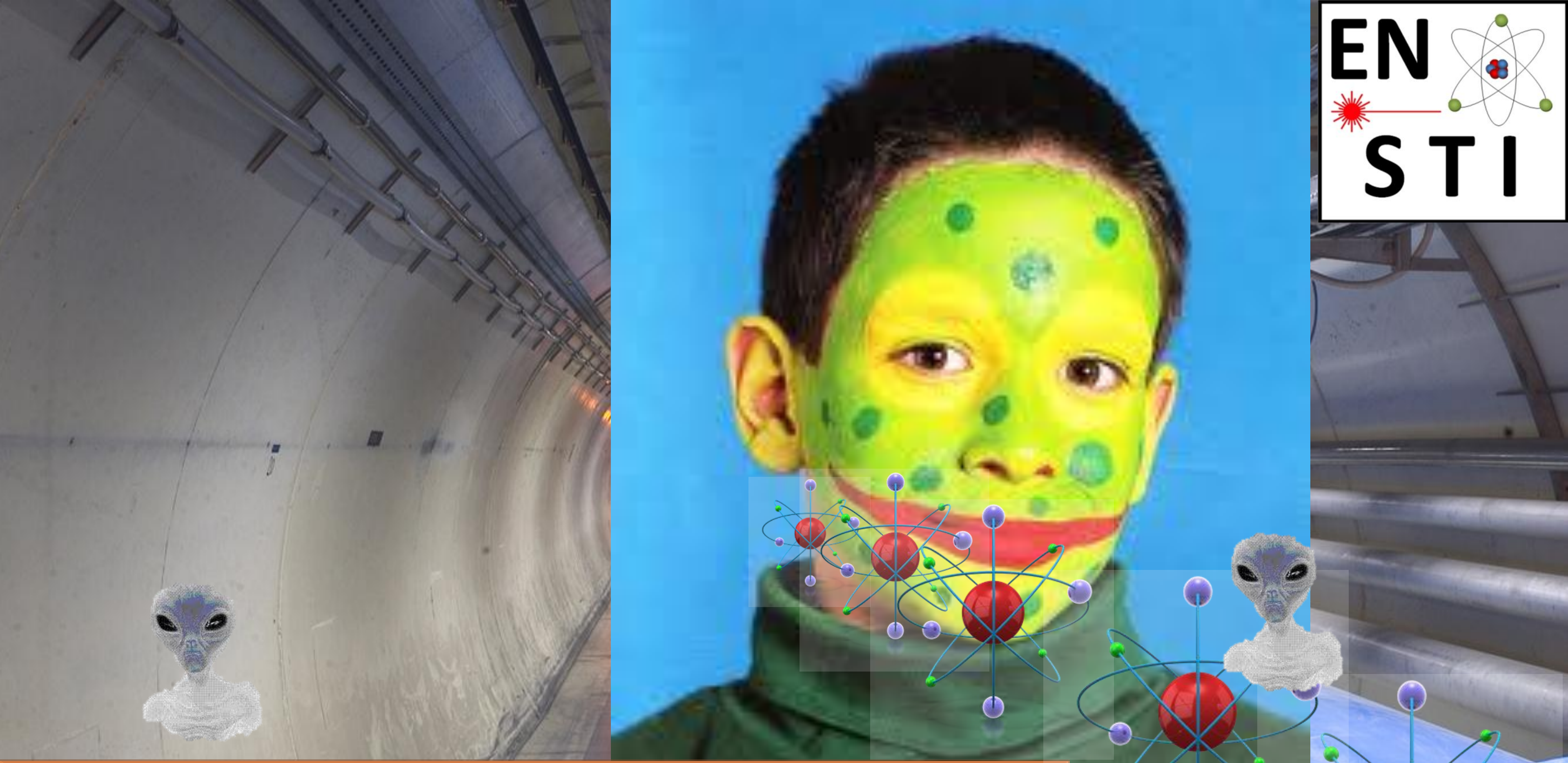
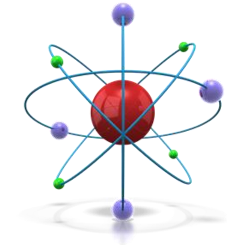


EFFECTS OF RADIATION IN ACCELERATORS

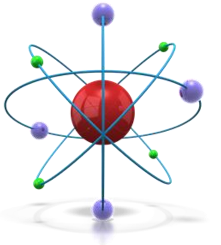
R. Losito, JUAS, 21/02/2013

Nice to meet you!



- I am an Electronic Engineer, specialized in Microwave Engineering!
- I started my career studying (and measuring) coupling impedances.
- Then, at CERN, I have been an engineer in
  - the RF group for 9 years,
  - then moved to Photoinjectors,
  - then to Controls,
- and now I lead a Group in the Engineering Department called:

Nice to meet you!



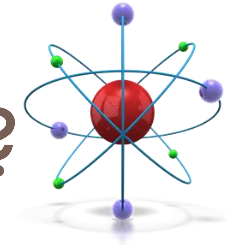
- Sources, Targets and Interactions (STI)
  - We design and operate (and dispose!!!)
  - **Sources**: Radioactive Ion sources and Photoinjectors
  - **Targets**: Collimators, Targets, Dumps (Beam Intercepting Devices)
  - **Interactions**: we study the effects of beams interacting with matter in accelerators

Acknowledgements

- I have stolen some material from different colleagues

  - P. Chiggiato (CERN)
  - A.Ferrari (CERN)
  - A. Ryazanov (Kurchatov Institute, Moscow)
  - D. Ricci (CERN)
  - D. Cano Ott (CIEMAT, Madrid)

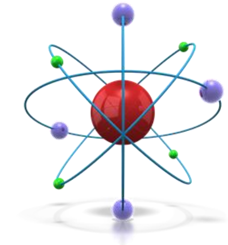
Why a seminar on Radiation effects ?



- … because accelerators generate radiation!!!
- Radiation influences (more and more!!!) the way we conceive our installations, accelerator components, the length and occurrence of shutdowns, the size of our teams…
- … because we have ethical and legal obligations towards our staff, our Host States, and towards society in general

What is radiation?

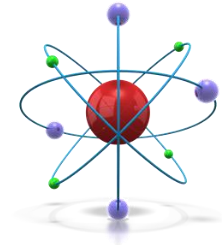
What is radiation?



- Radiation means “*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

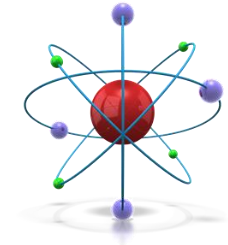
What is radiation?



- Biological effects of radiation on humans are studied by Radioprotection experts and will not be reviewed today (*you will have a lecture on March 8th*)

- I will introduce some typical problems we face everyday with radiation in the design of accelerator components

What is Radiation?

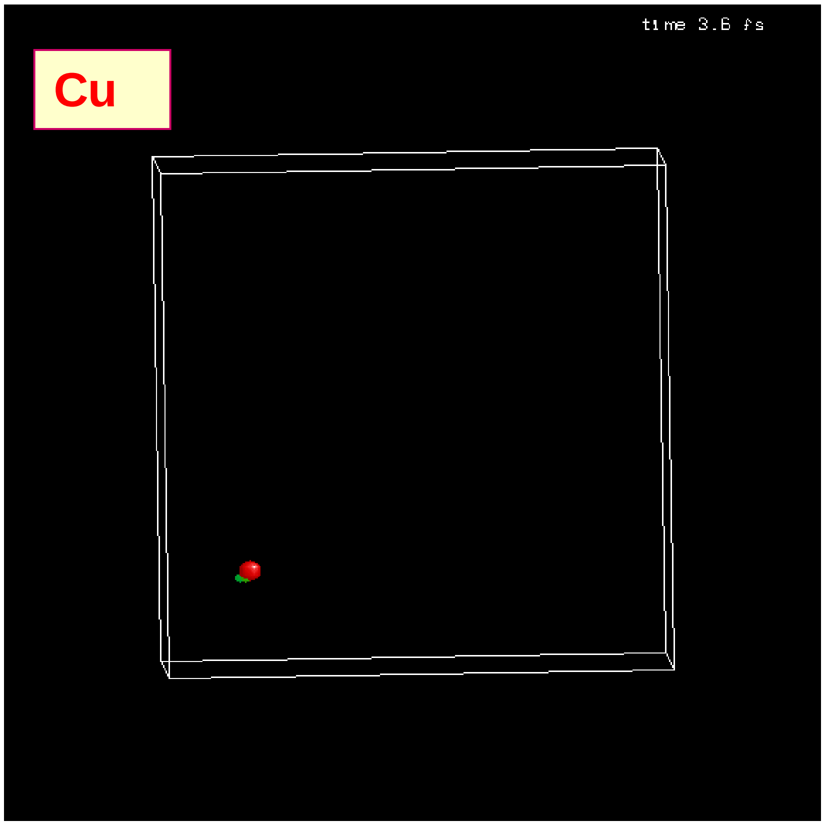


- Radiation is carried by Alpha, Beta, Gamma, neutrons, protons…
- Are the effects different?
- Yes and No, but they also depend on energy of the impacting particle, composition and purity of the target material, intensity etc…

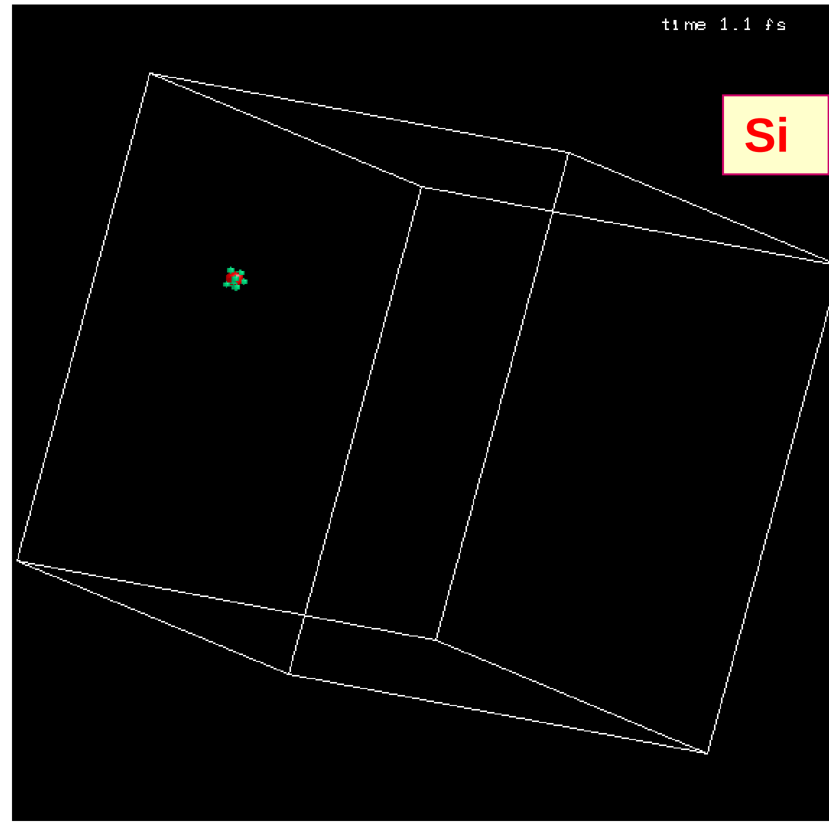
Effect is different for different materials

- Next slide from the lectures on radiation damage given at CERN by Alexander Ryazanov, from the Kurchatov Institute in Moscow

Comparison of cascade and sub-cascade formation in light and heavy materials.



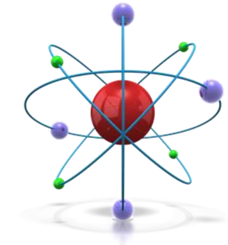
Atomic number 29



Atomic number 14

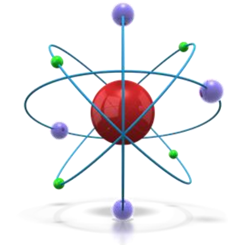
R. Losito, Effects of radiation in accelerators, JUAS 2013, Archamps

What is Radiation?



- Radiation is carried by Alpha, Beta, Gamma, neutrons, protons…
- Are the effects different?
- Yes and No, but they also depend on energy of the impacting particle, composition and purity of the target material, intensity etc…
- For our purposes, we are mainly interested at the macroscopic effects: we need a macroscopic description…

What is radiation?



Ionising Radiation

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

Non Ionising Radiation

- Microwaves and RF

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Why does radiation create damage?

Why does radiation create damage?

Ionising Radiation	Non Ionising radiation
□ Creates radicals (ions) that become chemically active □ Modifies the structure of materials by displacing atoms of the latti… □ Fragment… m… …g new …als □ …odifies the structure of the irradiated materials	□ Essentially, depos… energy in f… …t. □ For organi… …les (DN… …ak very l… …gy bonds and create Biological damage

"Accelerate Ageing of materials"

controversial

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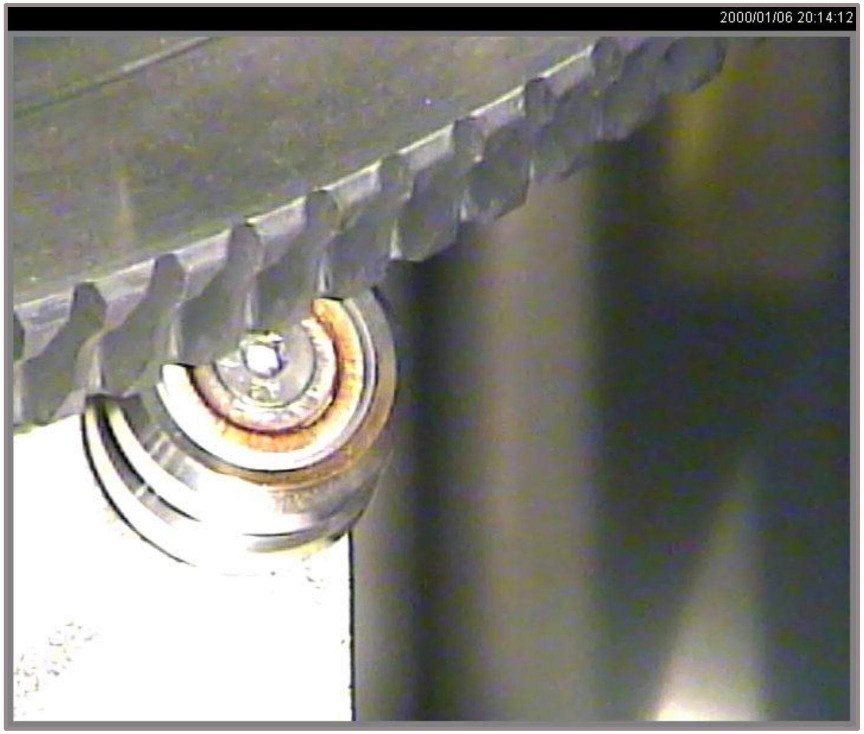
Some examples

Ionising Radiation

- Creates radicals (ions) that become chemically active

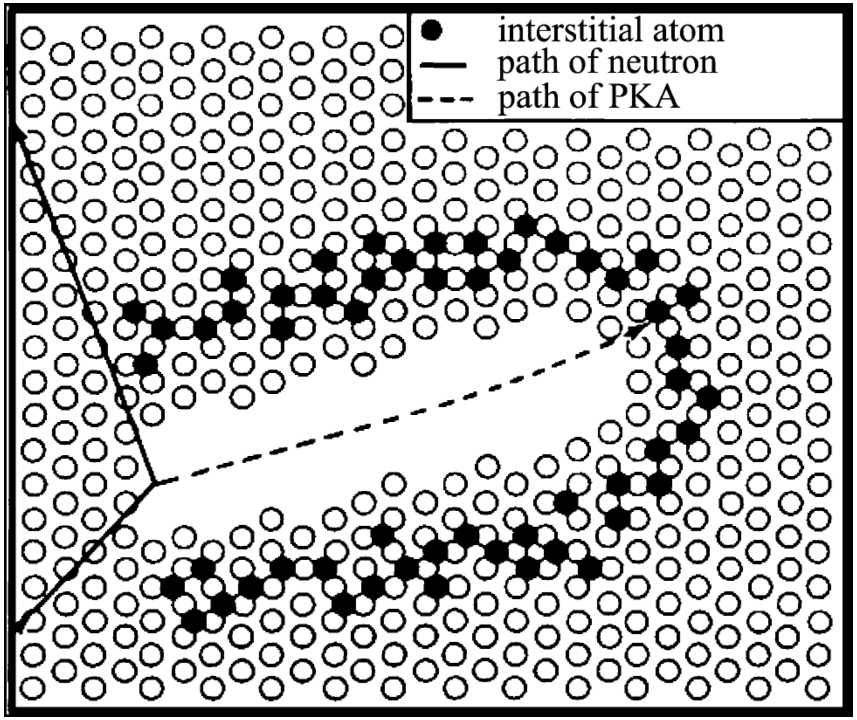
Ball bearings exposed to hadronic showers in air



Some examples (finally!!!)

Ionising Radiation	Displacement spike as drawn by Brinkman (1956)

- Creates radicals (ions) that become chemically active
- Modifies the structure of materials by displacing atoms of the lattice…



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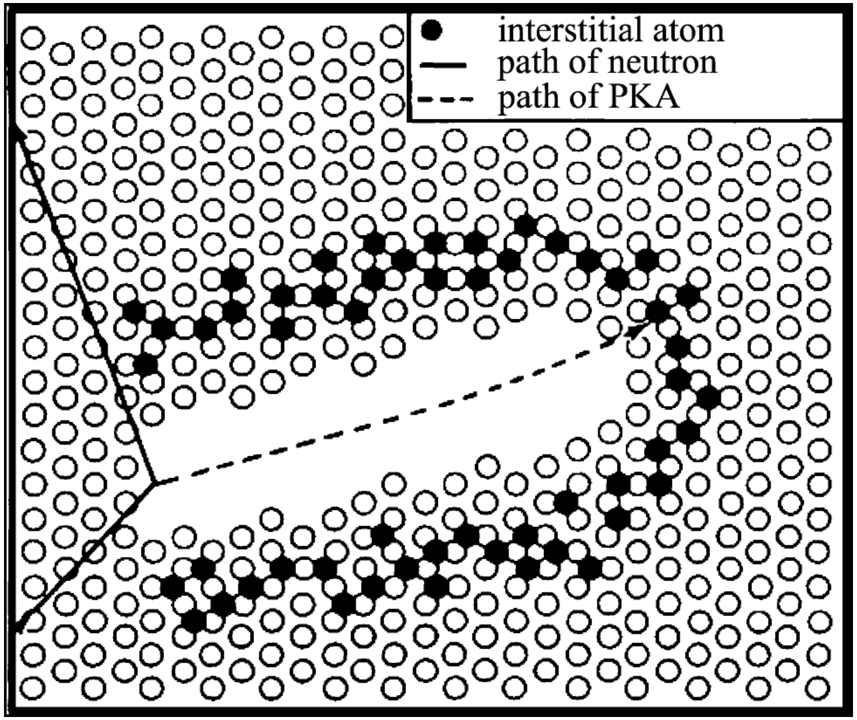
Some examples (finally!!!)

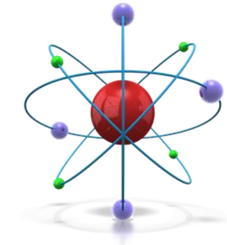
Ionising Radiation

- Creates radicals (ions) that become chemically active
- Modifies the structure of materials by displacing atoms of the lattice…
- Fragments atoms in the material creating new interstitials

Displacement spike as drawn by Brinkman (1956)



Some examples (finally!!!)



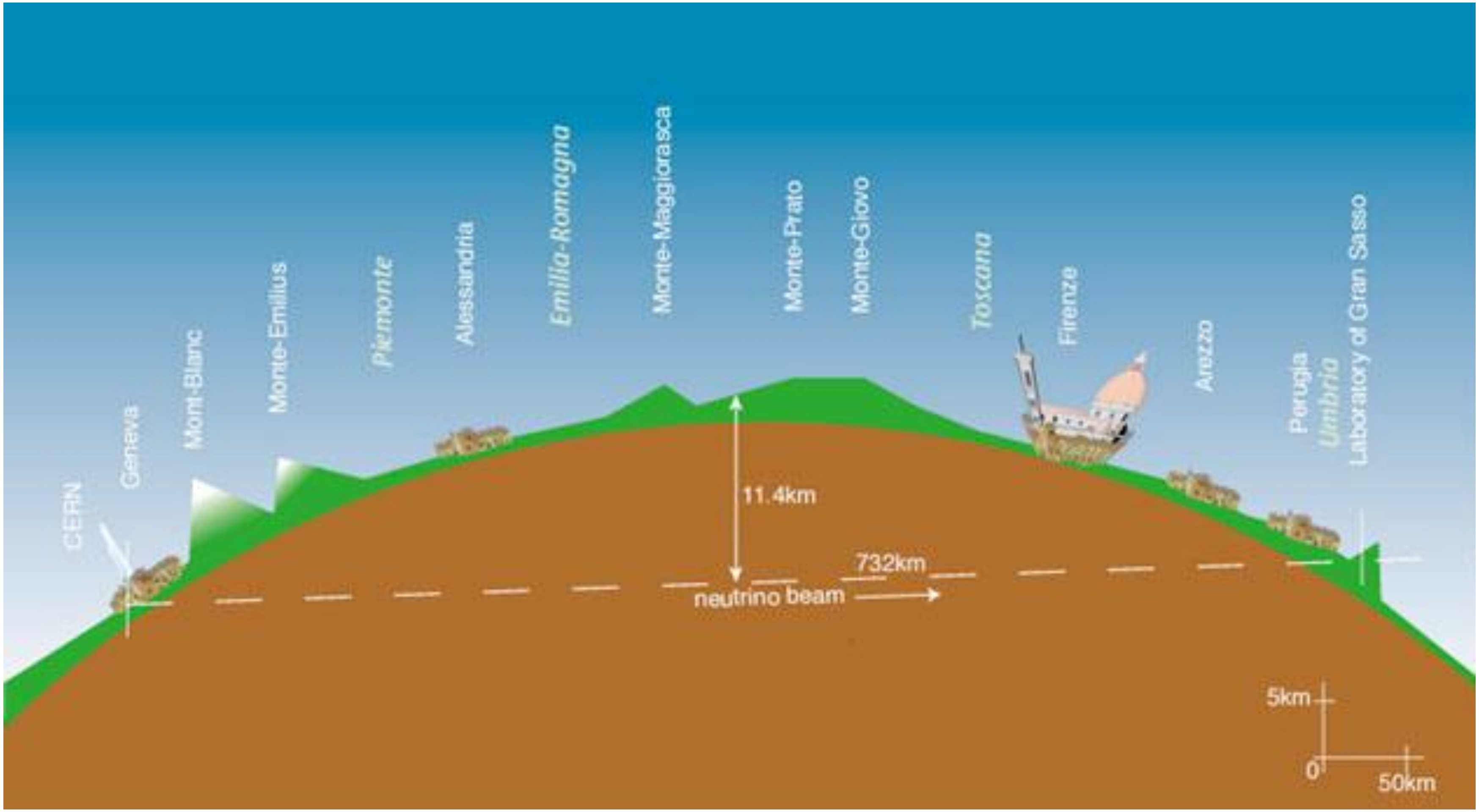
Ionising Radiation

- Creates radicals (ions) that become chemically active
- Modifies the structure of materials by displacing atoms of the lattice…
- Fragments atoms in the material creating new interstitials
- Modifies the structure of the irradiated materials

CNGS (graphite) target

- Due to transmutation, 1 atom every 20 (5%) is no more Carbon, but it is transformed into:
- 11-C -> 11-B
- 10-C -> 10-B
- 7-Be -> 7-Li
- 4-He
- 3-H

CNGS



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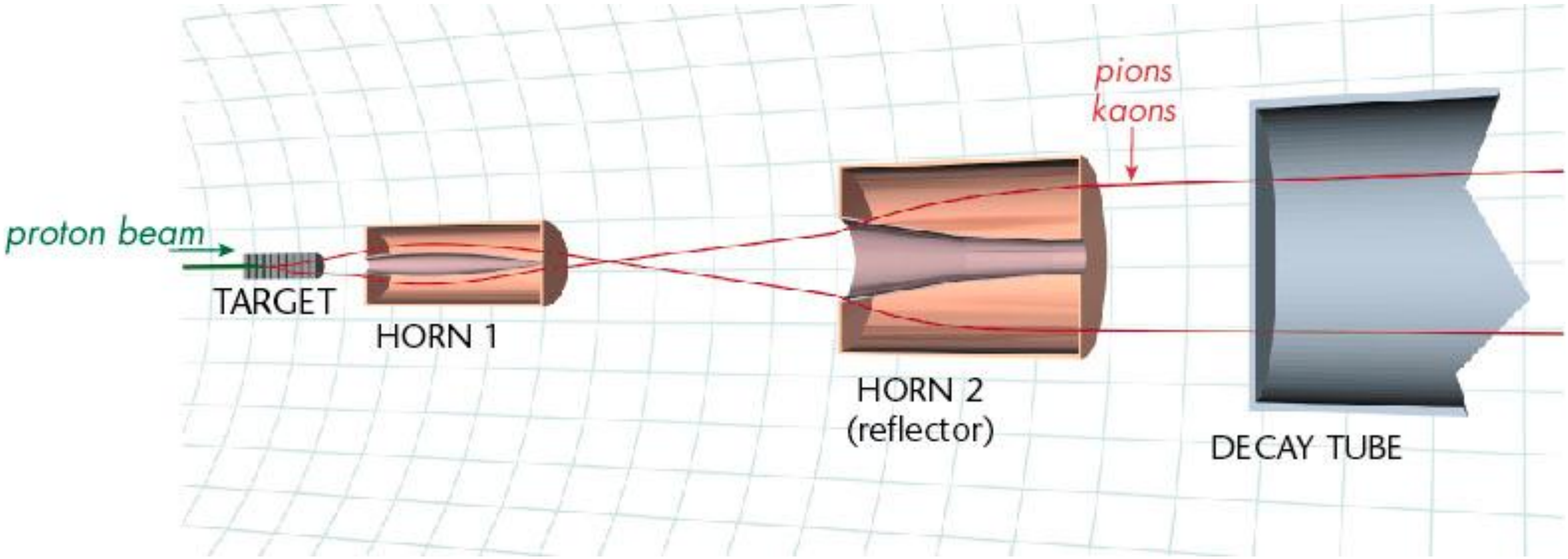
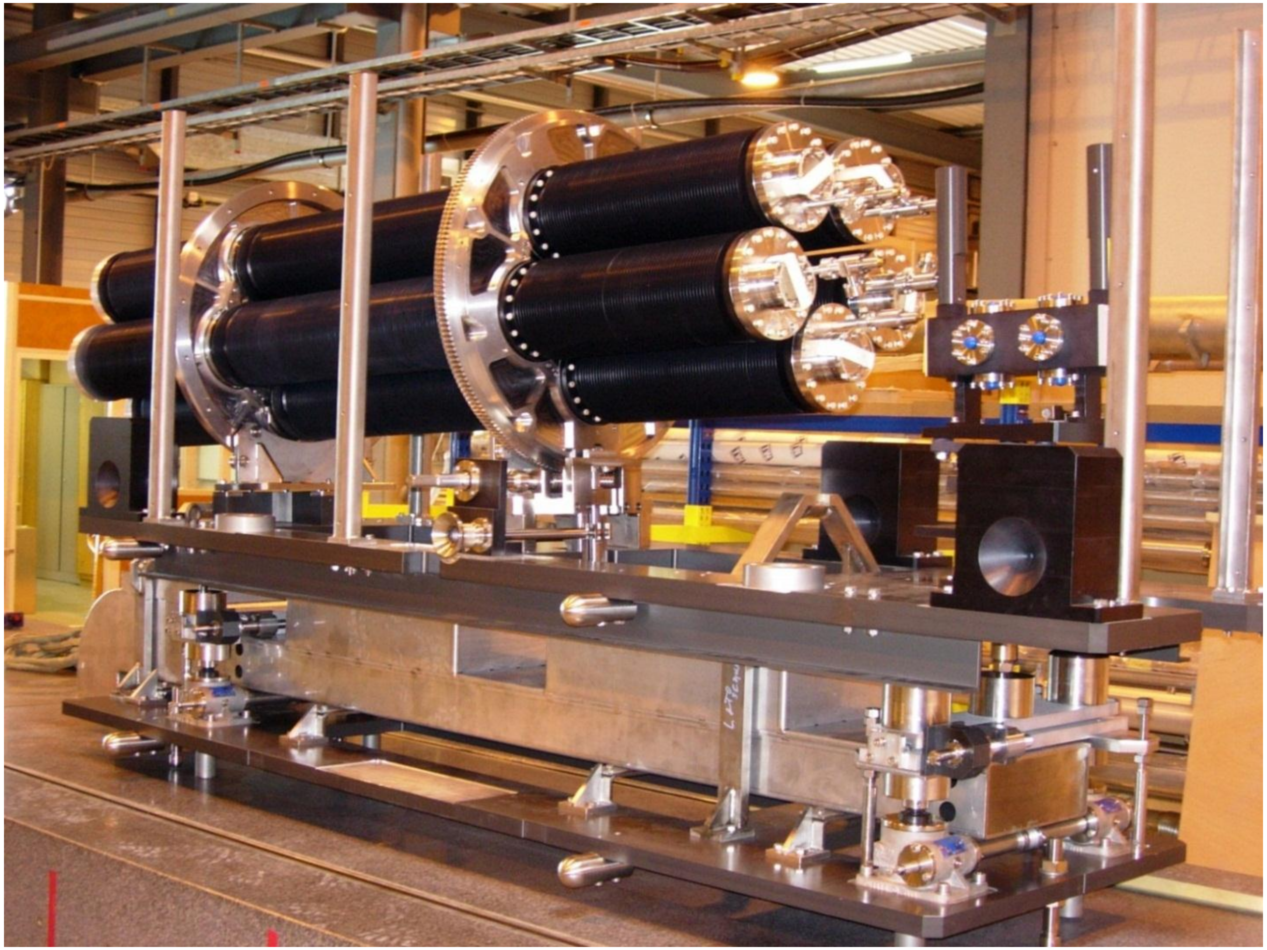
CNGS

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
CNGS Works
55m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
Decay tunnel
LEP/LHC tunnel
140m
pions
kaons
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
CNGS-OuvragesSouterrains-2001/06 CERN AC/DI/MM

CNGS secondary beam



CNGS Target



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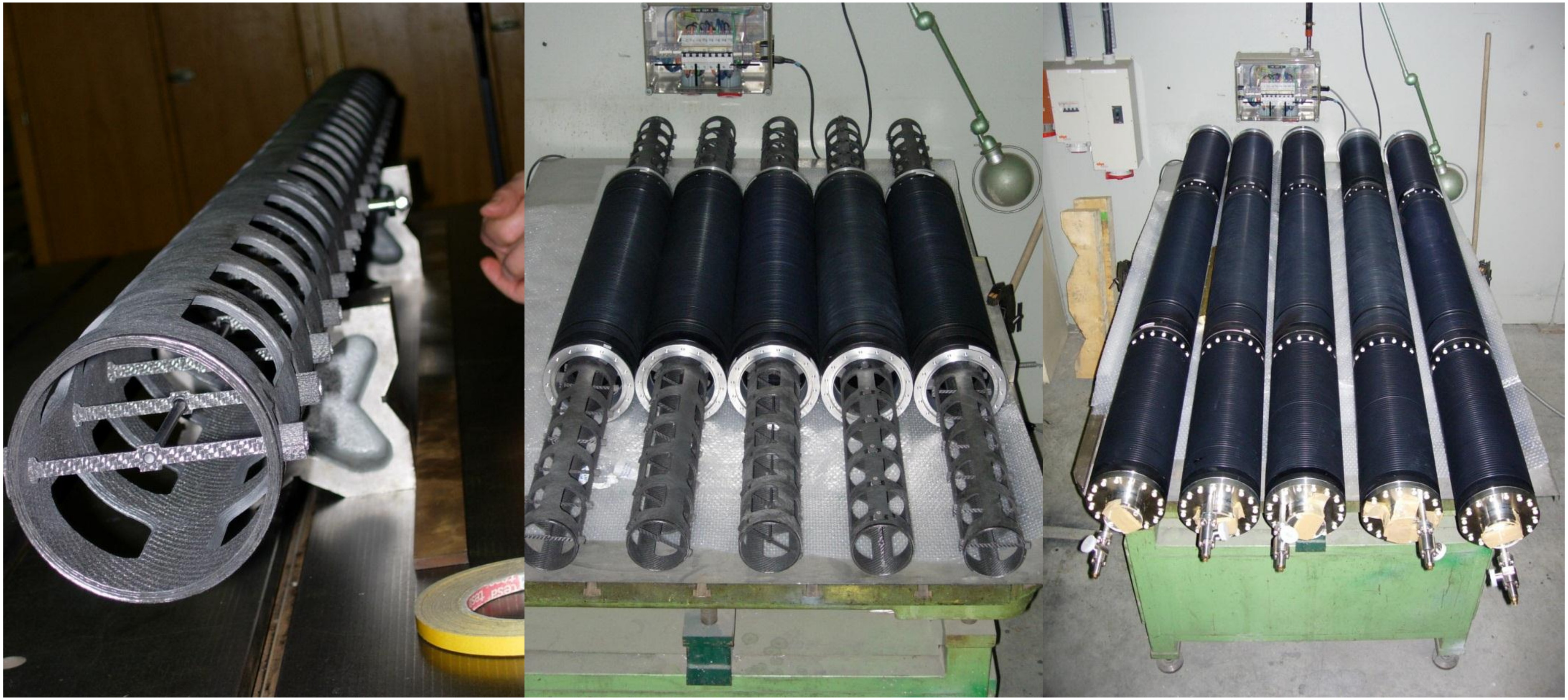
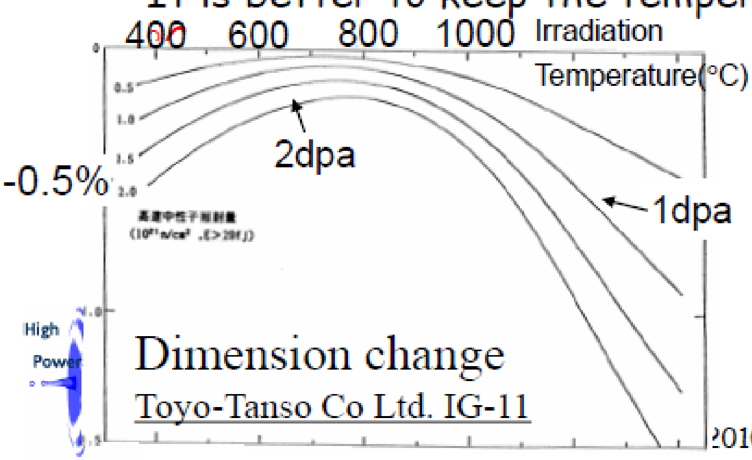
CNGS Target "Magazine"

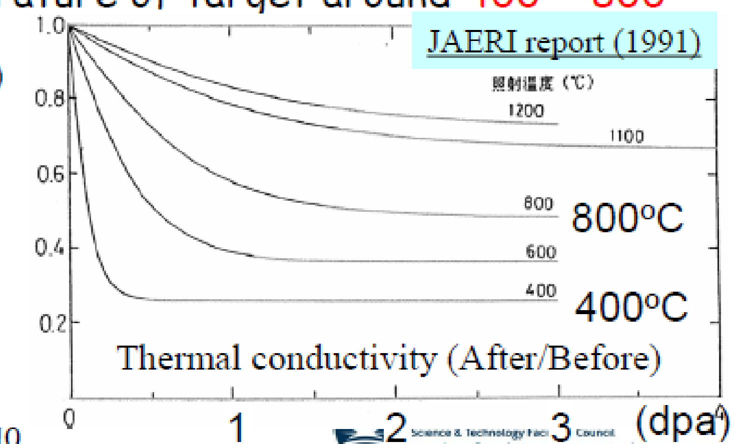


C. Densham, RAL

Irradiation effects on Graphite

- Expected radiation damage of the target
  - The approximation formula used by NuMI target group : 0.25dpa/year
  - MARS simulation : 0.15~0.20 dpa/year
- Dimension change : shrinkage by ~5mm in length in 5 years at maximum.
  ~75μm in radius
- Degradation of thermal conductivity … decreased by 97% @ 200 °C
  70~80% @ 400 °C
- Magnitude of the damage strongly depends on the irradiation temperature.
  - It is better to keep the temperature of target around 400 ~ 800

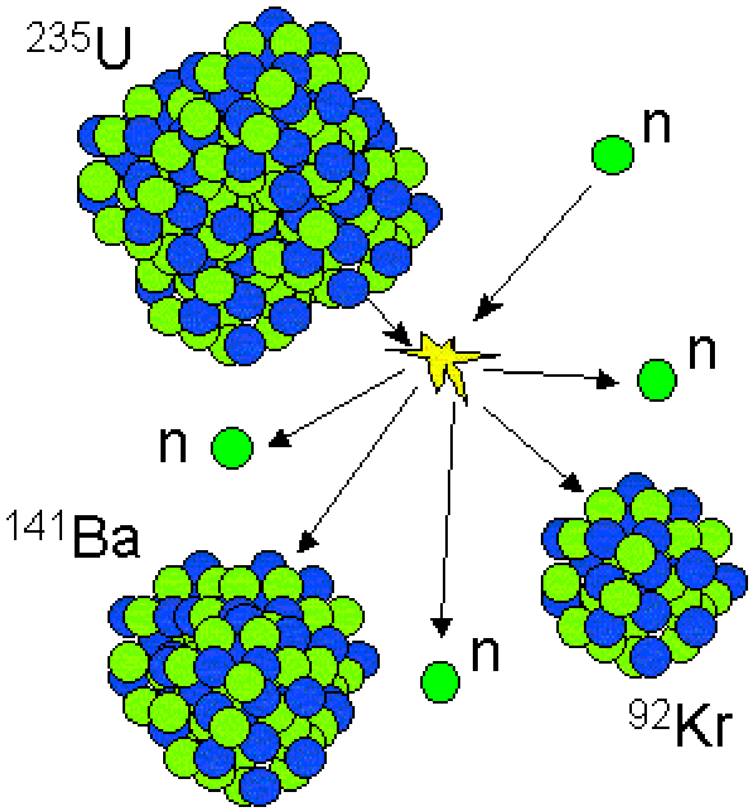




Radiation modifies materials

Ionising Radiation	http://www.astro.cornell.edu

- By breaking (un)stable atoms, ionising radiation can create new unstable atoms, that generate radiation by radioactive decay!
- 141 Ba → 141 La (18 min)
- 92 Kr → 91-92 Rb (1.8 s)



A special case: electronics!!!

- Electronics may suffer in several respects:
  - Total dose, generating slow drift of performance due to modified doping and finally unrecoverable failure
  - Deposits charge creating new electrons or vacancies and modifying the state of transistors (may even burn them!)

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Other important Radiation effect

- Gas production
  - mostly due to protons, deuterons, tritons, 3He and alphas stopping in the target material.
  - They can be beam particles ranging out in the target (low energy beams), or secondary particles produced by nuclear interactions in the target itself

Radiation as an engineering parameter for the design

Ingredients

- How to measure “radiation”
- How to measure the radiation “effect”

Measurement of radiation

- The way we measure radiation depends on the effect we want to measure:
  - Radioprotection takes into account the "sensitivity" of biological tissues to different wavelengths/energies (equivalent dose).
  - For materials, it depends on the type of radiation and on the effect to be studied (absorbed dose).
    - Macroscopic description (dose)
    - Microscopic description (single particle)

Measurement of radiation

- Referred to a given period
  (e.g. 1 year, or lifetime of an accelerator)

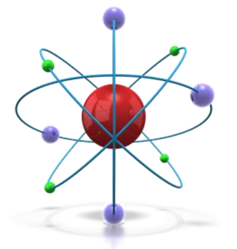
  - TID (Total Ionizing Dose): Energy deposited in a medium by ionizing radiation per unit mass (by whichever process)
    - Measured in Grays:

      1 Gray = 1 J/kg

  - For humans:
    - **Sievert**, dose weighted with response at different energies of human tissues.
    - Dose of a certain type of irradiation giving an equivalent biological effect as the same dose of gamma rays.

1 Gray (gamma) = 1 Sv
1 Gray (alphas) = 20 Sv

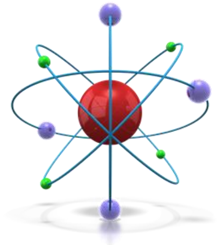
Measurement of radiation



- Referred to a given period
  (e.g. 1 year, or lifetime of an accelerator)

  - Fluence (or flux)
    - Nb of particles /cm^2 (/sec)
    - Used for Single Event Effects
    - Used also for displacement damage to materials for targets, nuclear plants…

Measurement of radiation



- Referred to a single particle
  - Ionising Energy loss:
    - energy lost by a particle in ionising atoms of the material
    - mainly due to electronic stopping power
    - Not for neutrons!!!
  - NIEL: Non Ionising Energy Loss
    - Rate of energy loss due to atomic displacements as a particle traverses a material (nuclear stopping power).

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Measurement of radiation

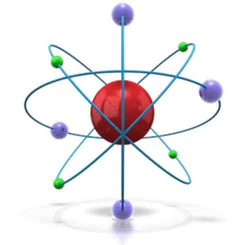
- ...NIEL x Fluence = total energy deposed in the material by displacement.
- ...IEL x Fluence = total energy deposed in the material by ionisation.

Measurement of radiation effect

- DPA: Displacement Per Atom
  - Number of times that every atom in the lattice has moved from its original position in the lattice
  - Cannot be measured!!!! Mainly a concept to anticipate failure of materials.

Some examples

Plastic



- Used in cable insulations, as structural material, for plugs, lamps, electrical cubicles…
- Plastics are organic materials!!!
  - They are derived from petrochemicals or from natural materials (resins, rubber…)
  - Contain Carbon
- Sometimes used as structural elements…

Plastic

- Effect of radiation:
  - Degradation of mechanical properties appears first (e.g. reduced elongation at break)
  - Degradation of electrical properties

Plastic

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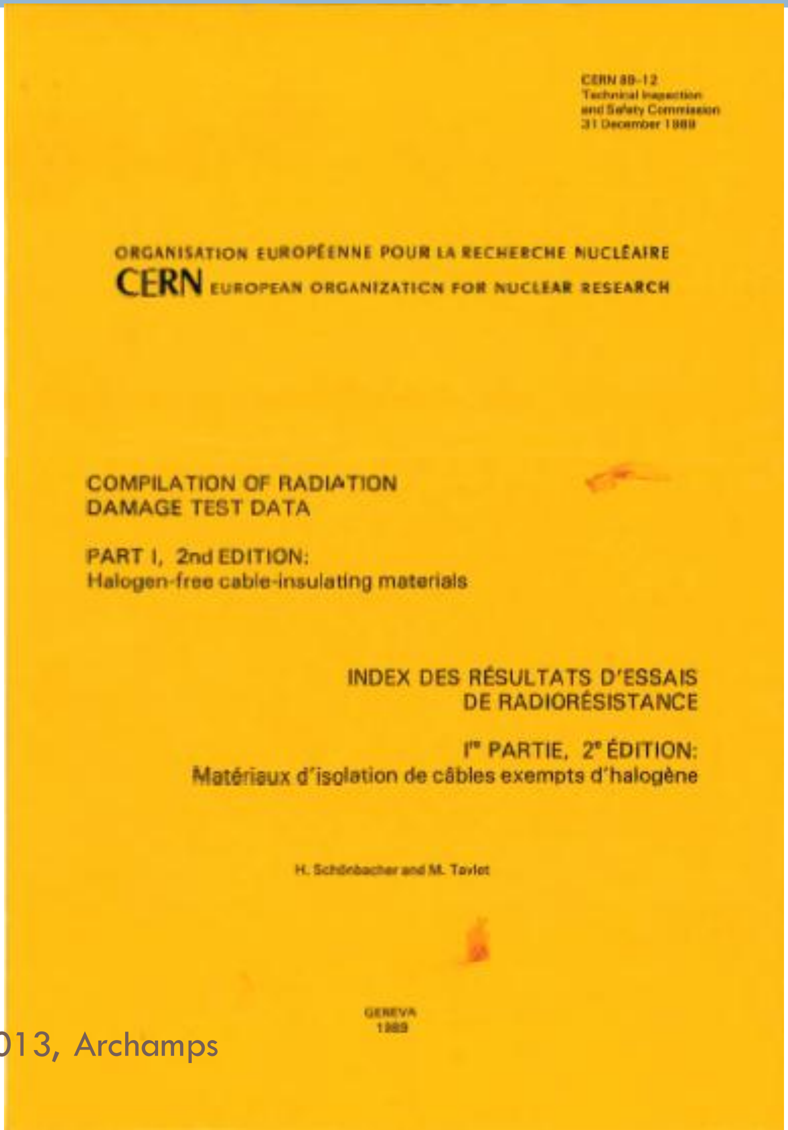
Plastic

- Can find useful information in CERN's Yellow books (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

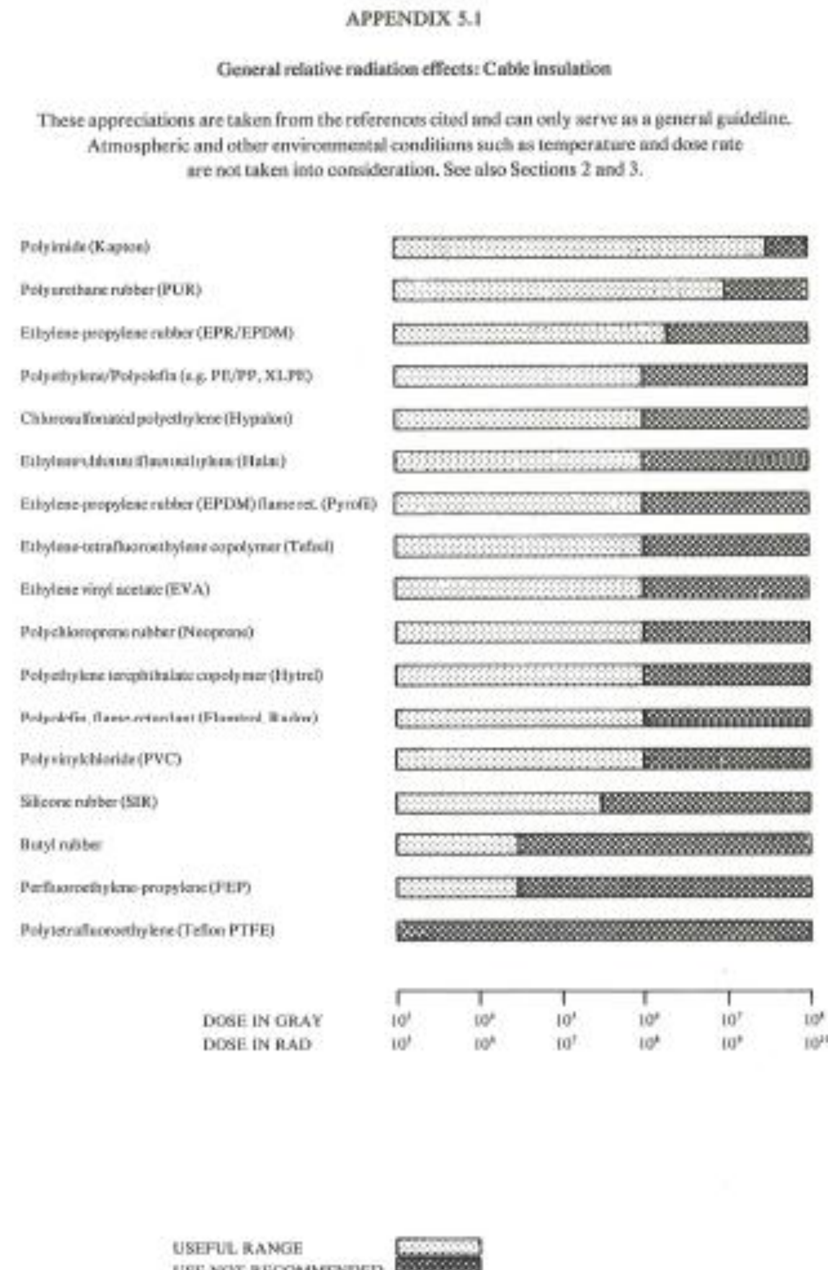
I^re PARTIE, 2^e ÉDITION:
Matériaux d'isolation de câbles exempts d'halogène

H. Schönbacher and M. Tavlet

GENEVA
1989

Plastic

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

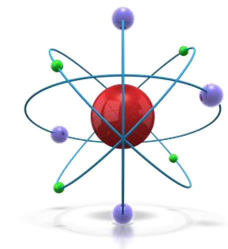


Halogens

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

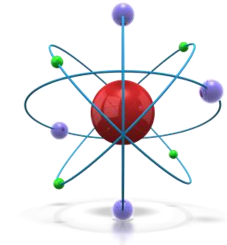
Halogens



- From Greek "halos genos", salt generators
- Most electronegative elements in the periodic table: easily gain an electron and become chemically active
- For this reason, in sufficient quantities they can be extremely dangerous
- Cl most common on earth

- Becomes aggressive and attacks metallic surfaces (and F even glass!!!)

Halogens, a special case: PVC



- From Wikipedia.org:

WIKIPEDIA
The Free Encyclopedia

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Polyvinyl chloride

From Wikipedia, the free encyclopedia

"PVC" redirects here. For other uses, see PVC (disambiguation).

Polyvinyl chloride, commonly abbreviated **PVC**, is the third most widely produced plastic, after polyethylene and polypropylene.[2] PVC is widely used in construction because it is durable, cheap, and easily worked. PVC production is expected to exceed 40 million tonnes by 2016.[3][4]

Because of its chemical resistance

Halogens, a special case: PVC

- From Wikipedia.org:

Health and safety

[edit]

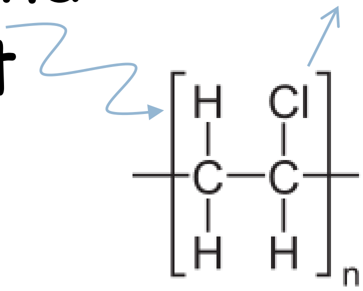
PVC is a useful material because of its inertness and this inertness is the basis of its low toxicity: "There is little evidence that PVC powder itself causes any significant medical problems."[7] The main health and safety issues with PVC are associated with "VCM", its carcinogenic precursor, the products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

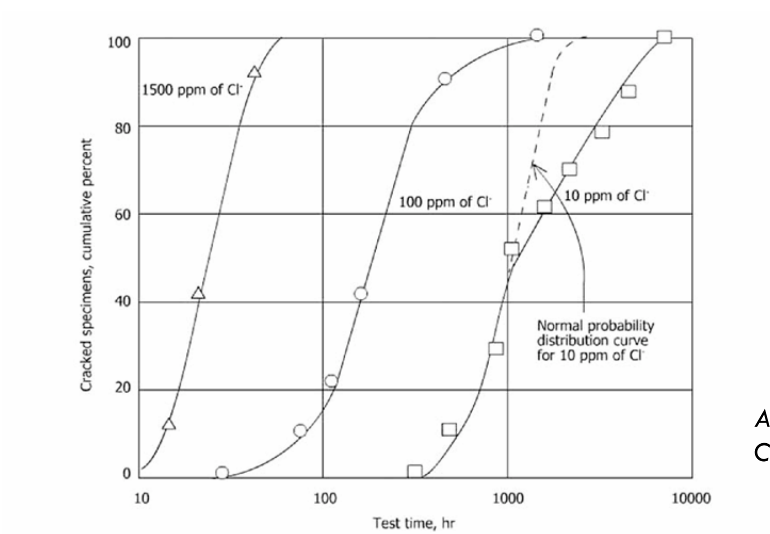
Probably the greatest impact of PVC on health and safety have been highly positive. It has revolutionized the safe handling of sewage and, being affordable, its use is widespread outside of developed countries.[7]

- For this reason no PVC and Halogens are allowed in confined space, tunnels etc…

Halogens, a special case: PVC

- **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





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

Halogens

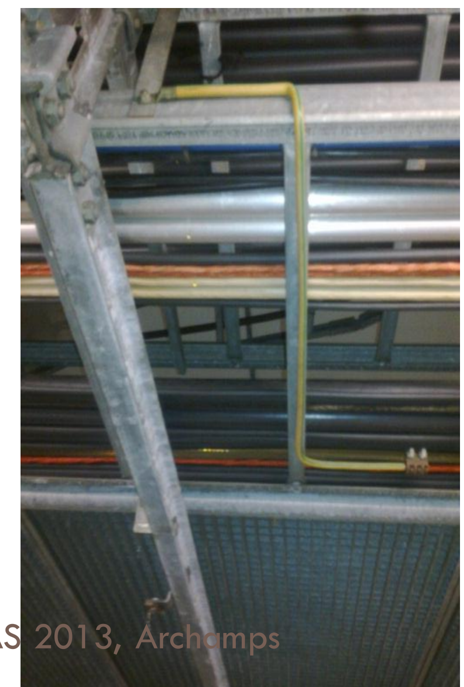
- Don't drink water in a swimming pool before interventions in radiation areas!!!!

Halogens

- How can it happen? … ***Moisture***
  - Leaking magnet cooling circuits
  - Leaking water valves
  - Infiltration from the tunnel ceiling

Halogens

- Condensed **water droplets charged with Cl^- ions** can fall onto accelerator components, in particular welds and bellows (mechanically stressed areas) generating **stress corrosion cracking** in unprotected stainless steel components…



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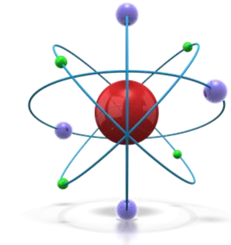
Halogens

- Few droplets, maybe a single one, are enough to generate corrosion and failure
- Once corrosion is there it cannot be passivated anymore!!!

Plastic

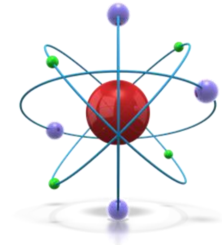


- Conclusions:
  - Plastic suffer from radiation, several compendia have been published by CERN wrt degradation of mechanical and electrical properties
  - Never use PVC, and avoid Chlorine based products (widely used in lubricants and cleaning products!!!)

Metals

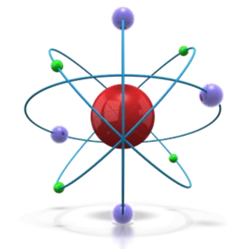
- A huge amount of studies are available for metals, for their use in reactors.
- Mechanical (macroscopic effects), are ultimately caused by formation of defects in the lattice structure
- Defects are : voids, gas bubbles, dislocations…
- Temperature has an effect. Annealing increases the mobility of defects, this has sometimes a positive impact by reconstructing the lattice, sometimes accelerates defects (especially if the material is subject to high stresses).

Metals: **hardening and embrittlement**

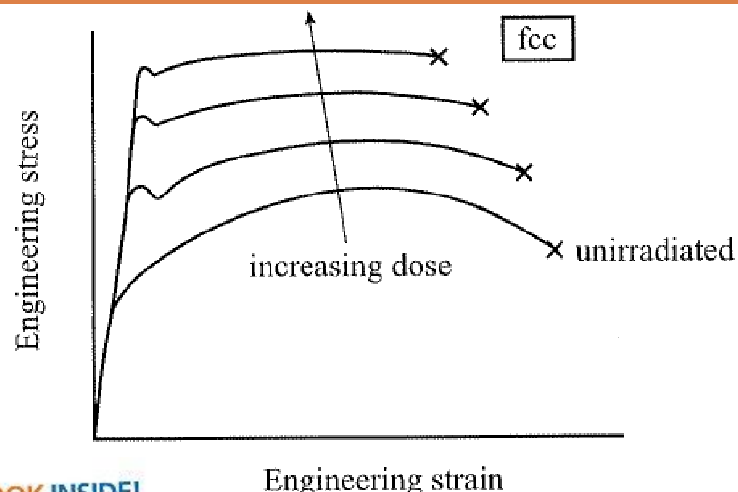


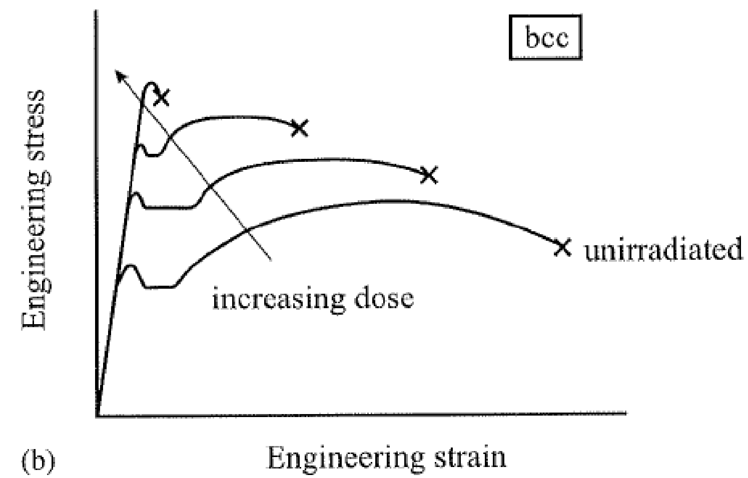
- **Hardness**: resistance of a material to permanent (plastic) deformation under an given load curve
- **Brittleness**: property of materials that break before showing any visible deformation
- Radiation modifies the stress/strain curve: yield strength is increased slightly enlarging the elastic region, but ductility is reduced. The material becomes more fragile…

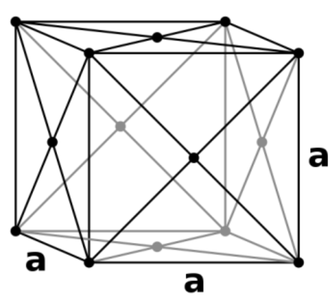
Metals: **hardening and embrittlement**

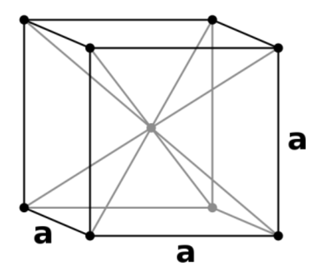


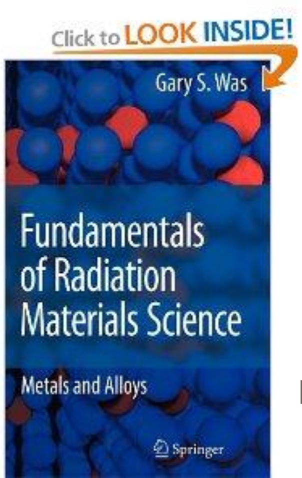
Austenitic Steel (face centered cubic)	**Ferritic steel** (body centered cubic)









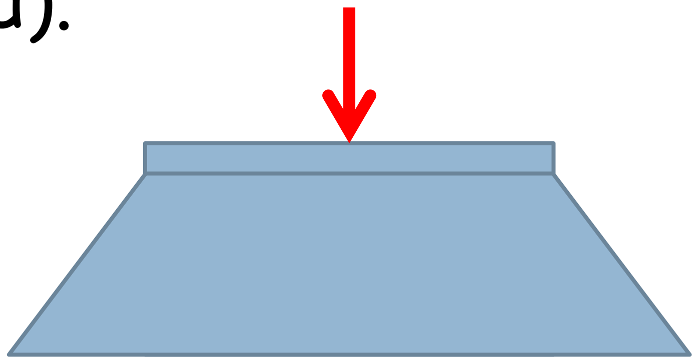


R. Losito, Effects of radiation in accelerators, JUAS 2013, Archamps

Metals: **deformation and creep**

- Bubbles, dislocations etc… are at the bases of growth in volume or deformation

- If the material is subject to constant stress, creep can be initiated (or accelerated).



Water!!

- Two effects are important in the interaction of particle beams (and radiation in general), and water

- Generation of Tritium

- Radiolysis

Tritium

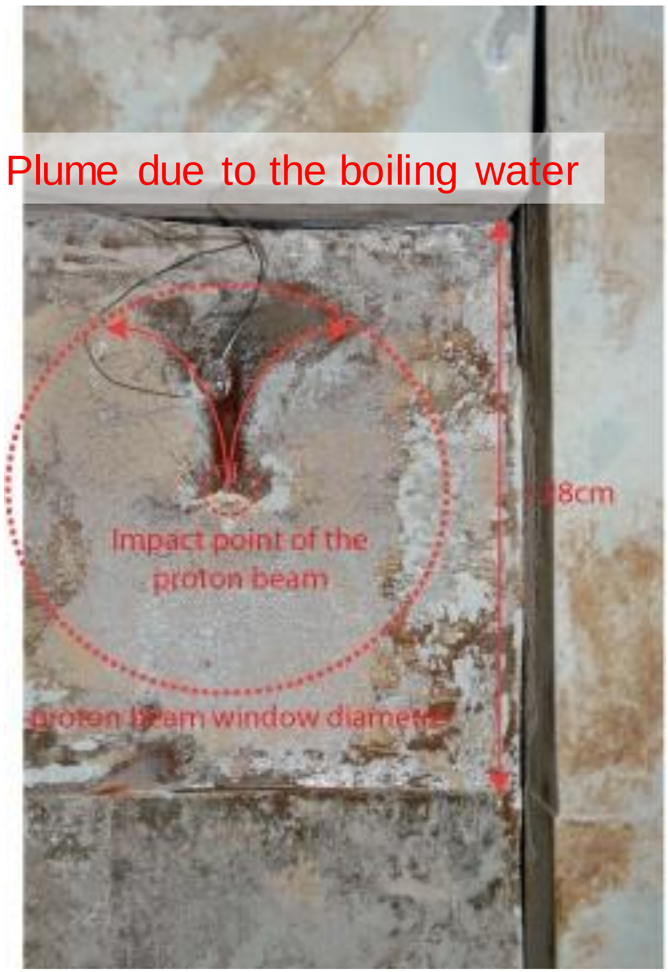
- Radiation induces generation of tritium by different mechanisms
  - $D + n \rightarrow T + \gamma$
  - $^{10}B + n \rightarrow T + {}^{8}Be + \gamma$

- Due to its relatively long half life (12.33 years), huge quantities of tritiated water may be accumulated in the cooling circuits of accelerators.
- In high radiation applications, water cooling has to be avoided!

Radiolysis

- Energy deposited by beams (or radiation) in water breaks the water molecule, and generates H_2 and O_2:
  - H2 is flammable, may provoke explosion
  - O2 (or O3) may attack metallic surfaces, provoking corrosion
- Water cooling circuits in high radiation areas have to include strict control of O2 and H2 concentration, and possibility to evacuate generated gas.

3. Water chemistry



There are very clear signs of a strong **pitting corrosion** at the entrance of the proton beam. Such effects are very well known in nuclear power plants (cracks in the fuel cladding): the very hot (boiling) water carries more oxygen, thus allowing the Pb to change its oxidation state to higher values:

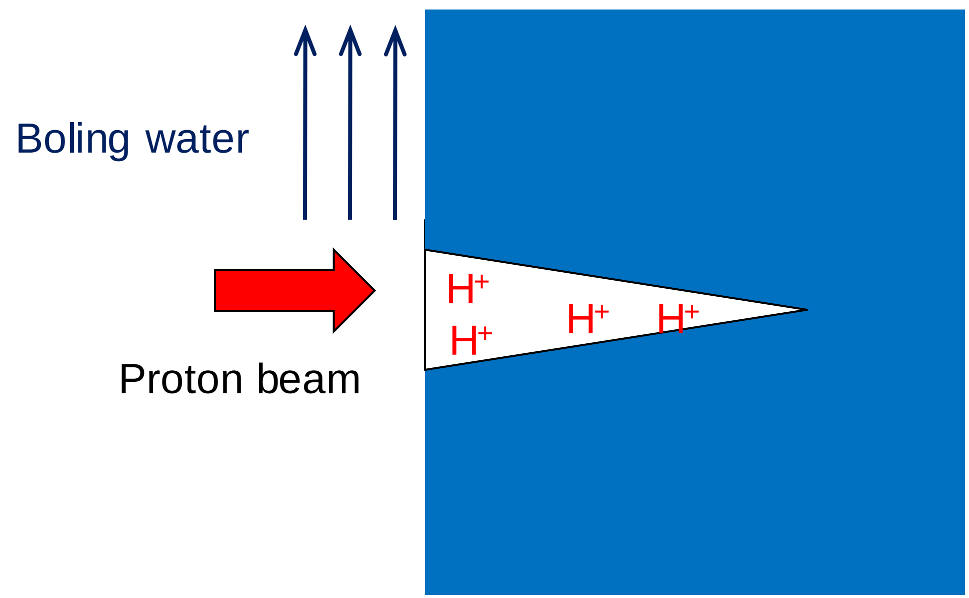
$Pb \rightarrow Pb^{2+} + 2e^-$

$Pb \rightarrow Pb^{4+} + 2e^-$

Hydroxides are formed and a very acid local medium which attacks the metal is produced:

$Pb^{2+} + 2H_2O \rightarrow Pb(OH)_2 + 2H^+$

$Pb^{4+} + 4H_2O \rightarrow Pb(OH)_4 + 4H^+$



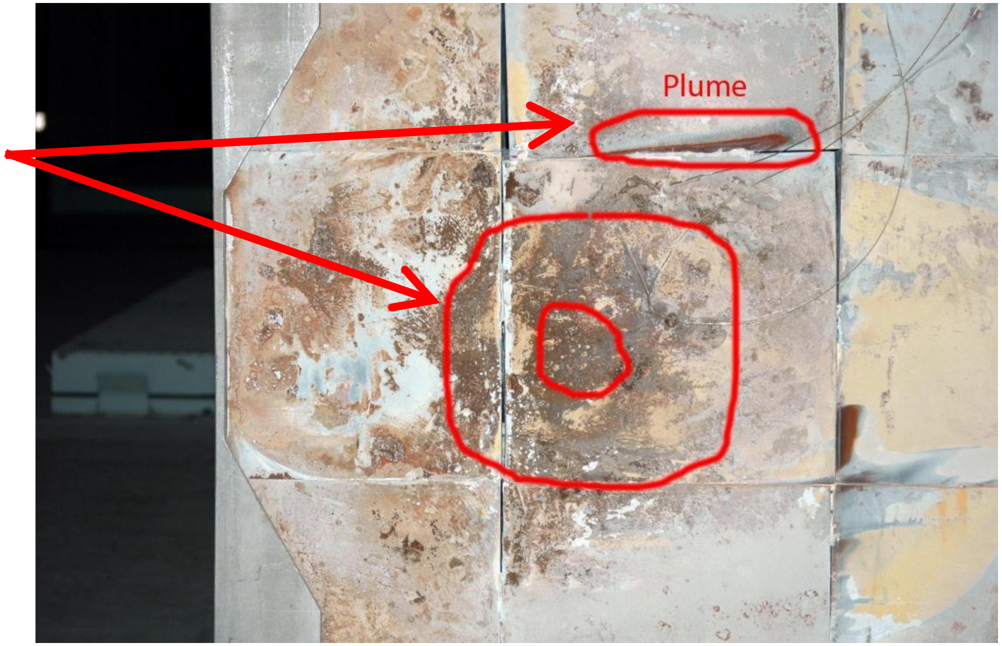
The whole Pb target surface is oxidised.

It is very clear that Pb oxide deposits a the exit face of the target follow the temperature distribution pattern. Moreover, a tentative identification of the oxide type by its colour indicates that higher oxidation states are reached at the hottest places. The higher the temperature, the higher is the oxidation state and the solubility. The insufficient cooling inhibits the passivation and stabilisation of the Pb oxide layer.

Plumes produced by water/steam at the Pb block junctions are also visible in the vicinity of regions where temperature inside the target is expected to be higher.

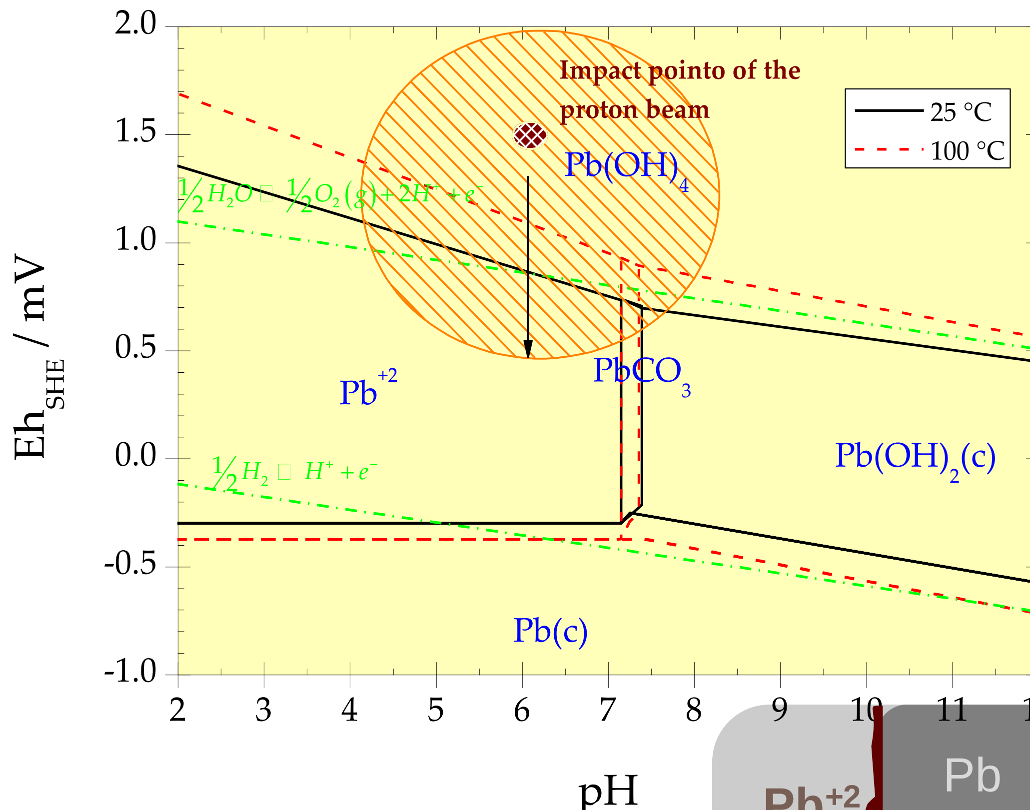
Compound	Colour
PbO	Red or yellow
Pb_2O_3	Black
Pb_3O_4	Orange
PbO_2	Brown or red
$Pb(OH)_{2,4}$	White
$2(PbCO_3)\cdot Pb(OH)_2$	White (used formerly as a pigment)

(*) The Pb oxides are ordered by increasing oxidation state

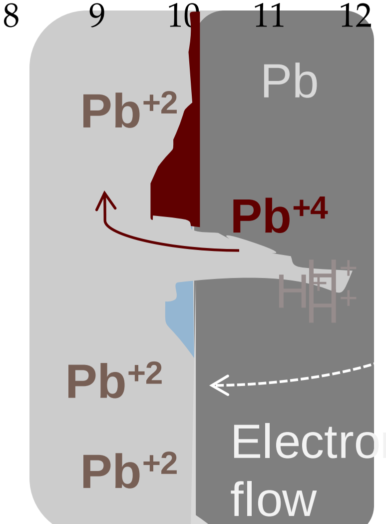


The corrosion has been modelled by a CIEMAT chemist.

- High oxidation conditions
  - Tª → Vapour phase
    - pH dependence
    - Eh (redox potential)
- Oxidation process
  - Pb(II)
  - Pb(IV)
  - Pitting corrosion



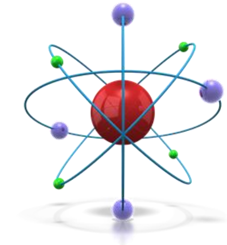
Pb^{+4}



Air

- Particle beams sometimes travel in air; interaction with atmosphere generate O_3.
- O_3 accelerate corrosion!!
- In highly radioactive areas, humidity has to be kept as low as possible …

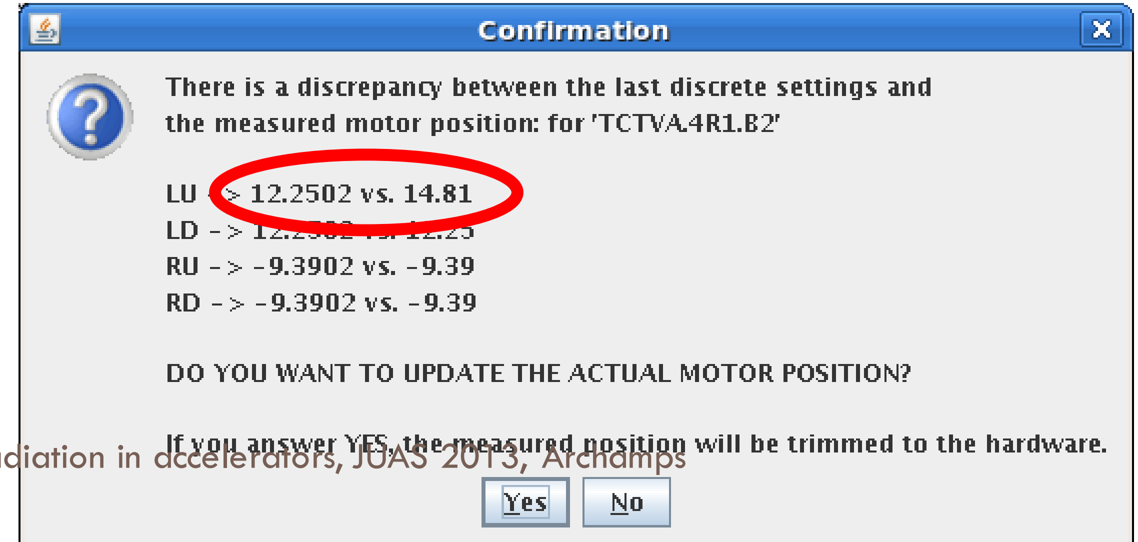
An example of single event: LHC collimator controls



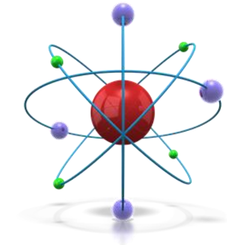
- LHC collimators are moved by stepping motors, which angular position is monitored with resolvers.
- In the control system, a counter is implemented to count the steps of the motor.
- Following an high intensity run, one control system installed in a relatively low radiation area has been struck by a Single event.

An example of single event: LHC collimator controls

- The tricky problem: the anomaly appeared while there was no beam (no source of radiation!!!)
  - Sending back the collimators to “parking” position, we realised that one position sensor was not giving a correct value



How can a problem appear while there is no beam????



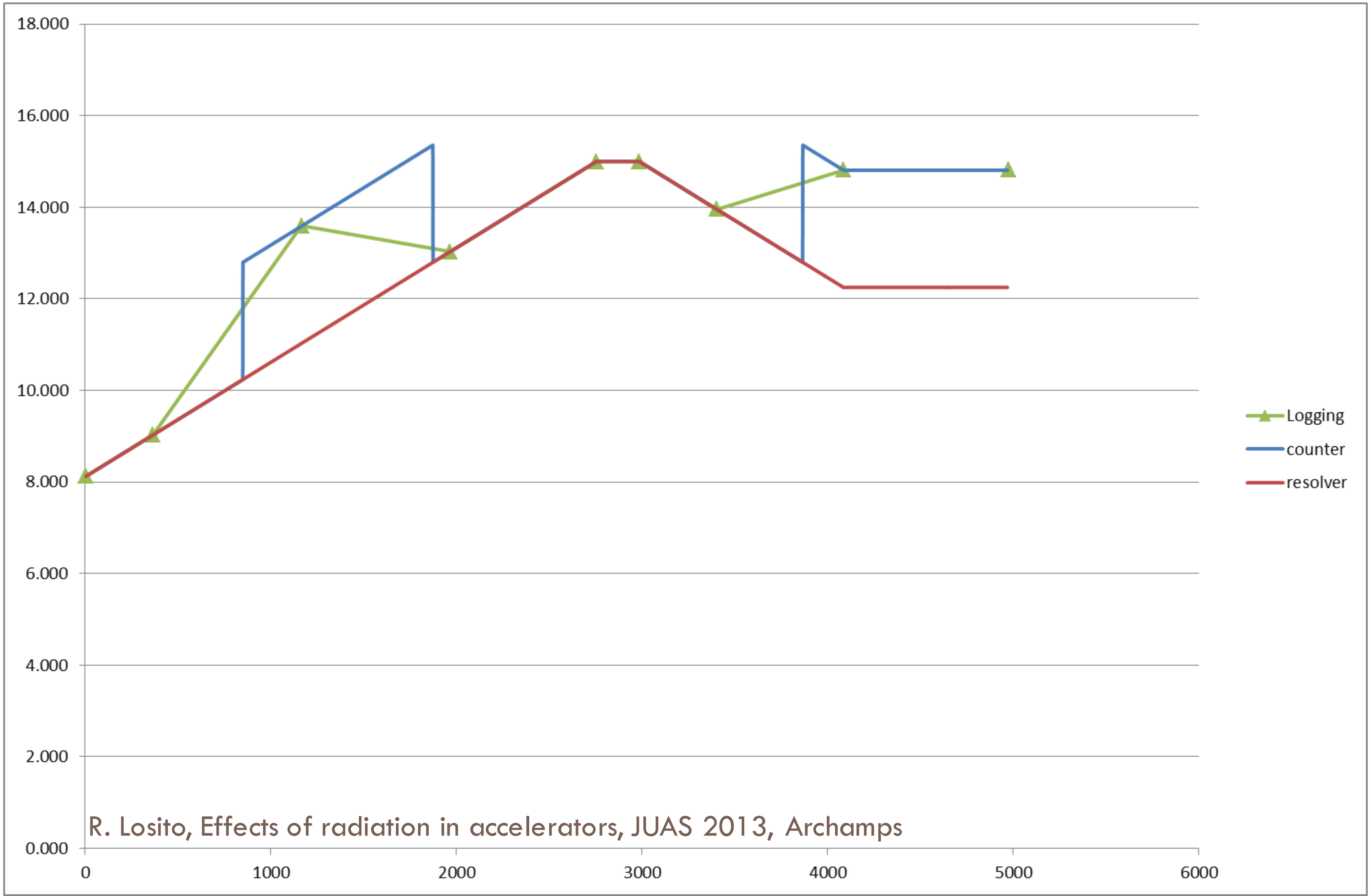
- First event

	position	register															
resolver	11.030	4412		0	1	0	0	0	1	0	0	1	1	1	1	0	0
counter	13.595	5438		0	1	0	1	0	1	0	0	1	1	1	1	1	0

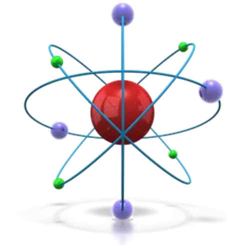
- Second event

	position	register															
resolver	12.250	4900		0	1	0	0	1	1	0	0	1	0	0	1	0	0
counter	14.810	5924		0	1	0	1	1	1	0	0	1	0	0	1	0	0

What happened?



Single Events



- Single Events Errors may be extremely difficult to understand and anticipate
- Avoid as much as possible to install electronics close to radiation sources!!
- If this is impossible, either need shielding or radiation tolerant-design!

R. Losito, Effects of radiation in accelerators, JUAS 2013, Archamps

Optic Fibers

- Optic fibers under irradiation tend to become opaque.
- In general, the effect is reduced by avoiding the presence of P in the fiber.
- The main effect is an increased attenuation factor, which may or may not affect the transmission of data: most common modulations used are base on PSK modulations, which are influenced mainly by change in phase response.
- 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
- Real and imaginary part of impedance are not independent variables (Paley-Wiener conditions)

Conclusions

- Radiation provokes a lot of undesired effect
- You cannot avoid them!!!
- The only rule is to anticipate damage
  - Think first!!!
- ALARA is the magic word: involves preparation of interventions, selection of materials, mitigation measures, remote handling…

Conclusions

- A special recommendation:
  - Irradiated materials will remain so for hundreds of years!!!
  - Think carefully at the materials you use
  - Ask yourself the question: is it really worth to do what I am doing?? And in the way I am going to do it?

Thank you for your attention!!!

Suggested readings