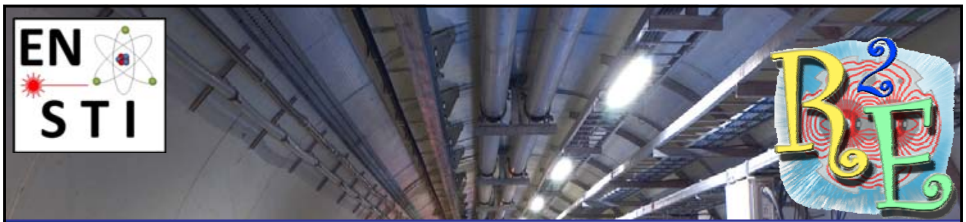


Radiation Damage and Its Consequences

CAS 2014

September 11th 2014

M. Brugger, CERN EN/STI & R2E Project

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

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?

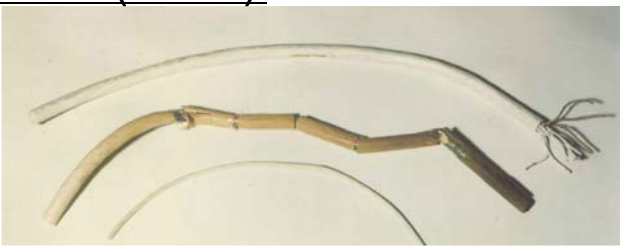
- **Radiation refers to "energy transported through space" by particles, photons, electromagnetic waves…**
- **Energy is then deposited into matter and provokes microscopic and macroscopic changes in its structure, chemical and physical properties -> Impact/Damage**
- *Biological effects of radiation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

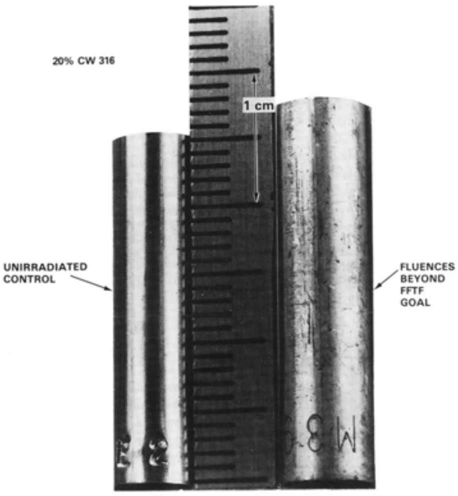
Why do we care

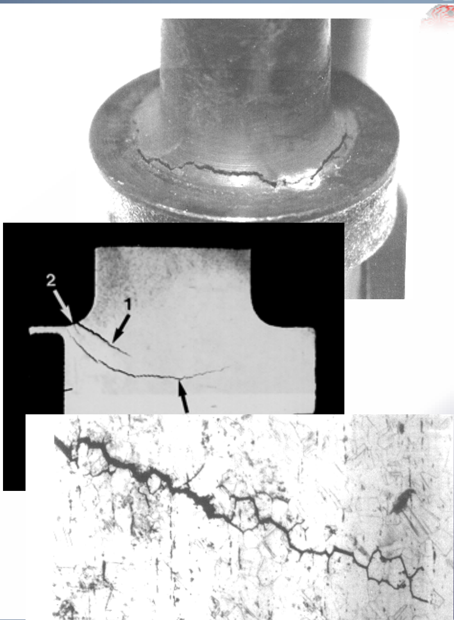
MATERIALS (Cables):



Why do we care

MATERIALS (Metals):



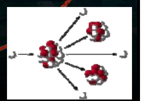


The LHC Challenge

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

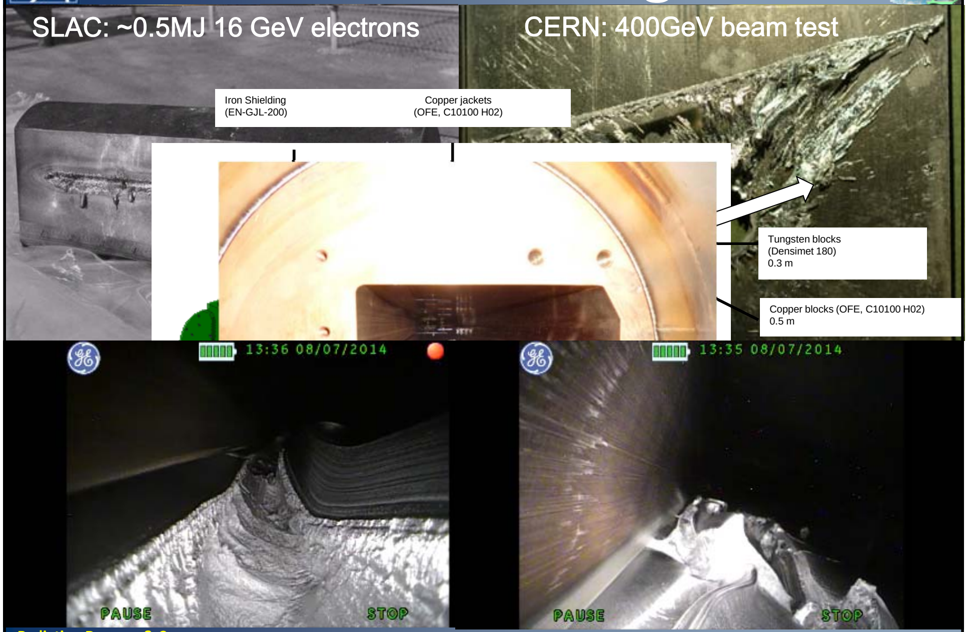


Equipment Failure Example

Vacuum system PLC (LHC_UJ76)

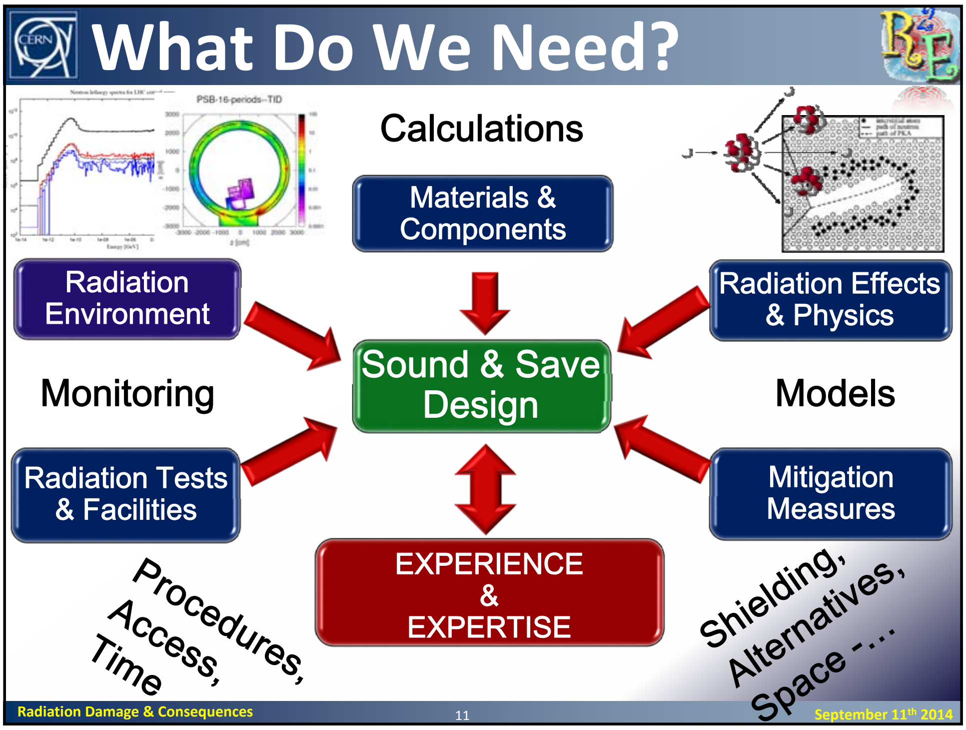
P. Supply 24VDC 5A

Beam Induced Damage



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



Radiation & Quantities of Concern

Material Damage

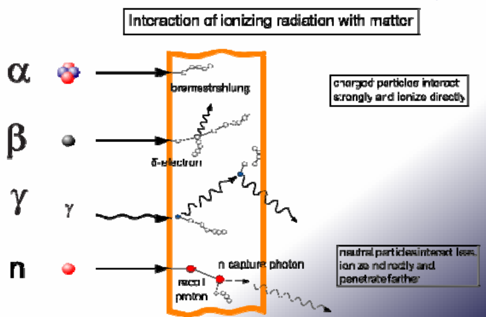
There are several physical mechanisms which can result in damage to the target material. They are related to:

- **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

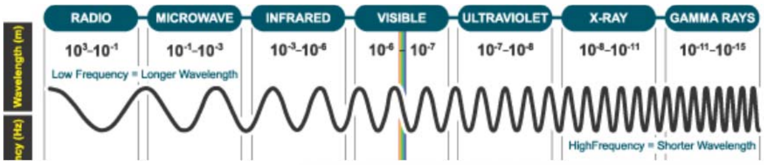
Indirectly ionizing radiation:

- **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

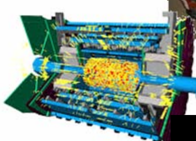
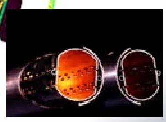
One Example – Gamma Radiation (Photos) :

- 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**
- Terminology note:
  - 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 deposited per 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

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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

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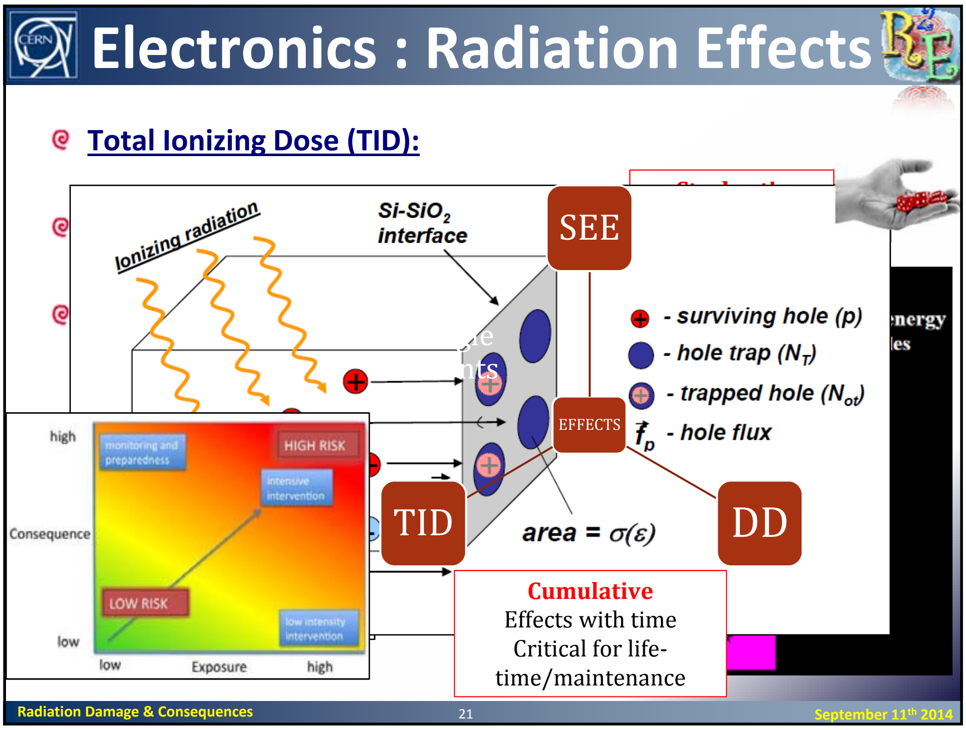
Electronics : Radiation Effects
Total Ionizing Dose (TID):
Ionizing radiation
Si-SiO$_2$ interface
SEE
- surviving hole (p)
- hole trap (N_T)
- trapped hole (N_{ot})
$\vec{f}_p$ - hole flux
EFFECTS
TID
DD
area = $\sigma(\varepsilon)$
high
Consequence
low
low
Exposure
high
monitoring and preparedness
HIGH RISK
intensive intervention
LOW RISK
low intensity intervention
Cumulative
Effects with time
Critical for life-time/maintenance
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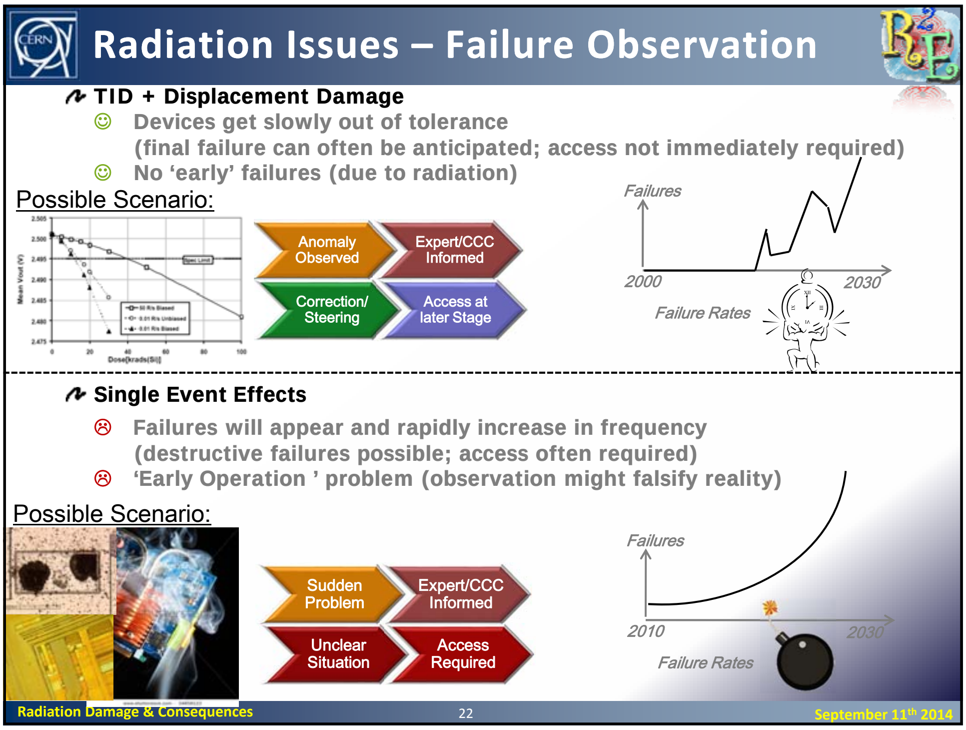
Radiation Issues – Failure Observation
TID + Displacement Damage
Devices get slowly out of tolerance
(final failure can often be anticipated; access not immediately required)
No 'early' failures (due to radiation)
Possible Scenario:
Anomaly Observed
Expert/CCC Informed
Correction/ Steering
Access at later Stage
Failures
2000
2030
Failure Rates
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:
Sudden Problem
Expert/CCC Informed
Unclear Situation
Access Required
Failures
2010
2030
Failure Rates
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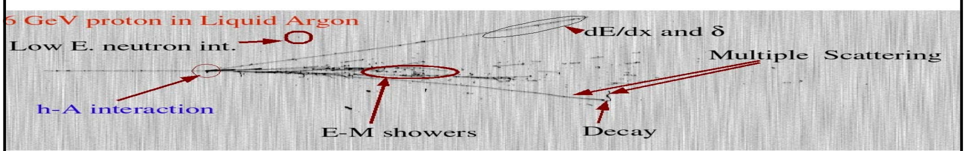
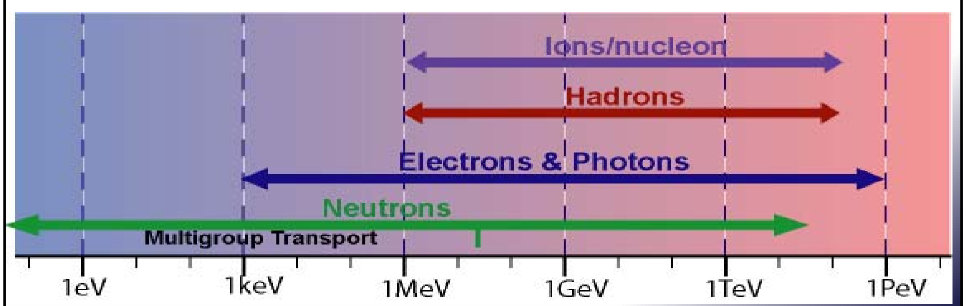
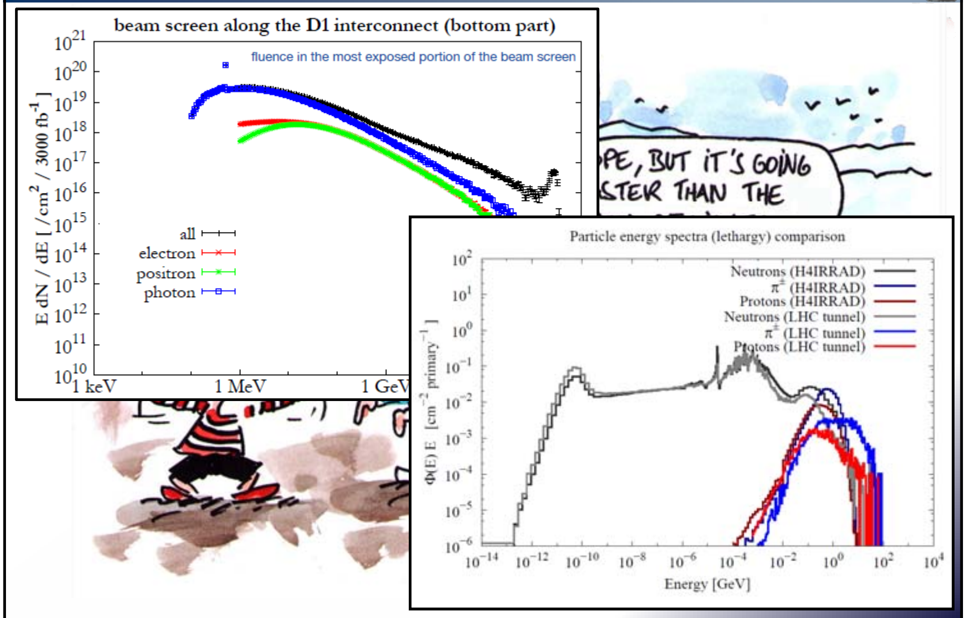
Radiation Environment

High-Energy Particle Interactions





Radiation Environment



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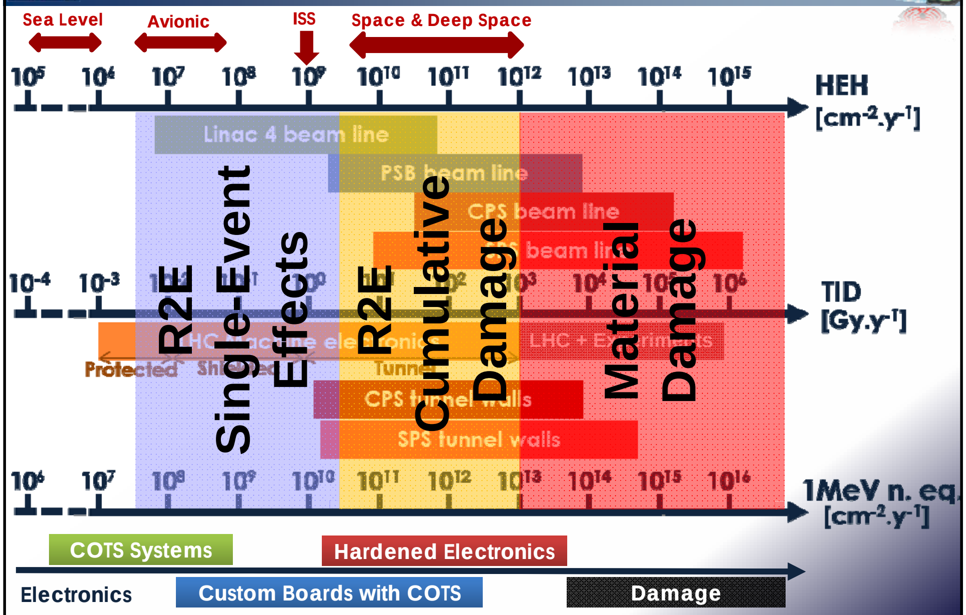
CERN Radiation Levels



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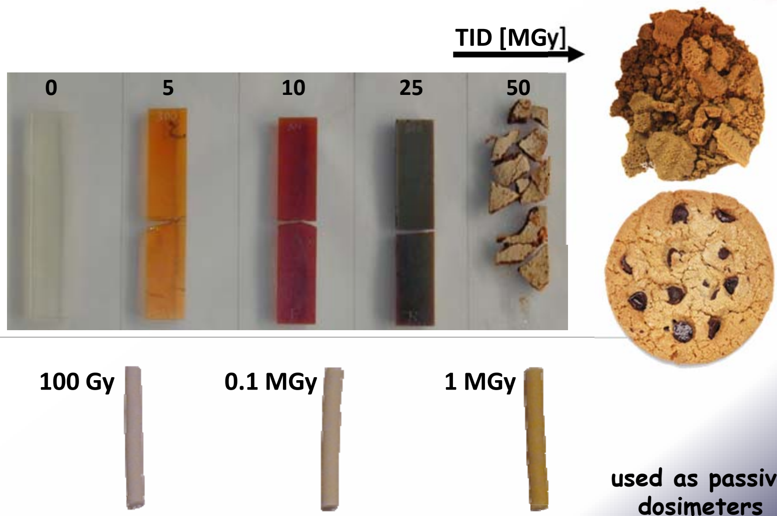
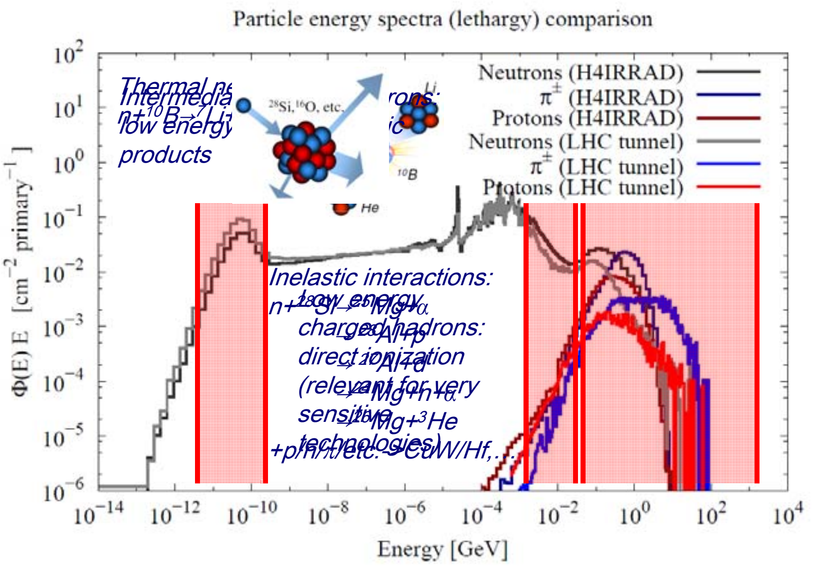
Beyond: Material Damage



used as passive dosimeters

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

Electronics: Energy Areas of Interest

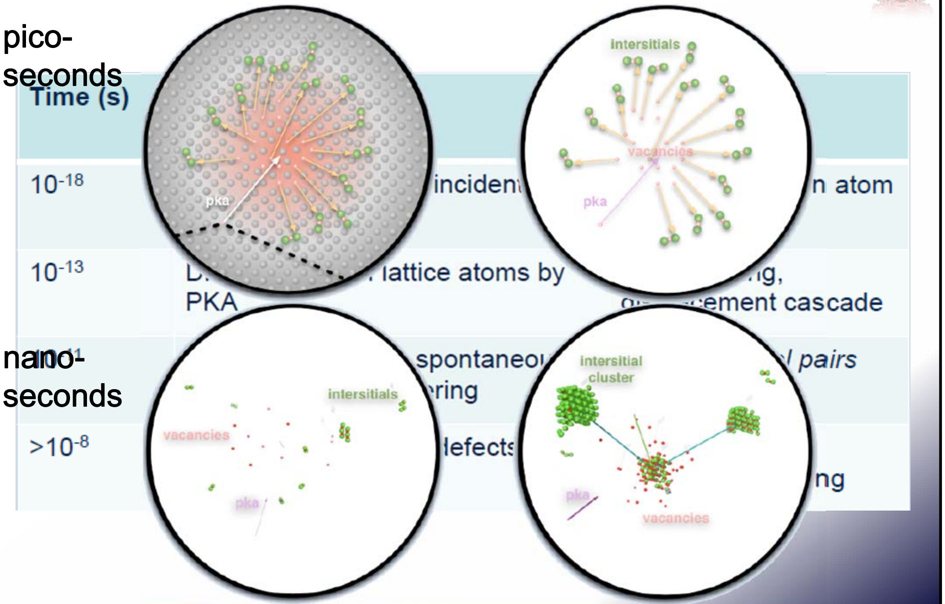


Damage & Consequences

What happens

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

Displacement Damage



Mechanical Parameters

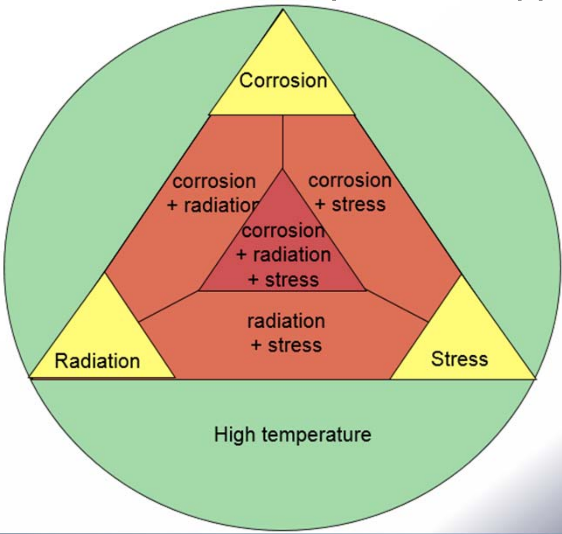
- Strong
- Ductile
- High thermal conductivity
- Stable
- Safe

- 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

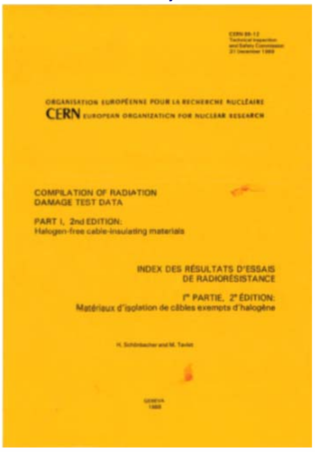
Effect of radiation:

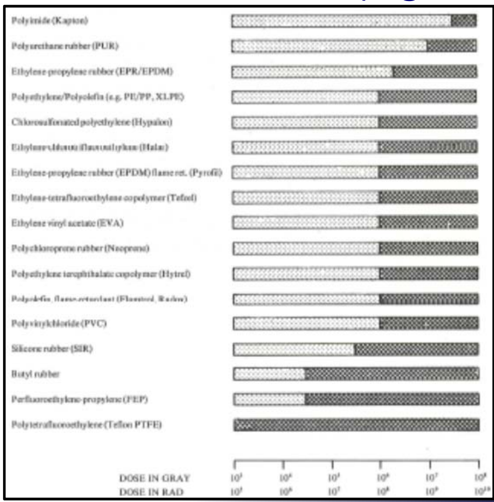
- **Degradation of mechanic**
  first (e.g. reduced elongat
- **Degradation of electrical**

Material Examples

Plastics

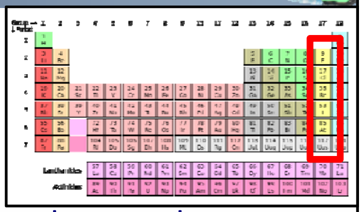
- useful information in CERN's Yellow books (e.g. CERN 82-10, or 89-12)





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!!!**

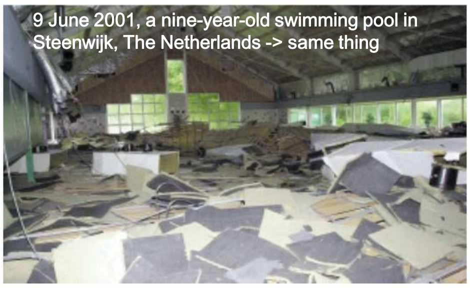
What's also needed: -> Moisture

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

Material Examples

Two "Famous" Examples

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



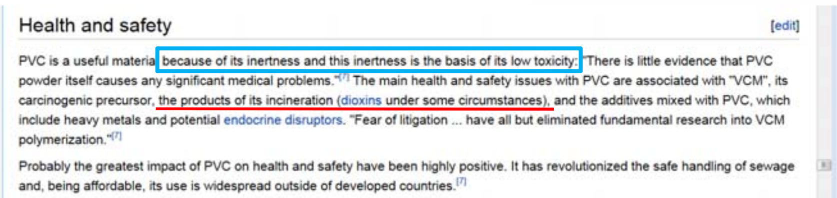
9 June 2001, a nine-year-old swimming pool in Steenwijk, The Netherlands -> same thing

- **& 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

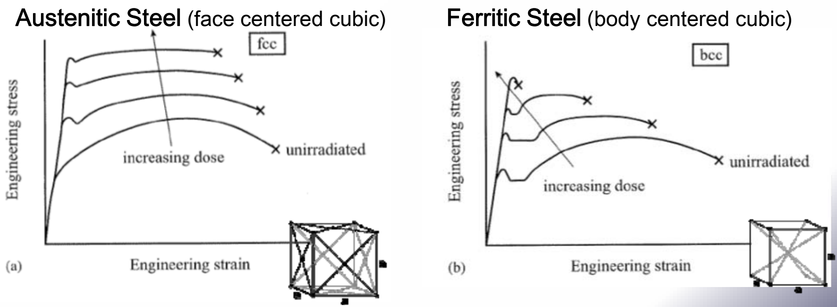
Metals (studies driven by reactor applications)

- 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.



- 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

Complexity ↓ / Time →

REQUIREMENTS
Electrical/system
Radiation environment and effects
Timeline

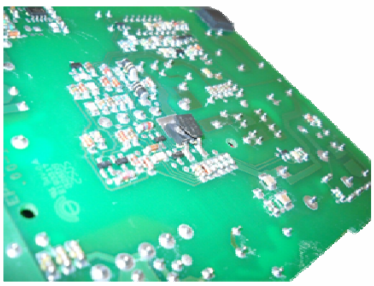
DESIGN
Specifications
Selection
Design

TEST
System
Component
Qualification

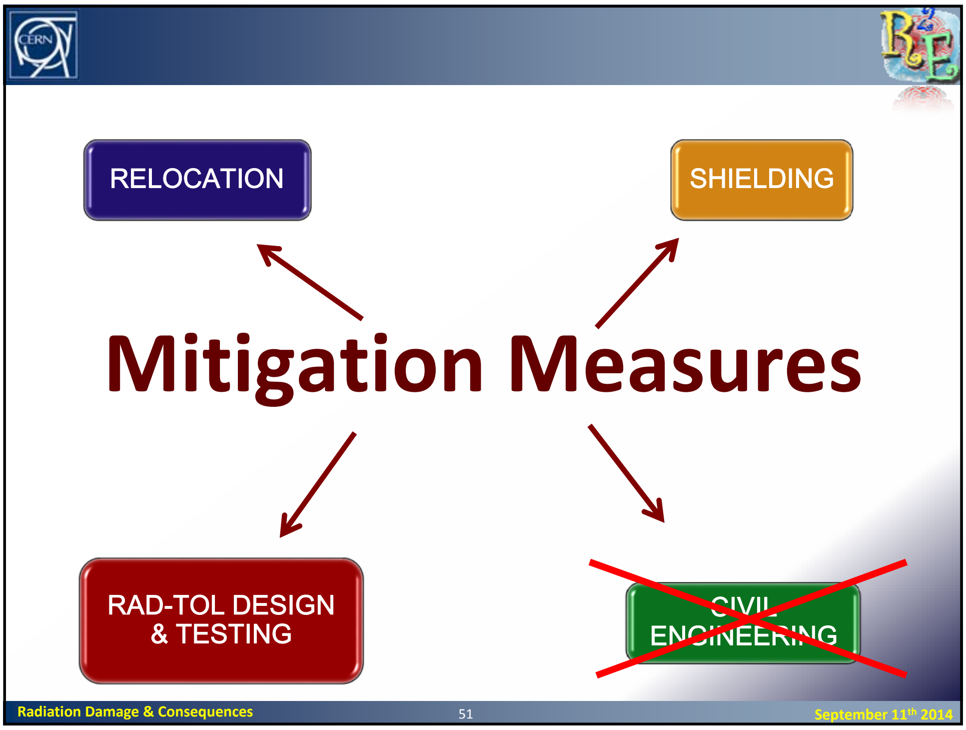
PROCUREMENT
Test boards
Prototype
Production

Equipment Failure Example

SEE: Power-Converter (LHC_RR)



⇒ Premature Beam Dump
& LHC Downtime


RELOCATION
SHIELDING
Mitigation Measures
RAD-TOL DESIGN & TESTING
CIVIL ENGINEERING
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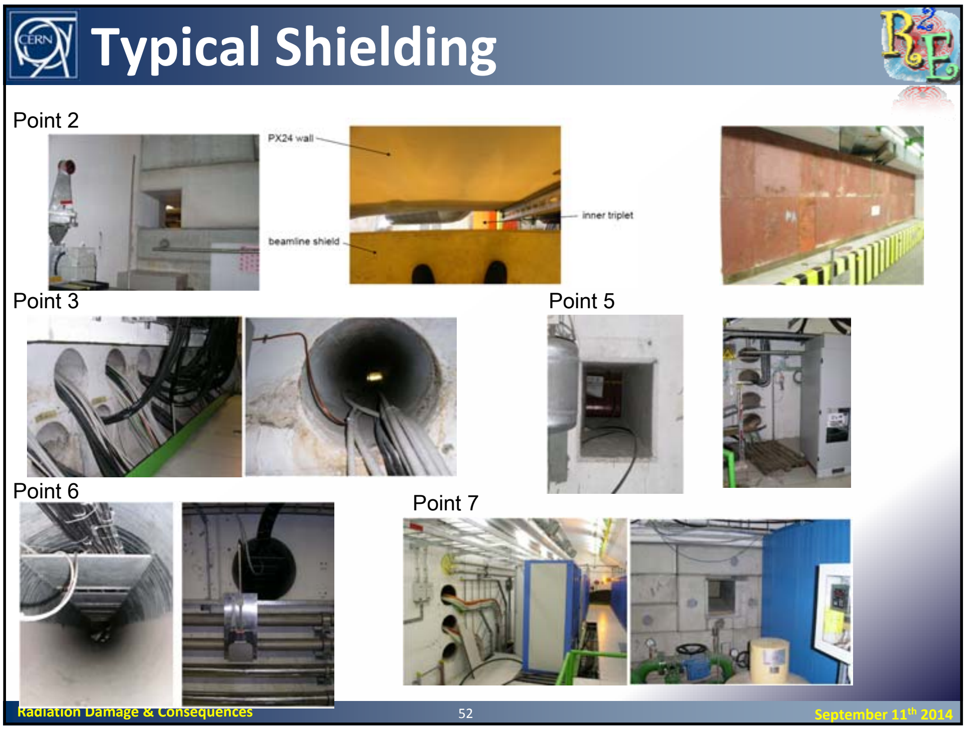
Typical Shielding
Point 2
PX24 wall
inner triplet
beamline shield
Point 3
Point 5
Point 6
Point 7
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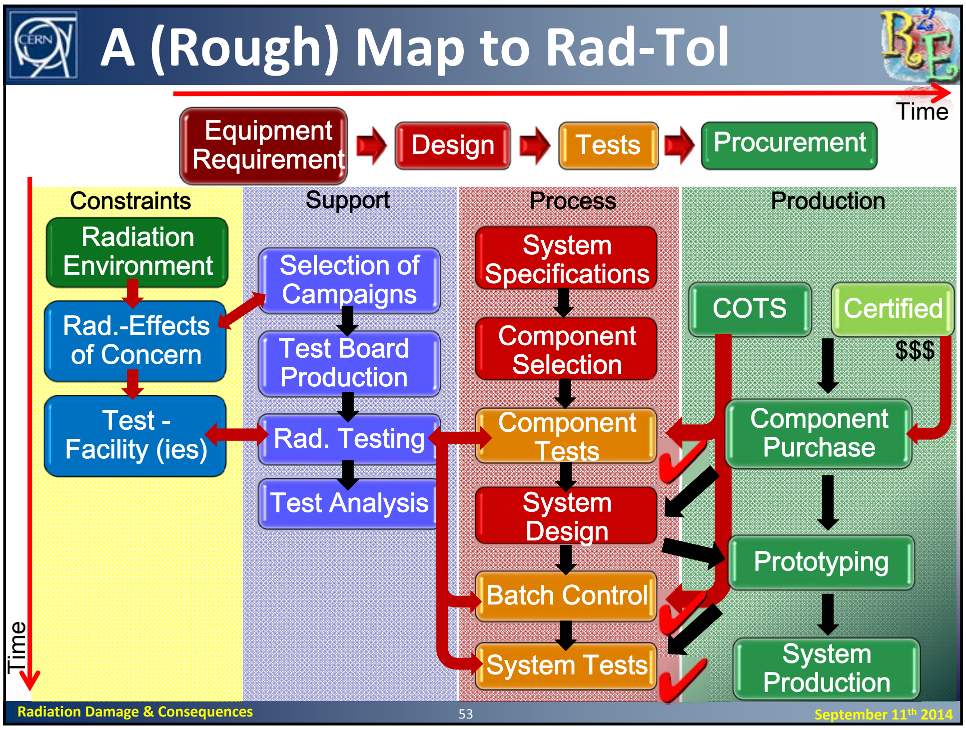
A (Rough) Map to Rad-Tol
Time
Equipment Requirement
Design
Tests
Procurement
Constraints
Support
Process
Production
Radiation Environment
Rad.-Effects of Concern
Test - Facility (ies)
Selection of Campaigns
Test Board Production
Rad. Testing
Test Analysis
System Specifications
Component Selection
Component Tests
System Design
Batch Control
System Tests
COTS
Certified
$$$
Component Purchase
Prototyping
System Production
Time
Radiation Damage & Consequences
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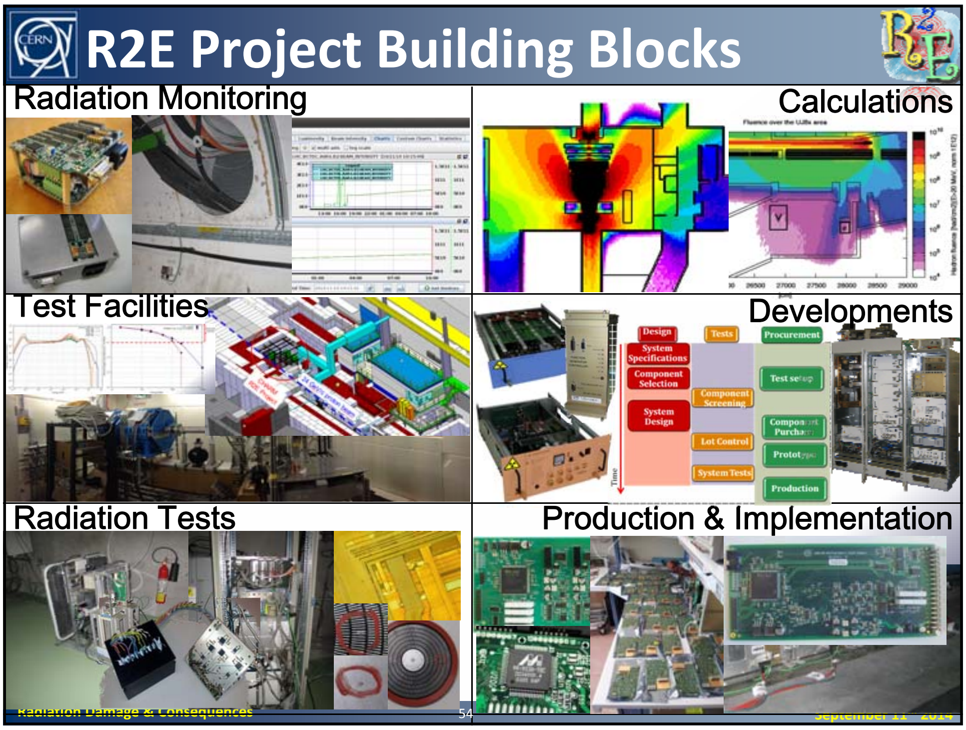
R2E Project Building Blocks
Radiation Monitoring
Calculations
Test Facilities
Developments
Radiation Tests
Production & Implementation
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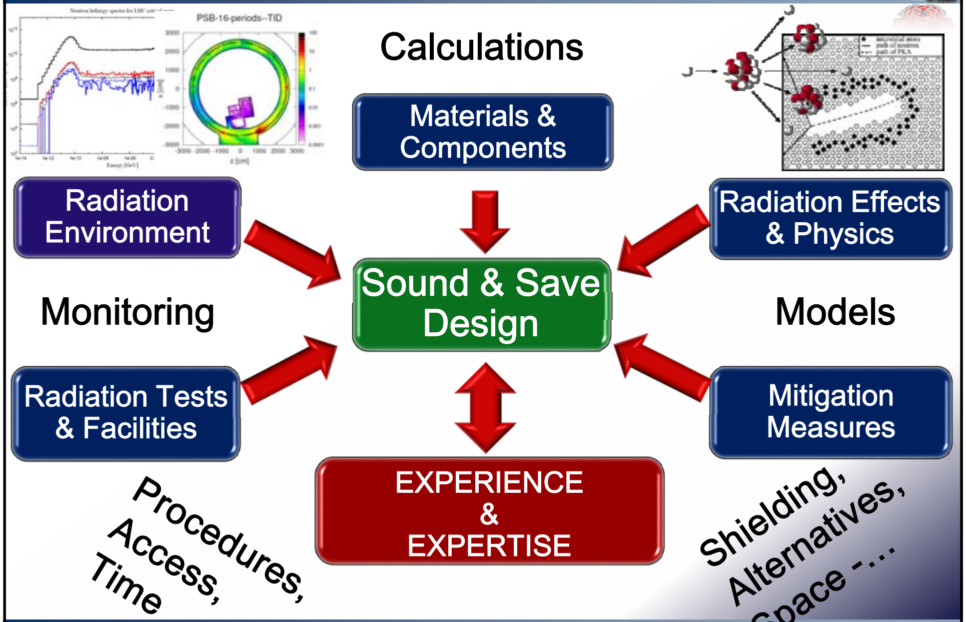
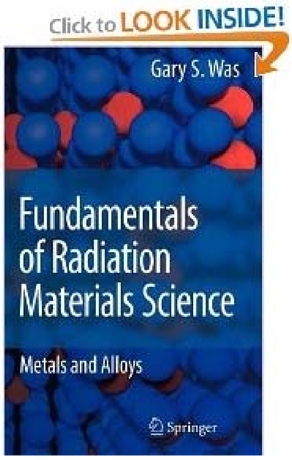
What Do We Need?



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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Gary S. Was
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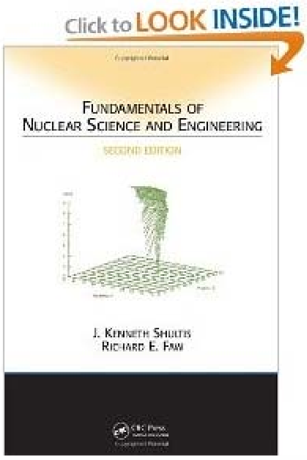
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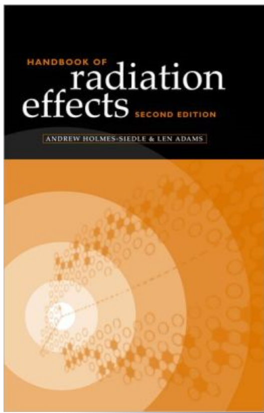
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