Radiation Damage and Its Consequences

CAS 2014

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!!! Many Thanks To All People Involved in related Activities !!!


BEER
THE REASON
I WAKE UP
EVERY
AFTERNOON
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Why Should You Care?

- … Accelerators Generate Radiation!!!
- Radiation (can) impacts:
  - People
  - Materials, accelerator components, electronics,…
  - Operation

In this sense:

- Radiation (more and more!!!) determines the way how we have to design installations, accelerator components & plan for shutdowns, …

What it's about?

What is Radiation?

- **Radiation refers to "energy transported through space" by particles, photons, electromagnetic waves…**
- **Energy is then deposited into matter and provokes microscopic and macroscopic changes in its structure, chemical and physical properties -> Impact/Damage**

- *Biological effects of radiation on humans, as well as how we treat radioactive waste are part of* ***Radioprotection*** *and* ***are not part of this talk!***
- **Here we will focus on challenges we face everyday with radiation in the design, operation and optimization of accelerators and their components**

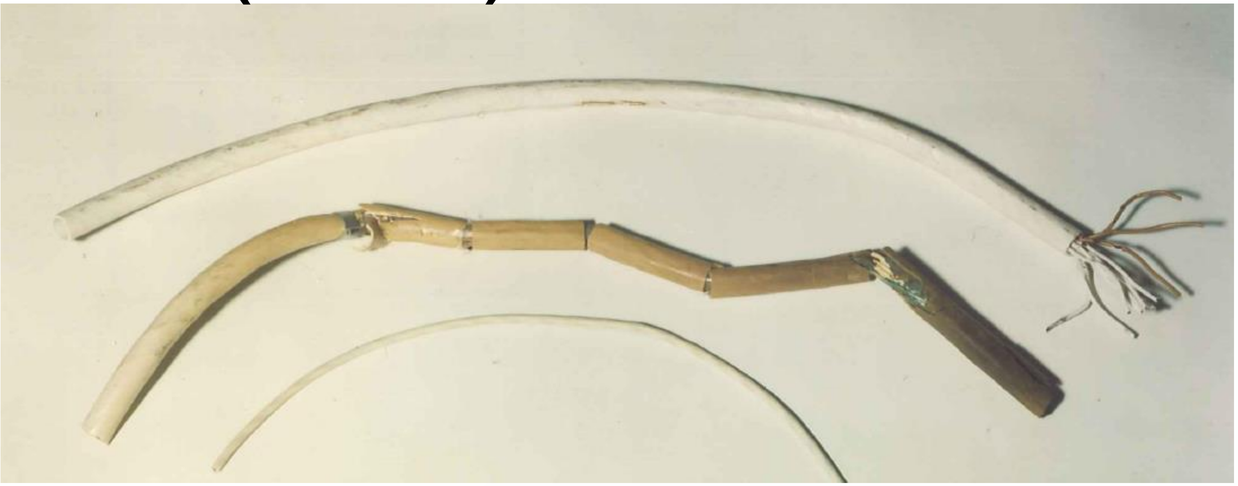
Overview

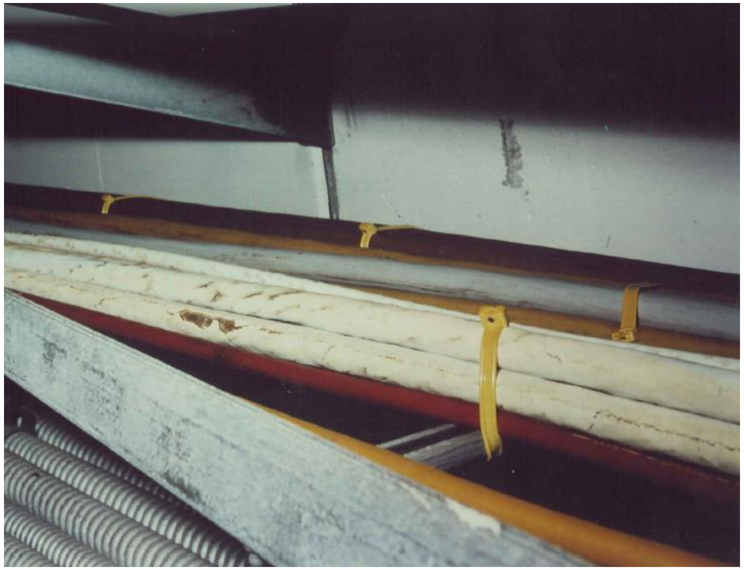
- Why do you (or should you) care about Radiation Damage?
- Quantities of concern
- Radiation Environment
- Radiation Effects & Failure/Damage Consequences
- Mitigation Measures
- Along the way: a few things you should remember

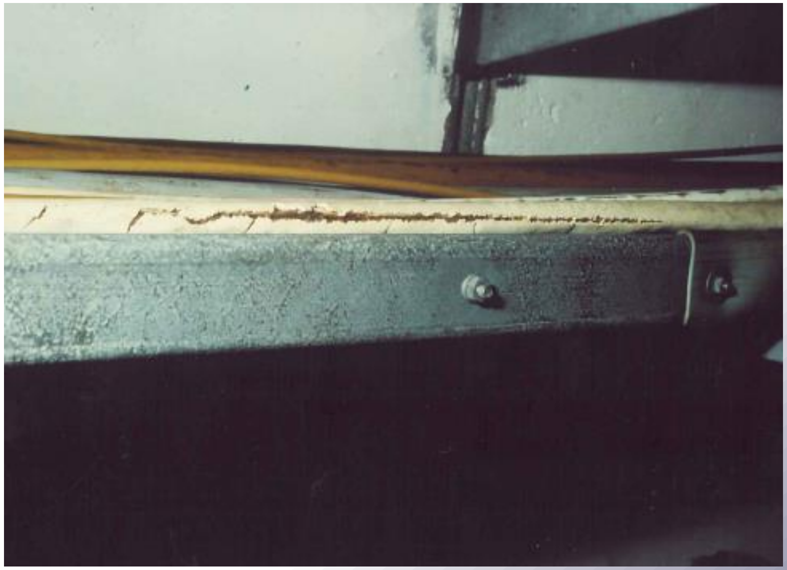
Radiation Damage

Why do we care

MATERIALS (Cables):

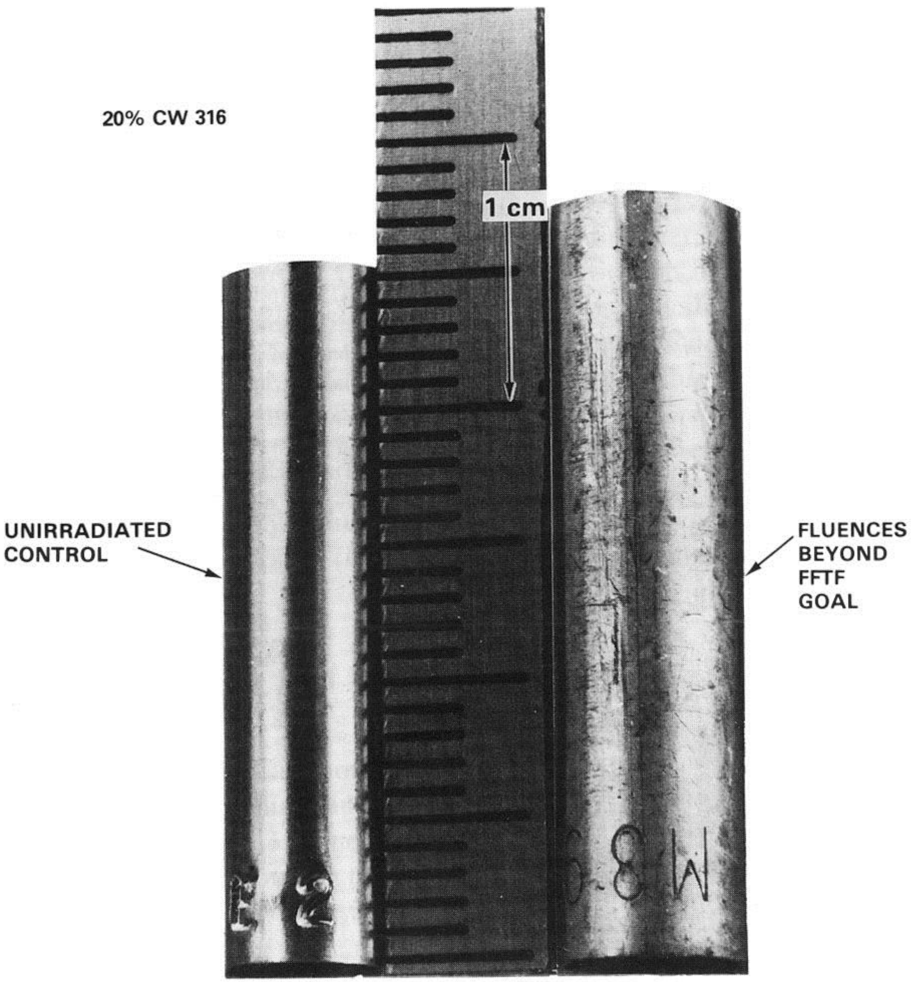


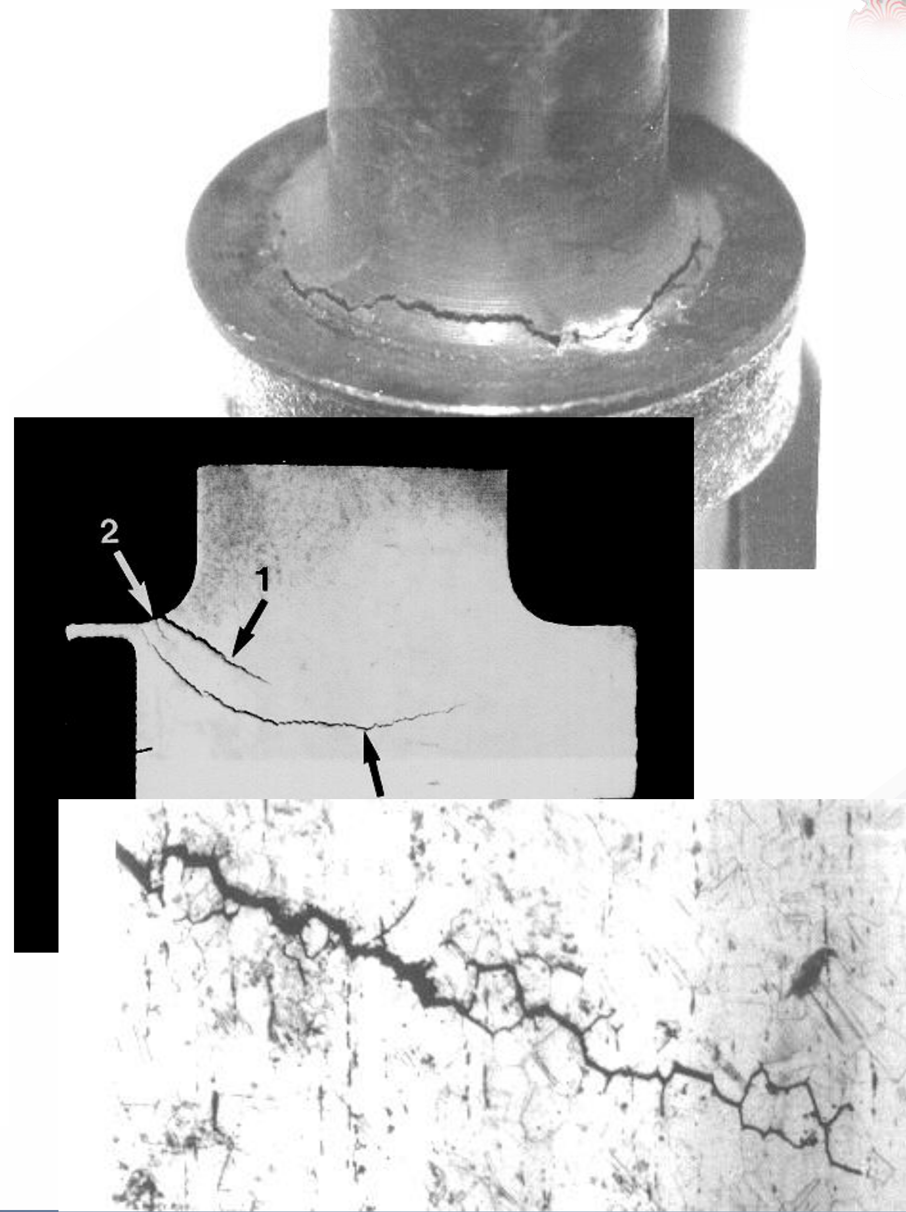




Why do we care

MATERIALS (Metals):





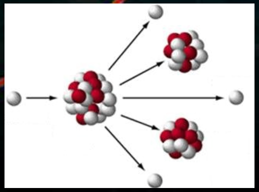
The LHC Challenge

LHC is a proton-proton (or ion/ion) collider

- 2 proton beams at 7 TeV of 3×10^{14} p^+ each
- Stored for 10-20 hours in collision
- Total stored energy of **0.7 GJ**
  Sufficient to melt **1 ton of Cu**
- ~5000 superconducting magnets

- Tiny fractions (few mJ) of the stored beam suffice to quench a superconducting LHC magnet or even to destroy parts of the accelerators.

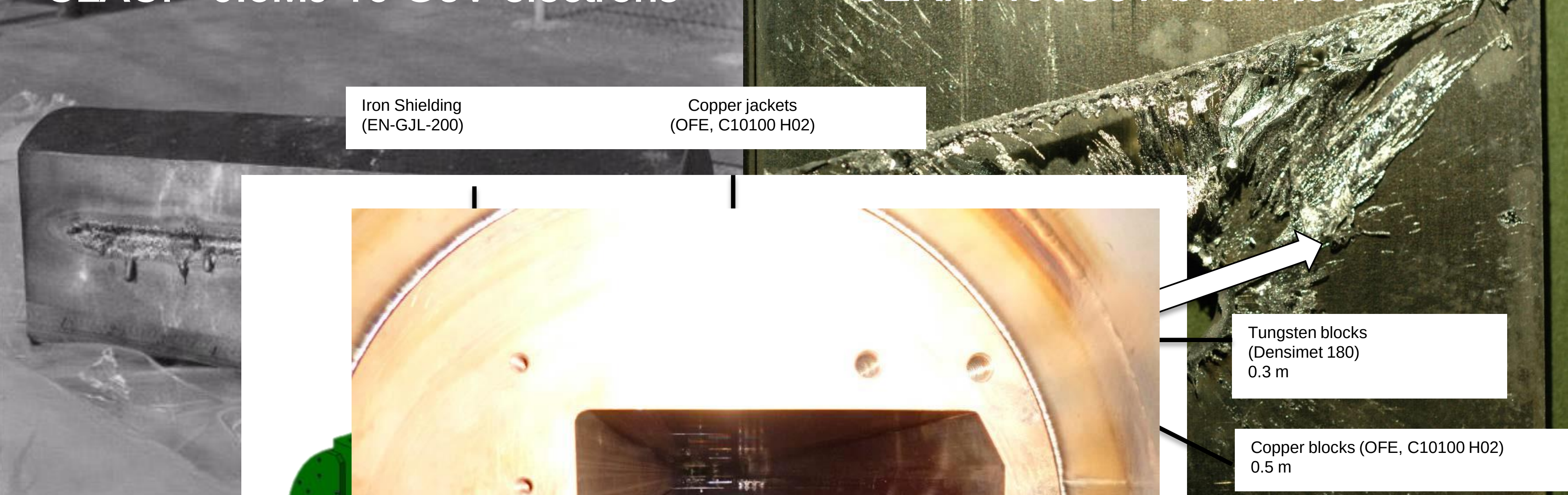
- Single particles can impact essential electronics and stop operation



Beam Induced Damage

SLAC: ~0.5MJ 16 GeV electrons

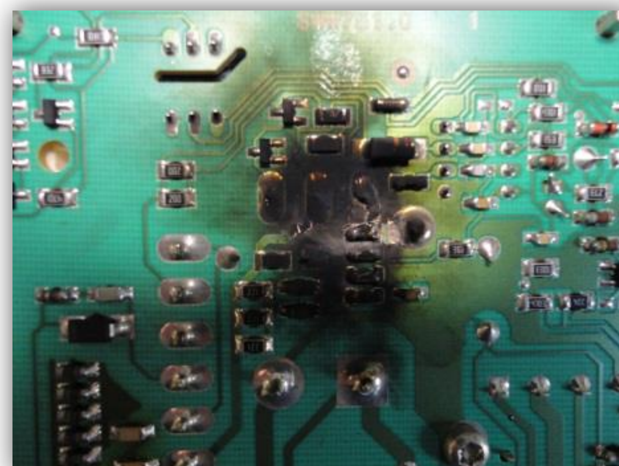
CERN: 400GeV beam test



Equipment Failure Example

Vacuum system PLC (LHC_UJ76)

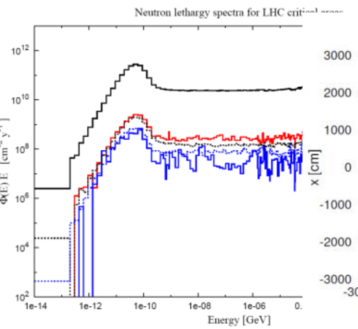
P. Supply 24VDC 5A

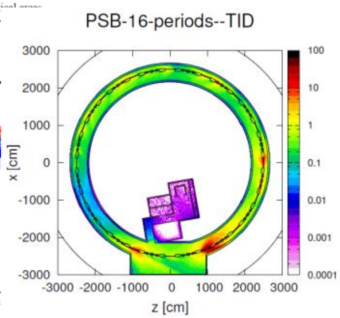


The "Victims"

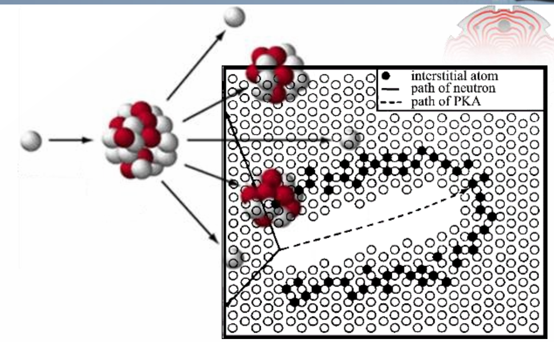
- Beam Intercepting Devices (Collimators, Scrapers, Dumps, etc.)
- Magnets (Insulators, etc.)
- Other beam-line elements
- Cables and optical Fibres
- Electronics (components & systems)
- Super-Conducting magnets/links/cavities/etc.
- …
- **All exposed parts at varying radiation levels**

What Do We Need?





Calculations



Materials & Components

Radiation Environment

Radiation Effects & Physics

Monitoring

Sound & Save Design

Models

Radiation Tests & Facilities

Mitigation Measures

EXPERIENCE & EXPERTISE

Procedures, Access, Time

Shielding, Alternatives, Space, …

Radiation
&
Quantities of Concern

Material Damage

There are several physical mechanisms which can result in damage to the target material. They are related to:

- **Ionizing energy losses/heating**, mostly connected to the electronic **stopping power**
- **Non ionizing energy losses (NIEL)**, mostly due to energy transfer to **atomic nuclei**. They can typically result in displacement damage to the crystalline/metallic structure of the target material
- **Gas production**, mostly due to protons, deuterons, tritons, ^{3}He and alphas **stopping in the target**. They can be beam particles ranging out in the target (low energy beams), or secondary particles produced by nuclear interactions in the target itself

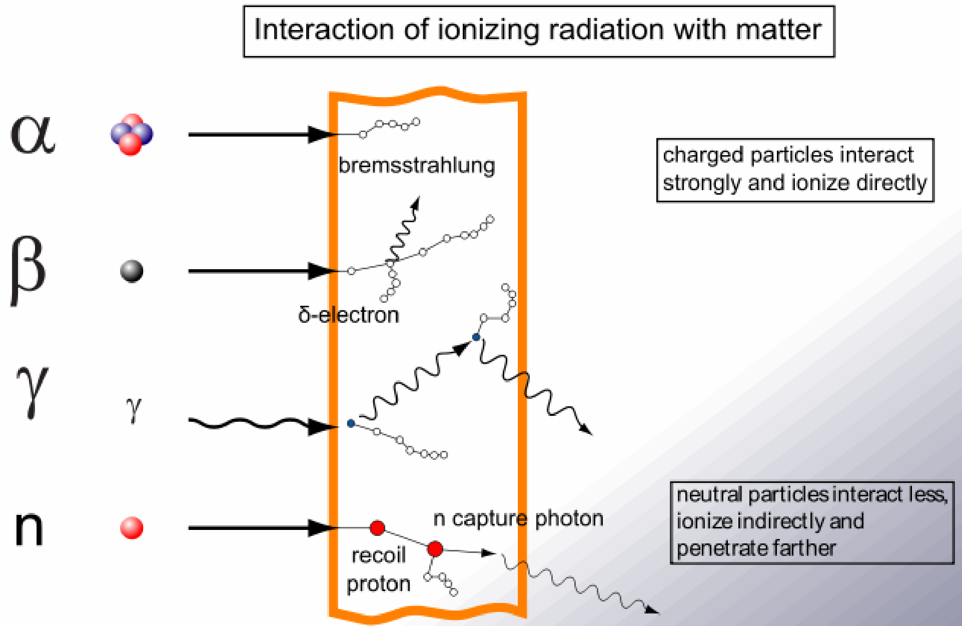
What is Radiation

Ionizing Radiation:

- **Particles whose energy is sufficient to ionize atoms or molecules (> few eV)**
  - Alfas, hadrons, cosmic rays…
  - Neutrons (nuclear reactions: capture, fission…)
  - Electromagnetic waves (Photons), with sufficiently low wavelength
  - …

Non-Ionizing Radiation:

- **Microwaves**
- **RF**
- **…**



Ionizing/Non-Ionizing – Damage?

Physics about what damaging/ionizing radiation is:

- The strength of **chemical bonds** is **~2-5 eV**
- Radiation where the particles have an energy (or better can **transfer energy**) high enough to break chemical bonds well enough to leave them permanently broken
- I.e. **particle energy > 5 eV or so may be ionizing** (since a single bond break is seldom stable)
- But the **exact limit depends on a lot of factors**

- *Thinking about it: laser irradiation in the visible range is thus clearly not ionizing – even though if the intensity is high enough, it can sure damage a material*

Ionizing Radiation

Directly ionizing radiation:

- **fast charged particles** (e.g., electrons, protons, alpha particles), which **deliver their energy to matter directly**, through many small Coulomb-force interactions along the particle's track

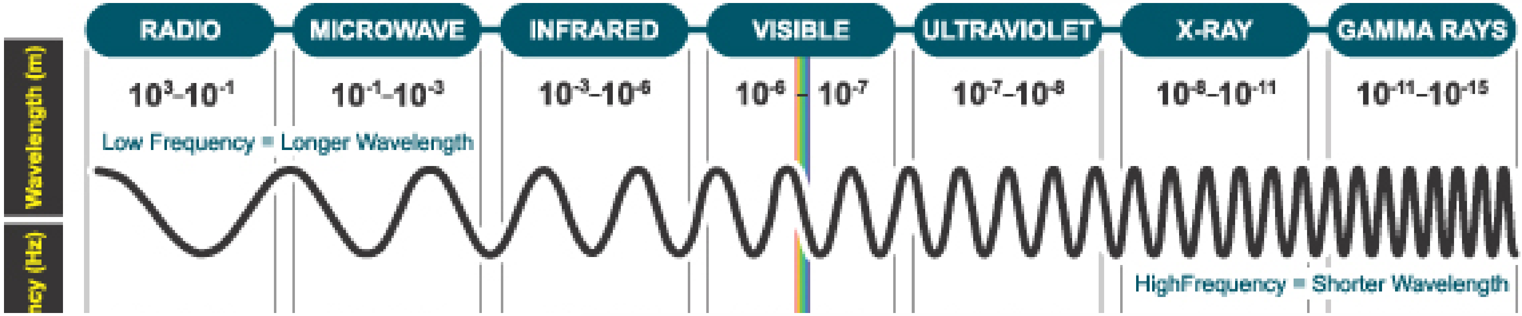
Indirectly ionizing radiation:

- **X- or γ-ray photons or neutrons** (i.e., uncharged particles), which **first transfer their energy to charged particles in the matter** through which they pass in a relatively few large interactions, or cause nuclear reactions
- the **resulting fast charged particles then deliver the energy** in matter
- the deposition of energy in matter by indirectly ionizing radiation is thus **a two-step process**
  - photon -> electron; neutron -> proton or recoiling nuclei

Radiation Source

One Example – Gamma Radiation (Photons) :

- Electromagnetic waves, whose quantum is the photon
- The electromagnetic spectrum as a function of photon energy:

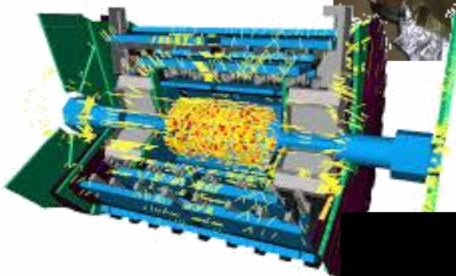


- **Upper Ultraviolet, X-ray and gamma radiation are ionizing**
- <u>Terminology note:</u>
  - X-rays photons come by definition from transitions in atoms
  - Gamma photons come by definition from nuclei
  - Synchrotron radiation comes from bremsstrahlung in high-energy accelerators and overlaps X-ray energies

Accelerators: Radiation Sources

- **Direct beam Losses**
  - collimators and collimator like objects
    injection, extraction, dump
  - **levels usually scale with beam intensity & energy**

- **Beam/Beam, Beam/Target Collisions**
  - around experimental areas
  - **scale with luminosity/p.o.t. & energy**



- **Beam-Residual-Gas**
  - circular machines: all areas along the ring
  - **scales with intensity, residual gas density & energy**

- **Synchrotron radiation** (lepton machines)

- **RF** (e.g, during conditioning)
- **Radiation sources**
  (irradiators, calibration, tomography, etc.)

Dose Terminology

Exposure is the process when a material is exposed to some kind of radiation

- Measures for the amount of exposure
  - **Dose**: **amount of energy deposited by radiation per mass**
    [units of Energy/mass 1Gy = 1J/kg, 1Gy = 100rad]
  - **Dose rate**: **Dose delivered in a given time**
    [units of Energy/(mass x time), Gy/s, Gy/h, Gy/y]
  - **Fluence**: **amount of energetic particle per unit area**
    [units of particles/area i.e. 1/area, cm^{-2}, m^{-2})
  - **Flux**: **Fluence delivered in a given time**
    [units of particles/(area x time) i.e. 1/(area x time), $cm^{-2}s^{-1}$,...]

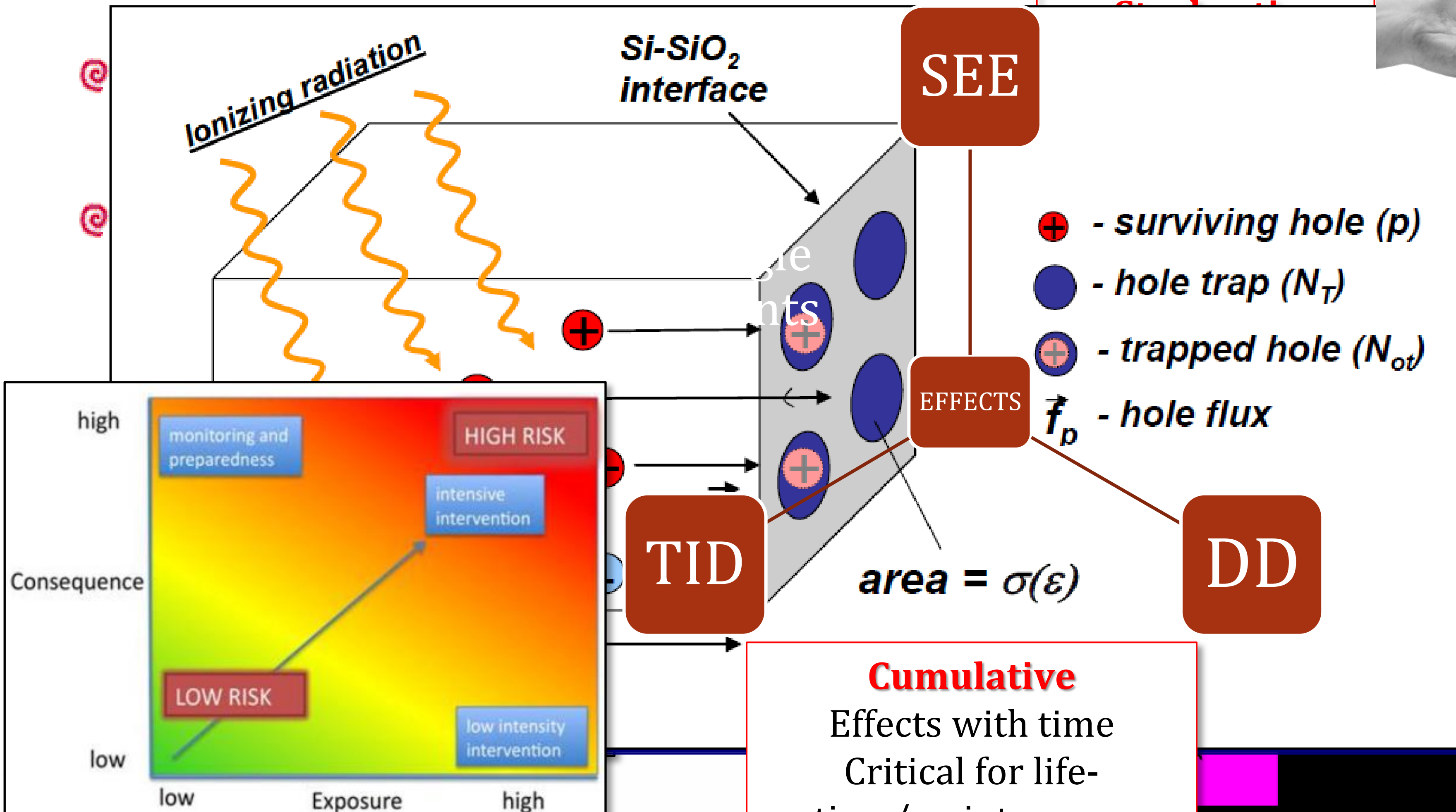
- **Activity**: amount of radiation produced by a radioactive sample

Damage & Dose Terminology

- <u>**Some central damage terminology:**</u>
  - **Radiation damage:**
    - any kind of damage to a material produced by radiation
  - **Defects:**
    - atoms that deviate from the order in a crystal or amorphous material
  - **Radiation damage to electronics:**
    - Radiation impacting the functioning of electronic devices (cumulative or stochastic nature)
- **Not all radiation damage is linked to defects**: e.g, amorphization of a material into a stable phase
- **Defects produced by irradiation have sometimes beneficial properties**. In this case it is misleading to call it damage

Electronics : Radiation Effects

Total Ionizing Dose (TID):

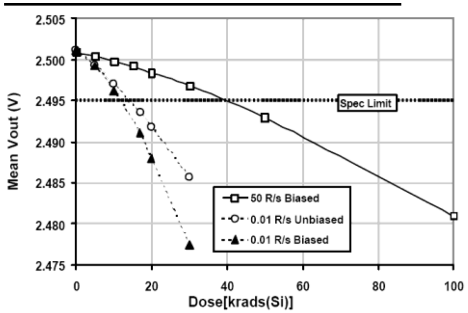


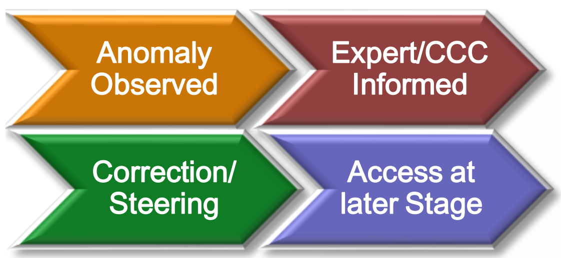
Cumulative
Effects with time
Critical for life-time/maintenance

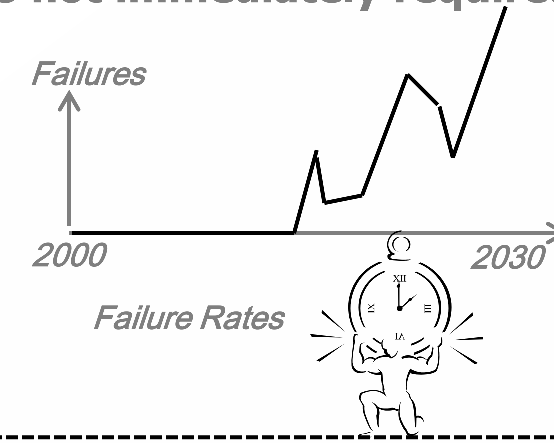
Radiation Issues – Failure Observation

- **TID + Displacement Damage**
  - ☺ **Devices get slowly out of tolerance (final failure can often be anticipated; access not immediately required)**
  - ☺ **No 'early' failures (due to radiation)**

Possible Scenario:

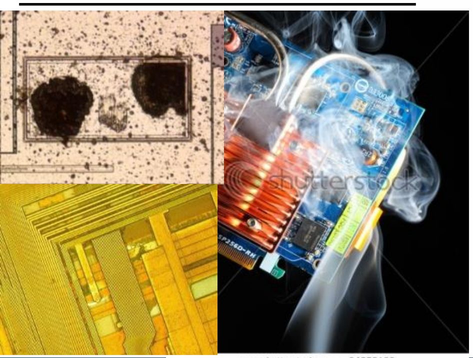


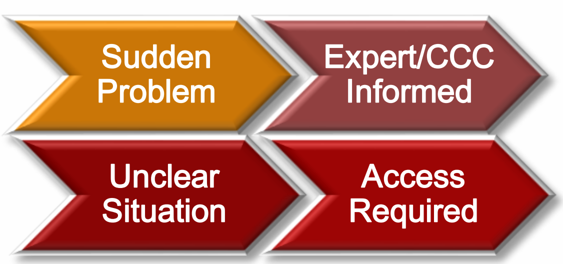


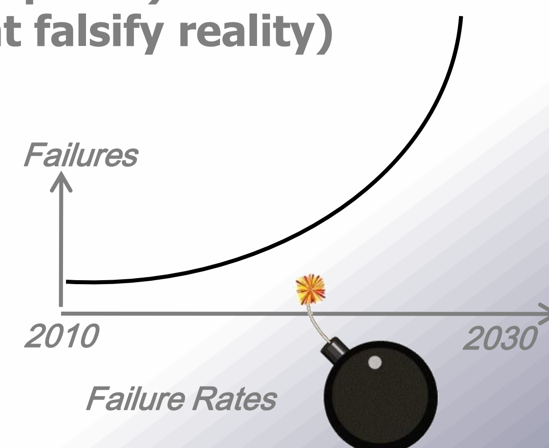


- **Single Event Effects**
  - ☹ **Failures will appear and rapidly increase in frequency (destructive failures possible; access often required)**
  - ☹ **'Early Operation ' problem (observation might falsify reality)**

Possible Scenario:

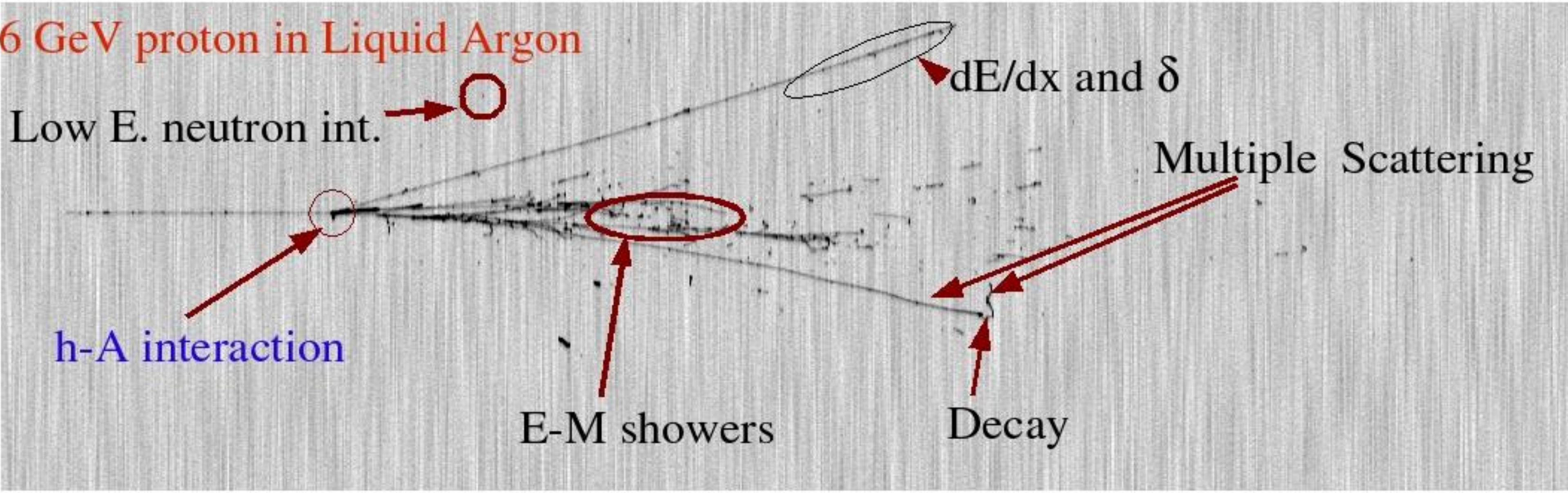


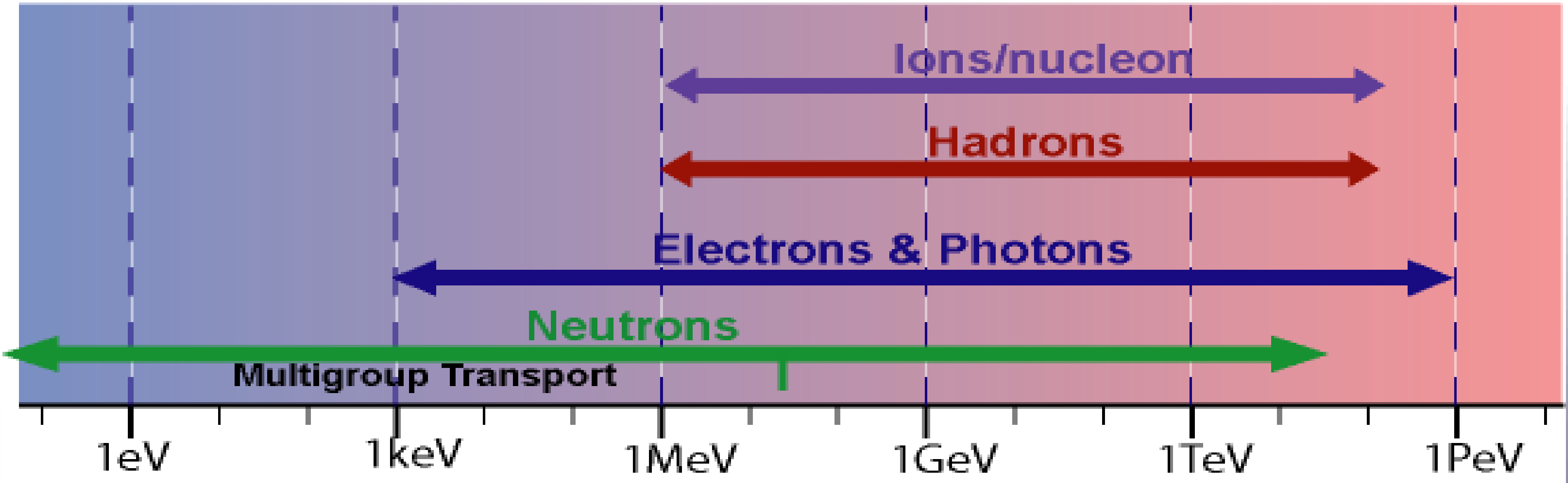




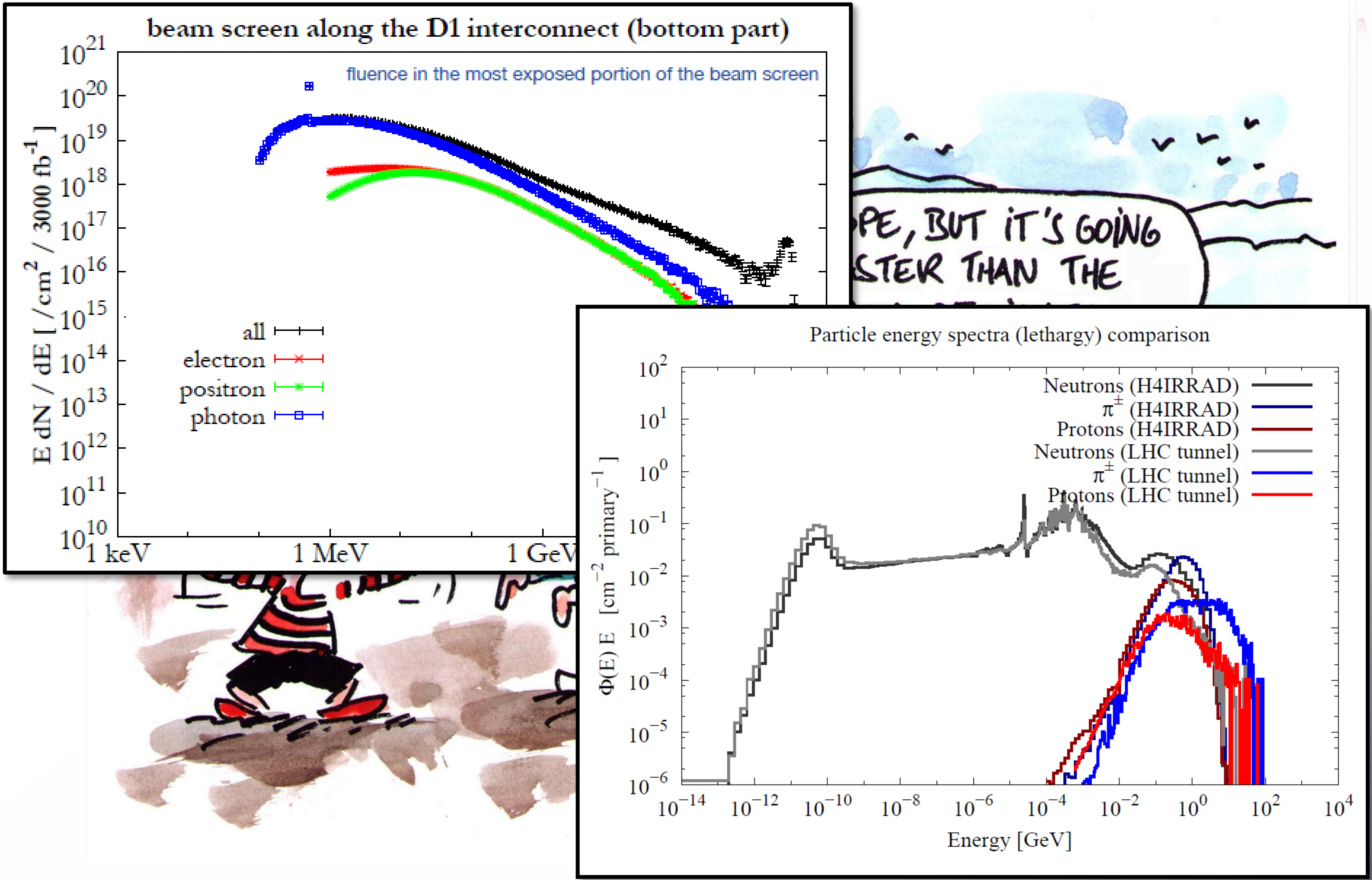
Radiation Environment

High-Energy Particle Interactions

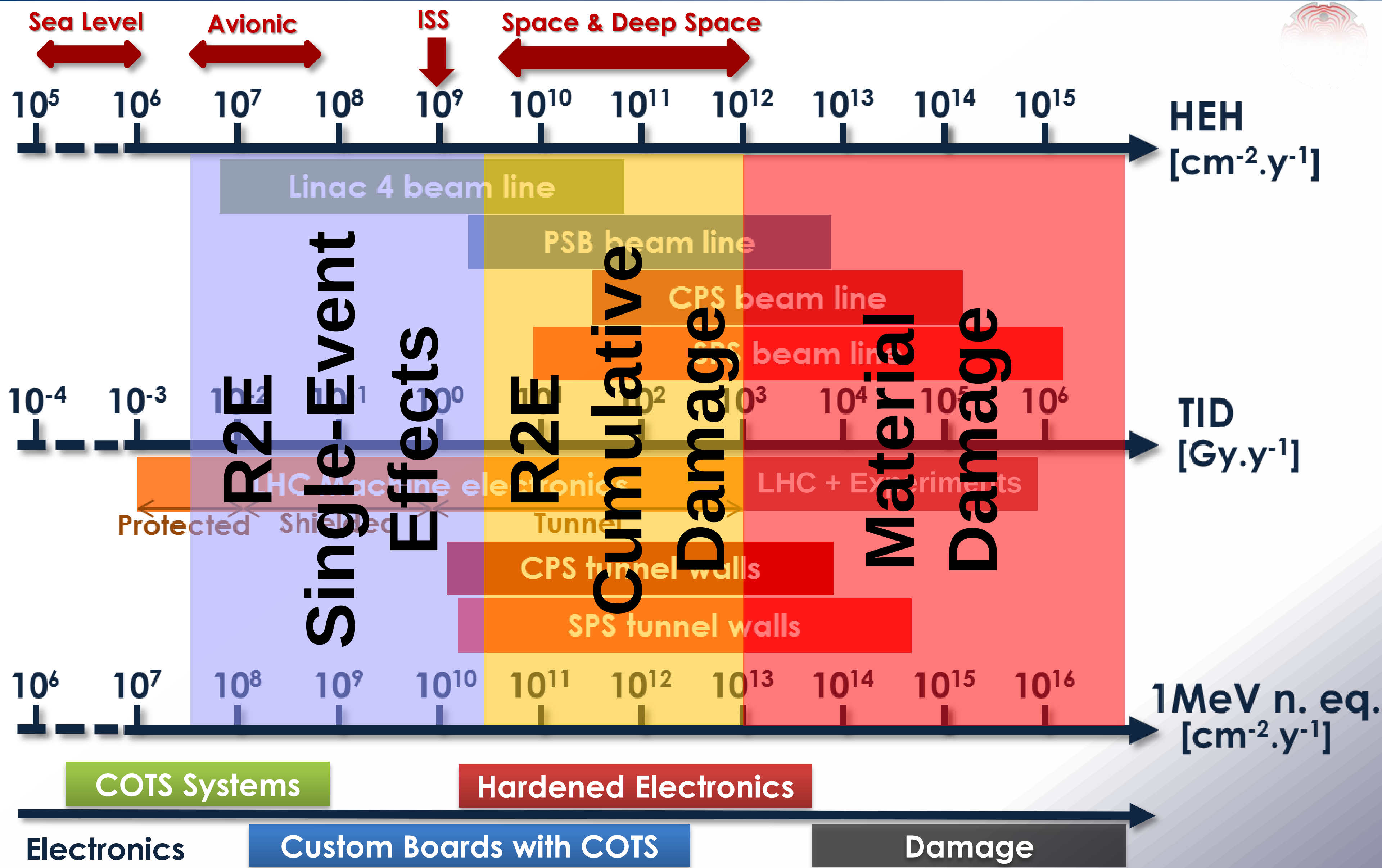




Radiation Environment

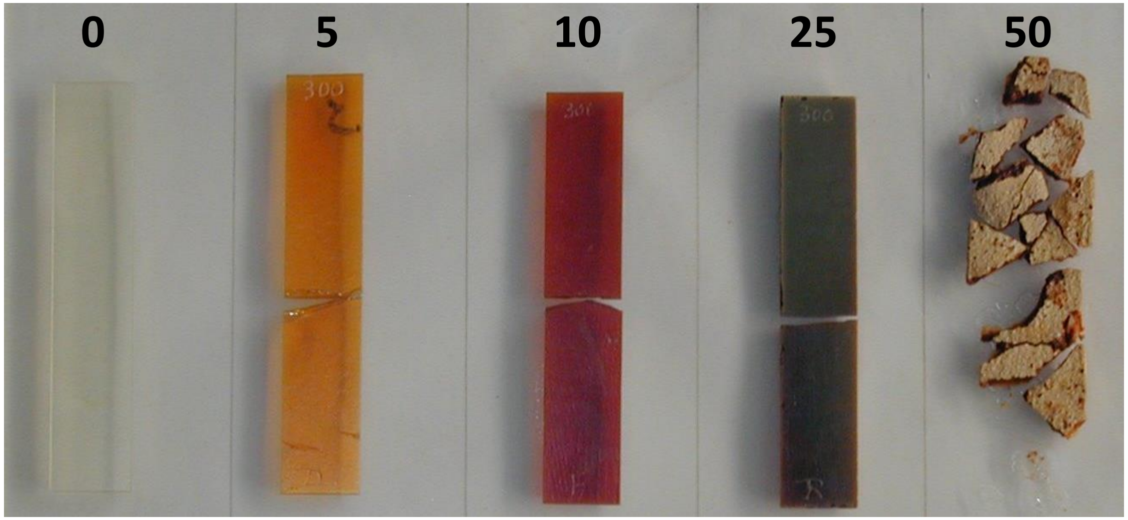


CERN Radiation Levels



Beyond: Material Damage

TID [MGy]



100 Gy

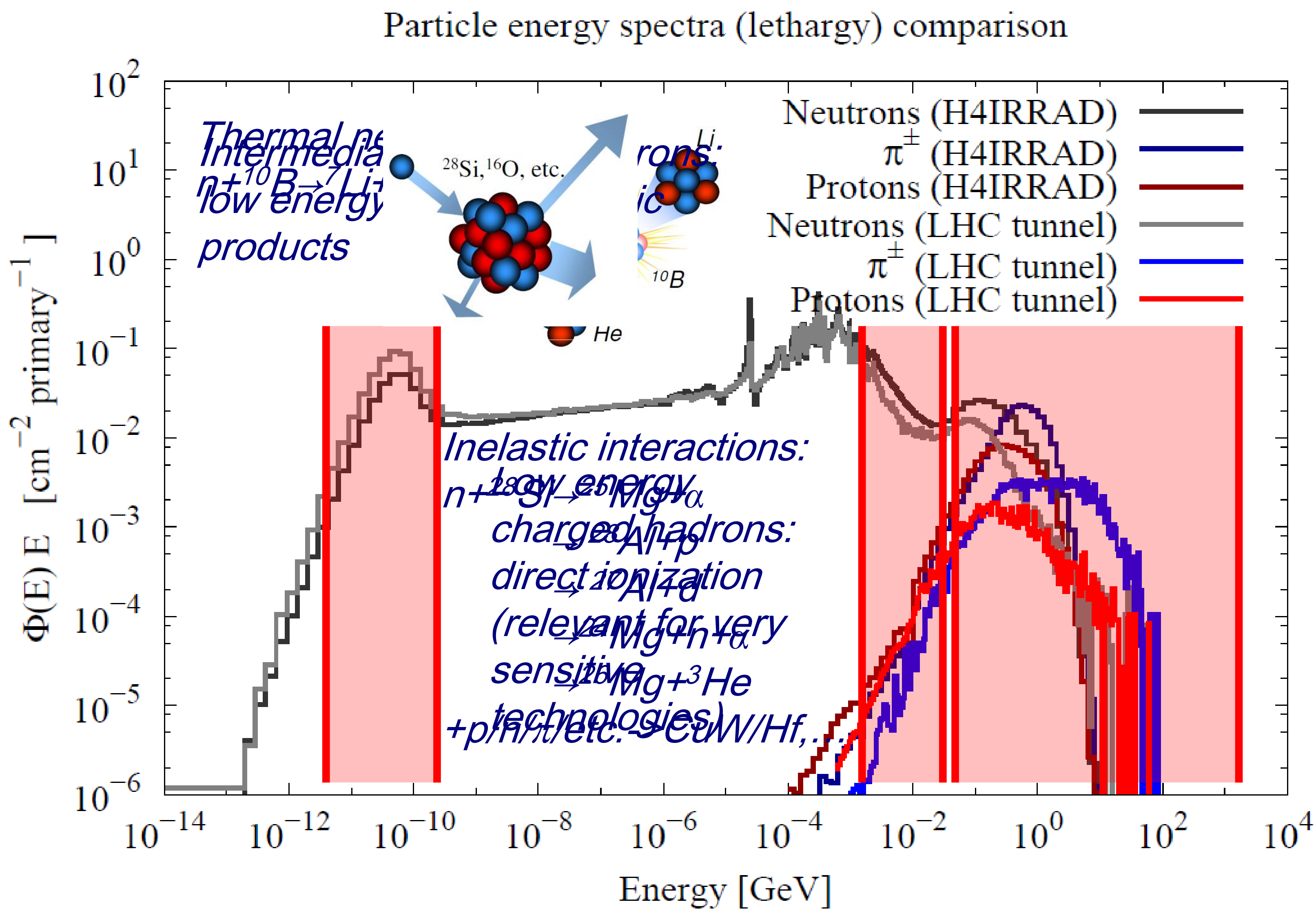
0.1 MGy

1 MGy

used as passive dosimeters

Cylinders of alanine/polymer mixture (~ 4 cm length)

Electronics: Energy Areas of Interest



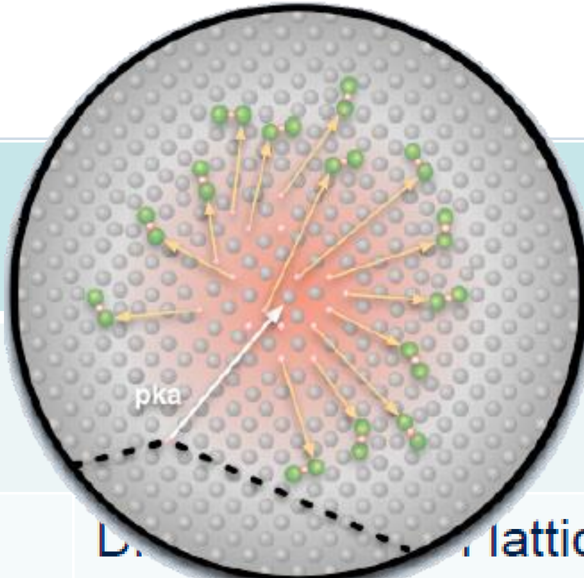
Damage & Consequences

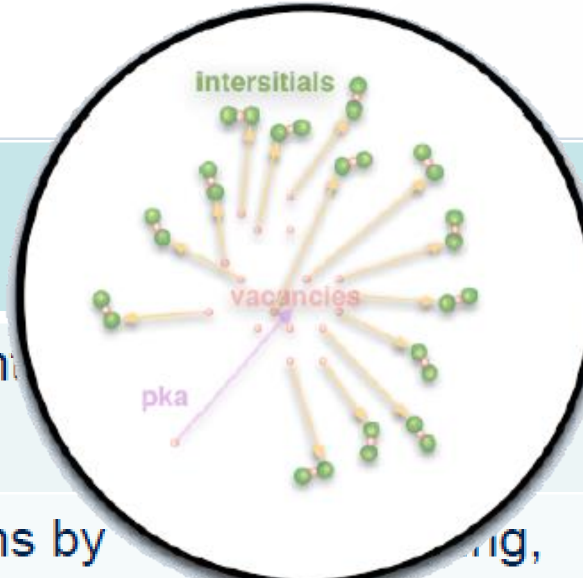
What happens

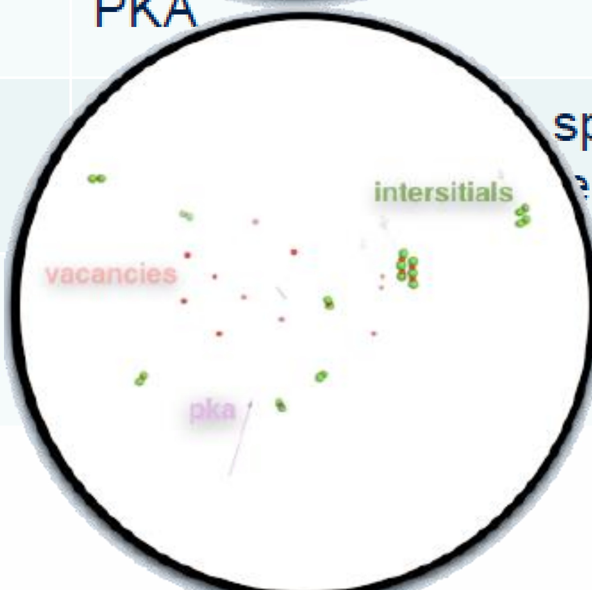
- **Energy deposition**
  - Heating
  - Shock-waves
  - Charge creation/collection
- **Displacement**
- Creation of **interstitials** through fragments
- Creation of **radicals**
- **Transmutation**
- **Gas** production
- **Activation**

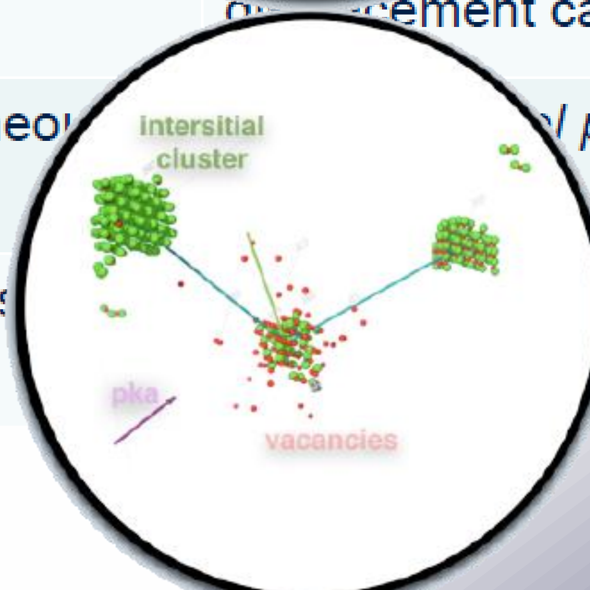
pico-
seconds

nano-
seconds









Time (s)		
10^{-18}	incident	n atom
10^{-13}	D… lattice atoms by PKA	…ng, …cement cascade
10^{-11}	spontaneou… …ering	*…l pairs*
$>10^{-8}$	…defects	…ng

DD – is it Natural?

Mechanical Parameters

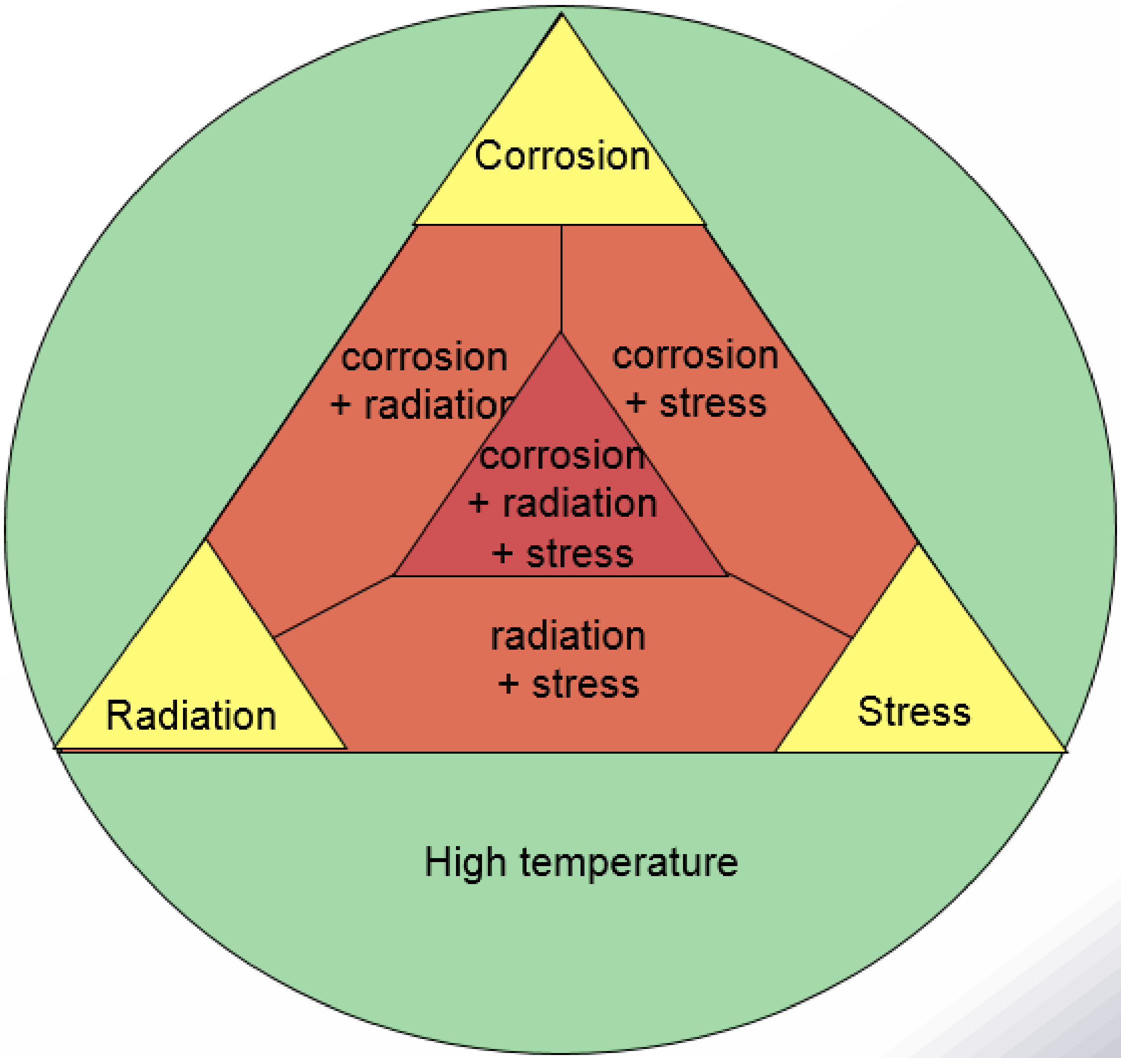
- Strong
- Ductile
- High thermal conductivity
- Stable
- Safe

- Weak
- Brittle
- Low thermal conductivity
- Unstable
- Dangerous

+

Other – linked - Parameters

Radiation effects and consequences have to be seen in the full context of the particular application!



Material Examples

Plastics

- cable insulations, structur
  lamps, electrical cubicles..
- **Plastics are organic mater**
- They are derived from pet
  natural materials (resins, r
- Contain Carbon

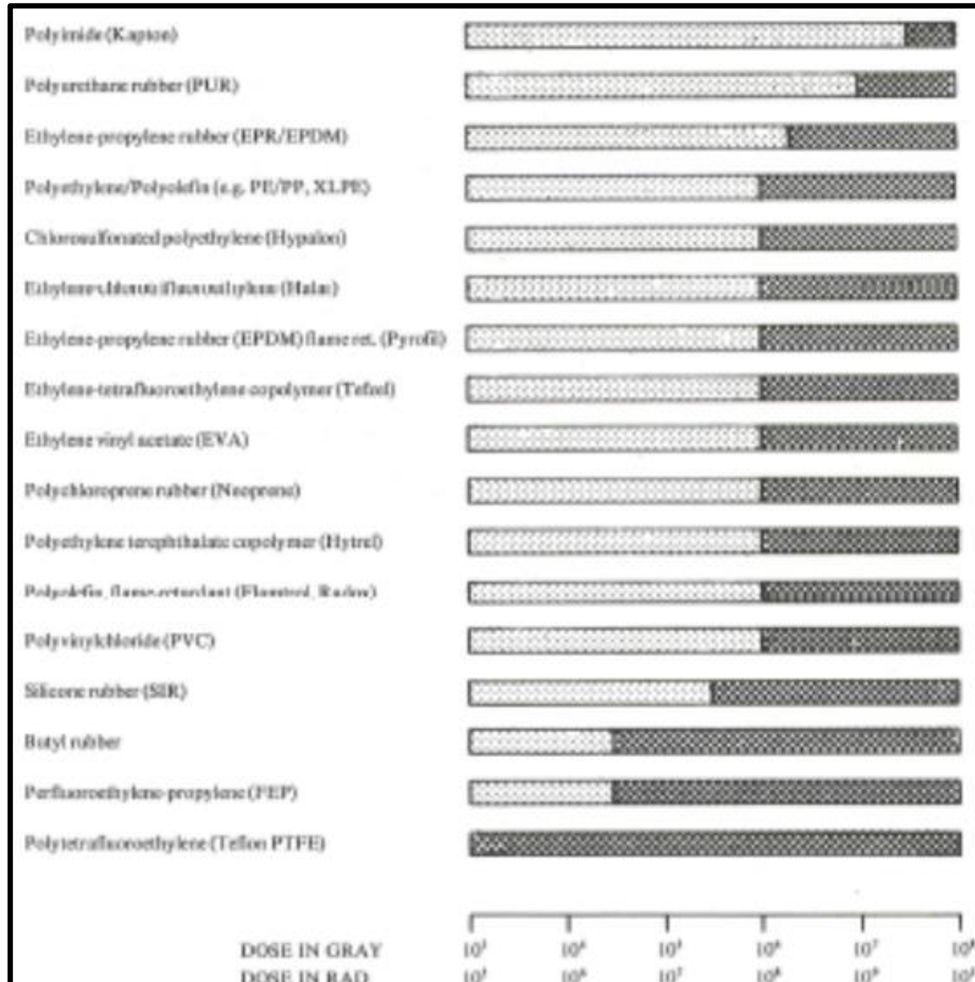
Effect of radiation:

- **Degradation of mechanic**
  first (e.g. reduced elongat
- **Degradation of electrical**

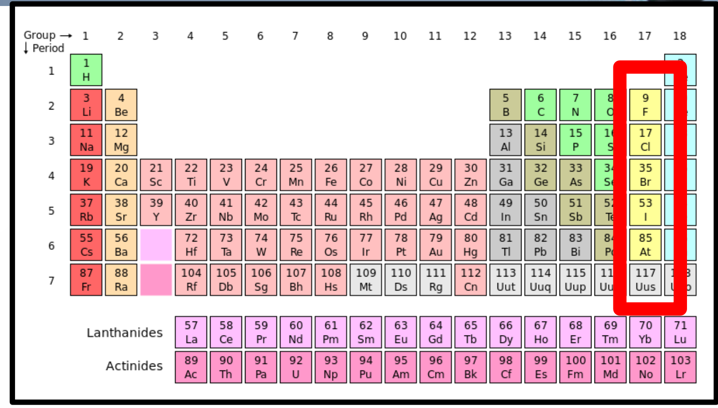
Material Examples

Plastics

- useful information in CERN's Yellow books (e.g. CERN 82-10, or 89-12)



Material Examples



Halogens

- Most electronegative elements: easily gain an electron
  - **chemically active!**
- For this reason, in sufficient quantities they can be extremely dangerous
- **Chlorine is the most common on earth**
  - **becomes aggressive and attacks metallic surfaces**
- **Fluorine even glass!!!**

What's also needed: -> Moisture

- Leaking magnet cooling circuits, water valves, etc.
- Infiltration from the tunnel ceiling

Material Examples

Two “Famous” Examples

& at Accelerators:

Material Examples

PVC as a bad example

- PVC = Polyvinyl Chloride
- Usually one worries about ‘burning’ them:

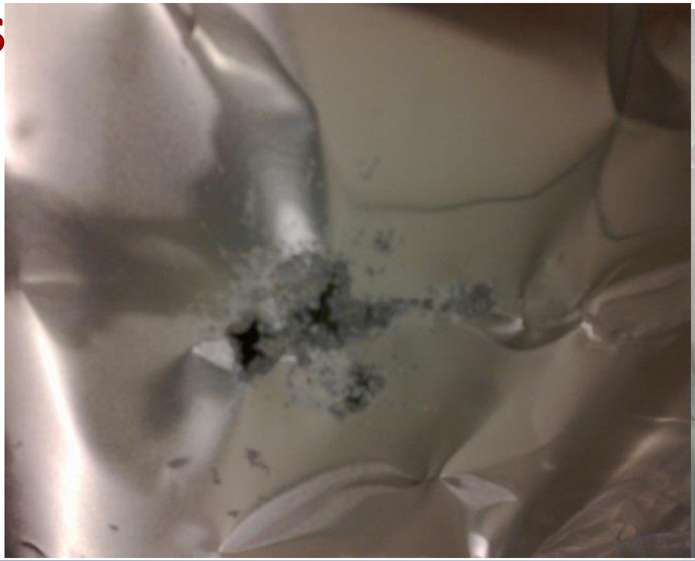
> **Health and safety** [edit]
>
> PVC is a useful material because of its inertness and this inertness is the basis of its low toxicity: "There is little evidence that PVC powder itself causes any significant medical problems."[7] The main health and safety issues with PVC are associated with "VCM", its carcinogenic precursor, the products of its incineration (dioxins under some circumstances), and the additives mixed with PVC, which include heavy metals and potential endocrine disruptors. "Fear of litigation ... have all but eliminated fundamental research into VCM polymerization."[7]
>
> Probably the greatest impact of PVC on health and safety have been highly positive. It has revolutionized the safe handling of sewage and, being affordable, its use is widespread outside of developed countries.[7]

- **PVC and Halogens are NOT allowed in confined space, tunnels etc.**
- AND **with radiation: Dehydrochlorination is the major mechanism of PVC degradation by X and γ-rays**
  - **Cl^- ions react with water droplets and create a very corrosive environment**

Material Examples

Halogens

- **Water droplets charged with Cl- ions** can fall onto accelerator components, generating stress corrosion cracking in unprotected stainless steel components
- Few droplets, maybe a single one, are enough to generate corrosion and failure
- **Once corrosion is there it cannot be passivated anymore!!!**



Material Examples

Metals (studies driven by reactor applications)

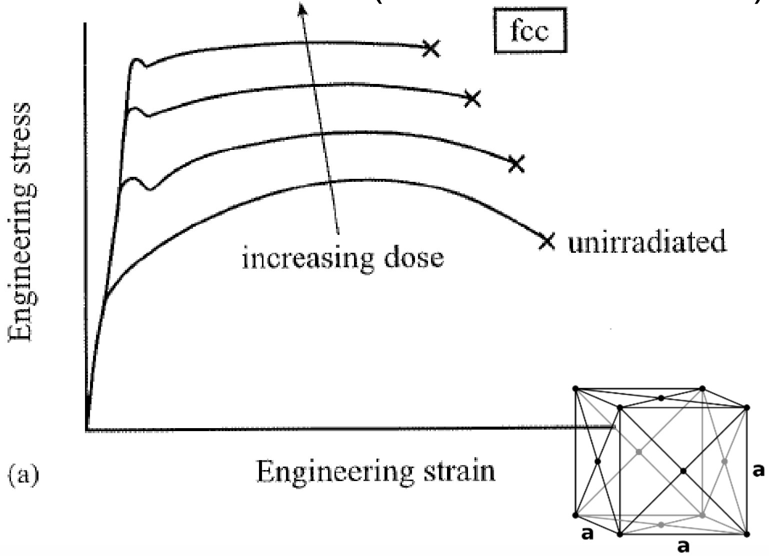
- Mechanical (macroscopic) effects, are ultimately caused by formation of **defects in the lattice structure**
- Defects are : voids, gas bubbles, dislocations…
- **Temperature** has an effect:
  - **Annealing** increases the mobility of defects
    - Often positive impact by reconstructing the lattice
    - BUT sometimes accelerates defects (especially if the material is subject to high stresses)
- **Hardness:** resistance of a material to permanent (plastic) deformation under an given load curve
- **Brittleness:** property of materials that break before showing any visible deformation

Material Examples

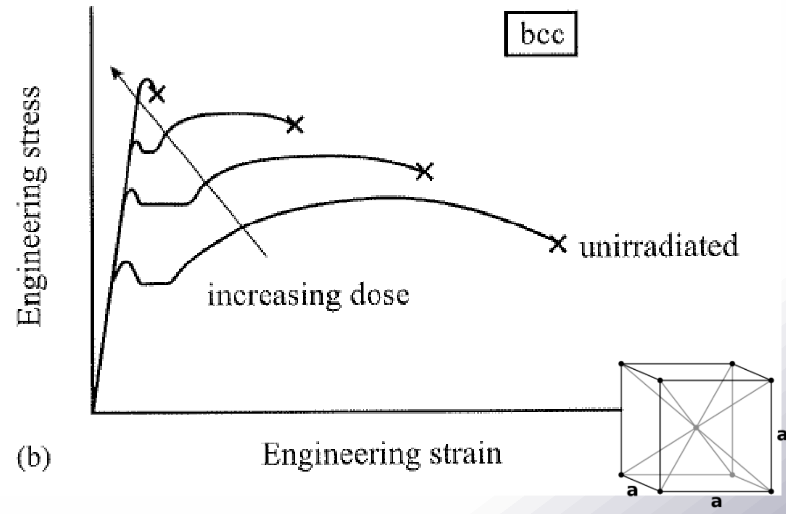
Metals

- **Radiation modifies the stress/strain curve**: yield strength is increased slightly enlarging the elastic region, but ductility is reduced.

Austenitic Steel (face centered cubic)



Ferritic Steel (body centered cubic)



- The **material becomes more fragile**…

Material Examples

Water (two effects are important):

- **Generation of Tritium**
  - **Radiation produces tritium** by different mechanisms
    - D + n -> T + γ
    - ^{10}B + n -> T + ^{8}Be + γ
  - long half life (12.33 years), thus **in high radiation applications, water cooling has to be avoided!**
- **Radiolysis**
  - **deposited energy breaks the water molecule**
  - H_2 is flammable, may provoke explosion
  - O_2 (or O_3) may attack metallic surfaces
  - Water cooling circuits in high radiation areas have to include **strict control of O_2 and H_2 concentration**

Material Examples

Air

- Particle beams (or radiation showers) might travel in air
- Their **interaction of the radiation with the atmosphere** generates O_3
- **O_3 accelerates corrosion!!!**

- **Enclosed areas with humidity can pose problems**

- In highly radioactive areas, humidity has to be kept as low as possible

- **Ventilation has to be designed accordingly**

Material Examples

Optical Fibres

- Optic fibers under irradiation tend to become opaque
  - **-> radiation induced attenuation (RIA)**
- The effect is reduced by limited presence of P in the fiber
- **Special radiation tolerant or even ‘hard’ fibres exist**
- The main effect is an increased attenuation factor, which may or may not affect the transmission of data (e.g, PSK)

- When planning radiation testing of a fiber, it is important to analyse the type of signal to be passed on the fiber, to address the problem properly and measure the degradation of the relevant characteristic

Materials to be avoided

A few examples:

- PMMA (Plexiglas) < 50 kGy
- Butyle based Caoutchoucs < 30 kGy
- Perfluoro-ethylène-propylène (FEP) < 30 kGy
- Acetal Resins (POM) (Delrin) < 10 kGy
- PTFE (Teflon) < 1 kGy

Others as mentioned before

- PVC
- P based fibres

Radiation Damage To Electronics (R2E)

In the Accelerator Context

“Failures of electronics caused by radiation are not necessarily a problem!”

“It’s their total number and impact on machine operation and system lifetimes!”

Exposed Equipment

- **Usually numerous systems affected (powering, control, cooling, monitoring, etc.)**
- **Several can be critical for beam operation**
- **Some to be located in "high-radiation" areas**

A few (simple) numbers on the example of the LHC

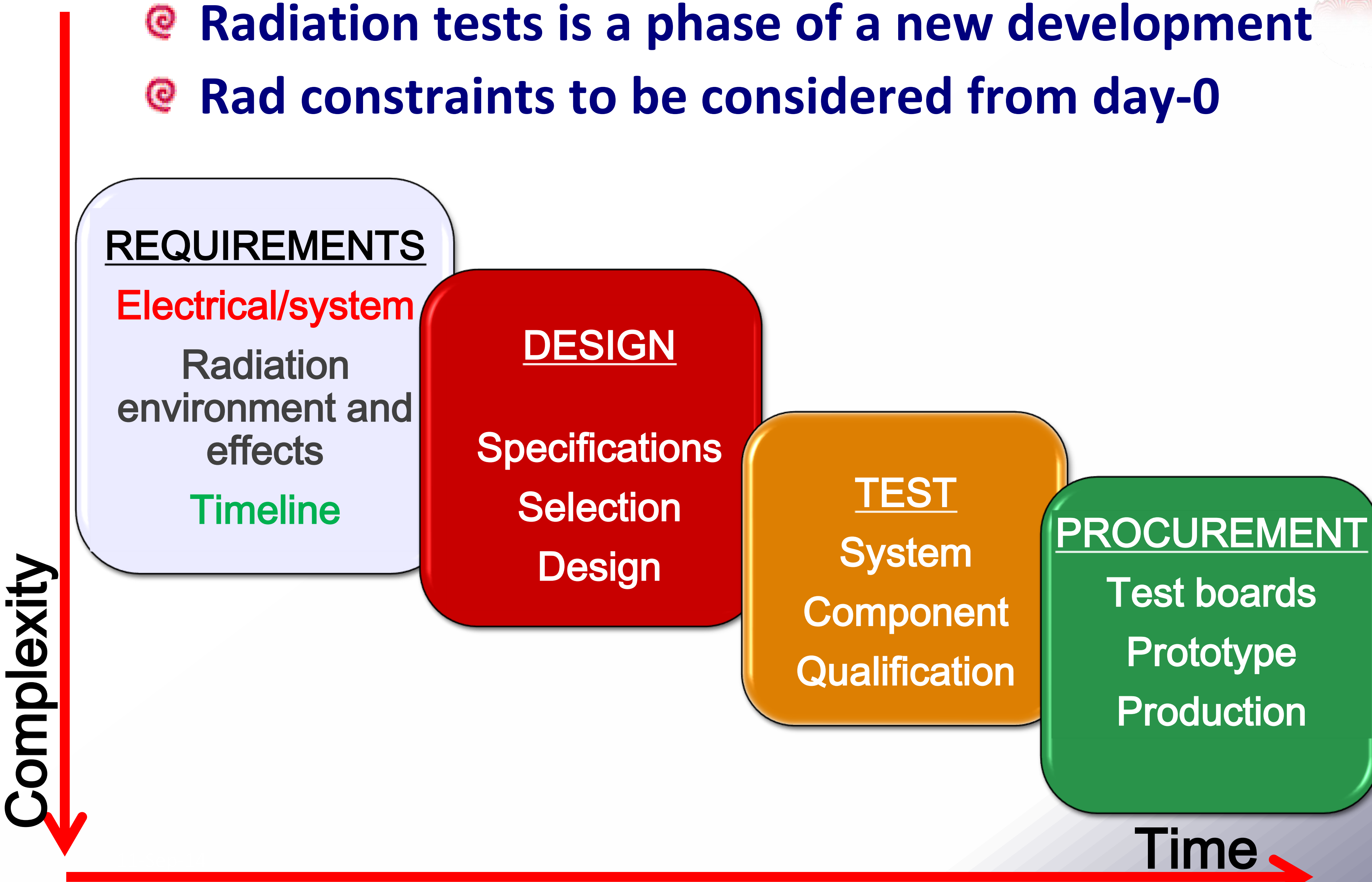
- ~20 different **exposed system**
- From a few to a **few thousand units** each
- number of parts per (per system) range **from a few to a few hundred**

$$N_{failures} = \int \phi(x)\sigma(x)dx \times N_{devices} \sim \Phi(x > X)\sigma \times N_{devices}$$

- **Reliability = low number of failures/short down-times!**

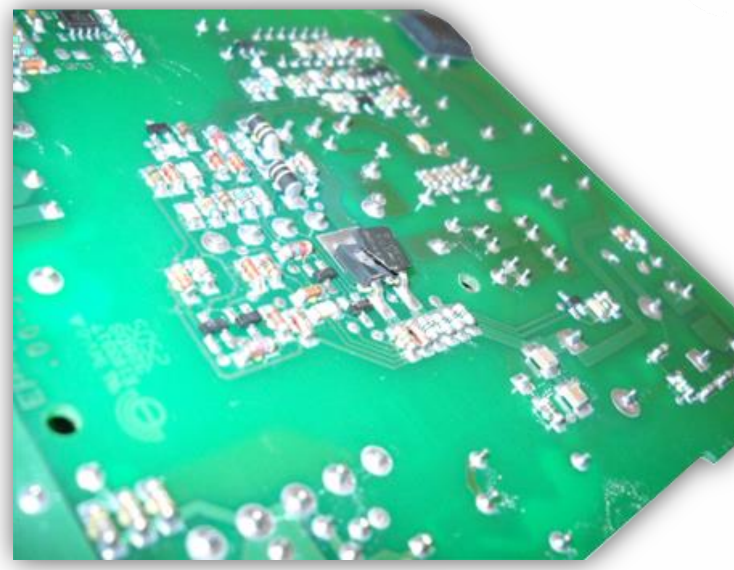
R2E Qualification Steps

- Radiation tests is a phase of a new development
- Rad constraints to be considered from day-0



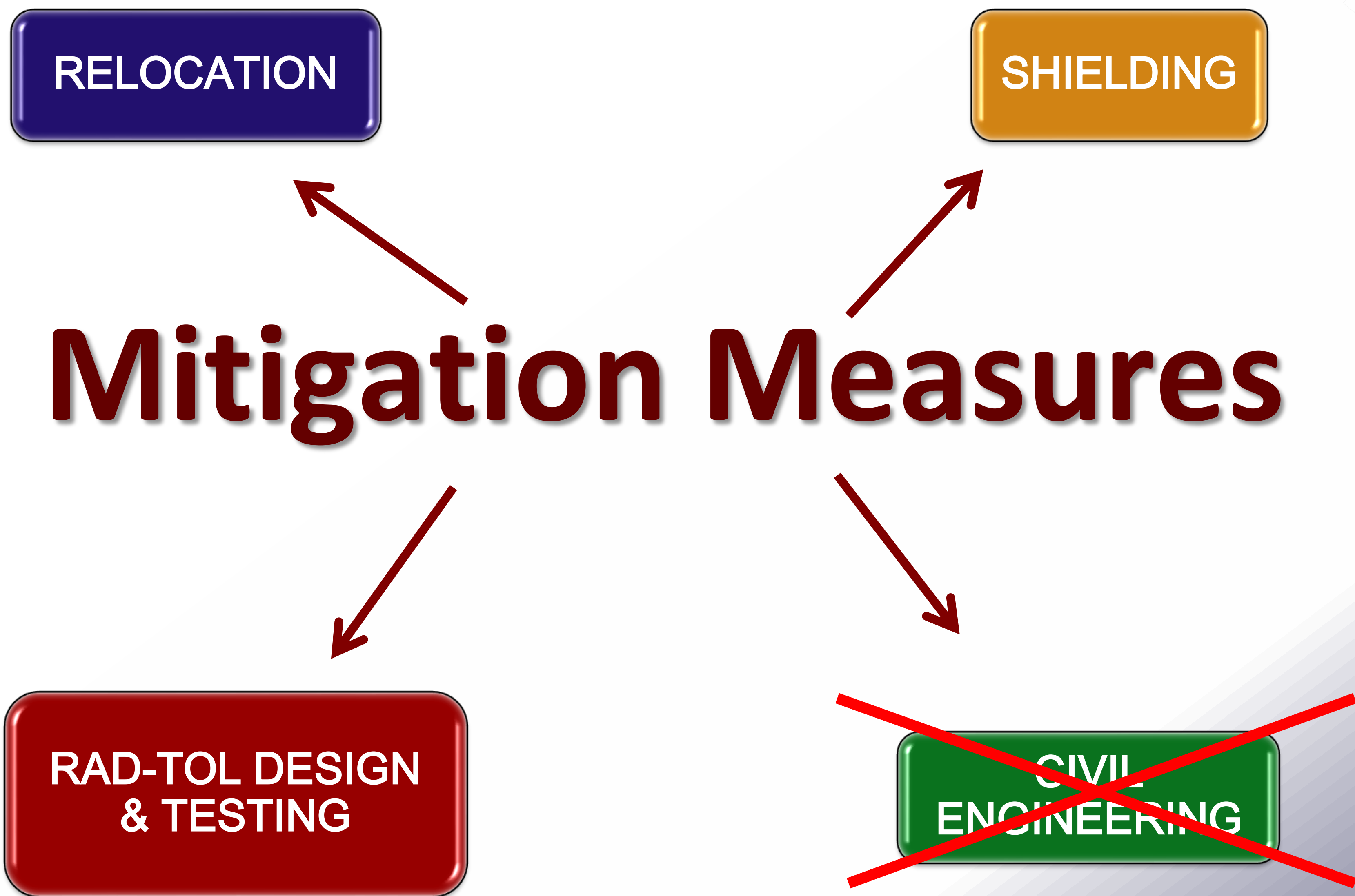
Equipment Failure Example

SEE: Power-Converter (LHC_RR)



⇒ **Premature Beam Dump**

& LHC Downtime

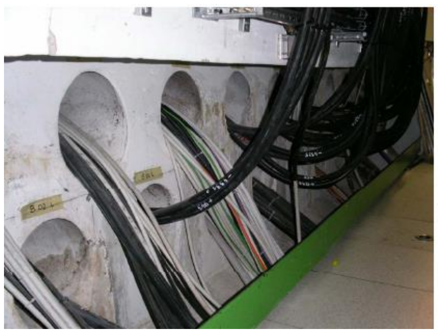

RELOCATION
SHIELDING
Mitigation Measures
RAD-TOL DESIGN & TESTING
CIVIL ENGINEERING

The Perfect Solution

Typical Shielding

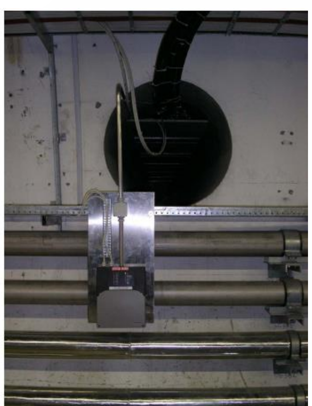
Point 2

Point 3



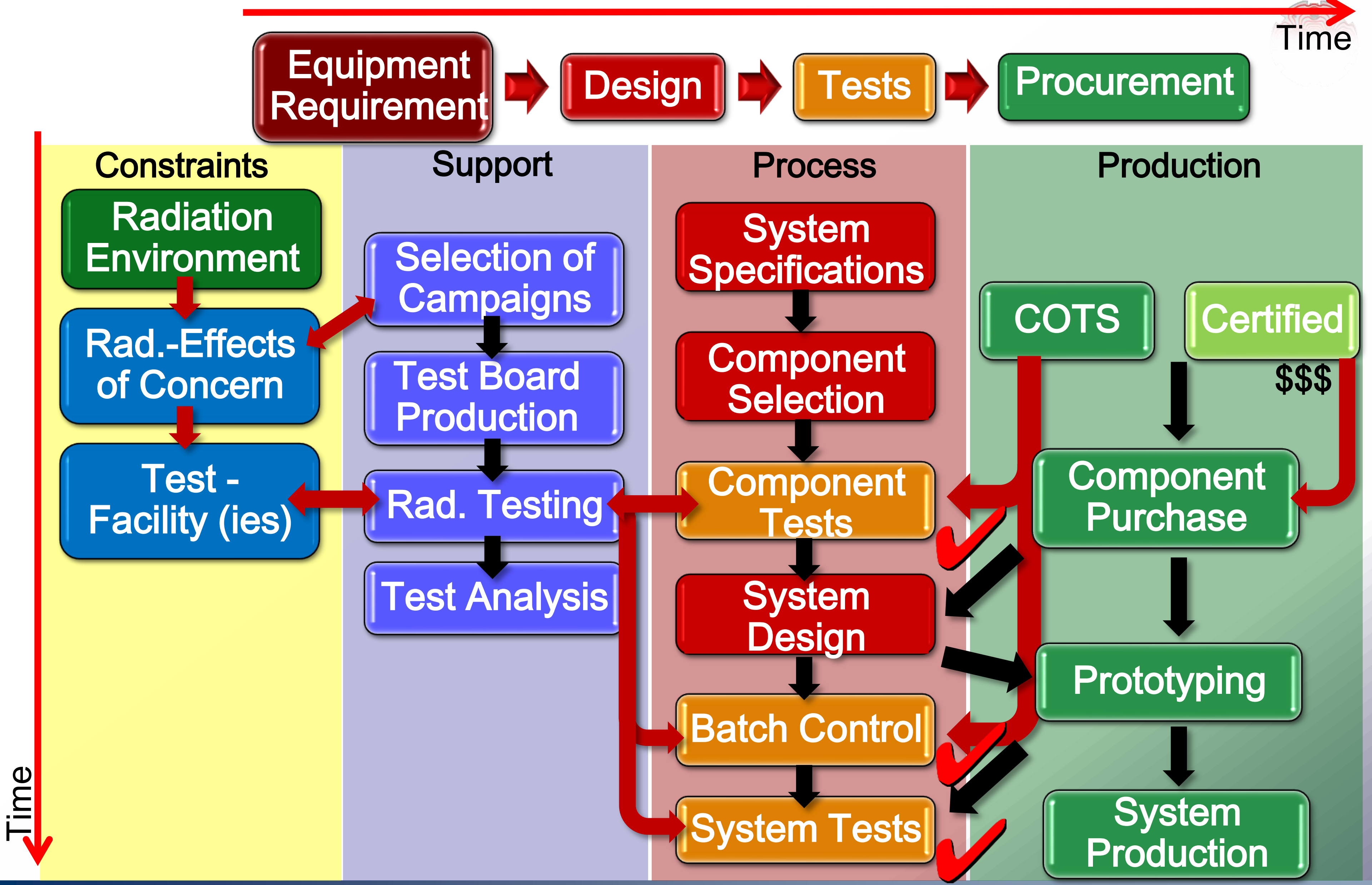
Point 5

Point 6



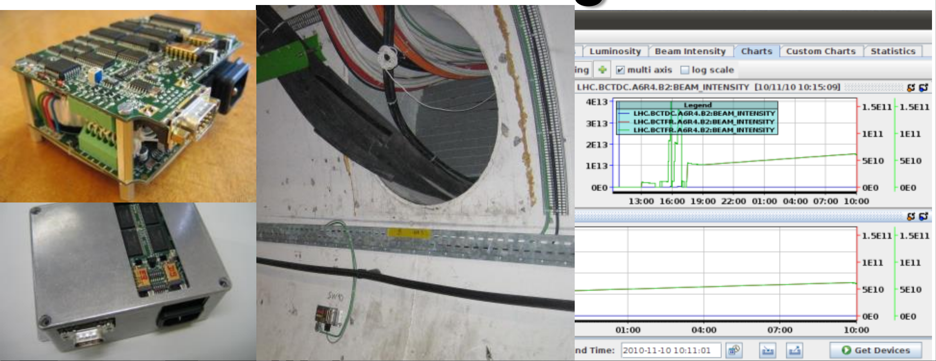
Point 7

A (Rough) Map to Rad-Tol

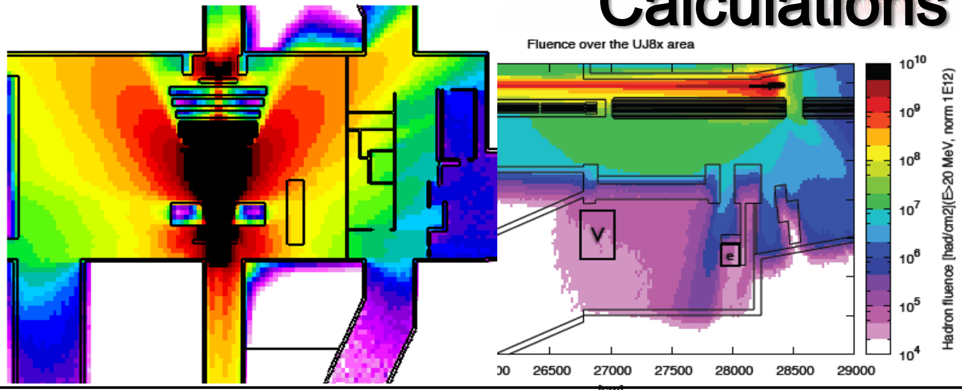


R2E Building Blocks

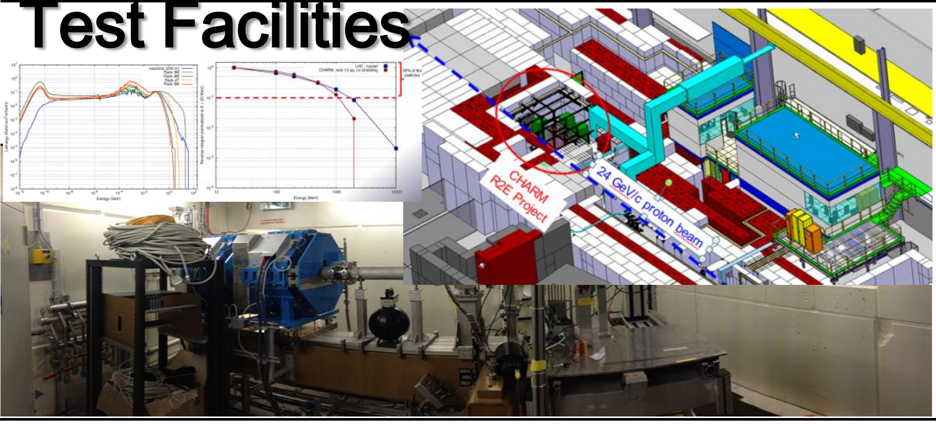
Radiation Monitoring



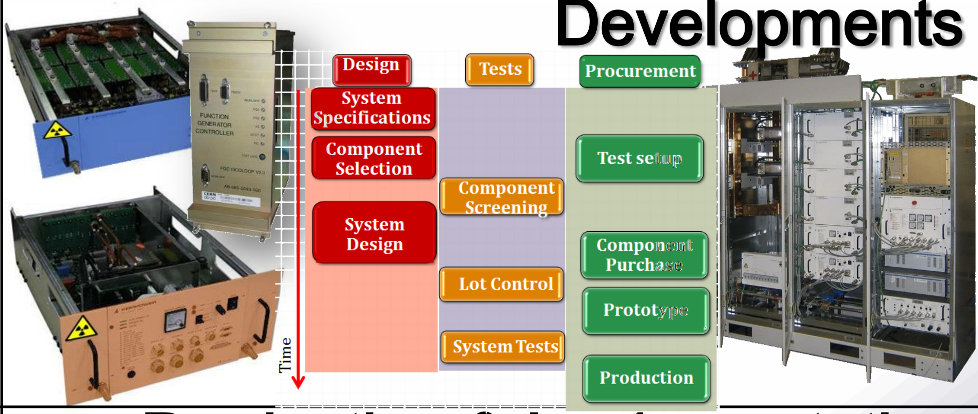
Calculations



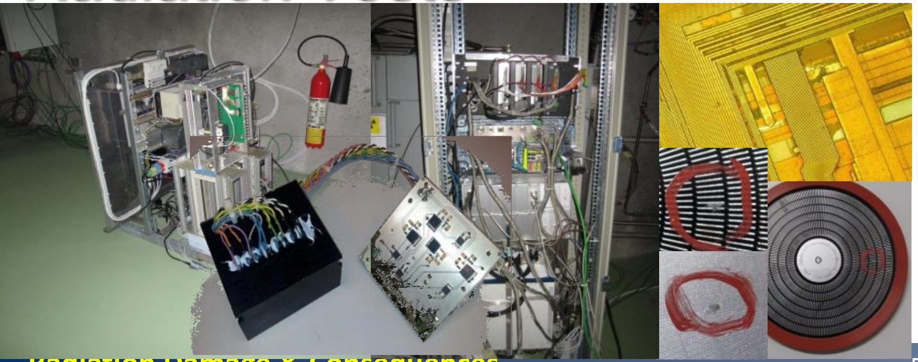
Test Facilities



Developments

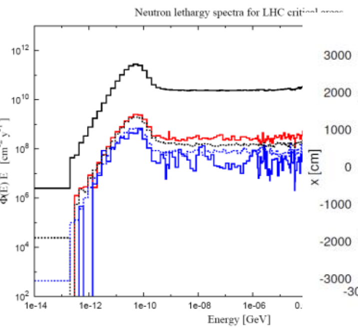


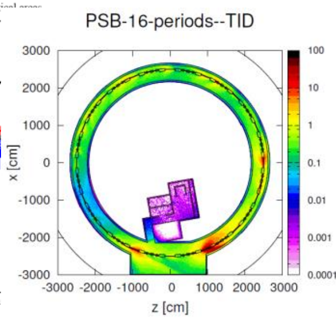
Radiation Tests



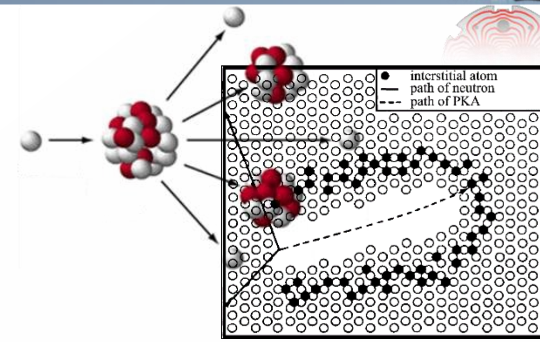
Production & Implementation

Do We’ve All We Need?





Calculations



Materials & Components

Radiation Environment

Radiation Effects & Physics

Sound & Save Design

Monitoring

Models

Radiation Tests & Facilities

Mitigation Measures

EXPERIENCE & EXPERTISE

Procedures, Access, Time

Shielding, Alternatives, Space -…

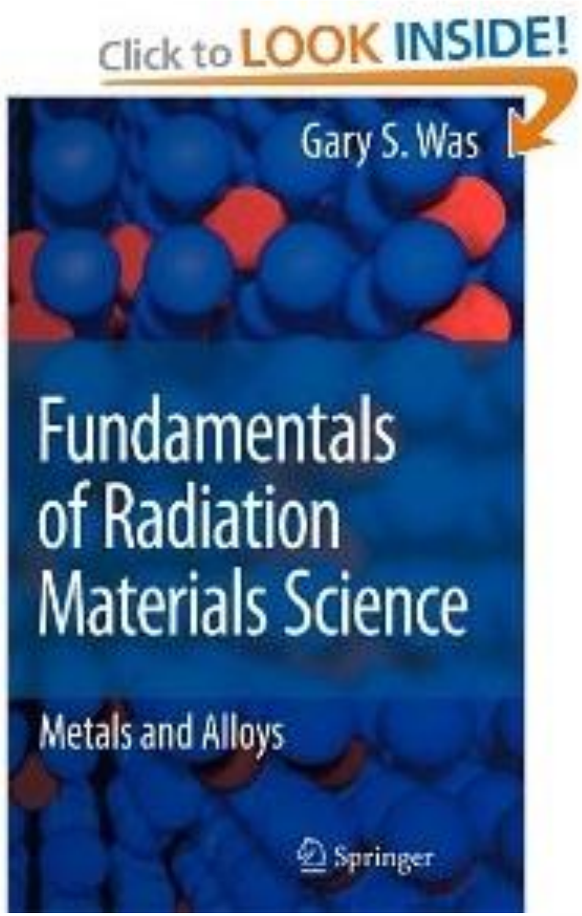
Conclusions

- **Radiation provokes a lot of undesired effect**
  - You cannot avoid them!!!
  - The only rule is to anticipate damage
  - ALARA is the magic word: and not only involves preparation of interventions, but also:
    - selection of materials, components, designs
    - mitigation measures

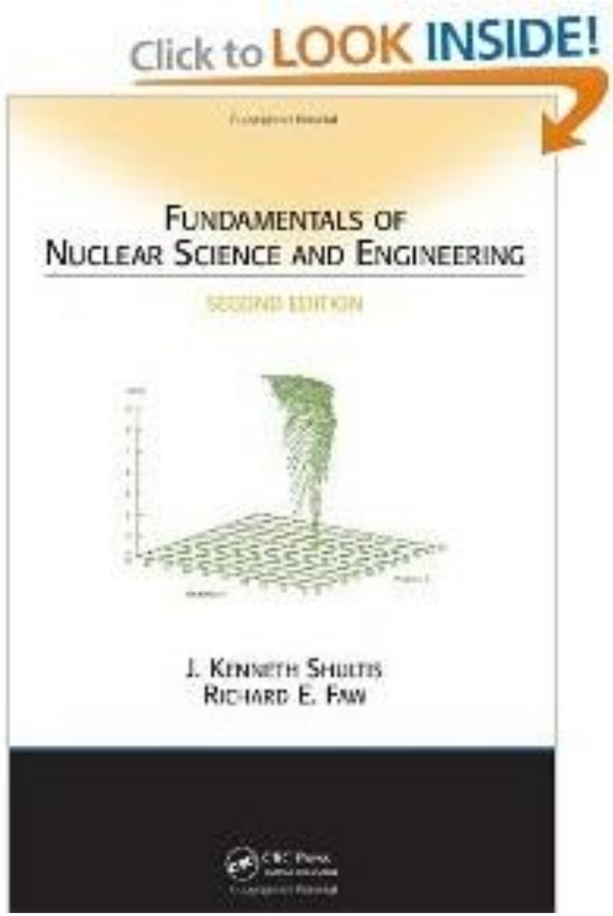
- **Think first & carefully of what you use where!**

  - **Ask yourself the question:**
    - **is it really worth to do what I am doing?**
    - **and in the way I am going to do it?**

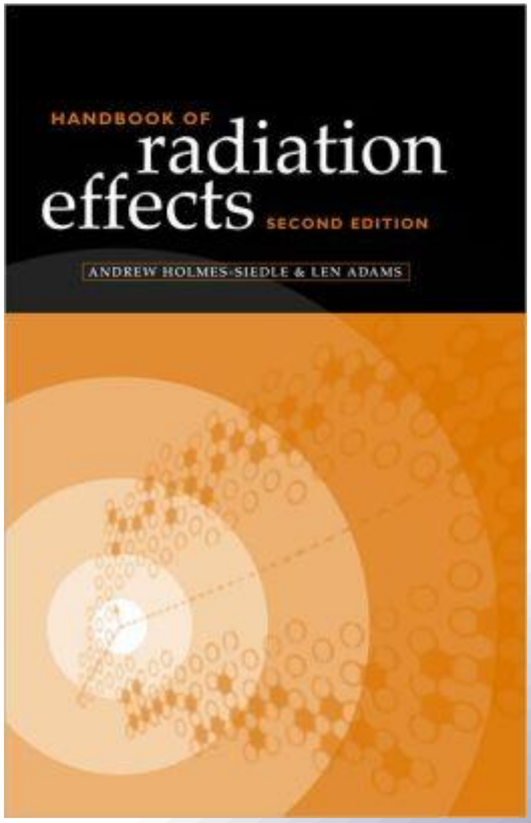
Literature



Click to LOOK INSIDE!
Gary S. Was
Fundamentals of Radiation Materials Science
Metals and Alloys
Springer



Click to LOOK INSIDE!
FUNDAMENTALS OF NUCLEAR SCIENCE AND ENGINEERING
SECOND EDITION
J. KENNETH SHULTIS
RICHARD E. FAW
CRC Press

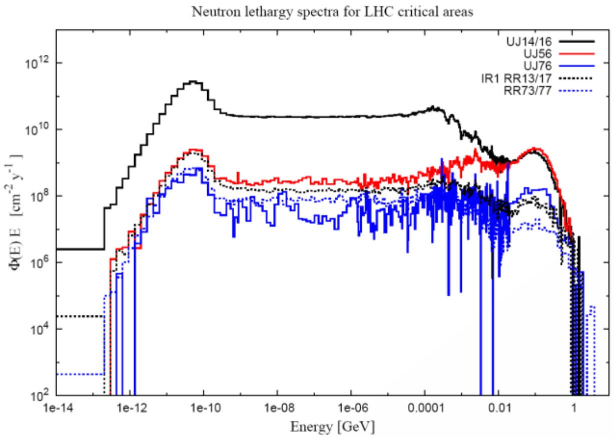


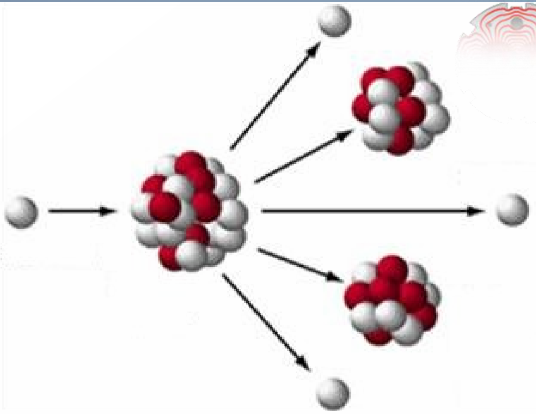
HANDBOOK OF radiation effects
SECOND EDITION
ANDREW HOLMES-SIEDLE & LEN ADAMS

Questions?

BACKUP

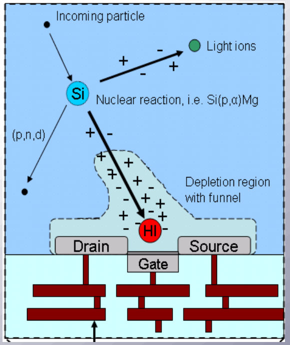
Approach & Requirements





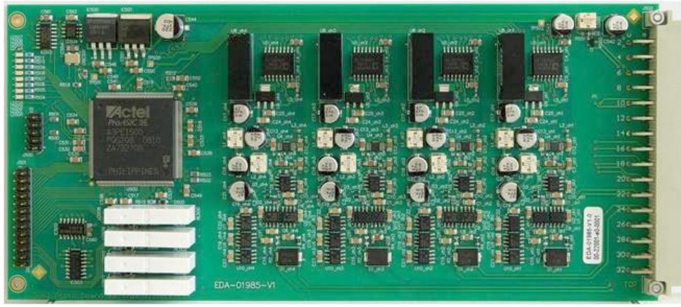
ELECTRONIC COMPONENTS ⟷ RADIATION ENVIRONMENT ⟷ PHYSICS MODELS

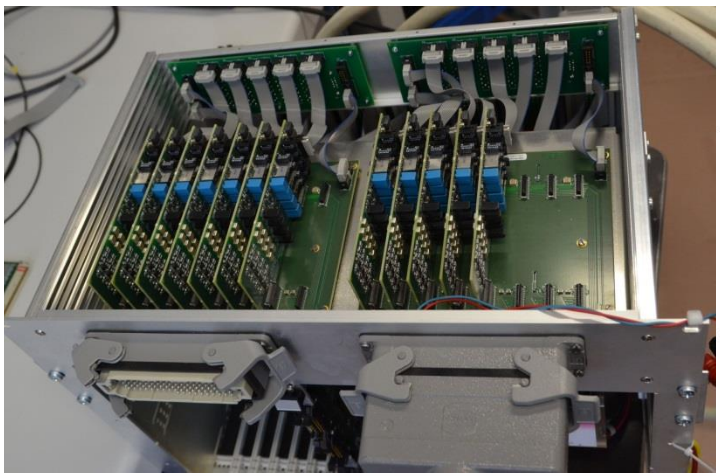
RADIATION EFFECTS
ANALYSIS
TESTS
MITIGATION

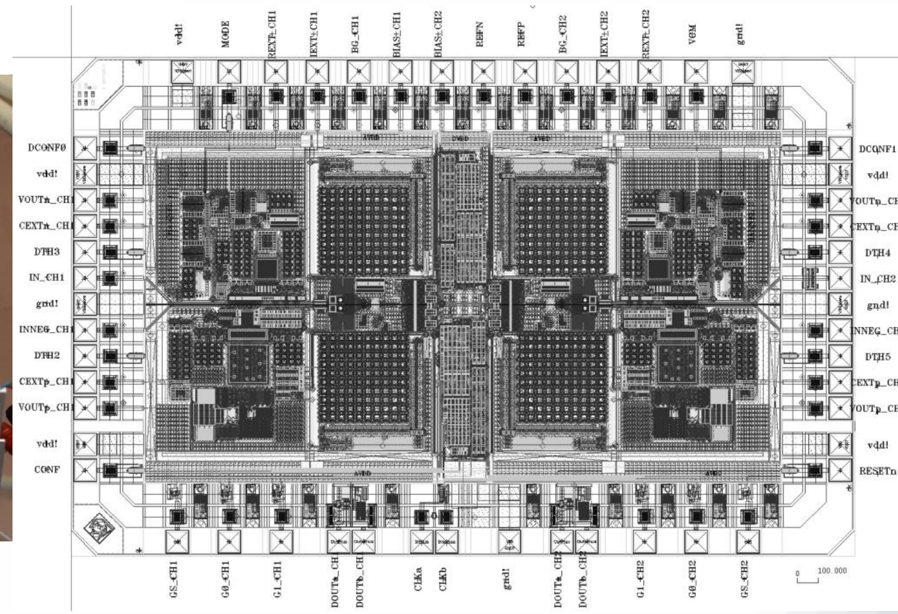


Equipment: Full COTS Systems

Equipment: Custom Boards







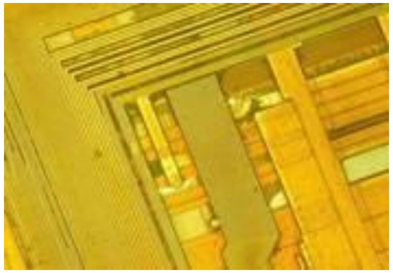
… often based on COTS

(for delay, financial and availability reason)

… individual failure mechanisms to be considered

"LHC"-life example: SEL on CPLD

- A Complex Programmable Logic Controller (CPLD) was tested using **60 MeV protons**
- **No SEEs** were **observed** for the **three devices** tested before these started failing due to total ionizing dose effects (cumulative) after 120 Gy.



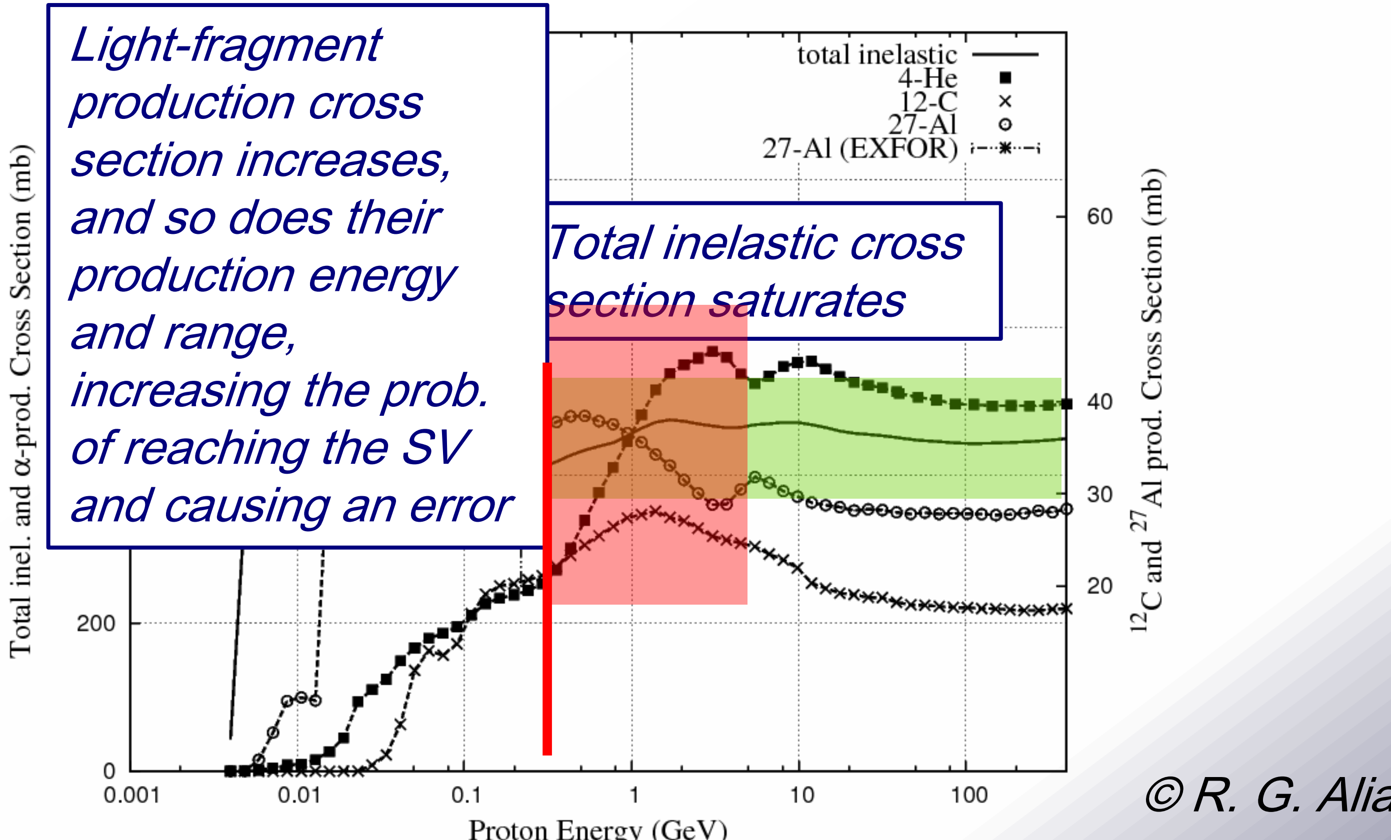
- The component was then exposed to high energy particle radiation at an **LHC-environment**. **Permanent destruction** of the part occurred in the **early stage** of the test.

- Importance of **testing** in the actual **operation environment** (not always feasible in a systematic way) and of being able to **model/predict** the **error rate** (energy dependence knowledge, for example)

Energy Dependence

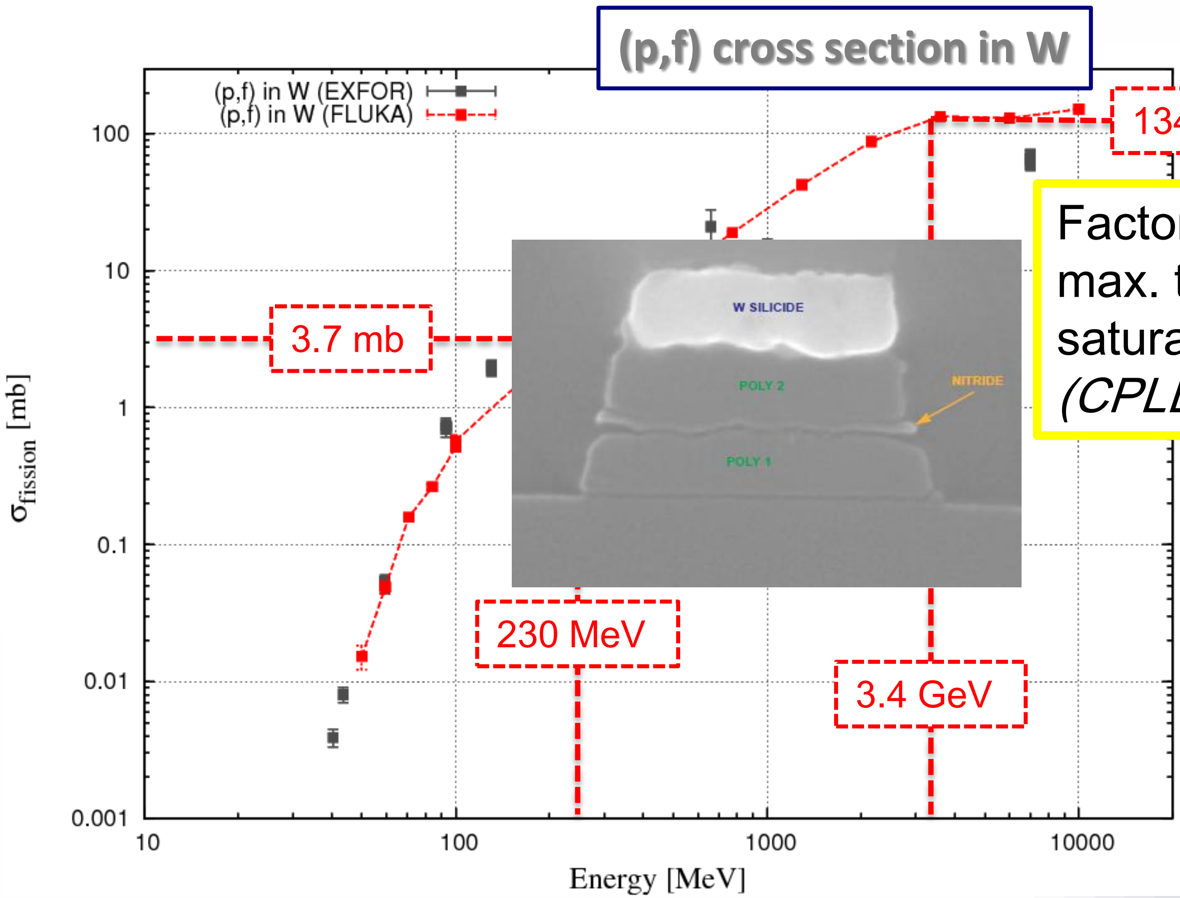
Above ~100 MeV, the total **hadron-Silicon** inelastic cross section is saturated, however:

- more light, long-ranged fragments are produced
- and they are produced with larger energies (and therefore ranges)



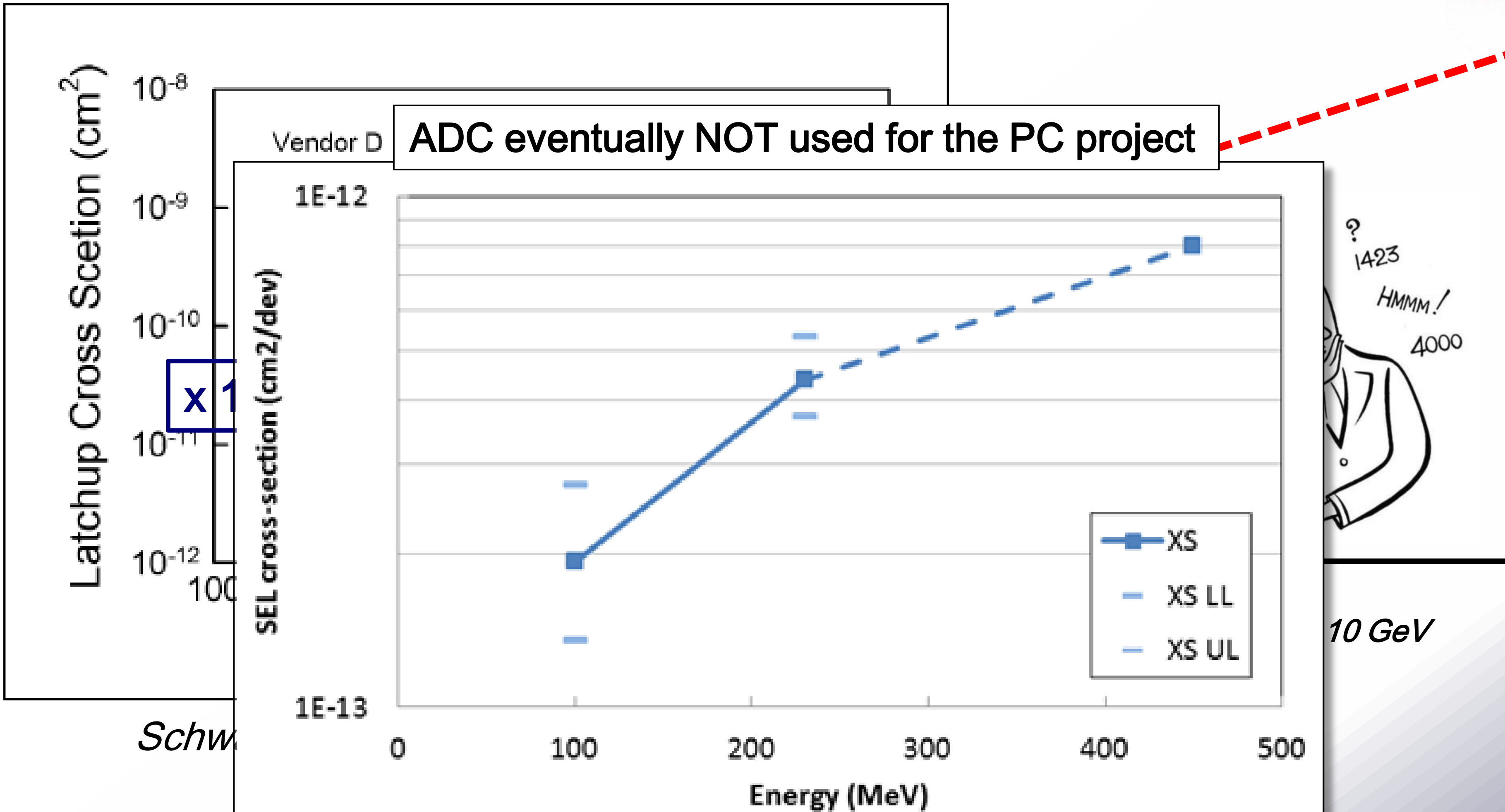
SEL & Fission: Energy Dependence

- **High-Z materials** (namely **tungsten**) are often used in the interconnection layers of the memories, **near the sensitive volumes**
- Energetic hadrons can induce **fission** in these materials, producing very **high-LET fragments** that can **dominate the SEE cross section**



Factor ~35 between max. test energy and saturation *(CPLD example!)*

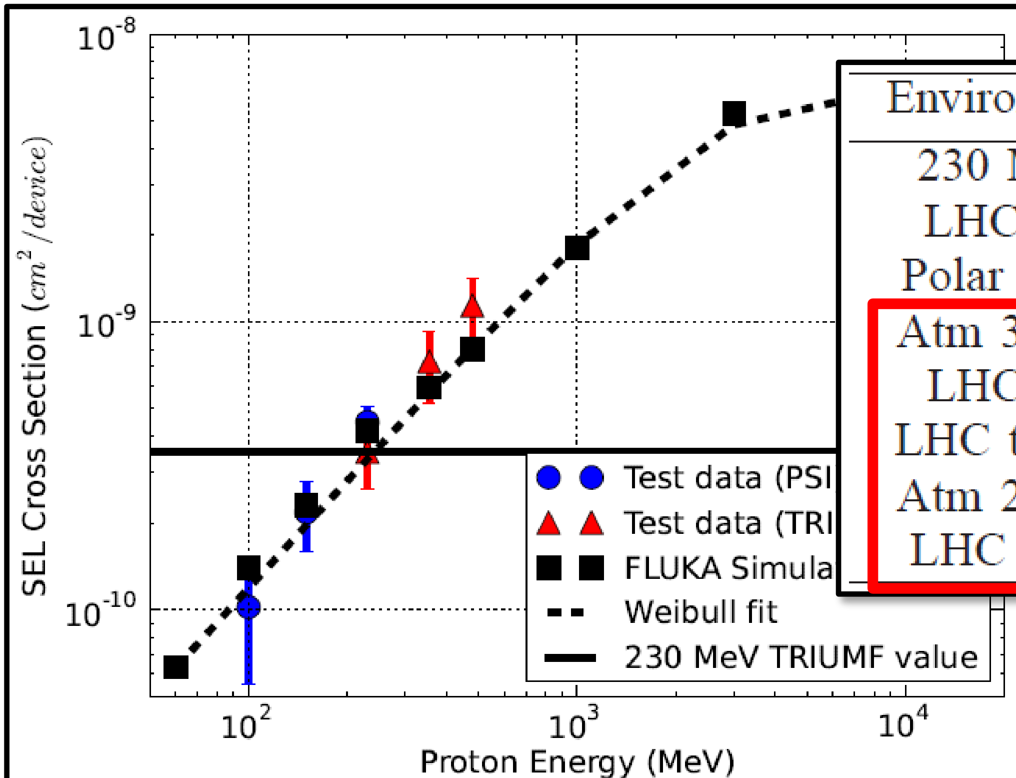
SEL: Energy Dependence



R. Garcia-Alia (IES & CERN Thesis 2012-2014)

SEL: Energy Dependence

- Important possible dependency for high-energies
- Strong impact on various radiation environments



Compared to 100MeV

Environment	Case I	Case II	Case III
230 MeV	1.8	2.8	**3.4** (1.0)
LHC HS	0.7	0.8	0.9
Polar Orbit	0.9	1.6	2.5
Atm 375 m	1.0	2.1	**3.3** (1.0)
LHC LS	1.3	**5.2** (1.9)	**9.7** (2.8)
LHC tunnel	1.5	**9.6 (3.4)**	**20 (5.8)**
Atm 20 km	1.2	**10 (3.6)**	**23 (6.7)**
LHC Exp.	1.6	**18 (6.3)**	**40 (12)**

No W — W from rev. Eng. — Full layer of W

Why do we (at CERN) care about SEEs?

- **Commercial components** used in systems operating **in or near the LHC-tunnel** (power converters, cryogenics, QPS system…)

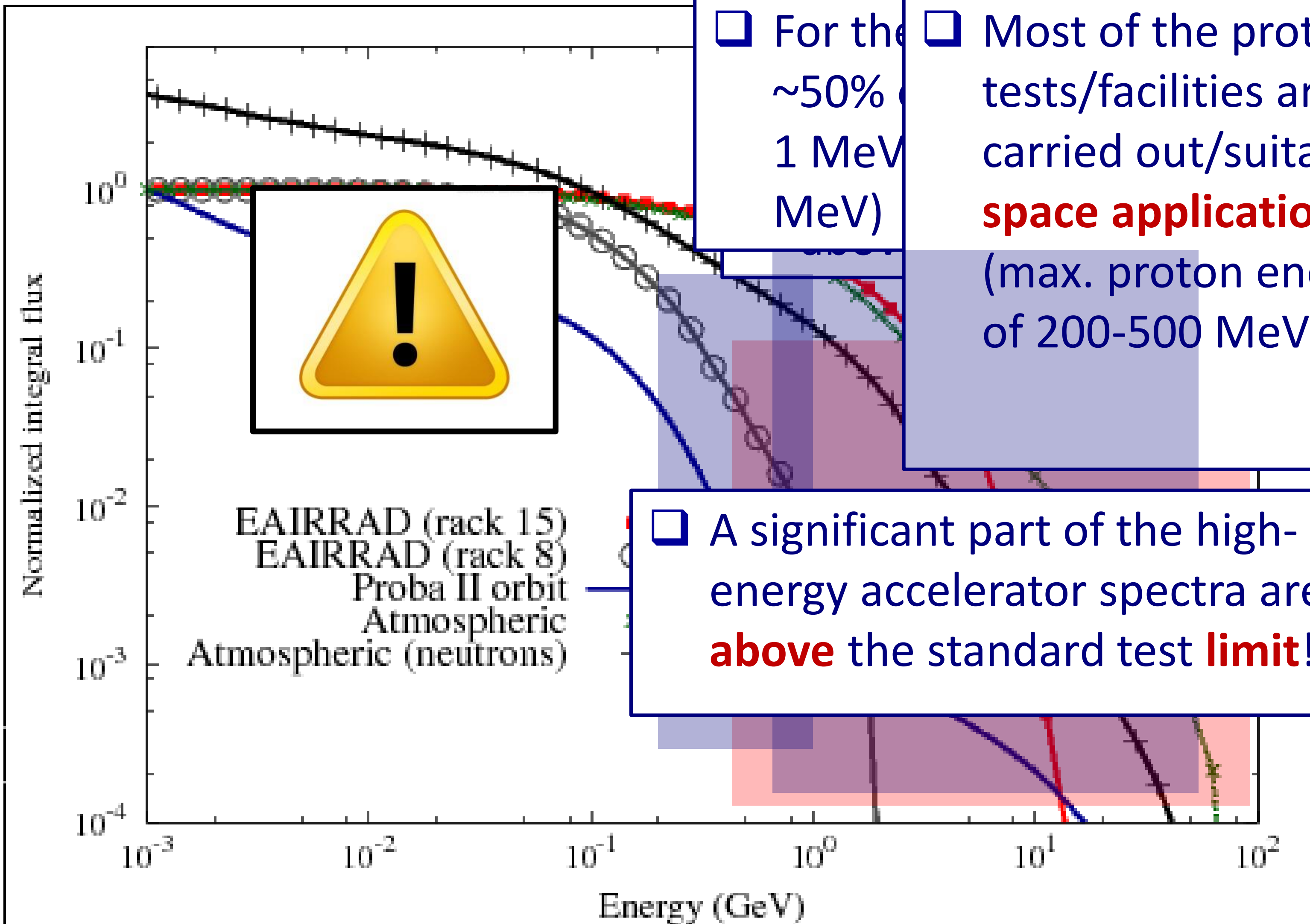
+

- **Intense radiation fields** at the locations of operation

=

- **SEEs, TID and DD** in components and systems **affect the operation of the accelerator** (beam dump, etc.)
- Need to **test, monitor, mitigate** and **predict** (R2E project).

Accelerator & Earth Environment



- For the
  ~50%
  1 MeV
  MeV)

- Most of the proton tests/facilities are carried out/suitable for **space applications** (max. proton energies of 200-500 MeV)

- A significant part of the high-energy accelerator spectra are **above** the standard test **limit**!

Hard Failure

An error induced by faulty device operation. DATA is lost AND data/function is lost and can no longer operate at that location.

Soft Failure

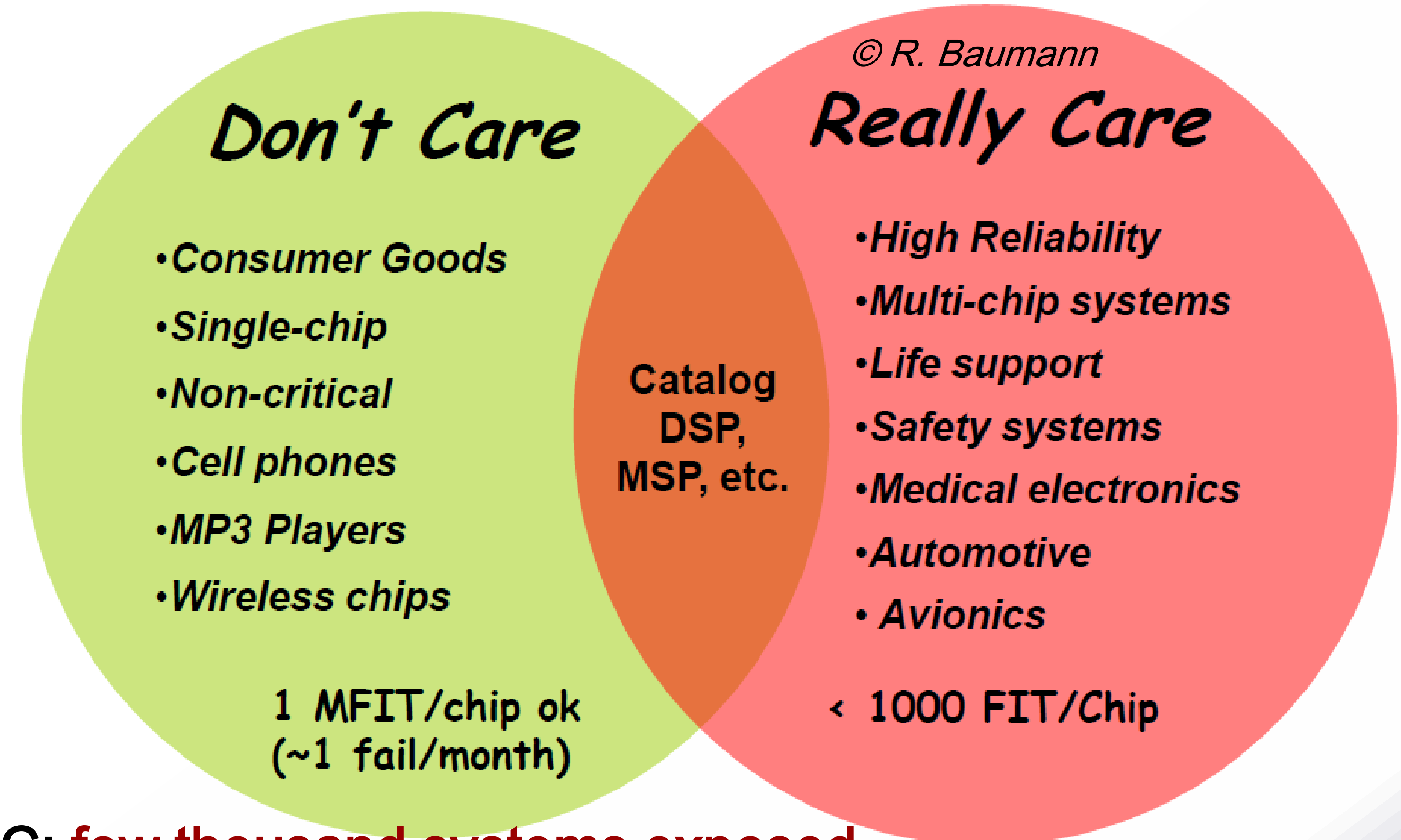
An event corrupting only the DATA stored in a device. The device itself is not damaged and functionality is restored when new data is written.

$$1\ \mathrm{FIT} = \frac{1\ \mathrm{failure}}{10^9\ \mathrm{dev-hrs.}}$$

1 FIT is 1 failure in 114,155 years!

or 100,000 FIT is ~ 1 failure/year

Only Satellites and Accelerators?



LHC: few thousand systems exposed

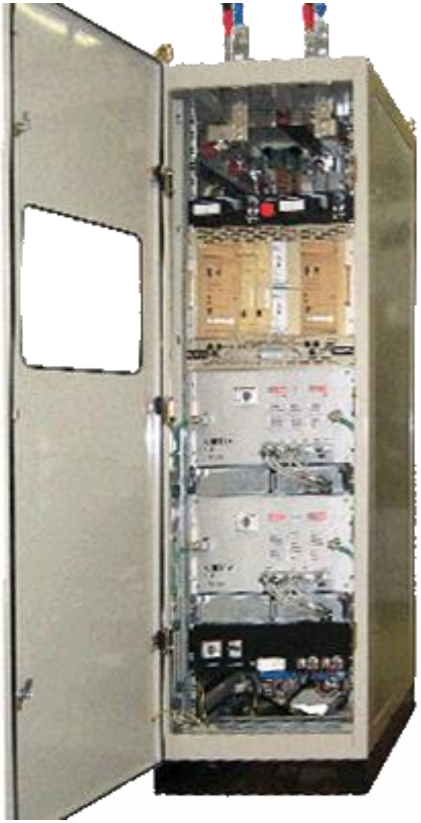
Aim: less than one radiation induced failure per operational week

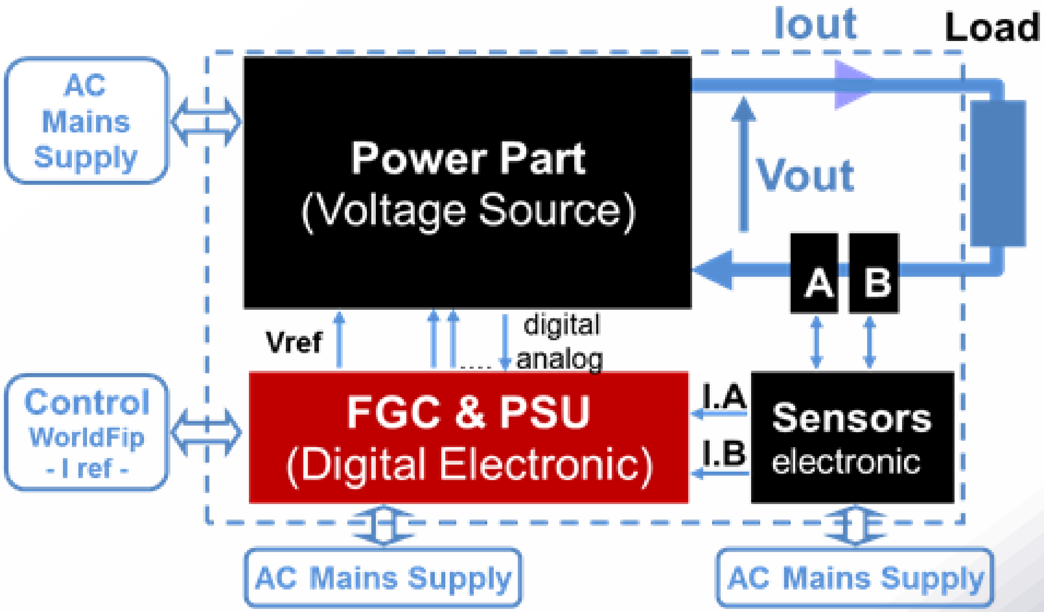
Reliability in FIT: -> aiming for about 1 FIT/SYSTEM!

Per Chip? (better don't do it)

LHC POWER CONVERTERs

- **Driving the magnets in the accelerator**
  - Partly high-precision requirements
  - Large number of internal components (high power, low voltage, control, etc.)
  - Very high number of exposed units



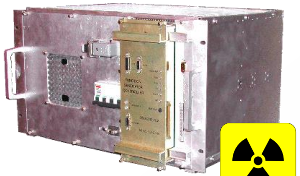


© Y. Thurel

LHC POWER CONVERTERs

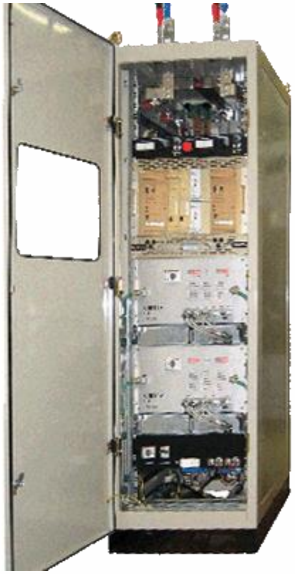
- **Minimize the number of converter types:**
  - Only the LHC60A-08V was specified for a radioactive environment !
  - 3 other converter types are part now of the radioactive sensitive areas!

LHC60A-08V
4-Quadrant
752 Units



LHC120A-10V
4-Quadrant
300 Units

LHC600A-10V
4-Quadrant
400 Units



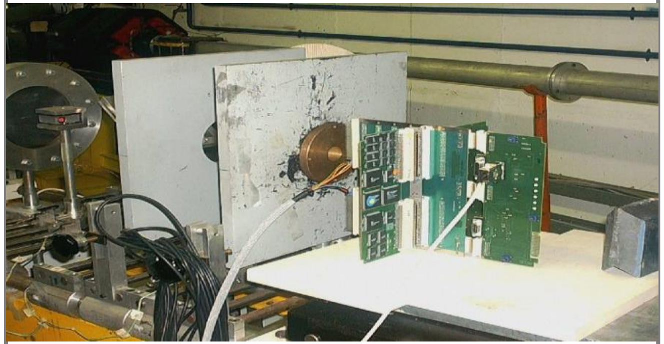
LHC4..6kA-08V
1-Quadrant
200 Units

Units : Quantity in all machine (UA, RR, UJ, tunnel)

© Y. Thurel

PCs: What was tested and where?

LOUVAIN (2003 - FGCs)

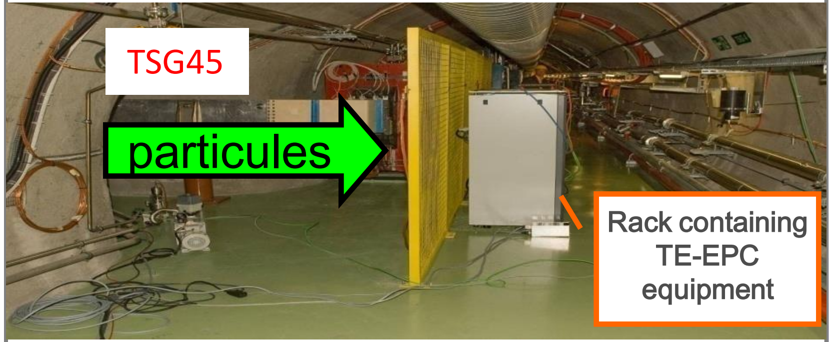


60 MeV proton components tests

PROSPERO (2009 - FGCs)

1MeV neutron displacement damage tests

CNGS (2008..2009 – FGCs, 60A, PSUs)



LHC-Environnement System Test

FGClite Development

Issue: present FGC2 is susceptible to radiation induced failure

FGC2 **Converter** **Location**

Consequence: >2015 – significant loss of LHC availability

Actions:
1. New hardware controller "FGClite":
   -> **optimized for radiation**
2. New control principle: regulation loop in gateway

© S. Uznanski

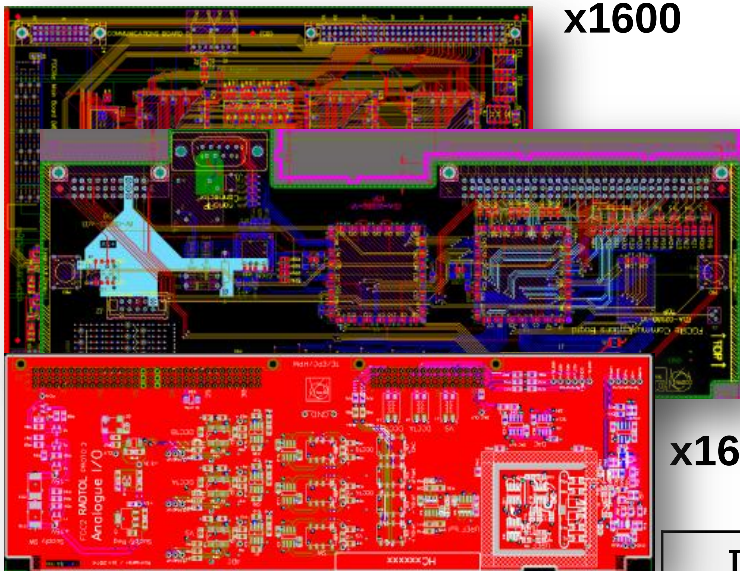
New Radiation-Tolerant design optimized for high availability !!!

6U casette

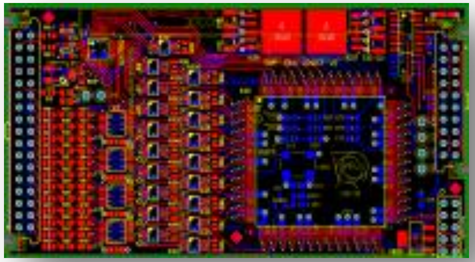
x1600

x1600

x1600



x3900



	Semiconductor			
	Board 1	Board 2	Board 3	Board 4
Diodes	8	13	59	6
LED		6		3
Quartz	1	2	2	1
Opto			4	
Transistor	7	20	27	
IC	22	5	26	30
Total	38	46	118	40

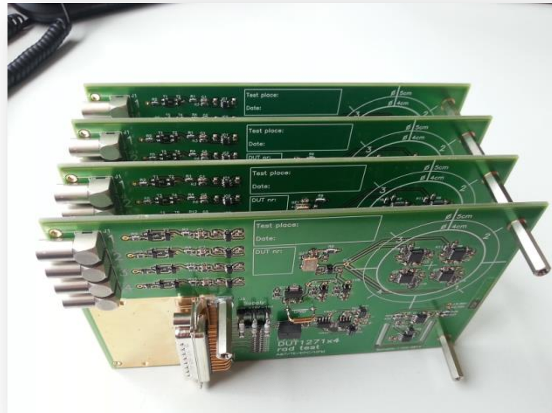
0.5M semiconductors/2.3M components

New testing infrastructure to qualify components under radiation

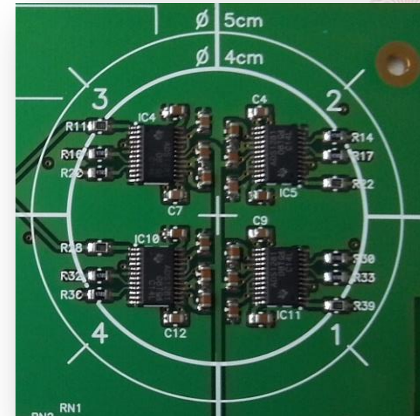
Real-time SEE & TID tests, & multiple components

FGClite Development

PSI Test Area

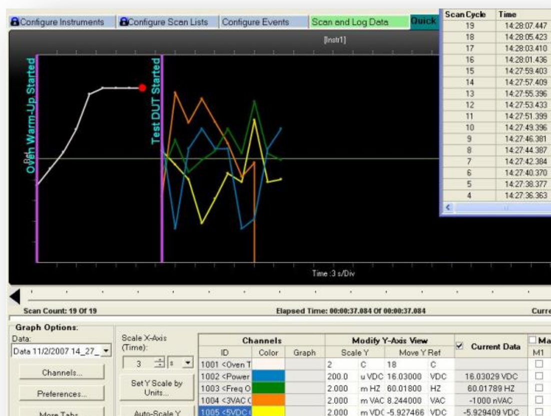


Cards Under Test

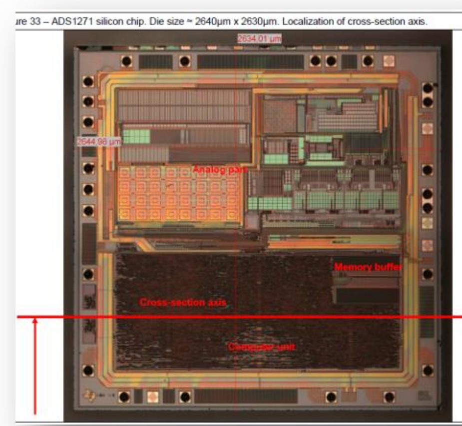


Irradiated Components

Tester Control Electronics



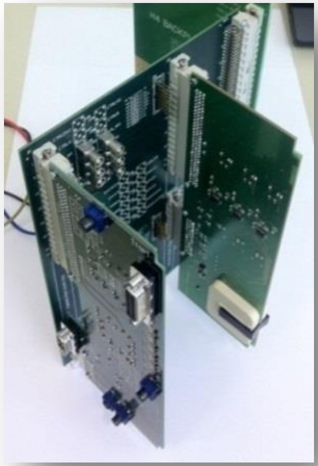
Tester Control Software



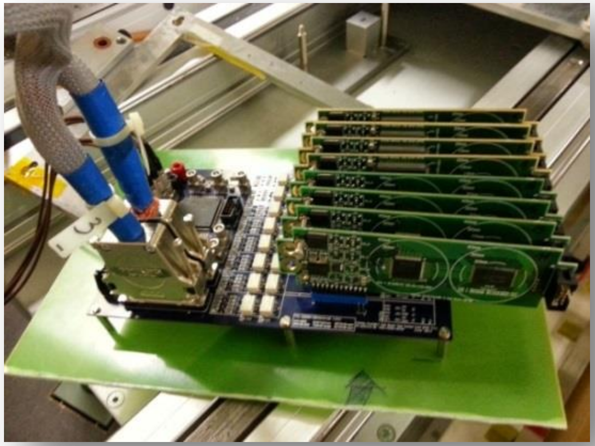
Effect Analysis

-> S. Uznanski: NSREC Talk: (SEE, Devices and ICs) D--4

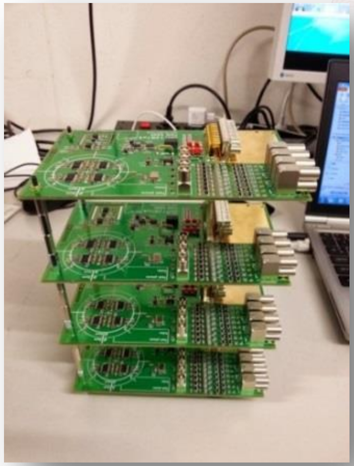
FGClite Constraints & Strategy



Prototype

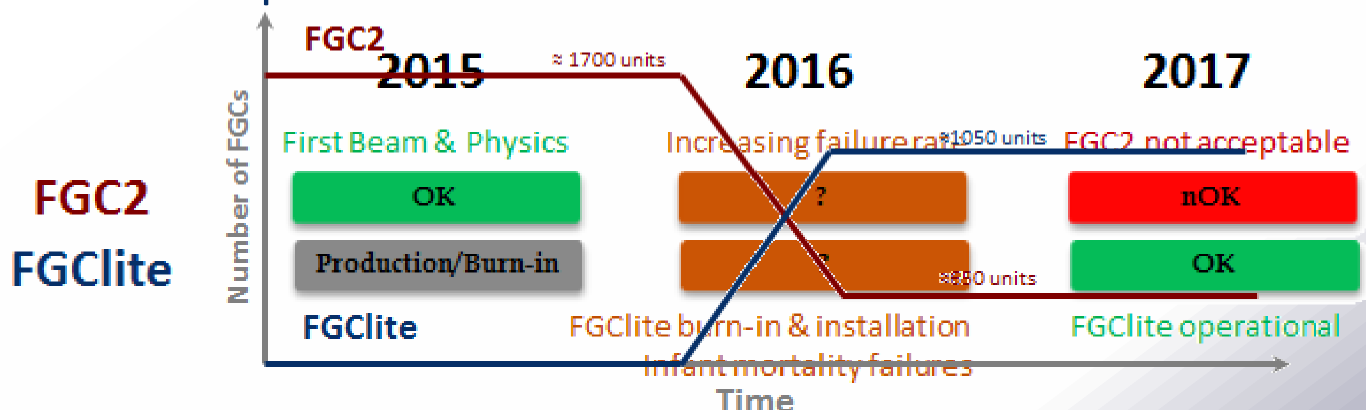


FPGA Type Tester



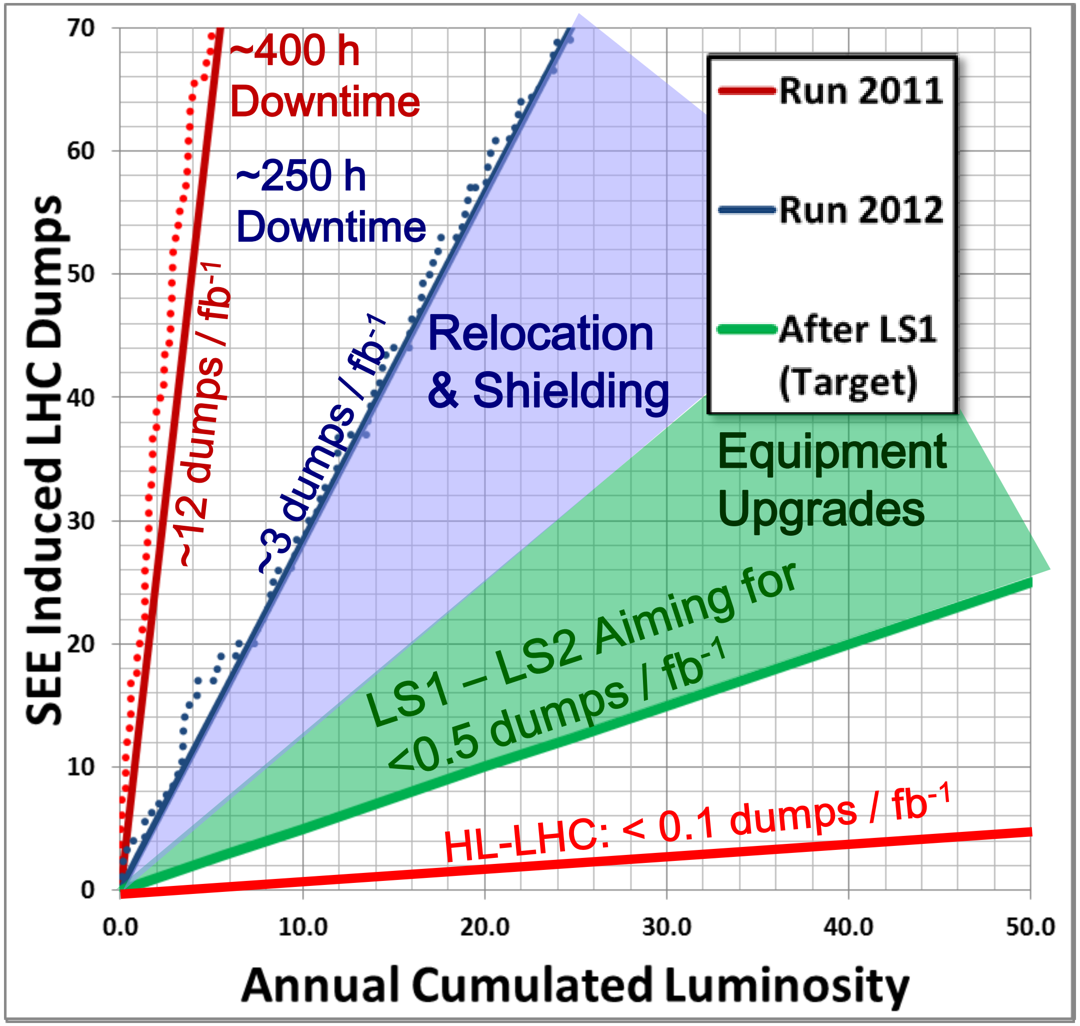
ADC Type Tester

- **2013** – hardware design, prototype available & component type testing
- **Q3/2014** – 10 fully validated FGClite proof-of-concept modules
- **Q3/2014** – start of component batch testing using CHARM (PS East Area)
- **Q2/2015** – Series production



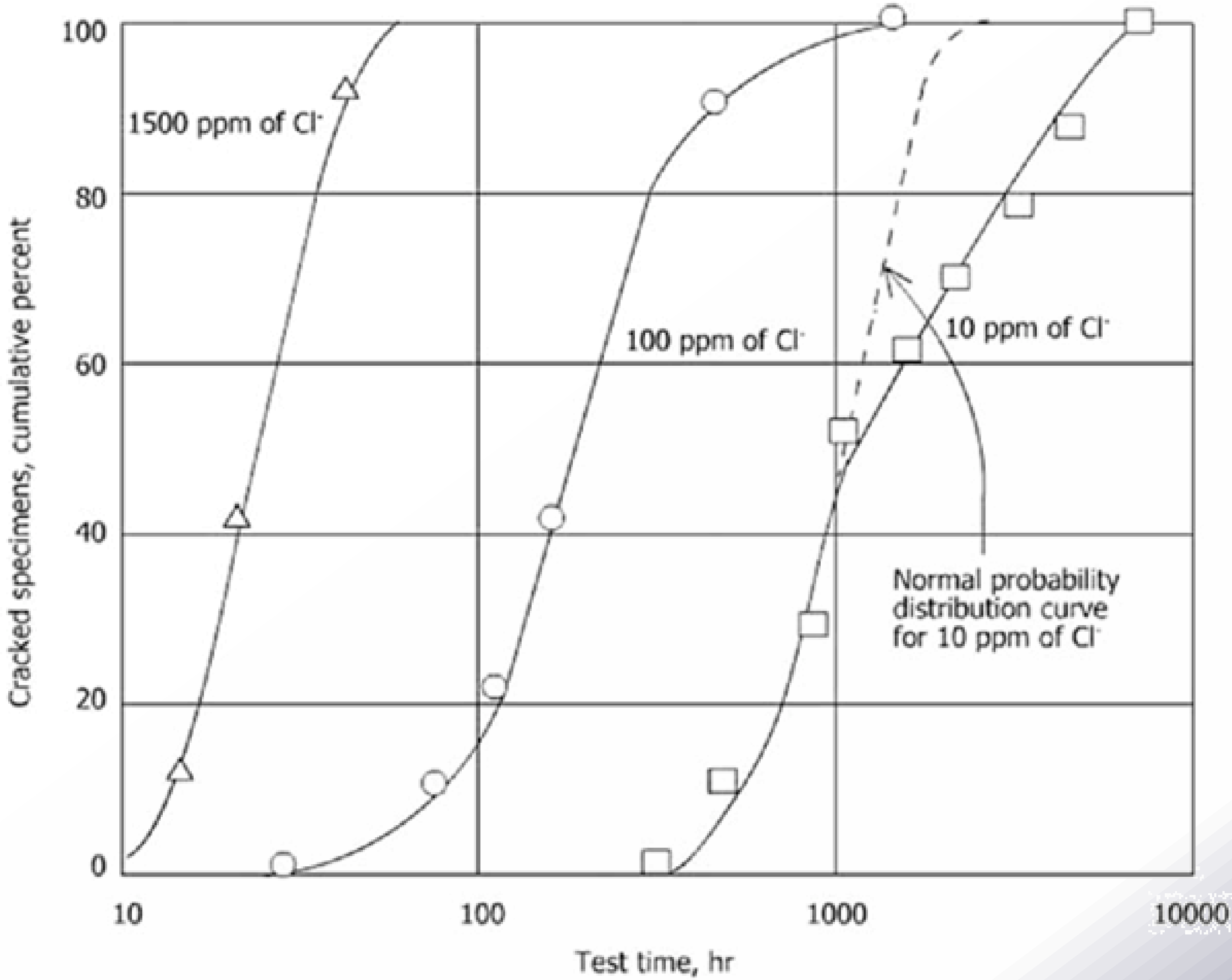
R2E LHC Target

R2E SEE Failure Analysis



- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on long downtimes and shielding
- **LS1 (2013/2014)**
  - Final relocation and shielding
- **LS1-LS2 (2015-2018)**
  - Tunnel equipment and power converters
- **-> LS3-HL-LHC**
  - Tunnel Equipment (**Injectors** + LHC) + RRs

Chlorine - Corrosion



Ahmad Zaki , Principles of Corrosion Engineering and Corrosion Control, Elsevier