of radiation sensors (RadFETs, Pin Diodes, SRAMs, RPL, optical fibers, Beam Loss Monitors…)
- The LHC Spectra are composed of various particle types (protons, pions, photons, muons, neutrons etc…) and energy (from meV up to GeV)
- Mainly a neutron-dominated environment
- Can be divided in three representative areas:



LHC Tunnel Spectra FLUKA simulation

Tunnel

- High Energies (up to tens of GeV)
- High hadrons contributions

RR (slightly Shielded)

- High energies relatively attenuated
- Hadron contributions attenuated

UJ (Heavily Shielded)

- High energies strongly attenuated
- Hadron contributions negligible

- Very different from space environment, more similar to nuclear reactor environments

CERN RHA & Testing Challenges

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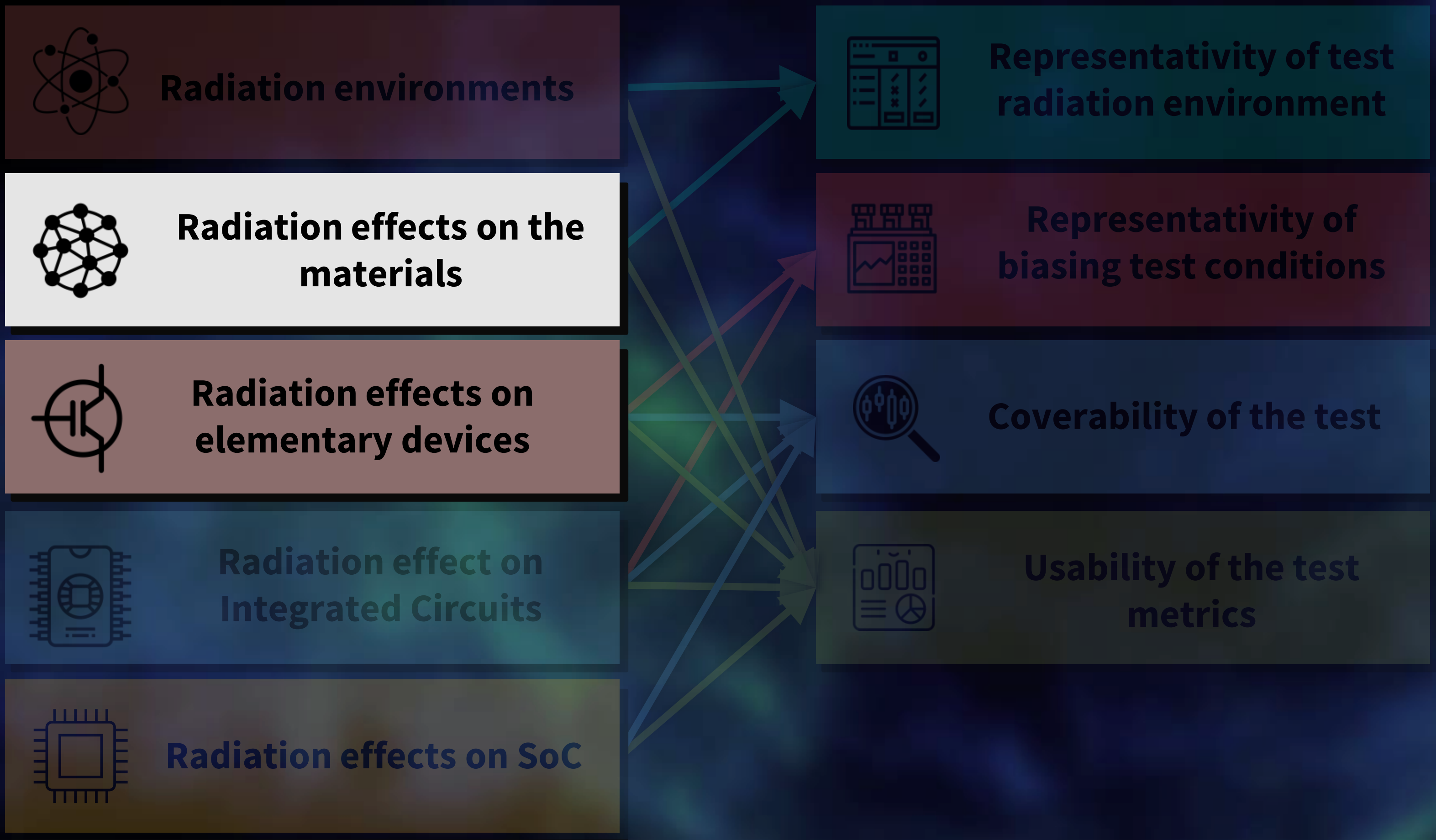

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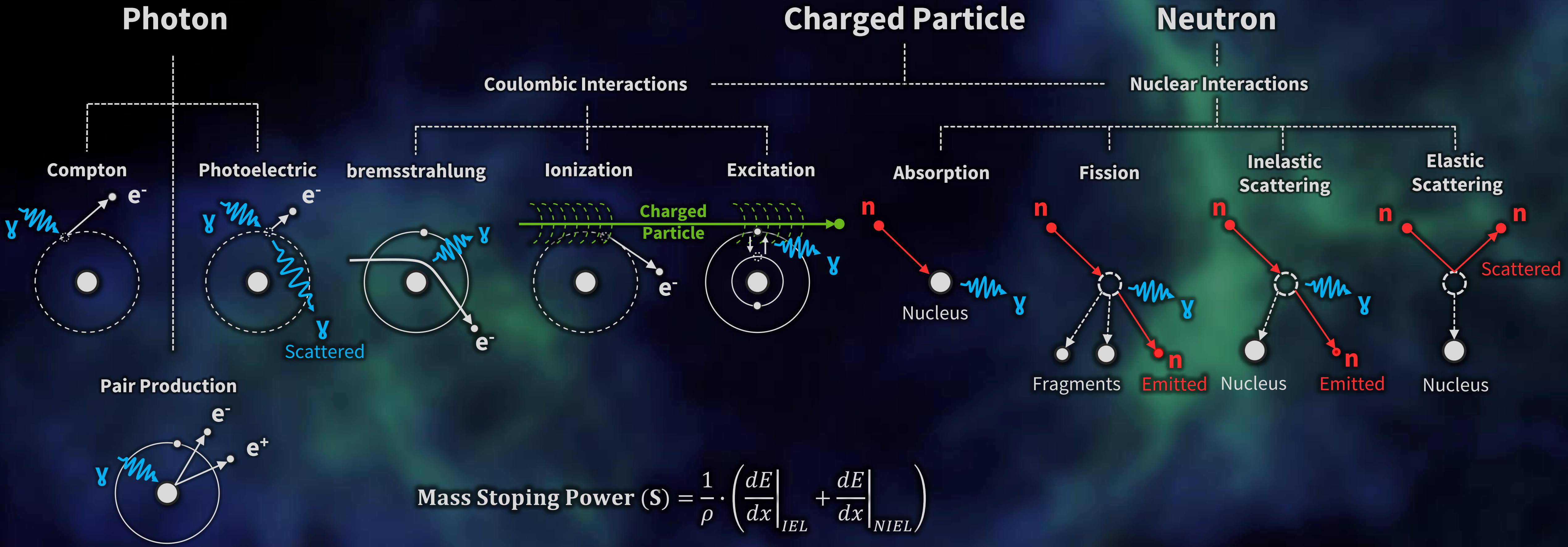
Radiative Particle Interactions



$$\text{Mass Stoping Power (S)} = \frac{1}{\rho} \cdot \left(\left. \frac{dE}{dx} \right|_{IEL} + \left. \frac{dE}{dx} \right|_{NIEL} \right)$$

IEL: Ionizing Energy Loss
NIEL: Non-Ionizing Energy Loss

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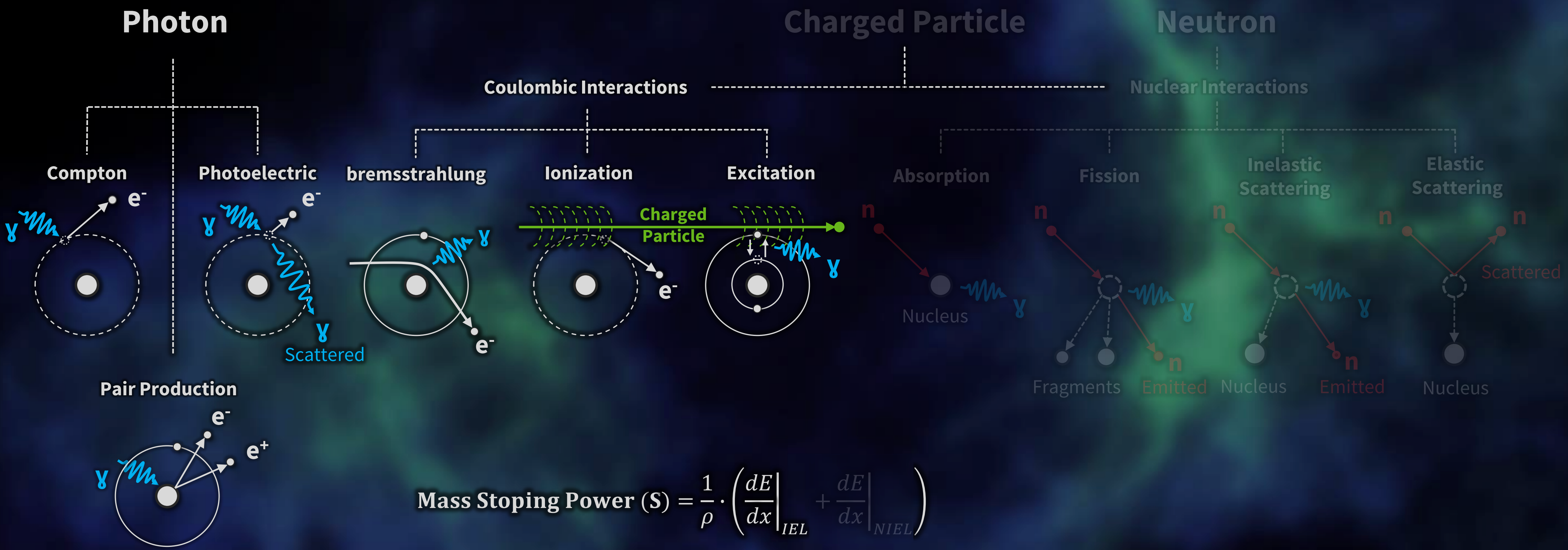

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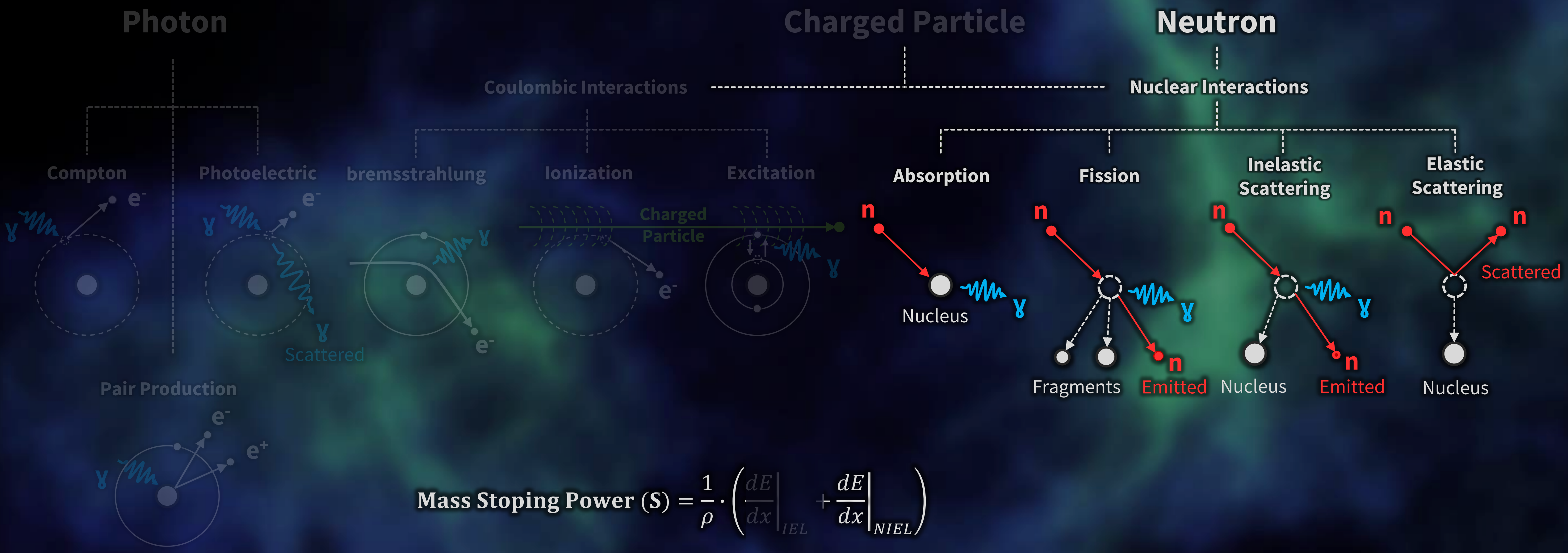

Photon

- Compton
- Photoelectric
- Pair Production

Charged Particle

- Coulombic Interactions
  - bremsstrahlung
  - Ionization
  - Excitation

Neutron

- Nuclear Interactions
  - Absorption
  - Fission
  - Inelastic Scattering
  - Elastic Scattering

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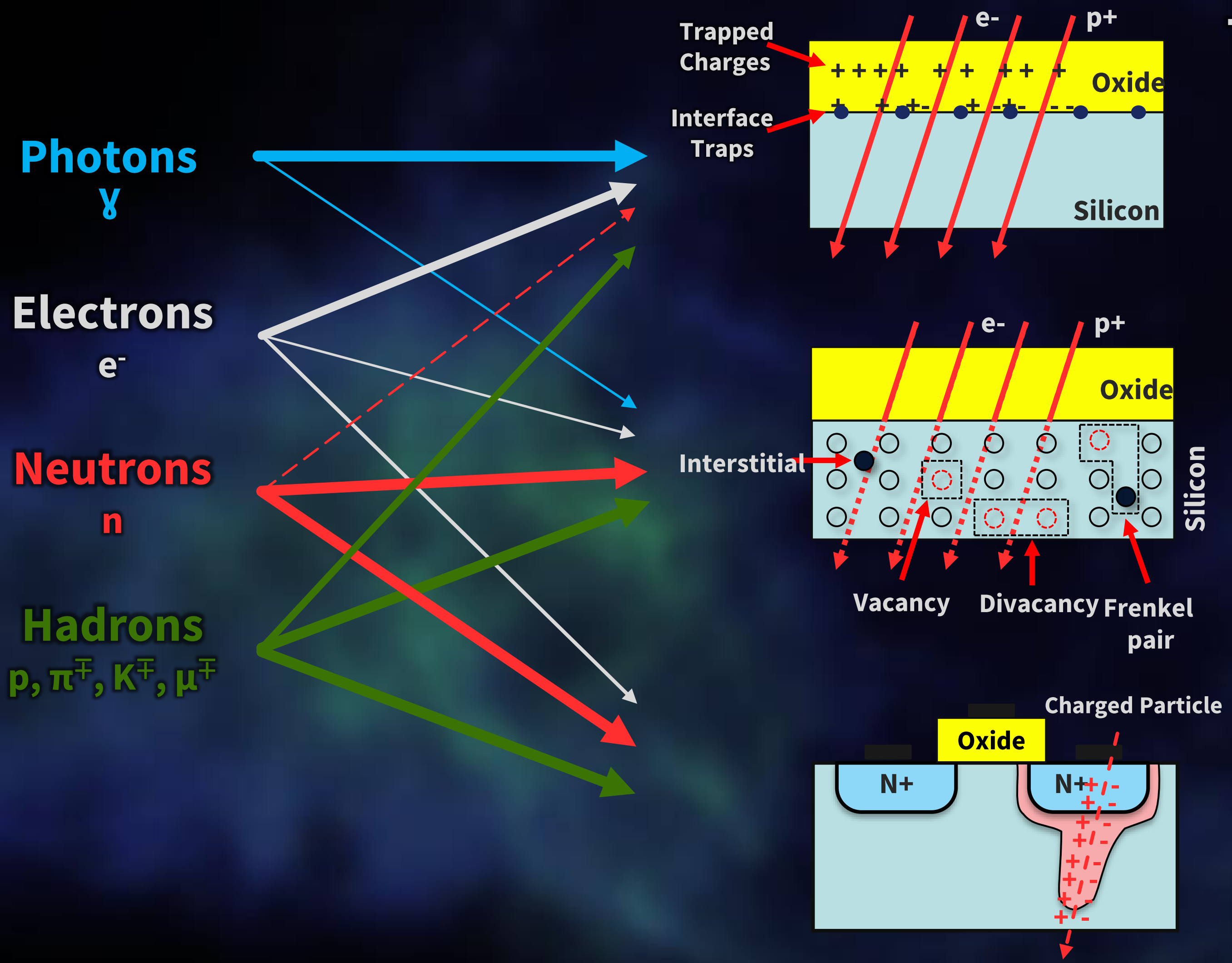
Radiation Effects on semiconductors



Total Ionizing Dose (TID)

- **Effect:** electron-hole pair generation in silicon oxide
  → positive charge trapped
- **Units: Gray (Gy)** → 1Gy = 100 rad = 1J/kg
- **Device Affected:** MOSFET, Bipolar Junction Transistor (BJT),

Displacement Damage (DD)

- **Effect:** Create defect in crystal lattice by atom displacement
- **Metric: D**isplacement **D**amage **E**quivalent **F**luence (**DDEF**)
- **Units:** neq.cm^{-2}
  → Amount of 1 MeV neutron fluence necessary to induce an equivalent DD to the fluence of the considered particle
- **Device Affected:** BJT, Optoelectronic

Single Event Effects (SEE)

- **Effect:** Create defect in crystal lattice by atom displacement
- **Metric:** High Energy Hadron Fluence (>20 MeV) (**HeH**)
- **Unit:** HeH.cm^{-2}
- **Device Affected:** MOSFET, BJT, Optoelectronic

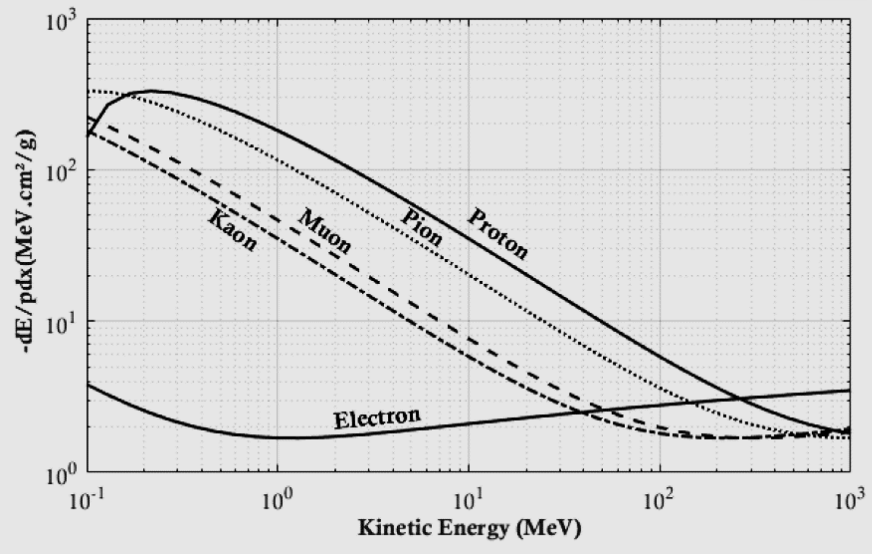
Total Ionizing Dose (TID)

Total Ionizing Dose is calculated from the particle Linear Energy Transfer (LET): $TID\ [\mathrm{Gy}] = K_{Gy}\cdot\frac{LET(E)}{\rho}\cdot\ \Phi(E)$

Φ: particle fluence in p.cm^{-2}
ρ: mass density in cm^{2}.g^{-1}
K_{Gy}: unit conversion factor 1.6 × 10^{-7} Gy.g.MeV^{-1}

$$LET = \left.\frac{dE}{dx}\right|_{IEL}$$

Berthe-Bloch formula:



$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e^2 c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - \frac{2C}{Z}\right]$$

$2\pi N_a r_e^2 m_e^2 c^2$ = 0.1535 MeV.cm2.g-1
r_e : electron radius (2.817 × 10-13 cm)
m_e : electron mass (511 keV)
N_a : Avogadro's number
Z : atomic number of absorbing material
A : atomic weight of absorbing material
z : charge of incident particle

β : v/c of incident particle
ρ : density of absorbing material
γ : $1/\sqrt{1-\beta^2}$: Lorentz factor
δ : density correction
C : shell correction
I : mean excitation potential
W_{max} : maximum transferable energy

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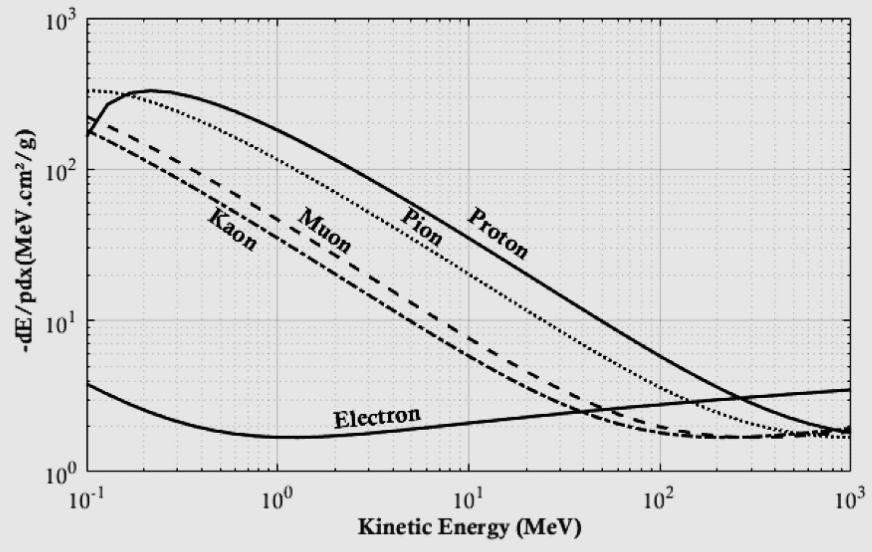
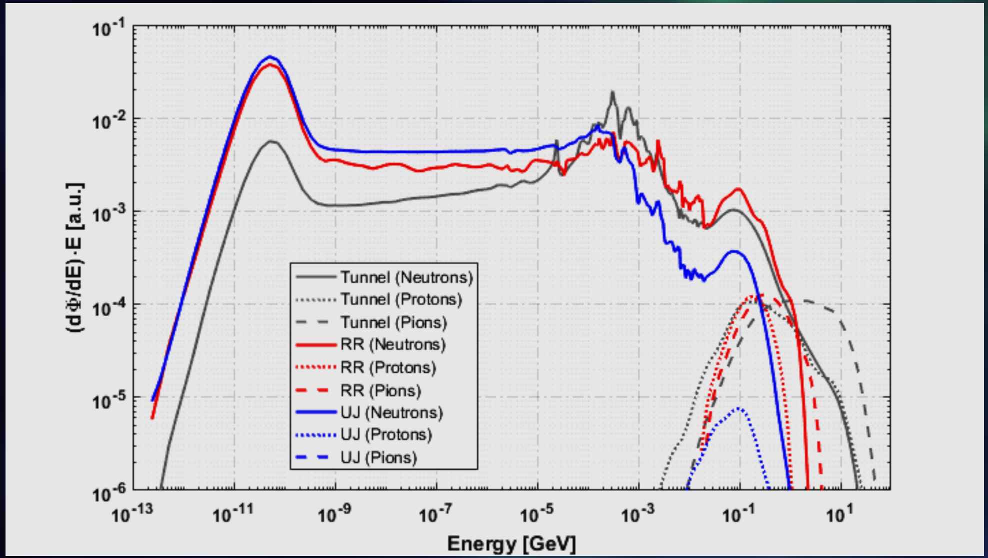




$$\underbrace{\hphantom{xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx}}$$

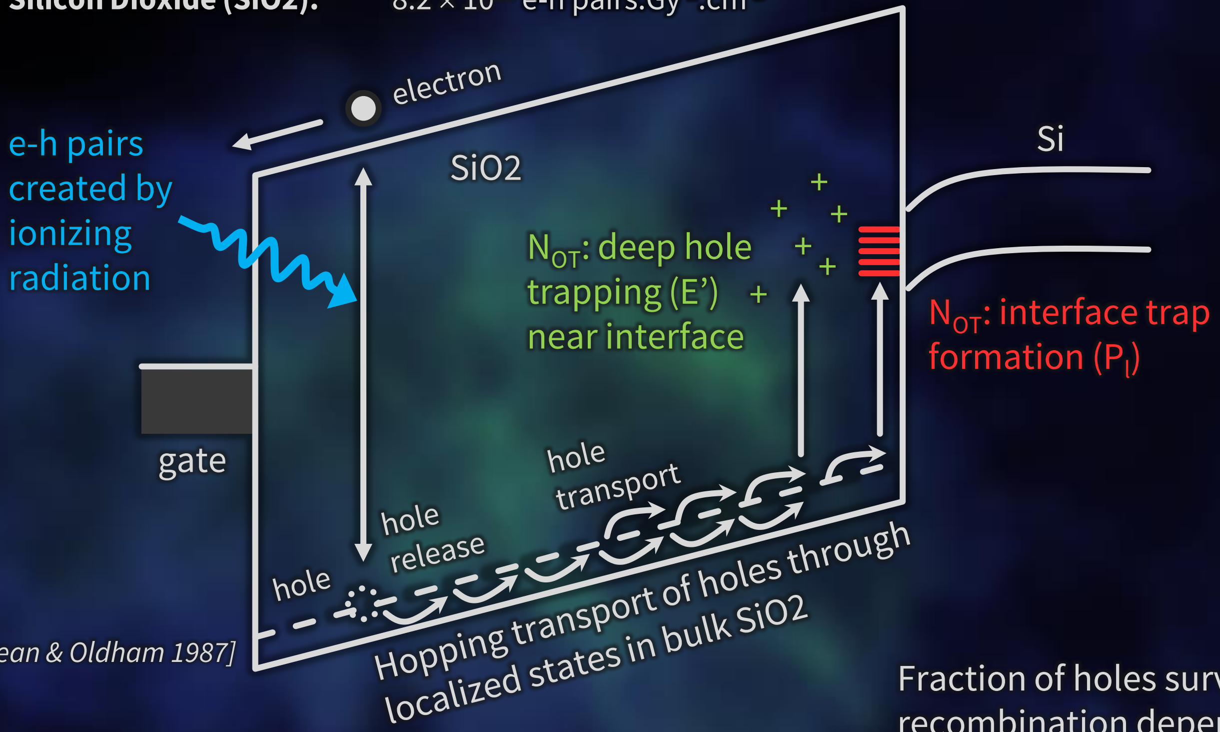
$$TID = K_{Gy} \sum_{p=e^{\pm},\pi^{\pm},p^{\pm},K^{\pm},\mu^{\pm}} \int \frac{LET(p,E)}{\rho} \cdot \Phi(p,E)\, dE$$

Total Ionizing Dose (TID)

Through ionization particles generates electron-holes pairs in semiconductor materials: $\frac{\#\mathrm{ehp}}{cm^3} = LET(E) \cdot \Phi(E) \cdot \frac{1}{\mathrm{E_p}}$

$\mathbf{E_p}$: Energy Threshold in #ehp.$\mathrm{MeV^{-1}}$
Si = 3.6, **SiO2** = 18 eV/ehp

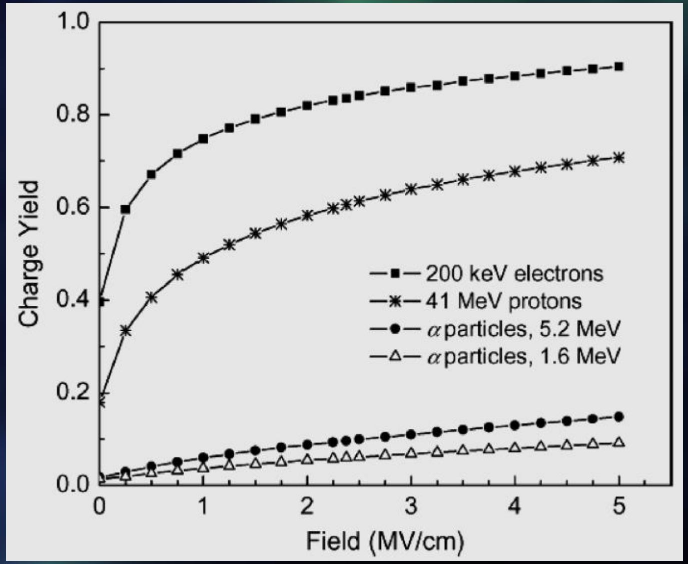
Silicon (Si): 4×10^{15} e-h pairs.$\mathrm{Gy^{-1}.cm^{-3}}$
Silicon Dioxide (SiO2): 8.2×10^{15} e-h pairs.$\mathrm{Gy^{-1}.cm^{-3}}$



[McLean & Oldham 1987]

Several processes occur:

1) Electron-Hole pair generation
2) Electron-hole pair recombination



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Fraction of holes surviving the recombination depends on particle **type** and **energy** and the **electric field**

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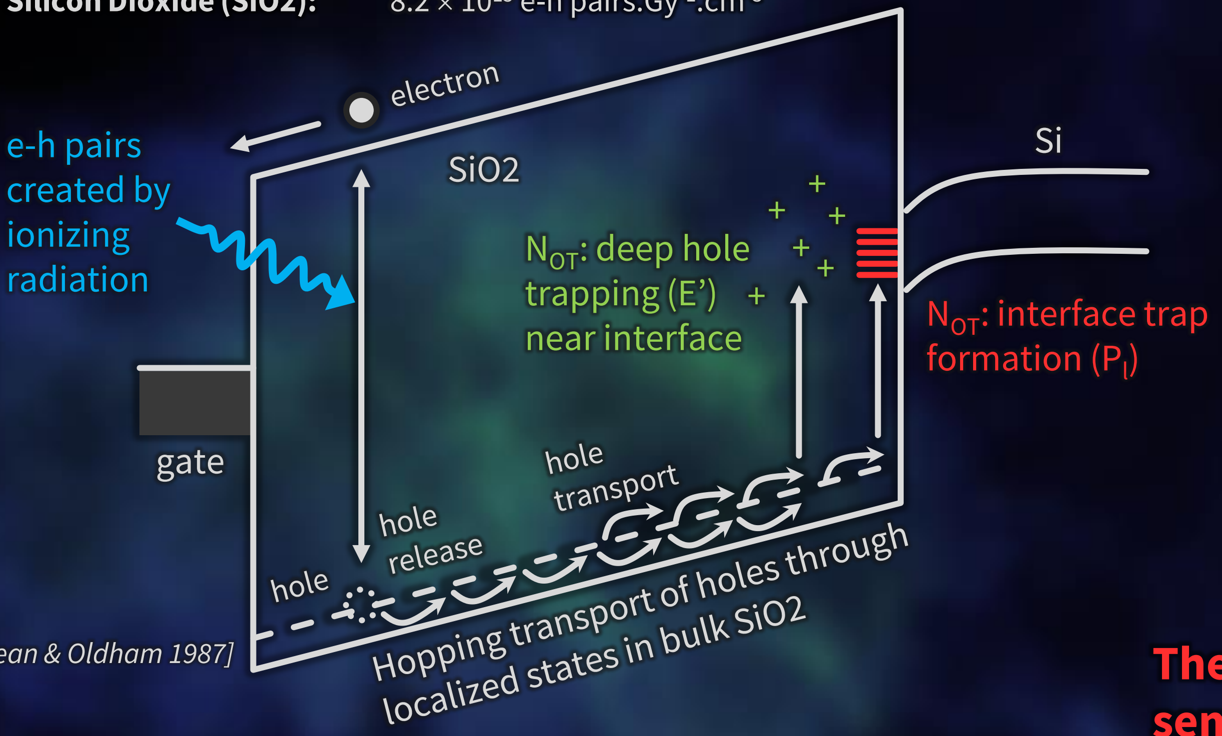


[McLean & Oldham 1987]

Several processes occur:

1) Electron-Hole pair generation
2) Electron-hole pair recombination
3) Hole transport
4) Defect formation:
    - Fixed oxide-trapped-charge (N_{OT})
    - Interface traps (N_{IT})

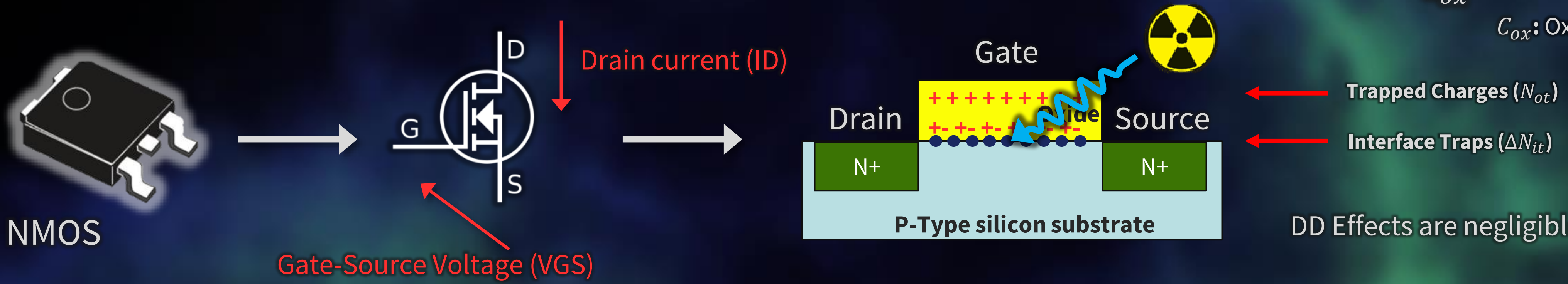
The two defect mechanisms are responsible for the semiconductor parametric degradation

Radiation Effects on MOSFETs

Main degradation mechanism is the voltage threshold shift:

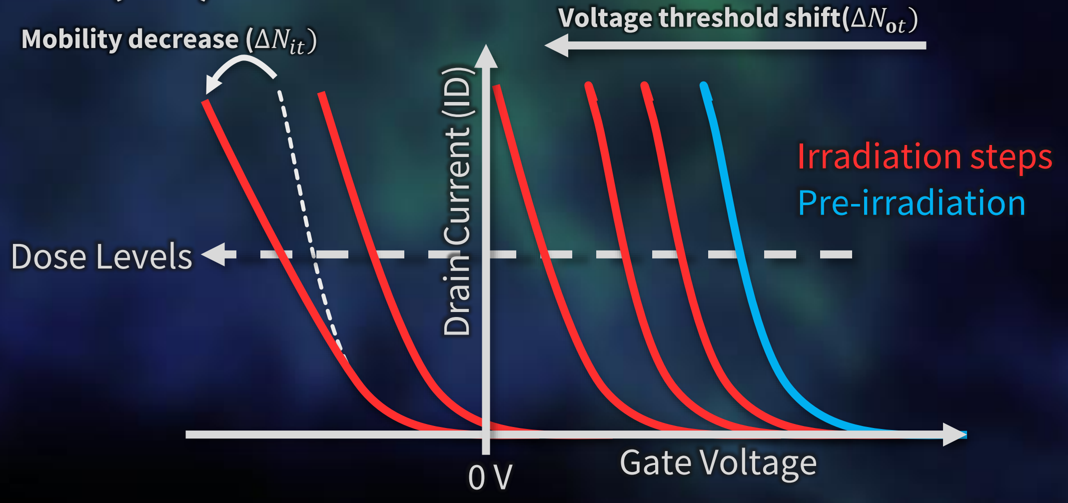
$$\Delta V_{th} = -q\frac{1}{C_{ox}}\Delta N_{ot} \pm -q\frac{1}{C_{ox}}\Delta N_{it}$$

C_{ox}: Oxide capacitance

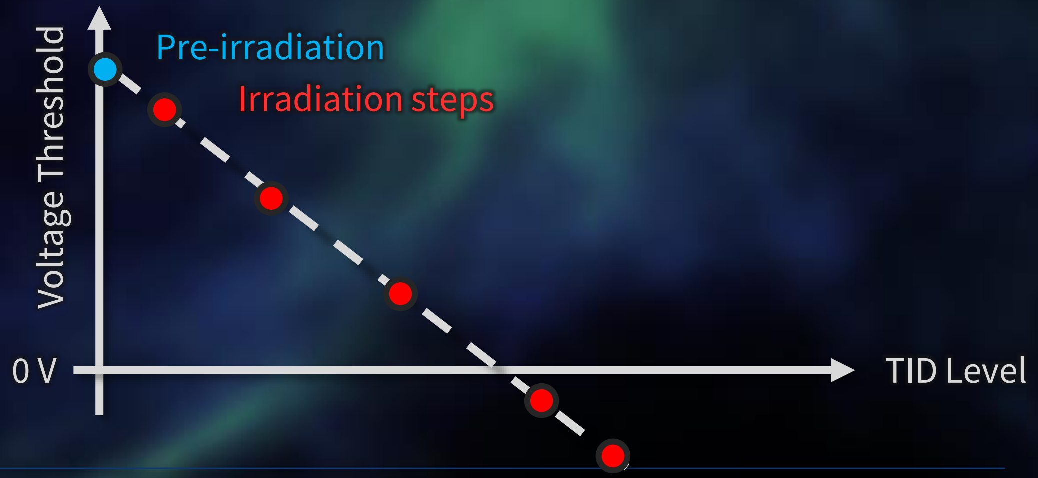


DD Effects are negligible on MOSFET

ID = f(VGS) characteristics:



Voltage Threshold Shift:



Radiation Effects on MOSFETs

Main degradation mechanism is the voltage threshold shift due to TID:

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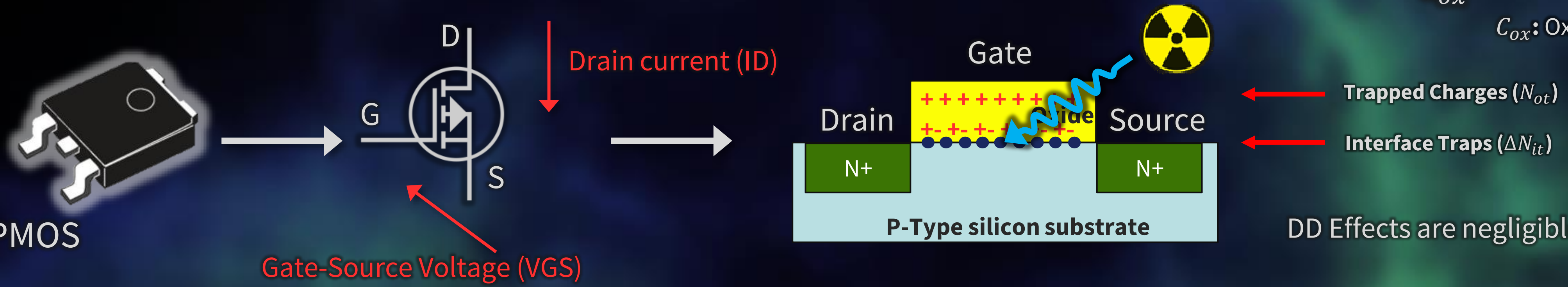

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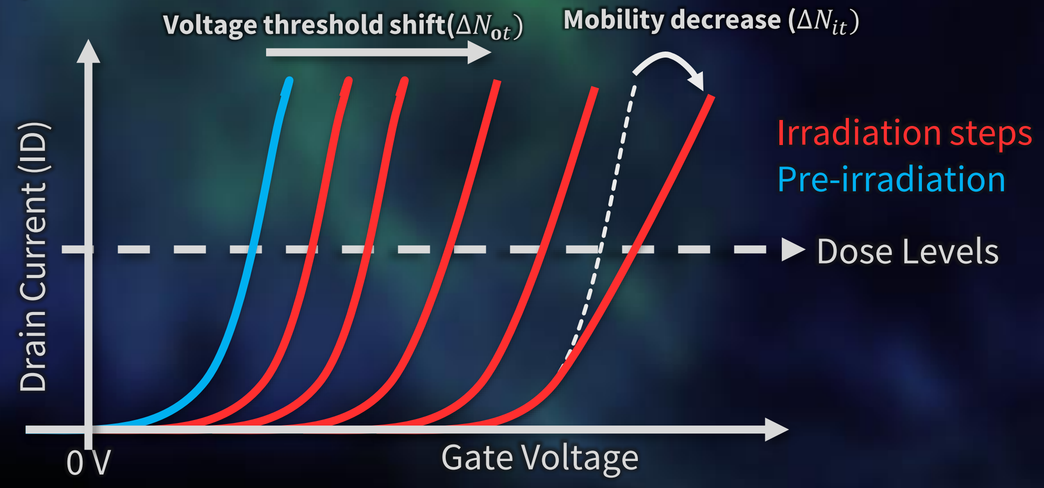
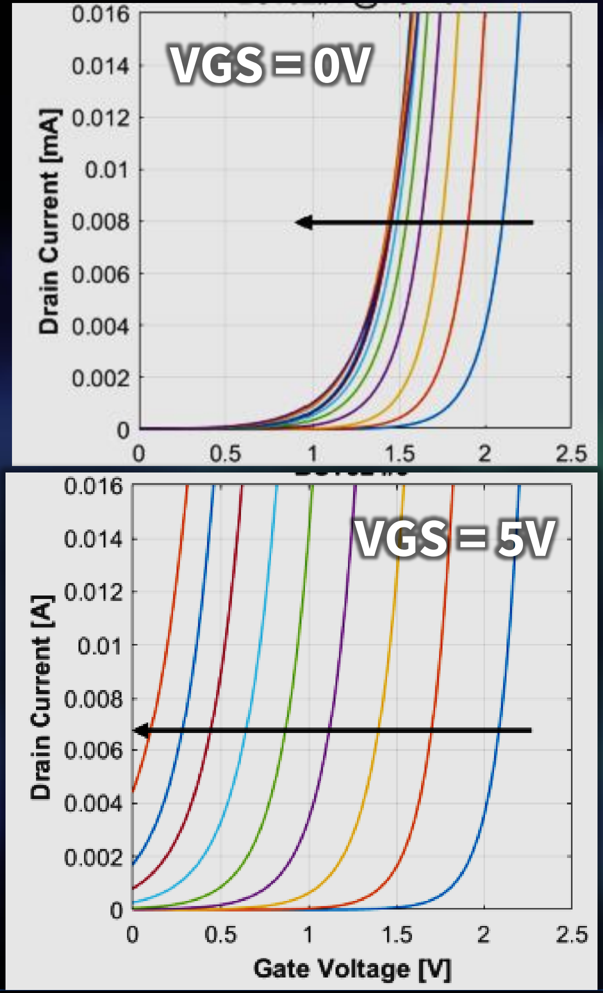


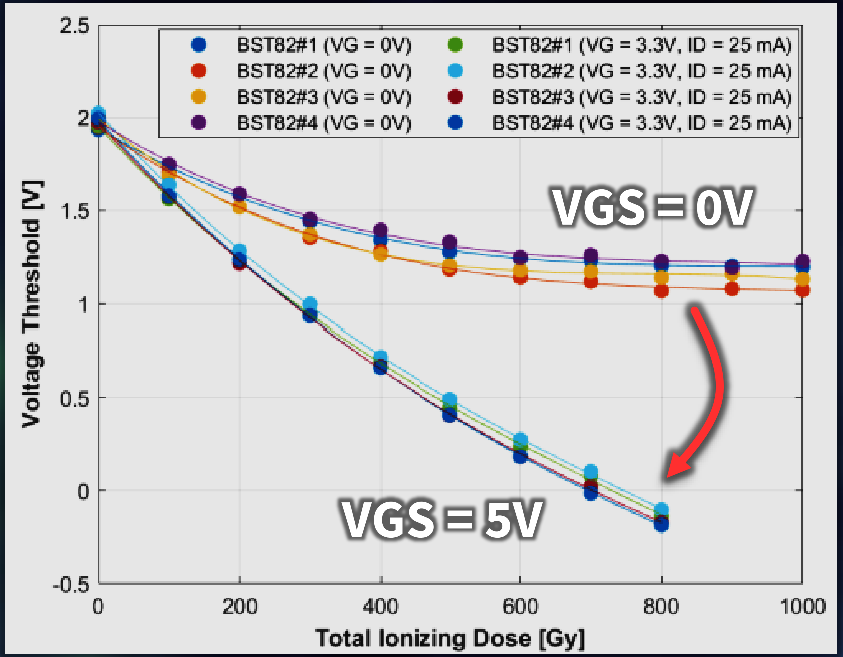
Voltage Threshold Shift:

Example of MOSFET degradations

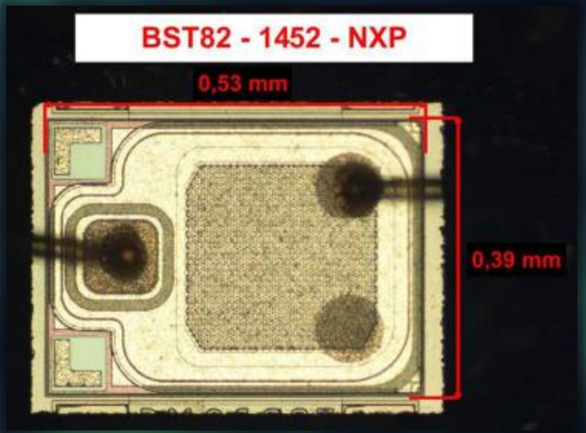
Voltage Threshold shift examples of MOSFET used in LHC systems:



Voltage Threshold Shift against TID:



BST82 NMOS:



Response sublinear when unbiased tend to linear with high electric field

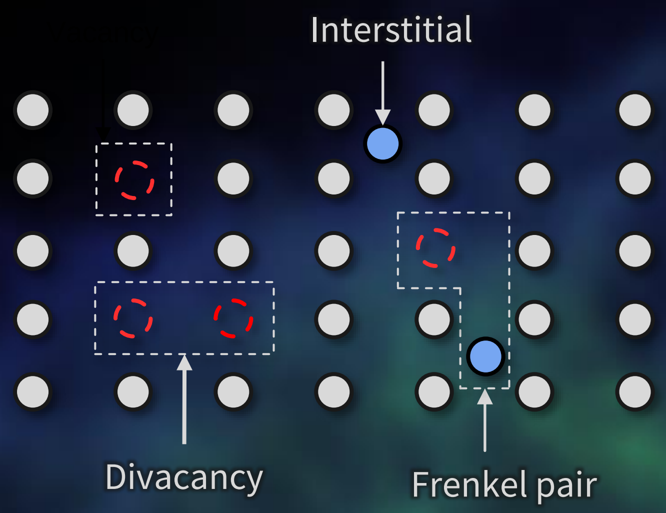
MOSFET degradation rate is dependent on the biasing conditions:

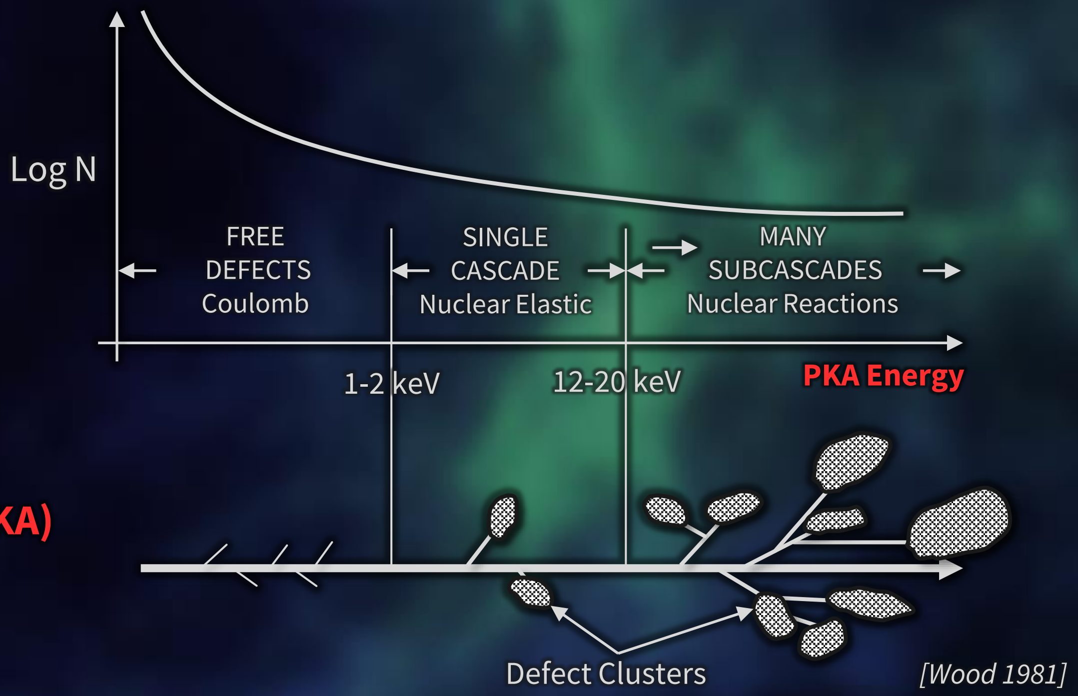
Higher the VGS, higher the degradation

→ Impact of electric field on the eh recombination rate

Displacement Damage (DD) Effects

Displacement Damage is generated through coulombic or nuclear scattering:





[Wood 1981]

- The atom initially displaced is called **Primary Knock-on Atom (PKA)**
- A single incident particle can create many PKAs
- A PKA can create other defects in return
- Displacement cascades can create large defect clusters
- The number of Frenkel pairs is directly proportional to the PKA and incident particle **Non-Ionizing Energy Loss (NIEL)**

Displacement Damage (DD)

- Non-Ionizing Energy Loss **(NIEL) scaling hypothesis**:

  → **DD induced by a particle are proportional to their NIEL in the material**

- Several units exist to quantify DD:

Displacement Damage Dose (DDD)

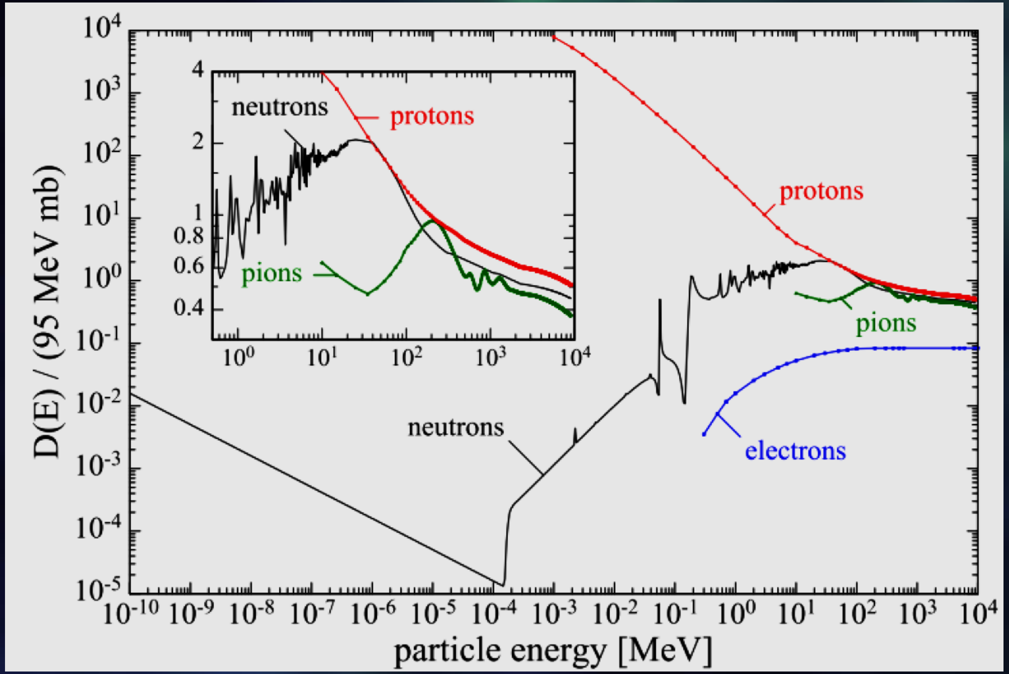
$$DDD = K_{Gy} \cdot \frac{NIEL(E)}{\rho} \cdot \Phi(E) \qquad [\mathrm{Gy\ or\ MeV.g^{-1}}]$$

Displacement Damage Equivalent Fluence (DDEF)

$$DDEF = \Phi_{1MeV\ neq.} = \frac{NIEL(E)}{NIEL(n_{1\ MeV})} \cdot \Phi(E)$$

$$DDEF = \sum_{p=e^{\pm},\pi^{\pm},p^{\pm},K^{\pm},\mu^{\pm}} \int \kappa(\mathrm{p},\mathrm{E}) \cdot \Phi(p,E)\,\mathrm{dE}$$

Silicon NIEL Models:

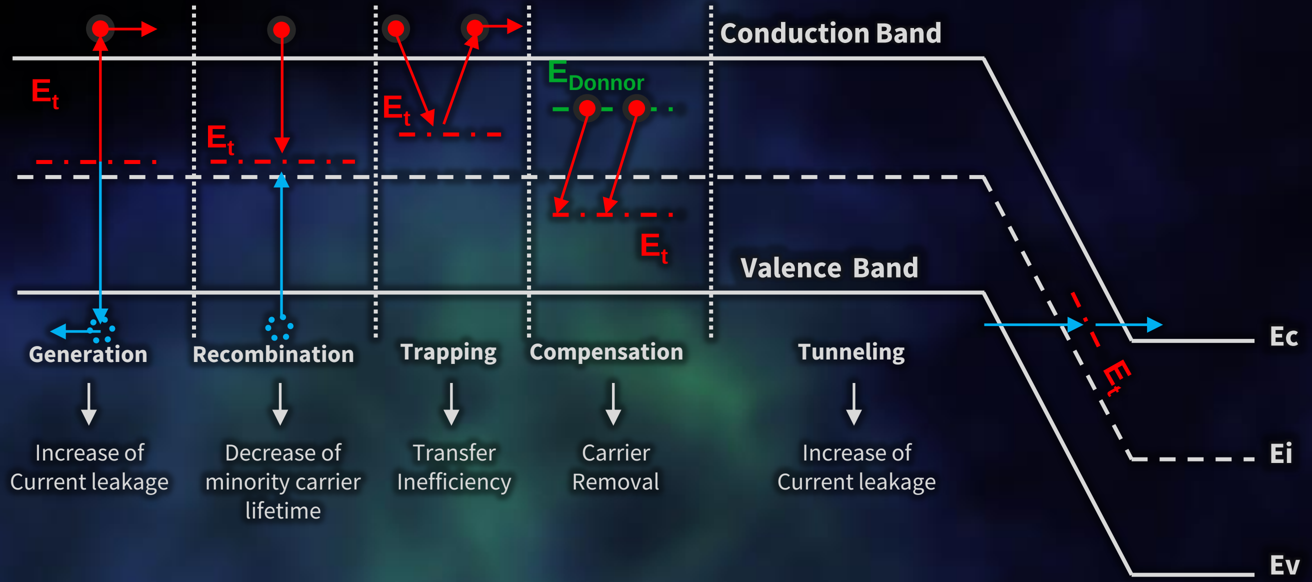


[A. Vasilescu (INPE Bucharest) and G. Lindstroem (University of Hamburg)]

The DDEF is more commonly used at CERN and in the community in general

Displacement Damage (DD)

Displacement Damage defects can have impact on different semiconductor processes:



Thermal Generation

Generation of electron-holes pairs, **increase the current leakage**

Recombination

Electron-hole pairs are captured and recombined → **Decrease of minority carrier lifetime**

Temporary Carrier trapping

A majority or a minority carrier is captured and then emitted back without capture

Donors/acceptors Compensation

Reduction of minority/majority carrier equilibrium through carrier removal

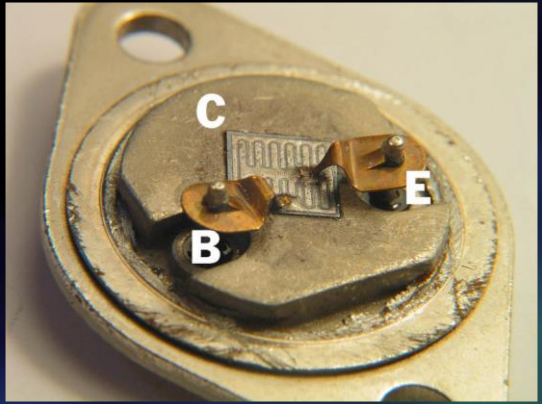
Carriers Tunnelling

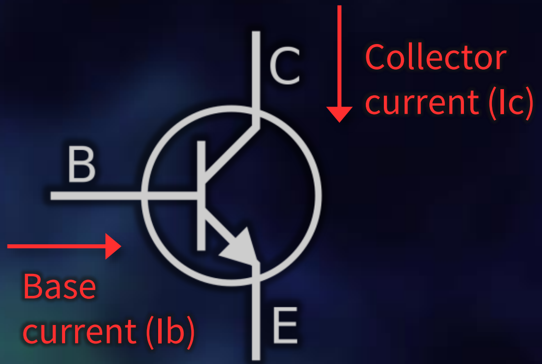
Carriers tunnelling through potential barriers due to defect levels → **increase current leakage**

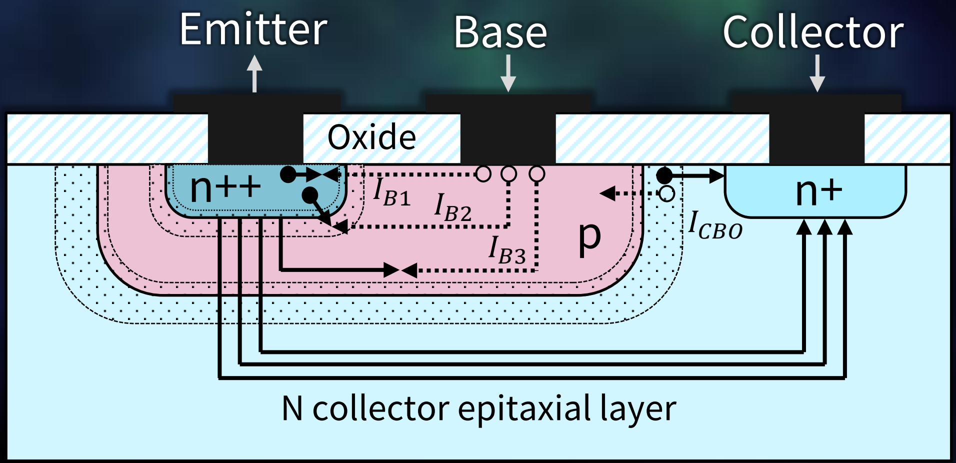
The different processes will induce different parametric degradations depending on device type

Radiation Effects on Bipolar Junction Transistor (BJT)

Bipolar Transistors are affected by both TID and DD:







Current-Gain (h_{fe}) degradation: $\downarrow h_{fe} = \frac{I_C}{\uparrow I_B}$

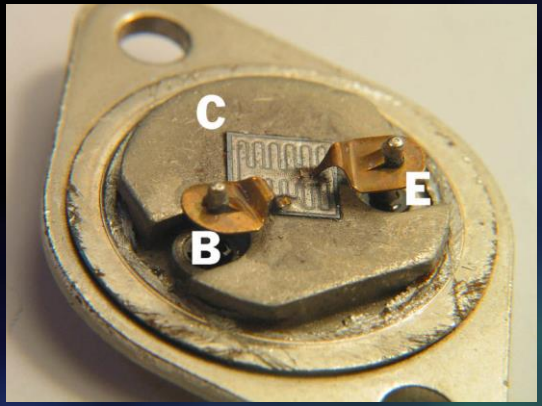
Base current composition:

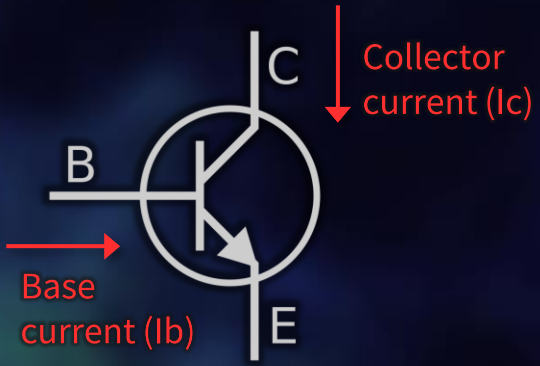
$$\frac{1}{h_{fe_0}} = \frac{\Delta I_{B1}}{I_{C_0}} + \frac{\Delta I_{B2}}{I_{C_0}} + \frac{\Delta I_{B3}}{I_{C_0}}$$

ΔI_{B1}: back-injection from base to emitter hole diffusion
ΔI_{B2}: recombination in the depletion area
ΔI_{B3}: recombination in the neutral base

Radiation Effects on Bipolar Junction Transistor (BJT)

Bipolar Transistors are affected by both TID and DD:





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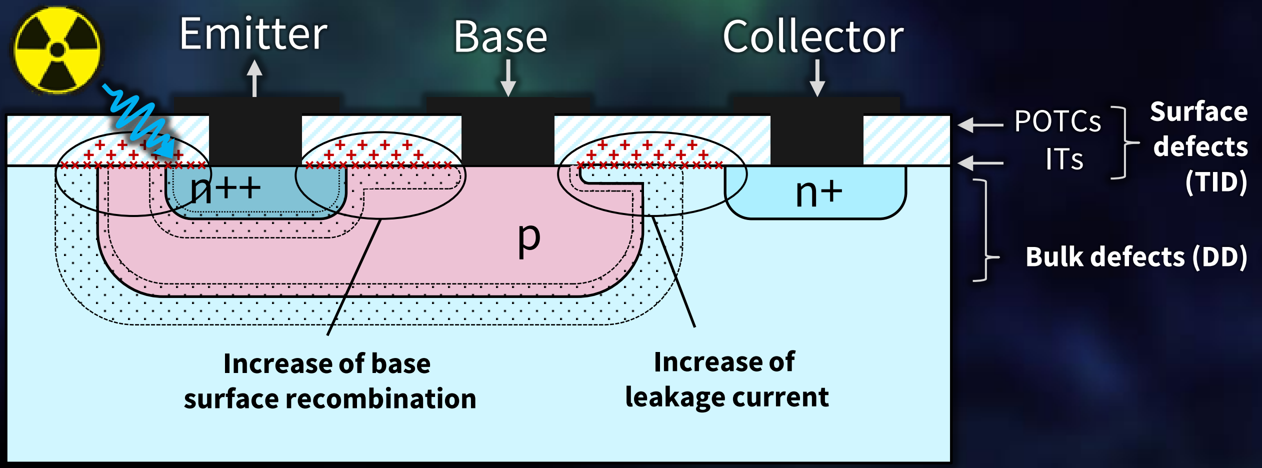
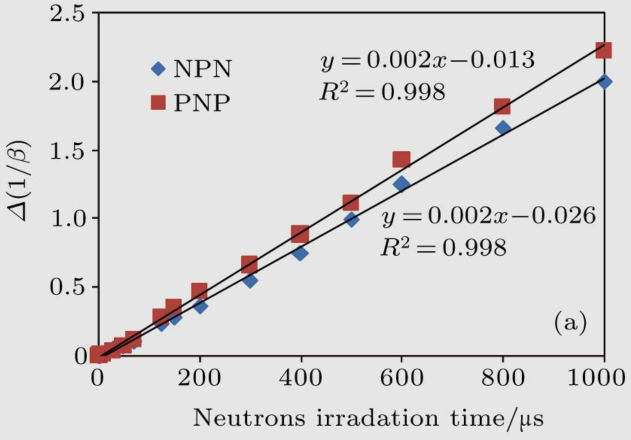


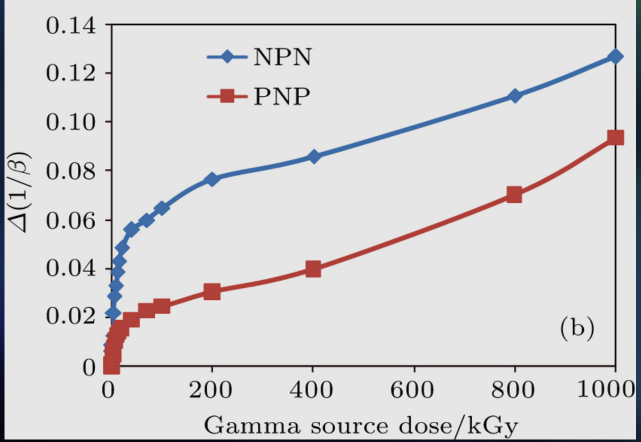
$$\frac{1}{h_{fe}} = \frac{1}{h_{fe_0}} + \frac{1}{h_{fe_{TID}}} + \frac{1}{h_{fe_{DD}}}$$

TID and DD effects are independent

Radiation Effects on Bipolar Junction Transistor (BJT)

Increase of base current due DD is linear while the one of TID is not:





[Assaf J. 2018]

DD Current-Gain (h_{fe}) degradation:

Linked to minority carrier lifetime decrease → Linear degradation

$$\frac{1}{\Delta\tau} = \frac{1}{\tau} - \frac{1}{\tau_0} = v_{bulk}\sigma\Delta N_T = K_\tau \cdot \Phi$$

$$\Delta I_{B3} = \frac{1}{h_{fe_{DD}}} = \frac{1}{2}\frac{{w_B}^2}{D_{pB}} K_\tau \Phi = K_{hfe_{DD}} \Phi$$

$\Delta\tau$: carrier lifetime decrease
τ τ_0: pre / post minority carrier lifetime
ΔN_T: Bulk trap increase
v_{bulk}: Bulk recombination velocity

TID Current-Gain (h_{fe}) degradation:

Linked to the increase of the depletion area (v_{surf}) and change in surface recombination rate (γ) → non-Linear degradation process

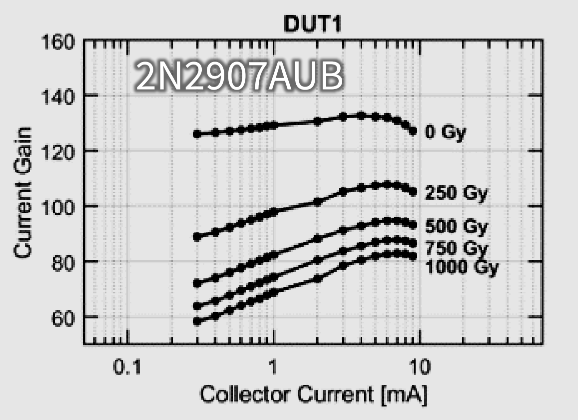
$$\Delta I_{B2} = \frac{\mathrm{qn}_i \mathrm{P}_E}{2} v_{surf} e^{\frac{\beta V_{BE}}{2}} \gamma(N_{ox}, V_{BE})$$

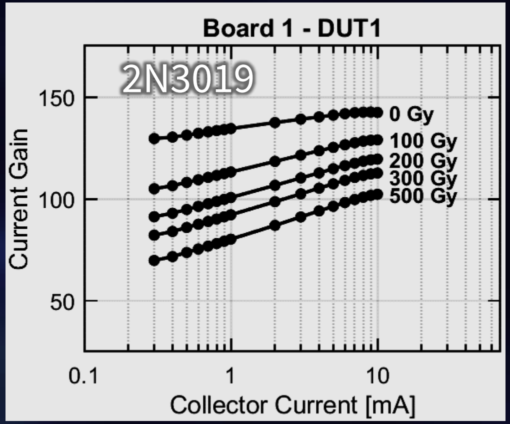
NPN more sensitive than PNP due to type of minority carriers

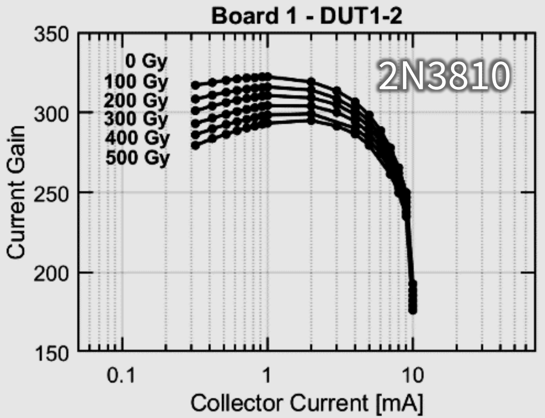
BJT Degradation Example

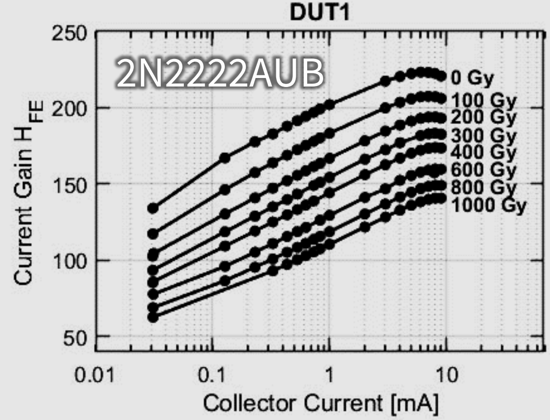
Gain degradation examples of BJT candidates to be used in LHC systems:

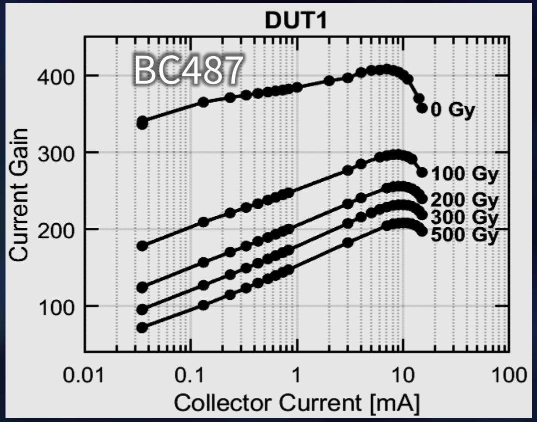
Dose

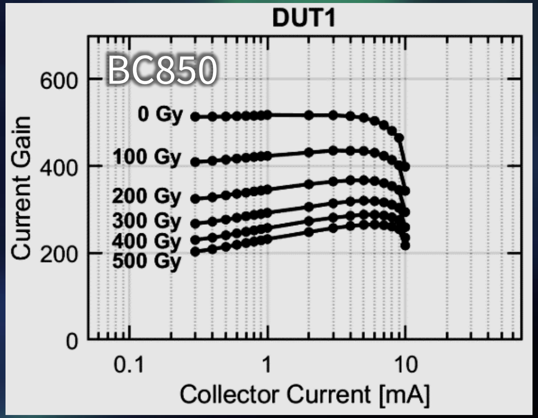






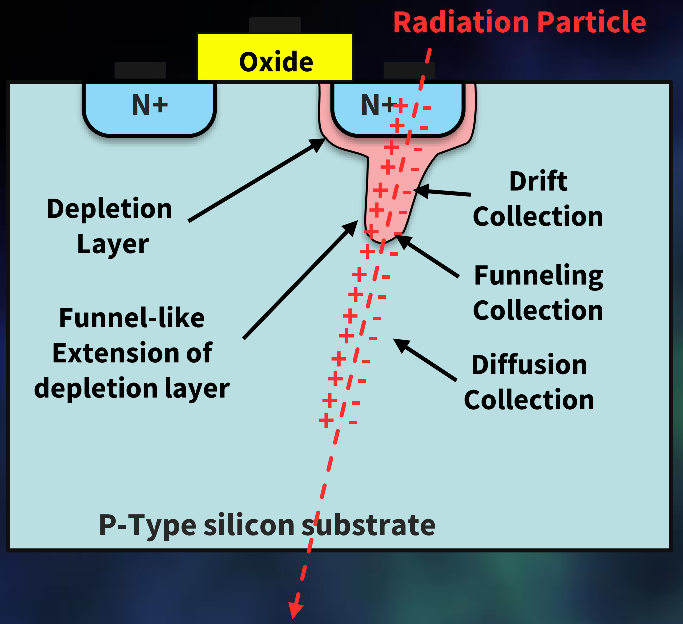


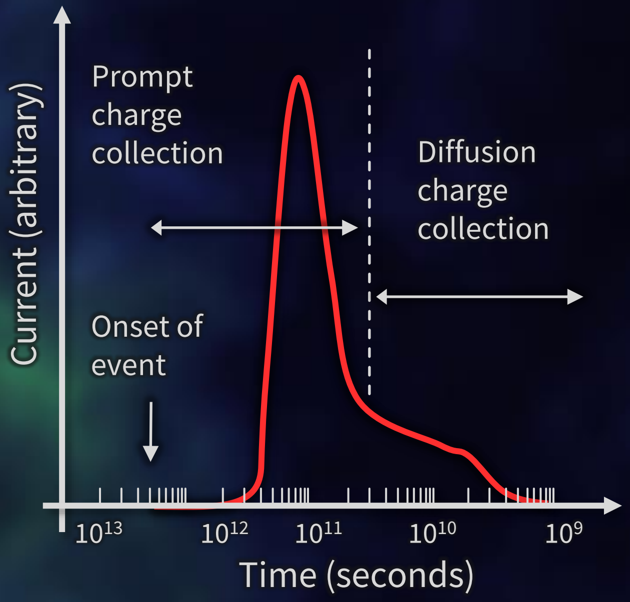




Single Event Effects (SEE)

Effects related to the interaction of a single particle:





Ionization:

A particle (through direct or indirect ionization) create an ionization path in the semiconductor generating e-h pairs

Free carrier drift/diffusion:

The free carriers can be either collected in the depletion layer or outside, extending the depletion layer and generating a local current.

→ Higher the deposited energy, higher the generated current

Trigger of non-destructive effects:

Can trigger a transient current (Single Event Transient - SET)

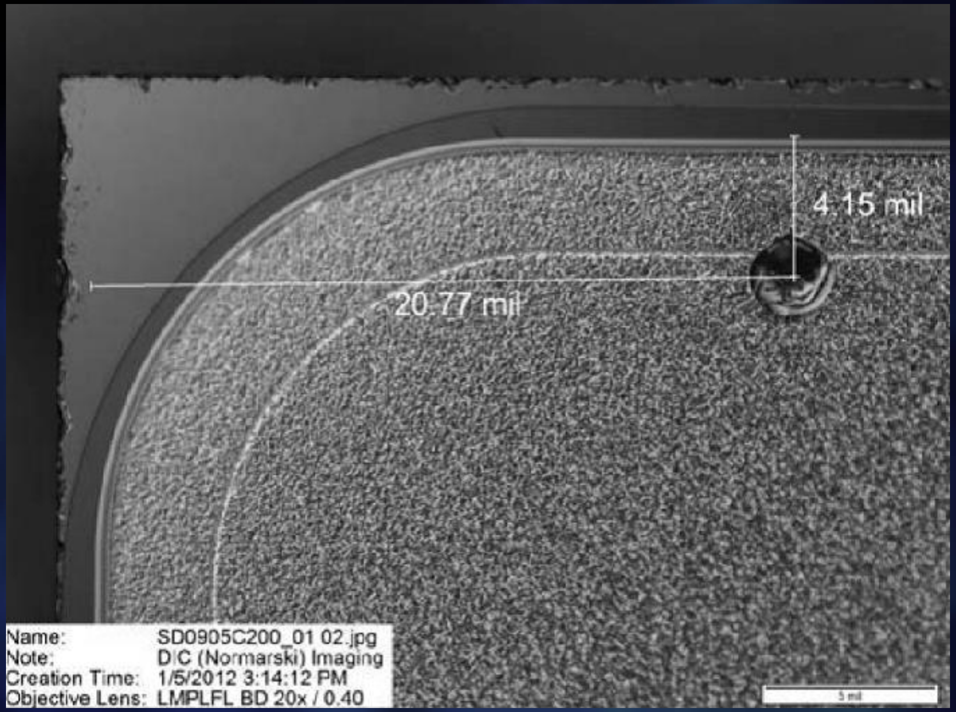
Trigger of destructive effects:

Depending on the transistor layout, with enough energy a particle can lead to destructive events:

Single Event Latchup (SEL)
Single Event Gate Rupture (SEGR)
Single Event Burnout (SEB)

Single Event Effects (SEE)

SEB on Schottky Diode:



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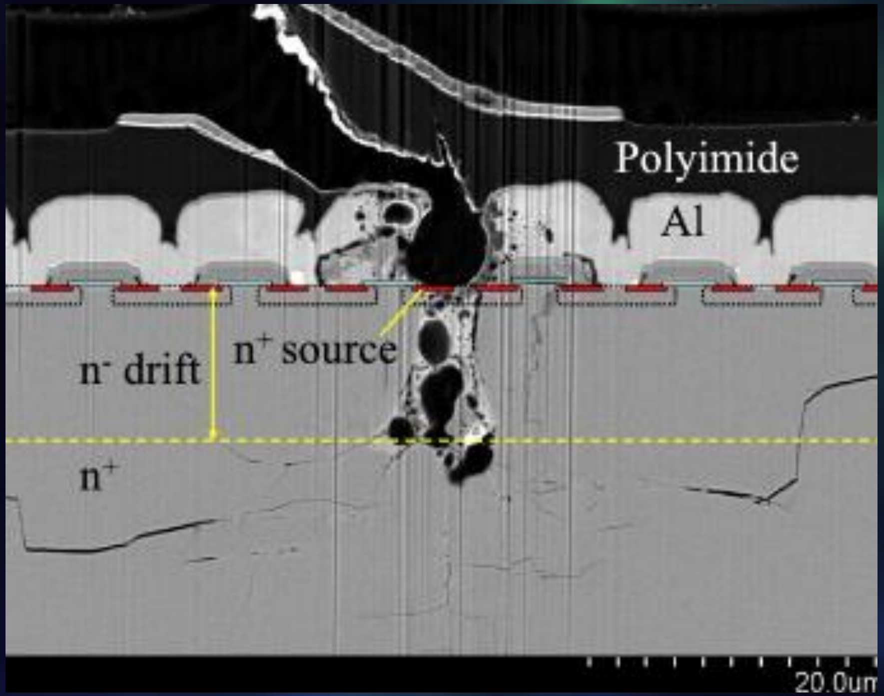
Note: DIC (Normarski) Imaging
Creation Time: 1/5/2012 3:14:12 PM
Objective Lens: LMPLFL BD 20x / 0.40

[Jeffrey 2013]

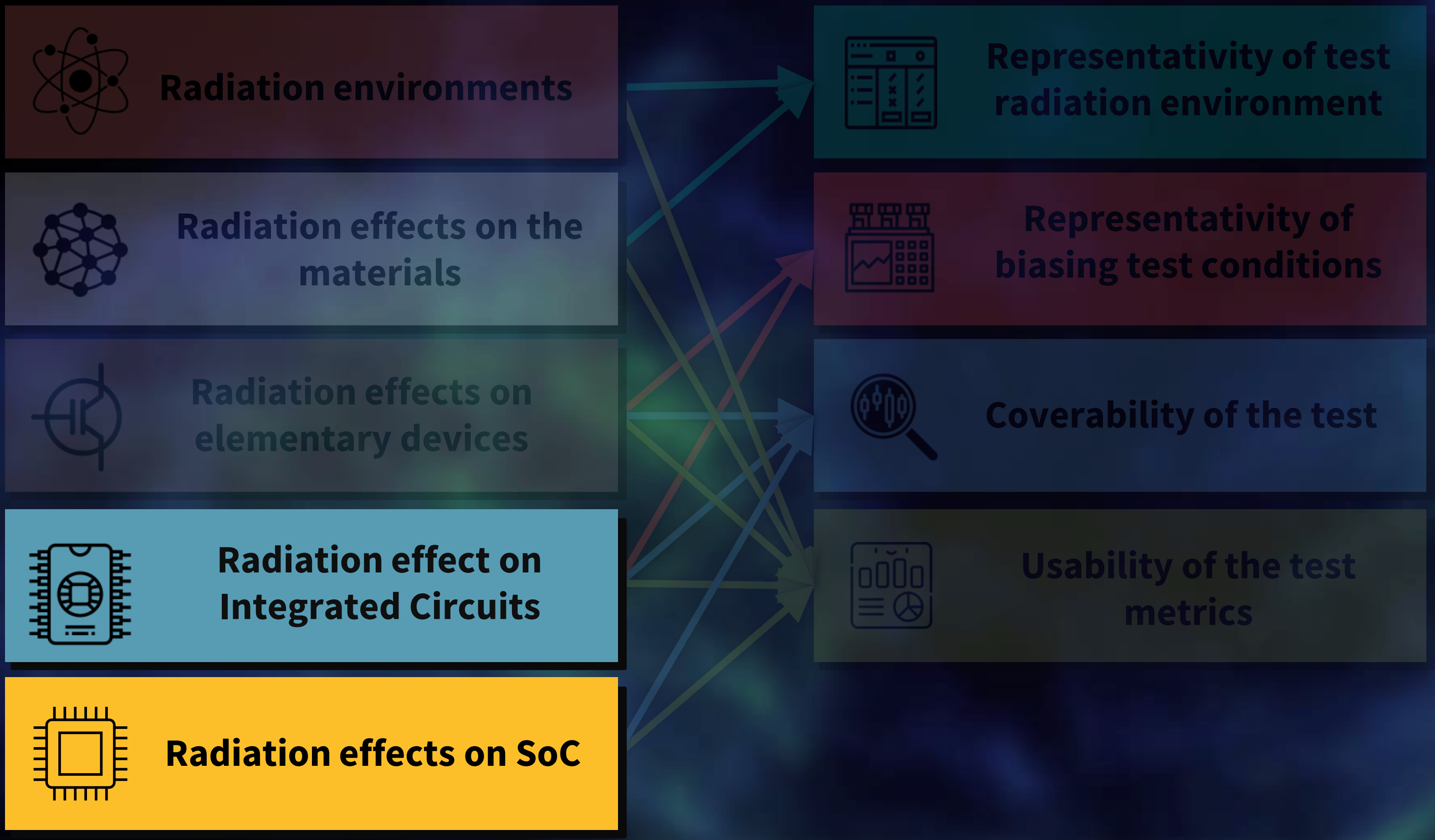
SEB on Power MOSFET:



[Shoji 2015]

CERN RHA & Testing Challenges

Reliable component qualification is obtained through a wide variety of knowledges and activities:



Radiation environments

Radiation effects on the materials

Radiation effects on elementary devices

Radiation effect on Integrated Circuits

Radiation effects on SoC

Representativity of test radiation environment

- Type/Energy of test particle(s)
- Radiation Effect(s)
- Flux, Dose Rate

Representativity of biasing test conditions

- Passive or active irradiation?
- Dynamic or static biasing?

Coverability of the test

- Circuit-level degradation
- Knowledge of failure modes
- Error propagation

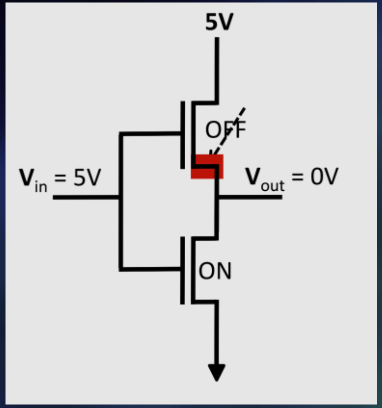
Usability of the test metrics

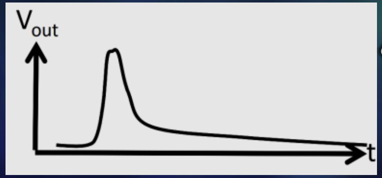
- Should allow a fine estimation in operation

Single Event Effects (SEEs) in digital circuits

An initial SET can then trigger various effects in digital circuits:

SET in inverters

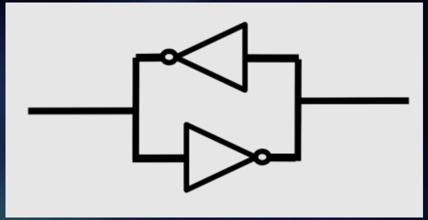




Single Event Transient

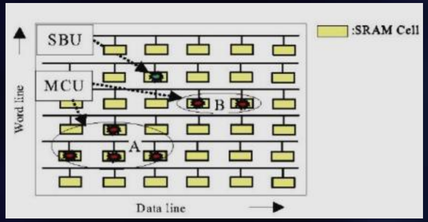
Static circuit

Single Event Upset (SEU):



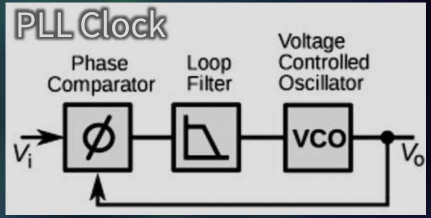
SRAM Memory Cell

Multiple Cell Upset:



SRAM

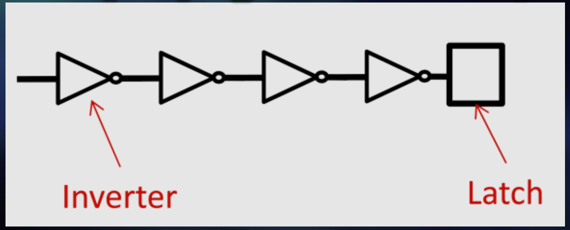
Analog Elements



Loss of locks

Dynamic circuit

SET propagation and capture:



SEU

Single Event Functional Interrupt (SEFI)

SEU can lead a device or a system to stop operating as it should do.

It can either recover by itself or the device must be reconfigured or reboot (power cycle)

SETs can also lead to a SEFI:

- Clock disturbance
- Radiation-induced resets
- Etc…

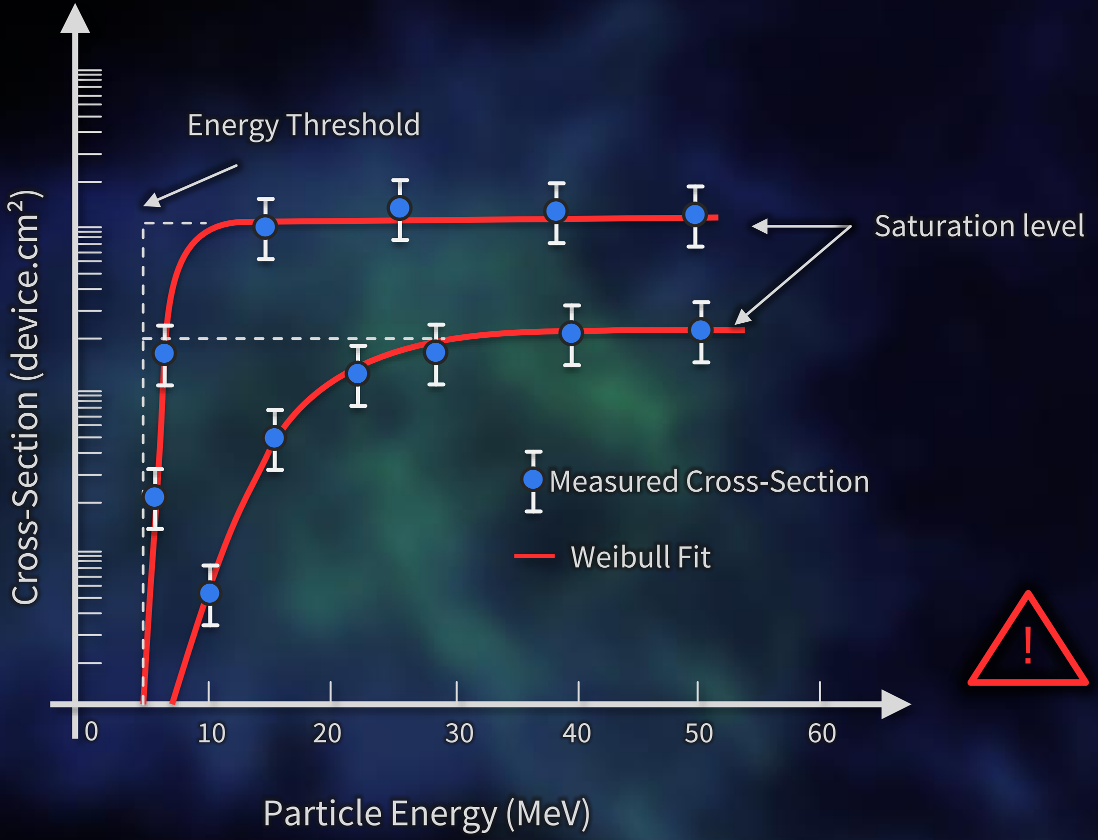
The device usually recover by itself

Single Event Effects (SEE)

The unit for SEE is the cross-section (σ), expressed per cm²:

$$\sigma(\mathrm{E}) = \frac{N_{events}}{\phi}$$

$\sigma(\mathrm{E})$: Cross-section for a given energy in cm²
N_{events}: Number of events observed during tests
ϕ: Particle test fluence in cm⁻²



- It is the probability that a particle crossing the device will cause an event.
- Cross-section usually follow a Weibull shape

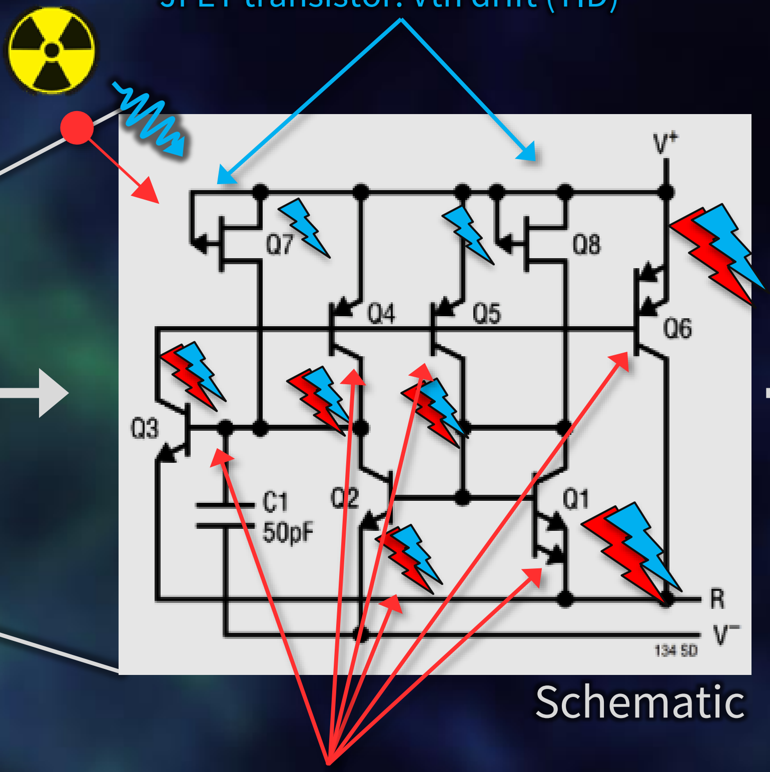
$$\sigma(\mathrm{E}) = \sigma_{sat}\left(1 - e^{\left(\frac{E-Tr}{W}\right)^{S}}\right)$$

- The energy threshold is usually in between 1-10 MeV
- In COTS the saturation effects usually occurs around 20 MeV
- Low energy neutron (thermal energies) can induce SEE through indirect ionization (absorption)
- Low energy protons can induce SEE through direct ionization

Cumulative Radiation effects on Integrated Circuits

- Integrated Circuits can be made up to thousand of transistors, experiencing all the effects at the same time
- Their radiation response is a complex combination of the response of all its internal transistors

LM334 Current Source

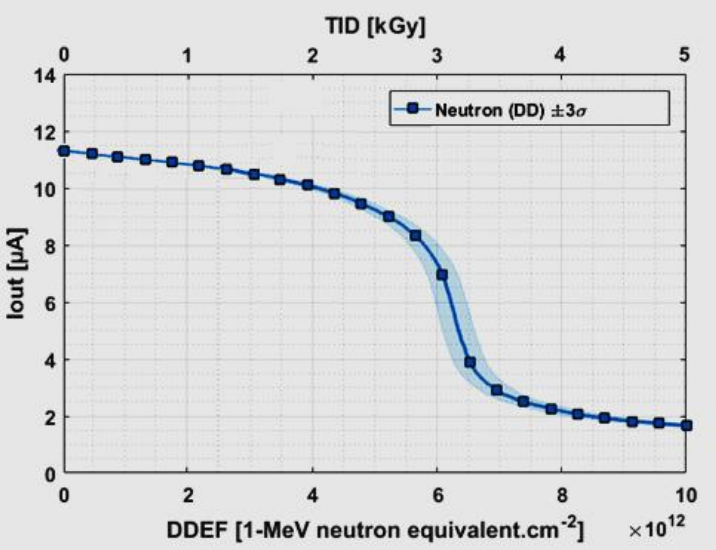


JFET transistor: Vth drift (TID)

BJT: Hfe degradation (TID+DD)

Schematic

Output Current degradation:



- ICs can have highly nonlinear responses

Cumulative Radiation effects on Integrated Circuits

- Cumulative effects can come in various forms depending on the type of components:

Voltage Regulators

Current Leakage
Output Change
Start-up voltage change

FPGA

Current Leakage
Increase of propagation delay
Inability to program
Design corruption

ADC

Stuck bits
Loss of linearity
Noise increase
Current leakage

Operational Amplifiers

Gain change
Input current leakage
Output offset change
Current leakage

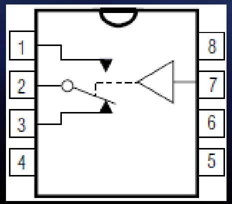
Flash Memories

Stuck bits
Inability to read/write
Current leakage

DAC

Stuck bits
Loss of linearity
Noise increase
Current leakage

Analog Switches



Inability to control
Resistance increase
Output offset
Current leakage

PLLs

Gain/Noise figure decrease

PWM Drivers

Duty cycle change
High State change
Low state change
Period change

Radiation Effects on Electronics

		SEE	TID	DD
Semiconductor Materials	**Si / SiO2** **III-V Compounds (GaAs…)**	Charge collection Carrier drift Depletion area extension	$\Delta N_{OT}, \Delta N_{IT}$	Minority carrier decrease Carrier removal Current leakage…
Active Elementary Devices	**Transistor:** MOSFET	SET, SEB, SEGR, SEL…	ΔV_{TH}	-
	Bipolar…	SET	$\Delta H_{CE}, \Delta I_{CE}, \Delta I_{BE}, \Delta V_{BE}$	$\Delta H_{CE}, \Delta I_{CE}, \Delta I_{BE}, \Delta V_{BE}$
	Diodes: Zener	SET	$\Delta V_F, \Delta I_L$	$\Delta V_F, \Delta I_L$
	LED	SET	$\Delta V_F, \Delta P, \Delta I_L$	$\Delta V_F, \Delta P, \Delta I_L$
	Schottky…	SET, SEB	$\Delta V_F, \Delta I_L$	$\Delta V_F, \Delta I_L$
Integrated Circuits	**Digital:** Memory	SEU, SEFI, SEL, MBU…	ΔI_{CC}	-
	FPGA		$\Delta I_{CC}, \Delta t_{PD}$, programmability	-
	µController		$\Delta I_{CC}, \Delta V_{REF}$ …	-
	Analog: Opamp	SET, SEL	$\Delta v_{off}, \Delta I_{BIAS}, \Delta G, \Delta I_{quiescient}$ …	$\Delta v_{off}, \Delta I_{BIAS}, \Delta G, \Delta i_{quiescient}$
	Regulators		$\Delta I_{CC}, \Delta V_{REF}, \Delta V_{START}$ …	$\Delta I_{CC}, \Delta V_{REF}, \Delta V_{START}$ …
	Mixed: ADC	SEU, SEFI, SEL, MBU,SET	$\Delta I_{CC}, \Delta V_{REF}, \Delta_{ENOB}$ …	-
	DAC		$\Delta I_{CC}, \Delta V_{REF}, \Delta_{ENOB}$ …	-
	Smart Power		$\Delta I_{CC}, \Delta T_P$	ΔT_P
	Optronics: Optocoupler	SET	$\Delta CTR, \Delta I_{TH}$	$\Delta CTR, \Delta I_{TH}$
	PhotoMOS		ΔI_{TH}, Switch capability	ΔI_{TH}
SoC Systems	**Can contains all the above**	Destructive events Temporary failures Permanent fault states	Performance degradation Parametric degradation	

Radiation Effects on Electronics

		SEE	TID	DD
Active Elementary Devices	**Transistor:** MOSFET Bipolar… **Diodes:** Zener LED Schottky…	MIL-STD-750, SEB/SEGR ESCC25100	ESCC22900 (ELDR) MIL-STD 883 1019.8 MIL-STD750E 1019.5 ASTM F 1892-06	No standard yet but guidelines
Integrated Circuits	**Digital:** Memory FPGA µController **Analog:** Opamp Regulators **Mixed:** ADC DAC Smart Power **Optronics:** Optocoupler PhotoMOS	**Guidelines, conferences, journals, litterature etc..:** *“Guideline for Optocoupler Ground Radiation Testing and Optocoupler Usage in the Space Radiation Environment”*, NASA *“Field Programmable Gate Array (FPGA) Single Event Effect (SEE) Radiation Testing”*, NASA *“SEE Testing of ADC and DAC”*, ESCIES *RADECS* Short courses *NSREC* Short courses		
SoC Systems	**Can contains all the above**	**No standards but Guidelines exist (with a big contribution from CERN/R2E):** H. Quinn, "Challenges in Testing Complex Systems,"in IEEE TNS, April 2014 A. Coronetti et al., "Radiation Hardness Assurance Through System-Level Testing: Risk Acceptance, Facility Requirements, Test Methodology, and Data Exploitation,“ IEEE TNS 2021 T. Rajkowski et al., “Comparison of the Total Ionizing Dose Sensitivity of a System in Package Point of Load Converter Using Both Component- and System-Level Test Approaches,” Electronics 2021		

CERN RHA & Testing Challenges

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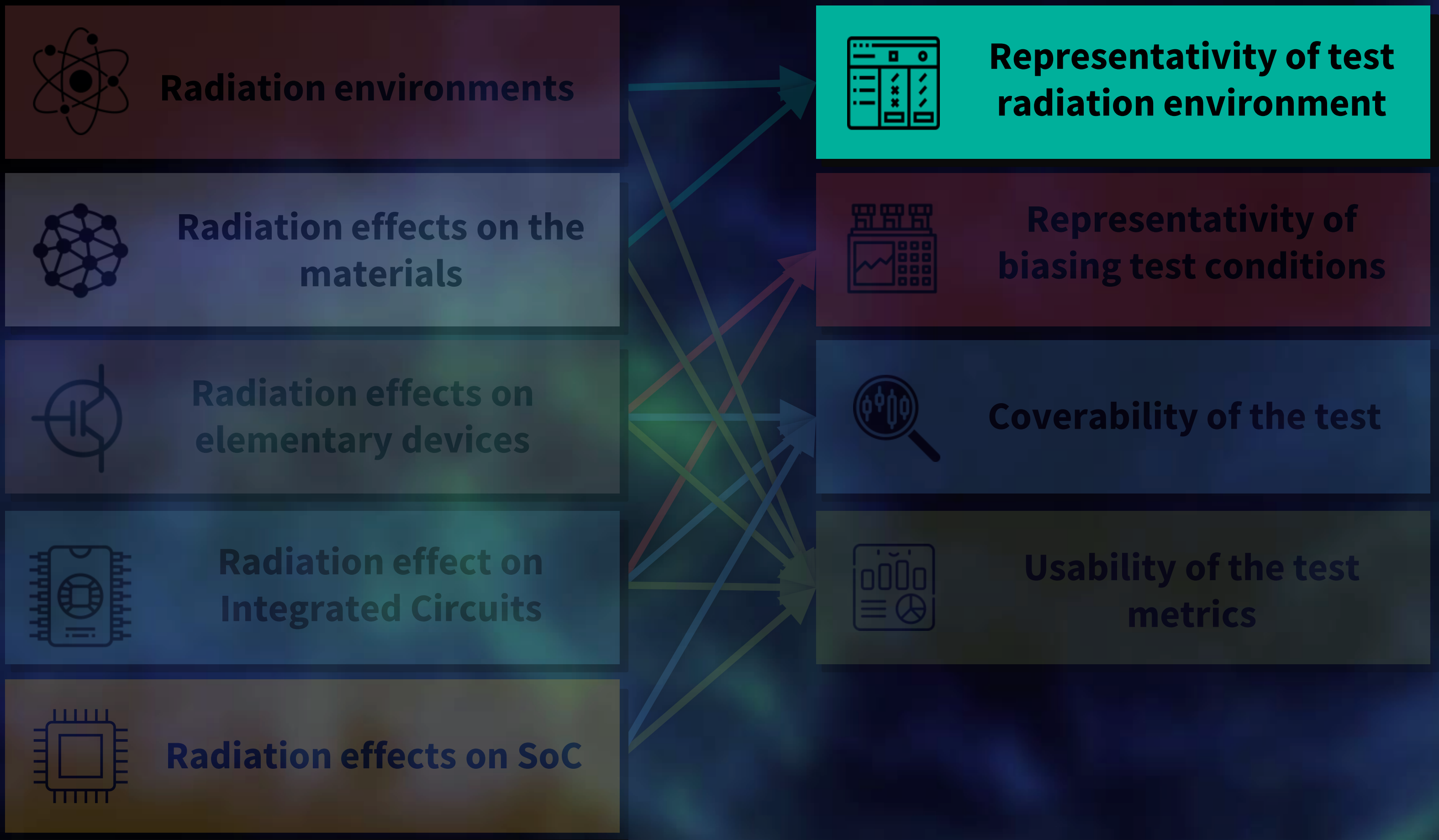


- Type/Energy of test particle(s)
- Radiation Effect(s)
- Flux, Dose Rate

- Passive or active irradiation?
- Dynamic or static biasing?

- Circuit-level degradation
- Knowledge of failure modes
- Error propagation

- Should allow a fine estimation in operation

Radiation Testing Facilities

- For each type of radiation effects, several type of Irradiation facilities:

Decreasing Priority

SEE - Destructive Events

SEL → Systematic test of all possibly sensitive devices
SEGR, SEB → Systematic tests of higher power Devices

SEE – Transient Events

SET → Tested on most of Analog Devices
SEFI → Tested on most of Digital Devices

SEE – Single Event Upsets

SEUs, MBUs, etc… → Tested on all digital electronics with memory registers

Combined TID-DD effects

Devices sensitive to TID+DD (Bipolar ICs, Bi-CMOS etc..) must be tested in representative TID/DD levels with representative biasing

Displacement Damages

Optoelectronics must be tested in representative LHC spectra

Total Ionizing Dose

TID sensitive only (MOSFETs) can be tested in any TID facility

SEE Facilities:

Proton beam
Electron beams
Neutron Spallation beams
Thermal Neutron beams

TID-DD Facilities

Proton beam (from mV to hundred of MeVs)
Mixed-beams / Mixed-Fields

DD Facilities:

Nuclear Reactor (About 1 MeV)
Neutron Generators (14 MeV)
Proton beams

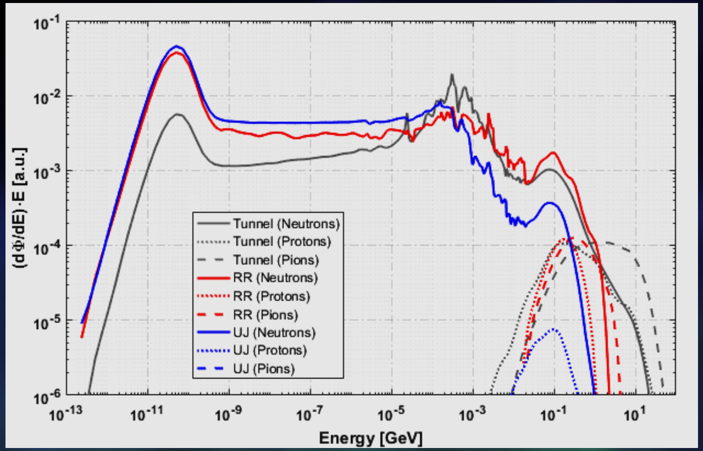
TID Facilities:

Cobalt 60 source (photons)
Electron beam
X Ray source (photons)

SEE Testing challenges

To estimate a component failure rate in operation we need to know its response against the various LHC spectra

LHC Spectra:



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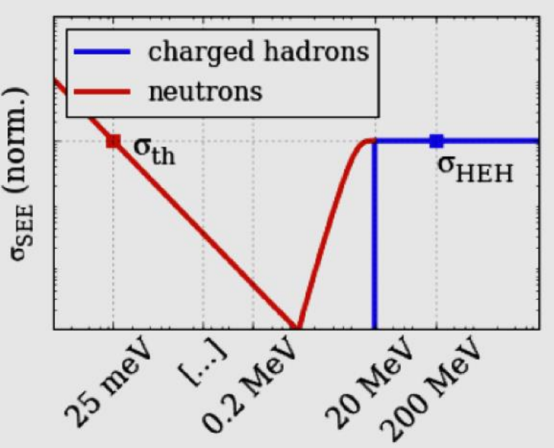
Device Cross section:



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Failure Rate

Concerns:

Do we test against all particles?

$p, \pi^{\mp}, K^{\mp}, \mu^{\mp}, N, e$

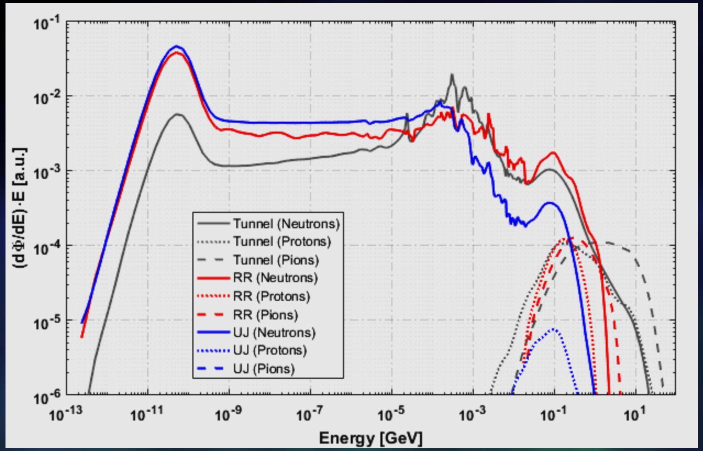
→

1) Hadrons have a similar probability to induce an event [ref]
   → A single hadron can be used for testing, usually protons
2) Electron cross-section much lower than hadrons and have low presence in LHC → Can be neglected
3) Modern electronic can embeds thermal neutron sensitive material (boron 10) → Thermal neutron test needed for low technology nodes

SEE Testing challenges

To estimate a component failure rate in operation we need to know its response against the various LHC spectra

LHC Spectra:



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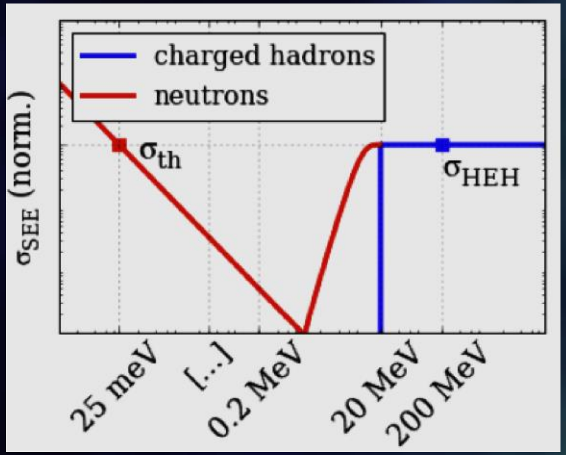
Device Cross section:



= **Failure Rate**

Concerns:

Do we test against all particles?

$p, \pi^{\mp}, K^{\mp}, \mu^{\mp}, N, e$

Do we test against all energies? →

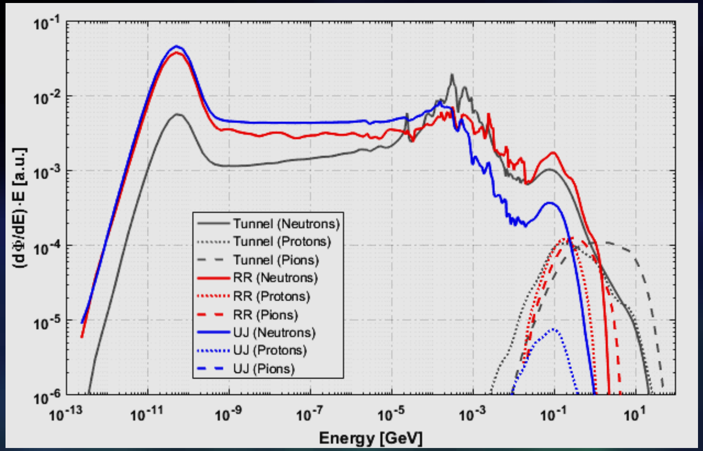
1) Scanning in energy is possible…
2) … but not necessary most of the time:

Measuring the saturation cross-section is enough to obtain a very good approximation, usually 200 MeV is used

SEE Testing challenges

To estimate a component failure rate in operation we need to know its response against the various LHC spectra

LHC Spectra:



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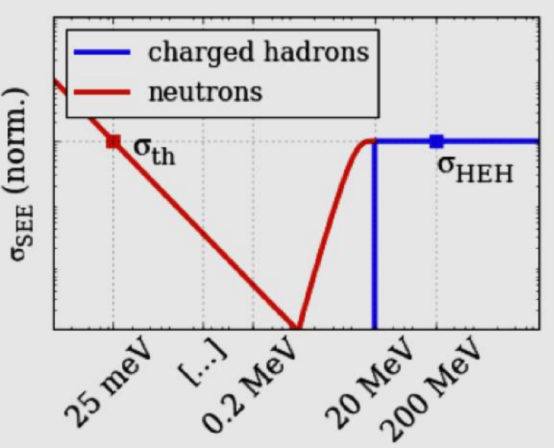
Device Cross section:



= **Failure Rate**

Concerns:

Do we test against all particles?

$p, \pi^{\mp}, K^{\mp}, \mu^{\mp}, N, e$

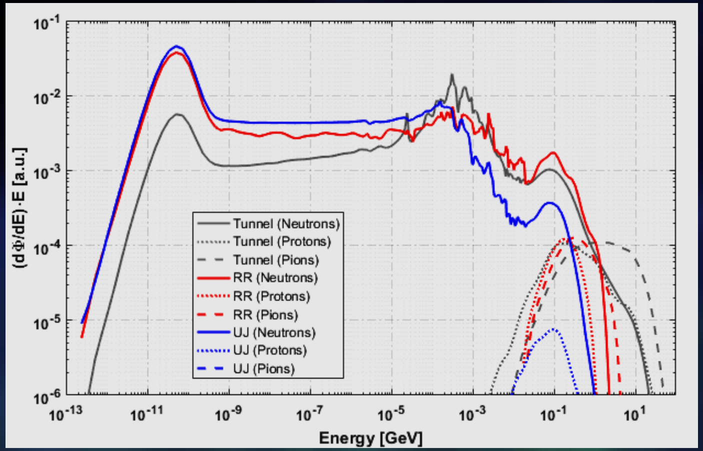
Do we test against all energies?

What flux to use? → Usually high flux (10^{8} p/cm^{2}) is preferred but can be lowered if failure rate is too high

SEE Testing challenges

To estimate a component failure rate in operation we need to know its response against the various LHC spectra

LHC Spectra:



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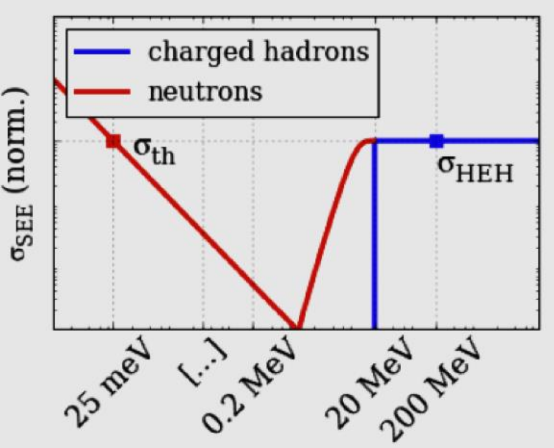
Device Cross section:



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Failure Rate

Concerns:

Do we test against all particles?

$p, \pi^{\mp}, K^{\mp}, \mu^{\mp}, N, e$

Do we test against all energies?

What flux to use?

What fluence to use? → Several devices can be placed in beam to increase the test fluence

Test fluence to be calculated according to:

Number of devices in operation

Total fluence to which **each** device will be exposed

Maximum failure rate tolerated

Example of thermal neutron criticality

PolarFire Flash-Based FPGA:

Tested against SEE:

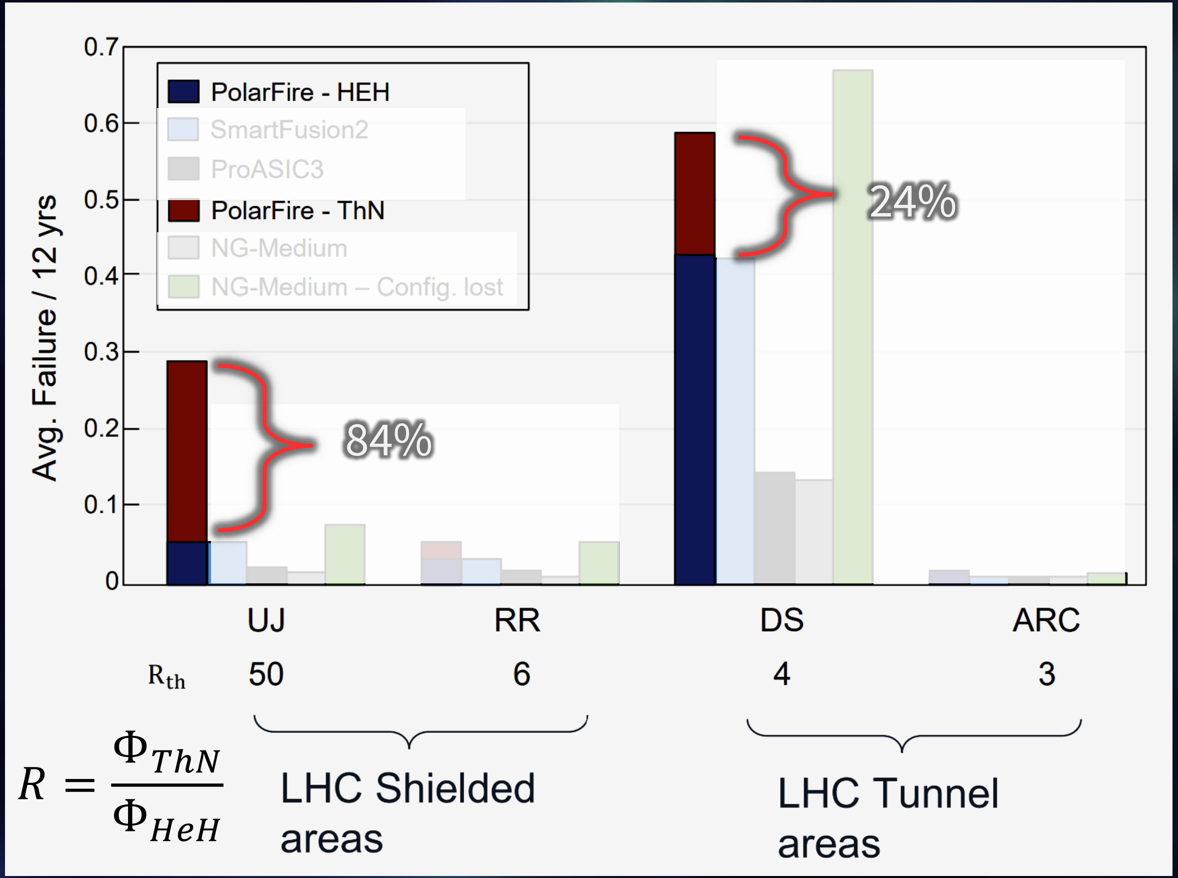
- 200 MeV protons
- Thermal neutrons

Tested with:

- B13 benchmark from ITC99

- ➢ Result showed a strong thermal neutron sensitivity
- ➢ In shielded areas with strong thermal neutron contributions, thermal neutron can represent up to 84% of the total failures
- ➢ Not considering thermal neutrons for qualification would lead to an underestimation of a factor 4 in these areas

Estimated Failure Rate in different LHC areas per year:



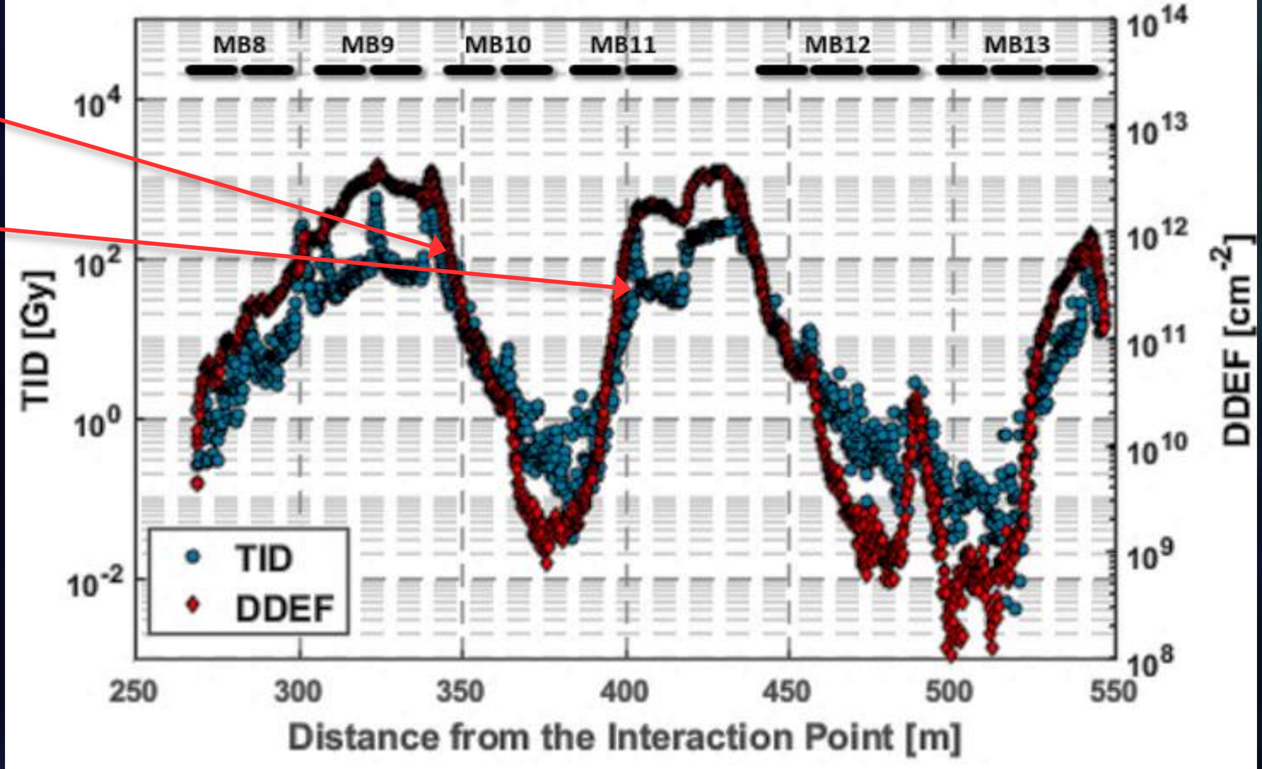
$$R = \frac{\Phi_{ThN}}{\Phi_{HeH}}$$

A. Scialdone et al., "FPGA Qualification and Failure rate estimation methodology for the LHC radiation environment using benchmark test circuits", 2022, IEE TNS

Cumulative Radiation Testing Challenges

- In terms of TID-DD effects, the LHC environment present a unique challenge:
  - Depending on the areas, a same system can experience different radiation levels:
    - **Below MB10 for 10 years:**
      - TID: 700 Gy
      - DDEF: 1 x10^{12} neq. cm^{-2}
    - **Below MB11 for 10 years:**
      - TID: 700 Gy
      - DDEF: 2x10^{13} neq. cm^{-2}

→ 20 times more DDEF for the same TID



DS area Fluka simulation of Radiation levels

Cumulative Radiation Testing Challenges

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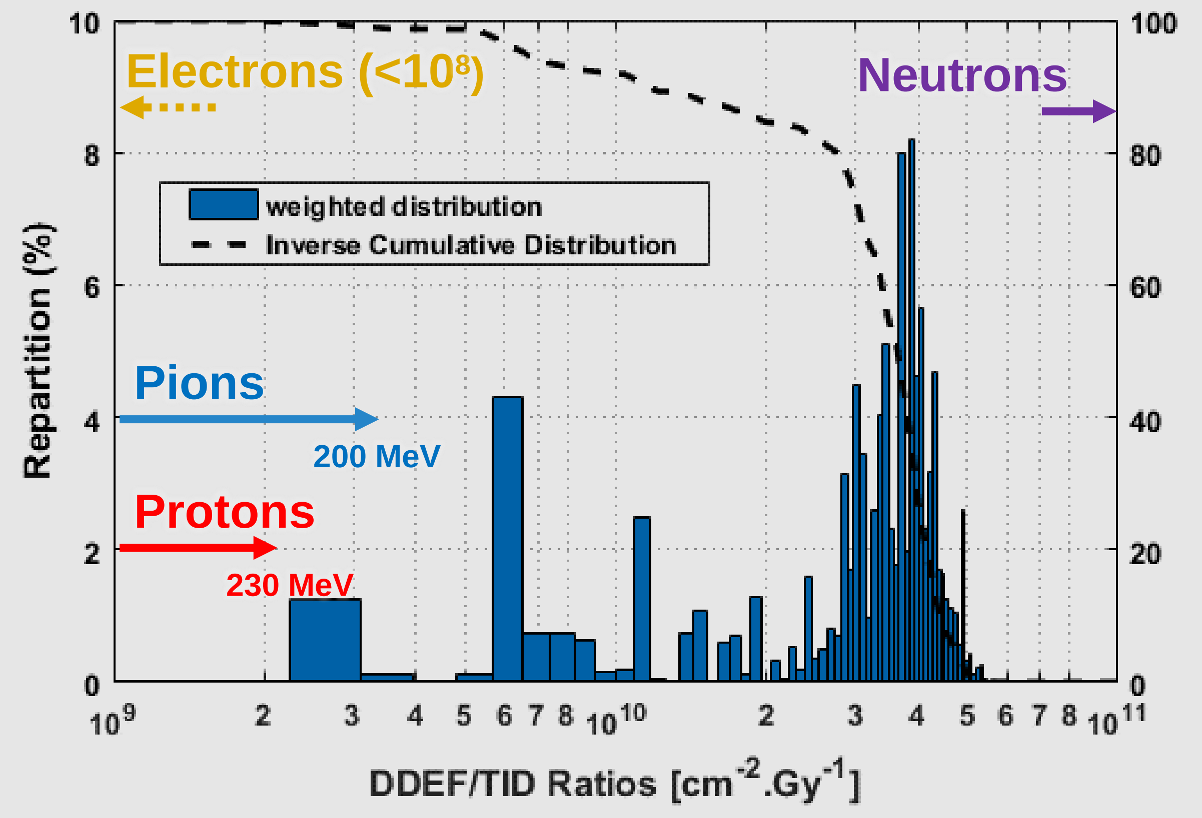
    - **Below MB11 for 10 years:**
      - TID: 700 Gy
      - DDEF: 2x10^{13} neq. cm^{-2}

      → 20 times more DDEF for the same TID
    - Wide variety of **DDEF/TID Ratio**:

      From **10^9** up to **10^{11} cm^{-2}.Gy^{-1}**

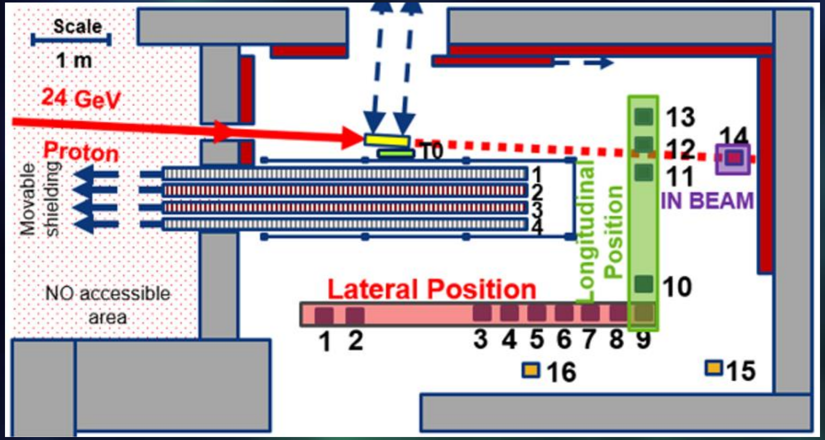
      → Can lead to various degradation profiles for devices sensitive to combined TID-DD



Another possibility exist for CERN! The CHARM Mixed-Field Facility

CHARM Mixed Field Facility

- Primary 24 GeV proton beam coming from PS impinges a target
- Secondary radiation fields similar to the LHC radiation fields.
- Radiation field can be modulated with:



➢ **Target:** 🟨

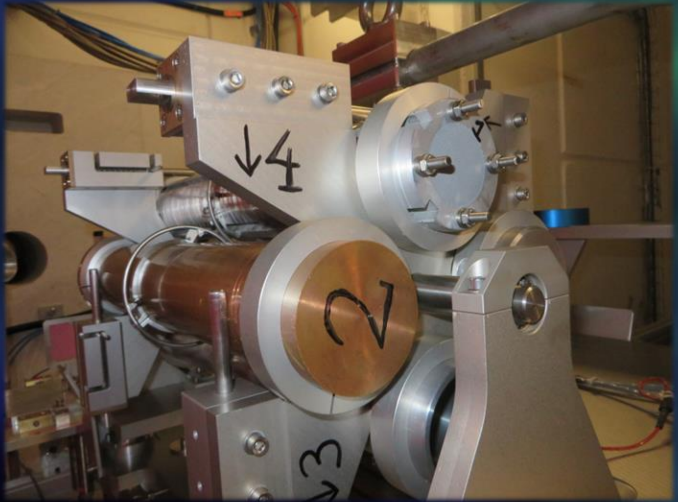
Cu - Copper
Al - Aluminium
AlH - Aluminium Hole

➢ **Shielding:**

C – Concrete (**1,4**) ▥
I – Iron (**2,3**) ▥

➢ **Positions:**

Lateral (**1:9**) 🟥
Longitudinal (**9:13**) 🟩



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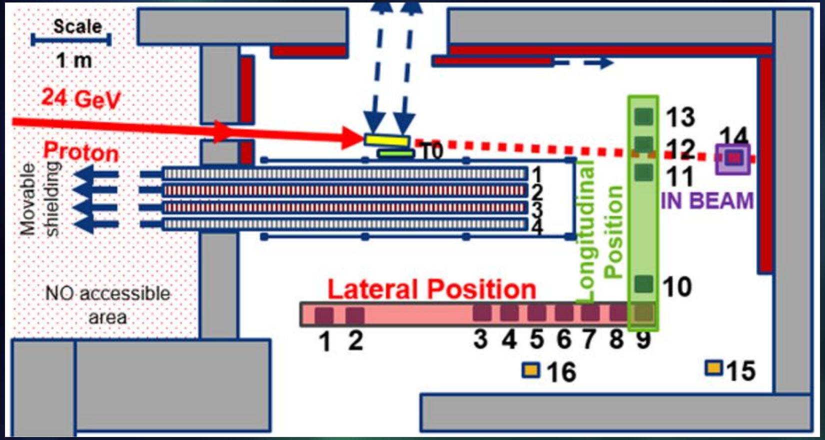

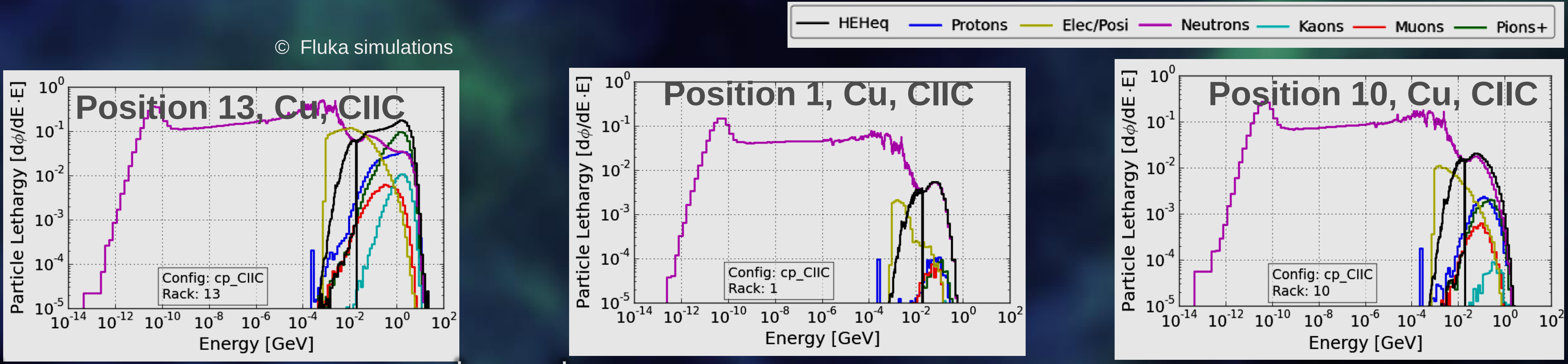

© Fluka simulations

Similar to Tunnel areas

Similar to Shielded Areas

CHARM Mixed Field Facility

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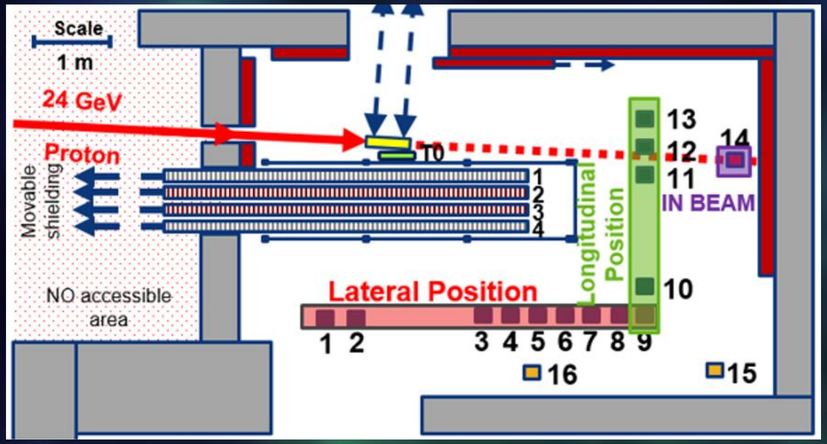

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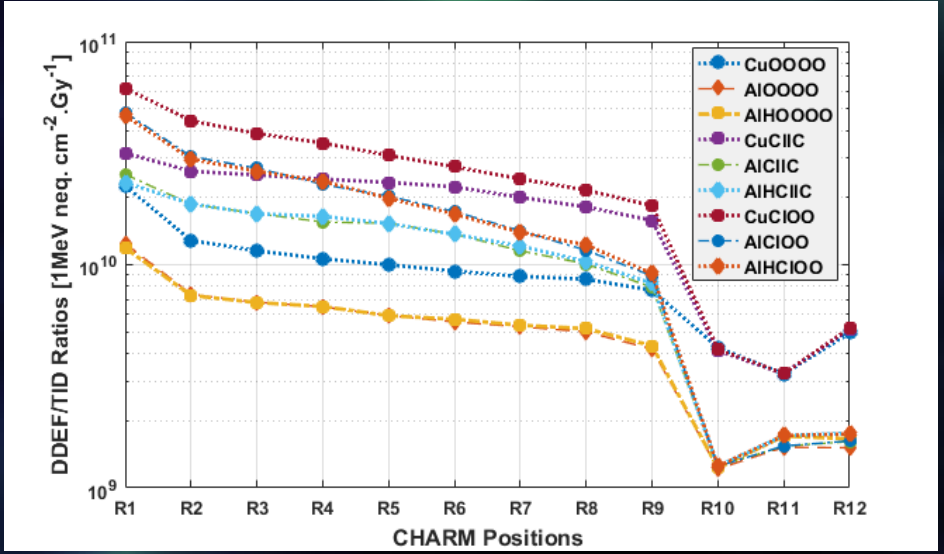
C – Concrete (**1,4**) ▥
I – Iron (**2,3**) ▥

➢ **Positions:**

Lateral (**1:9**) 🟥
Longitudinal (**9:13**) 🟩

→ TID/DD ratios can be changed by changing configurations

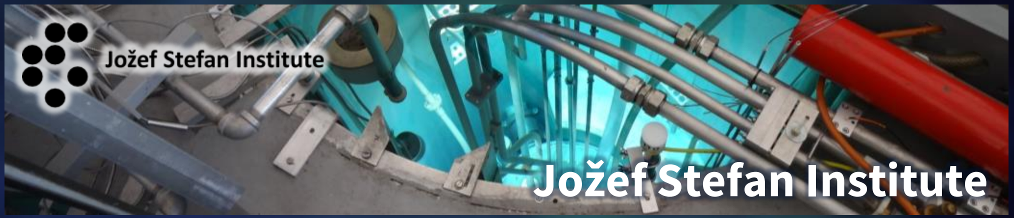
→ Facility allows to cover practically all the LHC DDEF/TID ratios



R. Ferraro *et al*., "Study of the Impact of the LHC Radiation Environments on the Synergistic Displacement Damage and Ionizing Dose Effect on Electronic Components," in *IEEE Transactions on Nuclear Science*, vol. 66, no. 7, pp. 1548-1556, July 2019, doi: 10.1109/TNS.2019.2902441.

R. Ferraro, R. G. Alía, S. Danzeca and A. Masi, "Analysis of Bipolar Integrated Circuit Degradation Mechanisms Against Combined TID–DD Effects," in IEEE Transactions on Nuclear Science, vol. 68, no. 8, pp. 1585-1593, Aug. 2021, doi: 10.1109/TNS.2021.3082646.

Radiation Test Facilities used for Qualification



PSI-PIF – Switzerland, Viligen
- 30-220 MeV Proton beam
- Combined **SEE**, **TID**, **DD** Tests
- **5 Years collaboration agreement with CERN up to 2027**

ILL – Genoble, France
- Thermal Neutron Beam
- Thermal neutron sensitivity Tests
- **Punctual use, possibility to make a contract**

CC60 – Switzerland, CERN
- 10 & 110 Tb Cobalt 60 Sources
- **TID** Tests
- **Available all the year**

JSI – Slovenia, Ljubljana
- Triga Mark II Nuclear Reactor
- **DD**, TID
- **Punctual use, possibility to make a contract**

CHARM – Switzerland, CERN
- Representative LHC Radiation mixed-fields
- SEE, TID, DD
- **Not available during technical stops**

Where do we test: Key point is the facilities

PSI-PIF – Switzerland, Viligen
- 30-220 MeV Proton beam
- Combined **SEE**, **TID**, **DD** Tests
- **5 Years collaboration agreement with CERN up to 2027**

ILL – Genoble, France
- Thermal Neutron Beam
- Th
- **Pu**

CC60 – Swit
- 10
- **TI**
- **Av**

JSI – Sloven
- Tr
- **DD**, TID
- **Punctual use, possibility to make a contract**

CHARM – Switzerland, CERN
- Representative LHC Radiation mixed-fields
- SEE, TID, DD
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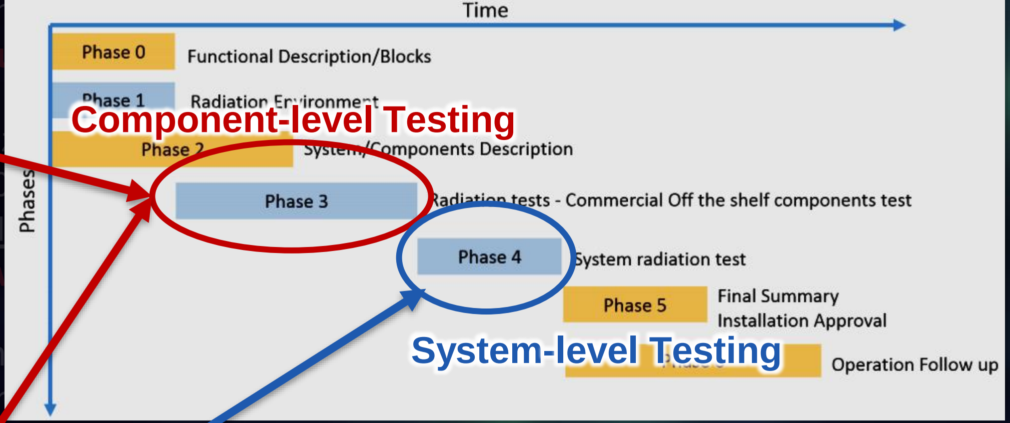
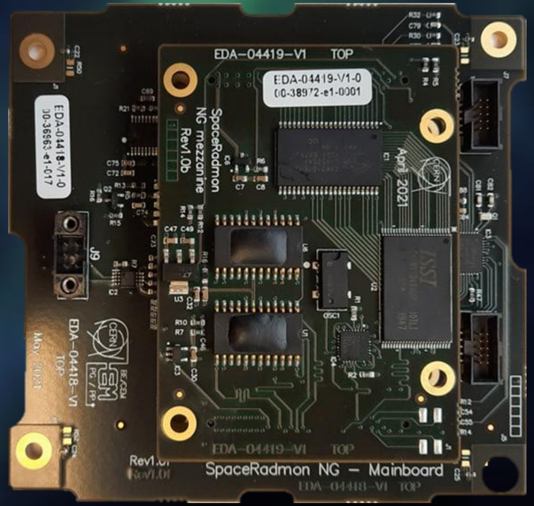


Testing R&D

- Many other activities are conducted by the service to face the new HL LHC challenges:

- **System-Level testing:**
  1) Testing and Validation Methodology for a Radiation Monitoring Systems for Electronics in Particle Accelerators
     → **Provides advices and considerations for system-level testing**
     (A. Zimmaro et al., in IEEE Transactions on Nuclear Science, 2022)
  2) Impact of flux selection, pulsed beams and operation mode on system failure observability during radiation qualification
     (A. Zimmaro et al., Accepted at RADECS 2022 Conference)
  3) Development and Qualification of a Radiation Tolerant Monitoring platform for Space application
     → **Allows developing, and testing new mitigation techniques, new architecture schemes and system-level test techniques**

"IoT BatMon: Wireless radiation monitoring at CERN"



"Space RadMon, a radiation tolerant monitor device for cubesats"

Testing R&D

- **FPGA Testing Techniques & LHC failure estimation:**
  1) FPGA Qualification and Failure Rate Estimation Methodology for LHC Environments Using Benchmarks Test Circuits

     Provides FPGA test guidelines & methodology for failure rate estimation in the LHC

     (A. Scialdone et al., in IEEE Transactions on Nuclear Science, 2022)

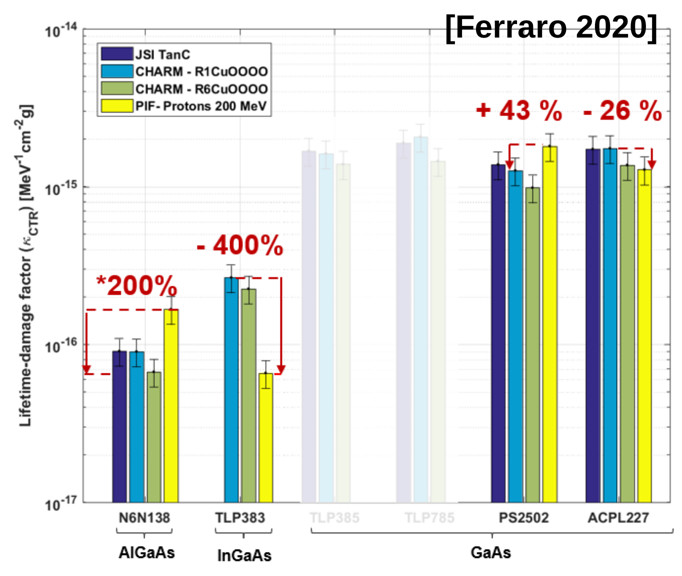
- **Component Test Methodology for CERN environments:**
  1) COTS Optocoupler Radiation Qualification Process for LHC Applications Based on Mixed-Field Irradiations

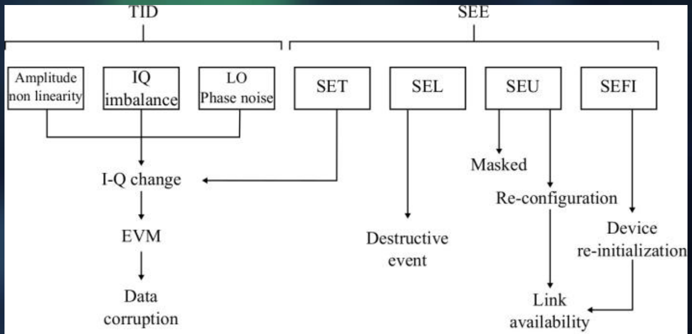
     (R.Ferraro, EEE Trans. Nucl. Sci. 67 (2020) 1395-1403)

     → **Proved the importance of carefully selecting the test environments to obtain reliable degradation rates**
  2) Qualification methodology for Radio Frequency Integrated Circuit for wireless-based platforms in radiation environments

     (A. Scialdone, Accepted at RADECS 2022 Conference)

     → **Provides methodology for wireless transceiver testing**



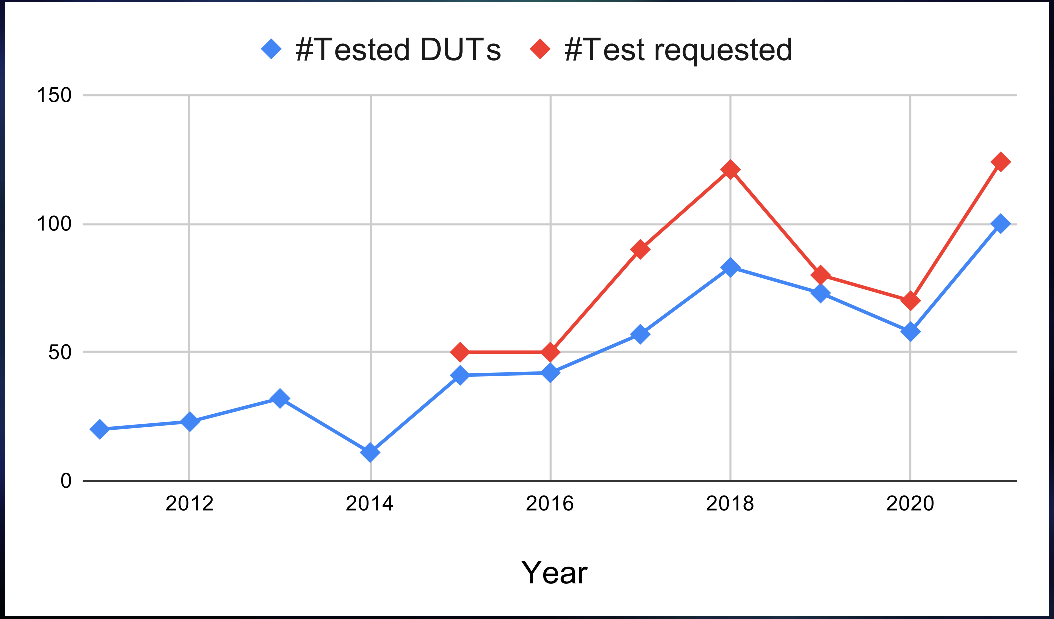


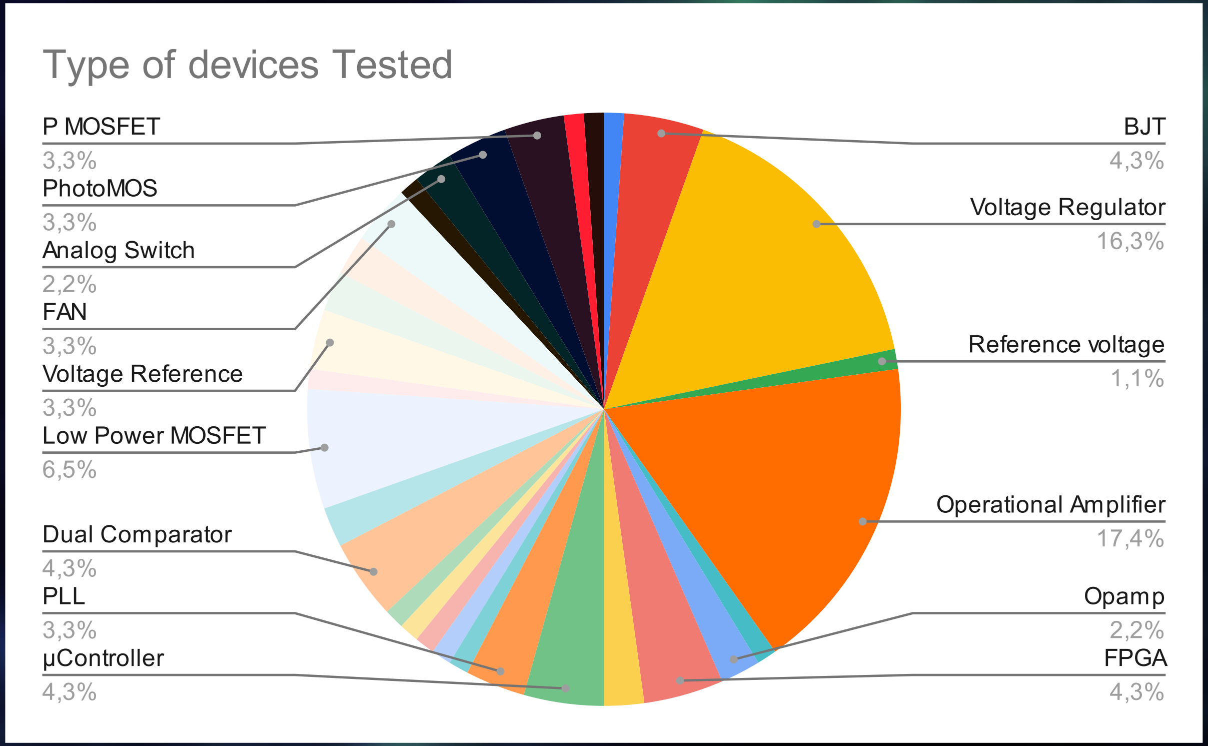
[Scialdone 2022]

Statistics about the service

- Since 2011:
  - 540 components have been tested
  - 90 Radiation campaigns

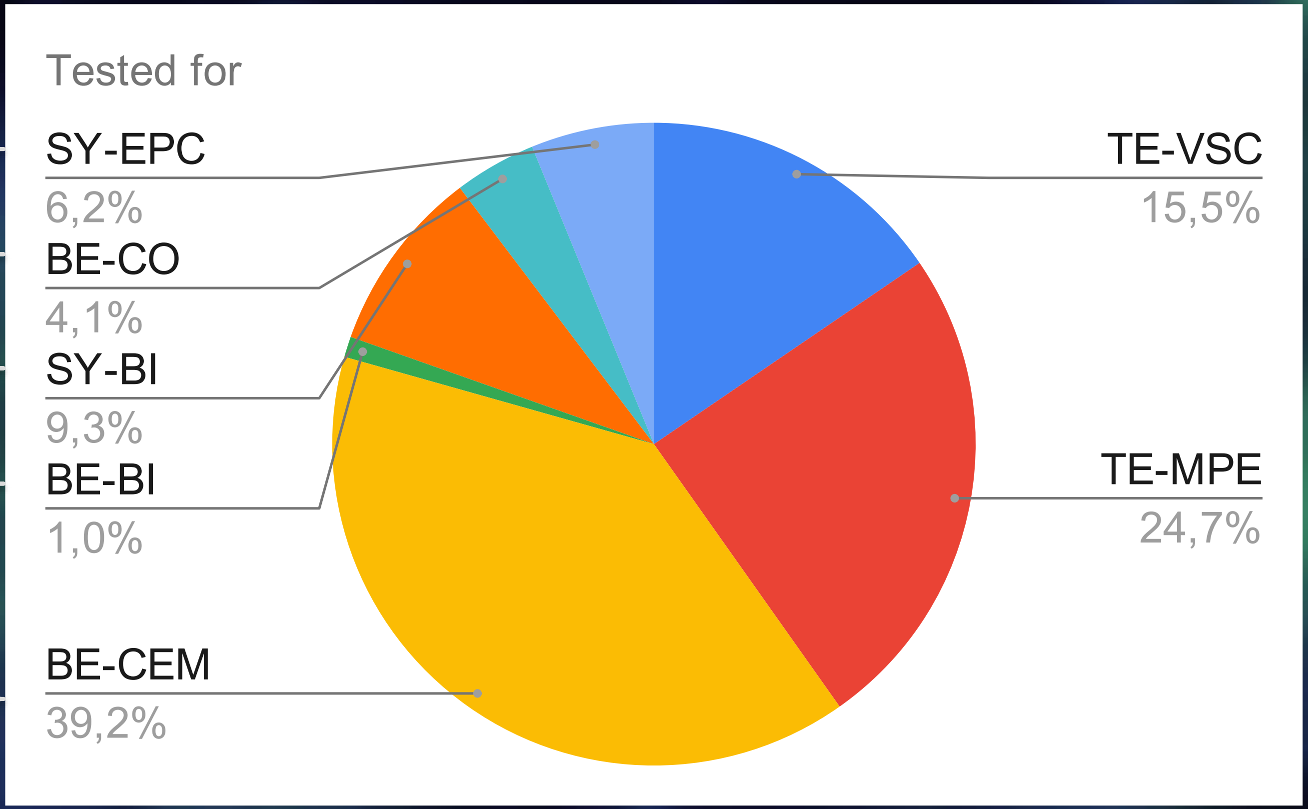
- We tested from the simplest component (BJT) to the most complex ones (FPGAs) and even complete systems





Statistics about the service, User distribution 2021

- Basically the equipment groups in charge of new developments requested to qualify their selected components



R2E-HL-LHC(60;120)A

RaToPUS

LHC BLM

BLM Crate

- BATMON
- IOT Humidity Mon.
- Space RADMON
- Common building block

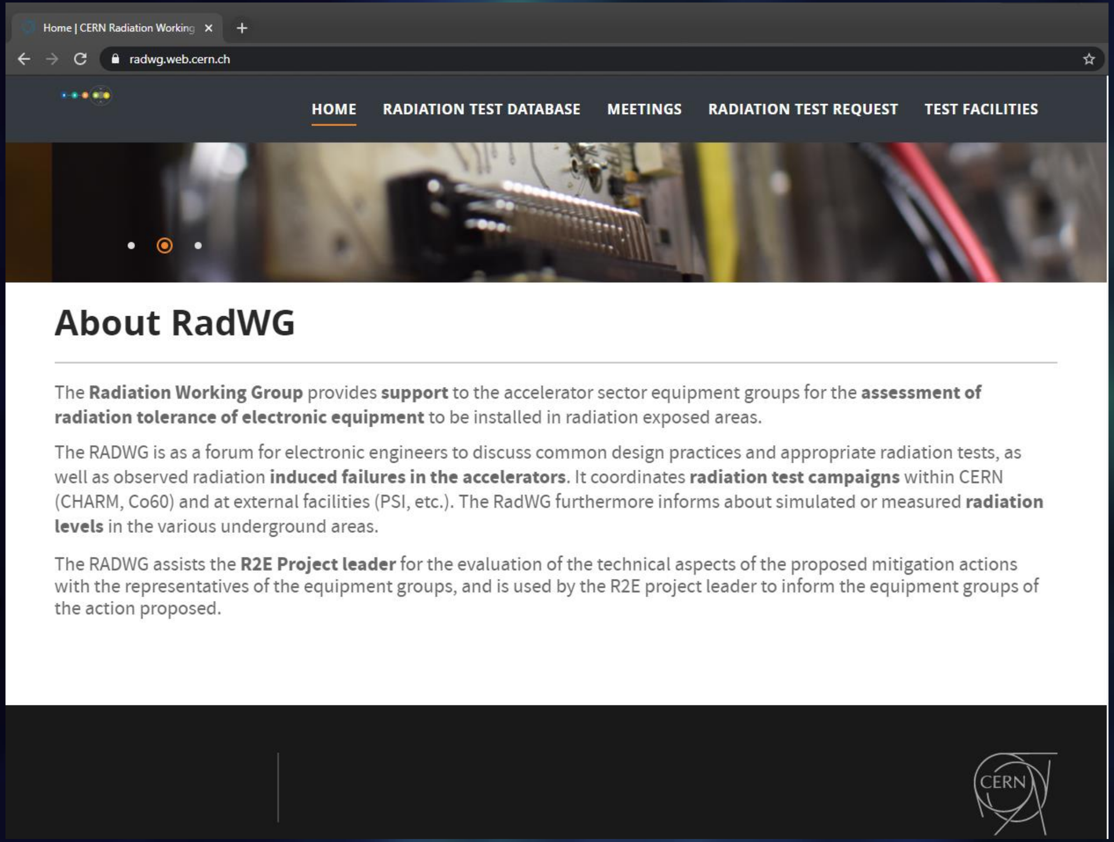
VSC Conditioning Electronics (Penning, log etc…)

- CIBU
- QPS
- LHC BPM

Number of components tested in 2021: **100**

Test results analysis and reporting

- The website https://radwg.web.cern.ch/ embeds an User-Friendly database
  - More than **540 reports** from the 2011 up to 2022
- The service produces reports in a common template for all the components tested
  - Test reports template ensure a coherent reporting
- The service maintains two databases accessible by all the equipment groups



About RadWG

The **Radiation Working Group** provides **support** to the accelerator sector equipment groups for the **assessment of radiation tolerance of electronic equipment** to be installed in radiation exposed areas.

The RADWG is as a forum for electronic engineers to discuss common design practices and appropriate radiation tests, as well as observed radiation **induced failures in the accelerators**. It coordinates **radiation test campaigns** within CERN (CHARM, Co60) and at external facilities (PSI, etc.). The RadWG furthermore informs about simulated or measured **radiation levels** in the various underground areas.

The RADWG assists the **R2E Project leader** for the evaluation of the technical aspects of the proposed mitigation actions with the representatives of the equipment groups, and is used by the R2E project leader to inform the equipment groups of the action proposed.

https://radwg.web.cern.ch

Conclusions

- LHC Electronics made of commercial devices can be affected by radiations, leading to the dump of the accelerator
- The R2E Project was created to ensure the reliability of the LHC electronics against radiations through various activities
- One of this activity is the systematic radiation qualification of active electronic components performed by the BE-CEM-EPR section
- Qualifying electronics against radiation requires knowledge of radiation effects from the lowest level (material) to the highest one (system) in addition of a fine knowledge of the radiation environment
- Testing standard & guidelines inherited from the space field provide a valuable starting point for our community
- But many of these standards do not apply to particle accelerator and a constant work is being done to develop qualification methods dedicated to CERN
- The Testing Service is continuously working on the development of such procedures that allowed to increase the overall reliability of the qualification process
- Up to now, 540 components and numerous systems were qualified by the Radiation Testing Service

Thank you for your attention!

Controls
Electronics &
Mechatronics

R2E