Radiation Da
and Its Conseq

CAS 2017 - Lund

M. Brugger, CERN & R2E Project

!!! 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

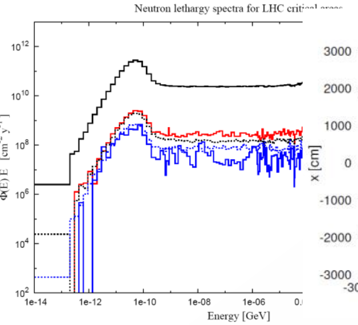
In this sense:

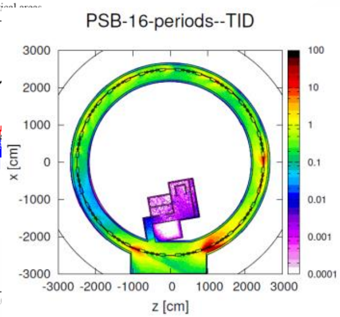
- Radiation (more and more!!!) determines the way how we have to design installations, accelerator components & plan for shutdowns, …

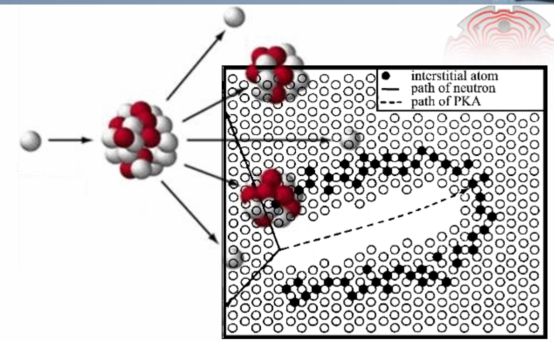
The “Victims”

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

What Do 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, …

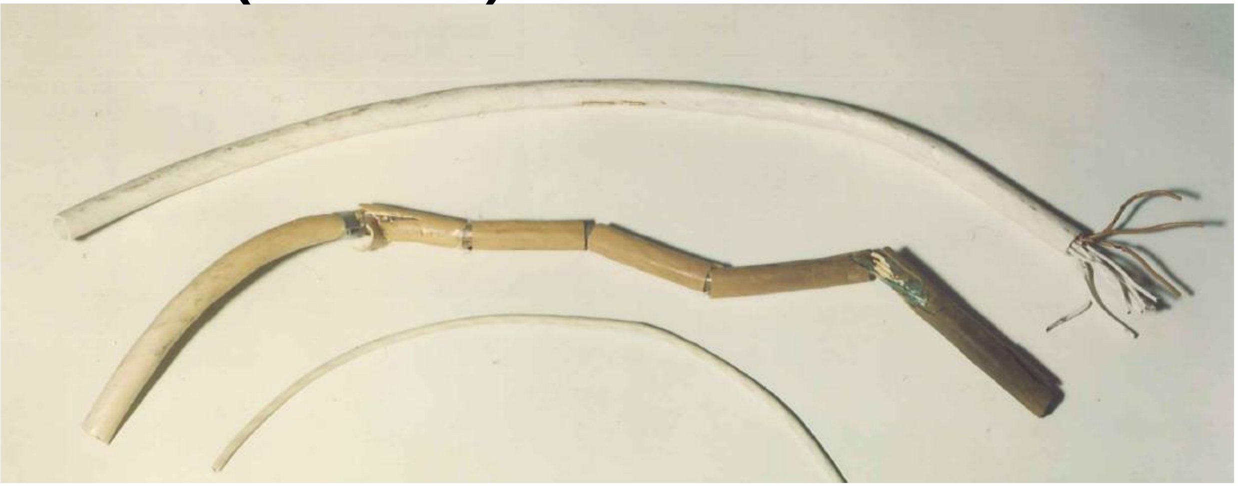
Overview

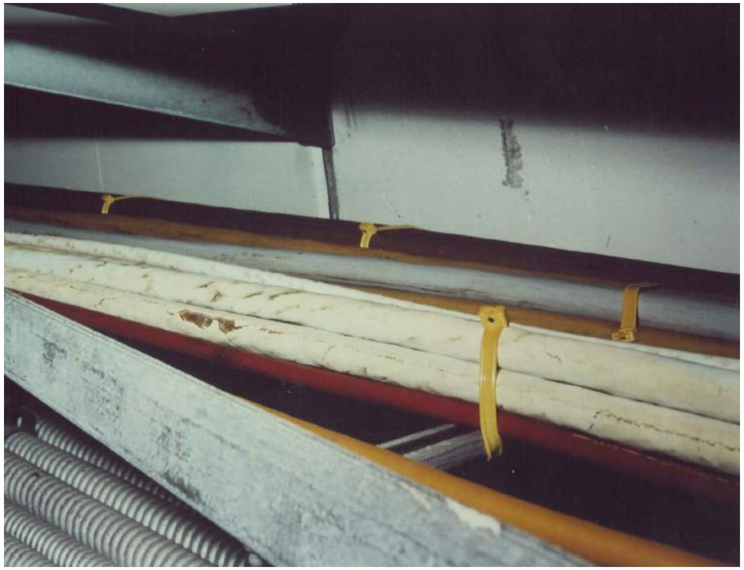
- Why do you (or should you) care about Radiation Damage?
- Quantities of concern
- Radiation Environment
- Radiation Effects & Failure/Damage Consequences
- Mitigation Measures & Radiation Hardness
- Recent examples for Vacuum Applications
- Along the way: a few things you should remember

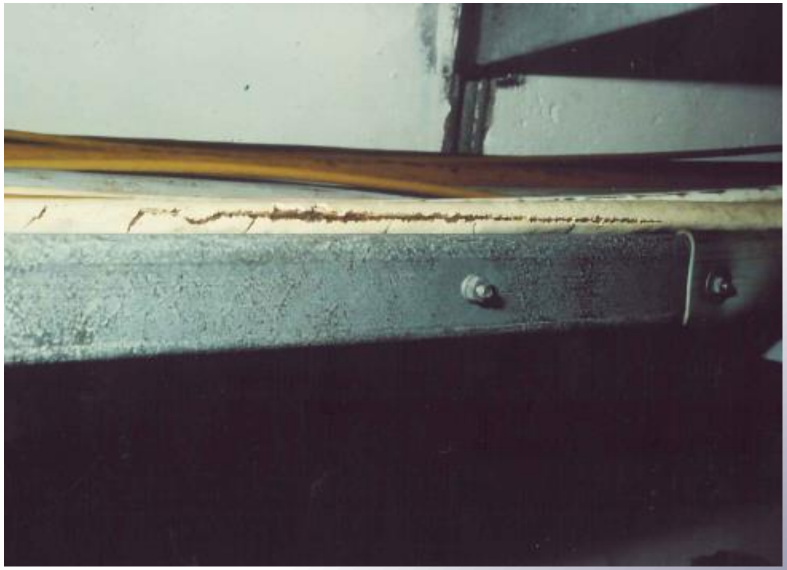
Radiation Damage

Why do we care

MATERIALS (Cables):

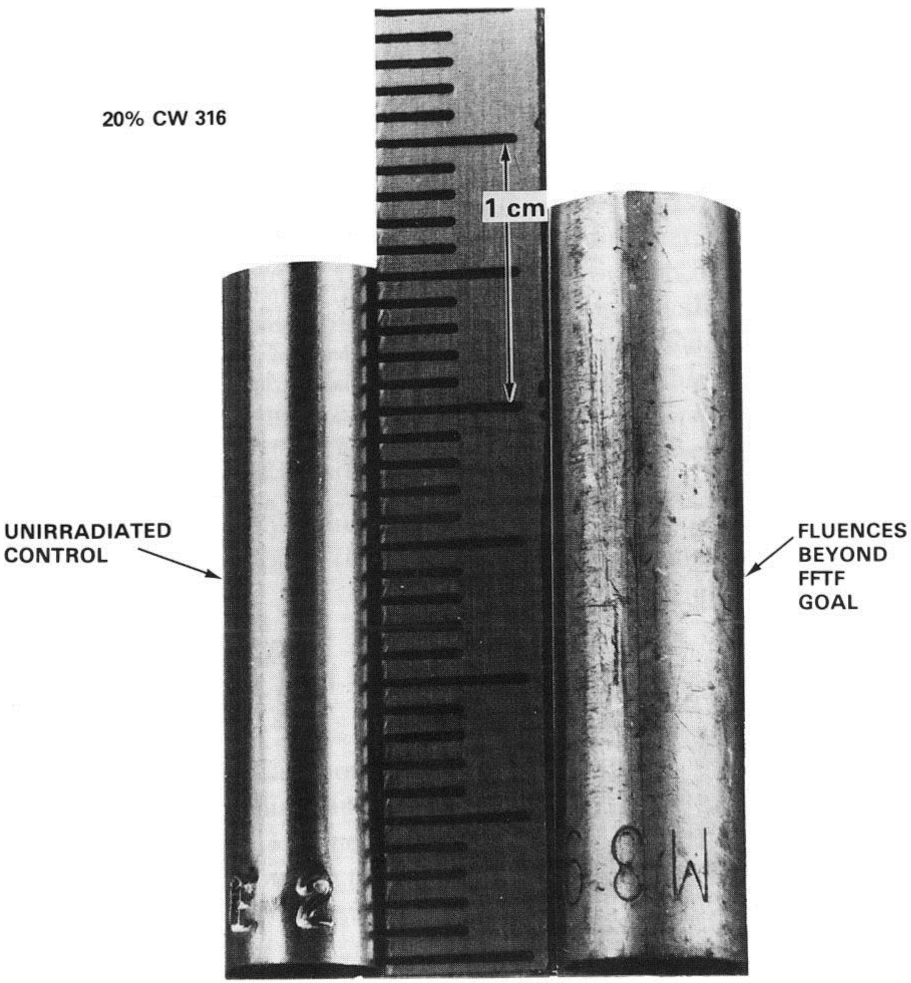


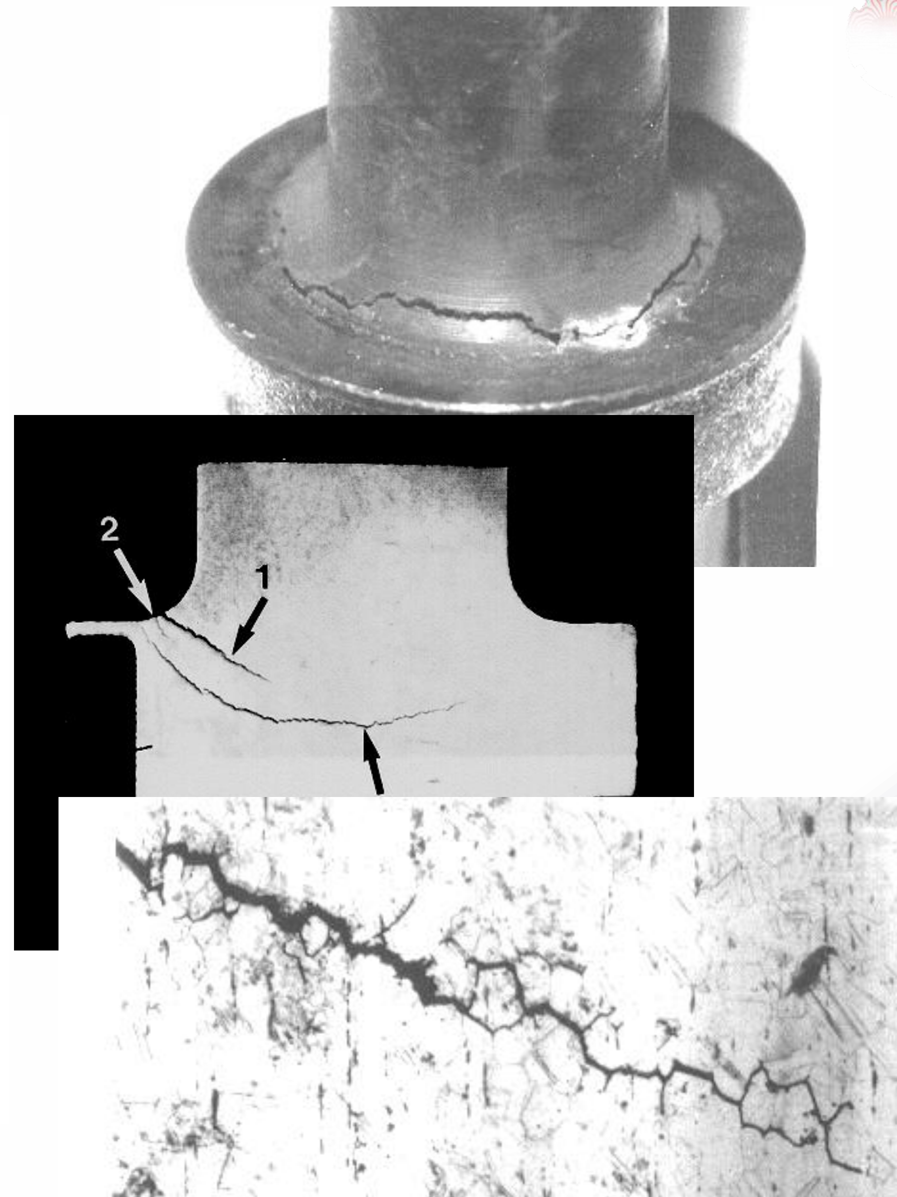




Why do we care

MATERIALS (Metals):





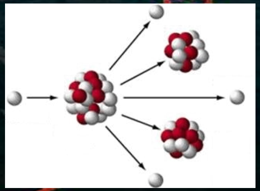
LHC as an Example

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

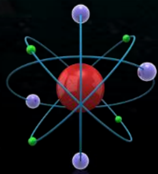
- 2 proton beams at 7 TeV of 3×10^{14} p^{+} each
- Stored for 10-20 hours in collision
- Total stored energy of **0.7 GJ**
  Sufficient to melt **1 ton of Cu**
- ~5000 superconducting magnets

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

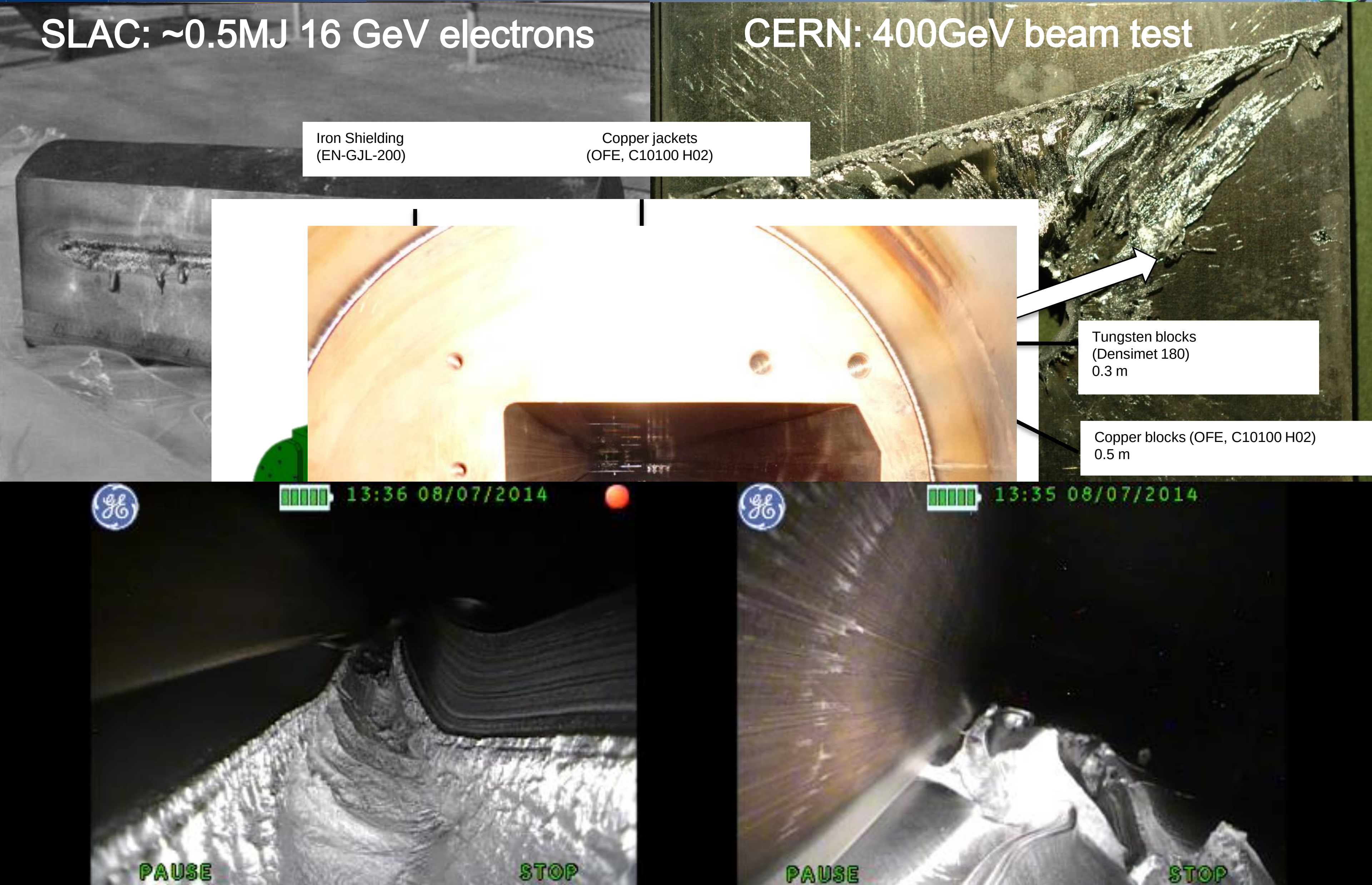
- Single particles can impact essential electronics and stop operation



- Radiation detoriates surrounding materials and equipment – repair & maintenance



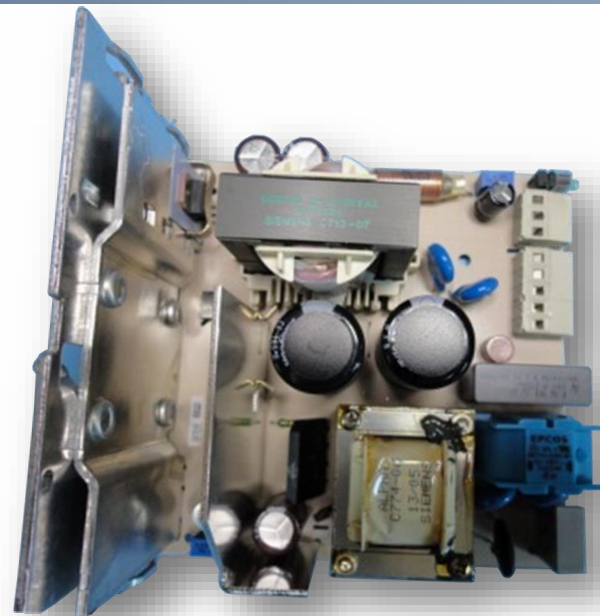
Beam Induced Damage

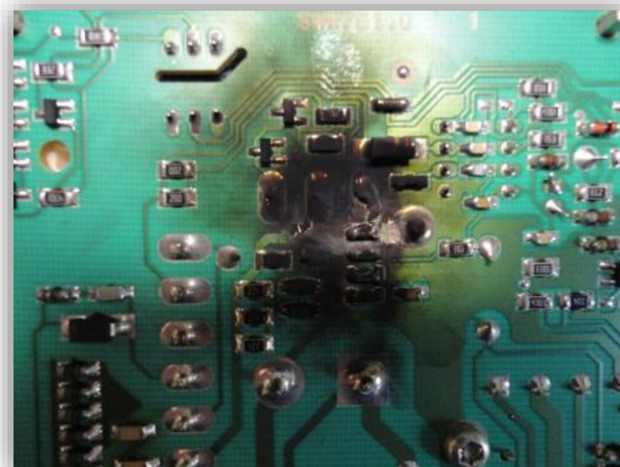


Equipment Failure Example

Vacuum system PLC (LHC_UJ76)

P. Supply 24VDC 5A





Radiation
&
Quantities of Concern
a quick re-cap from Francesco's Presentation

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

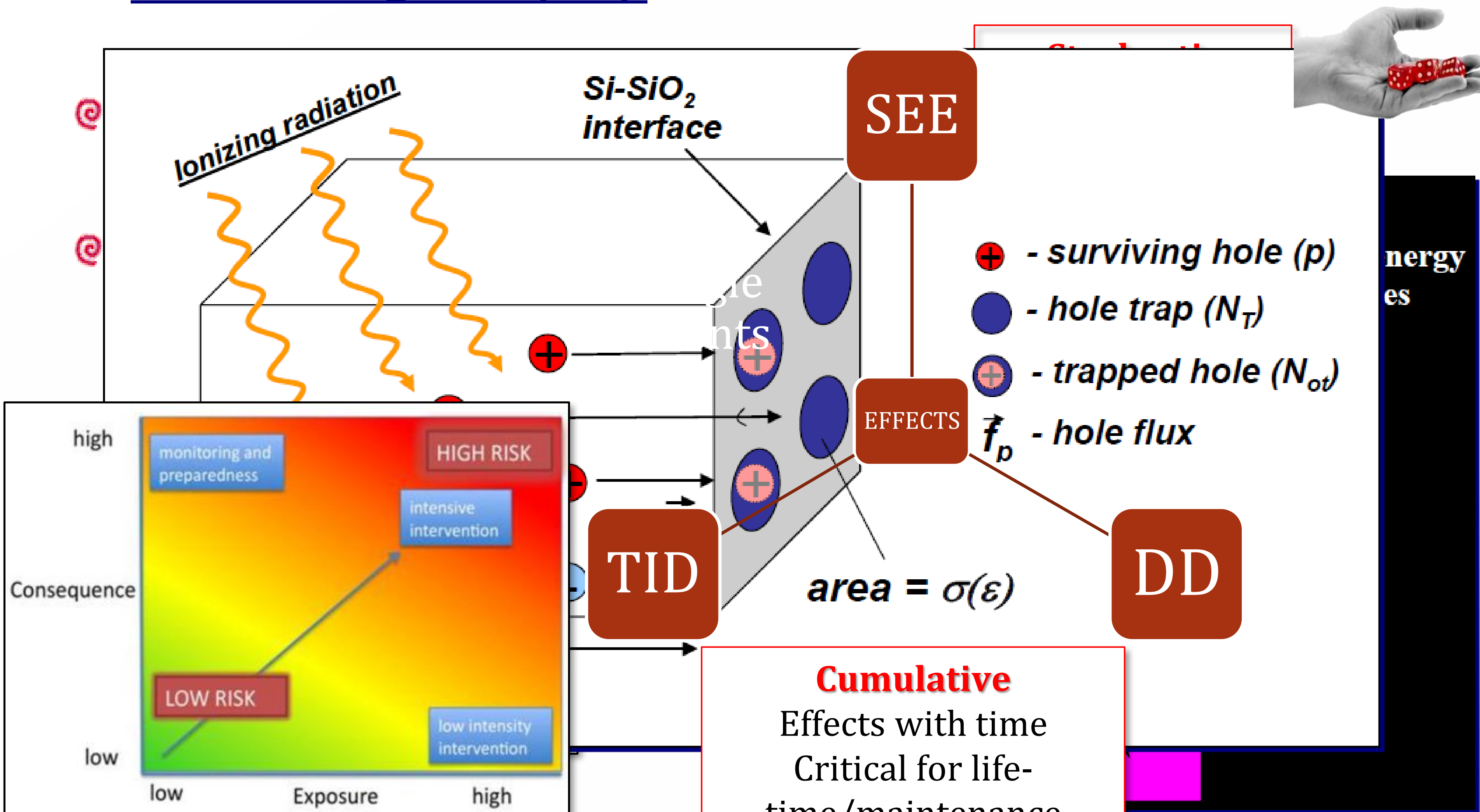
Dose Terminology

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

- **Total Ionizing Dose (TID):**

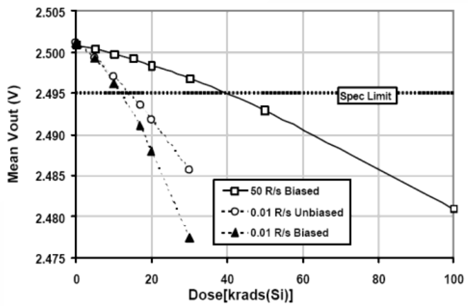


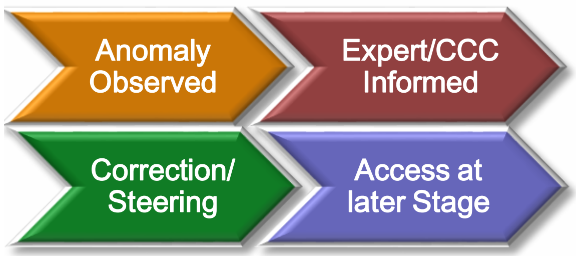
Cumulative
Effects with time
Critical for life-time/maintenance

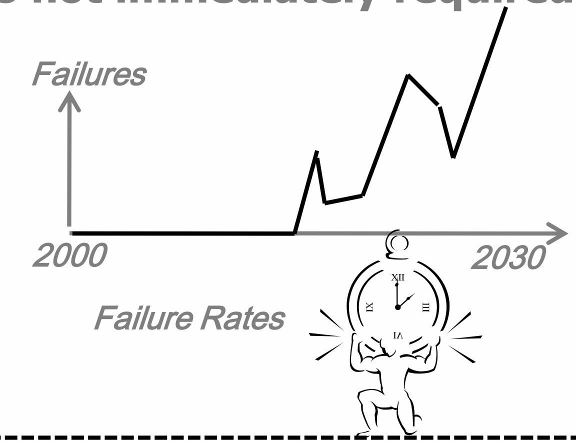
Radiation Issues – Failure Observation

- **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:

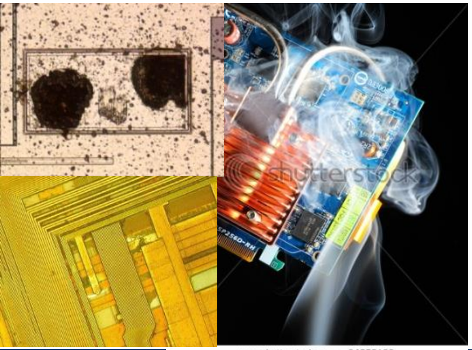


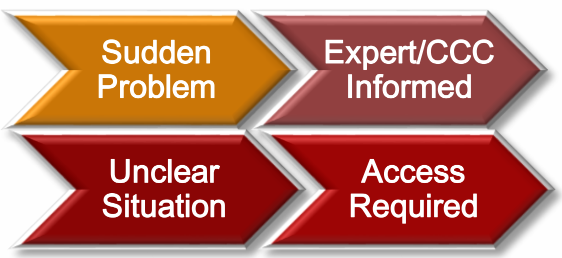


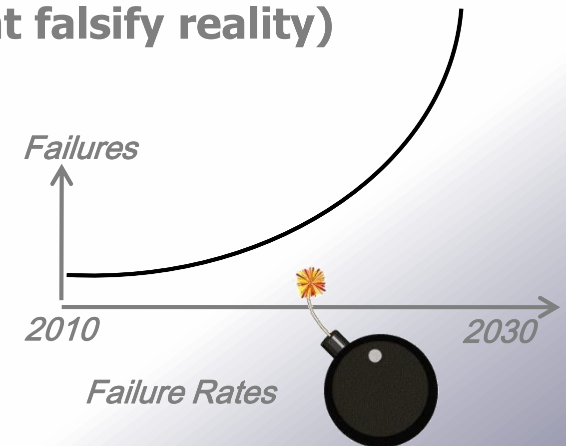


- **Single Event Effects**
  - ☹ Failures will appear and rapidly increase in frequency (destructive failures possible; access often required)
  - ☹ 'Early Operation ' problem (observation might falsify reality)

Possible Scenario:



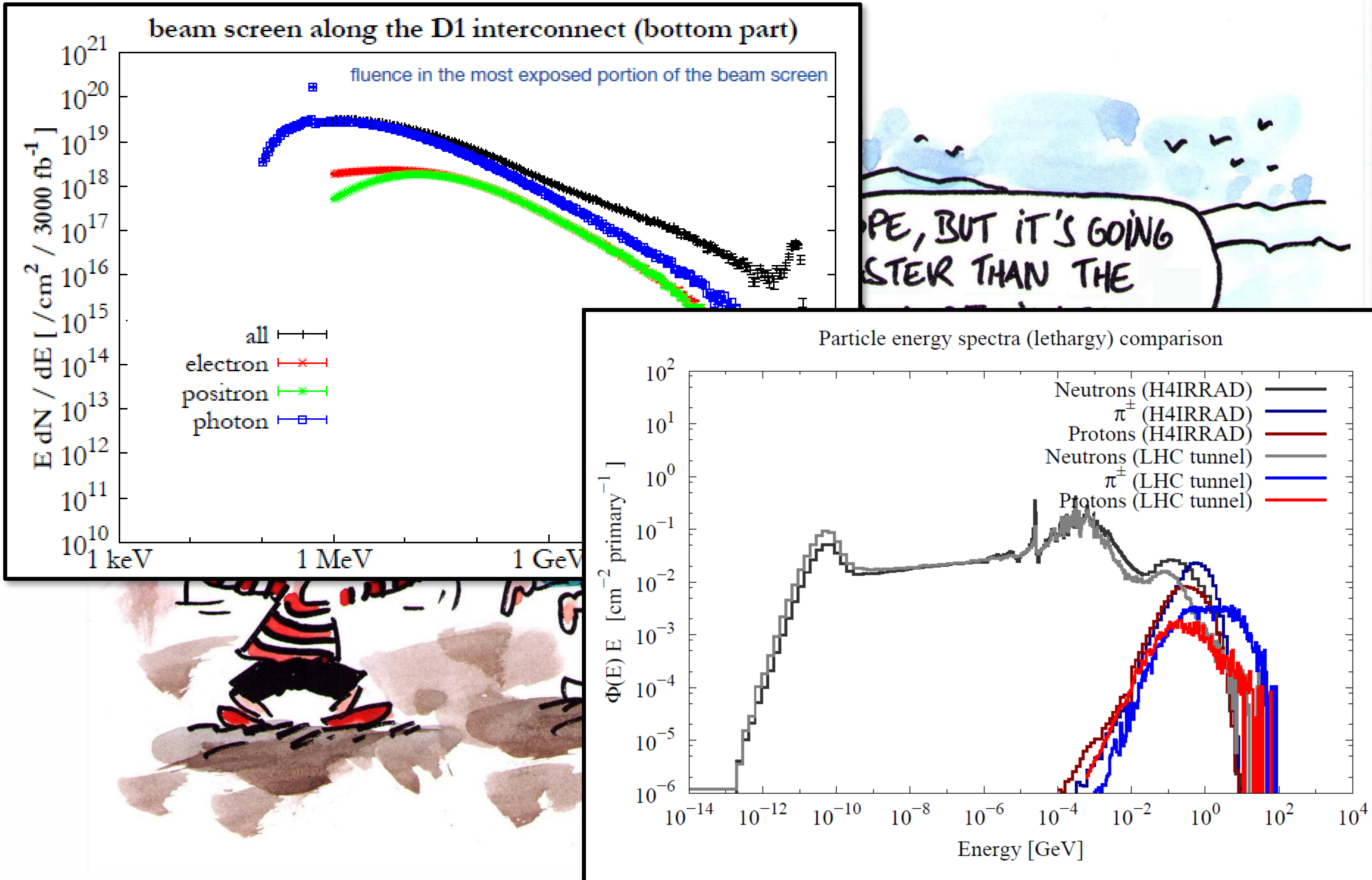




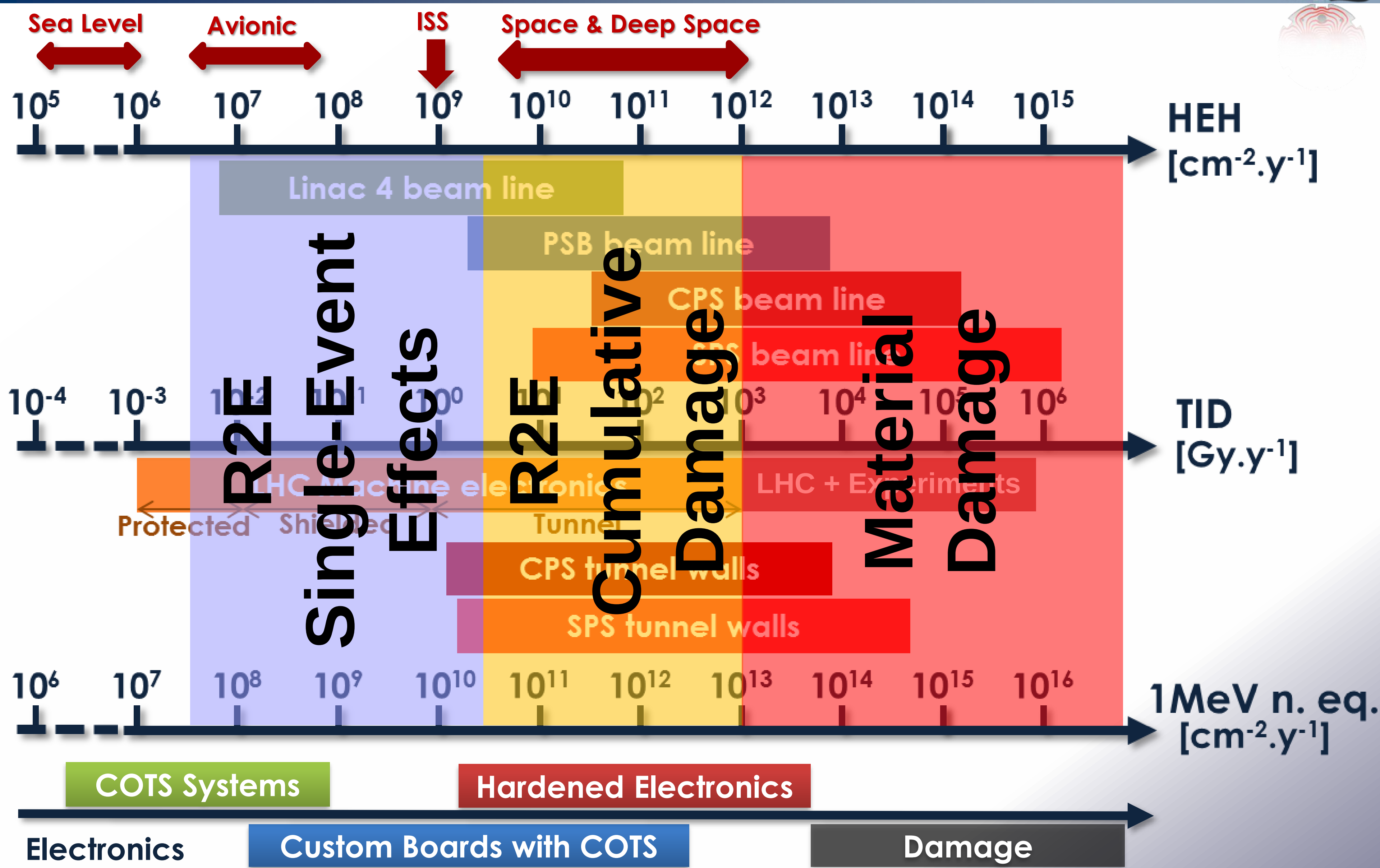
Radiation Environment

already mostly covered in Francesco's Talk

Radiation Environment

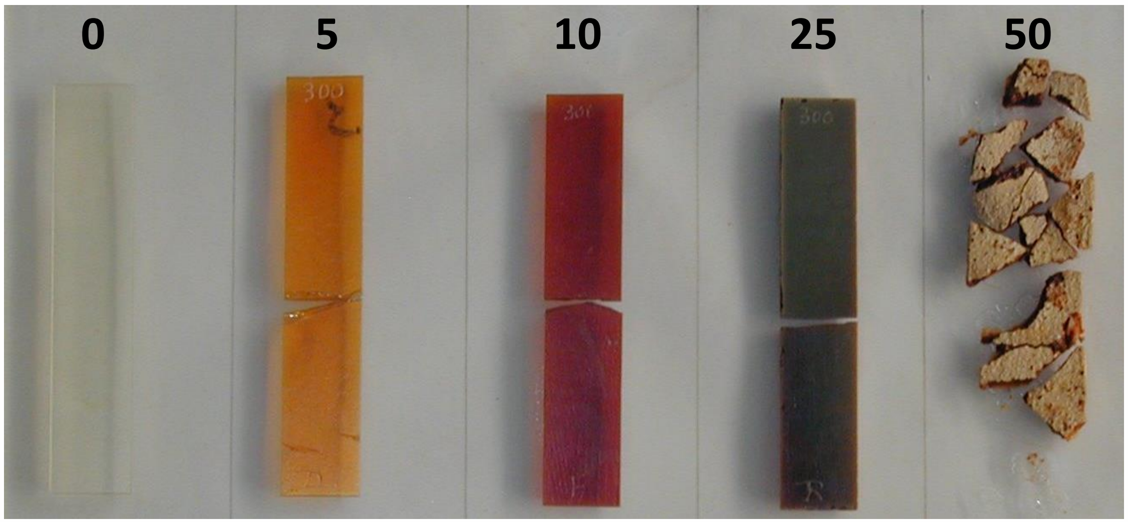


CERN Radiation Levels



Beyond: Material Damage

TID [MGy]



100 Gy 

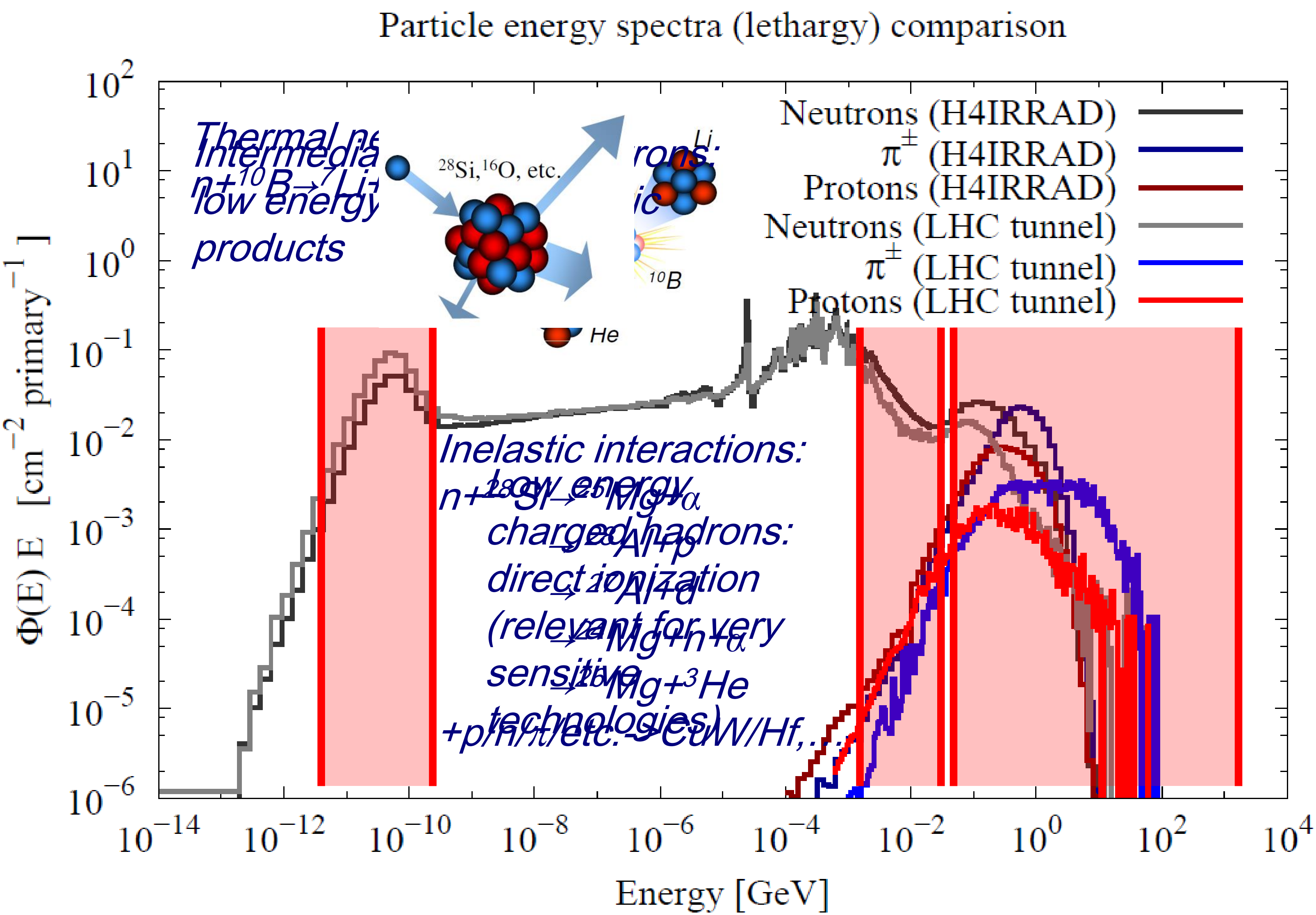
0.1 MGy 

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**

NIEL/DPA - A Complex Process

Cascade visualization

- High velocity balistic phase
  - **PKA** impact **SKA**
  - **SKA** impact **3KA**, **4KA**, …
- Low velocity balistic phase
  - **3KA**, **4KA** generate vacancies (V) and interstitial atom (I), as referred as Frenkel pair
- **Propagation of the thermal wave**
- Healing
  - Recrystallization of neighbors I + V

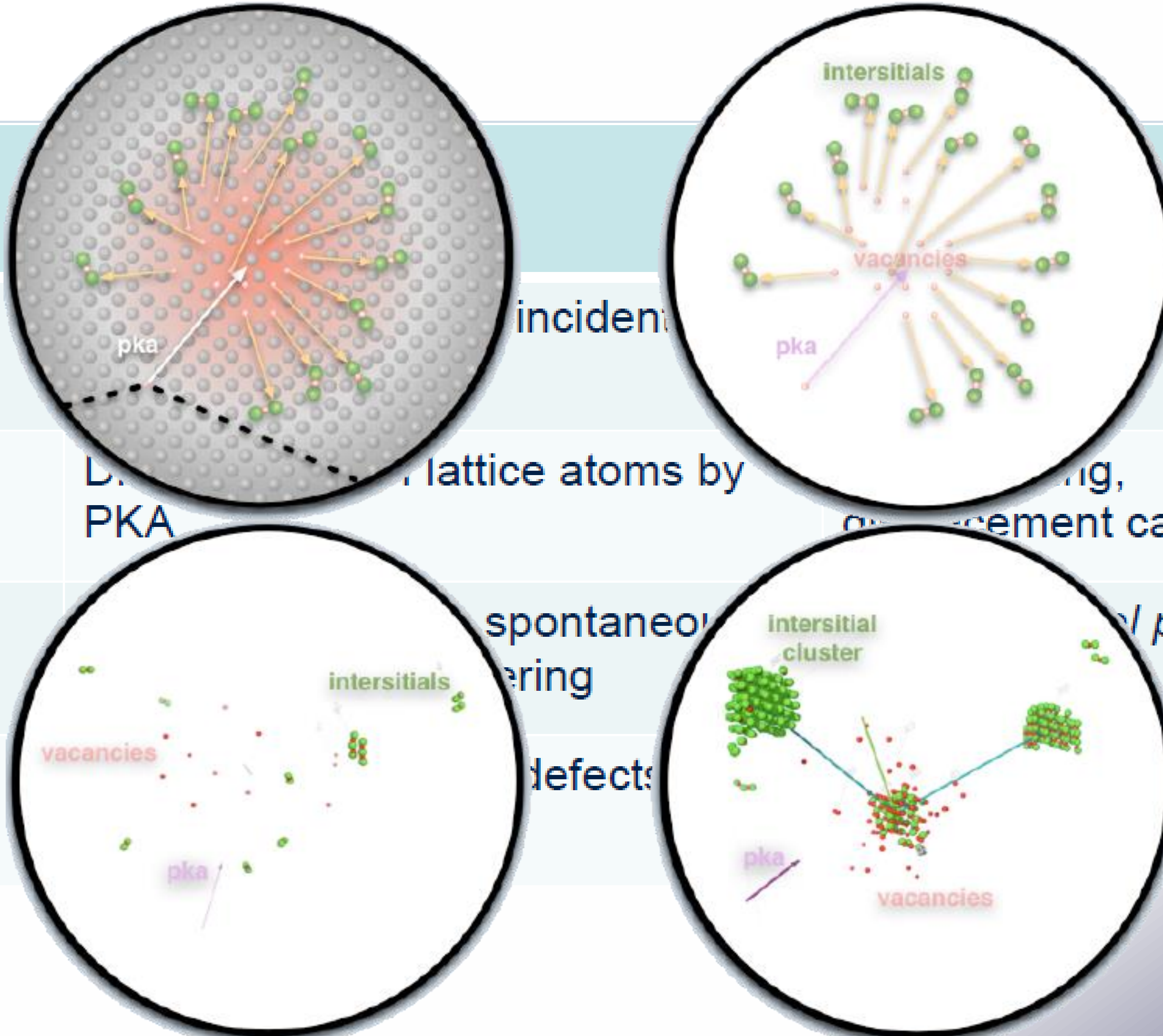
© C. Virmontois, CNES

Displacement Damage

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

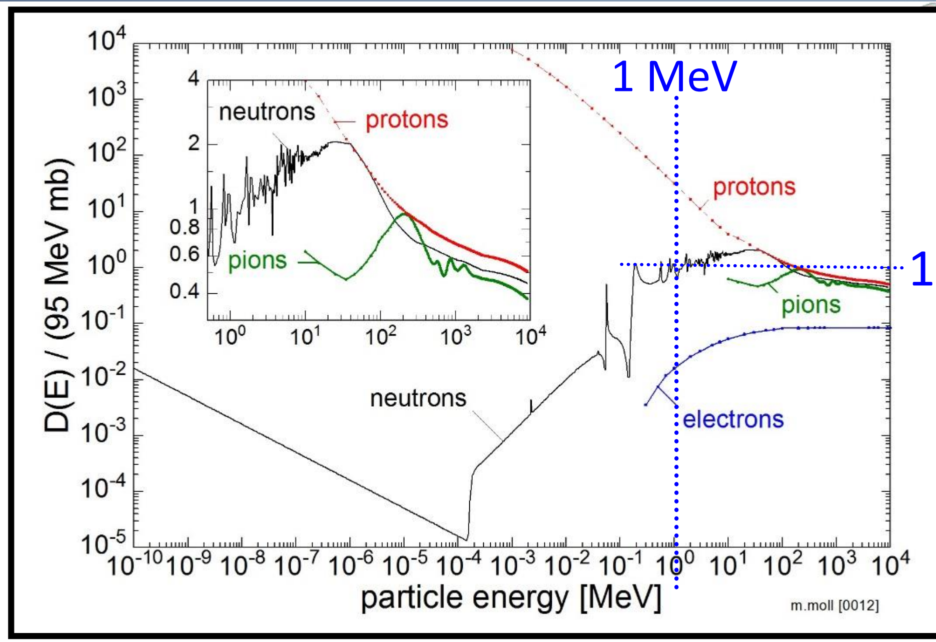


Particle Type & Energy Matter

- **Displacement Damage function**
  - Normalization of radiation fields to 1 MeV neutron equivalent damage (n_{eq})

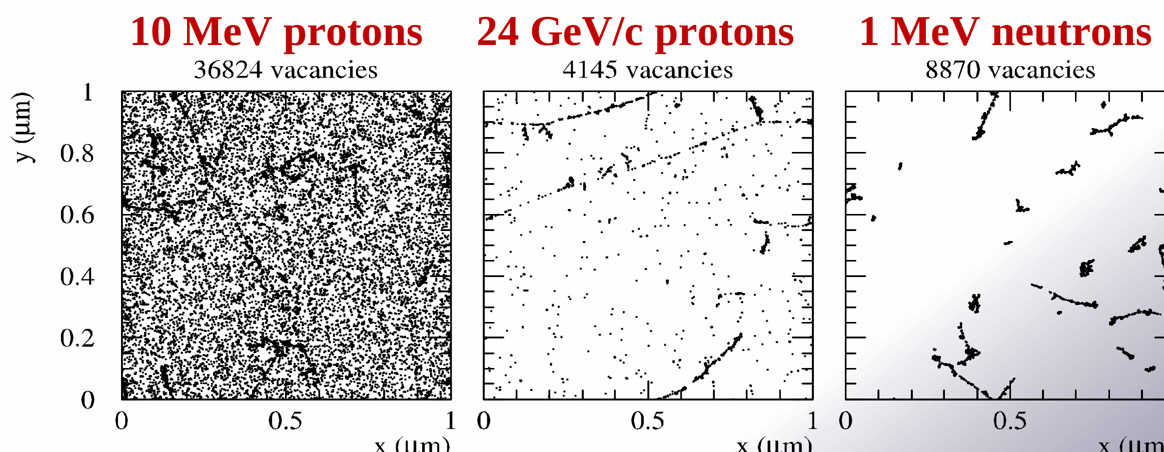
$$\Phi_{eq} = \kappa_x \Phi_x$$

κ_p =[0.52..0.62] (24 GeV/c protons)
κ_p = 1.85 (26 MeV protons)
κ_π = 1.14 (300 MeV pions)
κ_n = 0.92 (TRIGA reactor neutrons)



[Data: A.Vasilescu and G.Lindstroem]

- **NIEL Hypothesis:**
  - Assumption: NIEL scaling of damage parameters
  - Applied to predict damage of radiation fields in HEP
  - NIEL violation observed:
    - Material dependence
    - Proton vs. neutron damage
    - …



[M.Huhtinen, NIMA 491(2002), 194]

Simulation: Vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

DD – is it Natural?

Mechanical Parameters

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

→

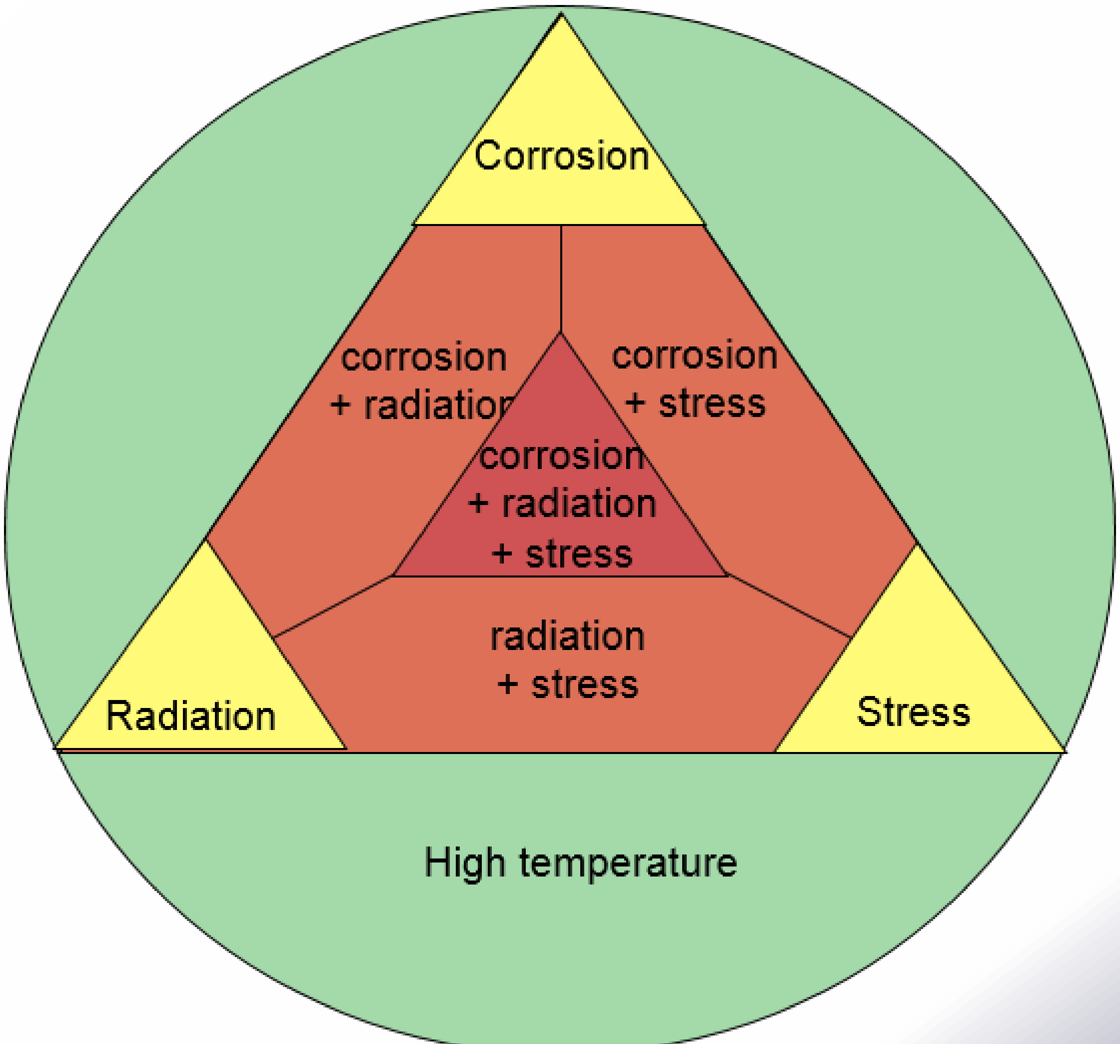
- Weak
- Brittle
- Low thermal conductivity
- Unstable
- Dangerous

+

→

Other – linked - Parameters

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



Material Examples

Plastics

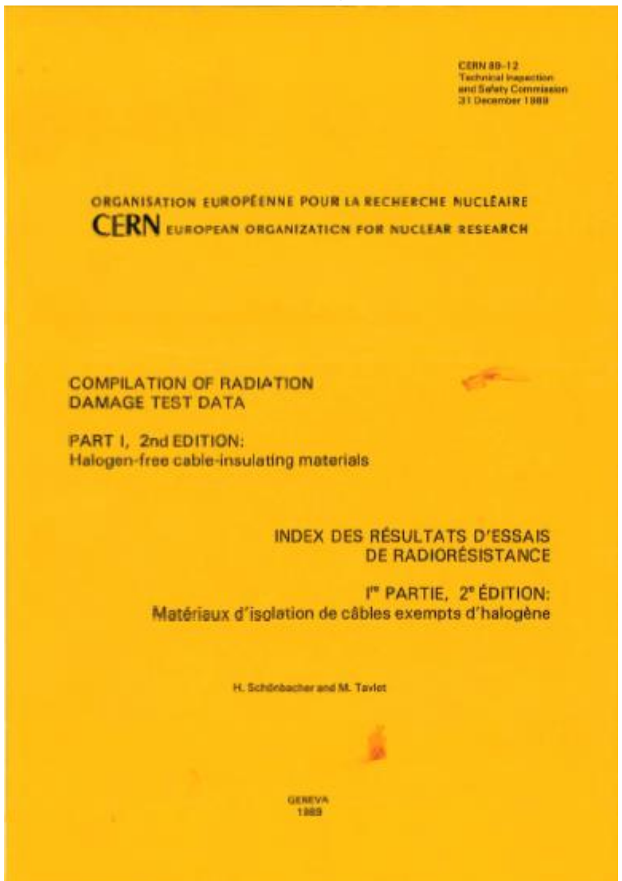
- cable insulations, structur
  lamps, electrical cubicles..
- **Plastics are organic mater**
- They are derived from pet
  natural materials (resins, r
- Contain Carbon

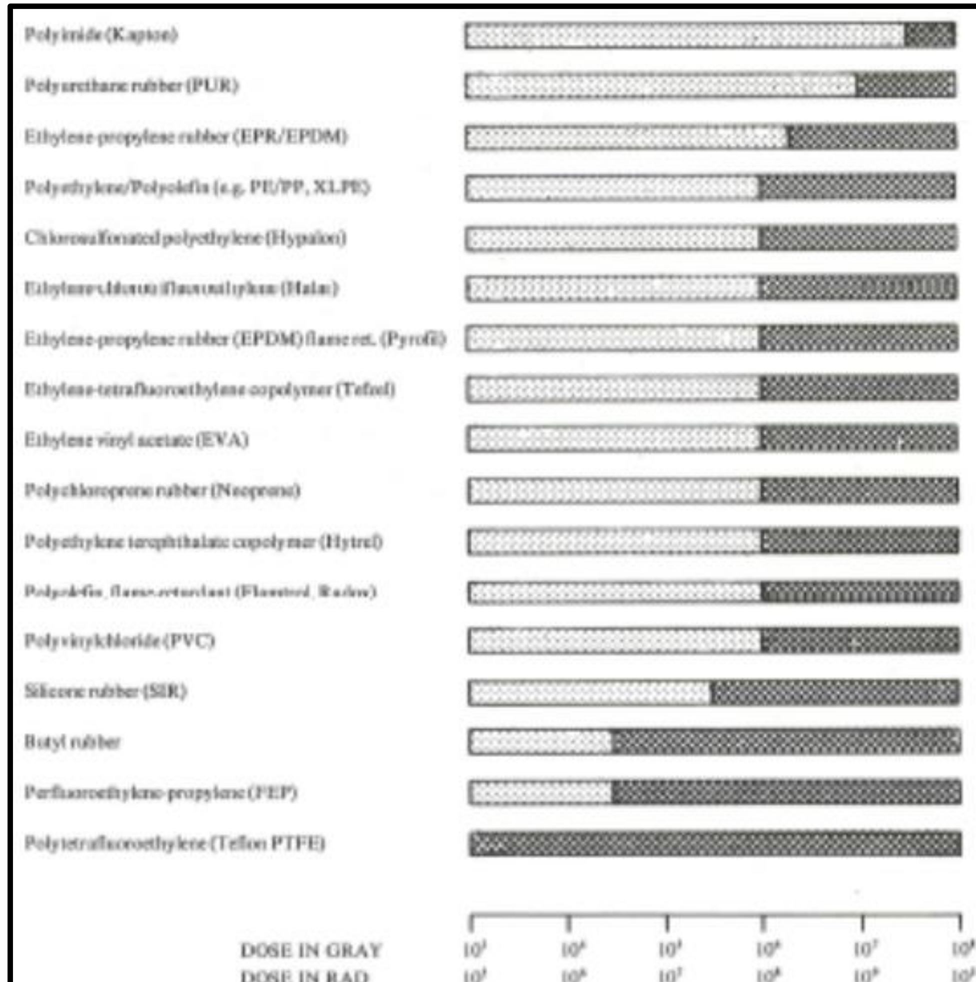
Effect of radiation:

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

Plastics

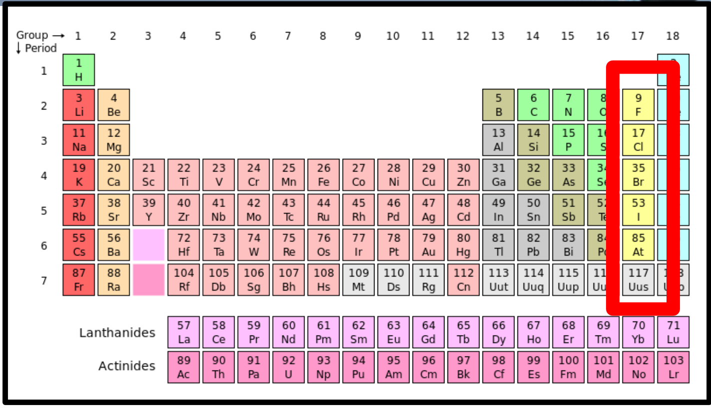
- useful information in CERN's Yellow books (e.g. CERN 82-10, or 89-12)





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

9 May 1985: suspended ceiling at Uster indoor swimming pool collapsed

M. Faller and P. Richner, Materials and Corrosion 54(2003)331

9 June 2001, a nine-year-old swimming pool in Steenwijk, The Netherlands -> same thing

& at Accelerators:

Material Examples

PVC as a bad example

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

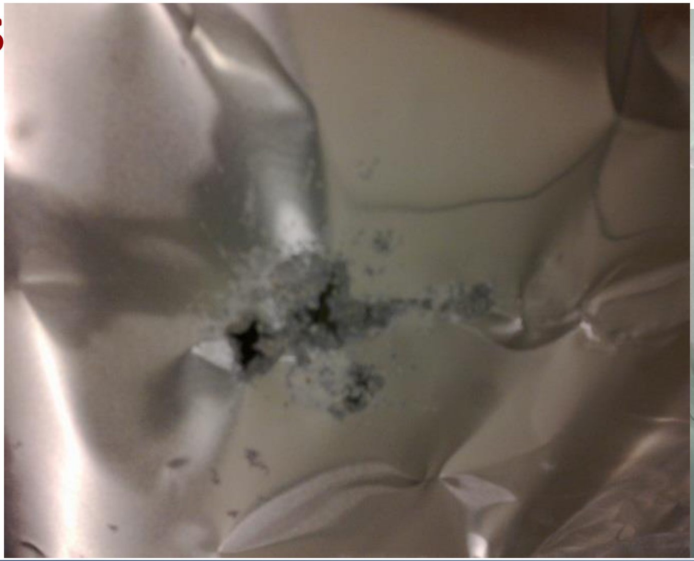
> **Health and safety** [edit]
>
> PVC is a useful material because of its inertness and this inertness is the basis of its low toxicity: "There is little evidence that PVC powder itself causes any significant medical problems."[7] The main health and safety issues with PVC are associated with "VCM", 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)

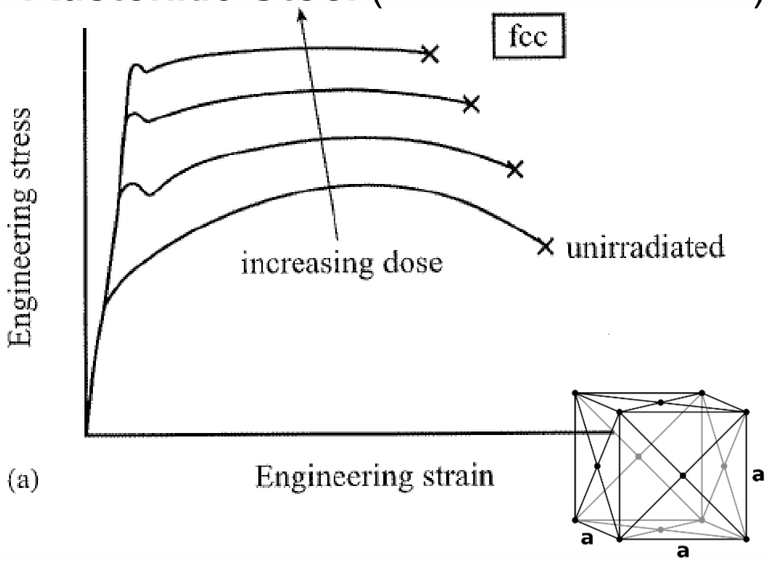
- Mechanical (macroscopic) effects, are ultimately caused by formation of **defects in the lattice structure**
- Defects are : voids, gas bubbles, dislocations…
- **Temperature** has an effect:
  - **Annealing** increases the mobility of defects
    - Often positive impact by reconstructing the lattice
    - 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

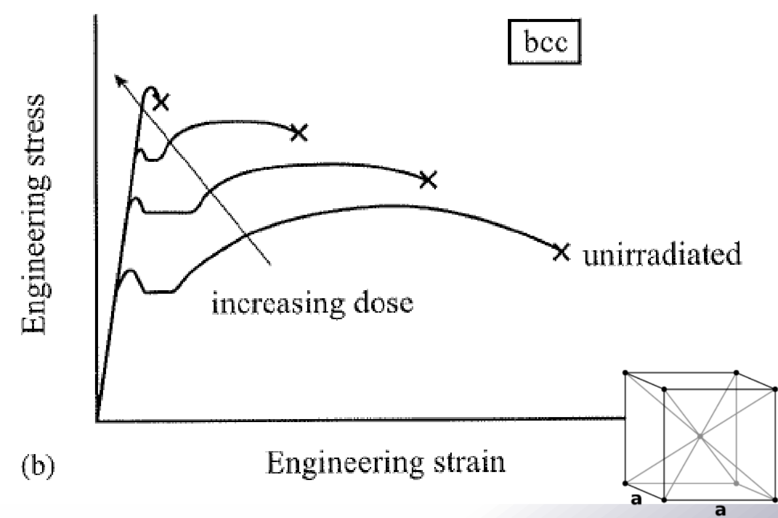
Metals

- **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

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-doped 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

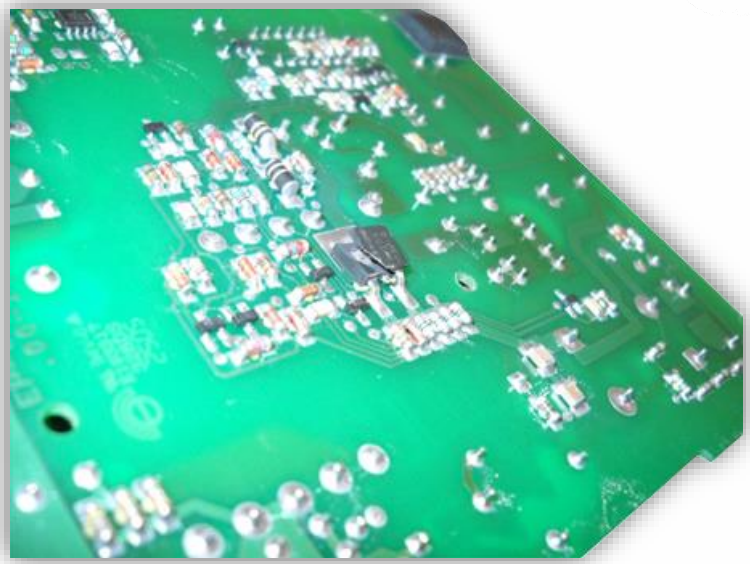
- ~20 different **exposed system**
- From a few to a **few thousand units** each
- number of parts per (per system) range **from a few to a few hundred**

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

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

Equipment Failure Example

SEE: Power-Converter (LHC_RR)

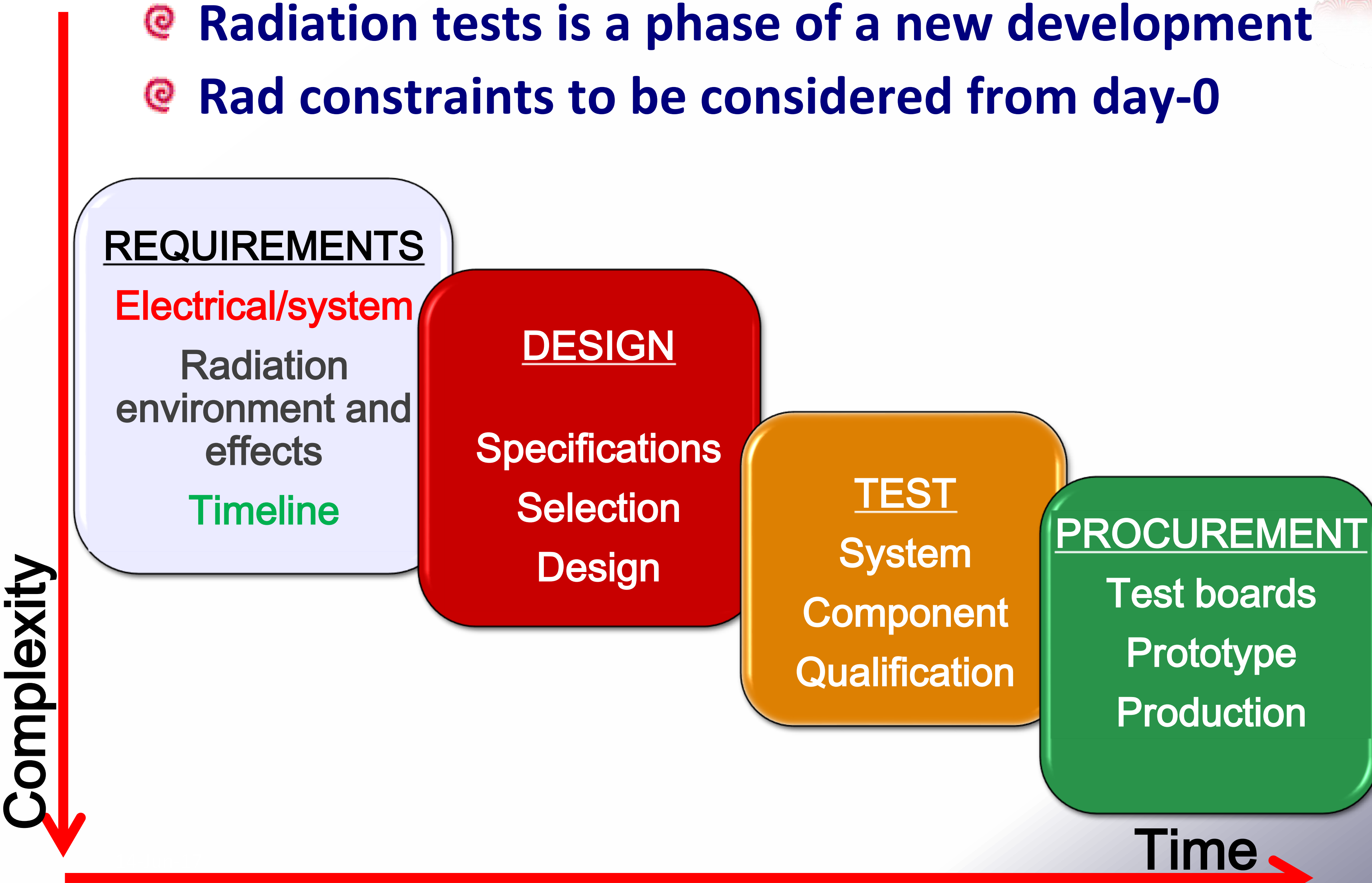


⇒ **Premature Beam Dump**

& LHC Downtime

R2E Qualification Steps

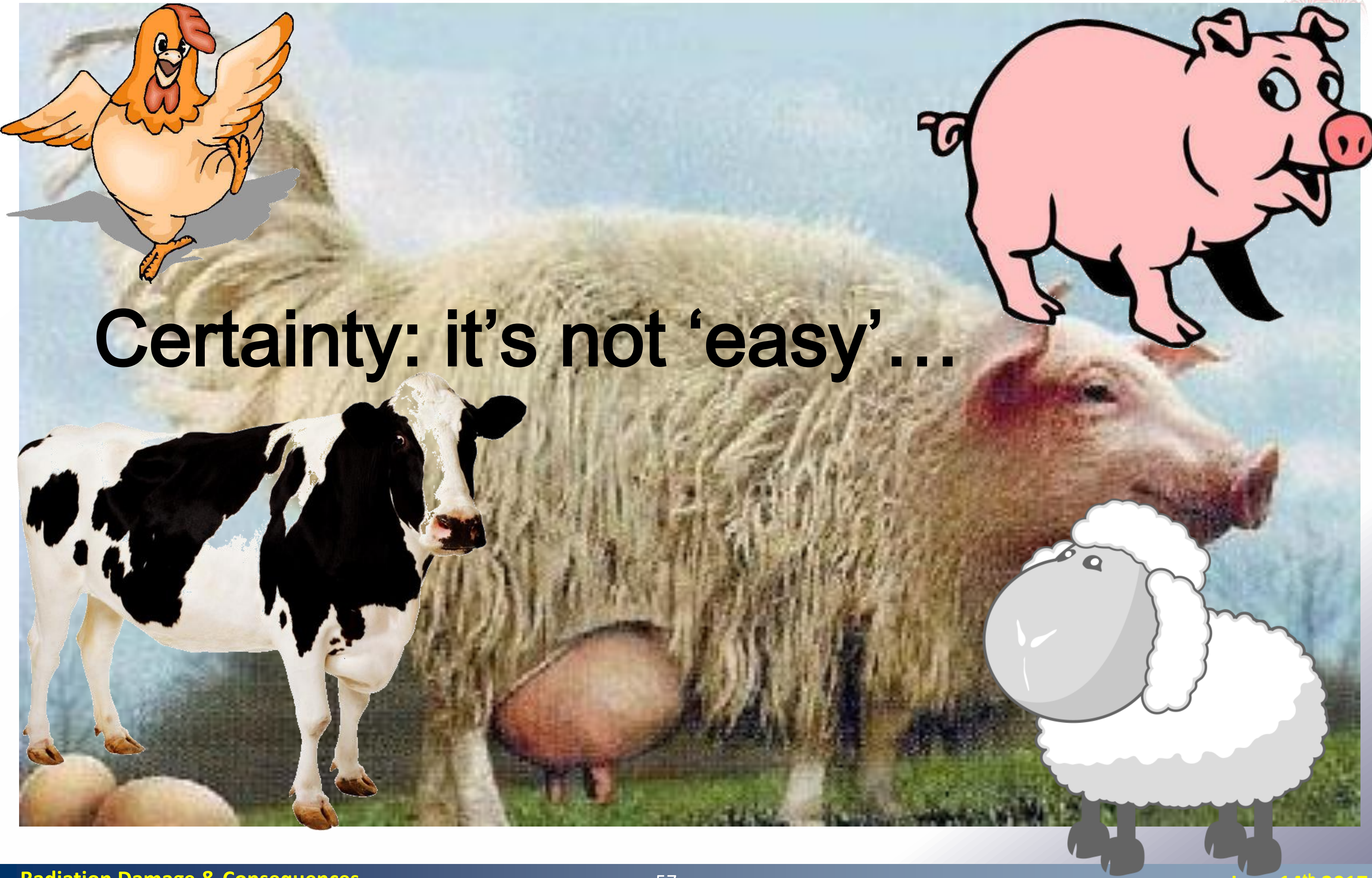
- Radiation tests is a phase of a new development
- Rad constraints to be considered from day-0



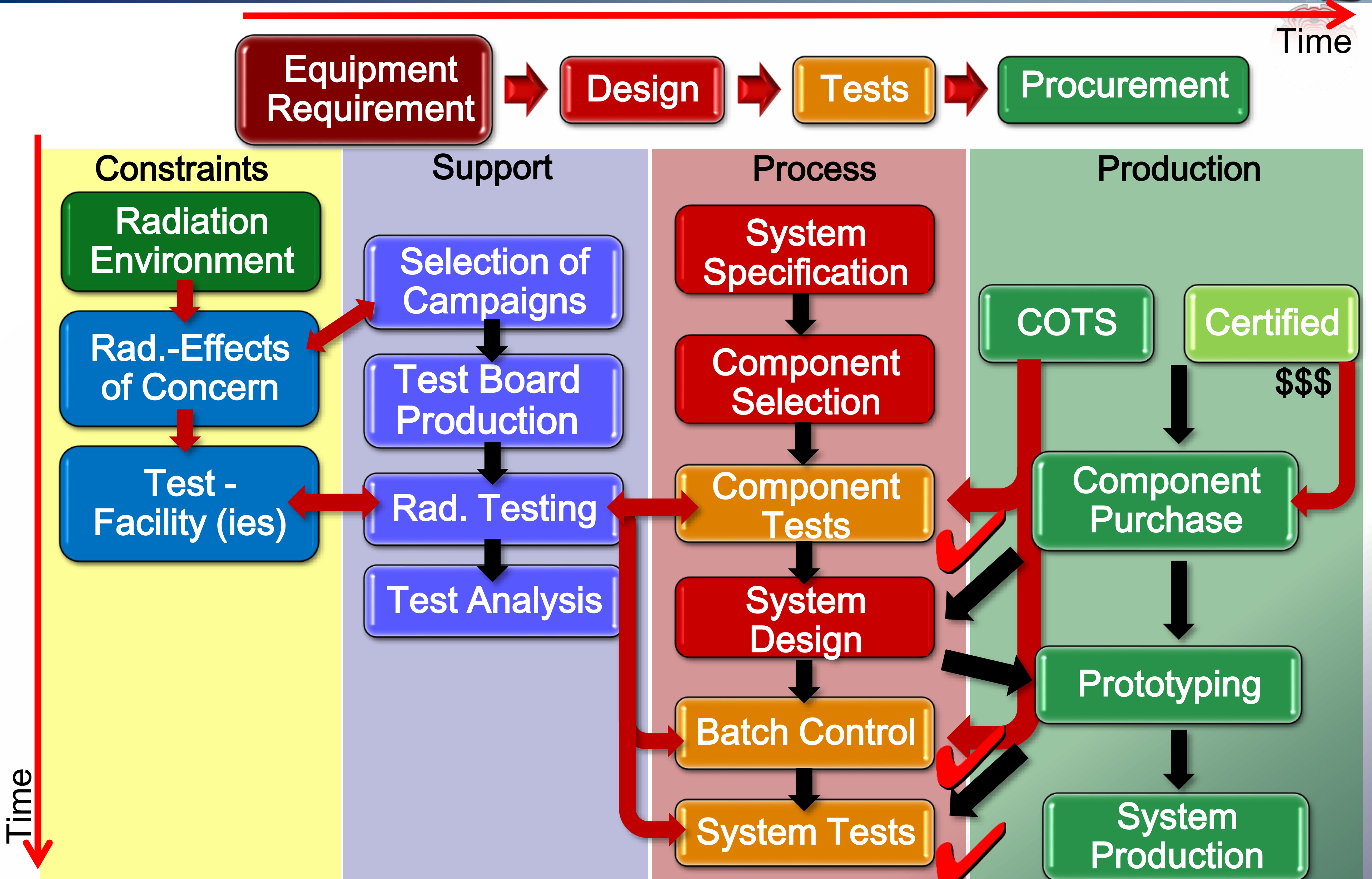
Mitigation Measures

- RELOCATION
- SHIELDING
- RAD-TOL DESIGN & TESTING
- ~~CIVIL ENGINEERING~~

The Perfect Solution



A (Rough) Map to Rad-Tol

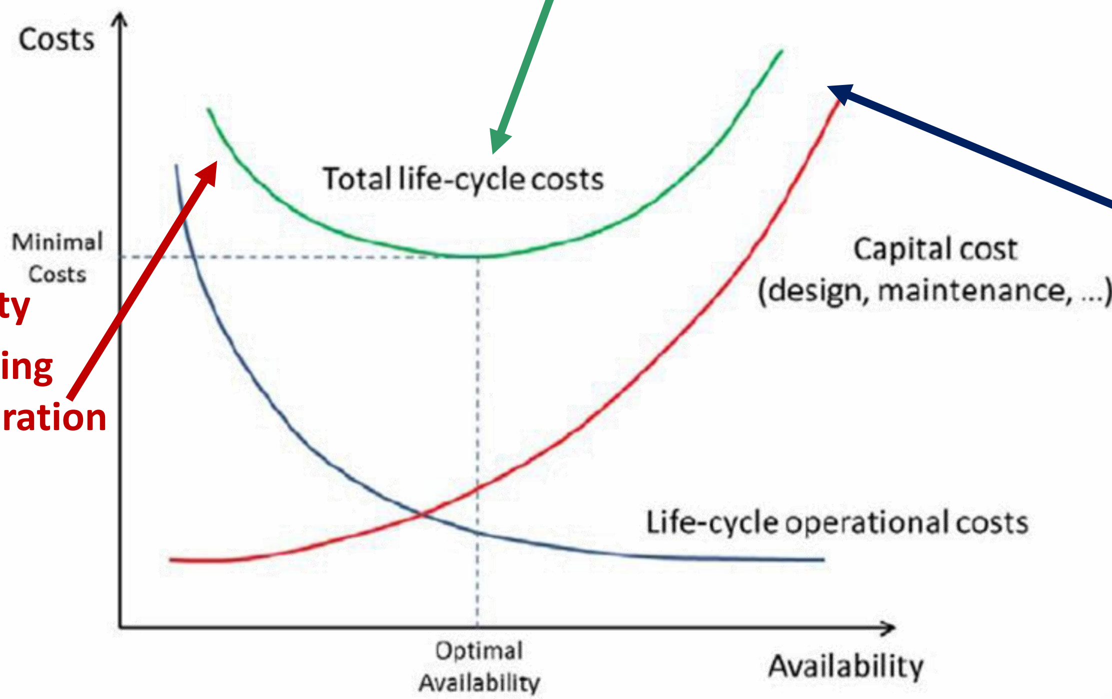


System Availability vs. Development Cost

Optimum between **reliability/availability** for operations and **design/qualification costs**

Low system reliability/availability

High cost of mitigating failures once in operation



Large design margins
Rad-Hard components

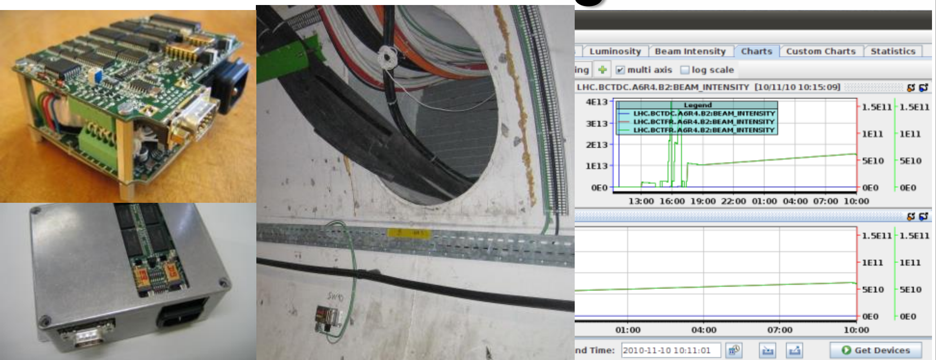
High system reliability at high cost

Optimum depends on: radiation levels, criticality for operations, system failure rate

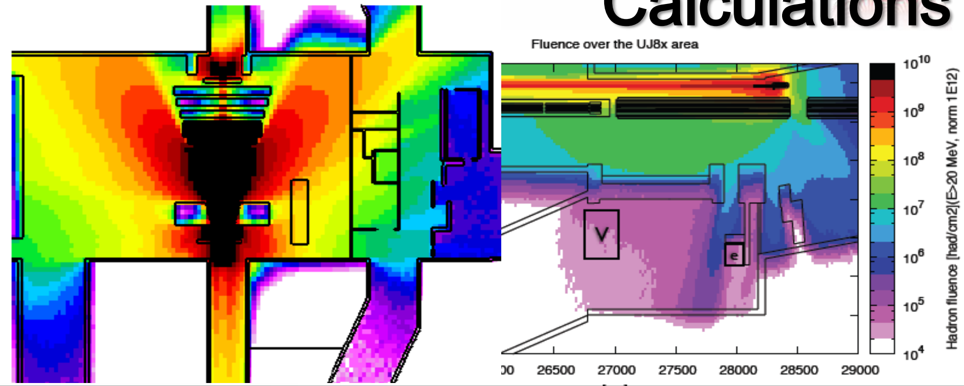
Combining **top-down** (from system to component) and **bottom-up** (discrete component qualification)

R2E Building Blocks

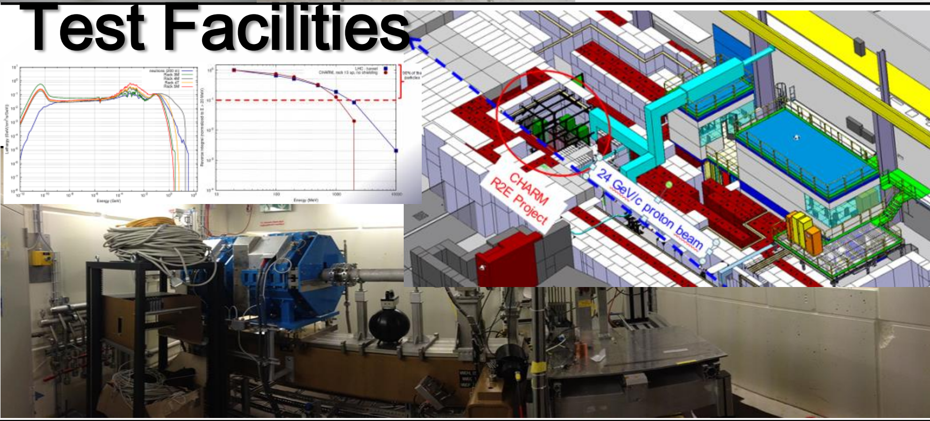
Radiation Monitoring



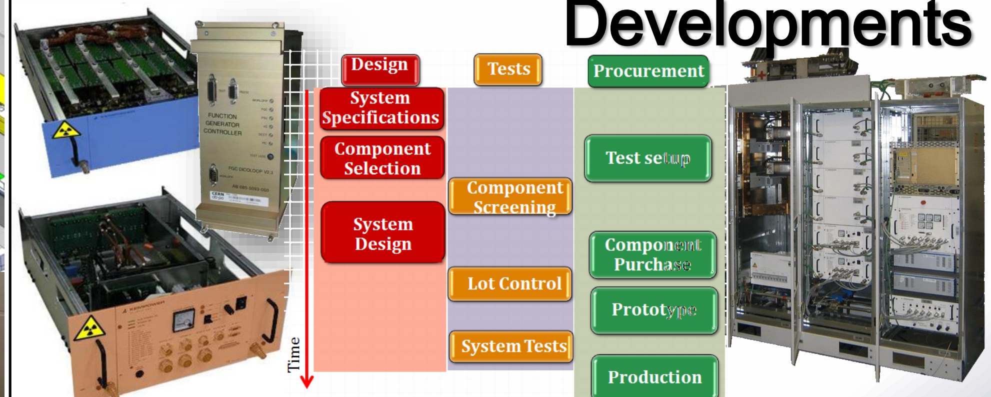
Calculations



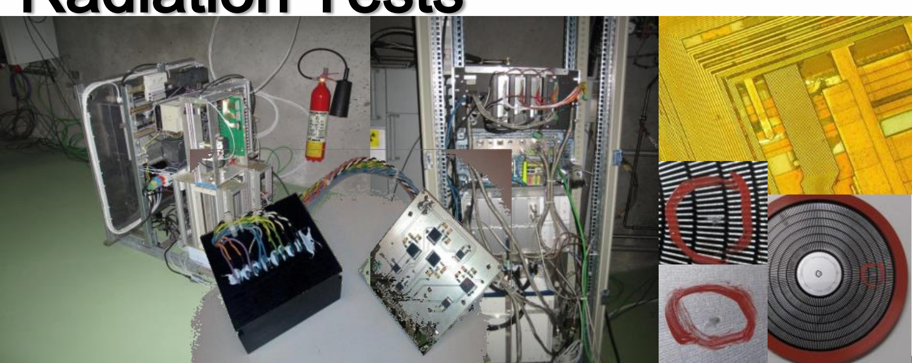
Test Facilities



Developments

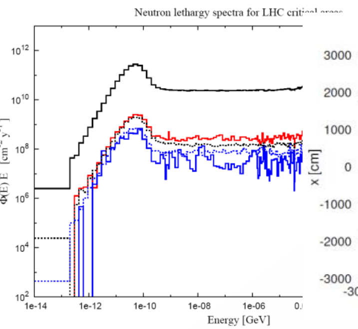


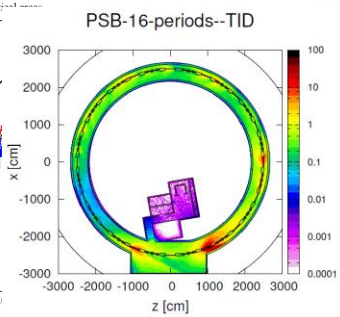
Radiation Tests

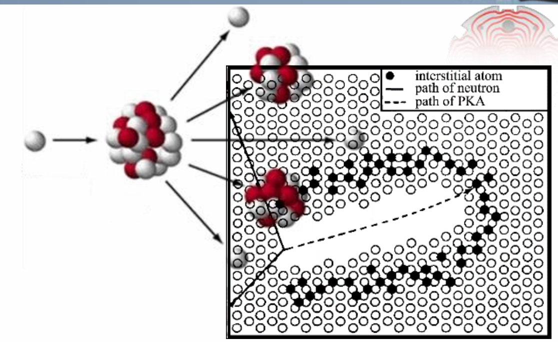


Production & Implementation

Do We've All We Need?







Calculations

Materials & Components

Radiation Environment

Radiation Effects & Physics

Monitoring

Sound & Save Design

Models

Radiation Tests & Facilities

Mitigation Measures

EXPERIENCE & EXPERTISE

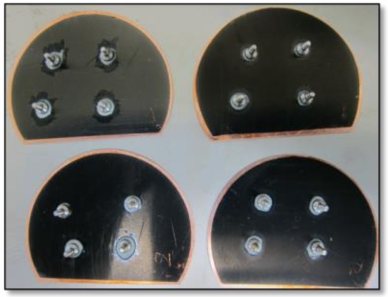
Procedures, Access, Time

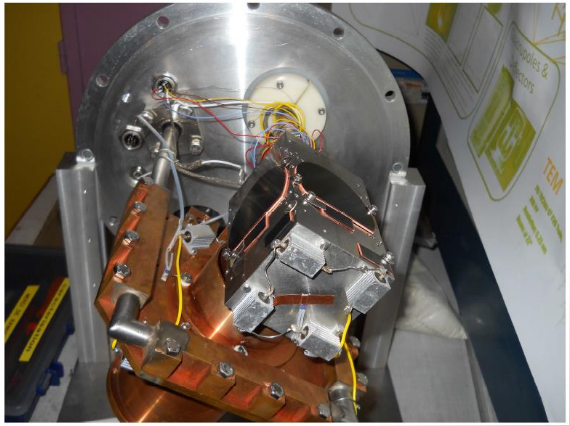
Shielding, Alternatives, Space -…

Few Examples for Vacuum Applications

Carbon Coatings for HL-LHC

- amorphous carbon coatings (200-500 nm on copper) to lower the SEY and prevent electron cloud development
- worst case: a dose of 1GGy of photons at MeV energy
- two test campaigns:
  - Belgium: 150keV protons (limited penetration depth)
  - Italy: 3MeV protons
- What has been tested: SEY & Adhesion,



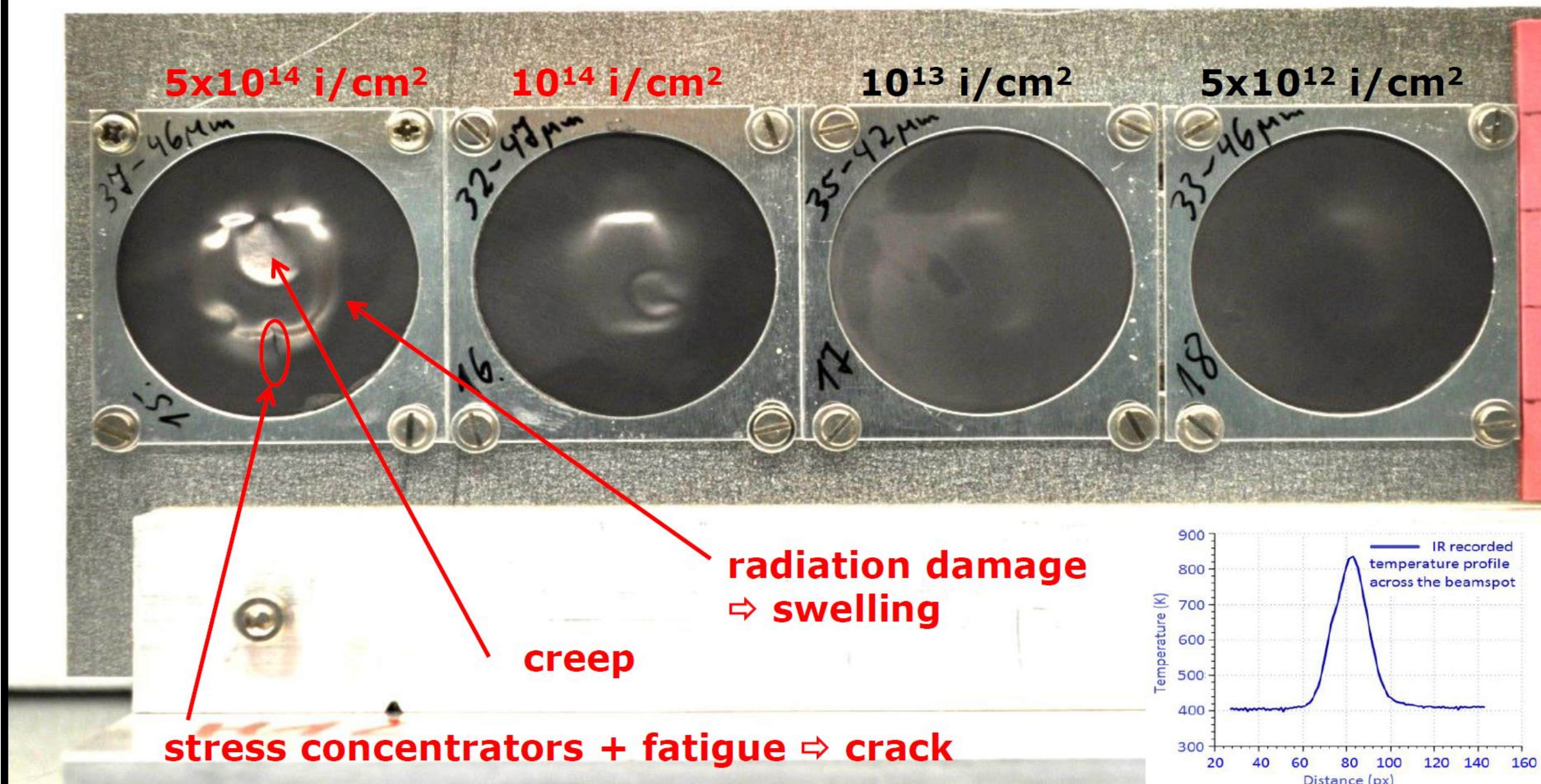


- Challenges: Temperature, reference samp., 'damage path'
- Conclusion: ok for the ionizing damage, open question on NIEL at coating boundary (no good literature exists)

Carbon Windows

© M. Tomut, GSI

^{238}U, 1.14 GeV; 1.5 x10^{10} i/pulse ; 150 µs, 1 Hz



Glassy Carbon

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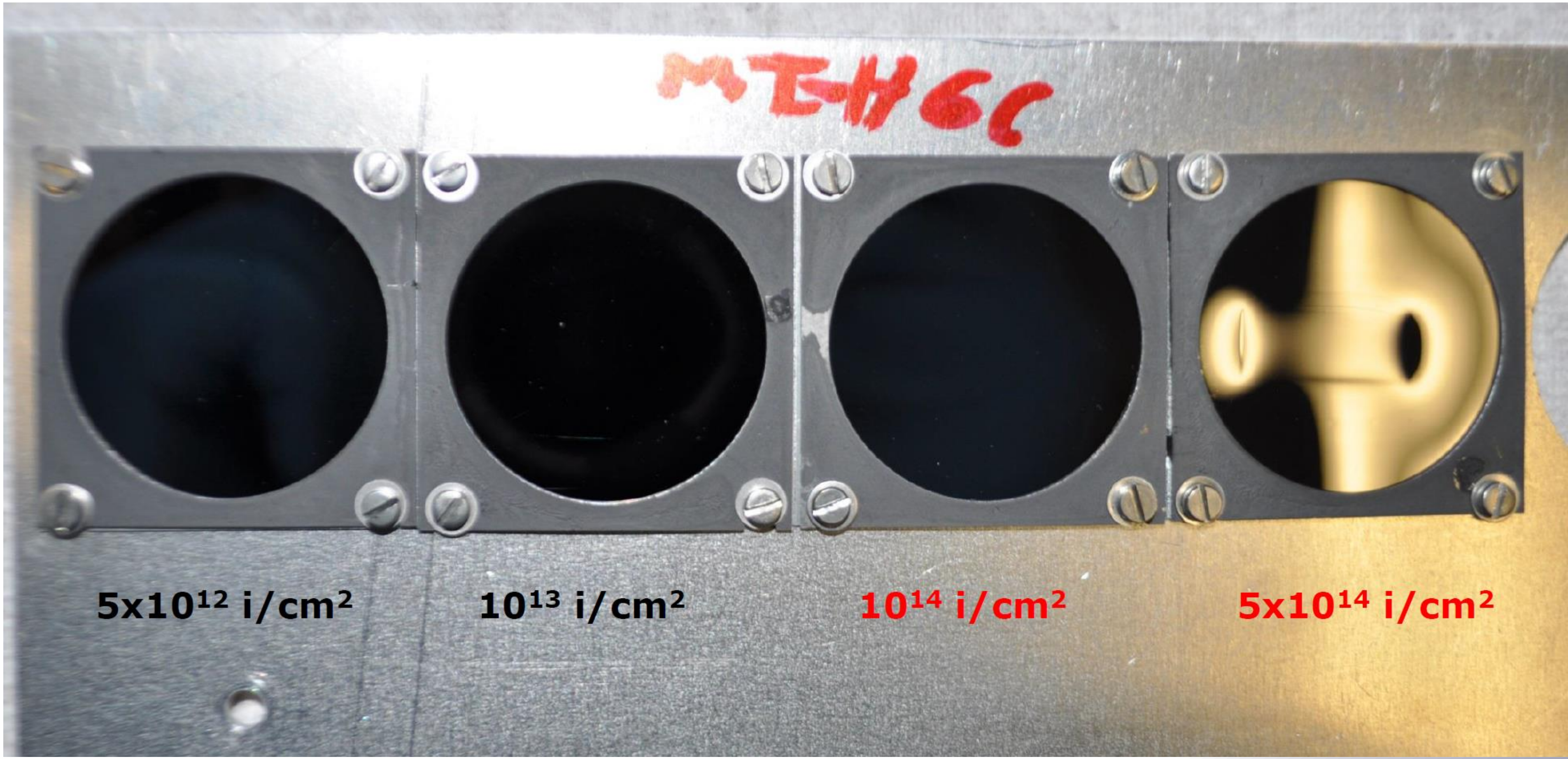
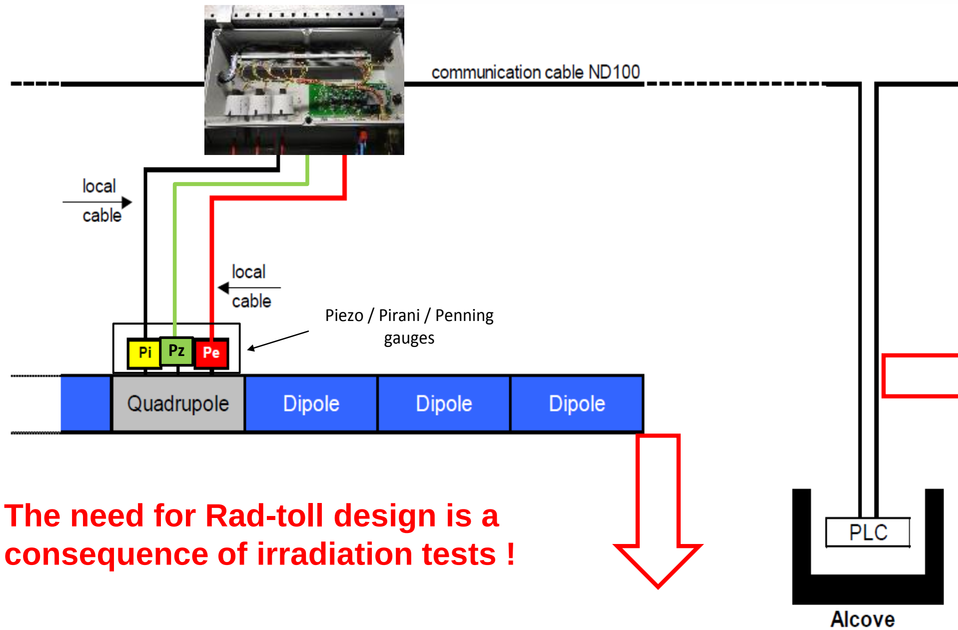


Active Gauges and 24VDC

LHC ARC/DS: TARGET LIFETIME DOSE: FEW HUNDRED GY

UHV measurement in the LHC ARCs



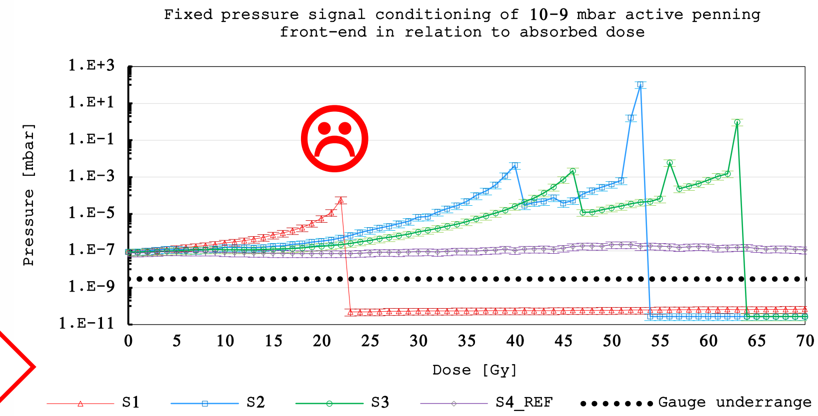
The need for Rad-toll design is a consequence of irradiation tests !

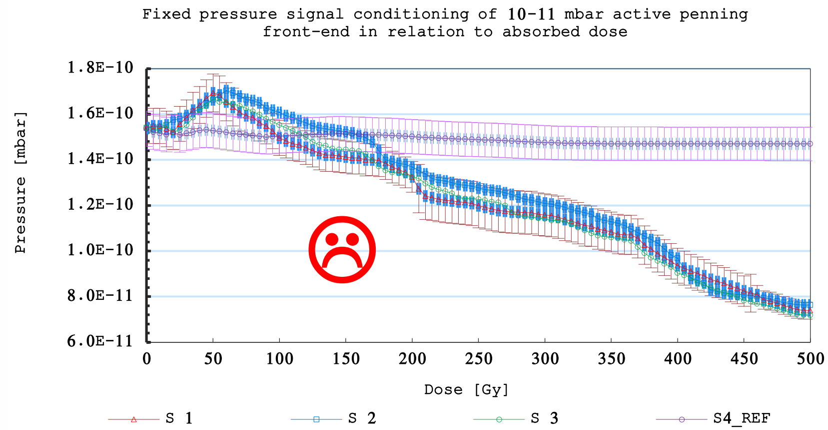
Dry runs at CERN

Dry runs at Fraunhofer INT.

Co60 gamma irradiation

Provide Alarms for cryogenic system





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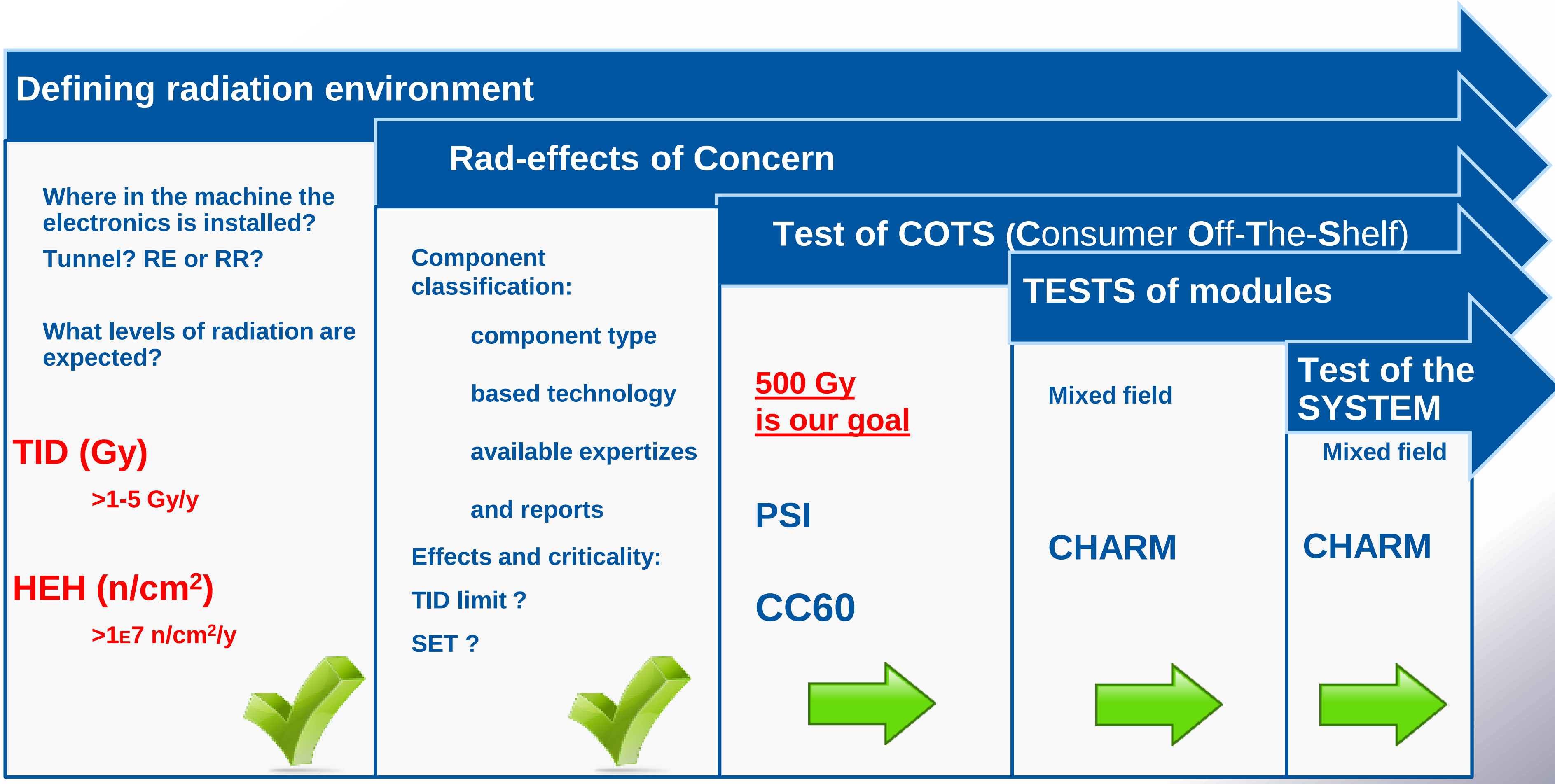
Active Gauges and 24VDC



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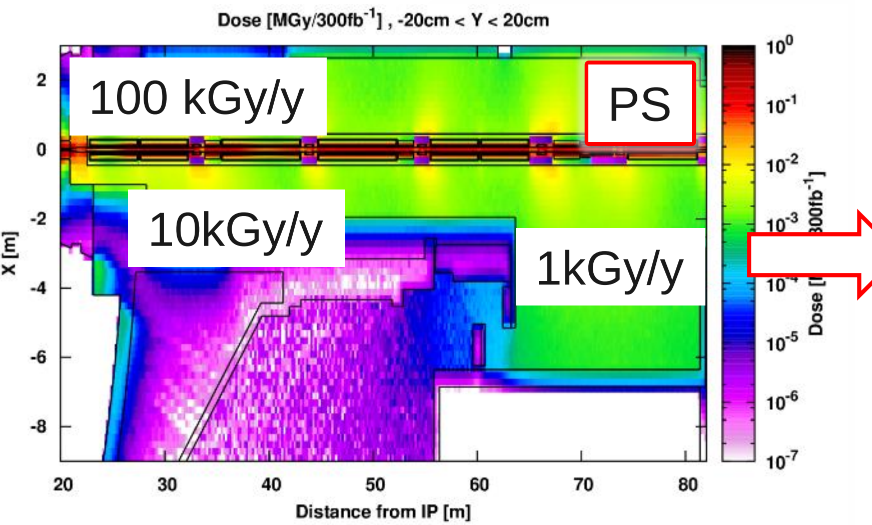
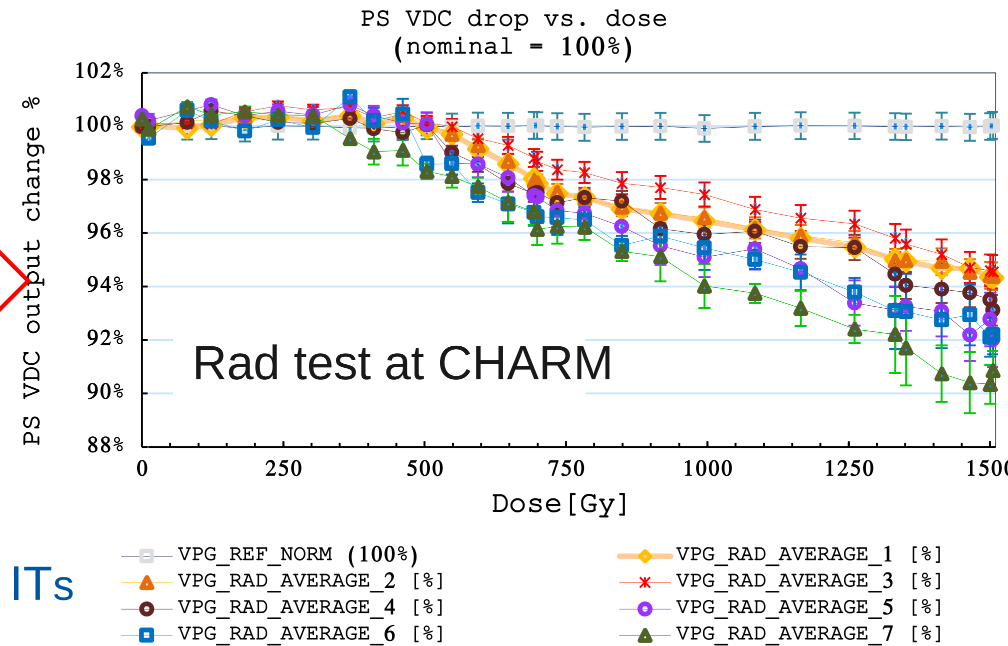
Active Gauges and 24VDC

HOWEVER, LHC INNER TRIPLETS -> EARLIER ACTION REQUIRED



FLUKA map for P1/P5 L&R for HL-LHC ITs



PS cannot stay in current area -> mitigation:

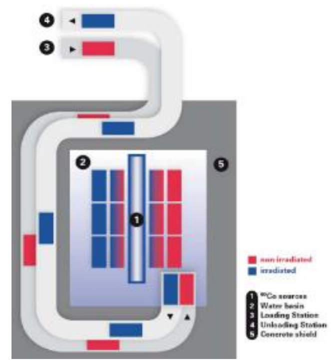
- Removal of 24VDC PS
- 24VDC will be supplied from protected service areas
- Voltage drop along the cable will be compensated by:

© P. KRAKOWSKI: RESULTS PRESENTED AT RADECS AND REPORTS AVAILABLE

Numerous Other Campaigns

Material characterisation

Irradiation conditions and preparation



Irradiation and quality check at CERN and BGS

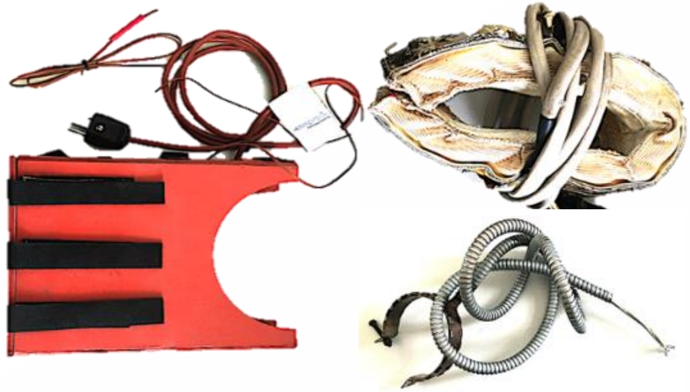
Some FKM (Viton) -> early damage

DONE | ONGOING | CONTINUATION | NEW TASKS

Schedule	Activity
• Task 1: O-ring seals	Preparation
	Irradiation
	Analysis (LRCCP)
• Task 1.2: F14 Formulation O-Rings under compression	Preparation
	Irradiation
	Analysis (LRCCP)
• Task 2: Permanent bake-out components	Preparation
	Irradiation
	Analysis
• Task 2.2: New bake out jackets for the LHC bellows close to the collimators	Preparation
	Irradiation
	Analysis
• Task 3: NiTiNb SMA (shape memory alloy) connectors	Preparation
	Irradiation
	Analysis
• Task 3.2: SMA connectors set-up North Area (TDC2) long term exposure	Preparation
	Irradiation
	Analysis
• Task 4: Primary and turbo pumps	Preparation
	Irradiation
	Analysis
• Task 5: Micro switches and distributors for sector valves	Preparation
	Irradiation
	Analysis
• Task 6: Passive penning gauges and its HV cable under radiation	Preparation
	Irradiation
	Analysis
• Task 6.2: Radiation induced current in coaxial/triaxial cables	Preparation
	Irradiation 6.2
• Task 6.3: Radiation induced cables aging impact on their electrical performance	Irradiation 6.3
	Analysis
• Task 7: Polymer, Silicon rubbers and polyurethanes clamps VacSeal and other epoxies	Preparation
	Irradiation
	Analysis
• Task 8: Piezoelectric venting valve	Preparation
	Irradiation
	Analysis
• Task 9: Passive piezo resistive gauges in the LSS & dump lines	Preparation
	Irradiation
	Analysis

Numerous Other Campaigns

Radiation induced ageing Example: examples for Bake-out Jackets



Heating jackets and collars

250 kGy

Noticeable supply
cable aging

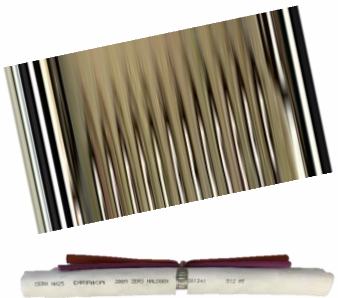
500 kGy

Jacket hardening
Further cable aging

1 MGy

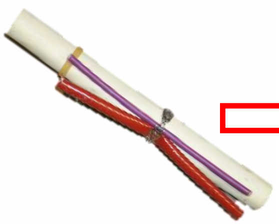
Advanced jacket hardening
and cables disintegration

10MGy?



Cables and connectors

500 kGy



Preparation

Measurements

Test developed and
performed by VSC-SCC
(B.Teissandier, P.Bole)

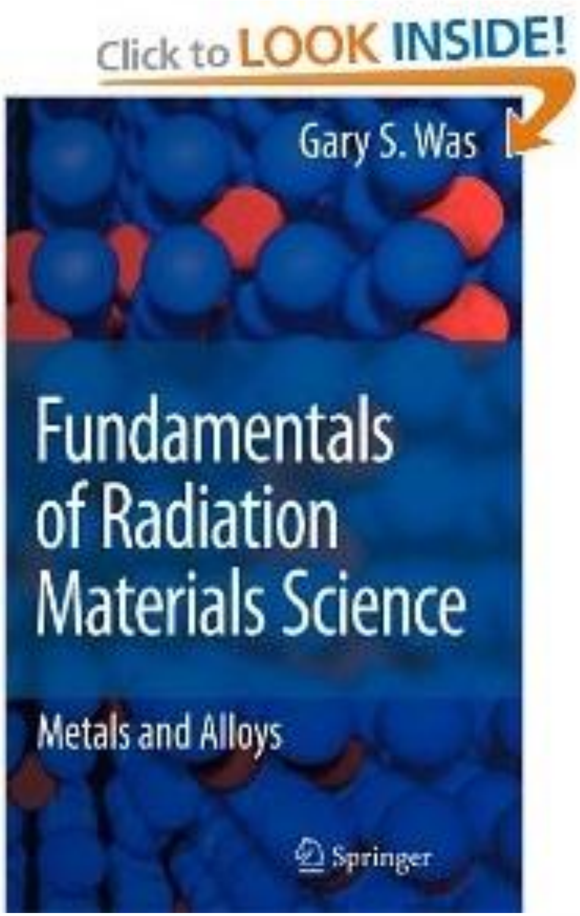
Rubbers and epoxy glued kapton (polyimide) + NEG Amphenol connectors

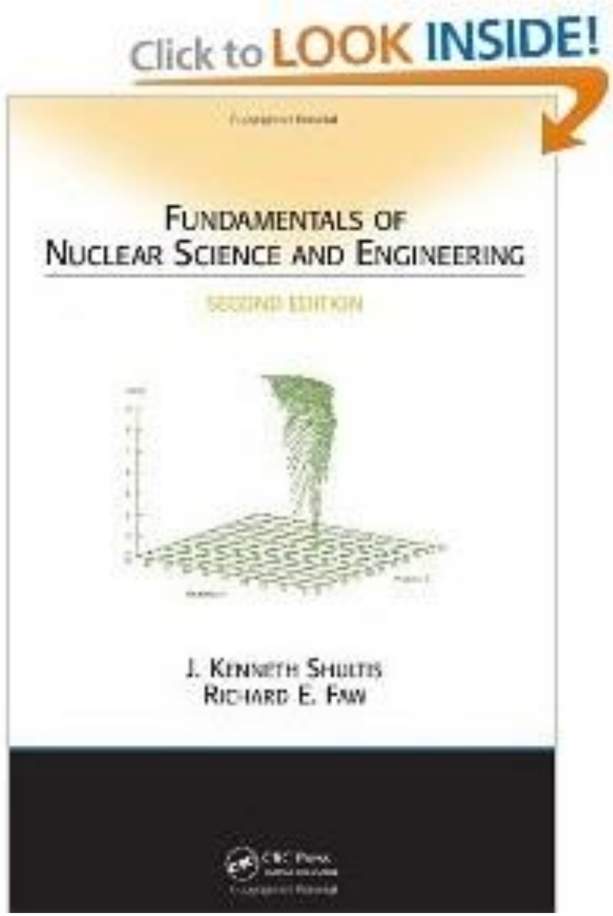
Less than 1 minute of
Oxidation Induction Time !
Cables are not protected in 10^5
Gy range

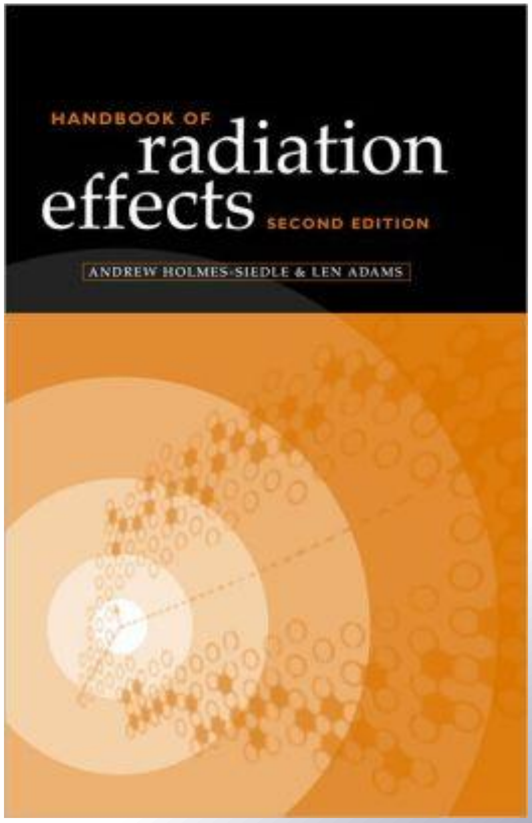
Conclusions

- **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?**
- **Don’t hesitate asking**
  - **Lot’s of expertise exists, sometimes close-by!**

Literature


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

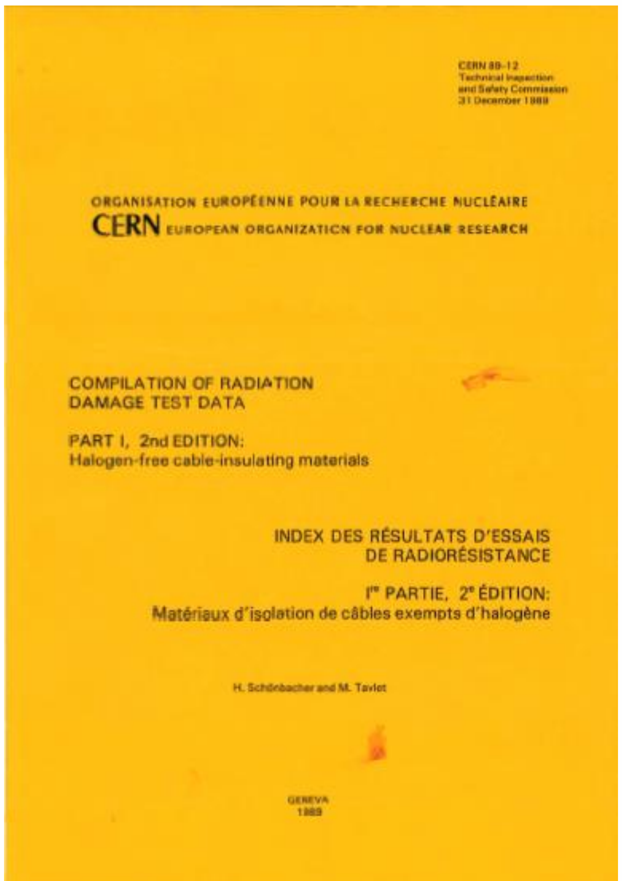

Click to LOOK INSIDE!
FUNDAMENTALS OF NUCLEAR SCIENCE AND ENGINEERING
SECOND EDITION
J. KENNETH SHULTIS
RICHARD E. FAW
CRC Press


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

Literature

CERN Yellow Reports – Material "Bibles"

- e.g: CERN 82-10, or 89-12)


CERN 89-12
Technical Inspection
and Safety Commission
31 December 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COMPILATION OF RADIATION
DAMAGE TEST DATA

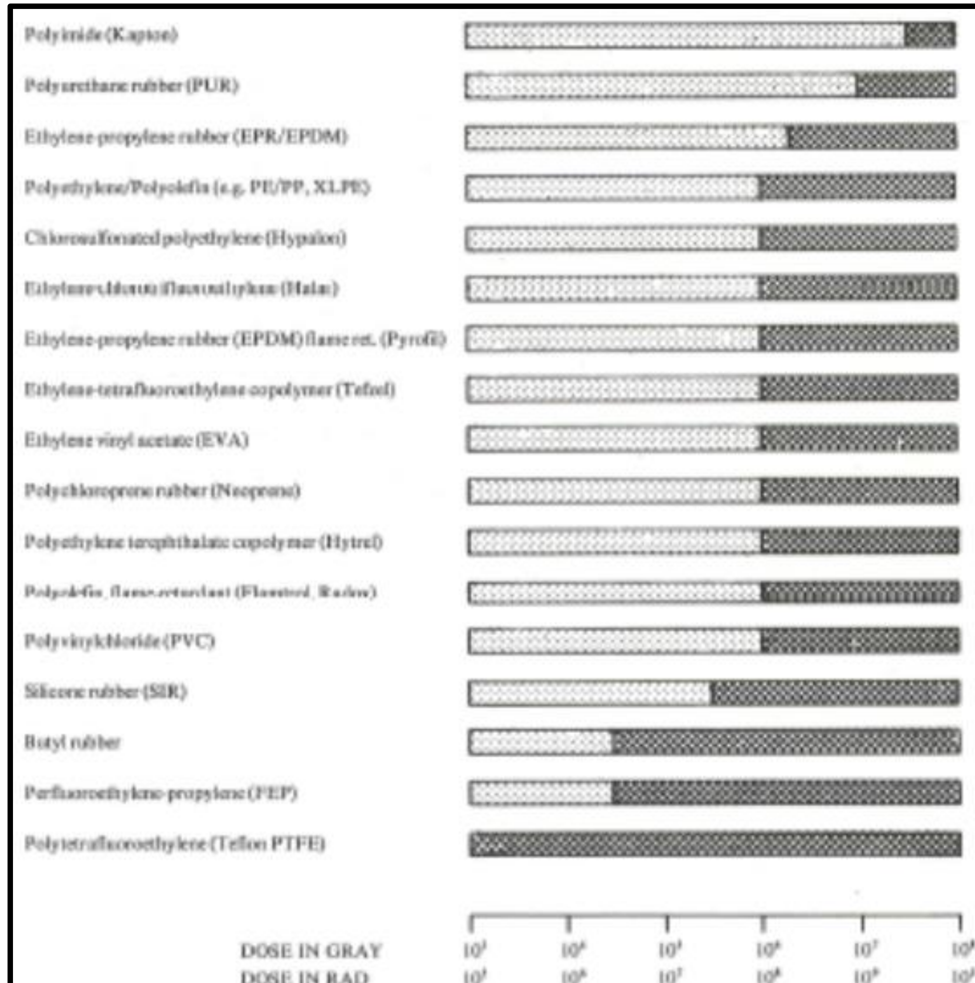
PART I, 2nd EDITION:
Halogen-free cable-insulating materials

INDEX DES RÉSULTATS D'ESSAIS
DE RADIORÉSISTANCE

Iʳᵉ PARTIE, 2ᵉ ÉDITION:
Matériaux d'isolation de câbles exempts d'halogène

H. Schönbacher and M. Tavlet

GENEVA
1989

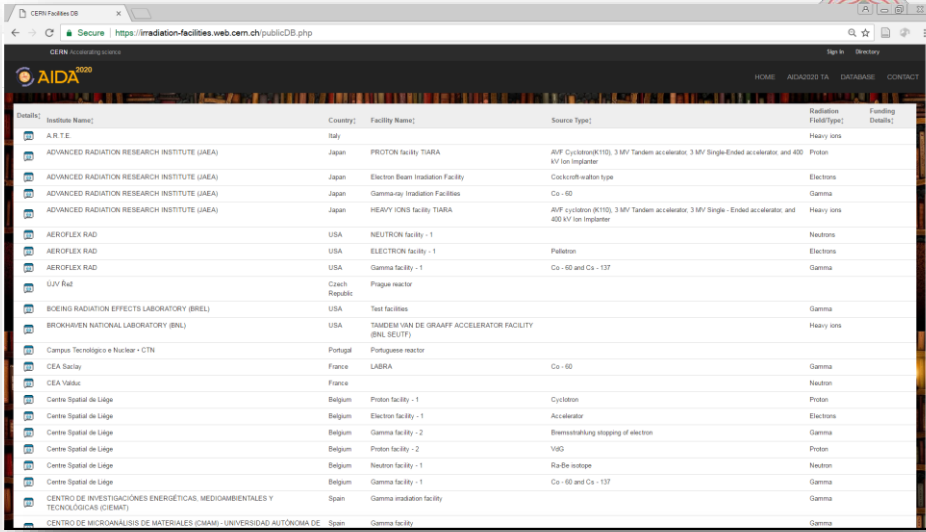


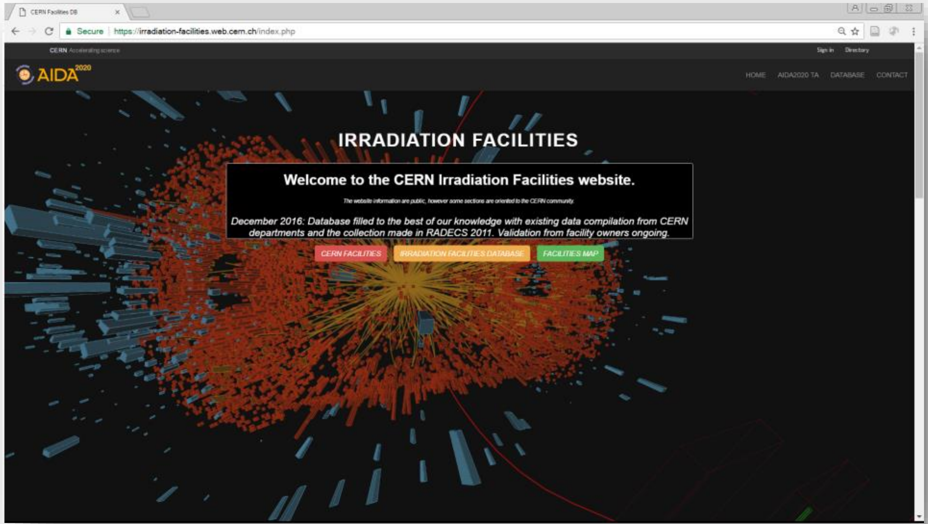
Useful Contacts @ CERN

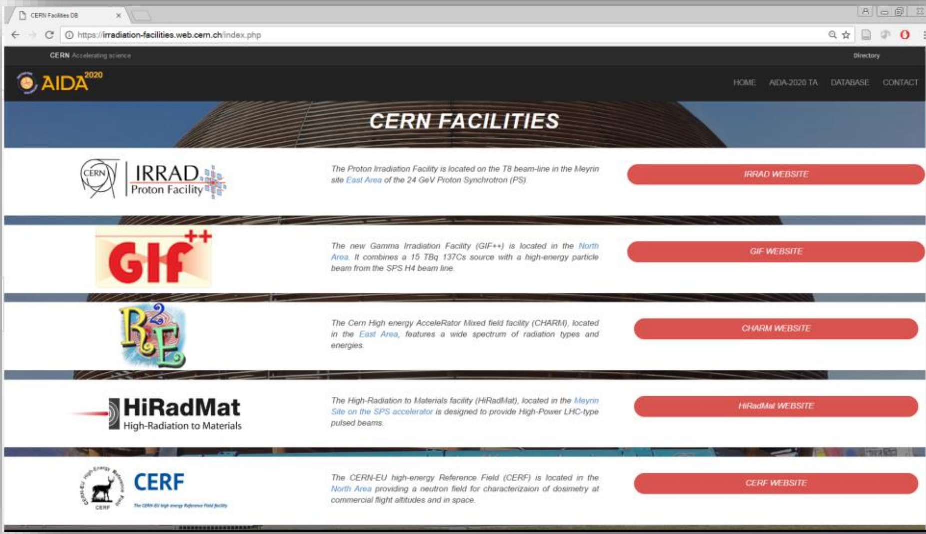
- **FLUKA Team:** Francesco Cerutti
- **Radiation Working Group:** Salvatore Danzeca
- **Radiation Damage to Materials:** Elisa Guillermain
- **Monitoring & Calculation WG:** Yacine Kadi
- **R2E Project:** Markus Brugger & Ruben Garcia Alia
- **EP Electronics Group (EP-ESE):** Phlippe Farthouat
- **CHARM Facility, Testing at PSI, Co-60:** Salvatore Danzeca
- **IRRAD Facility:** Federico Ravotti
- **Vacuum related R2E/M:** Pawel Krakowski et al.

Test Facilities (World-Wide)

- EU-project **AIDA-2020**
- Entry point for irradiation facilities worldwide
- Facilities for **TID, DD, SEE** testing
- **182 entries** initially loaded





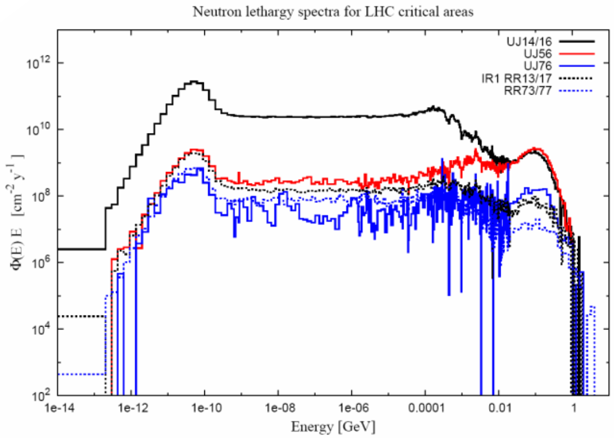


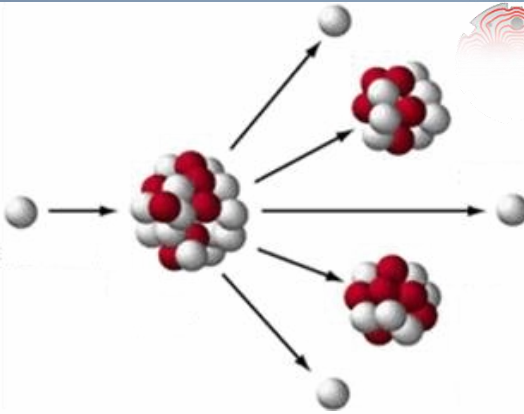
irradiation-facilities.web.cern.ch

Questions?

BACKUP

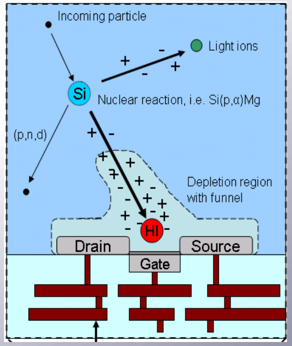
Approach & Requirements



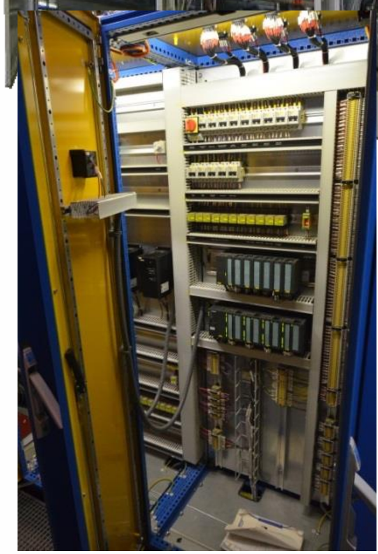


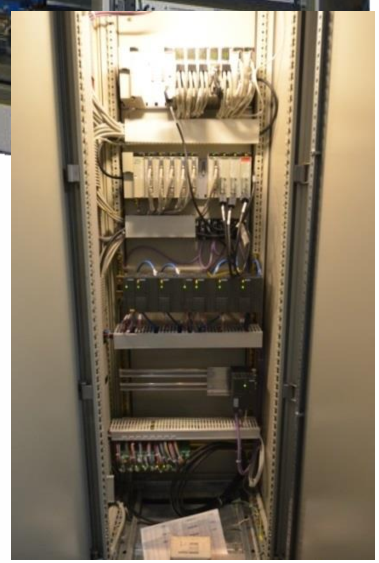
ELECTRONIC COMPONENTS ⟷ RADIATION ENVIRONMENT ⟷ PHYSICS MODELS

RADIATION EFFECTS
ANALYSIS
TESTS
MITIGATION

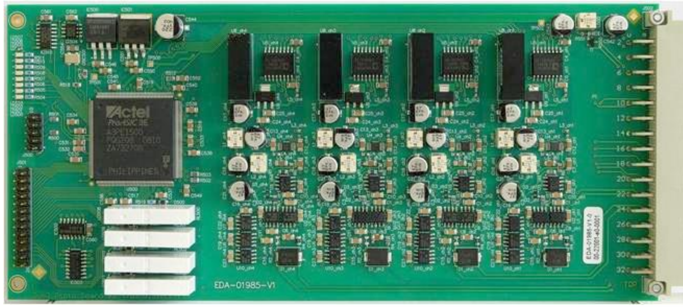


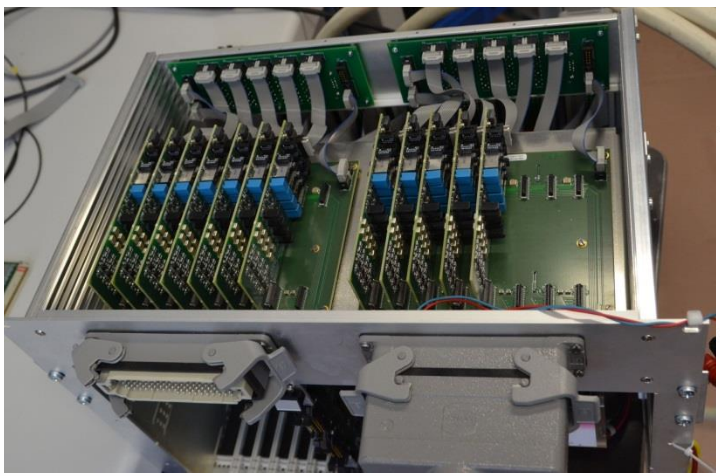
Equipment: Full COTS Systems

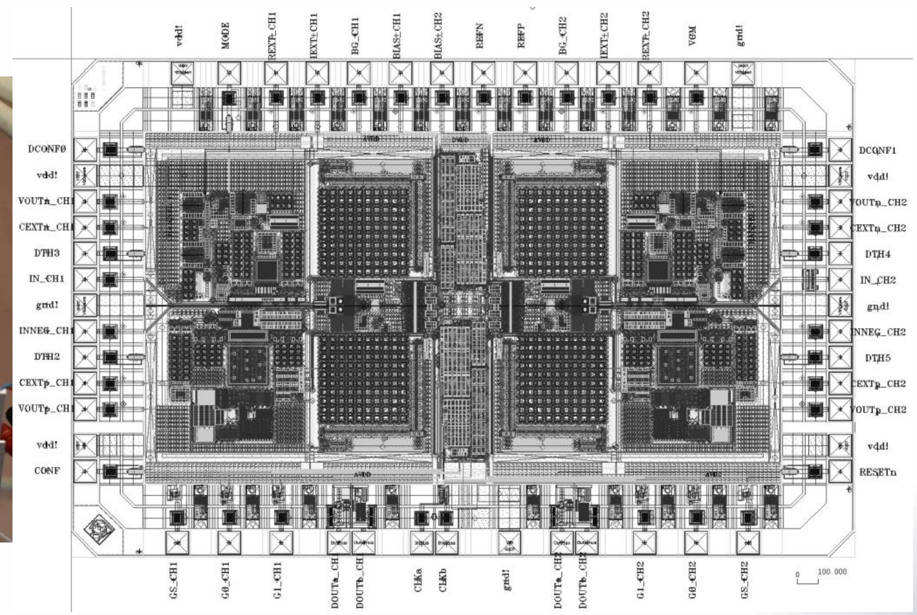




Equipment: Custom Boards







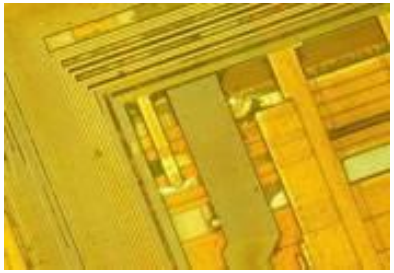
... often based on COTS

(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.



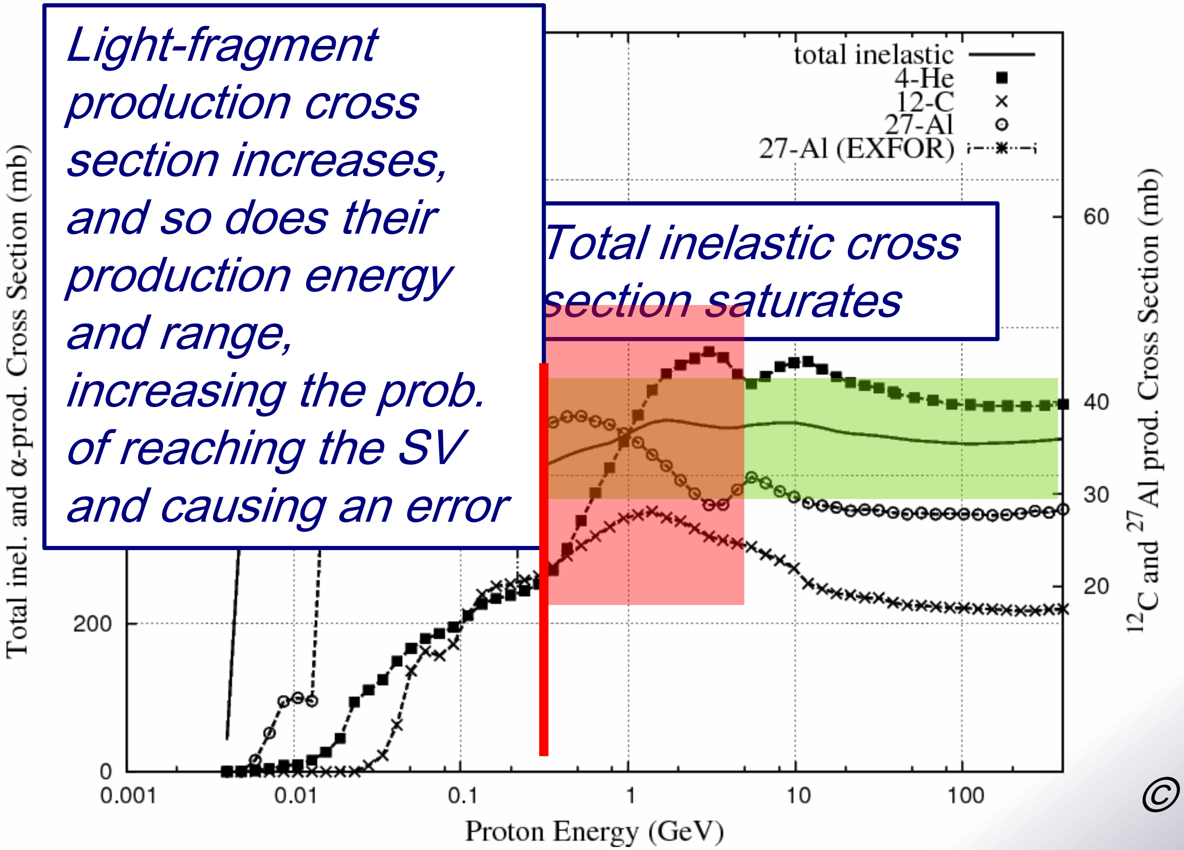
- The component was then exposed to high energy particle radiation at an **LHC-environment**. **Permanent destruction** of the part occurred in the **early stage** of the test.

- 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)

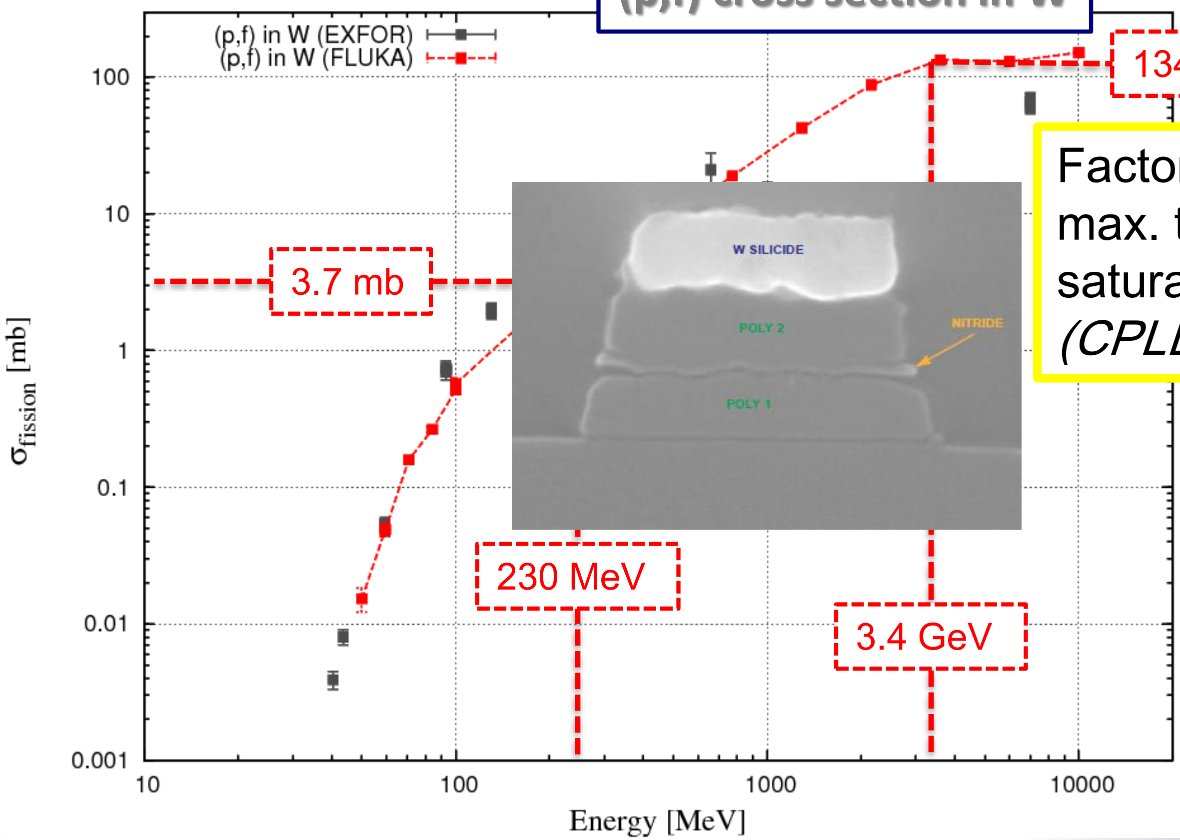


© R. G. Alia

SEL & Fission: Energy Dependence

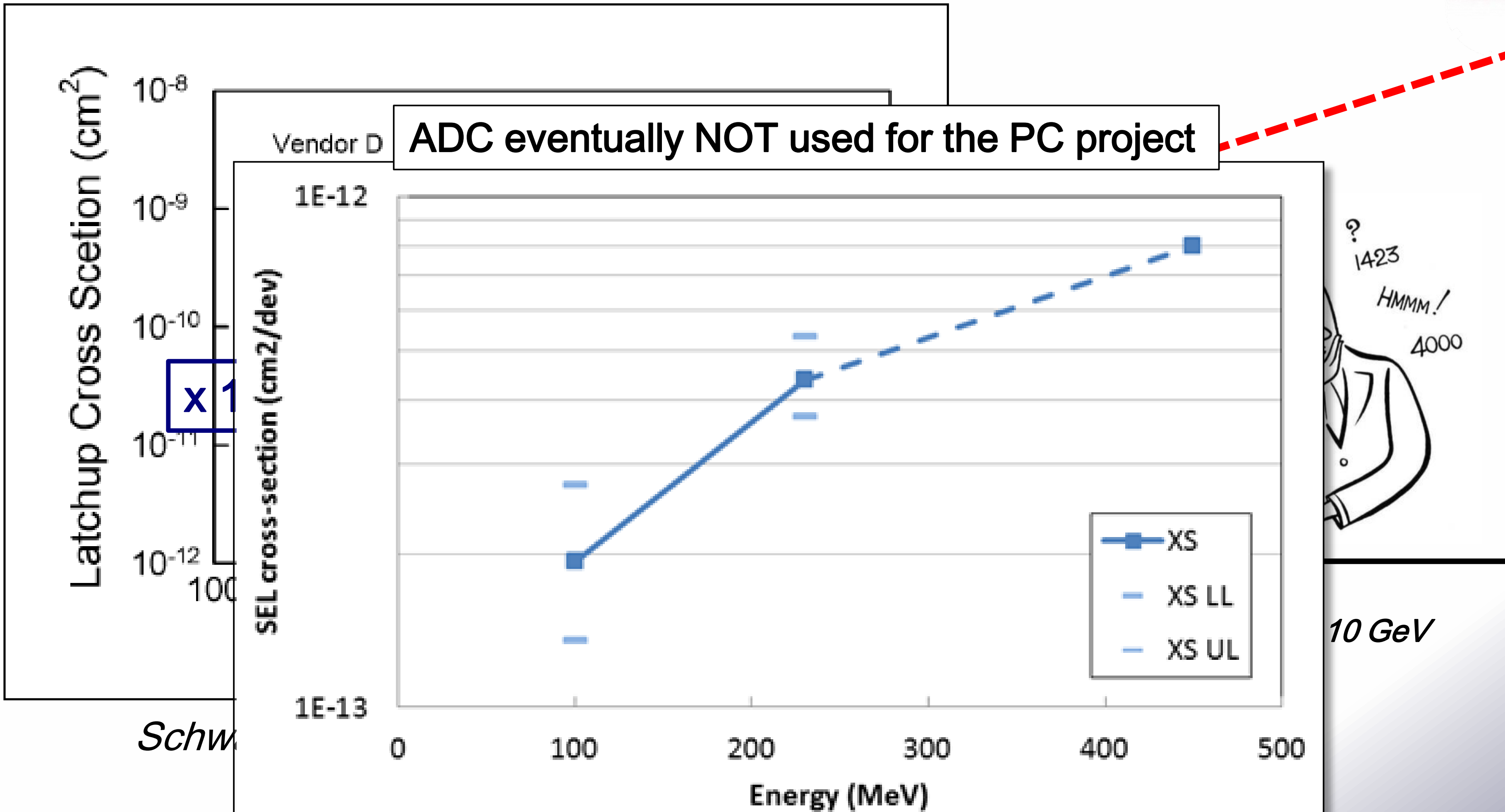
- **High-Z materials** (namely **tungsten**) are often used in the interconnection layers of the memories, **near the sensitive volumes**
- Energetic hadrons can induce **fission** in these materials, producing very **high-LET fragments** that can **dominate the SEE cross section**

(p,f) cross section in W



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

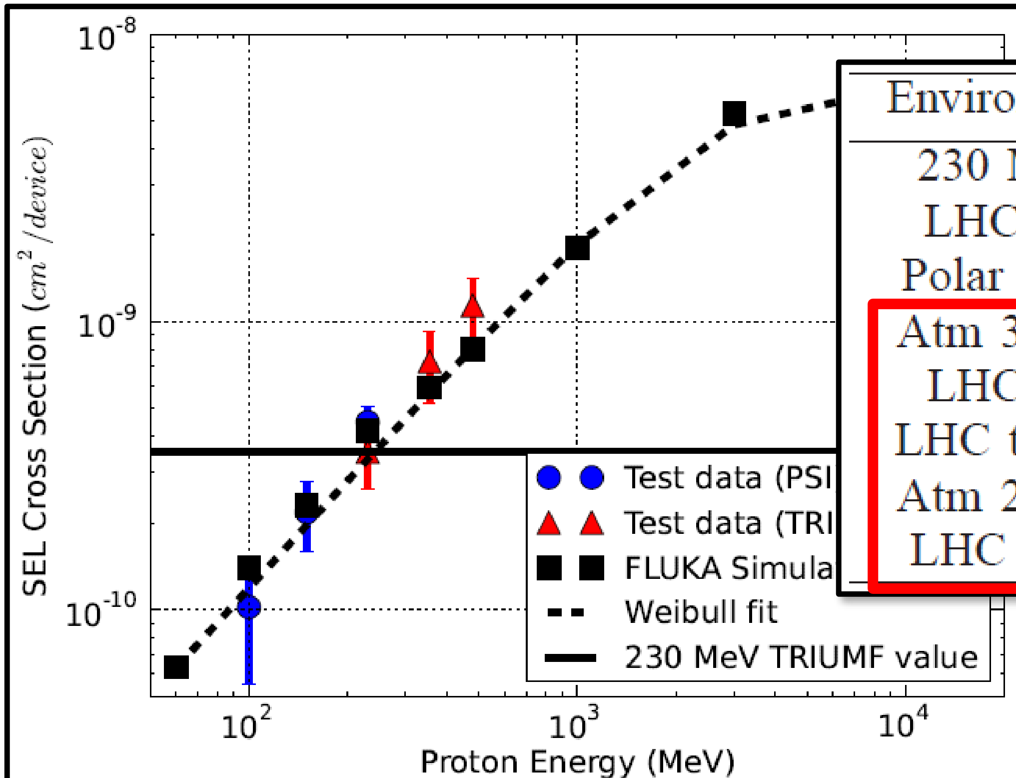
SEL: Energy Dependence



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)**

Case I: No W

Case II: W from rev. Eng.

Case III: 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…)

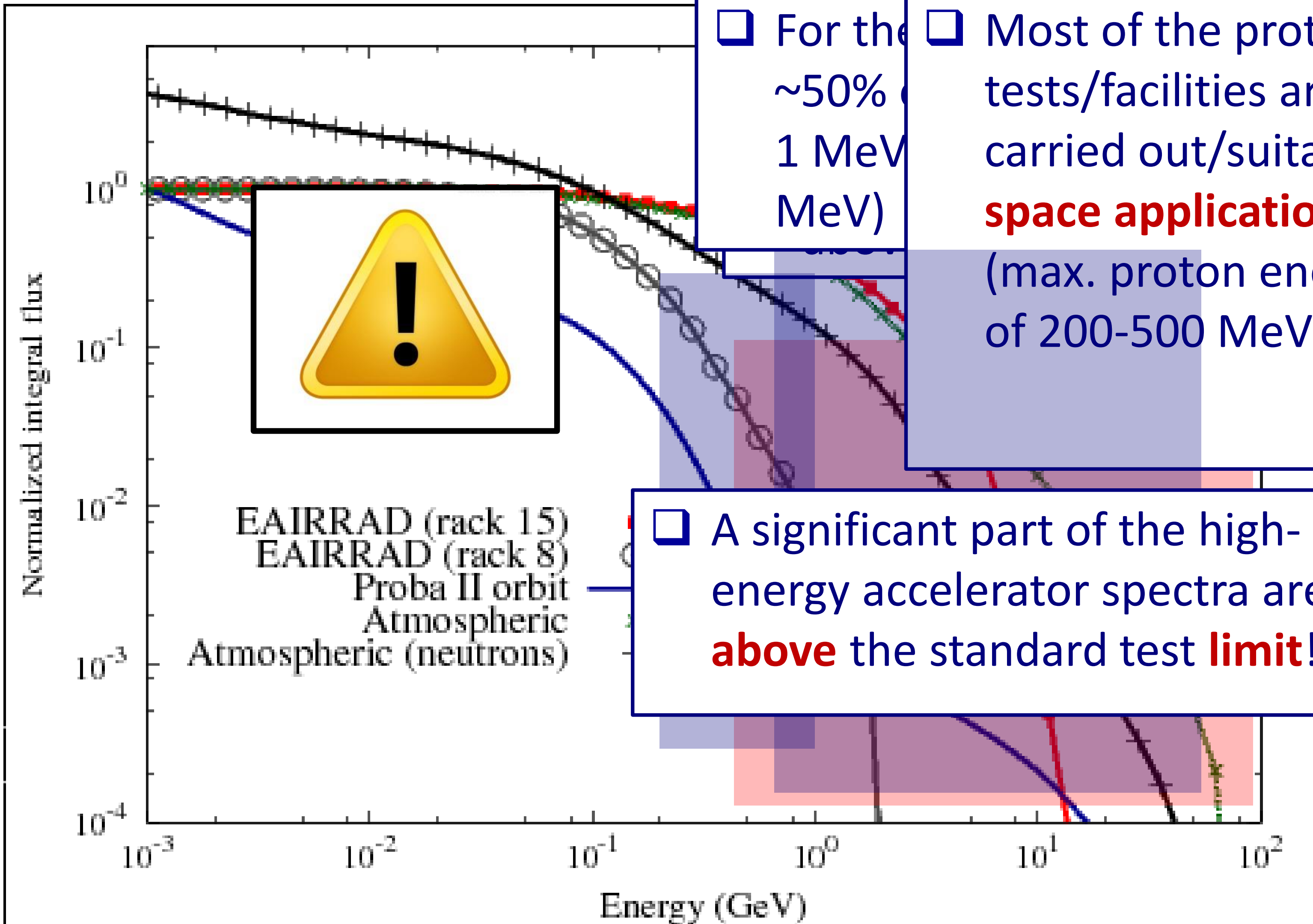
+

- **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

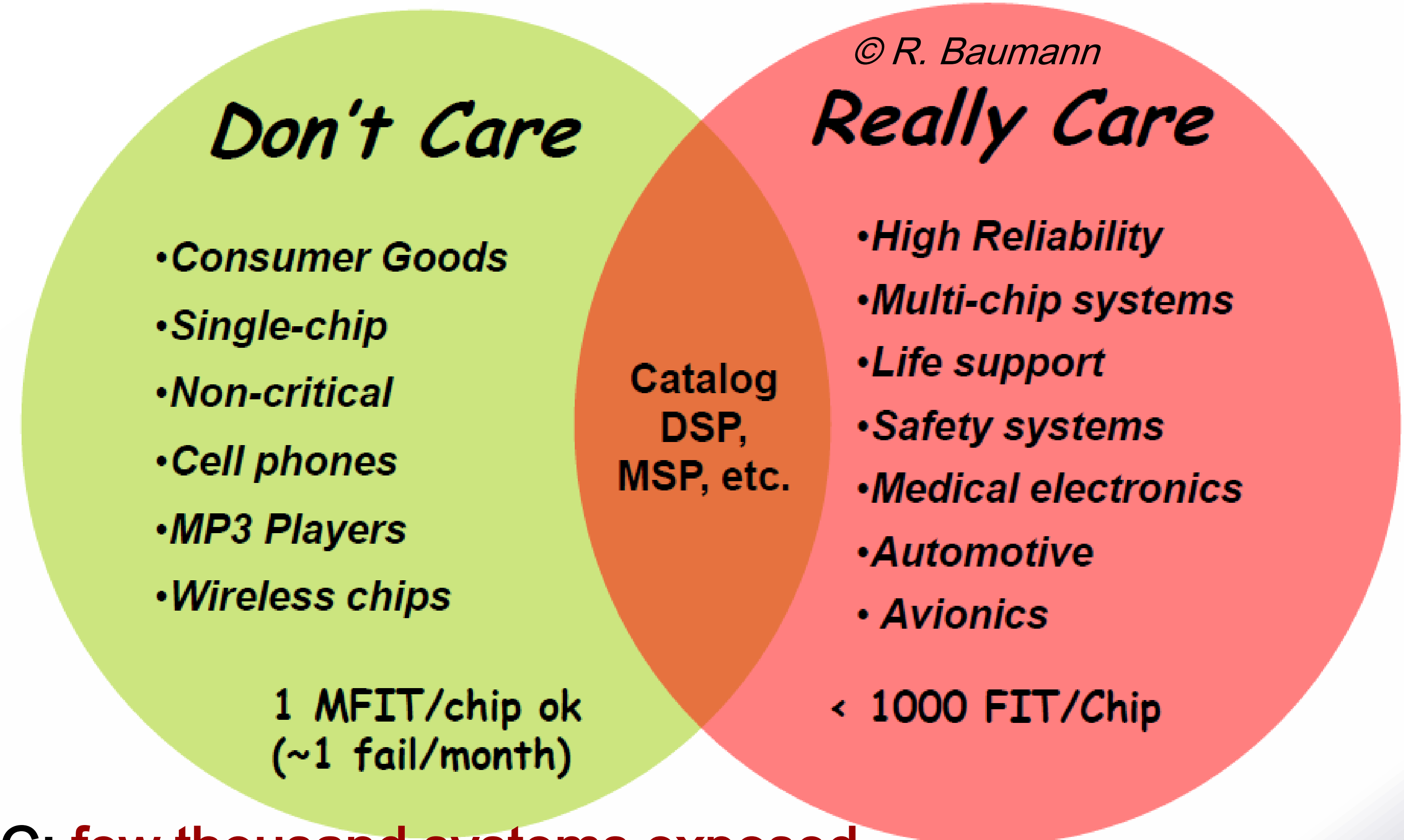
An event corrupting only the DATA stored in a device. The device itself is not damaged and functionality is restored when new data is written.

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

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

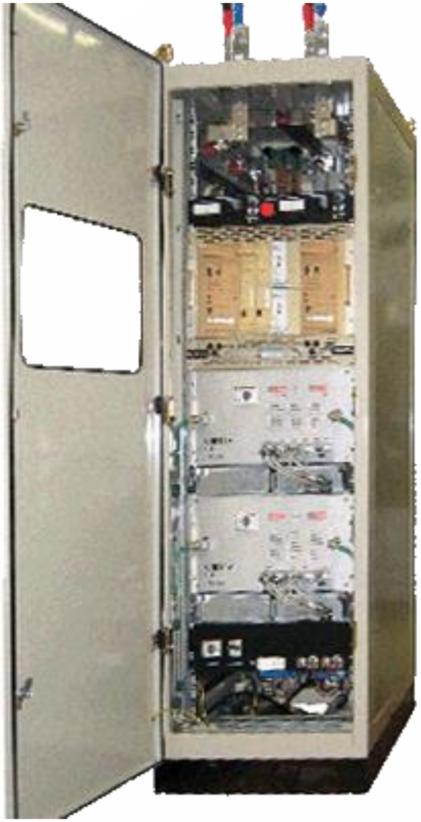
Aim: less than one radiation induced failure per operational week

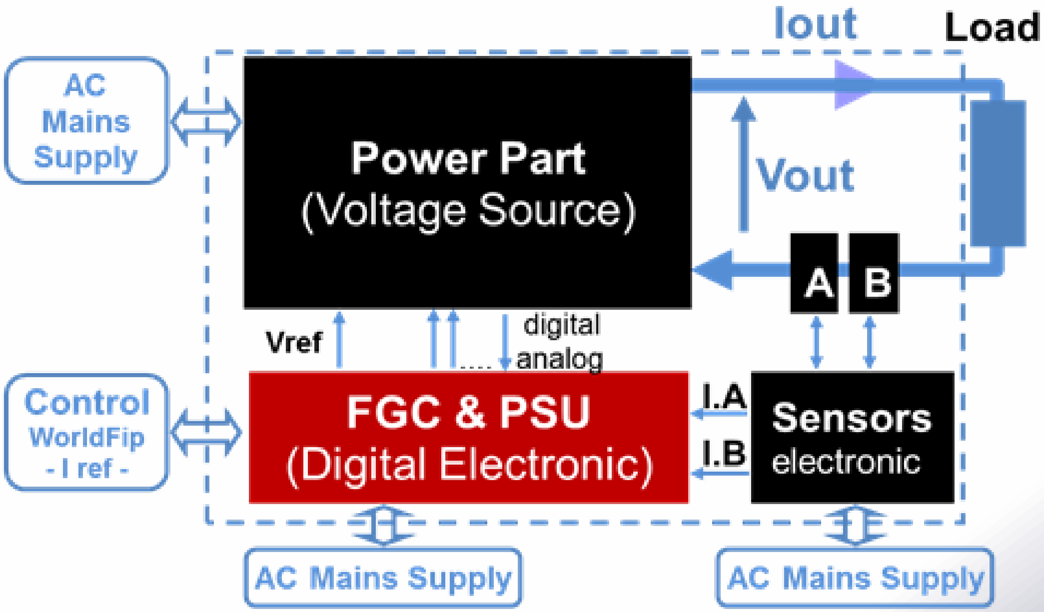
Reliability in FIT: -> aiming for about 1 FIT/SYSTEM!

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!

LHC120A-10V
4-Quadrant

300 Units

LHC600A-10V
4-Quadrant

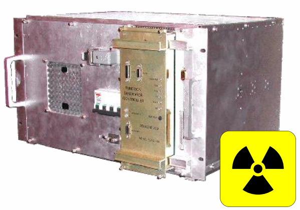
400 Units

LHC4..6kA-08V
1-Quadrant

200 Units

LHC60A-08V
4-Quadrant

752 Units

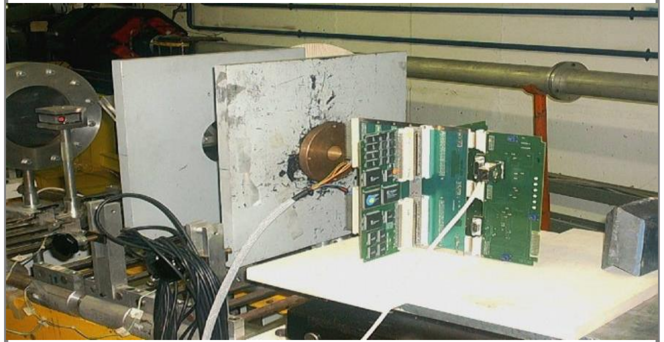


Units : Quantity in all machine (UA, RR, UJ, tunnel)

PCs: What was tested and where?

LHC60A-08V FGC PSUs

LOUVAIN (2003 - FGCs)

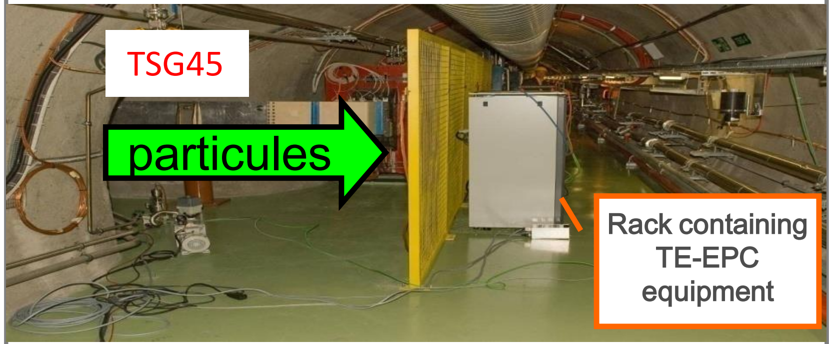


60 MeV proton components tests

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

FGClite Development

© S. Uznanski

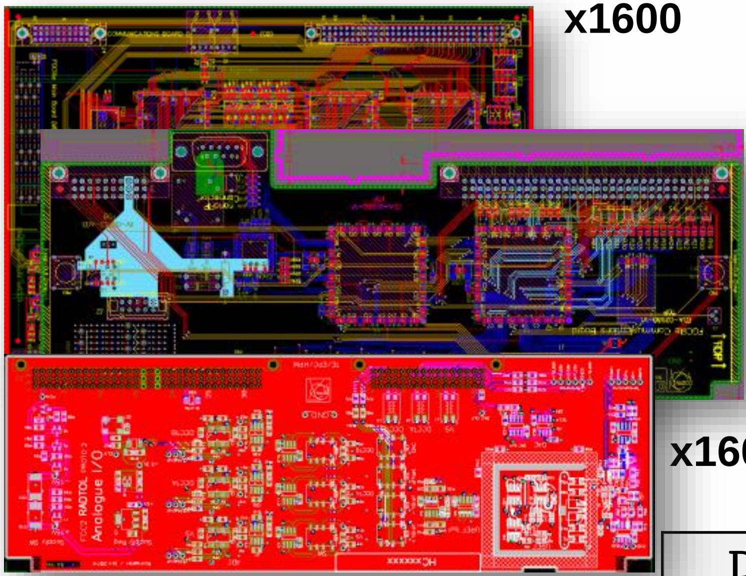
New Radiation-Tolerant design optimized for high availability !!!

6U casette

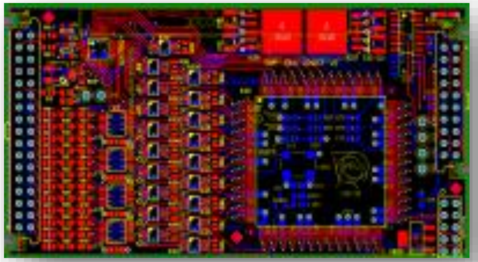
x1600

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

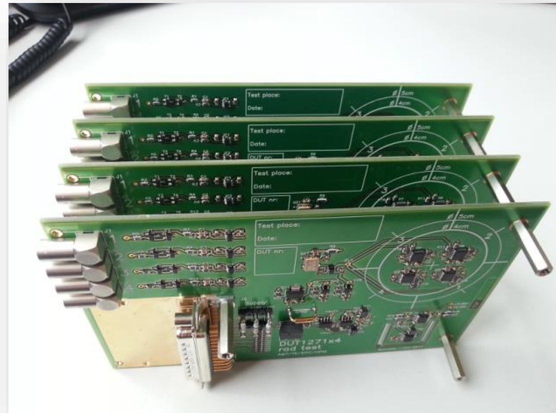
0.5M semiconductors/2.3M components

New testing infrastructure to qualify components under radiation

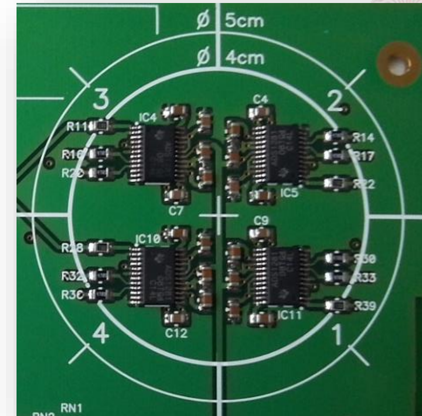
Real-time SEE & TID tests, & multiple components

FGClite Development

PSI Test Area

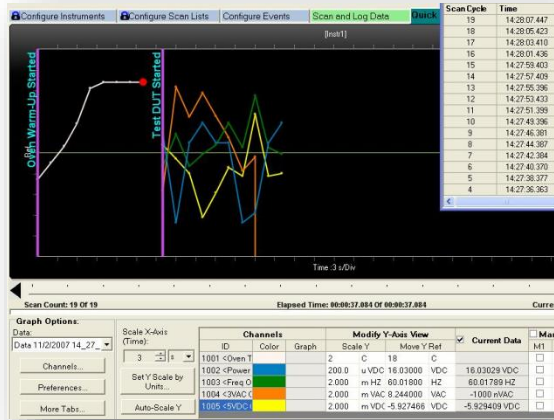


Cards Under Test

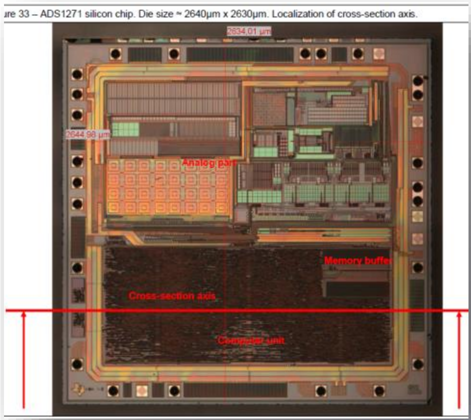


Irradiated Components

Tester Control Electronics



Tester Control Software

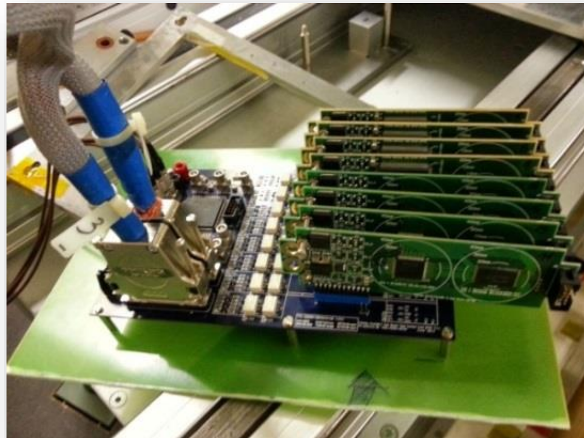


Effect Analysis

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

FGClite Constraints & Strategy

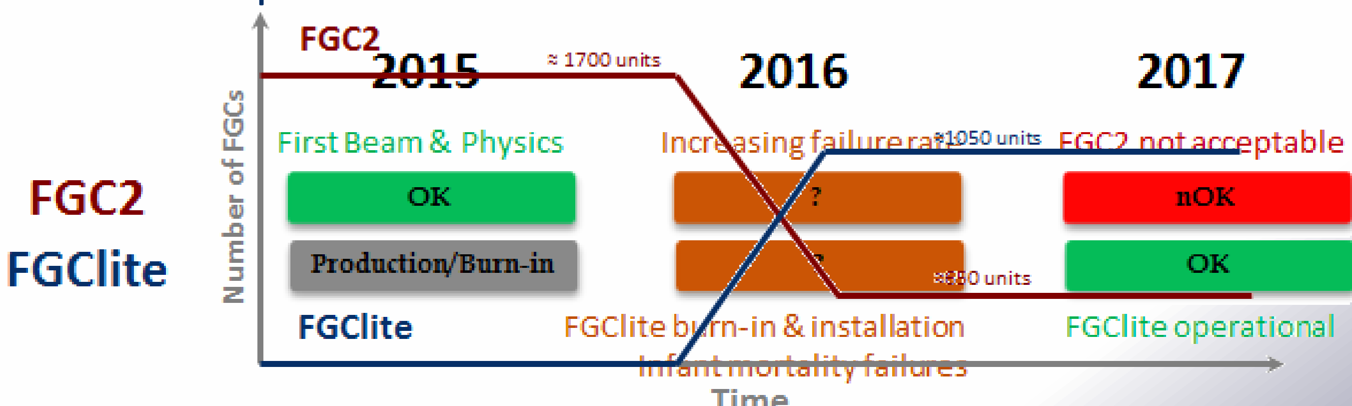
Prototype



FPGA Type Tester

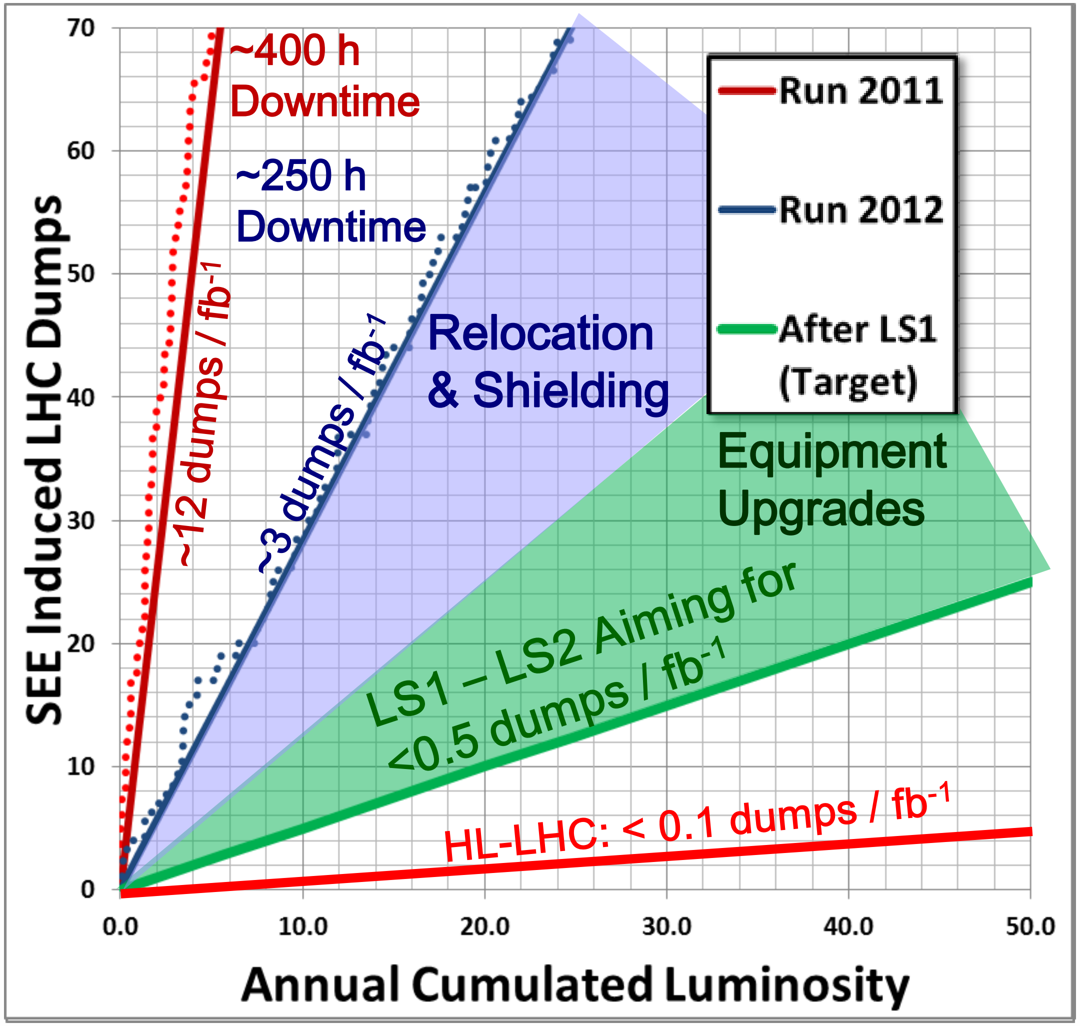
ADC Type Tester

- **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



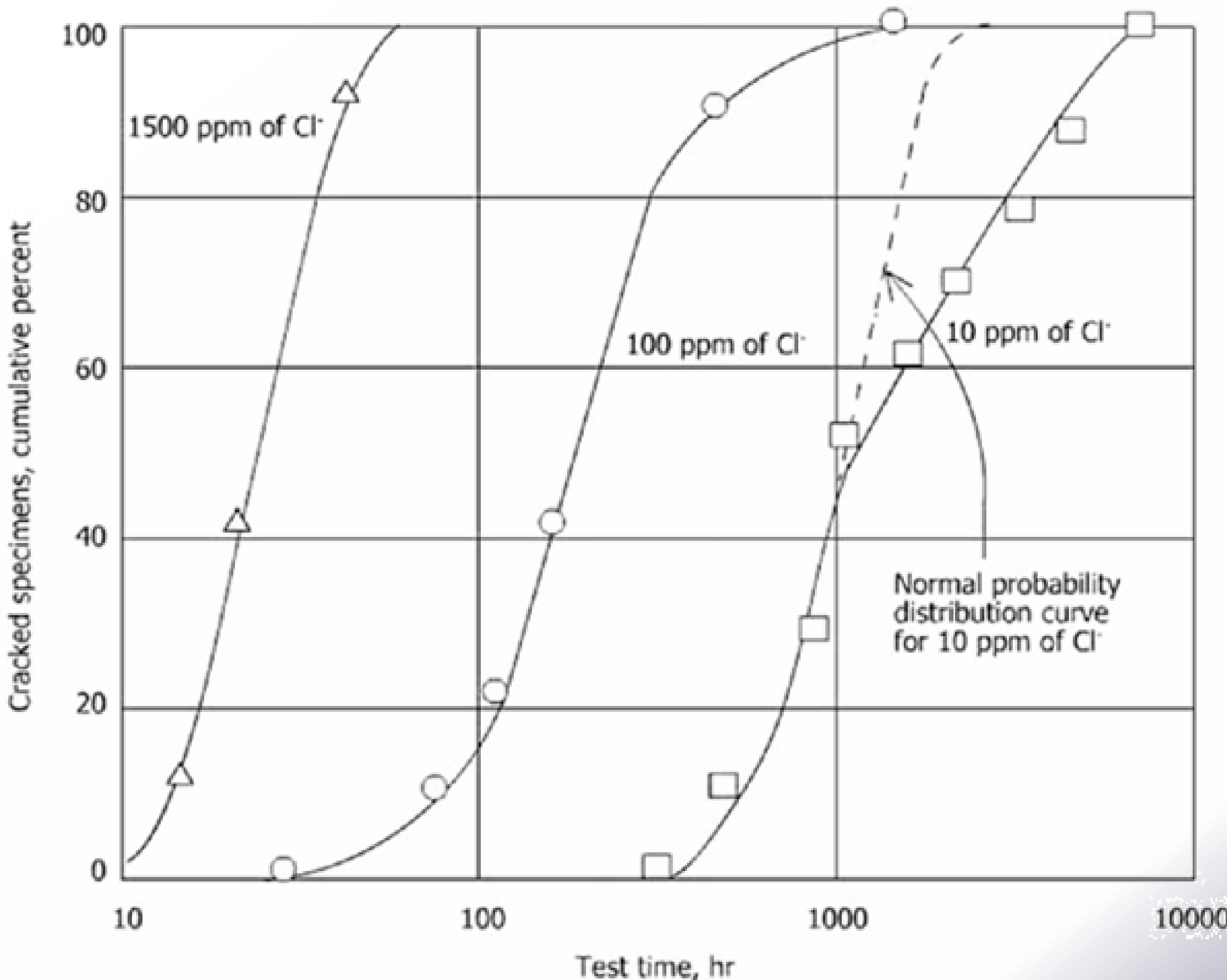
R2E LHC Target

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