Radiation Protection at High Energy Accelerator Laboratories

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CAS, Divonne 27 February 2009

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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
- …

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

Definition of Radiation Safety

Radiation safety: The achievement of proper operating conditions, preventions of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards.

- shielding
- beam operation
- access system
- fire prevention
- ventilation
- optimized design of facility
- …

Responsibility of **the owner of the source** emitting ionizing radiation
(CERN: Departments BE, PH, ENG, TE)

Ionising Radiation

www.bfs.de

Ionising radiation are

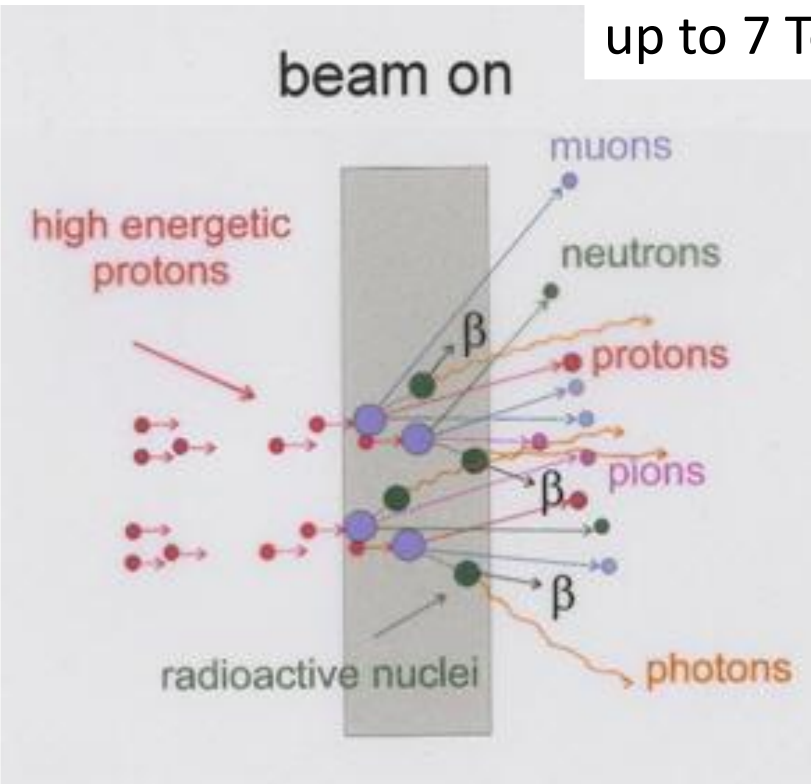
- photons (X-rays, γ-radiation)
- particles (α-, β- (e^+, e^-), p^+,p^-,n, π^+, π^-, μ^+, μ^-...)

transporting sufficient energy to ionise atoms and molecules

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

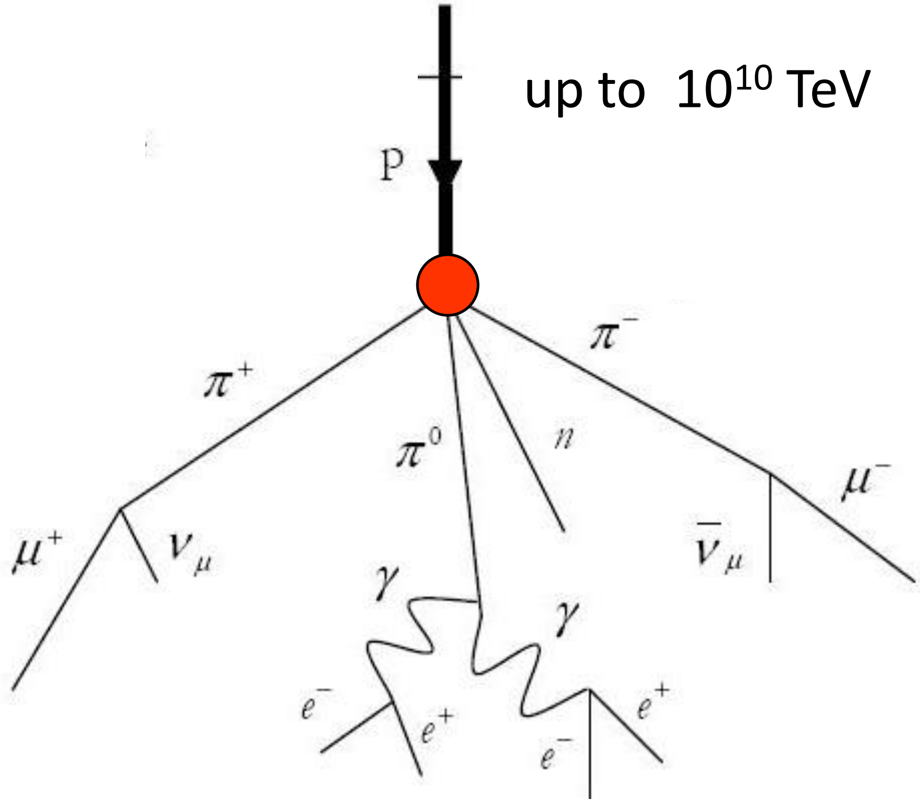
Ionising radiation is part of the nature and of human activities in medicine, research, industry, energy production and military

Prompt Ionising Radiation



up to 7 TeV

hadron accelerator



up to 10^{10} TeV

cosmos

high energy, mixed radiation fields

Radiation Showers

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

Hadronic shower only

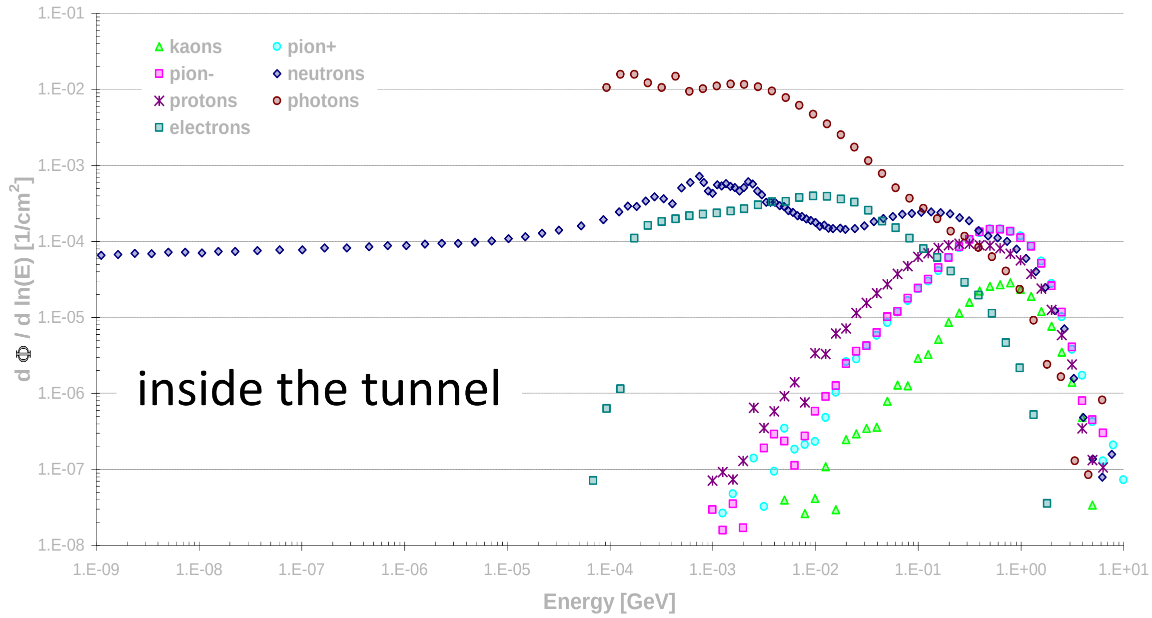
Hadronic shower + photons

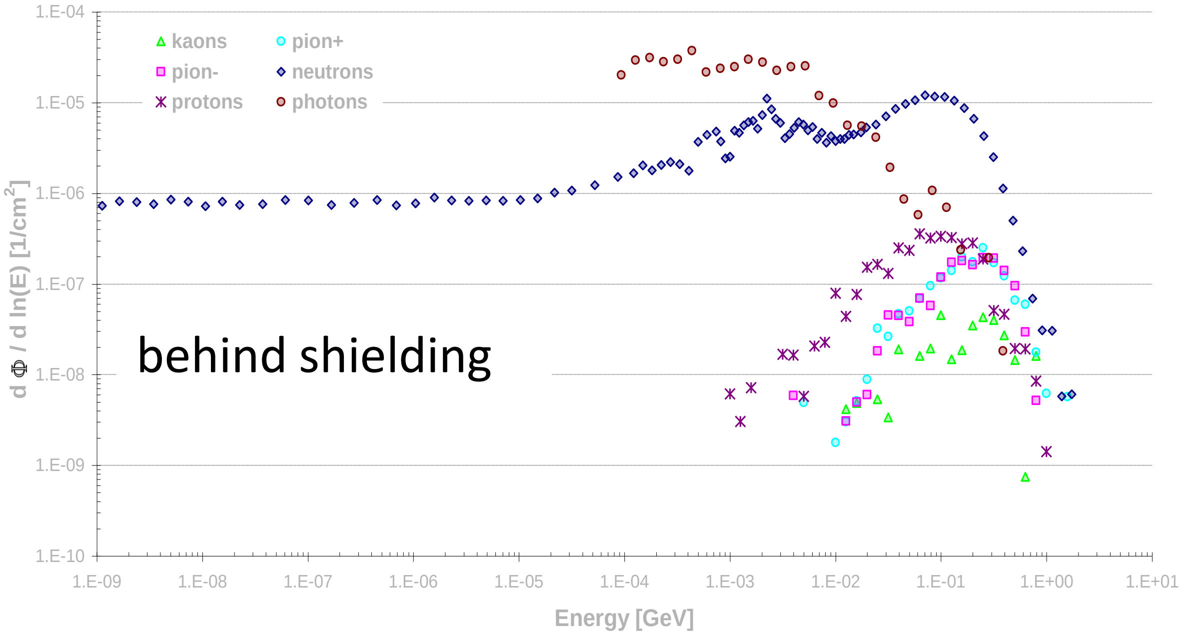
Particle fields (SPS)

Attenuation of radiation H_0 (point source):

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

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





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

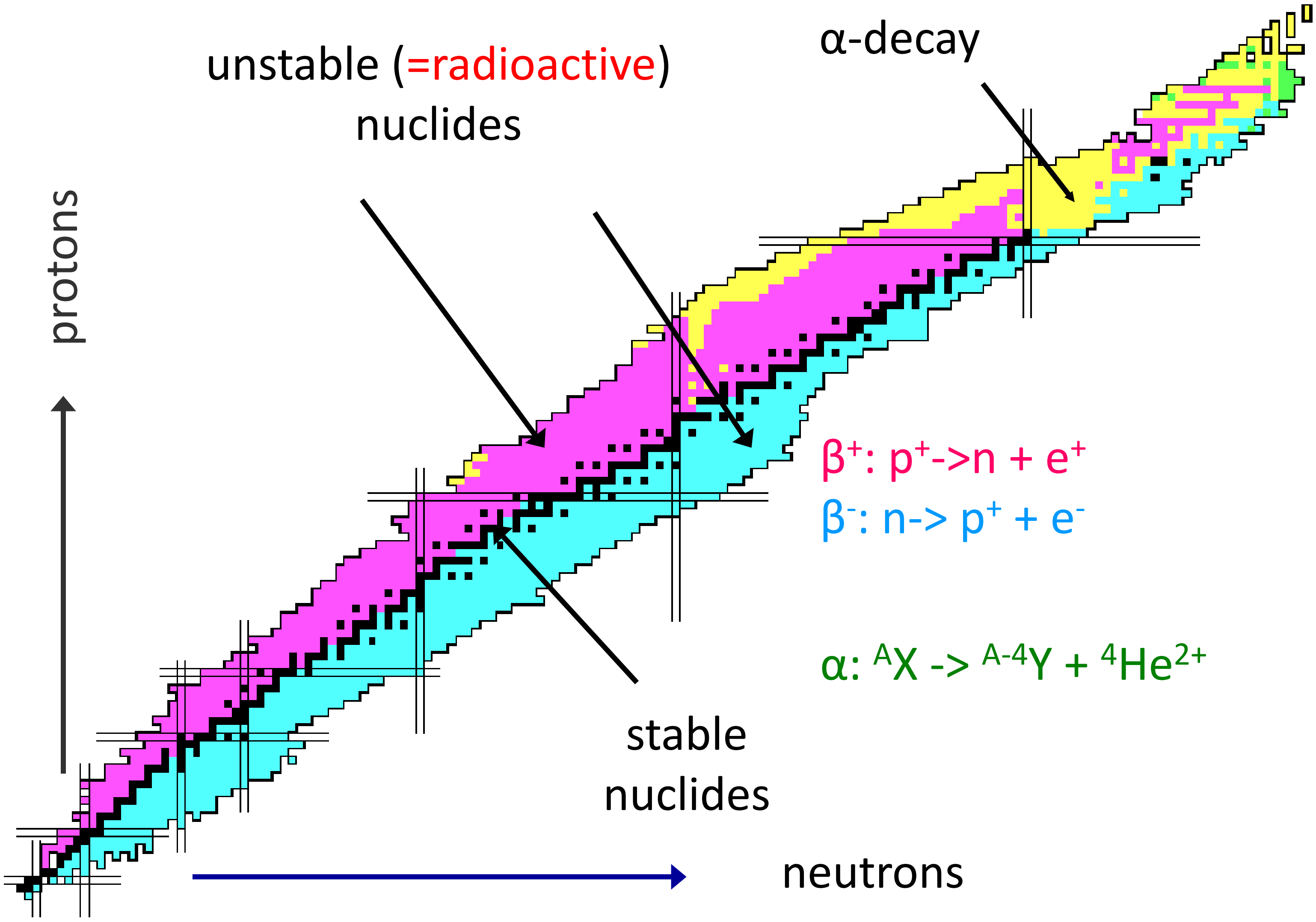
$$A(t) = -dN/dt\ [Bq] \qquad 1\ Bq = s\text{-}1$$

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



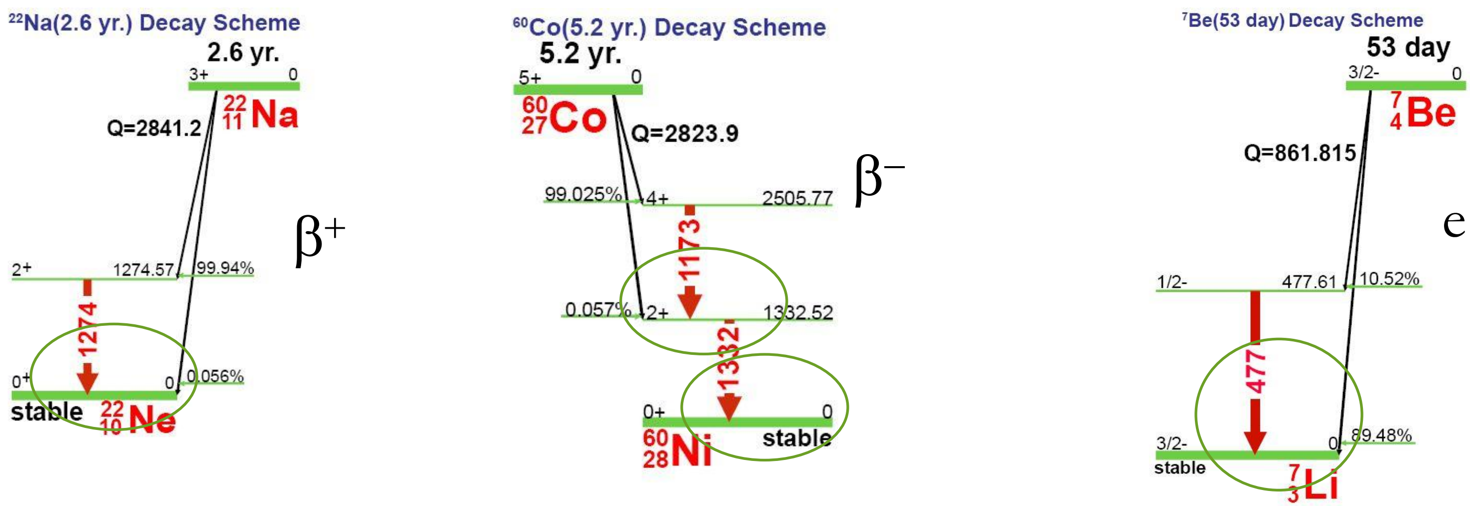
β^+: $p^+ \rightarrow n + e^+$

β^-: $n \rightarrow p^+ + e^-$

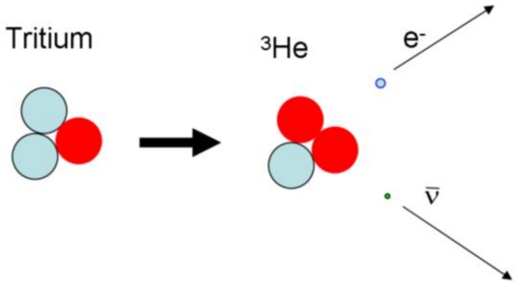
α: ${}^{A}X \rightarrow {}^{A-4}Y + {}^{4}He^{2+}$

Radioactivity

β-, γ-emitter:



pure β-emitter:



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

Terrestriel Radionuclides

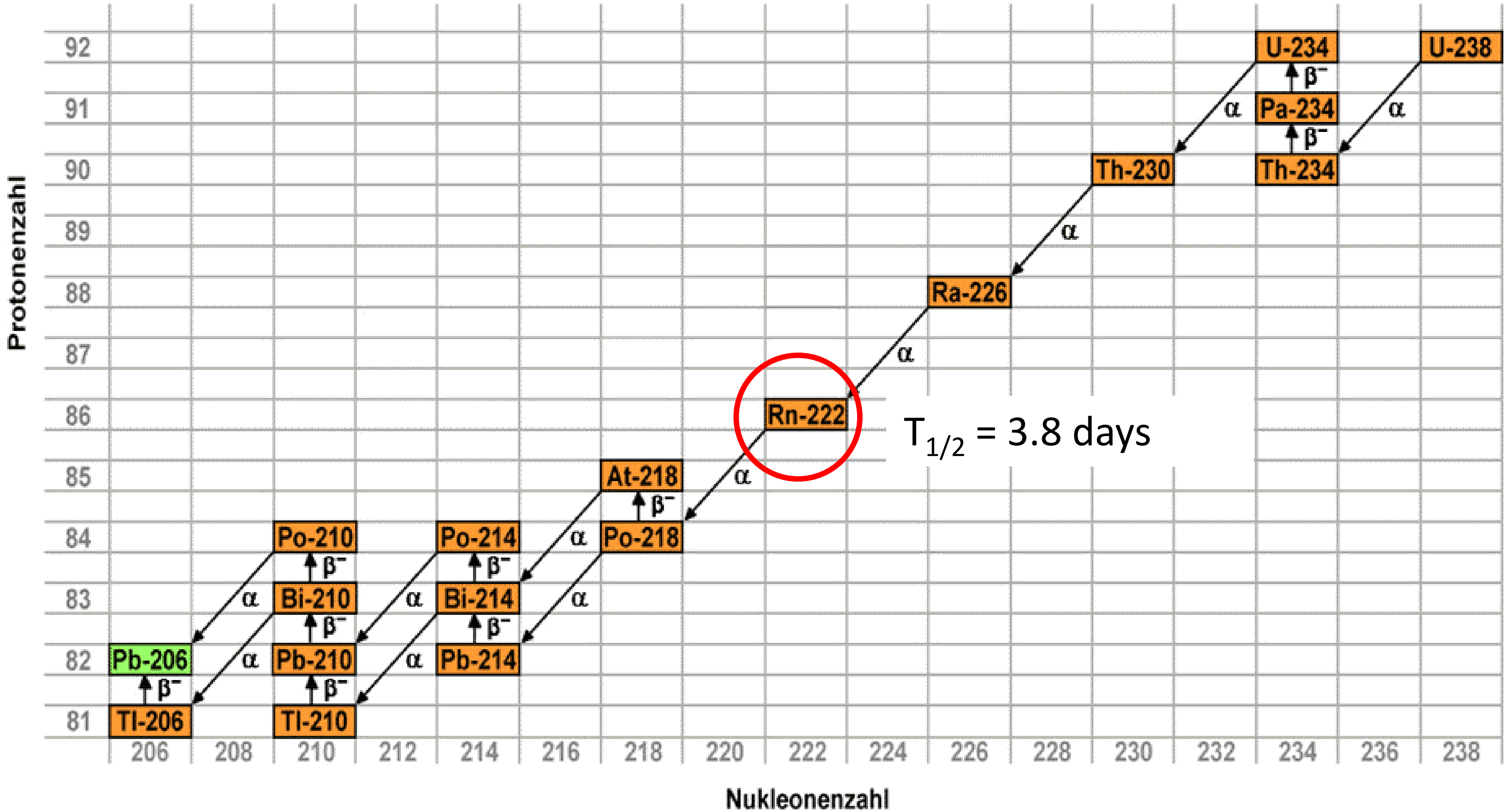
During the creation of the earth, terrestrial nuclides had been incorporated into the earth crust ($T_{1/2}$ some millions of years)

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:

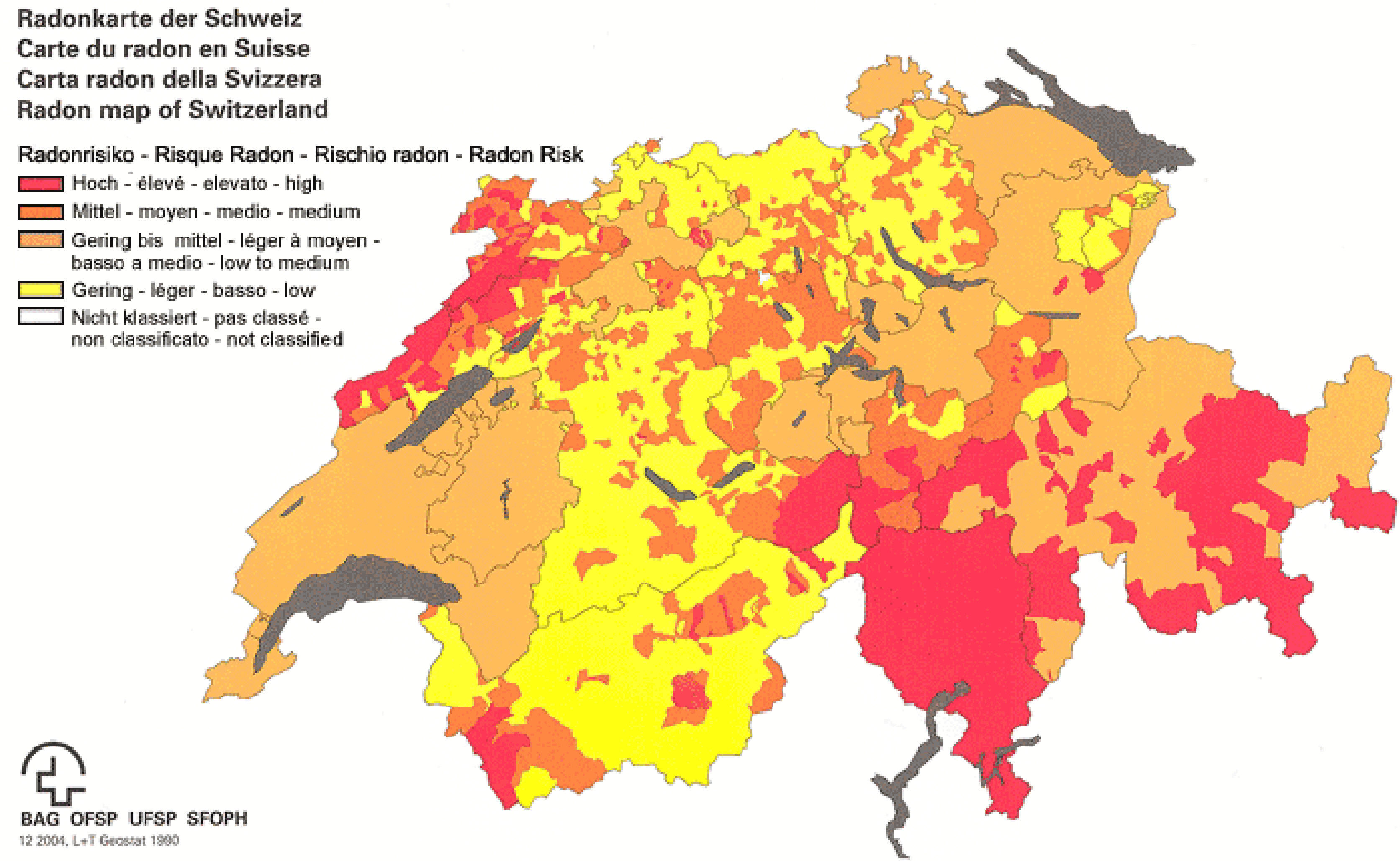
^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, … ^{190}Pt, ^{192}Pt, ^{209}Bi, …

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, …

...and we find radioactivity in our body

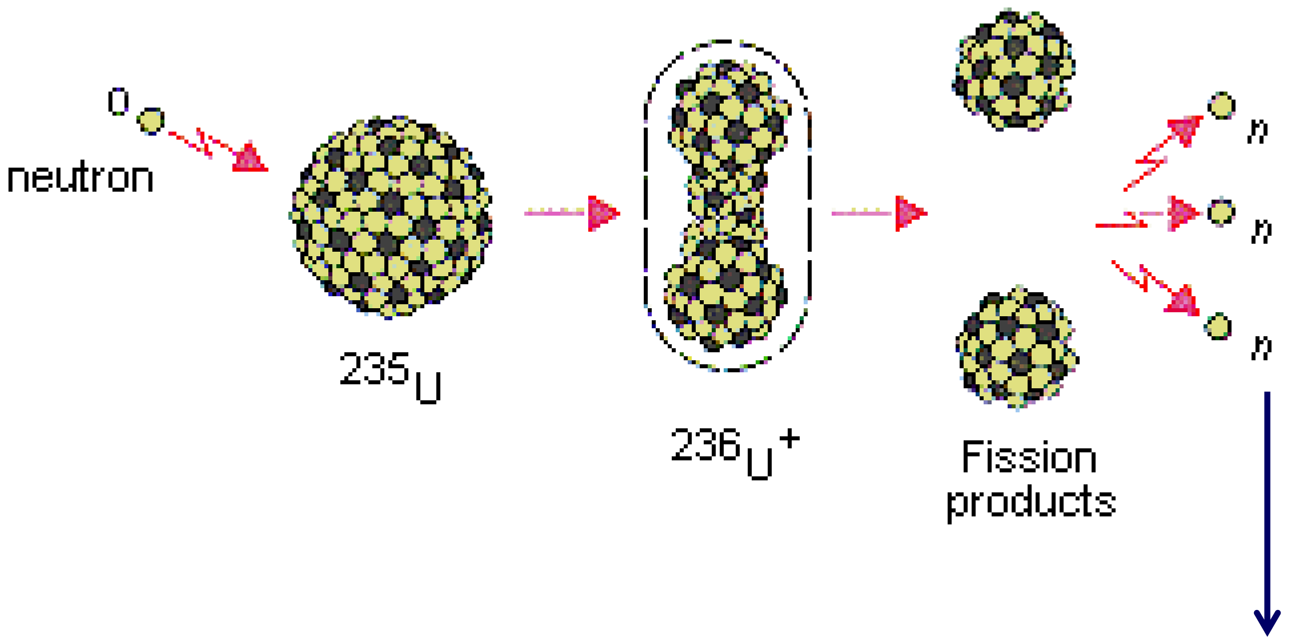
Nuclide	Total activity in human body (~ 70 kg)
Uranium	~ 1 Bq
Thorium	~ 0.1 Bq
Potassium 40	~ 4 - 5 kBq
Radium	~ 1 Bq
Carbon 14	~ 15 kBq
Tritium	~ 20 Bq

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

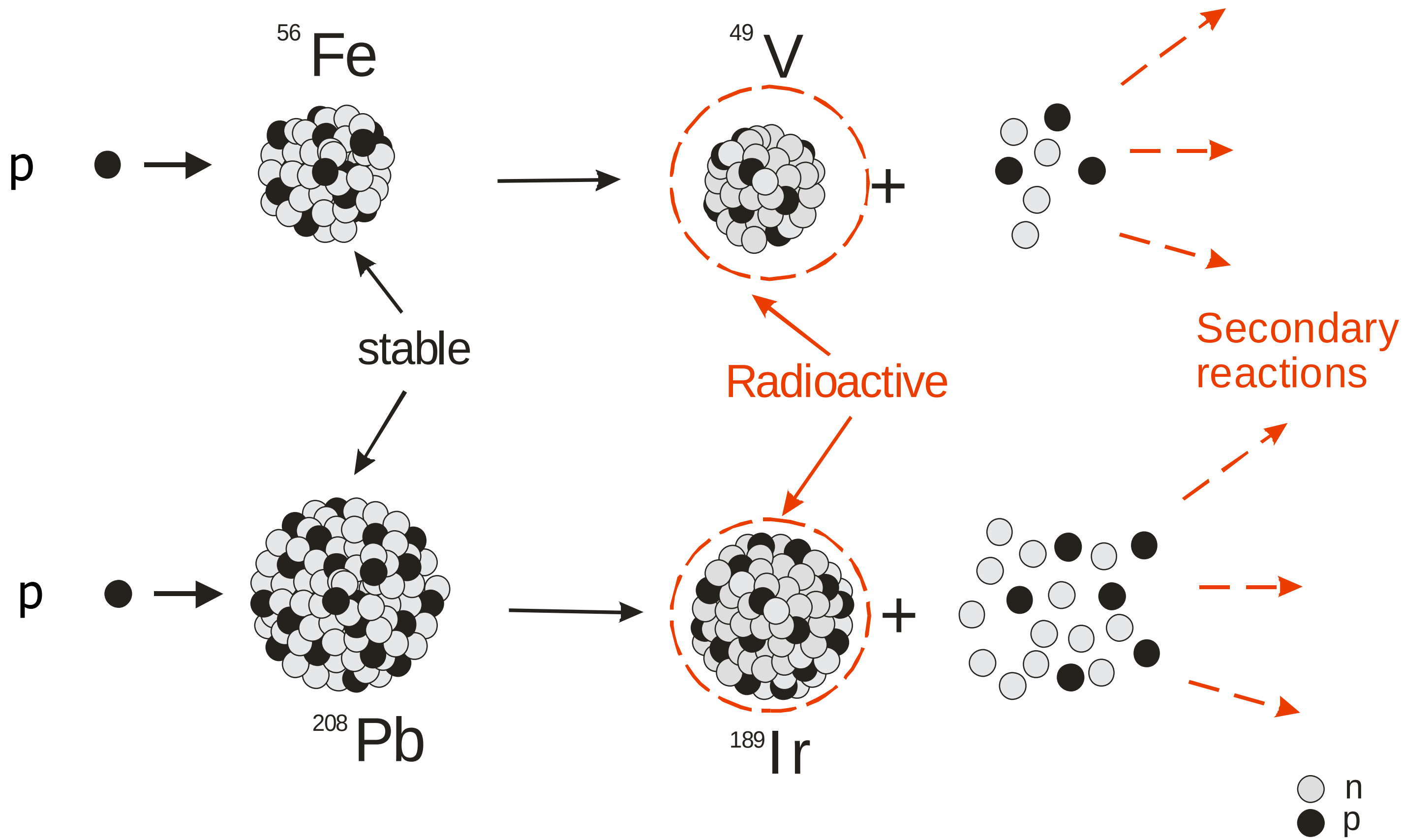


thermal neutron capture

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

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

Spallation

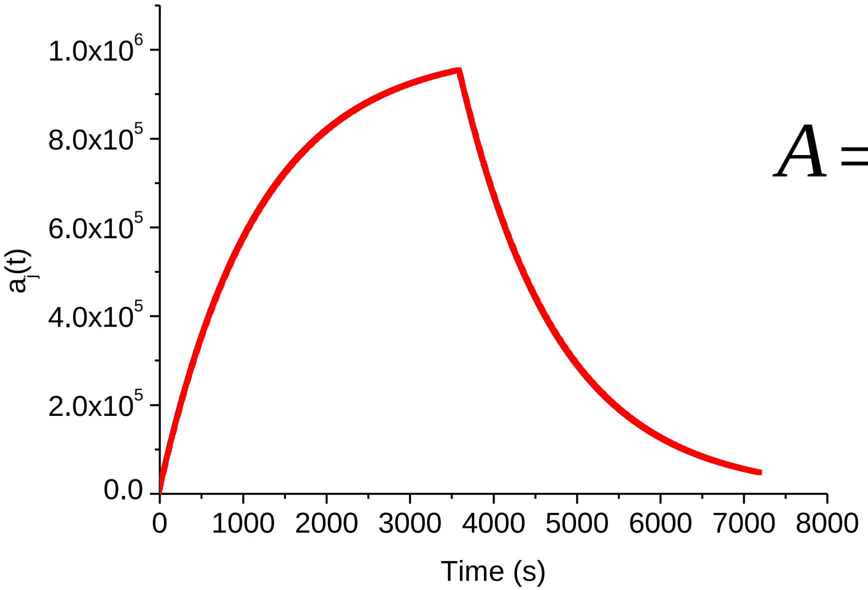


56 Fe
49 V
p
+
stable
Radioactive
Secondary reactions
p
+
208 Pb
189 Ir
n
p

Production and Decay of Radionuclides

Rule-of-thumb (probably very obvious):

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

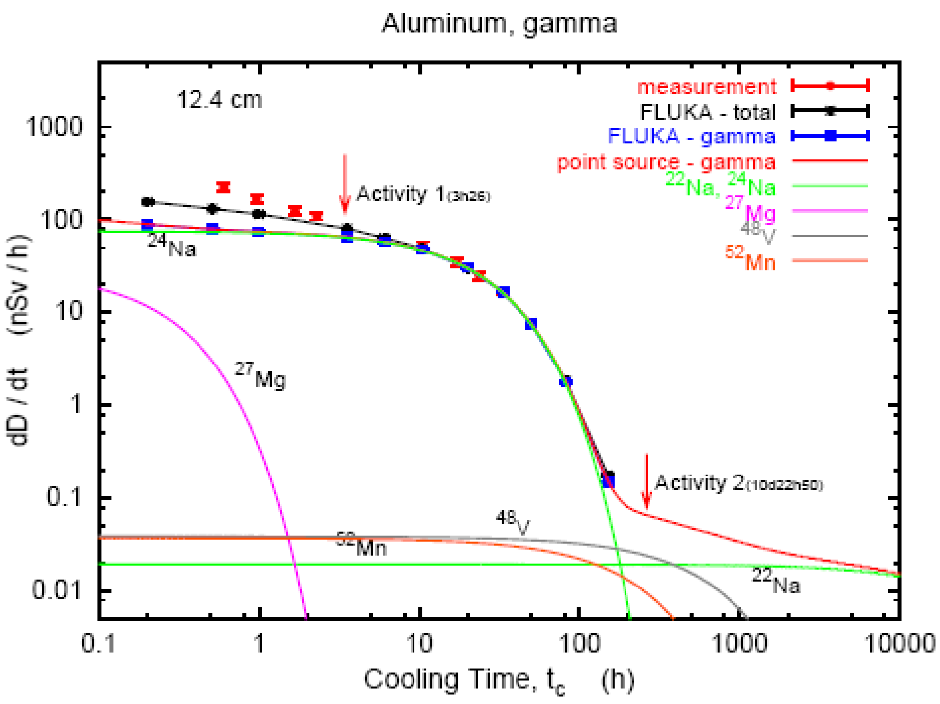


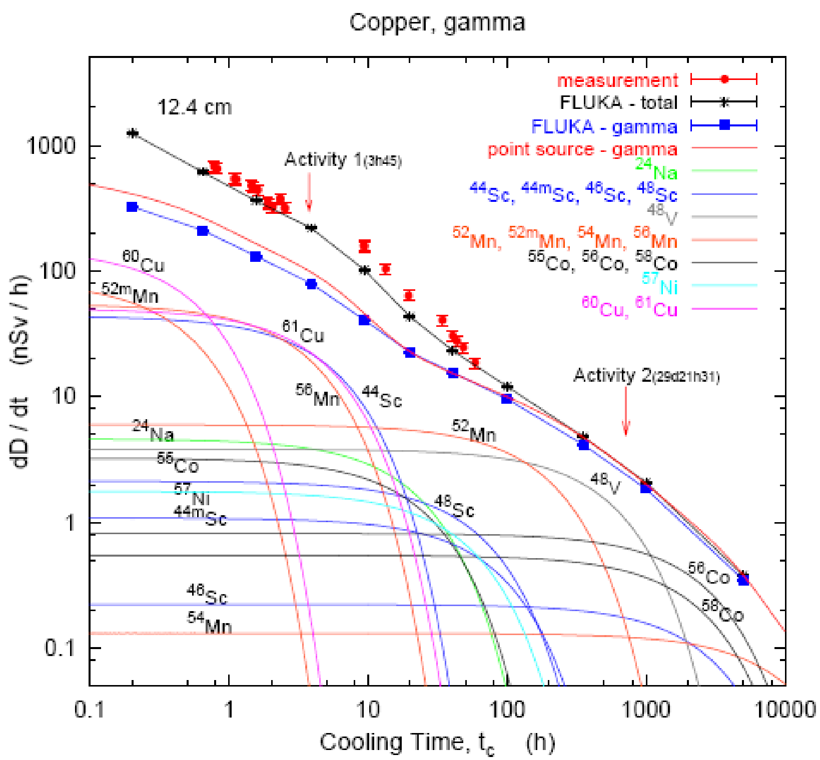
$$A = A_s (1 - e^{-t_{irr}/\tau}) e^{-t_{dec}/\tau}$$

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

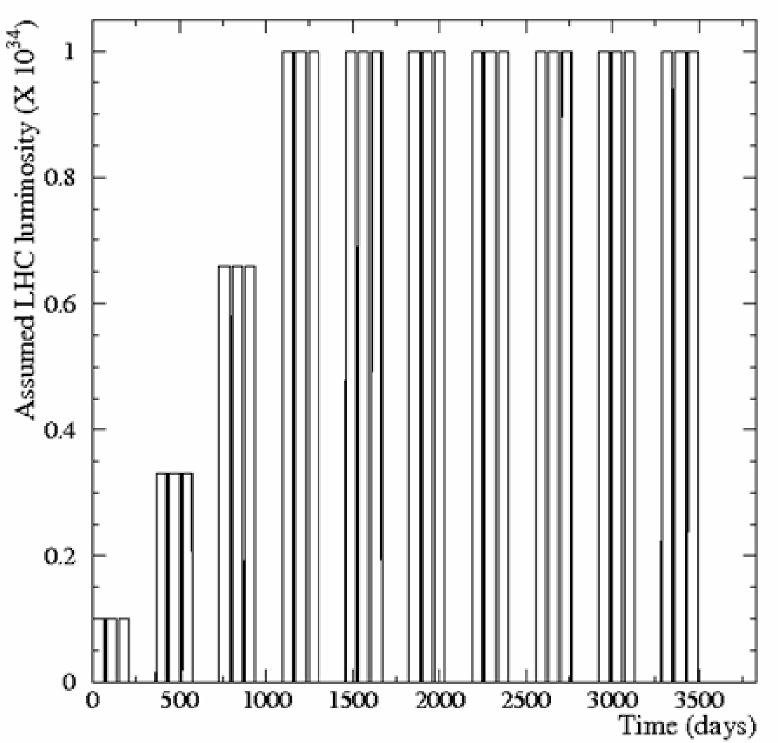
Activation of Material

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

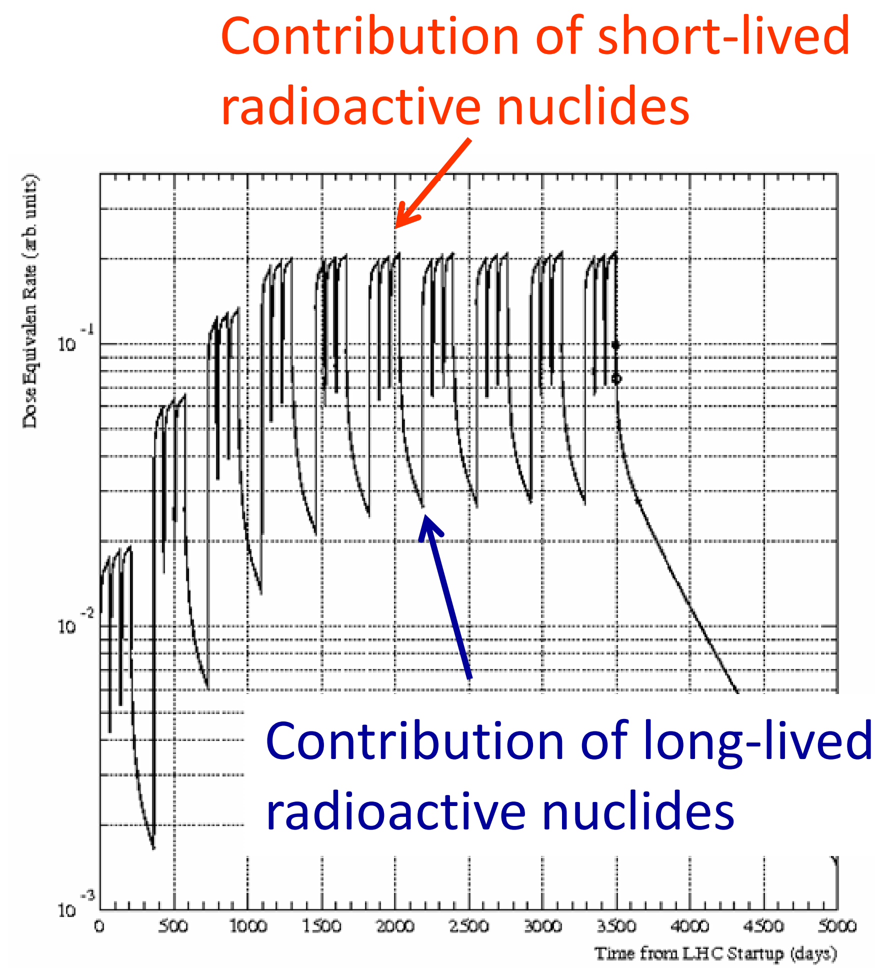




Ambient Dose Equivalent Rate as Function of LHC Operation

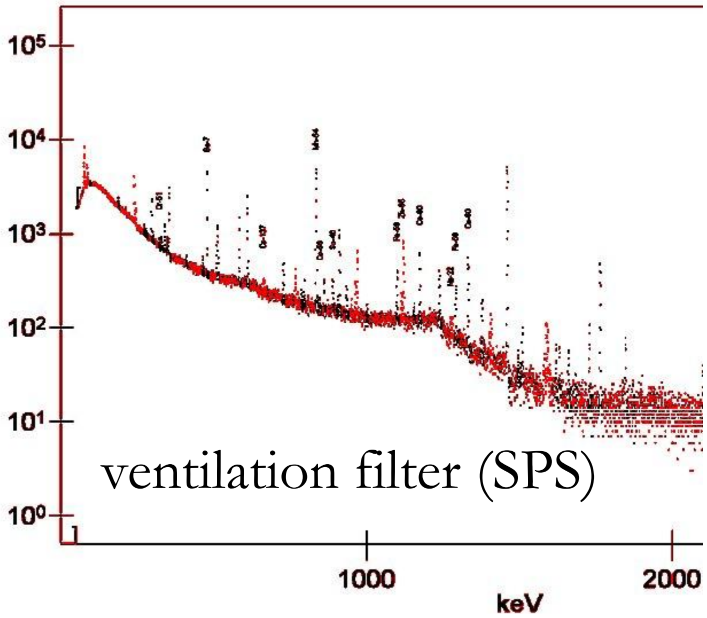


M. Huhtinen, RPC/2003/XXXVIII/138



Activation

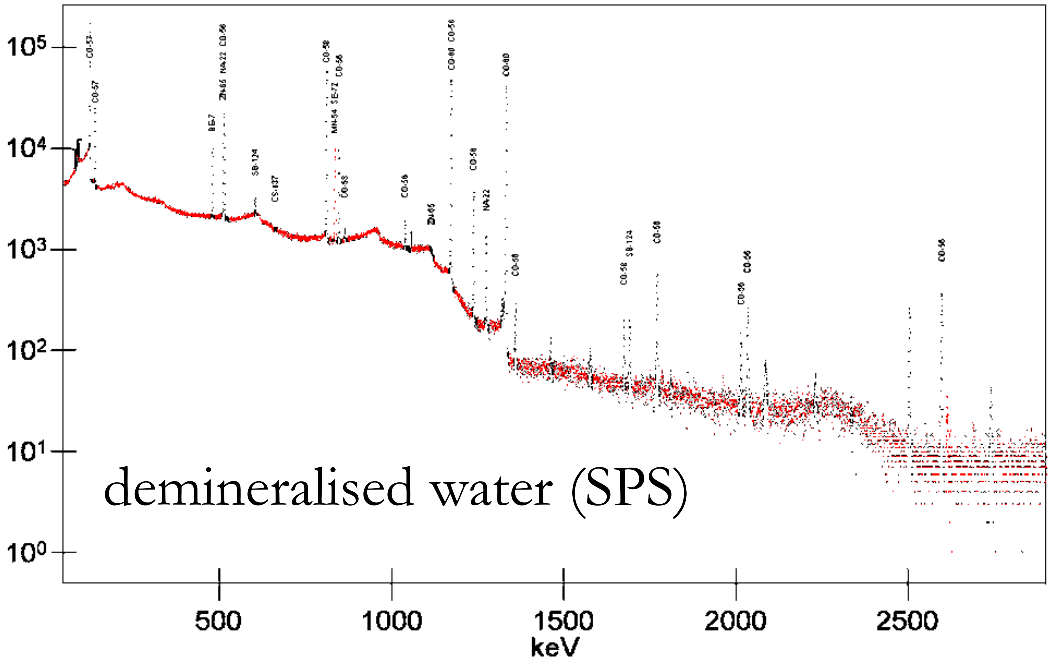
of air, gas, water, cooling liquids,



ventilation filter (SPS)

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



demineralised water (SPS)

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

Radiological Quantities and Units

Absorbed Dose D: energy absorbed per mass

Unit: 1 Gy = 1 J/kg

$$D_T = \frac{1}{m_T} \int_{m_T} D\,dm$$

Equivalent Dose H: absorbed dose of organs weighted by the radiation weighting factor wR of radiation R:

Unit: 1 Sv (= w_R x Gy)

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

Effective dose E: Sum of all equivalent doses weighted with the weighting factor wT for tissue T

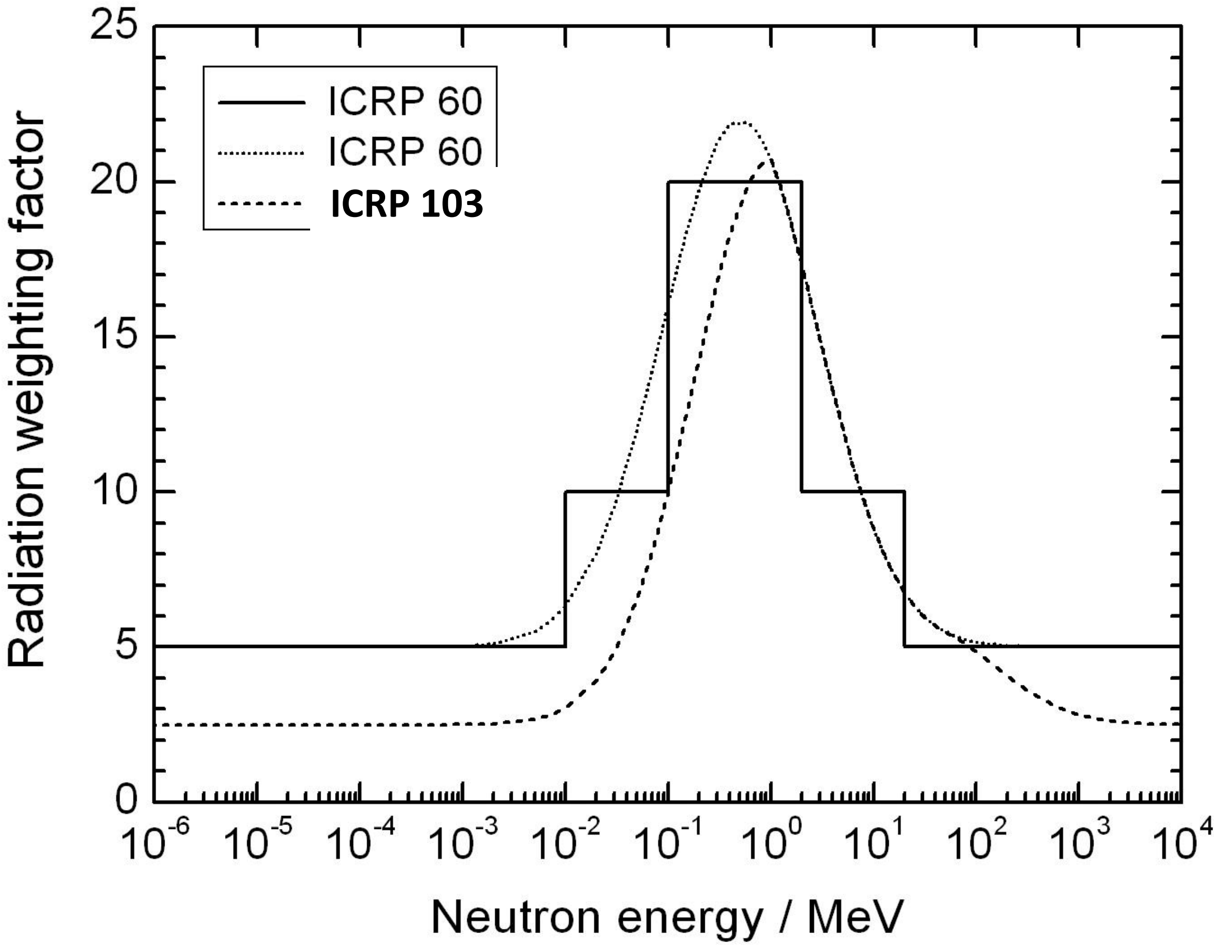
Unit: 1Sv

$$E = \sum_T w_T H_T$$

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 ICRP 103 (protons and charged pions)	5 (2)
Alpha particles, fission fragments, heavy nuclei	20

Neutron Radiation Weighting Factors (ICRP 103)



Values for neutrons replaced by a continuous function in ICRP 2007

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 dependent on the amount of absorbed dose

delayed health detriments

Deterministic effects:

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

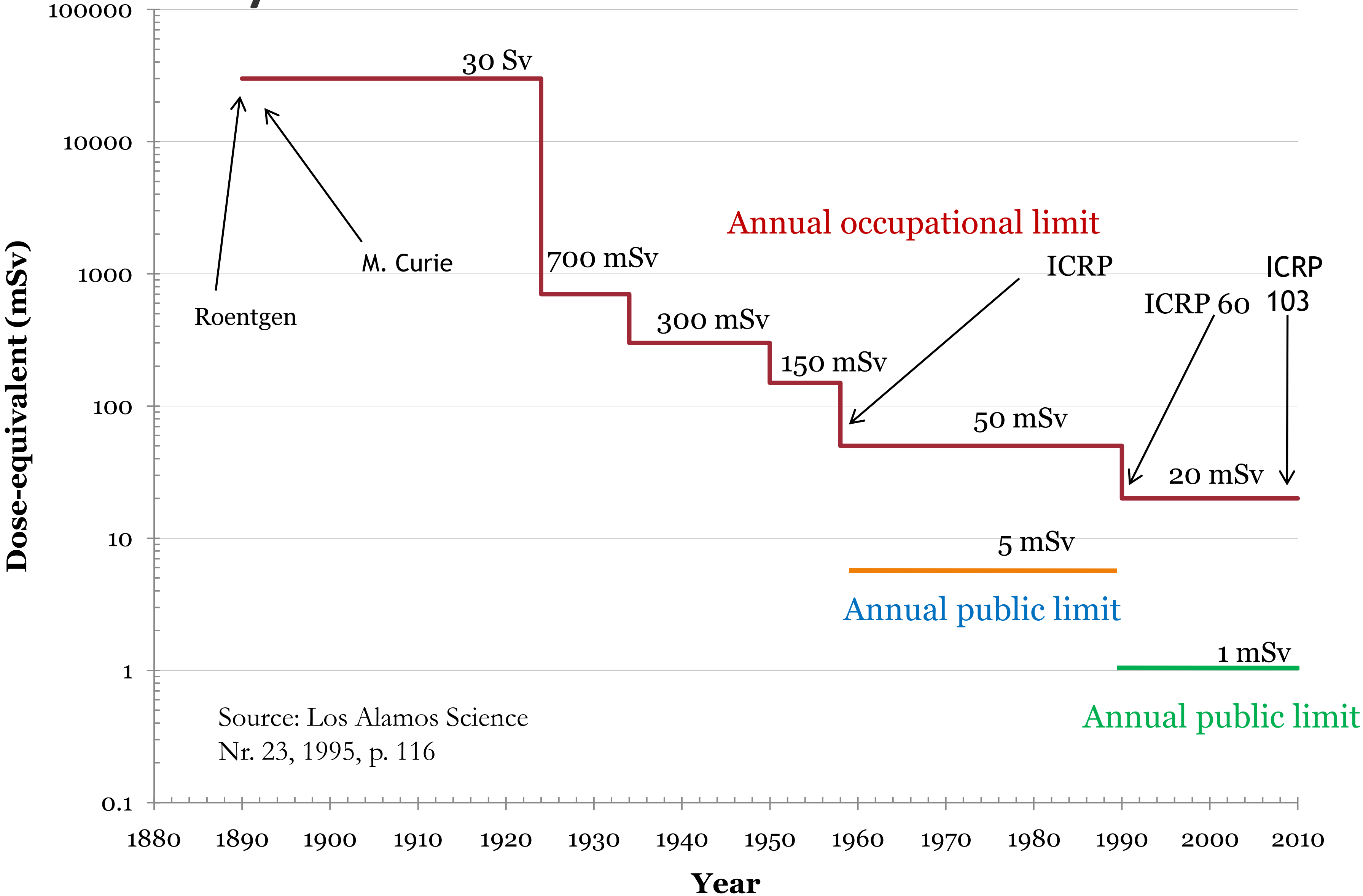
immediate consequences:

- vomiting
- immun deficiency
- erythema and necrose

health detriments are function of the dose

lethal dose: 5 – 7 Sv

History of Radiation Protection



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	
		A	B
EURATOM	< 1	< 6	< 20
Germany	< 1	< 6	< 20
CERN	< 0.3	< 6	< 20
Switzerland	< 1	< 20	

CERN's Area Classification

	Area	Dose limit [year]	Ambient dose equivalent rate		Sign	
			Work place	Low occupancy	RADIATION ZONE SURVEILLÉE / RADIATION ZONE CONTRÔLÉE CONTROLLED AREA	
	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 Protection Radioprotection	
Radiation Area	Simple	20 mSv	10 µSv/h	50 µSv/h	Dosimeter obligatory Dosimètre obligatoire Radiation Protection Radioprotection	Controlled Area
Radiation Area	Limited Stay	20 mSv		2 mSv/h	LIMITED STAY SÉJOUR LIMITÉ Dosimeters obligatory Dosimètres obligatoires Radiation Protection Radioprotection	Controlled Area
Radiation Area	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION HAUTE RADIATION Dosimeters obligatory Dosimètres obligatoires Radiation Protection Radioprotection	Controlled Area
Radiation Area	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA ZONE INTERDITE No Entry Défense d'entrer Radiation Protection Radioprotection	Controlled Area

Courtesy N. Conan, M. Widorski

Safety Instruction S3-GSI1, EDMS 810149

Optimization

- Any justified job is considered as optimized when different appropriate solutions have been evaluated and judged against each other from the radiation protection viewpoint,

- The decisional process leading to the chosen solution can be reconstructed at any time, and the risk of failure and the elimination of radioactive sources have been taken into account.

- Optimisation can be considered as respected if the activity never gives rise to an annual dose of more than 100 μSv for persons professionally exposed or 10 μSv for members of the public

CERN Reference Levels

Environment: The annual effective dose to the members of the reference group of the population (the most exposed group outside CERN) should stay **below 10 uSv per year**. The limit is 300 uSv per year.

Effective dose in uSv/year

Year	From air/water releases	From stray radiation	Total
2003	3	21	24
2004	5	10	15
2005	2	10	12
2006	5	3	8

Courtesy: P. Vojtyla SC-IE

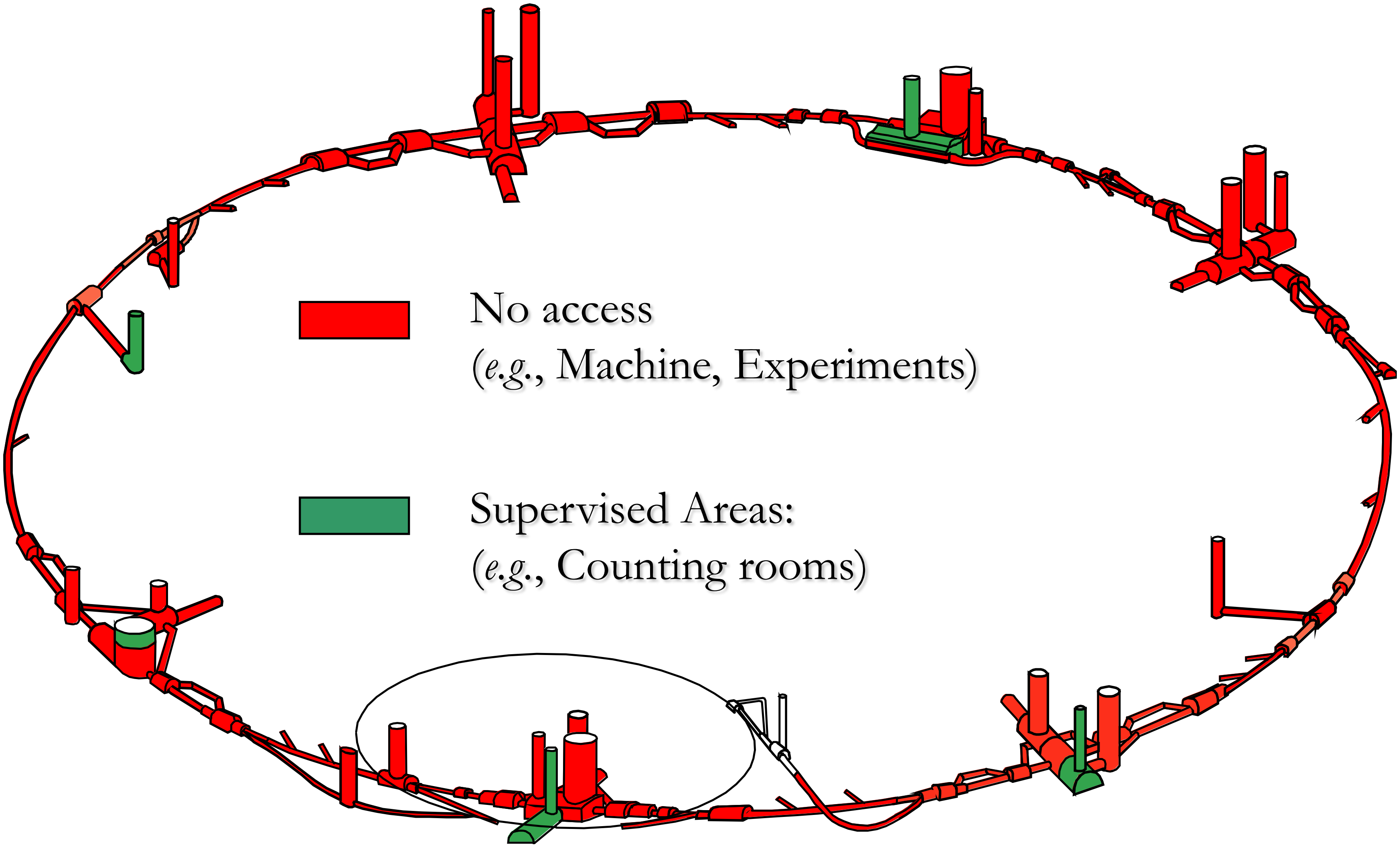
Annual dose due to natural radiation in Geneva area: ~ 800 uSv per year

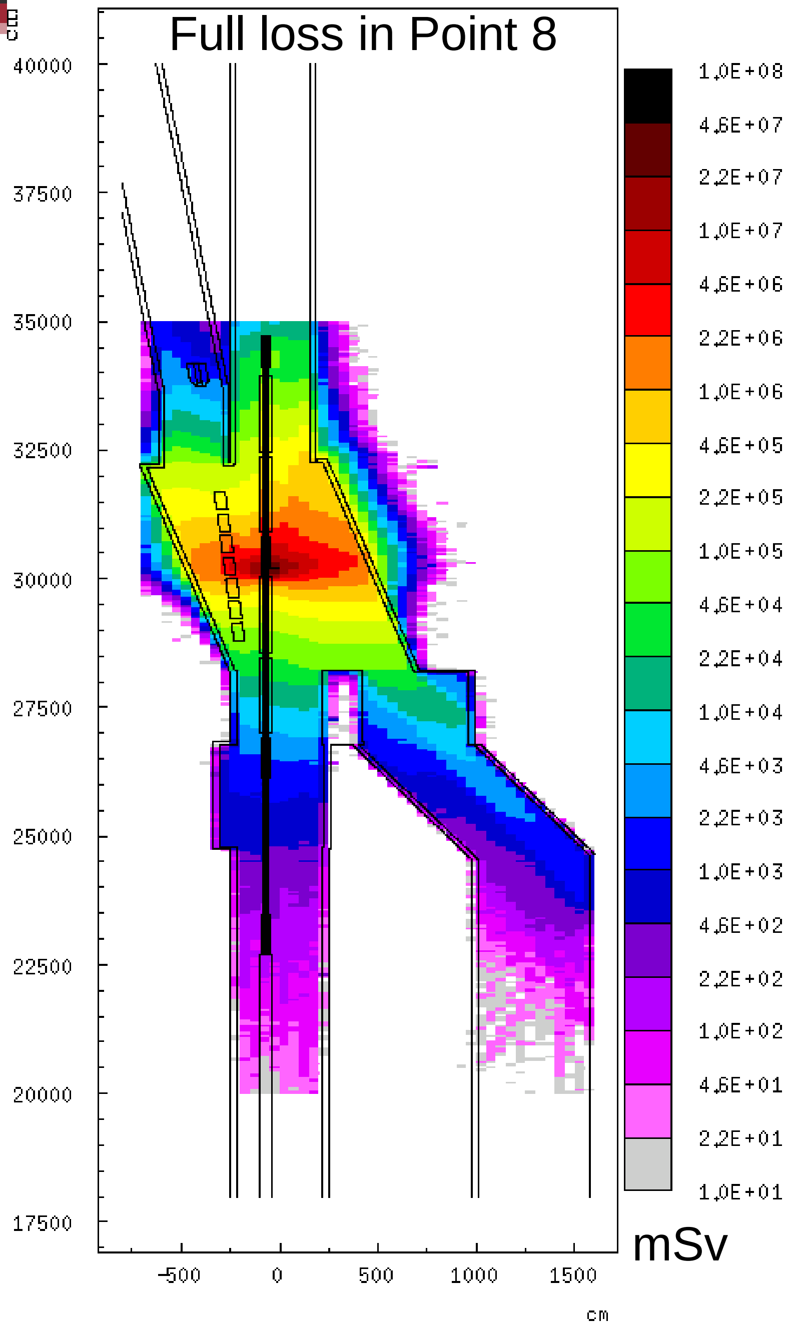
CERN Reference Levels

Occupationally exposed workers: Annual individual, effective dose should stay below 6 mSv

Year	Number of persons with effective doses above 6 mSv/year	Activity
2000	13	Cable changes, maintenance of beam instrumentation, transport, radiation protection
2001	2	Transport, maintenance of beam instrumentation
2002	2	Transport
2003	5	Transport, radiation protection, Gamma radiography
2004	0	
2005	0	
2006	0	
2007	0	

LHC Area Classification – Beam On





Distance to beam line (without shielding)	Dose for full beam loss (Gy)	Dose rate at quench limit (Sv/h)	Dose rate caused by beam gas interactions (mSv/h)	
			ultimate	nominal
1 m	5500	10	20	14
2 m	2500	5	10	7
3 m	1200	3.3	7	5
5 m	500	2	4	3

Remark: all dose and dose rates have to be doubled inside and increased by a factor of 20 % to 30 % outside due to photonic contribution

Quench limit: 1E7 protons/(m s)

Beam gas interactions (ultimate): ~1E16/year (200 days) ➔ 21400/(m s)

Attenuation of concrete:

100 cm concrete ➔ factor ~ 10

200 cm concrete ➔ factor ~ 100

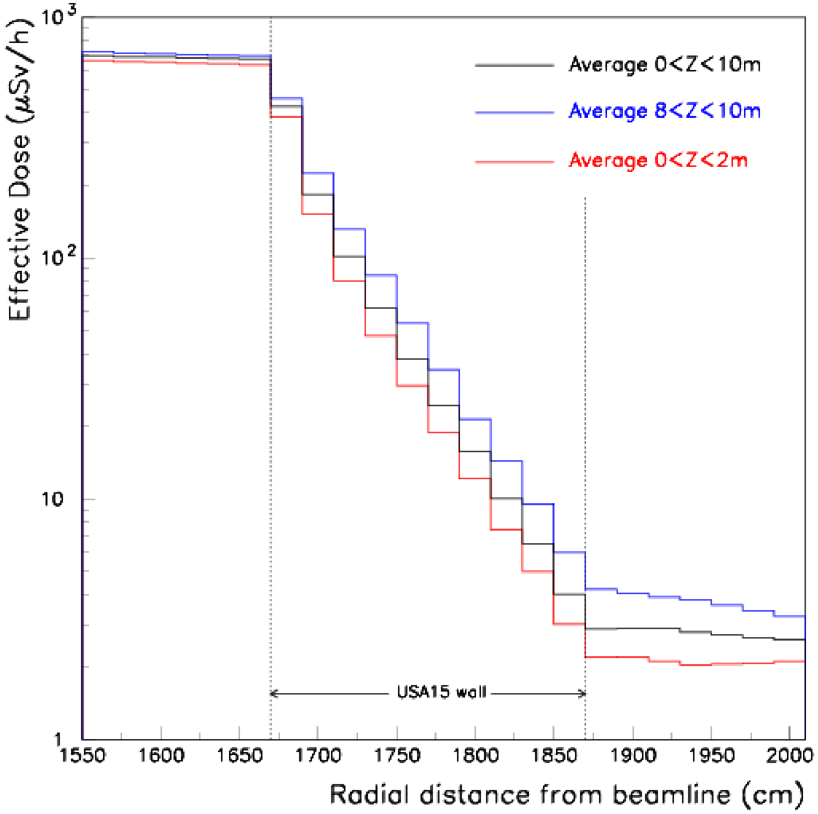
300 cm concrete ➔ factor ~ 1000

Sv/Gy: approximated with 5

Design of ATLAS shielding

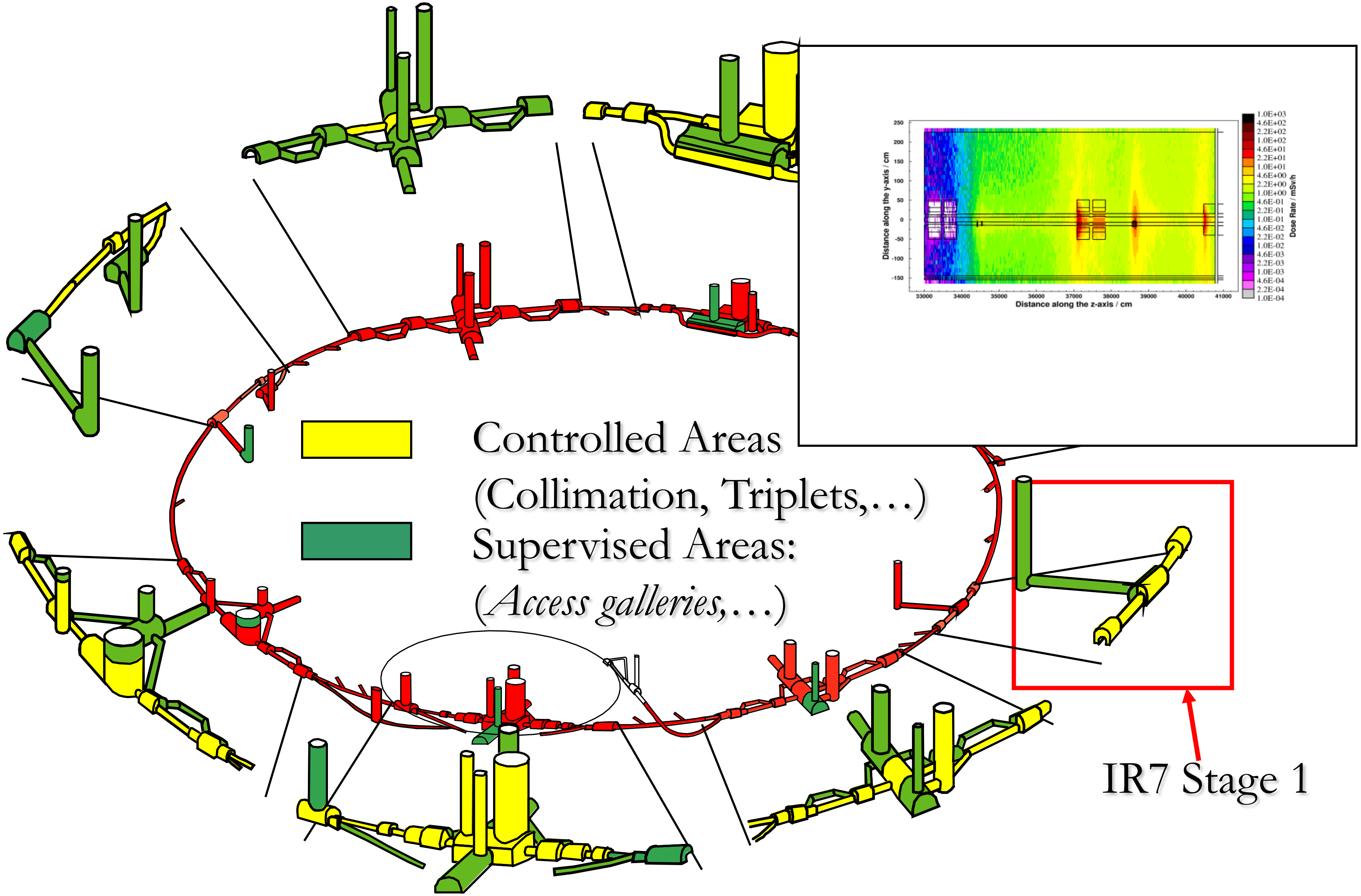
Effect of trigger holes is small (~15%). When these holes are filled their impact will be even smaller.

Dose rate varies in USA15 along the wall. Worst case are *~4 uSv/h*, and *~2uSv/h* in the central region where the trigger cable ducts are located.



Courtesy: Ian Dawson

LHC Area Classification – Beam Off



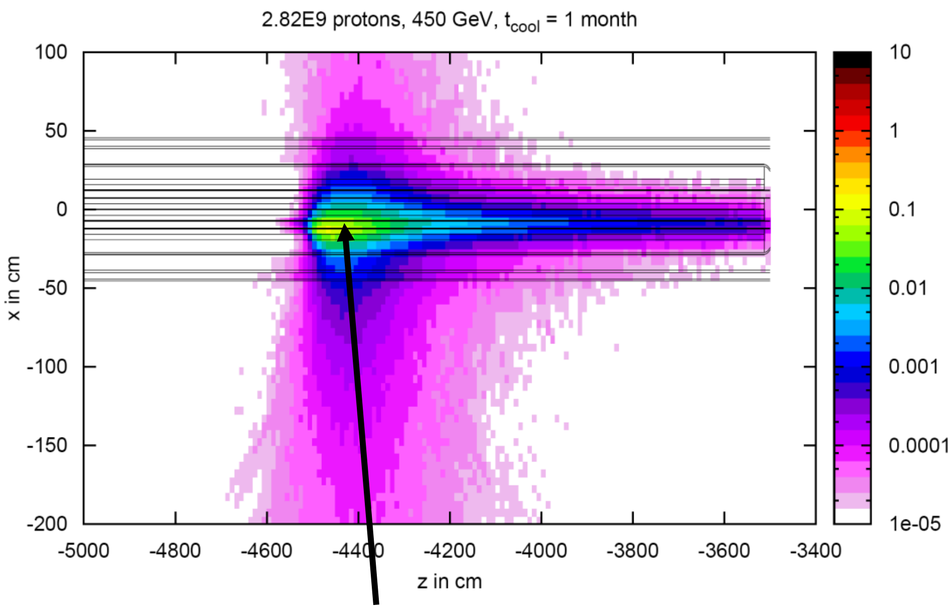
Arc: Loss of Single Bunch (2.82 x 10^9 protons)

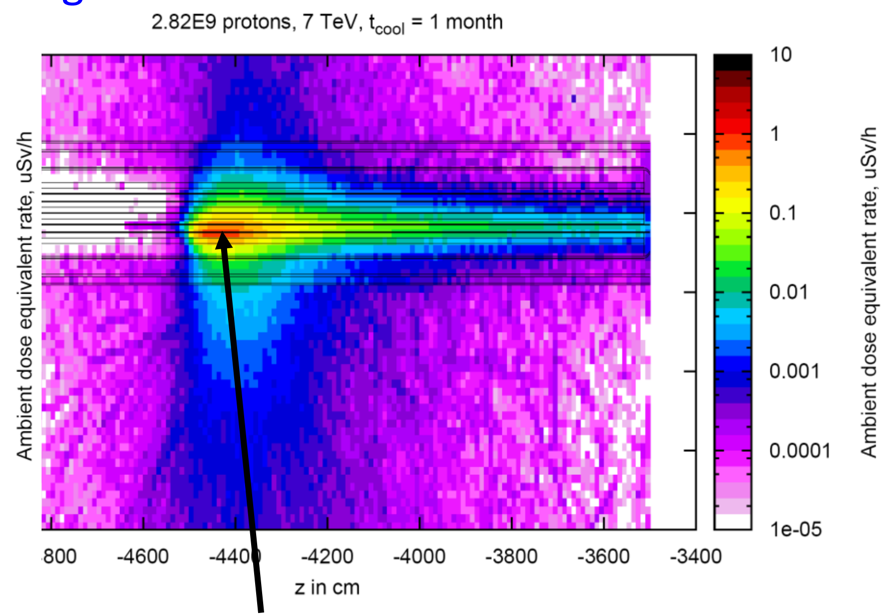
Ambient dose equivalent rate

450 GeV

1 month cooling

7 TeV





<150 nSv/h (contact)

~1 μSv/h (contact)

Residual dose rates scale with beam energy approximately like $E^{0.8}$

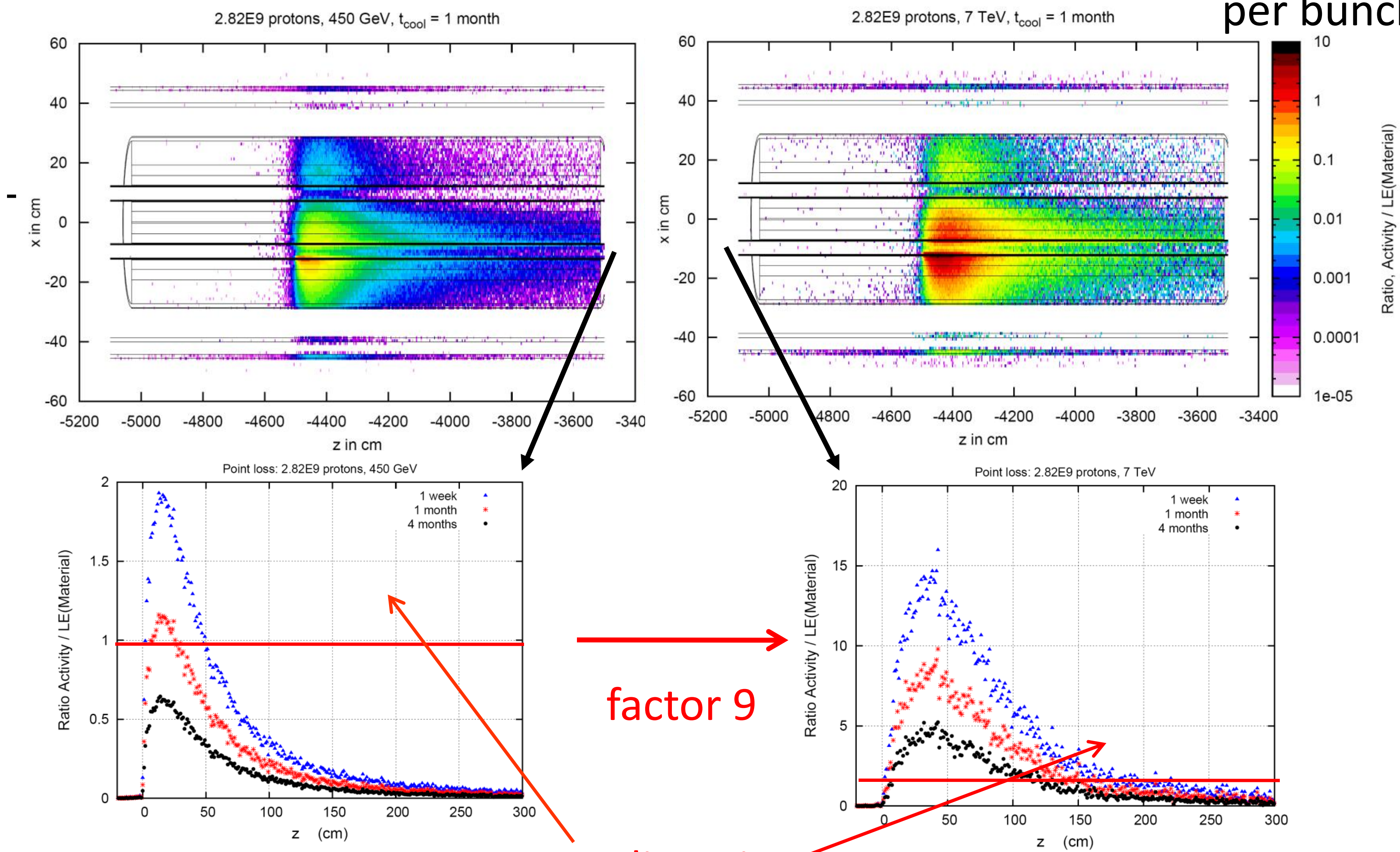
$(7000 \text{ GeV} / 450 \text{ GeV})^{0.8} = 9.0$

$(5000 \text{ GeV} / 450 \text{ GeV})^{0.8} = 6.8$

Arc: Specific Activity after Single Bunch Loss

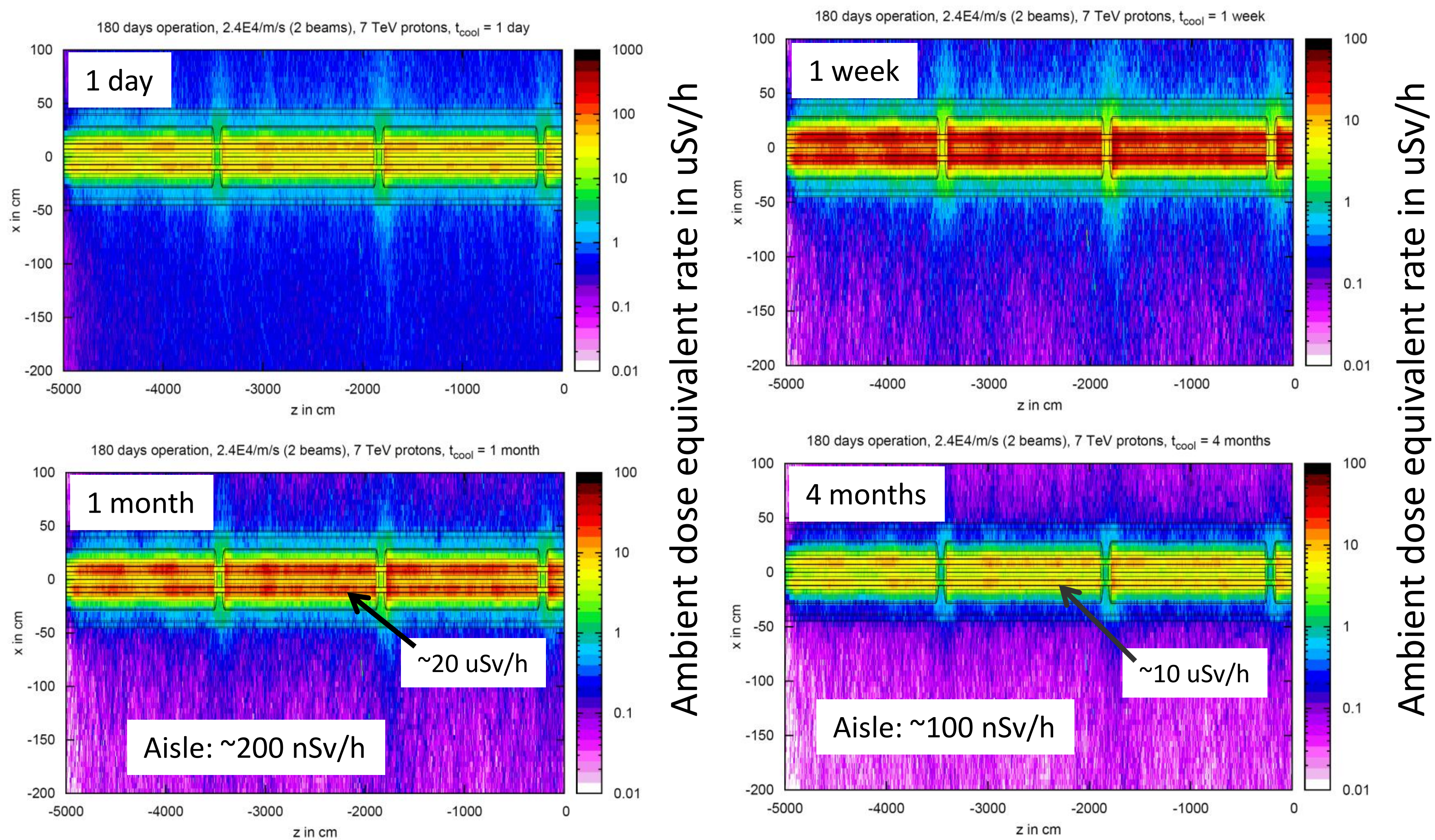
450 GeV 1 month cooling 7 TeV

2.8×10^9 p per bunch

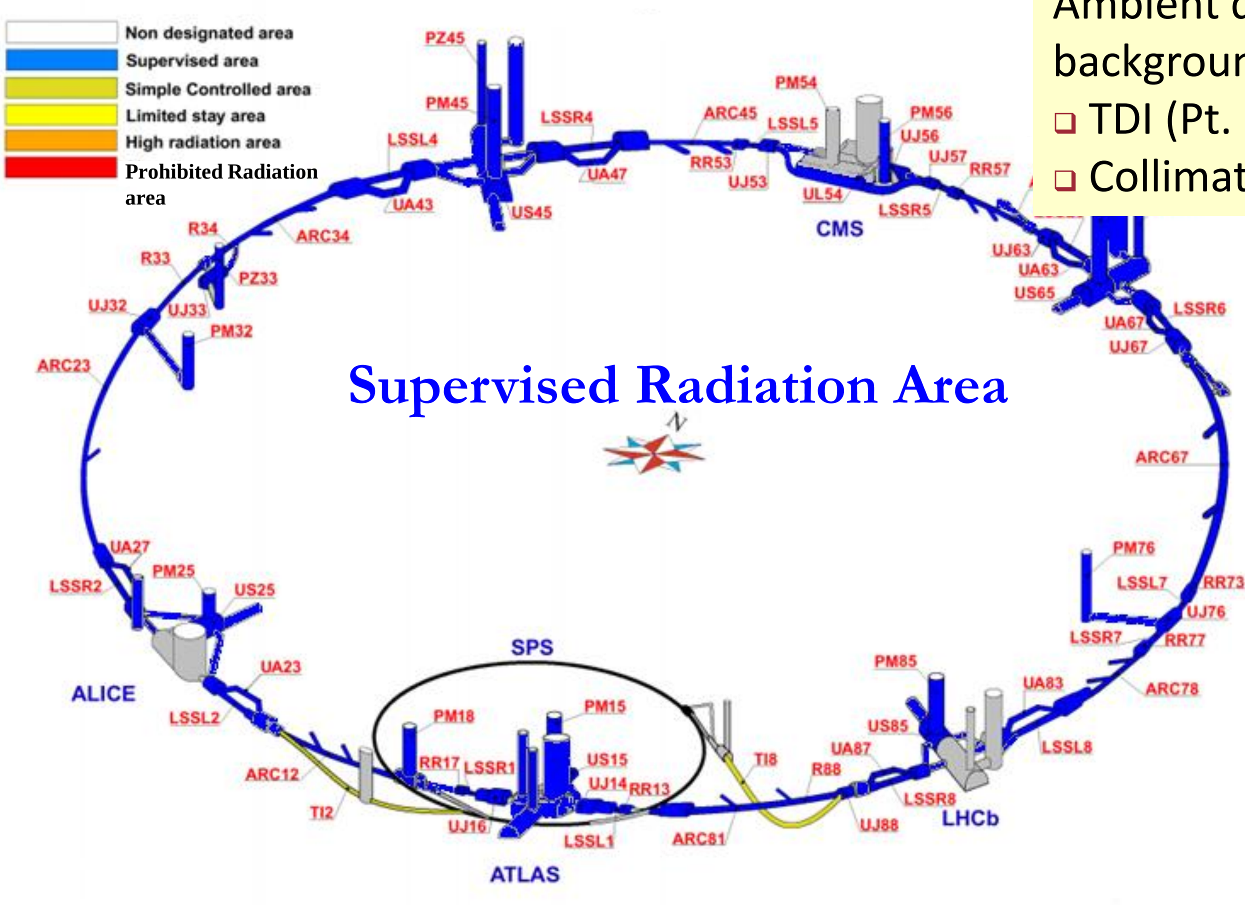


Arc: Beam Gas Interaction (nominal)

Assumption :2.4 10^4 protons/m/s (both beams), 7TeV, lost for 180 days continuously (corresponds to an H_2-equivalent beam gas density of 4.5 10^{14} /m^3)



LHC since 19th September 2008



Ambient dose equivalent rate is background with exception of

- TDI (Pt. 2 + 8)
- Collimators and absorbers (Pt. 3 + 7)

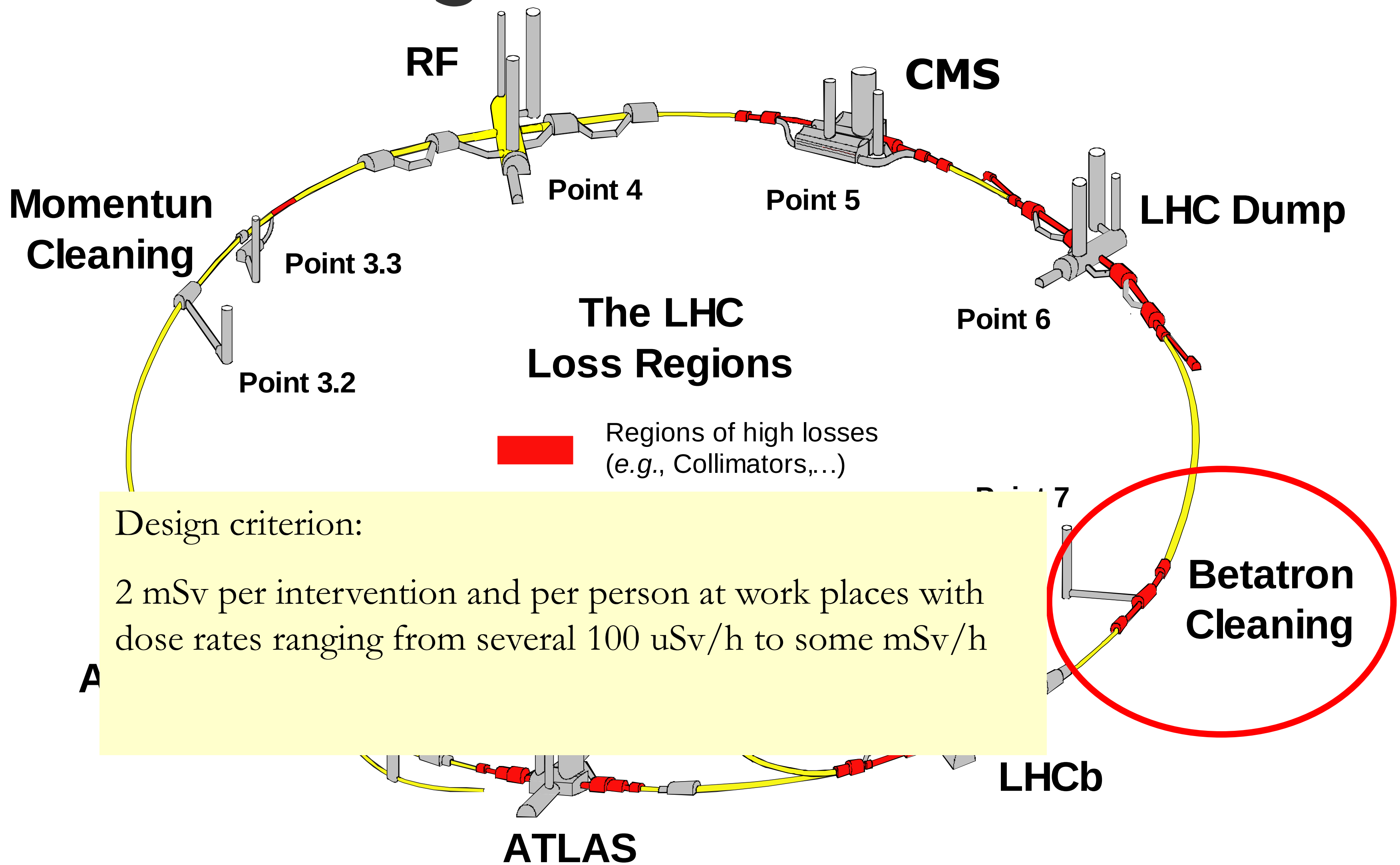
Survey collimateurs Point 3 LHC le 21/11/08	
N° CERCA	**Mesures en µSv/h**
TCS031	‹ 0.1
TCS014	‹ 0.1
TCS051	1.4
TCT023	5.2
TCT035	1.5
TCT047	‹ 0.1
TCSG 5R3S	‹ 0.1
TCAPA 6R3 B2	‹ 0.1
TCT074	‹ 0.1
TCT065	‹ 0.1
TCP 6L3 B1	‹ 0.1
TCSG A5R3 B1	‹ 0.1
TCSG B5R3 B1	‹ 0.1
TCP 6R3 B2	‹ 0.1

Cooling liquids and gases not radioactive

Future Critical Regions of LHC

- Momentum and betatron cleaning regions at Points 3 and 7
- Beam dump caverns
- TCDQ/TCDS diluter system at Point 6
- TAS collimators in the ATLAS and CMS interfaces
- TAN neutral particle absorbers at Points 1 and 5
- Low-β regions at Points 1 and 5
- Dispersion suppressor regions at Points 1 and 5

Critical Regions

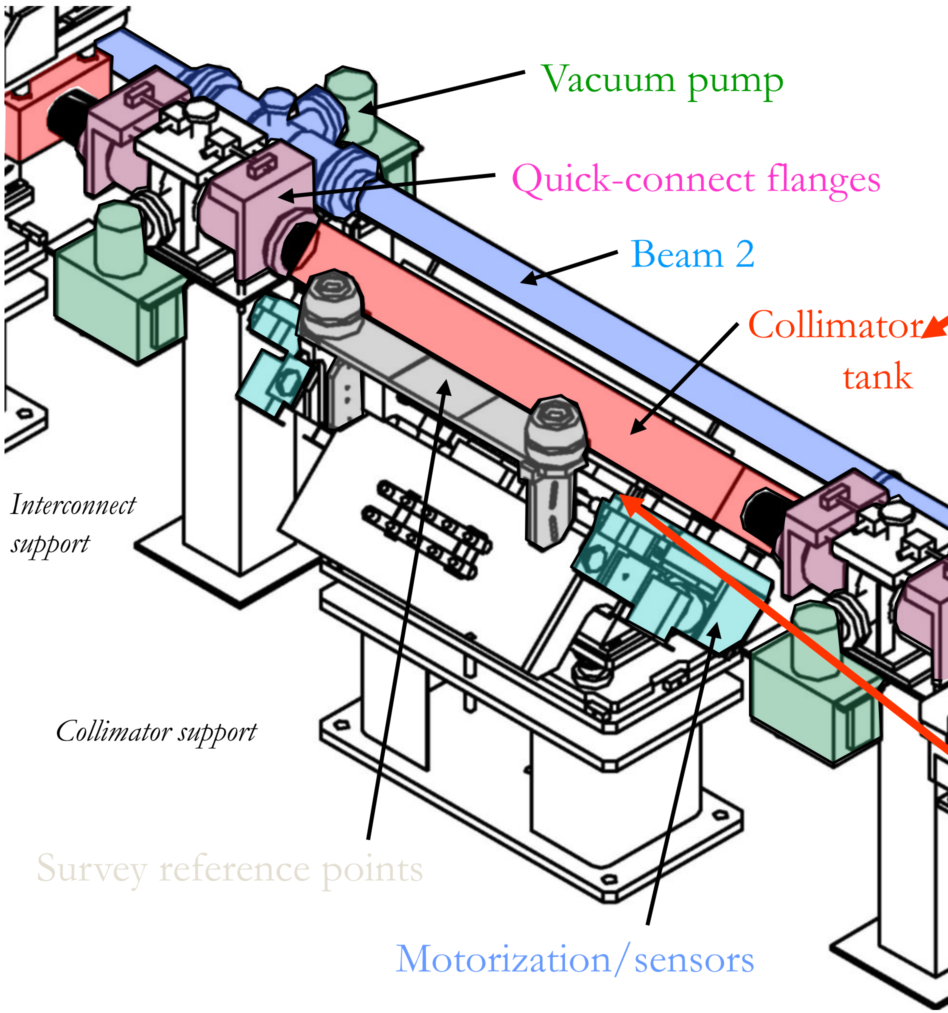


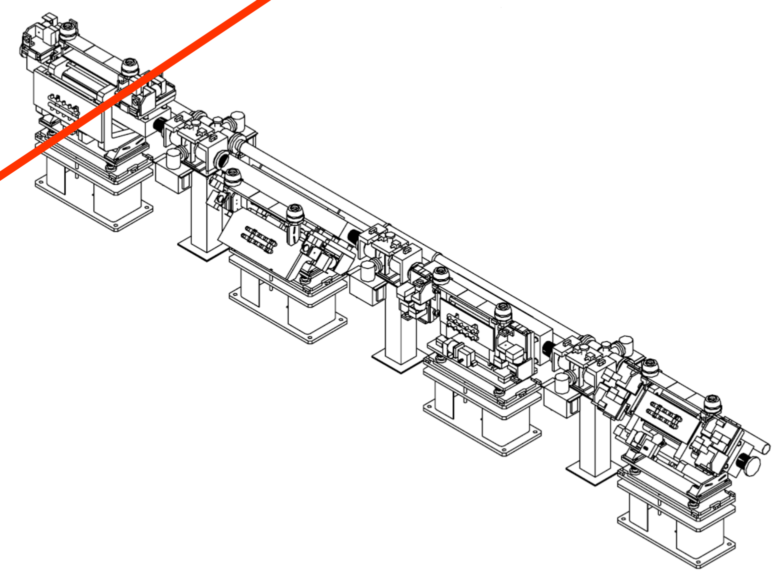
Design criterion:

2 mSv per intervention and per person at work places with dose rates ranging from several 100 uSv/h to some mSv/h

How will it look like ?

Narrow, thus difficult access



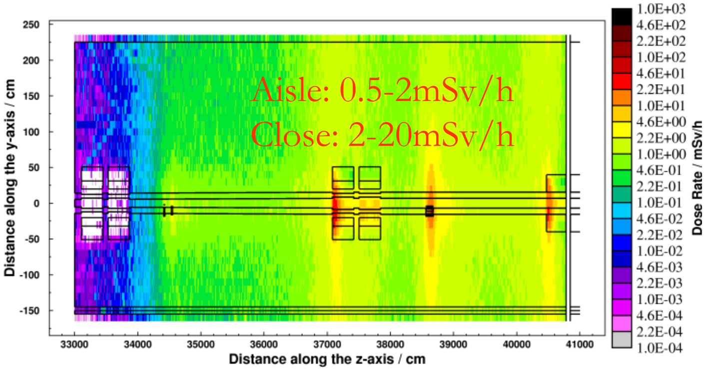


e.g. Exchange of motor on the tunnel side position in case of a tilted collimator

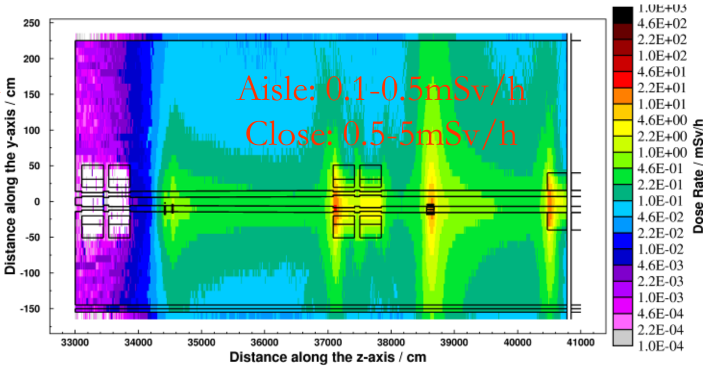
Detailed MC Calculations

- Remanent Dose Rates ranging from 0.1-20 mSv/h (cooling time of 8 hours to 4 months)
- Regular interventions
- Possible additional interventions on nearby elements (e.g., vacuum pumps, magnet modules, beam instrumentation
- Possible failure of elements

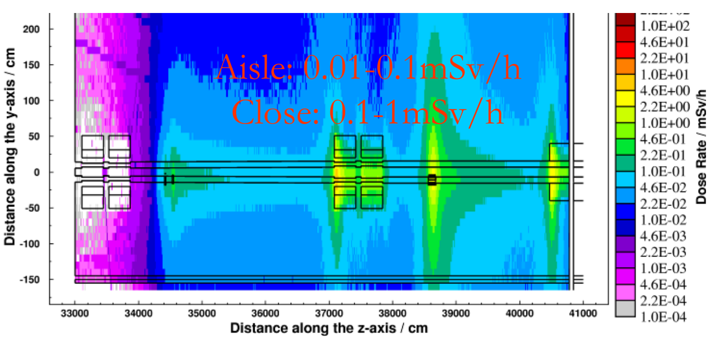
8 hours



1 week

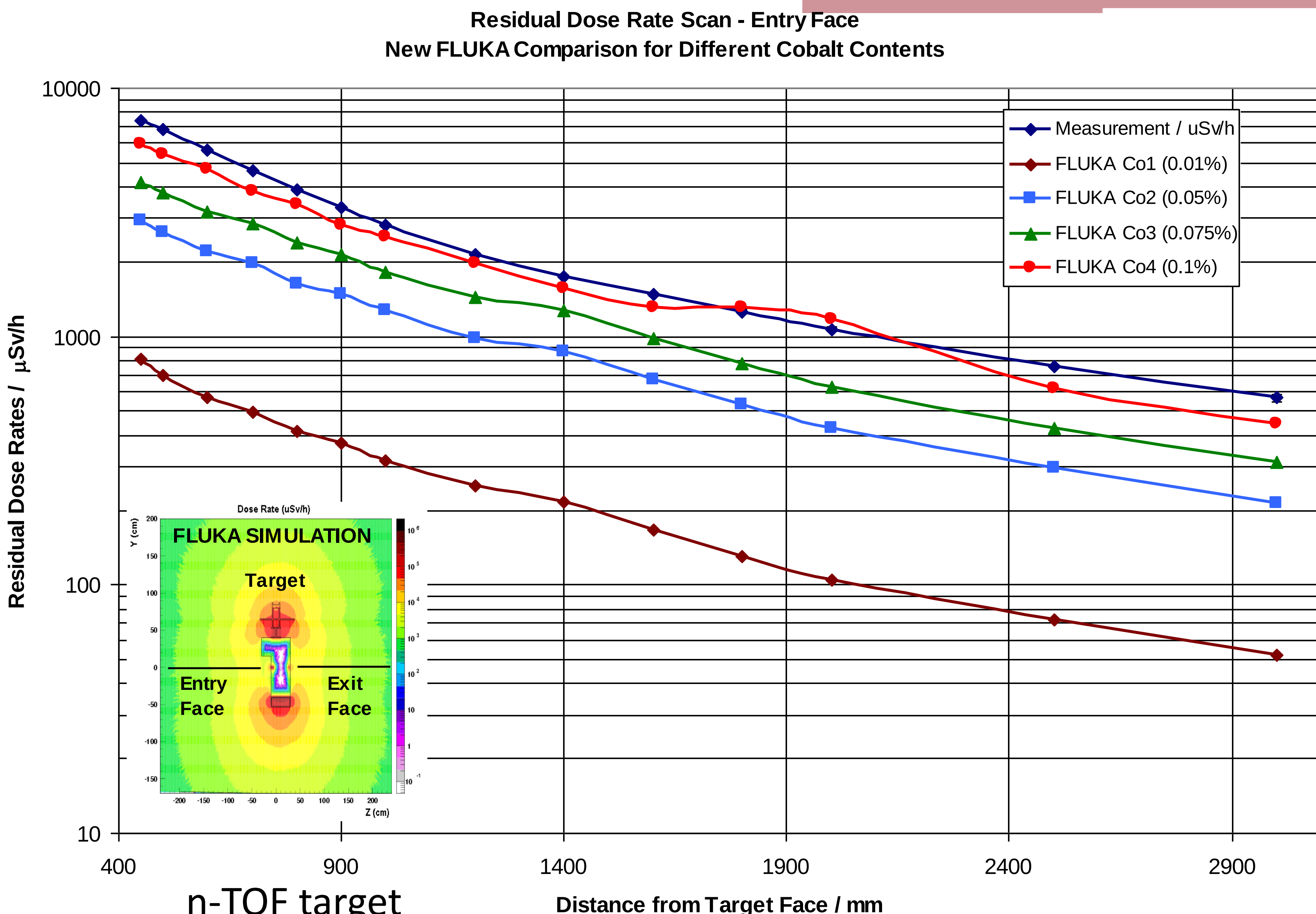


4 months



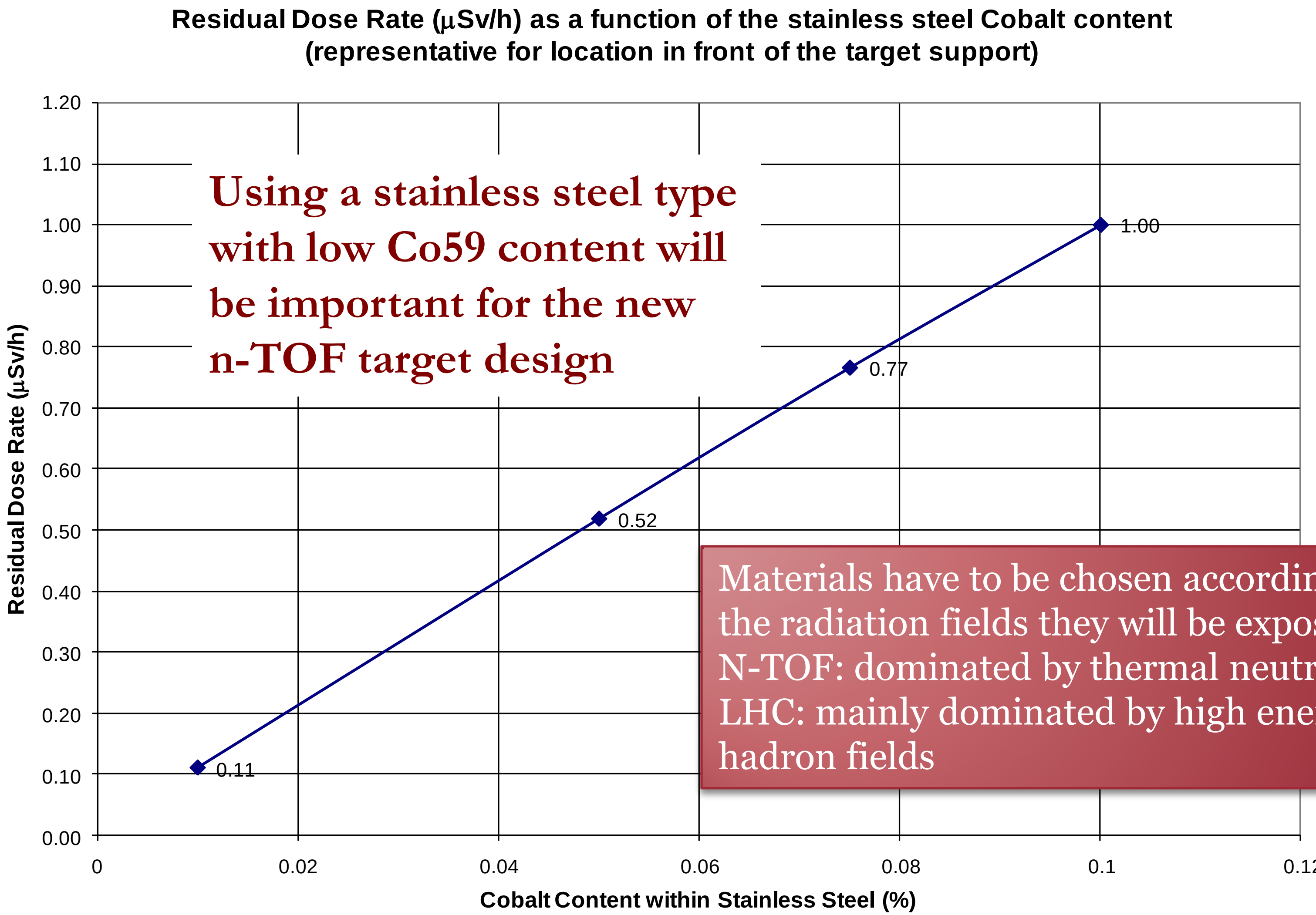
ALARA: Collimator Exchange LHC Point 7

Actions	Collective Dose / mSv					
	1h	8h	1d	1w	1m	4m
without permanent bakeout						
CF with bolts	54.5	38.7	26.5	12.3	7.2	3.1
CF with chain clamps	51.4	36.5	24.9	11.5	6.8	2.9
CF with bolts + 2nd beam line	99.4	70.7	48.0	21.8	12.9	5.6
CF with chain clamps+ 2nd beam line	95.3	67.8	45.9	20.7	12.3	5.3
with permanent bakeout						
CF with bolts	28.0	19.5	13.9	6.7	3.9	1.7
CF with chain clamps	24.9	17.3	12.3	5.9	3.4	1.5
CF with bolts+ 2nd beam line	46.3	32.2	22.8	10.7	6.2	2.7
CF with chain clamps+ 2nd beam line	42.2	29.3	20.7	9.6	5.5	2.4


Residual Dose Rate Scan - Entry Face
New FLUKA Comparison for Different Cobalt Contents
Residual Dose Rates / μSv/h
10000
1000
100
10
400
900
1400
1900
2400
2900
Distance from Target Face / mm
Measurement / uSv/h
FLUKA Co1 (0.01%)
FLUKA Co2 (0.05%)
FLUKA Co3 (0.075%)
FLUKA Co4 (0.1%)
Dose Rate (uSv/h)
FLUKA SIMULATION
Target
Entry
Face
Exit
Face
Y (cm)
Z (cm)

n-TOF target

Dependency on Cobalt Content



Using a stainless steel type with low Co59 content will be important for the new n-TOF target design

Materials have to be chosen according to the radiation fields they will be exposed to
N-TOF: dominated by thermal neutrons.....
LHC: mainly dominated by high energetic hadron fields

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.)

Examples:

- Use of plug-in systems, e.g. for collimators allowing short installation and replacement times.
- Orientation of accelerator components in order to facilitate the access to the connection boxes at their less-radioactive end.

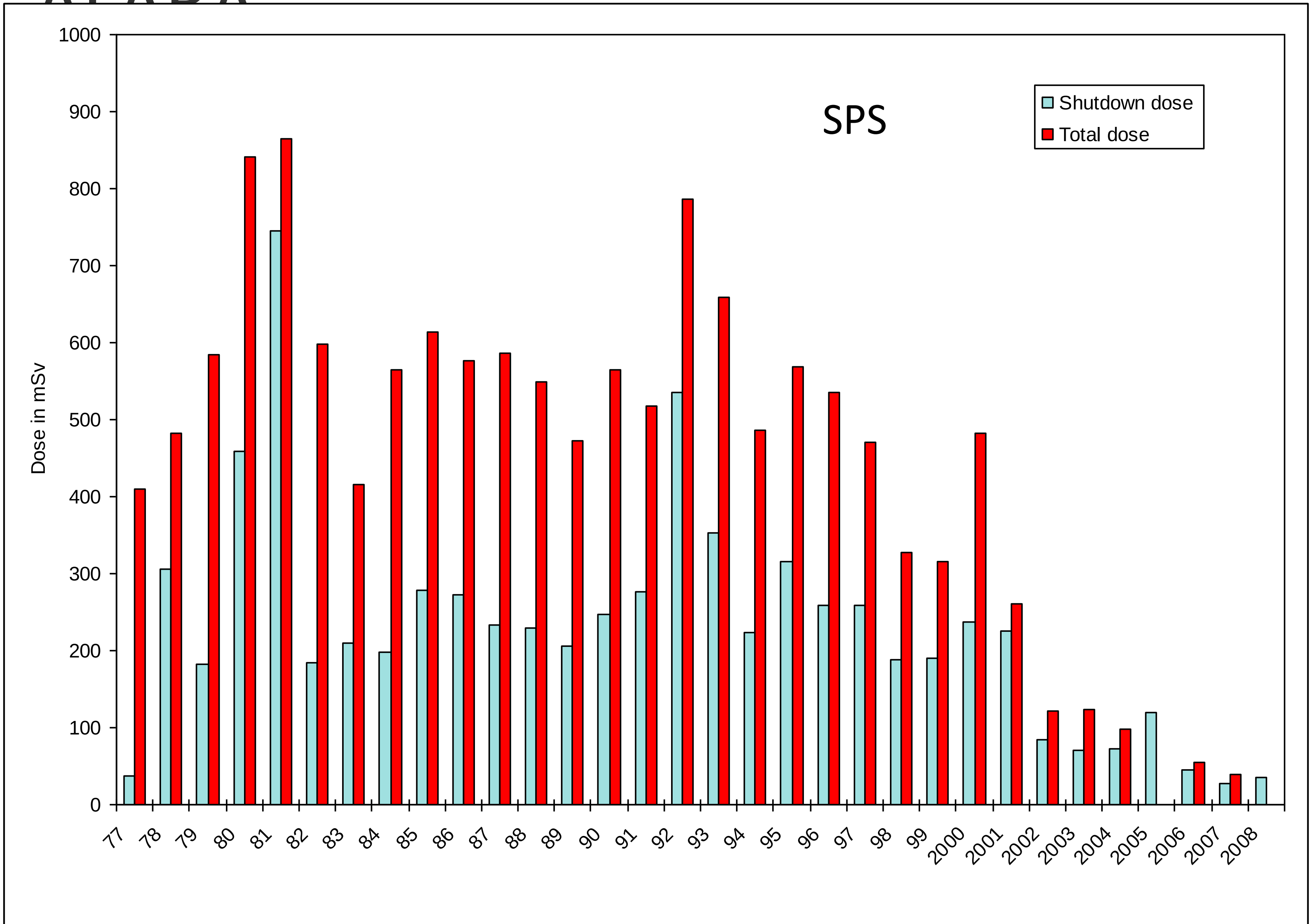
ALARA

Starts already during at the design phase:

Examples:

- 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.
- and….

ALARA



SPS
Shutdown dose
Total dose
Dose in mSv
1000
900
800
700
600
500
400
300
200
100
0
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
2000
2001
2002
2003
2004
2005
2006
2007
2008

Acknowledgement

M. Brugger (EN-STI)

I. Brunner

N. Conan

A. Hess

A. Herve

C. Tromel