Radiation Protection at CERN

Heinz Vincke, D. Forkel-Wirth, S. Roesler,
M. Silari, C. Theis, Helmut Vincke
DGS-RP, CERN

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Definition of Radiation Protection

Radiation protection: The protection of people from the effects of ionizing radiation, and the means for achieving this.

- Radiation Protection Training
- Assessment of radiological risks at work places
- Area monitoring
- Individual monitoring of personnel
- Control and characterization of radioactive material and waste
- Management of radioactive sources and waste
- Assessment of radiological risks related to new projects
- …

At CERN: Responsibility of **CERN's Radiation Protection Unit,** providing expert advice, authorizing activities and controlling compliance of activities with RP rules.

Radiological Quantities and Units

Absorbed Dose D: energy absorbed per mass
Unit: 1 Gy = 1 J/kg
[1 Gy = 100 rad]

$$D = \frac{1}{m}\int E dV$$

Equivalent Dose H: absorbed dose of organs weighted by the radiation weighting factor w_R of radiation R:
Unit: 1 Sv (= w_R x Gy)
[1 Sv = 100 rem]

$$H_T = \sum_R w_R D_{T,R}$$

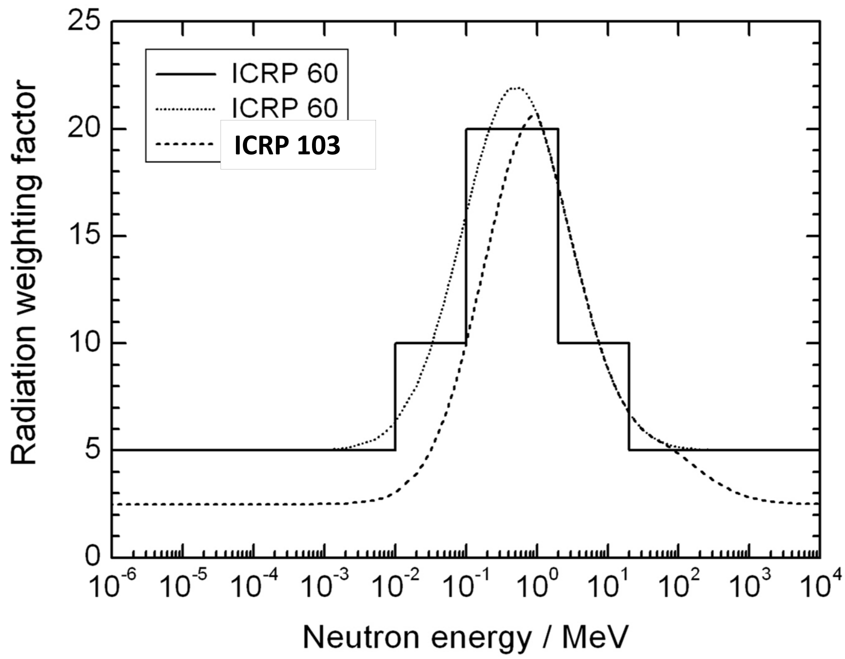
Effective dose E: Sum of all equivalent doses weighted with the weighting factor w_T for tissue T
Unit: 1Sv

$$E = \sum_T w_T H_T$$

Radiation Weighting Factors

Type and energy of radiation R	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons:	
<10 keV	5
10 to 100 keV	10
> 0.1 to 2 MeV	20
> 2 to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, E > 2 MeV	2
Alpha particles, fission fragments, heavy nuclei	20

Neutron Radiation Weighting Factors

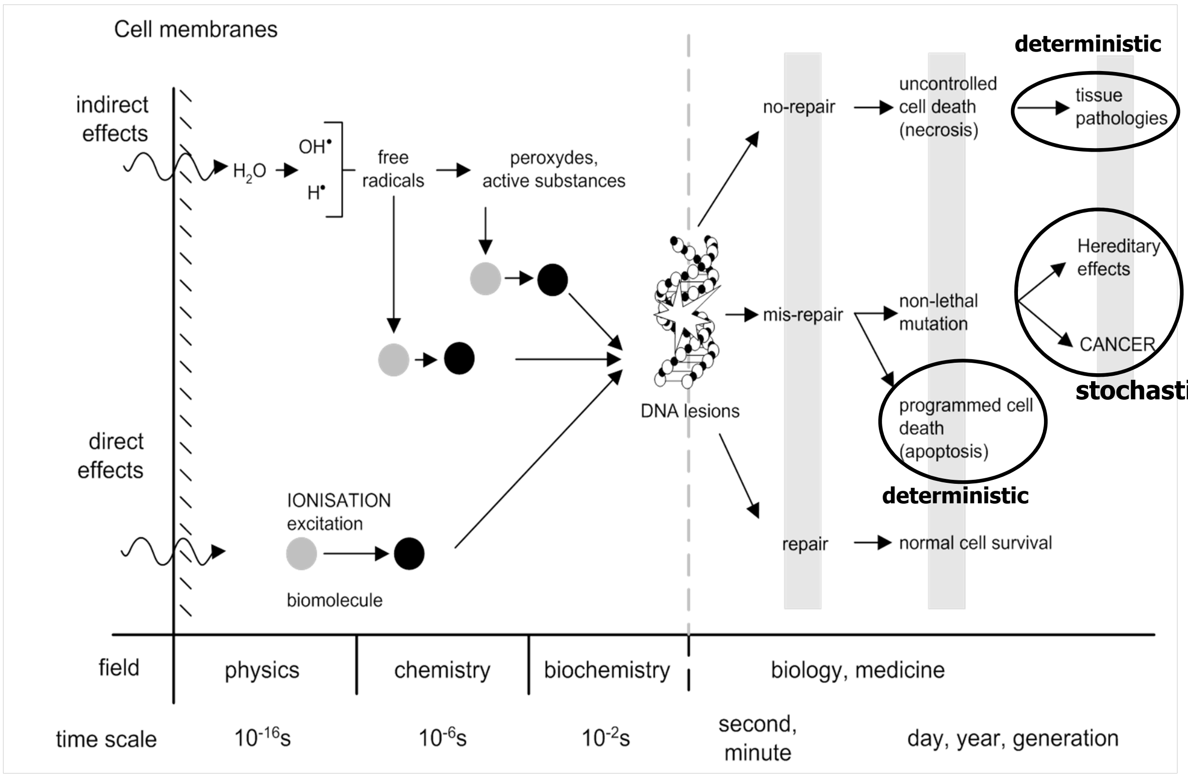


Values for neutrons replaced by a continuous function in ICRP 103 (2007)

Tissue sensitivity

Sensitivity	Organ or tissue
High	Haematopoietic and lymphatic systems (bone marrow, spleen, thymus, ganglions), intestinal mucosa, gonads, lens
Intermediate	Skin, eye (exception lens)
Low	Lung, liver, kidneys
Resistant	Hart, nervous system(adult), muscle, supporting tissue

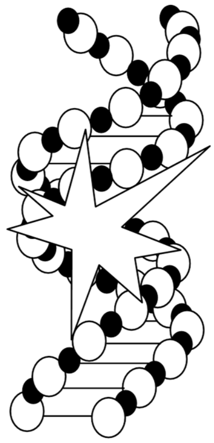
Steps of the biological action of the radiation



Damages to the DNA

- Type of damage caused by radiation:
  - damage to a DNA-base : 80 %
  - single strand breaks (SSB) : 20 %
  - double strand breaks(DSB) : 1 %
  - LMDS :0,3 %

  (locally multiplied damaged site):



Biological Effects

Stochastic effects:

no dose threshold (linear function of dose)

increase of probability by 5% per Sv for:
- genetic defects
- cancer

result does not depend on the amount of absorbed dose but the probability of having the effects is proportional to the dose absorbed.

delayed health detriments

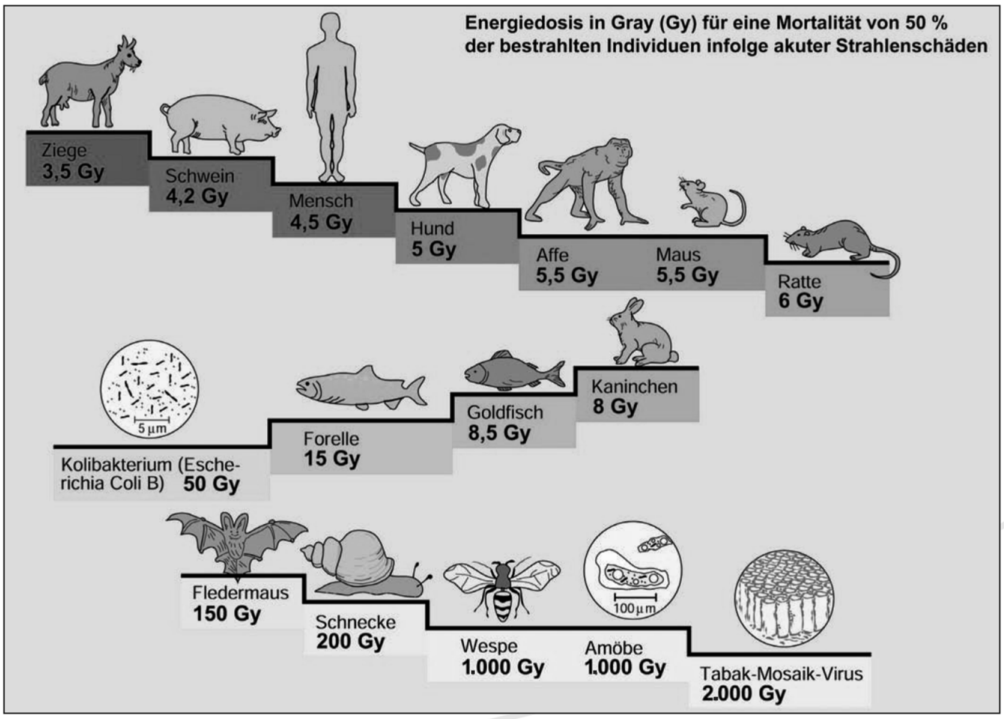
Deterministic effects:

dose received in short time interval
dose threshold: > 500 mSv

immediate consequences:
- vomiting
- immun deficiency
- erythema and necrose

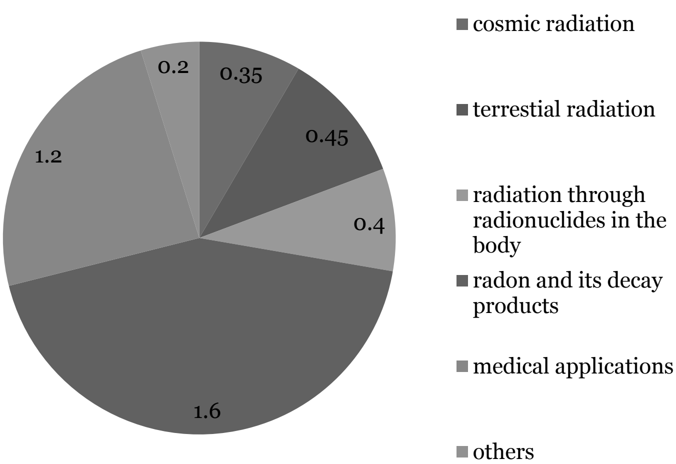
health detriments are function of the dose

Lethal dose ($LD_{50/30}$)



Source: Martin Volkmer, Radioaktivität und Strahlenschutz, Informationskreis Kernenergie

Mean radiation exposure in Switzerland in mSv



Total 4.2 mSv

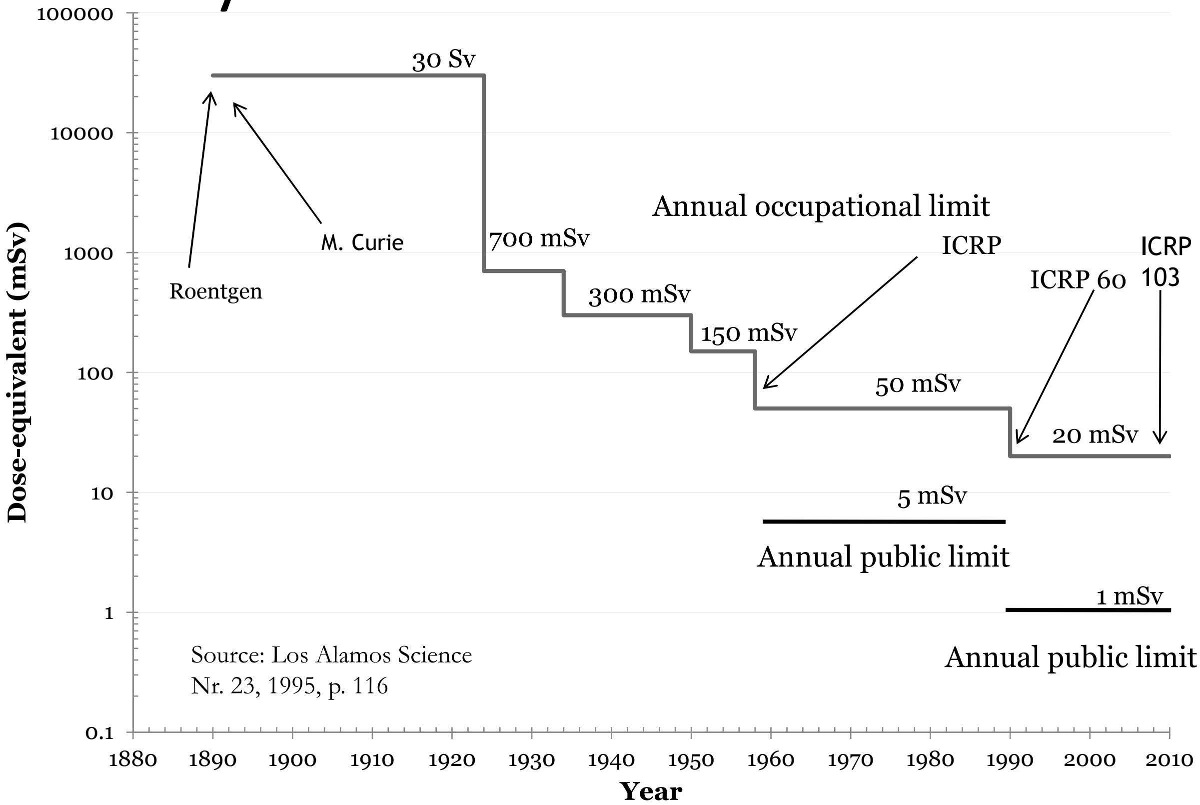
Source: BAG Switzerland

Radiation exposure in X-ray and CT Examinations

ABDOMINAL REGION:	
Computed Tomography (CT)-Abdomen and Pelvis	15 mSv
BONE:	
Radiography (X-ray)-Spine	1.5 mSv
CENTRAL NERVOUS SYSTEM:	
Computed Tomography (CT)-Head	2 mSv
Computed Tomography (CT)-Spine	6 mSv
CHEST:	
Computed Tomography (CT)-Chest	7 mSv
Radiography-Chest	0.1 mSv
DENTAL:	
Intraoral X-ray	0.005 mSv
WOMEN'S IMAGING:	
Mammography	0.4 mSv

Source: www.radiologyinfo.org

History of Radiation Protection



Ionising Radiation

www.bfs.de

Ionising radiation are

- photons (X-rays, γ-radiation)
- particles (α, β^+, β^-, e^+, e^-, p^+,p^-,n, π^+, π^-, μ^+, μ^-...)

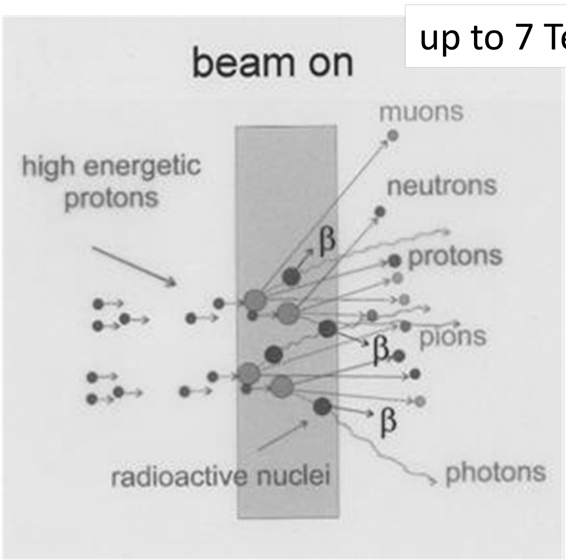
transporting sufficient energy to ionise directly and indirectly atoms and molecules

The interaction between ionising radiation and matter results in an energy absorption and a subsequent potential radiation damage of matter.

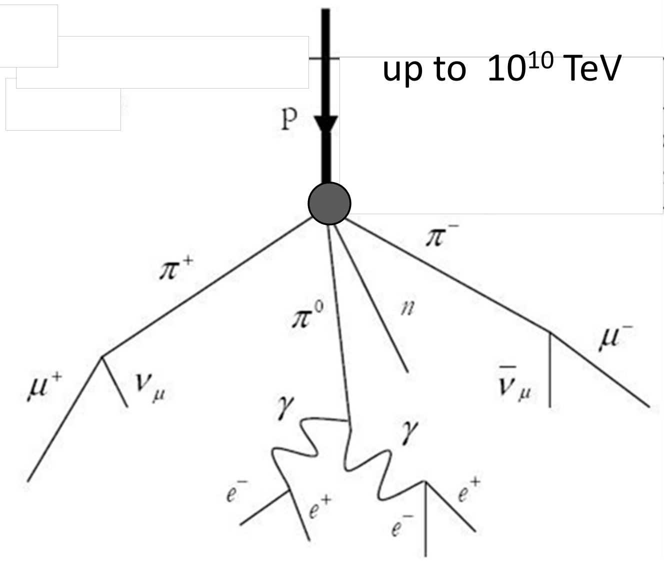
Ionising radiation is part of the nature and of human activities in medicine, research, industry, energy production and military

Prompt Ionising Radiation

up to 7 TeV



up to 10^{10} TeV



hadron accelerator | cosmos

high energy, mixed radiation fields

Radiation Showers

Radiation showers development after impact of **ONE** hadron (120 GeV/c) on a copper target

<u>Hadronic shower only</u>

<u>Hadronic shower + photons</u>

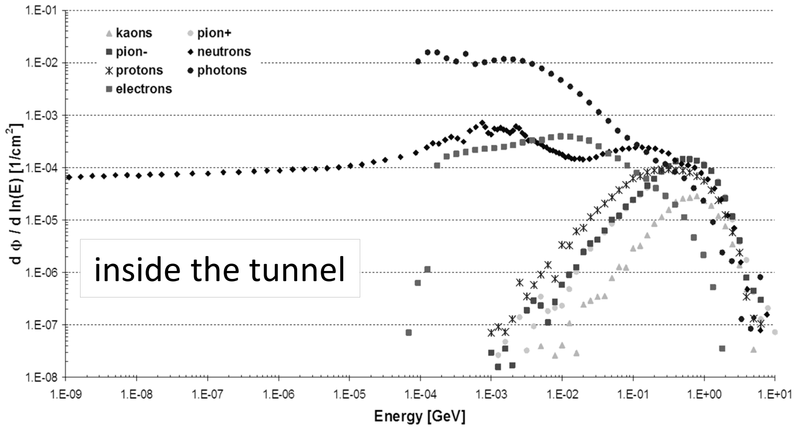
Particle fields

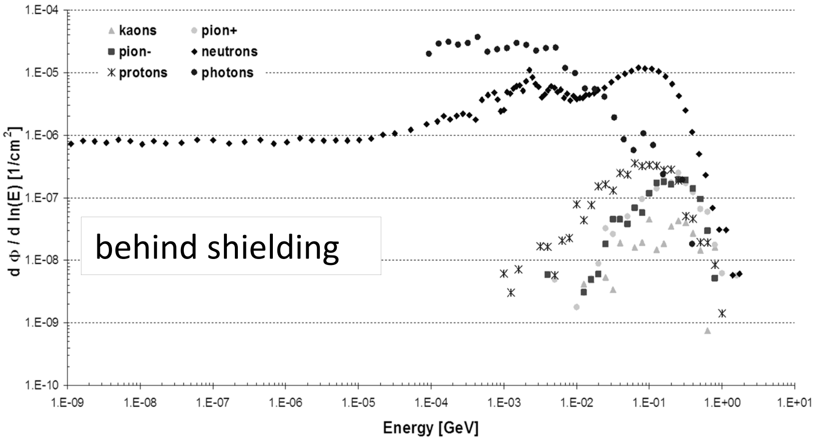
(120 GeV proton beam)

Attenuation of radiation H_0 (point source):

$$H = \frac{H_0 * e^{-d/l}}{R^2}$$

d: shielding thickness
R: distance
l: attenuation free path
concrete: l = 40 cm
iron: l= 17 cm





Ambient Dose Equivalent Behind Shielding

	Fraction of ambient dose equivalent
• Neutrons	~ 80 %
• Protons • Charged Pions • Muons • Photons • Electrons + Positrons	~ 20 %

Ionising Radiation due to Radioactivity

Radioactivity: the phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of ionising radiation. The rate at which this nuclear transformations occurs in matter containing radionuclides is called **activity**. The equation is

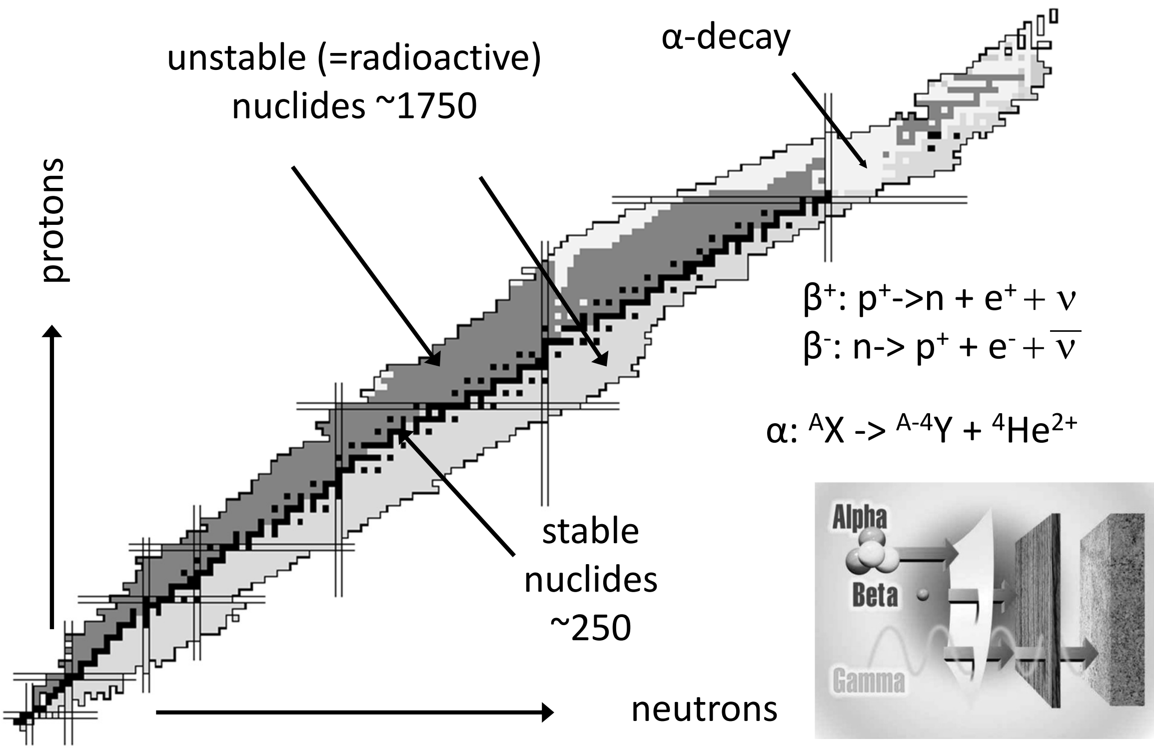
$$A(t) = -dN/dt\ [Bq] \qquad 1\ Bq = s^{-1} \qquad [1\ Ci = 3.7\times10^{10}\ Bq]$$

where N is the number of nuclei of the radionuclide, and hence the rate of change of N with time is negative.

The radioactive **half-life** of a radionuclide is the time necessary for half of the nuclei present in the sample to decay

Radionuclides are either natural occurring or produced by nuclear reactions (artificial radionuclides).

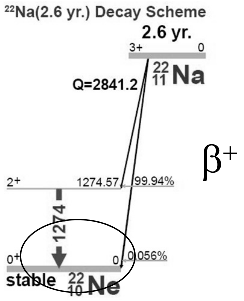
Chart of Nuclei

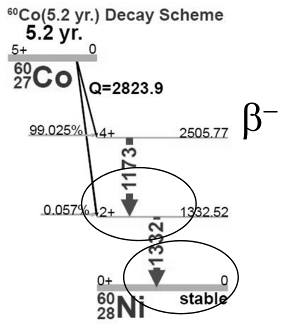


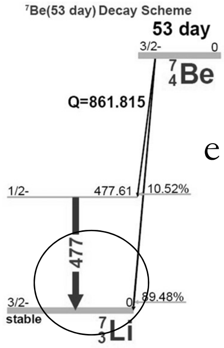
$$\beta^+: p^+ \rightarrow n + e^+ + \nu$$
$$\beta^-: n \rightarrow p^+ + e^- + \overline{\nu}$$
$$\alpha: {}^{A}X \rightarrow {}^{A-4}Y + {}^{4}He^{2+}$$

Radioactivity

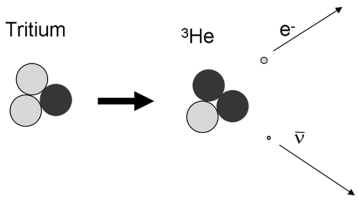
β-, γ-emitter:







pure β-emitter:



α, β and γ are emitted with energies up to few MeV

Terrestrial Radionuclides

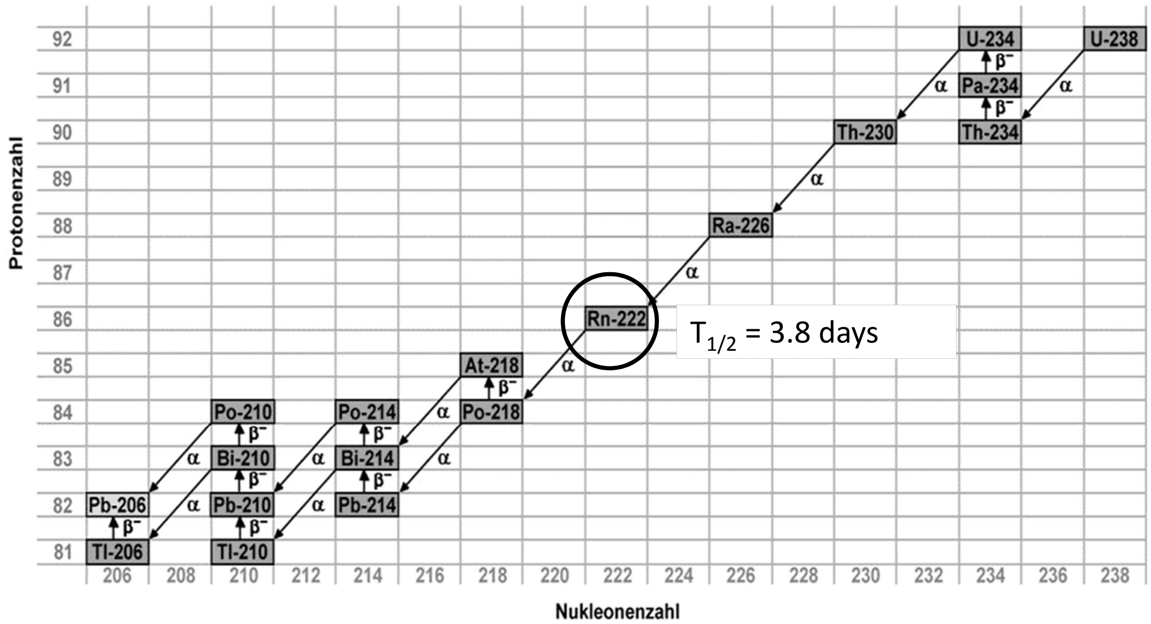
During the creation of the earth, terrestrial nuclides had been incorporated into the earth crust ($T_{1/2}$ some millions of years)

Nuclide	Symbol	Half-life	
Uranium-235	^{235}U	7.04×10^{8} a	0.72% of natural Uranium
Uranium-238	^{238}U	4.47×10^{9} a	99.3% of natural Uranium
Thorium-232	^{232}Th	1.41×10^{10} a	
Potassium-40	^{40}K	1.28×10^{9} a	Earth: 0.037-1.1 Bq/g

...and some more:

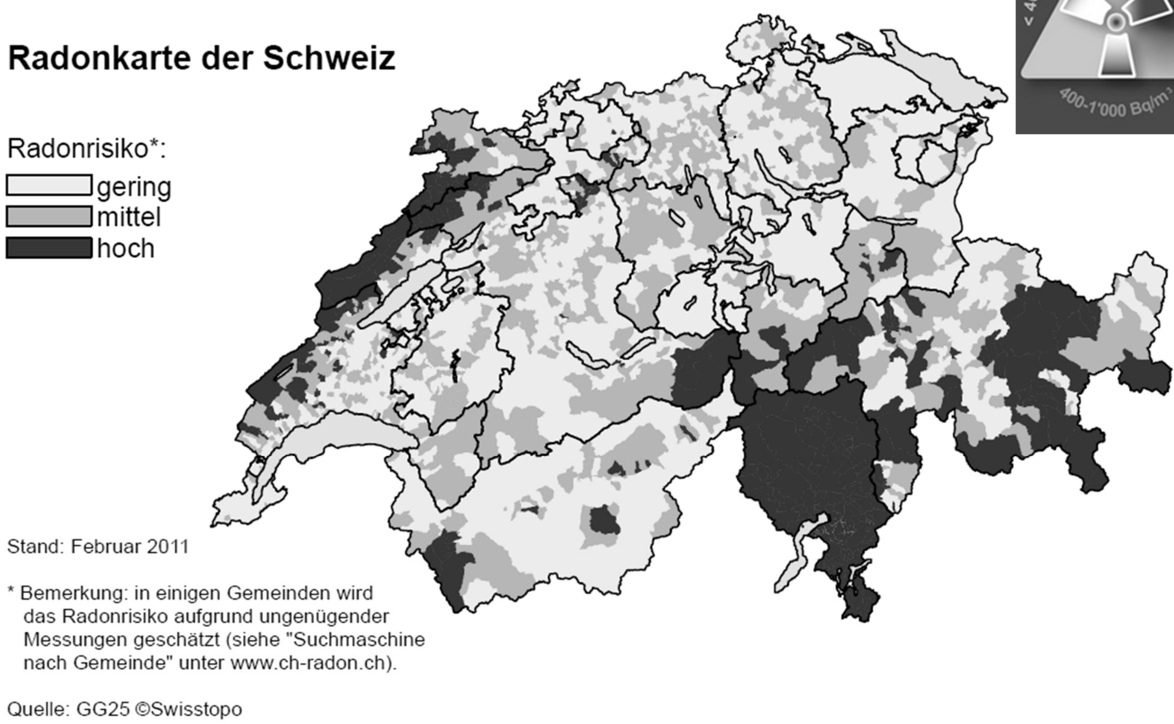
^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, … ^{190}Pt, ^{192}Pt, ^{209}Bi, …

Uranium-Radium Decay Chain



www.periodensystem.net

Radon Map of Switzerland



Cosmogenic Radionuclides

Cosmogenic nuclides are produced by nuclear reaction of cosmic particles with stable nuclei of the atmosphere

Nuclide	Symbol	Half-life	Nuclear Reaction
Carbon-14	^{14}C	5730 a	e.g. $^{14}N(n,p)^{14}C$;
Tritium-3	^{3}H	12.3 a	Interaction of cosmic radiation with N or O; $^{6}Li(n,alpha)^{3}H$
Beryllium-7	^{7}Be	53.28 d	Interaction of cosmic radiation with N or O

More cosmogenic radionuclides:
^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, …

Note: ^{7}Be and Rn decay products are always found in intake filters

...and we find radioactivity in our body

Nuclide	Total activity in human body (~ 70 kg)
Uranium	~ 1 Bq
Thorium	~ 0.1 Bq
Potassium 40	~ 4 - 5 kBq
Radium	~ 1 Bq
Carbon 14	~ 15 kBq
Tritium	~ 20 Bq

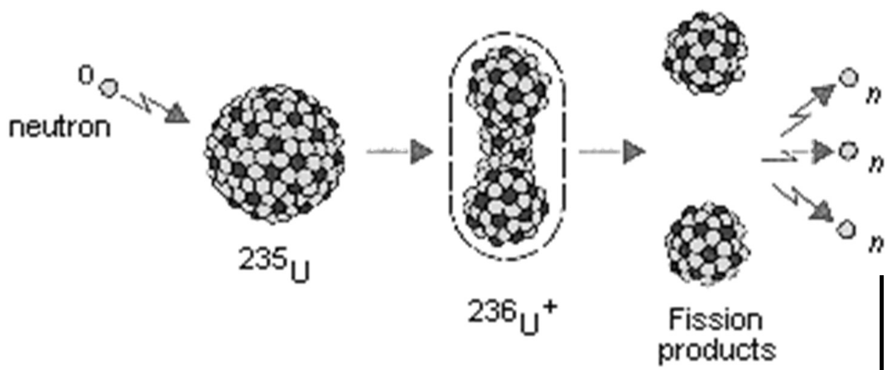
...e.g. the more muscles, the more Potassium 40..

Artificial Radioactivity

Reaction Mechanism:

- *Fusion*
- Fission
- High Energy Nuclear Reaction (Spallation)
- more hadronic nuclear reactions (p,n), (n,γ), ….
- Gamma induced nuclear reaction (γ,n)

Fission

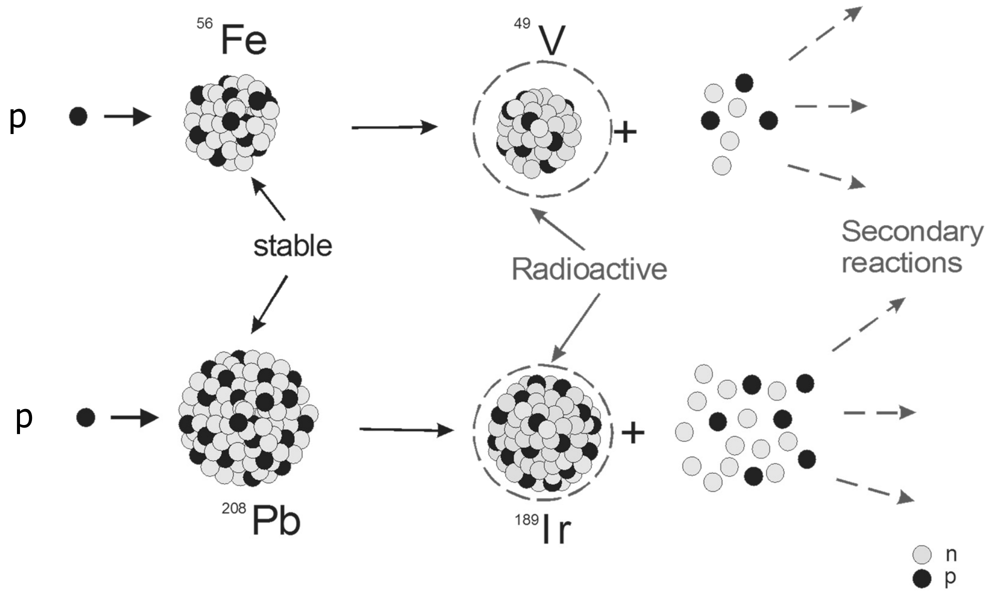


thermal
neutron capture

$^{59}Co + n \rightarrow {}^{60}Co$

$^{23}Na + n \rightarrow {}^{24}Na$

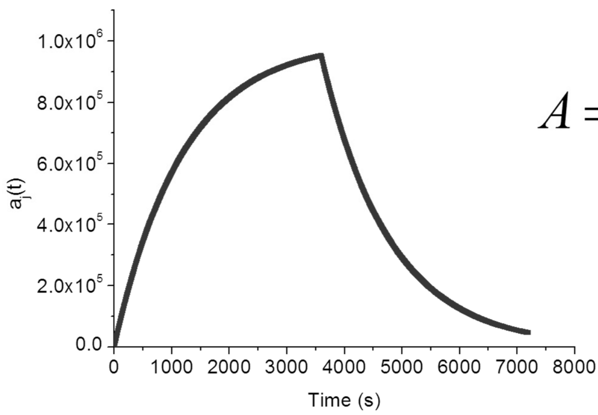
Spallation



Production and Decay of Radionuclides

Rule-of-thumb (probably very obvious):

the shorter the half-life, the faster the build-up, the faster the decay



$$A = A_s(1 - e^{-t_{irr}/\tau})e^{-t_{dec}/\tau}$$

t_{irr} irradiation time
t_{dec} decay time
τ mean lifetime
$\tau = T_{1/2}/\ln(2)$

It takes about 5 half-lives to reach saturation of activity

When is a material radioactive? (specific for CERN)

- **Activity**
  - *Specific activity* exceeds the CERN exemption limits

  AND
  - *total activity* exceeds the CERN exemption limits

OR

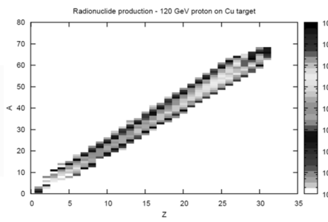
- **Dose rate**
  - Ambient dose equivalent rate measured in 10 cm distance of the item exceeds 0.1 uSv/h after subtraction of the background.
    - Slightly radioactive < 10 uSv/h
    - Radioactive < 100 uSv/h
    - Highly radioactive > 100 uSv/h

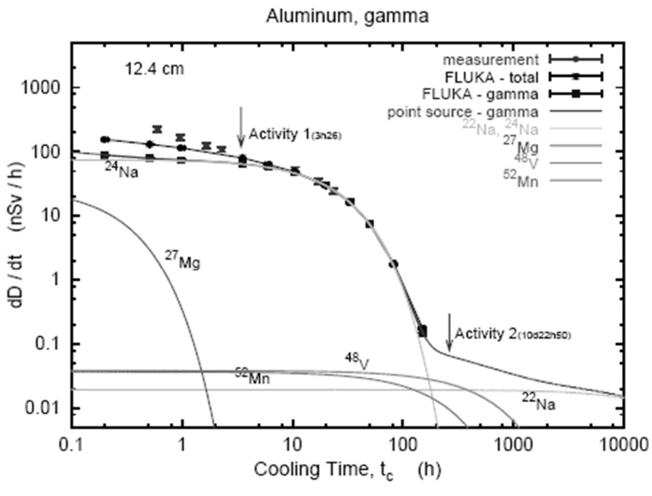
OR

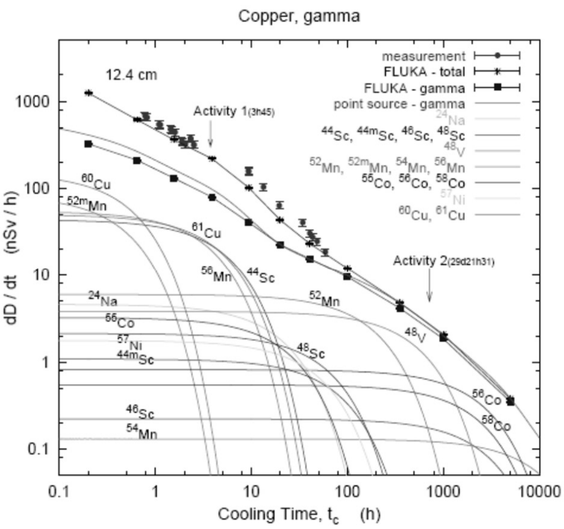
- **Surface contamination**
  - 1 Bq/cm^2 in case of unidentified beta- and gamma emitters and 0.1 Bq/cm^2 in case of unidentified alpha emitters. Once a radionuclide has been identified then the published *CS*-values can be used.

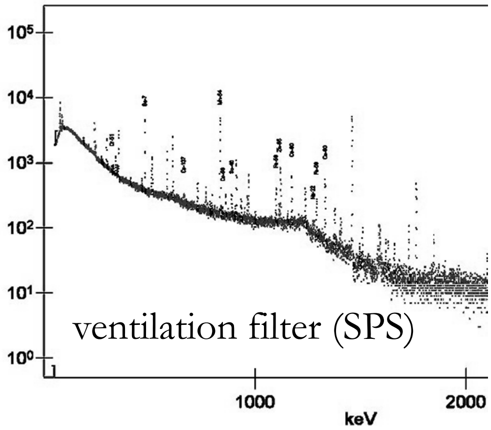
Activation of Material at Hadron Accelerators

Beam losses result in the activation of material (beam line components, tunnel structure, etc.)







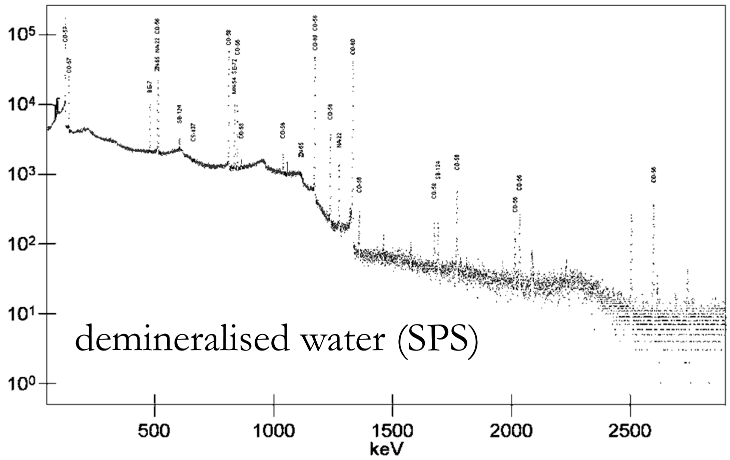


Nuclide	Halflife
Be-7	53 D
Na-22	3 Y
Sc-46	84 D
Cr-51	28 D
Mn-54	312 D
Co-56	77 D
Fe-59	45 D
Co-60	5 Y
Zn-65	244 D

γ-emitter only

Activation

of air, gas, water, cooling liquids at hadron accelerators



Nuclide	Halflife
BE-7	53 D
NA-22	3 Y
CO-56	77 D
CO-57	271 D
CO-58	71 D
CO-60	5 Y
ZN-65	244 D
SB-124	60 D

γ-emitter only

General Principles of Radiation Protection Legislation

1) Justification

any exposure of persons to ionizing radiation has to be justified

2) Limitation

the personal doses have to be kept below the legal limits

3) Optimization

the personal doses and collective doses have to be kept as low as reasonable achievable (ALARA)

Dose Limits

	Dose limits for 12 months consecutive (mSv)		
	Non-occupationally exposed persons	Occupationally exposed persons	
		B	A
EURATOM	< 1	< 6	< 20
Germany/France	< 1	< 6	< 20
CERN	< 1	< 6	< 20
Switzerland	< 1	< 20	

Radiation Area Classification – One Mean to Limit Doses

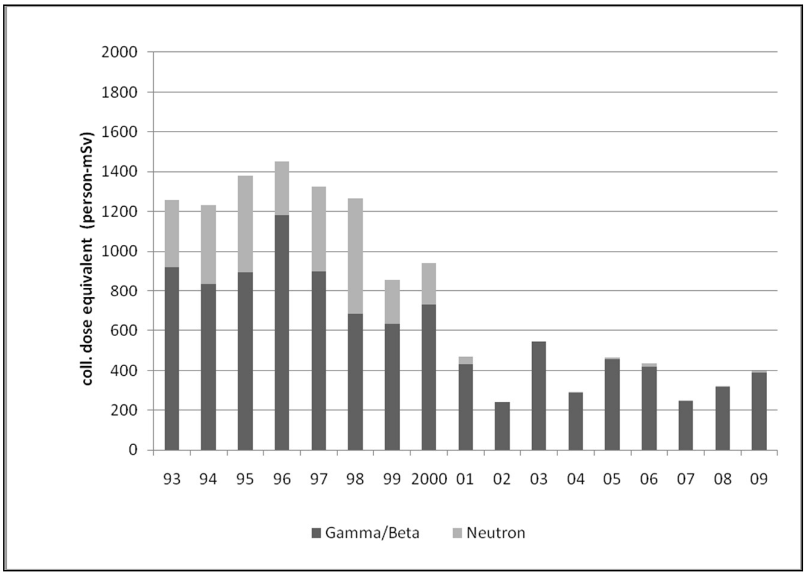
CERN

	Area	Dose limit [year]	Ambient dose equivalent rate: Work place	Ambient dose equivalent rate: Low occupancy	Sign	
	Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h		
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory / Dosimètre obligatoire	
Radiation Area	Simple	20 mSv	10 µSv/h	50 µSv/h	Dosimeter obligatory / Dosimètre obligatoire	Controlled Area
Radiation Area	Limited Stay	20 mSv		2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ / Dosimeters obligatory / Dosimètres obligatoires	Controlled Area
Radiation Area	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION / HAUTE RADIATION / Dosimeters obligatory / Dosimètres obligatoires	Controlled Area
Radiation Area	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA / ZONE INTERDITE / No Entry / Défense d'entrer	Controlled Area

Courtesy N. Conan, M. Widorski

Safety Instruction S3-GSI1, EDMS 810149

Occupational Exposure of CERN Personnel



Evolution of collective dose equivalent for personnel monitored in person-mSv per year

The decrease of collective neutron dose equivalent is due to the subtraction of natural background (1999) and to the introduction of a technically more advanced dosimeter (2001).

Distribution of Personal Annual Doses

Dose interval (mSv)	Persons Concerned (2005)	Persons Concerned (2006)	Persons Concerned (2007)	Persons Concerned (2008)	Persons Concerned (2009)
0.0	3074	4192	5131	5143	5042
0.1-0.9	1522	1738	898	1020	1219
1.0-1.9	53	37	33	40	39
2.0-2.9	9	17	2	3	13
3.0-3.9	3	4	1	1	2
4.0-4.9	4	2	1	1	-
5.0-5.9	1	-	-	-	-
> 6.0	-	-	-	-	-

Distribution of personal annual dose equivalent from 2004 on in intervals of increasing personal dose. The majority of monitored persons did not receive any personal dose. In 2009 only 54 persons exceeded an annual dose of 1 mSv.

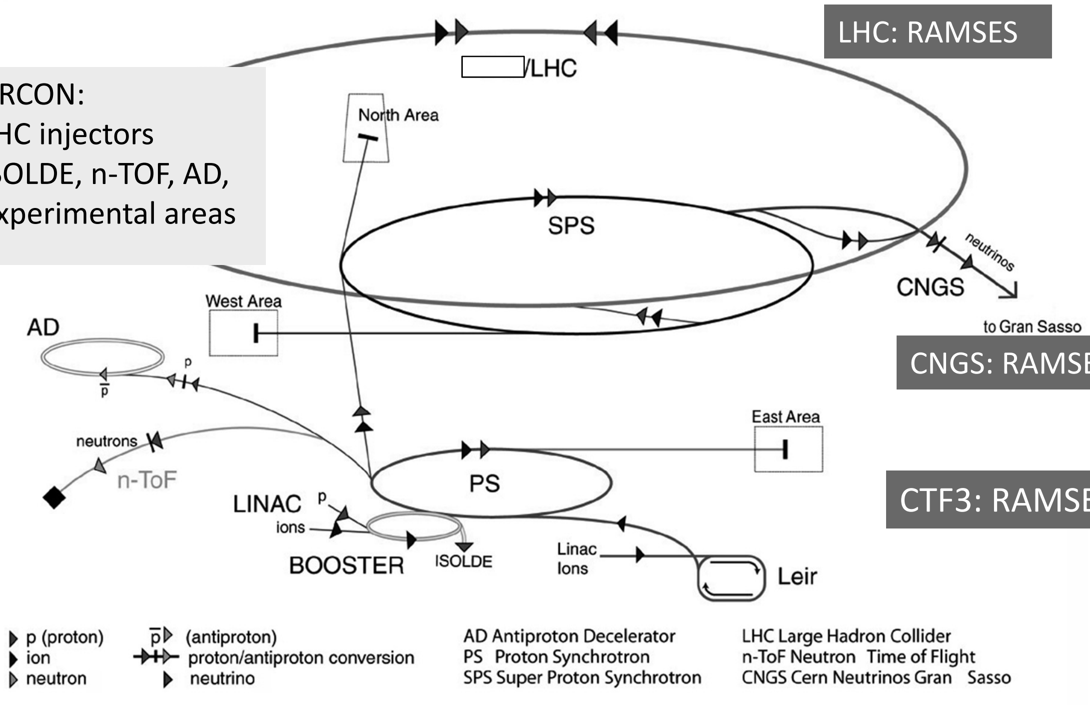
Radiation Monitoring - ARCON/RAMSES

ARCON:
LHC injectors
ISOLDE, n-TOF, AD,
Experimental areas

LHC: RAMSES

CNGS: RAMSES

CTF3: RAMSES



Monitors for Protection of Environment

ARCON and RAMSES use the same/similar type of monitors

Stray radiation Monitoring

EPIC

ERC

Water Monitoring station

RWM - RWS

Ventilation Monitoring

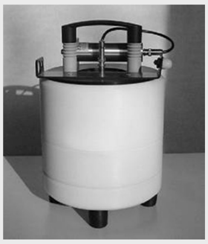
VGM - VAS

Wind onitoring

USA

Operational Radiation Protection Monitors

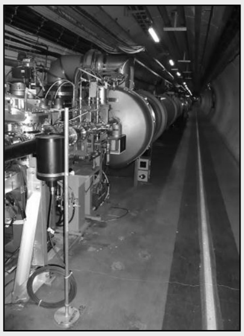
ARCON and RAMSES use the same/similar type of monitors

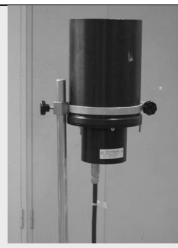


REM counter

Gas filled, high pressure ionization chamber

Beam-on: to protect workers in areas adjacent to accelerator tunnels and experiments against prompt radiation (mainly neutrons, E < some GeV)
Alarm function





Air filled ionisation chamber

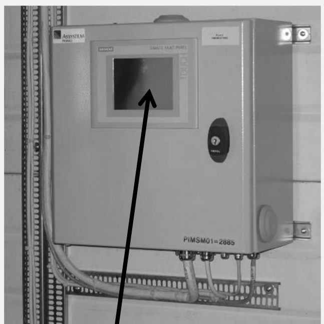
Beam-off: to protect workers during maintenance and repair against radiation fields caused by decay of radionuclides (mainly gammas, E < 2.7 MeV)
No alarm function

Operational Radiation Protection Monitors

Special monitors

Hand&Foot monitor

Site Gate Monitor

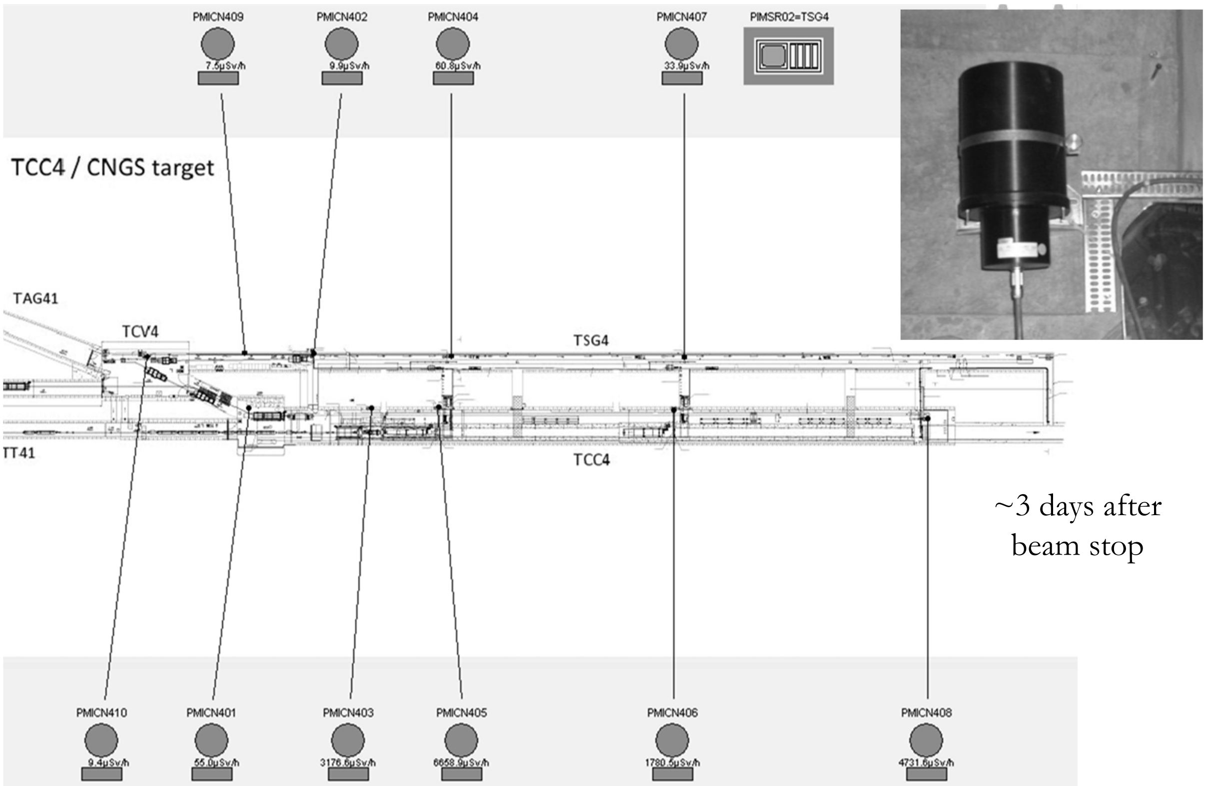


Monitoring station

RAMSES: reading of radiation levels directly available ≠ ARCON

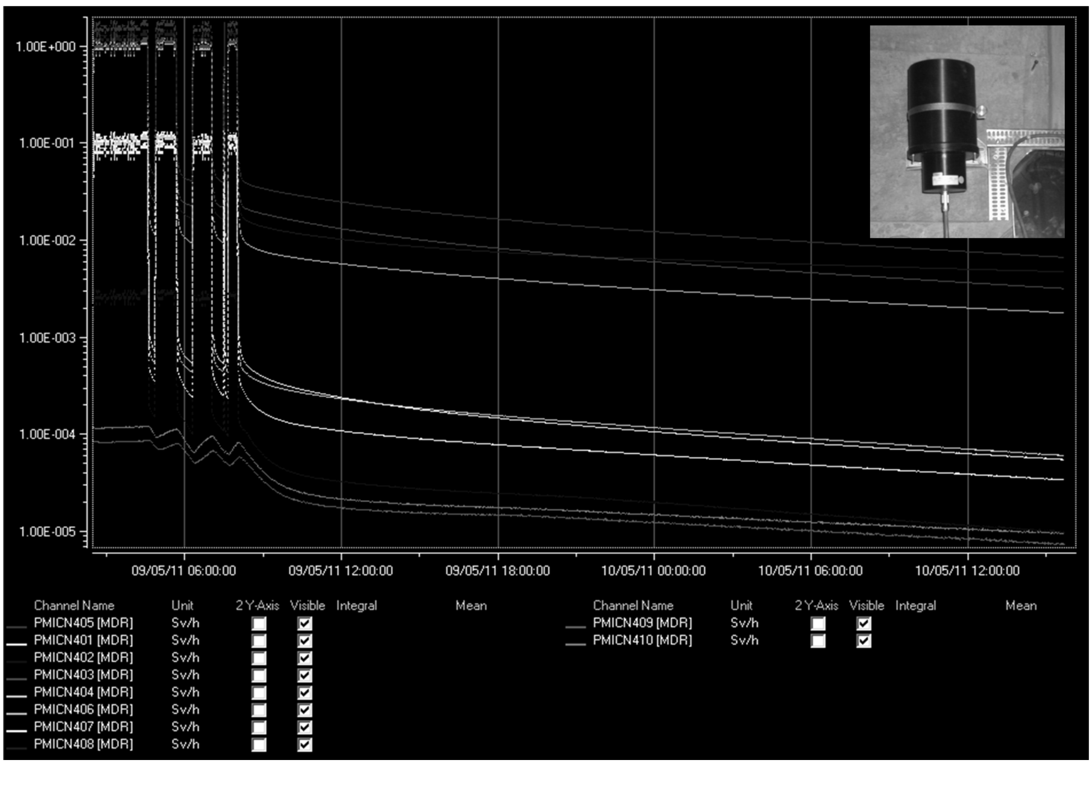
Radiation Alarm Unit (RAMSES)

Induced activity monitoring in CNGS (CERN Neutrinos to Gran Sasso)

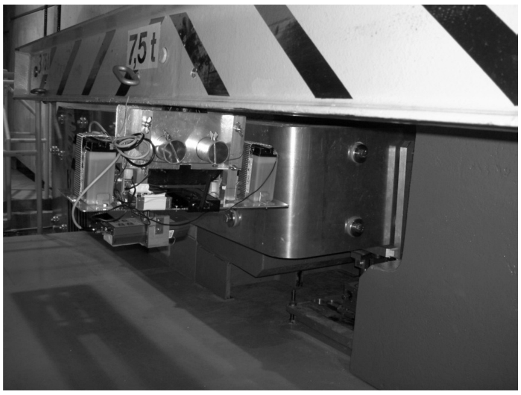


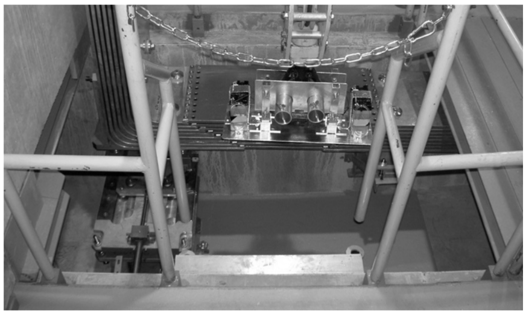
~3 days after beam stop

Ambient dose equivalent rate in CNGS

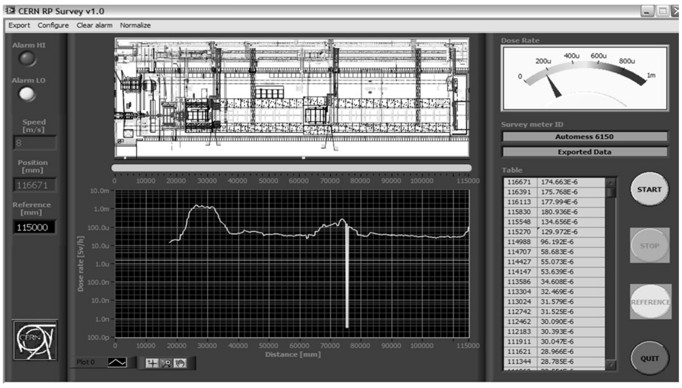


Remotely controlled radiation survey





A survey platform has been developed to measure the residual dose rate in the CNGS cavern remotely.
The platform can be mounted on the crane



Reaches nearly any location in the target chamber.

Prevents exposure of personnel to high radiation levels during manual measurements

Passive individual dosimetry

- Continuous measurement of βγ-dose (DIS-system) and integration of the neutron dose (track dosimeter)
- Obligation to wear the dosimeter in supervised and controlled areas
- Wearing of the dosimeter on the chest
- Reading at least once a month at a reader (~50 available on the site)
- Possibility of checking the dose associated with a given operation (read the dosimeter before and after)
- Annual measurement of the neutron-dose or if the βγ-dose exceeds 2mSv in a month or 5 mSv since issue

Operational dosimetry

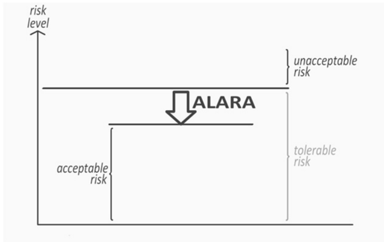
- Obligation to wear an operational dosimeter in a Controlled Radiation area
- Continuous $\beta\gamma$-dose measurement
- Instrument: DMC
- Display of Hp(10) (resolution of 1 μSv)
- Dose alarm adjustable
- Dose rate alarm adjustable
- Audible detection signal (« bip »)
- Record the dose before and after the operation

Passive monitoring of the environment

Thermoluminescence dosimeters (TLD) inside a polyethylene moderators are used to monitor neutron and gamma doses in the experimental areas and in the environment.

TLDs are passive devices used CERN-wide to integrate radiation doses over a period of several months.

Implementation of ALARA at CERN



Already since December 2006:
- systematic, formalized approach
- since 2009 applied to CERN radiation areas

With the goal to optimize work coordination, work procedures, handling tools, and even the design of entire facilities. Consequently, a close collaboration between RP and many departments in CERN is required.

All work in radiation areas has to be optimised

- Supervised Radiation Area: general optimisation by shielding, optimised installation of workplaces…
- Controlled Radiation Areas: All work must be planned and optimised including an estimate of the collective dose and of the individual effective doses to the workers participating in the completion of the task (Dossier D'Intervention en Milieu Radioactif - DIMR).

most of the ALARA elements were already used all over CERN in the past.

ALARA at CERN – 3 levels

CRITÈRE DE DÉBIT DE DOSE

Débit d'équivalent de dose prévisionnel ($\dot{H}$) dans la zone d'intervention :

niveau I	50 µSv·h^{-1}	niveau II	2 mSv·h^{-1}	niveau III

CRITÈRE DE DOSE INDIVIDUELLE

Équivalent de dose prévisionnel individuel (H_i) pour l'intervention, ou pour l'ensemble des interventions de même nature lorsque celles-ci sont répétées plusieurs fois sur une année :

niveau I	100 µSv	niveau II	1 mSv	niveau III

CRITÈRE DE DOSE COLLECTIVE

Équivalent de dose prévisionnel collective (H_c) pour l'intervention, ou pour l'ensemble des interventions de même nature lorsque celles-ci sont répétées plusieurs fois sur une année :

niveau I	500 µSv	niveau II	10 mSv	niveau III

CRITÈRE DE CONTAMINATION ATMOSPHÉRIQUE

Activité aérienne spécifique CA :

niveau I	5 CA	niveau II	200 CA	niveau III

CRITÈRE DE CONTAMINATION SURFACIQUE

Activité surfacique spécifique CA :

niveau I	10 CS	niveau II	100 CS	niveau III

ALARA procedures – 3 levels:
- If the rad. risk is **low**
  <> very light procedure
- If it is **medium**
  <> an optimization effort is required
- If it is **high**
  <> an optimization effort is required, the procedure will be submitted to the ALARA committee

CERN aims to optimize

- work coordination
- work procedures
- handling tools
- design
- material

to reduce dose to personnel

ALARA

Starts already during at the design phase:

- Choose the right material
- Design the components for optimised maintenance and repair (imagine yourself maintaining a radioactive component)
- Design the whole facility for optimised maintenance and repair (optimised lay-out, space, cranes, easy access to equipment, etc.)
- Consider remote handling as an option

Examples:

- Use of plug-in systems for very radioactive items allowing short installation and replacement times.
- Flanges for vacuum pipes which allow for easy coupling/de-coupling.
- Remote bake-out system for critical parts.
- Patch-panels for cables allowing an easier replacement and the use of especially radiation-resistant cables in high-loss areas.
- Use of cables with a radiation resistance of at least 500kGy.
- Placement of ionization chambers (PMI) to monitor remotely residual dose rates at locations with the highest expected losses.
- …..

Assessments of RP quantities for new facilities or upgrades/modification of existing facilities

- Prompt doses to areas: Their limitation and minimization can be achieved with placing sufficient shielding and an appropriate design of access passages. The assessment shall include accident scenarios.
- Air activation and releases into the environment: The results of related studies define the requirements on the ventilation system that will be designed and implemented accordingly. It has to minimize both the releases into the environment as well as doses to personnel entering the accelerator and experimental areas.
- Activation of beam-line components and dumps: Significant experience exists at CERN in design optimizations of components and their handling in order to limit dose to personnel according to the ALARA principle. In particular, residual dose rates have to be sufficiently low in areas where frequent accesses are required.
- Activation of liquids, especially cooling and infiltration water and concrete/soil: Depending on the predicted activation levels handling constraints and release pathways will be defined.

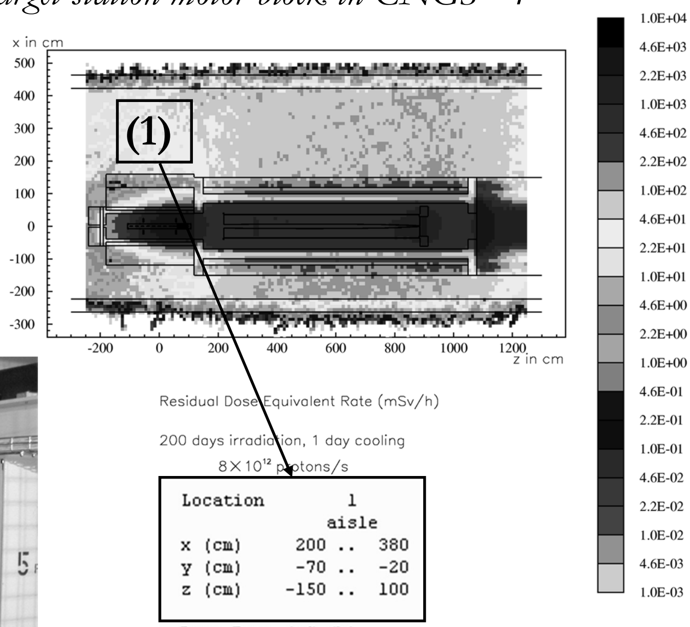
Assessments of RP quantities for new facilities or upgrades/modification of existing facilities

- Definition and implementation of a radiation monitoring system in order to control prompt dose rate levels in adjacent accessible areas during operation, to assess residual dose rates during beam-off periods as well as to monitor releases of air and liquids into the environment.
- An estimation of the production of radioactive waste: It has to include an optimization in the choice of materials in order to minimize costs for waste disposal.
- Furthermore, radiation safety aspects have to be considered and related systems designed (e.g., the access and interlock system) in order to allow a safe operation of the facility.

Interventions

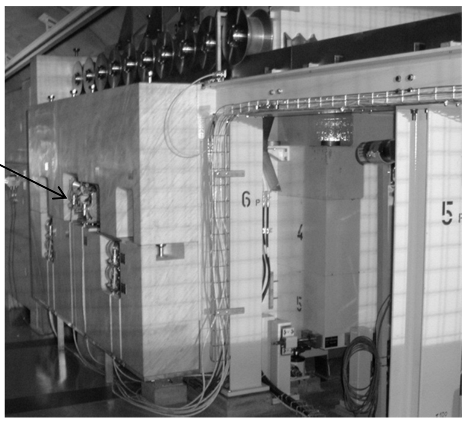
Exchange of target station motor block in CNGS - 1

1. Install lights **(1)**
2. Remove faulty motor block **(1)**
3. Transport of material (*e.g.,* new motor block) **(1)**
4. Install new motor block **(1)**
5. Transport of material (*e.g.,* faulty motor block) **(1)**
6. Remove lights **(1)**



Dose Rate (uSv/h)	
1 day	30494
1 week	470
1 month	254
2 months	190
4 months	149
6 months	124

motor block



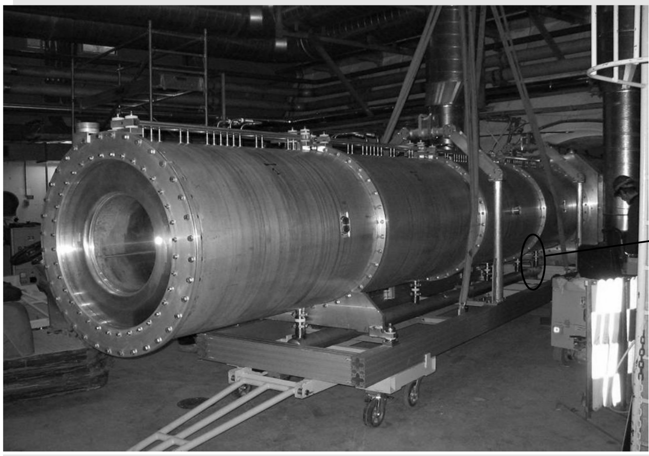
Interventions

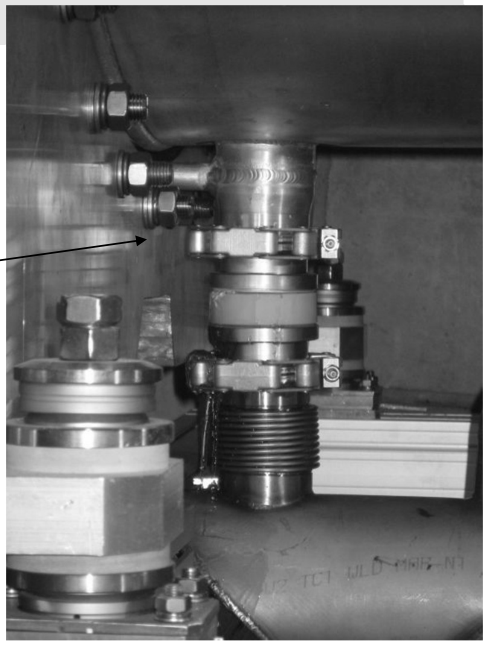
Exchange of target station motor block in CNGS -2

Intervention step	Duration (min)	Location	Accumulated dose (uSv) 1d	1w	1m	2m	4m	6m
Install lights	1.	1	508	7	4	3	2	2
Remove faulty motor block	5.	1	2541	39	21	15	12	10
Transport of material (e.g., new motor block)	2.	1	1016	15	8	6	4	4
Install new motor block	5.	1	2541	39	21	15	12	10
Transport of material (e.g., faulty motor block)	2.	1	1016	15	8	6	4	4
Remove lights	1.	1	508	7	4	3	2	2
Total (μSv):			8130	122	66	48	36	32

Examples – CNGS horn water circuit repair

Leak in water outlet of cooling circuit of reflector





Observation:

- High refill rate of closed water circuit of reflector cooling system
- Increased water levels in sumps

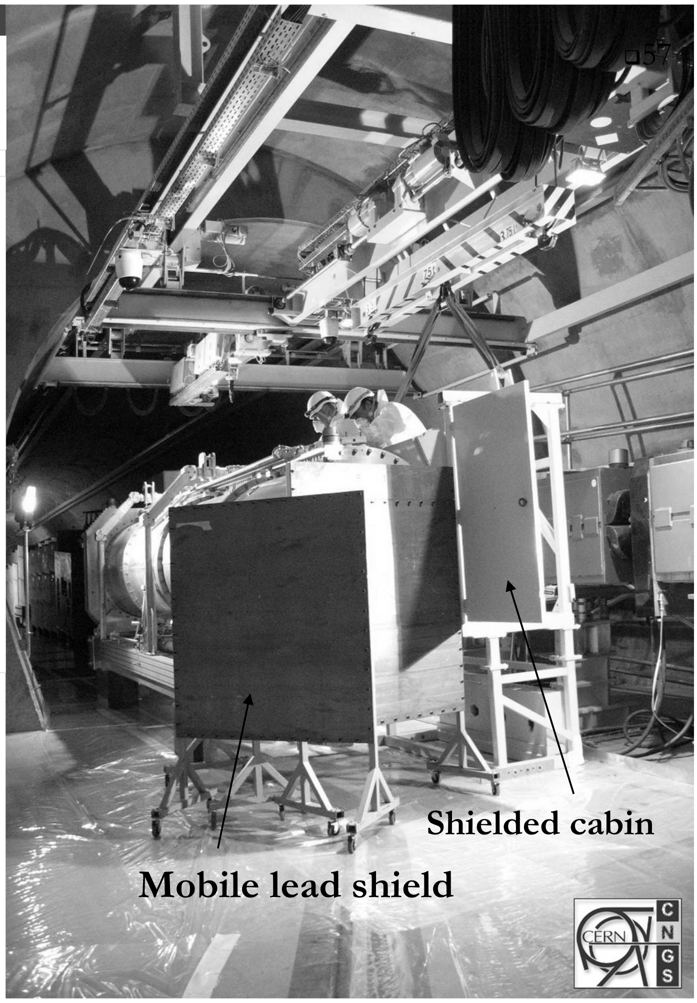
Reason:

- Inadequate design of water outlet connectors (machining, brazing)

Horn and Reflector Repair

→ Repair and exchange
- Detailed radiation dose planning and minimization
- Practice of repair/improvement work on the spare horn in order to reduce exposure time
- Personal protection equipment
- Each work step executed by up to 4 persons to reduce individual dose
- Additional local shielding (EN/MEF)

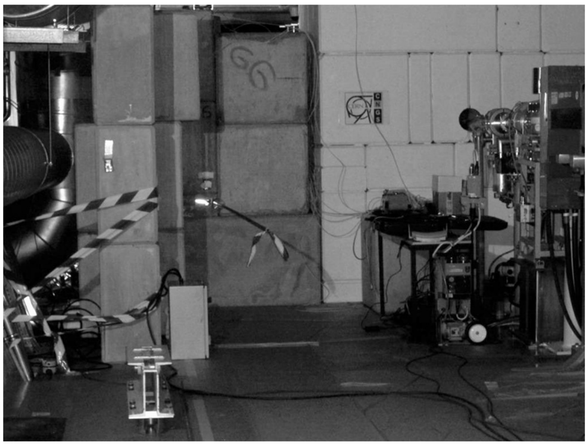
  → total integrated dose: 1.6 mSv

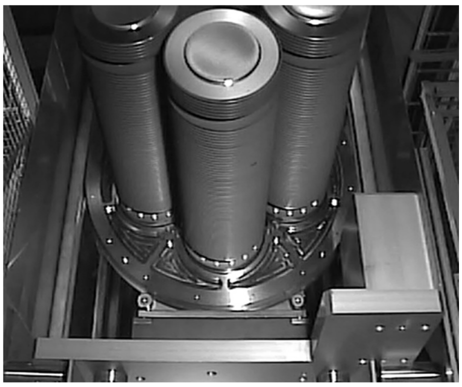


Inspection of the CNGS target

- Dry runs on spare target
- Installation of
  - temporary concrete shielding + thick lead glass + plastic cover on the floor
  - remote controlled cameras
  - Motor to rotate the target
- Remote controlled transport of the target
- Inspection done with an endoscope

  → total integrated dose: 287 uSv (17 persons, dose max 48 uSv)





Dismantling of TCX blocks in TCC6

- Modification of a forklift
  - Installation of a lead shield and lead glass
  - Design of a new 'fork'

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