Introduction to Radiation Protection

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- Radiation, Effects and Framework of Protection
  - Dose and effective dose
  - Radiation effects: from radiobiology to epidemiology
  - Acceptable risk, legal dose limits
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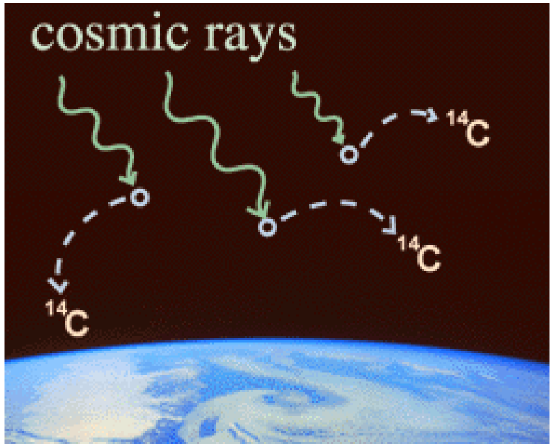
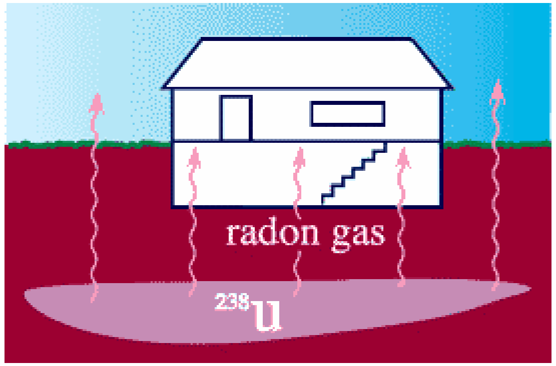
  - Protection against prompt radiation
  - Optimisation of maintenance work
  - Prospective and preventive radiation protection

Radiation is Everywhere

- Cosmic radiation (muons, neutrons, …)
- Cosmogenic radioactive elements (^{14}C, ^{7}Be, ^{3}H)



- Terrestrial radiation (U, Th, Ra, Rn …)



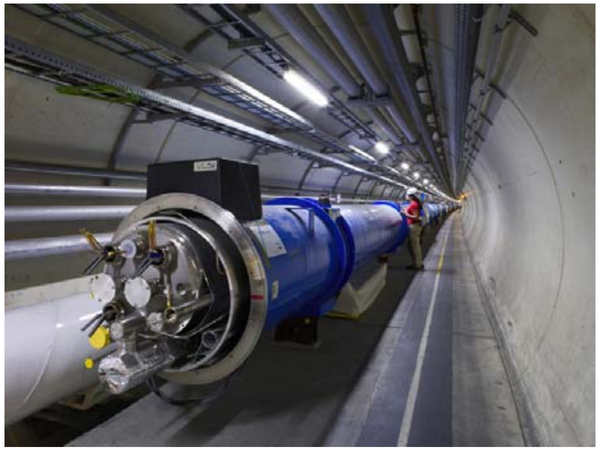
- Your body content: ^{40}K

Beneficial Use of Radiation

Energy Generation

Radiodiagnostics
Radiotherapy

Research



Hazards of Ionising Radiation

Deterministic effects:
e.g. Radiation burn

Stochastic effects:
e.g. viable cell mutation

Anderson et al, PNAS 99, 12167 (2002) (*in vitro*)

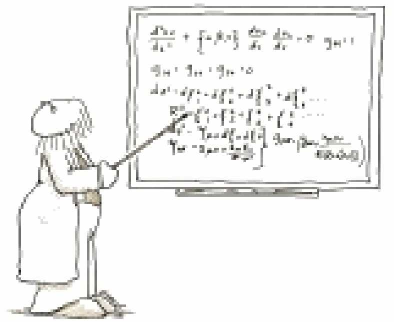
Anderson et al, Radiat Res 163, 26 (2005) (in humans)

Objective of Radiation Protection

- Protection of man and the environment from detrimental effects of ionising radiation.
- Not included: Protection of the patient during medical applications of ionising radiation
- Included: Naturally occuring radioactive materials (NORM), e.g. Rn

An Interdisciplinary Field

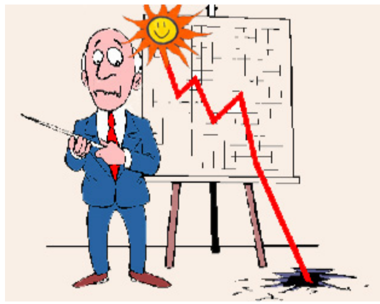
To achieve its goal, Radiation Protection draws upon



Physics

Legislation

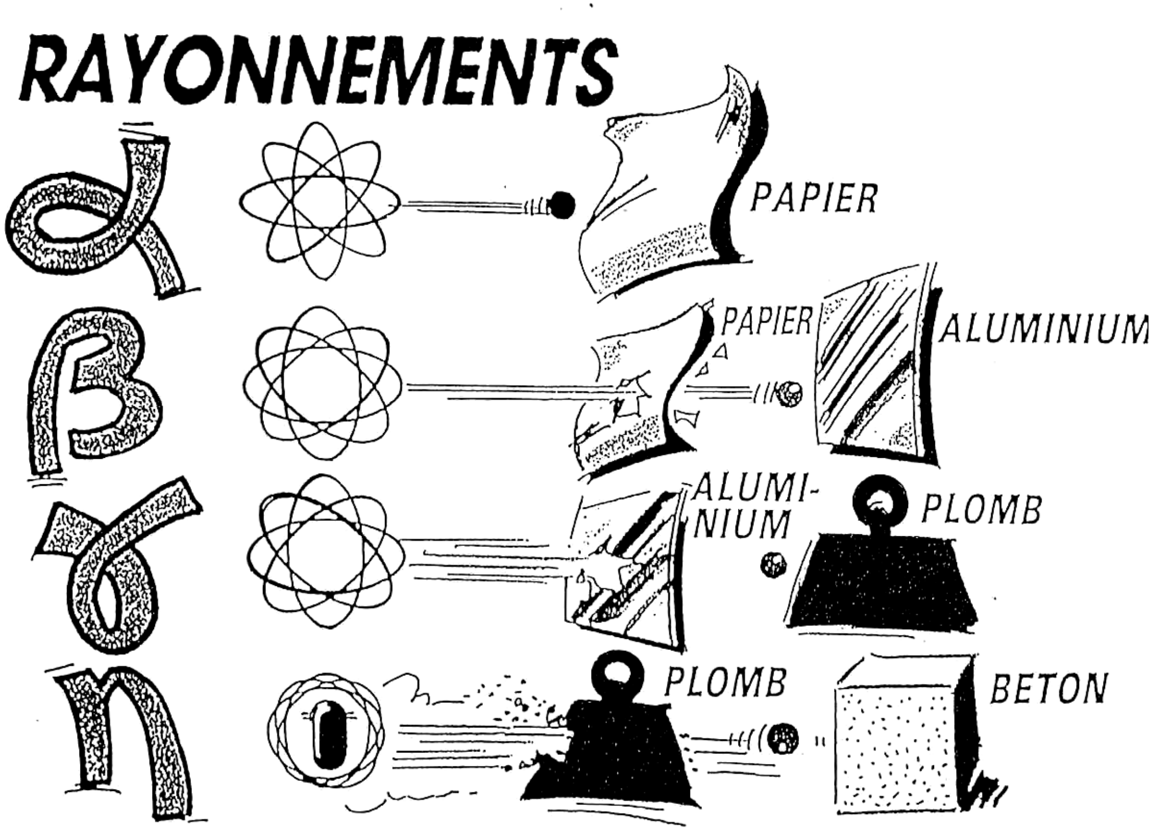
Biology



Economy,
Sociology

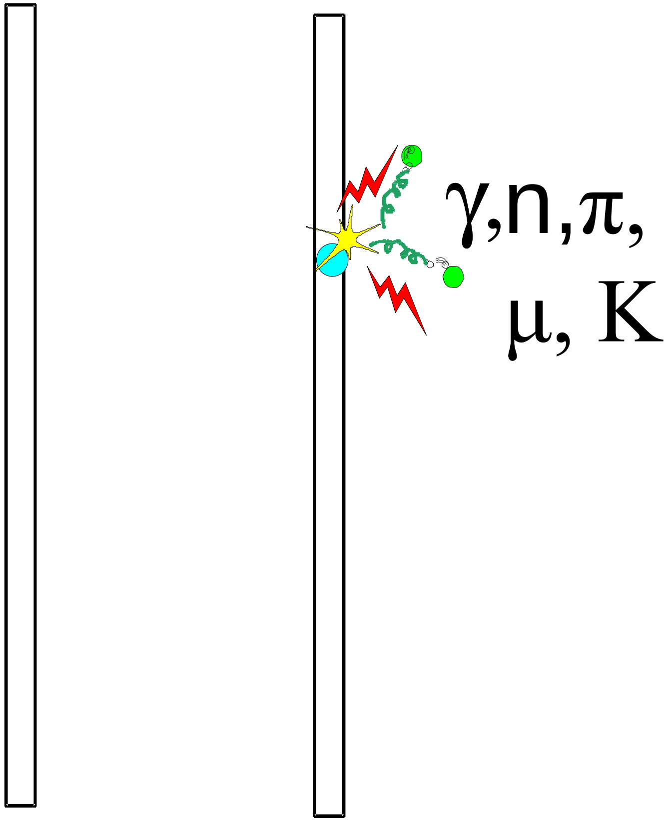
- Physics:
  - Characterise sources of radiation
  - Quantify radiation exposure: dosimetry
  - Physical means of protection: shielding
- Biology:
  - Quantify radiation risk: radiation biology, epidemiology
- Sociology, Economy:
  - What level of risk is acceptable ?
  - Which level of protection is affordable ?
- Legislation:
  - Codification of protection standards into laws and refgulations

Physics: Types of Radiation



Screens	Distance of penetration (air)
Paper, water	Several cm
Low density materials	Several m
High density materials	Several tens of m
Hydrogenated materials	Several hundred m

Radiation in an accelerator



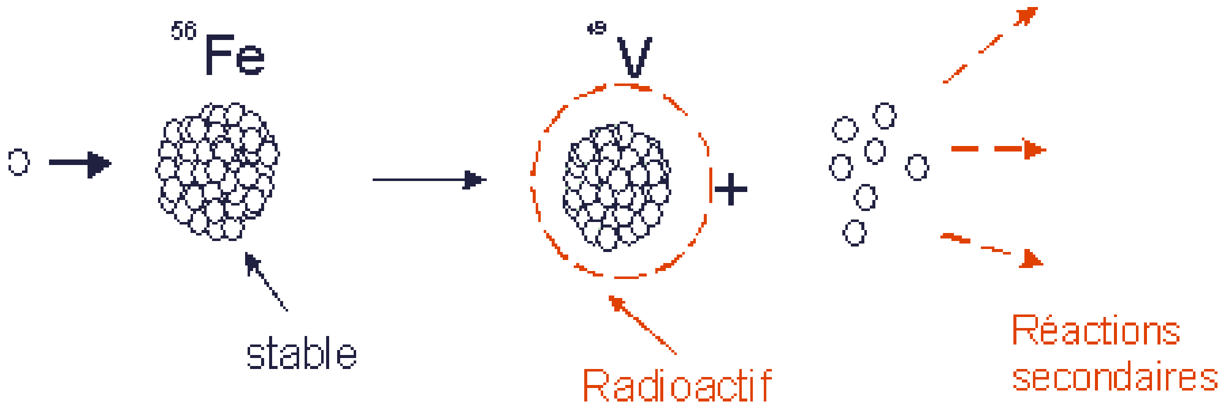
Particles (protons, electrons) are guided in an accelerator or beamline

Beam loss – collision of accelerated particles with the accelerator structure

It leads to emission of ionising radiation in form of particles and e.m. radiation

Activation of material

- Energetic particles can activate material by nuclear reactions (spallation, fission, fragmentation)



- Objects exposed to beam (loss) become emitters of ionising radiation (mostly β/γ)

Physics: Dosimetry

- Quantification of ionising radiation

The **absorbed dose**, D, is the quotient of dε by dm, where dε is the **mean energy imparted** by ionising radiation to matter of mass dm, thus

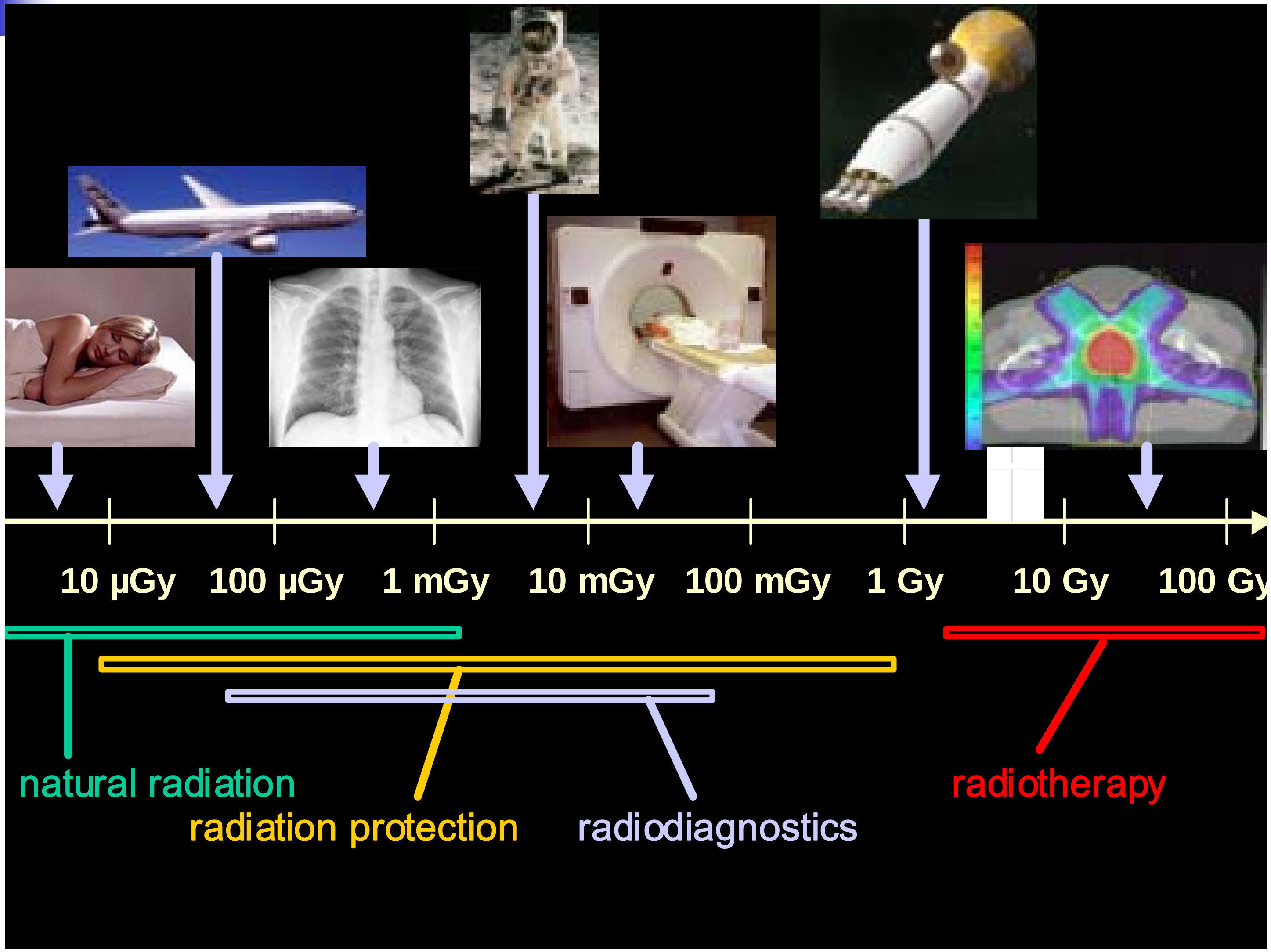
$$D = \frac{d\varepsilon}{dm}$$ (Unit : J/kg or gray)

Energy imparted is a *stochastic quantity* which is described by probability distributions.

(definition by ICRU)

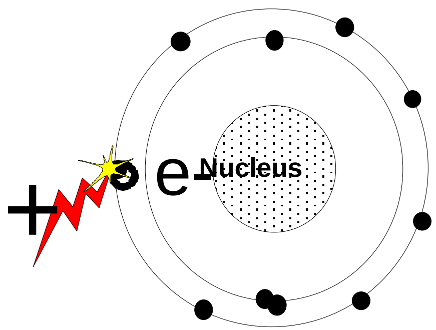
N.B.: an absorbed dose of 1 Gy leads to a temperature increase of only 2.4 .10^{-4} °C

Dose Ranges


10 µGy
100 µGy
1 mGy
10 mGy
100 mGy
1 Gy
10 Gy
100 Gy
natural radiation
radiation protection
radiodiagnostics
radiotherapy

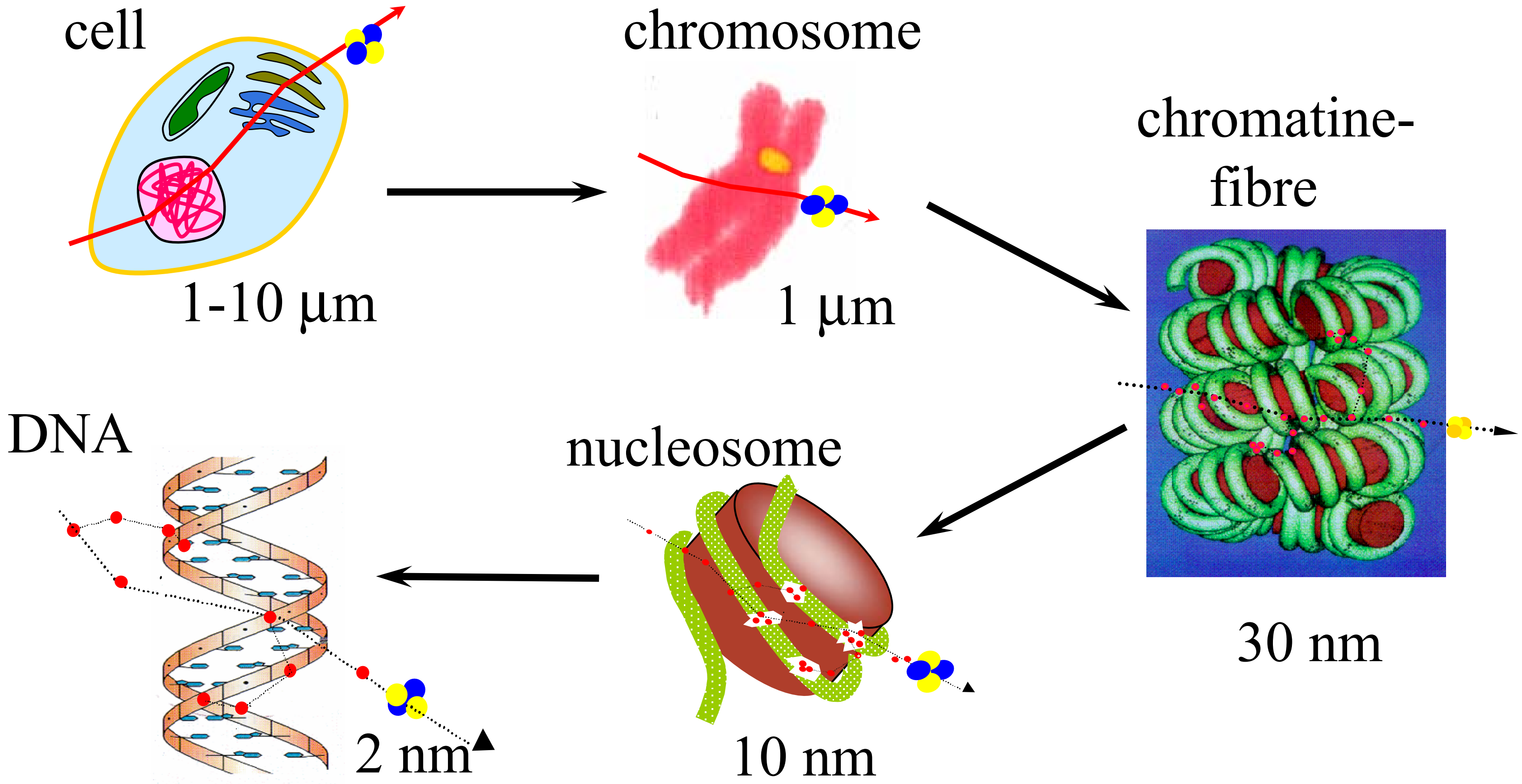
Physics: ionisation

Interaction with matter is stochastic and discontinuous:



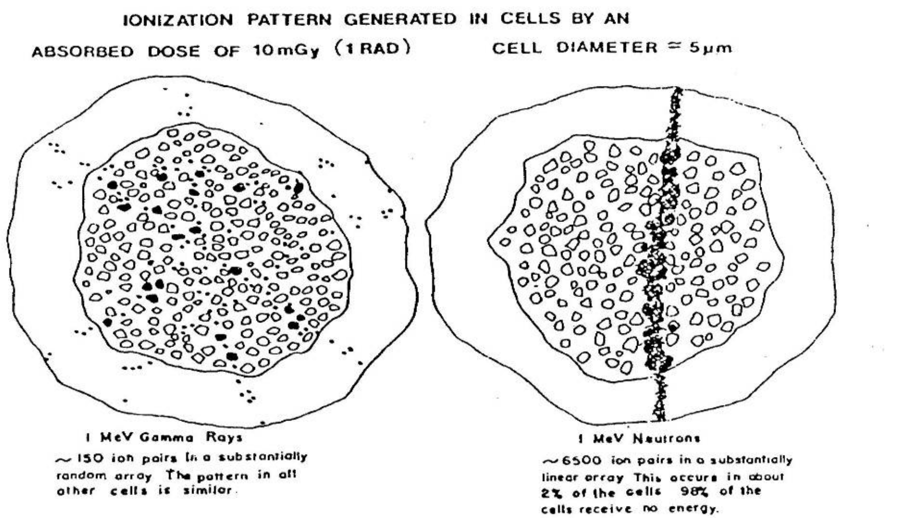
Ionising radiation delivers energy in “packages” large enough to bring about physical and chemical changes on the atomic level

Biology: Cellular and molecular radiation effects

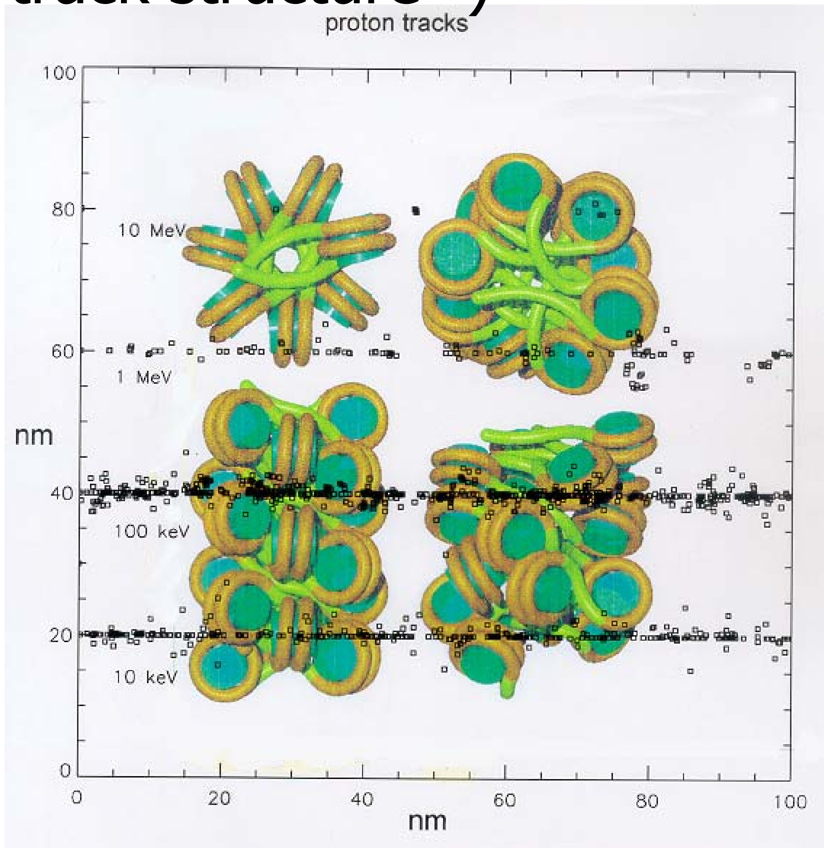


Relative Biological Effectivenes

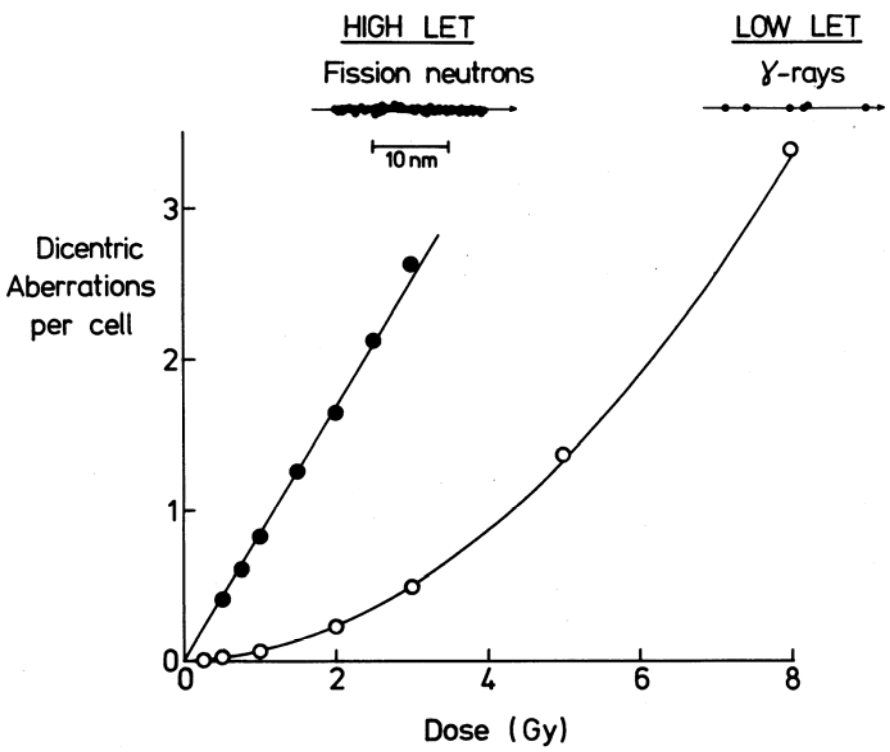
Spatial distribution of radiation interaction depends on type and energy of particle ("track structure")



ROSSI H.H. - The role of microdosimetry in radiobiology. Radiat. Environ. Biophys., 1979, 17, 29-40.



Biology: Chromosome aberrations



(Data replotted from Lloyd et al)

neutrons : $E(D) = a_n \,.\, D_n$

photons: $E(D) = \alpha \,.\, D\gamma + \beta \,.\, D\gamma^2$.

- Damaged DNA may lead to
  - Viable mutated cells
  - Tumor ?
  - Hereditary effects
- Study in
  - Cell cultures (in vitro)
  - Experimental animals (in vivo)
  - Large populations (epidemiology)

Effective Dose E (ICRP, 1991)

Absorbed dose per organ ("tissue"), weighted for radiation (w_R) and tissue (w_T) type and summed over the body

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} [Sv]$$

$w_R = 1 \ldots 20$; $w_T = 0.01 \ldots 0.20$

Purpose:

Approximately quantify radiation risk at small doses with the aim of risk limitation and optimisation.

Epidemiology

- Case-Control Studies observe large populations exposed to a certain risk factor and compare with unexposed populations
- $\lambda_{u,}$ λ_e: probability of an event (e.g. cancer) in the unexposed and the exposed population

- Relative risk : $RR = \lambda_e / \lambda_u$
- Excess relative risk: $ERR = (\lambda_e - \lambda_u) / \lambda_u = RR - 1$
- Excess absolute risk : $EAR = \lambda_e - \lambda_u = \lambda_u \, ERR$

Epidemiology: Life Span Study

- Follow up of the survivors of the nuclear bombs on Hiroshima and Nagasaki (1945)
- 87 000 individuals followed for more than 50 years
- From 1950 – 1997:
  - 9335 solid cancer deaths
  - 8995 expected (from control group)
  - 440 excess cancer deaths from radiation
- Excess risk related (proportional) to radiation dose

ERR for different cancers

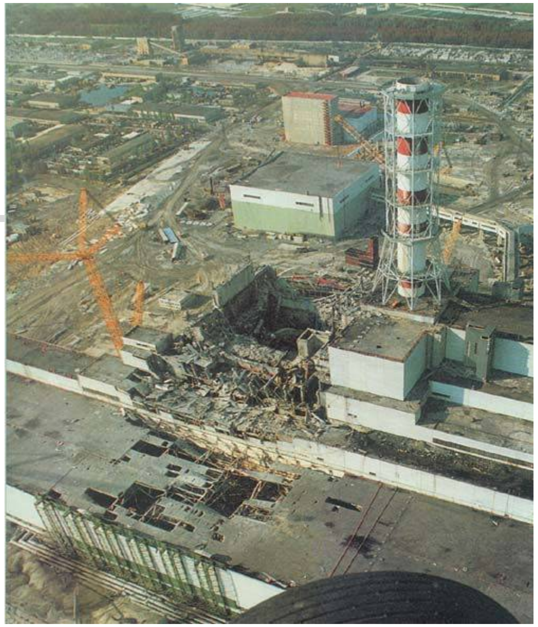
Organ	ERR (Sv^{-1})
All solid cancers	0,63 (0,52 – 0,74)
Stomach	0,32 (0,16 – 0,50)
Colon	0,72 (0,29 – 1,30)
Liver	0,49 (0,16 – 0,92)
Lungs	0,95 (0,60 – 1,40)
Skin	1,0 (0,41 – 1,9)
Breast (female)	1,6 (1,1 – 2,2)
Ovaries	0,99 (0,12 – 2,3)
Bladder	1,0 (0,48 – 2,1)
Thyroid	1,2 (0,48 – 2,1)

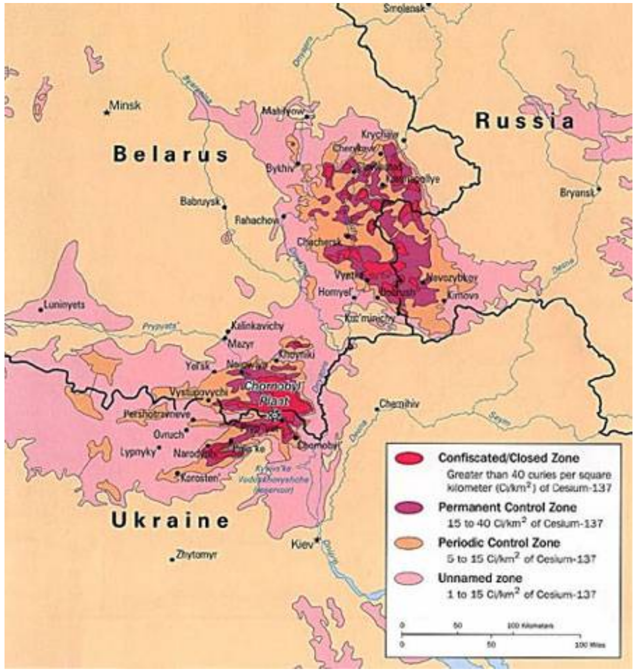
Spontaneous risk to die from cancer: $\lambda_u \approx 0.25$ % y^{-1}
ERR $\approx$ 0.5 Sv^{-1}, EAR = λ_u 0.5 Sv^{-1} = 0.125 Sv^{-1} y^{-1}

Lifetime absolute risk (40 years following irradiation)
LAR = 40 y EAR = 5% Sv^{-1}

Chernobyl

- On 26. 4. 1986, an explosion and fire occurred in reactor 4 of the Chernobyl nuclear power plant.
- Thousands of "liquidators" worked on the Chernobyl site to secure the damaged reactor
- Widespread radioactive contamination affected Ukraine, Bielorussia, Russia and to a lesser degree, Western Europe

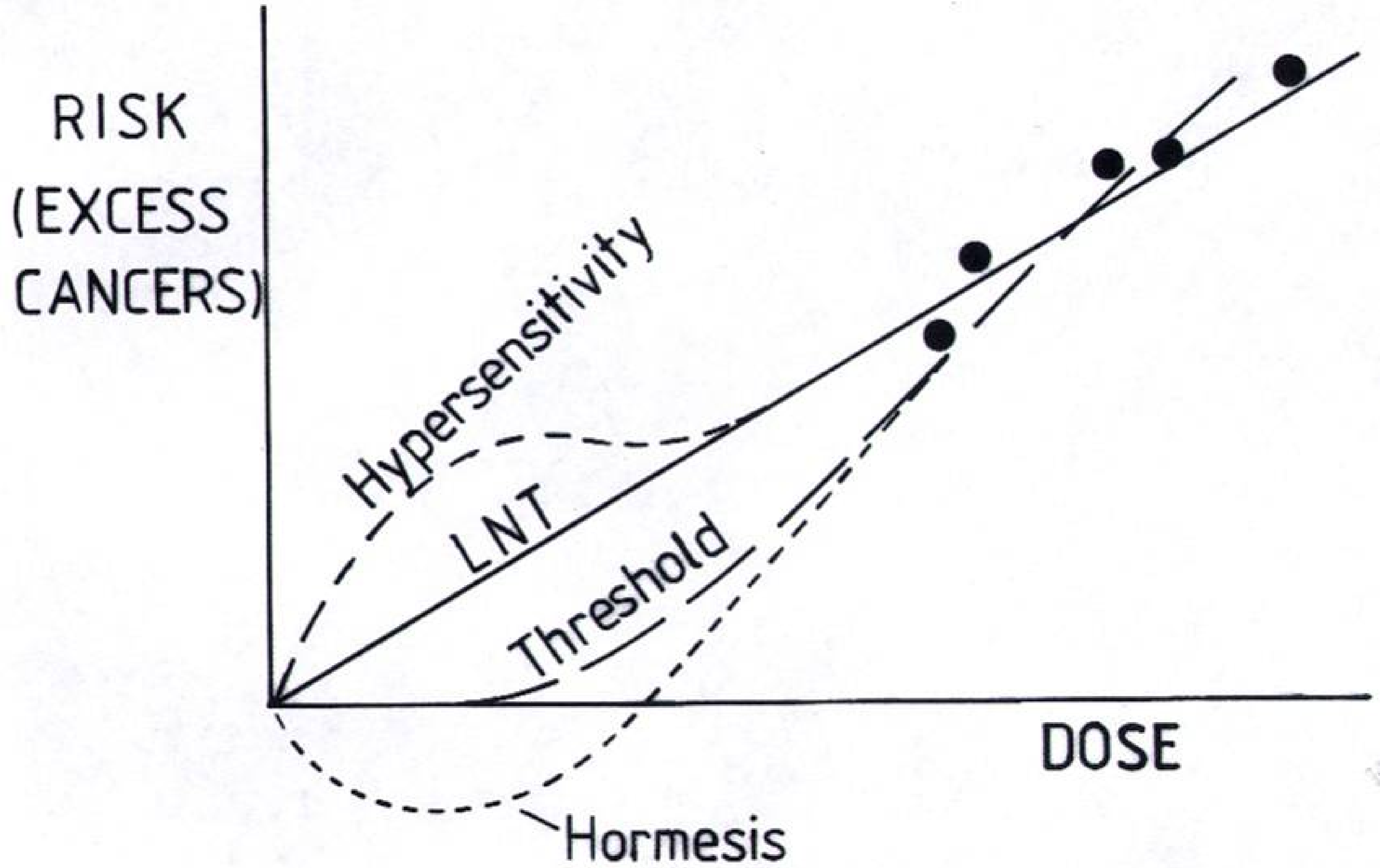




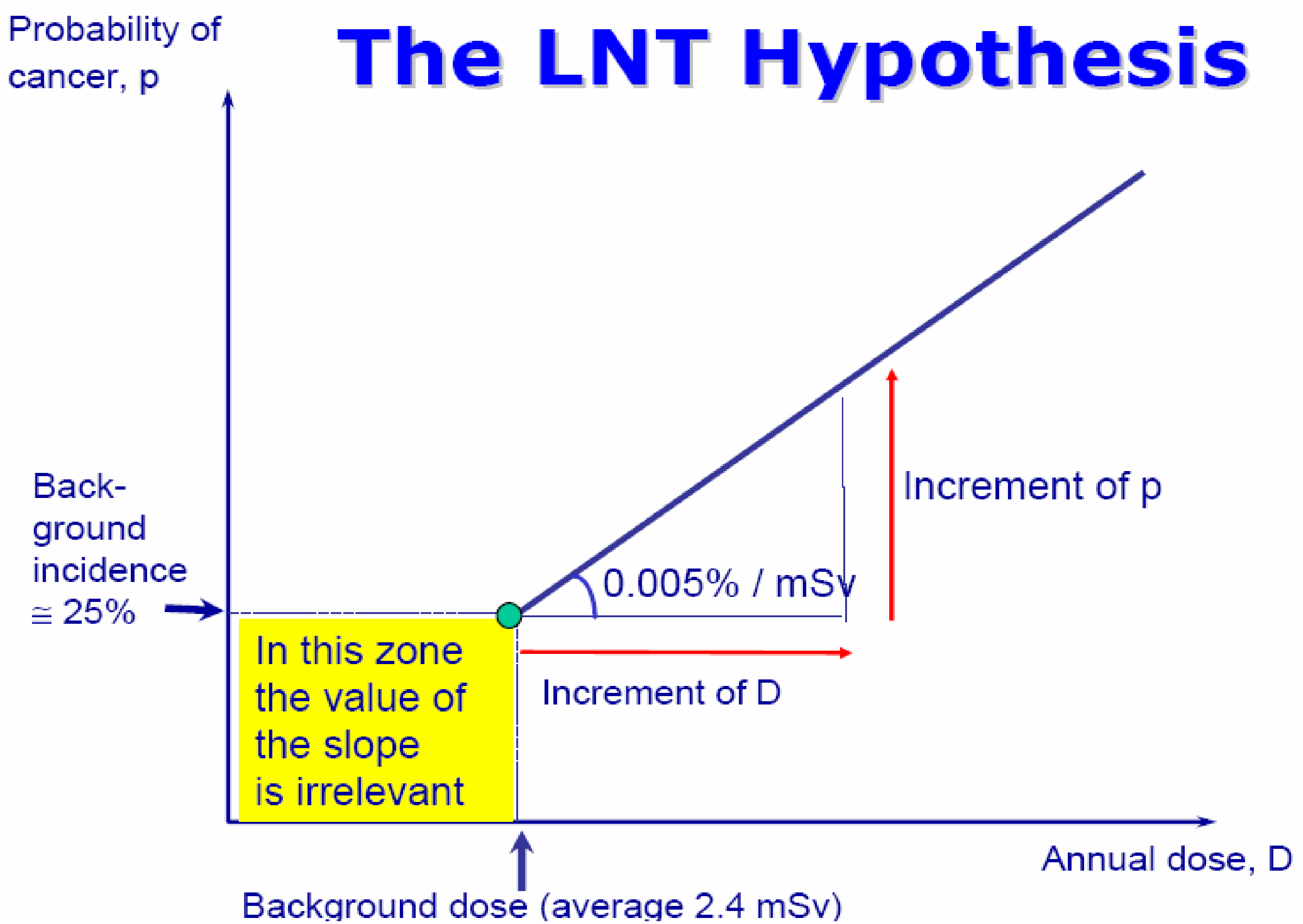
What did we learn from Chernobyl ?

- Significant increase in thyroid cancers after uptake of ^{131}I during childhood
- No epidemiological life-span study has been conducted
  - "Liquidators" were drafted and sent back to their home regions after the intervention
  - Dose of residents (town of Pripyat) only few mSv
  - Poor dosimetry
  - Dissolution of the Soviet Union in 1990
- Reports of spurious cases of malformations seem to be compatible with natural frequency

Low Dose Extrapolation



The LNT Hypothesis



Acceptable Risk

- Radiation Risk is acceptable, if it is comparable to risk of mortality in "other" industries

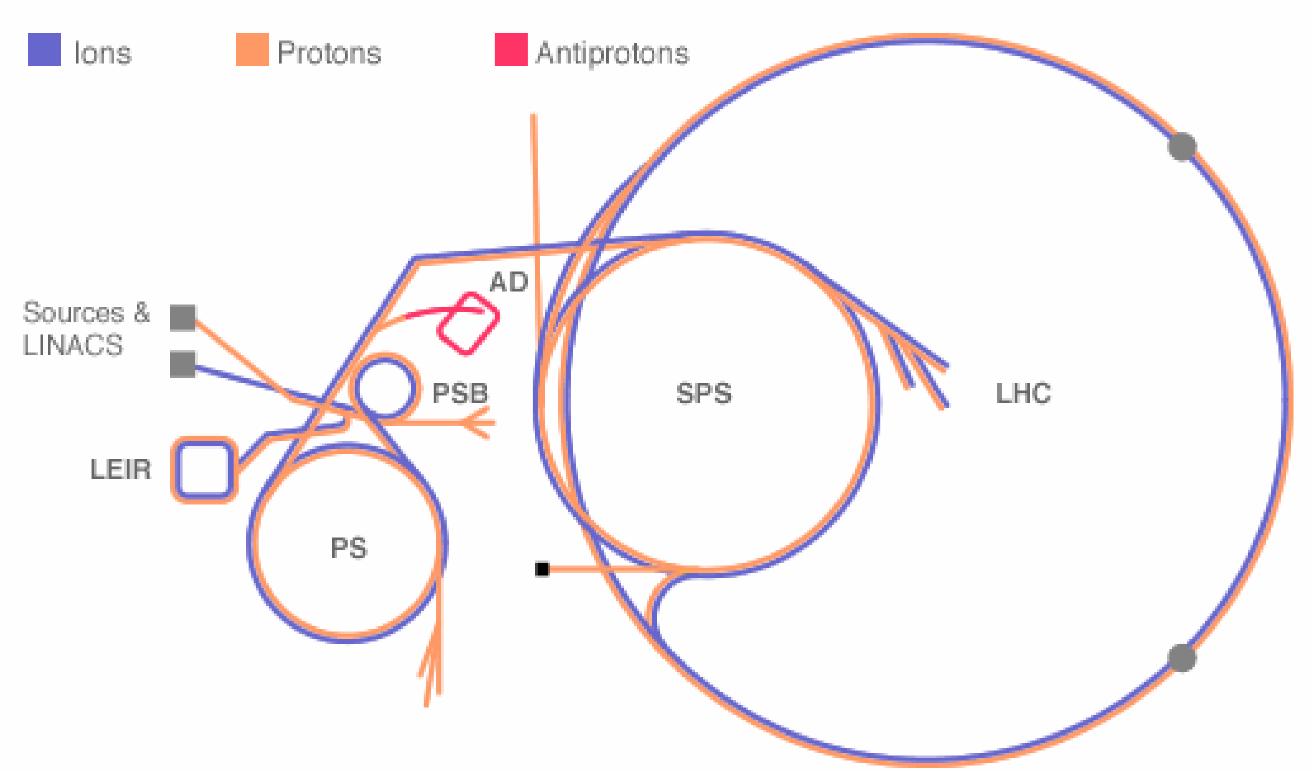
Occupation	**Annual risk of death**
Steeplejack	$1.4\ 10^{-2}$
Mining (USA)	10^{-3}
Exposure to 20 mSv	10^{-3}
Exposure to 6 mSv	$3\ 10^{-4}$
Construction	$2\ 10^{-4}$

Three Fundamental Principles

- Justify every use of ionising radiation
- Limit the exposure to ionising radiation to legal limits
  (transcribed from accepted values)
- Optimisation: Further minimise the exposure while retaining the benefits and maintaining the effort reasonable

	Dose	Risk
unacceptable	1 Sv	$5\ 10^{-2}$
	100 mSv	$5\ 10^{-3}$
	20 mSv	$1\ 10^{-3}$
Optimisation region (for workers)	10 mSv	$5\ 10^{-4}$
	1 mSv	$5\ 10^{-5}$
	100 µSv	$5\ 10^{-6}$
(for public)	10 µSv	$5\ 10^{-7}$
broadly acceptable	1 µSv	$5\ 10^{-8}$

CERN's Accelerators



During Accelerator operation, protect against prompt radiation from beam loss

During maintenance, protect against radiation from activated material

Protection against prompt Radiation

- Shielding: attenuate prompt radiation from beam losses (high dose rate)

- Access control: deny entrance to prohibited areas, control access for maintenance

Designation of areas

Designation	Potential annual dose	Access conditions
Supervised area	> 1 mSv/a < 6 mSv/a	occupationally exposed personnel
Controlled area	> 6 mSv/a < 2 mSv/h	with electronic dosimeter, after optimisation
High Radiation	> 2 mSv/h < 100 mSv/h	with specific authorisation
Prohibited	> 100 mSv/h	

Maintenance Work

Maintenance and repair have to be performed on activated accelerator components

The items are often unique, tailor made exemplars.

Fault-search and repair can become very time-consuming

Optimisation Process

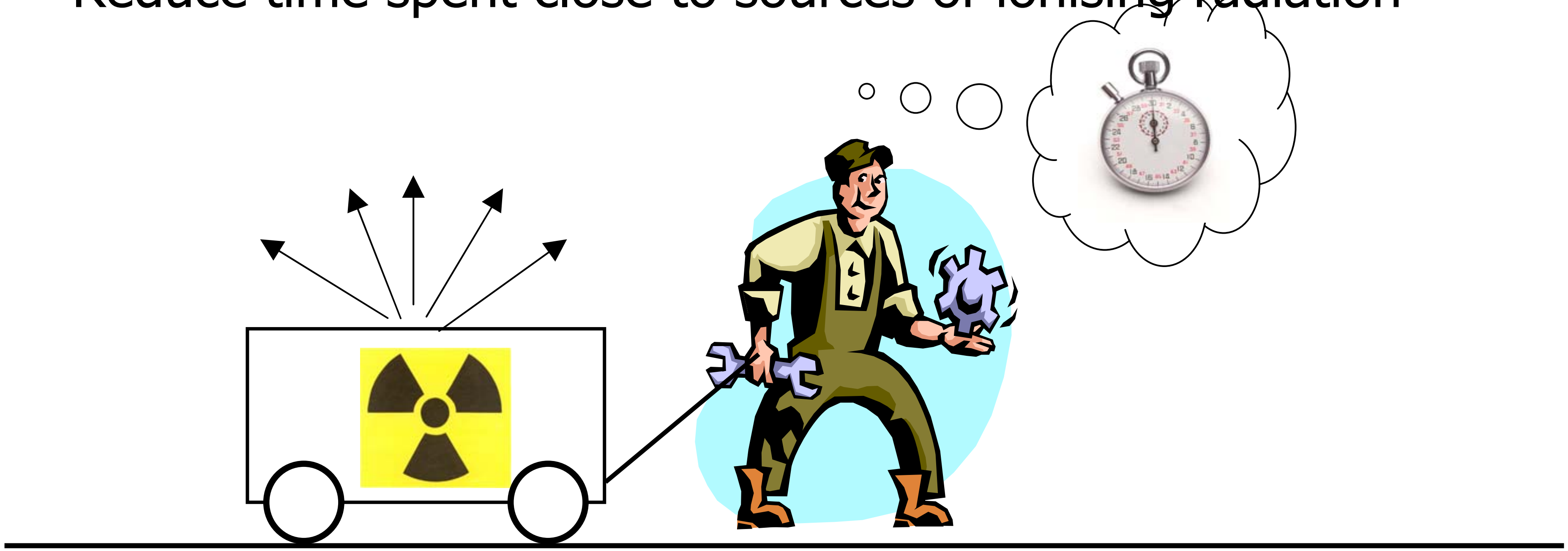
Based on a detailed plan for the work, look for alternatives resulting in a smaller personal dose

Collimator exchange due to leak: CF flanges with bolts.										
Actions		Duration (min)	Accumulated Dose (μSv)							
			1h	8h	1d	3d	1w	1m	4m	1y
(1)	Transportation of material	4×5	120	84	39	21	15	9	3	3
(3)	Connection of 2 pumping stations	2×15	301	203	161	126	98	49	21	14
(3)	Connection of leak detector	5	51	34	27	21	16	8	4	2
(3)	Leak detection	10	102	69	55	43	33	17	7	5
(2)	Fine leak detection / confirmation	10	129	86	69	52	40	21	10	5
(4)	Installation of venting line	5	155	108	94	73	59	31	14	7
(4)	Collim. exch. : Disconnection	4	129	90	78	61	49	25	12	6
(4)	Cleaning of flanges	2	62	43	37	29	23	12	6	3
(4)	Install. of new collim.	5	155	108	94	73	59	31	14	7
(4)	Connection	2×12	739	515	448	347	280	146	67	34
(3)	Starting the pumping	5	51	34	27	21	16	8	4	2
(3)	Pumping follow-up	5	51	34	27	21	16	8	4	2
(3)	Leak detection	10	102	69	55	43	33	17	7	5
(3)	Beak out follow-up	10	102	69	55	43	33	17	7	5
(3)	Disconnection of equipment	15	151	102	81	63	49	25	11	7
(1)	Transportation of material	4×5	120	84	39	21	15	9	3	3
	Sum		**2520**	**1732**	**1386**	**1058**	**834**	**433**	**194**	**110**

Collaborative effort between operators and radiation protection personnel

Option 1: Reduce Time

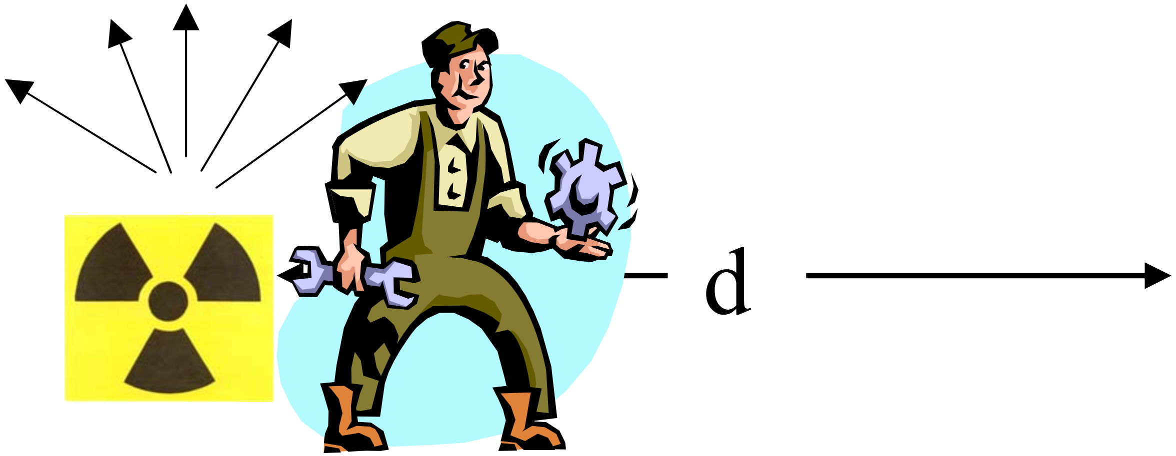
Reduce time spent close to sources of ionising radiation



$$\text{Dose} \propto t$$

Option 2: Increase Distance

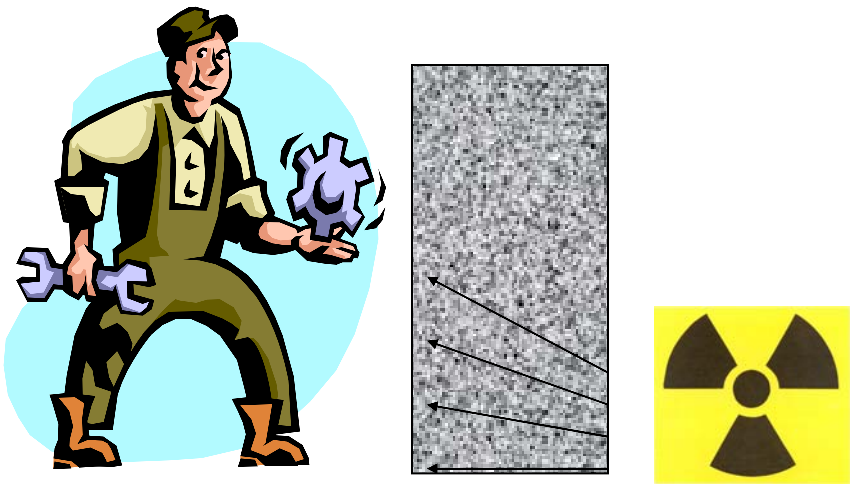
- Increase your distance to sources of ionising radiation



$$\text{Doserate} \propto \frac{1}{d^2}$$

Option 3: Use Shielding

- Shielding attenuates radiation



$$\text{Doserate} \propto \exp\left(-\frac{d}{\lambda}\right)$$

Quantify the Dose: Dosimetry

- Before the intervention:
  - Ambient dosimetry, input value for the dose estimates
- During the intervention:
  - Operational personal dosimetry, on-line follow-up of the workers' dose uptake
- After the intervention:
  - 'Legal' personal dosimetry, assure that legal limits have been respected

Personal Dosimetry

- Operational Dosimeter

LCD dose display

Dose rate indication ("bip-bip")

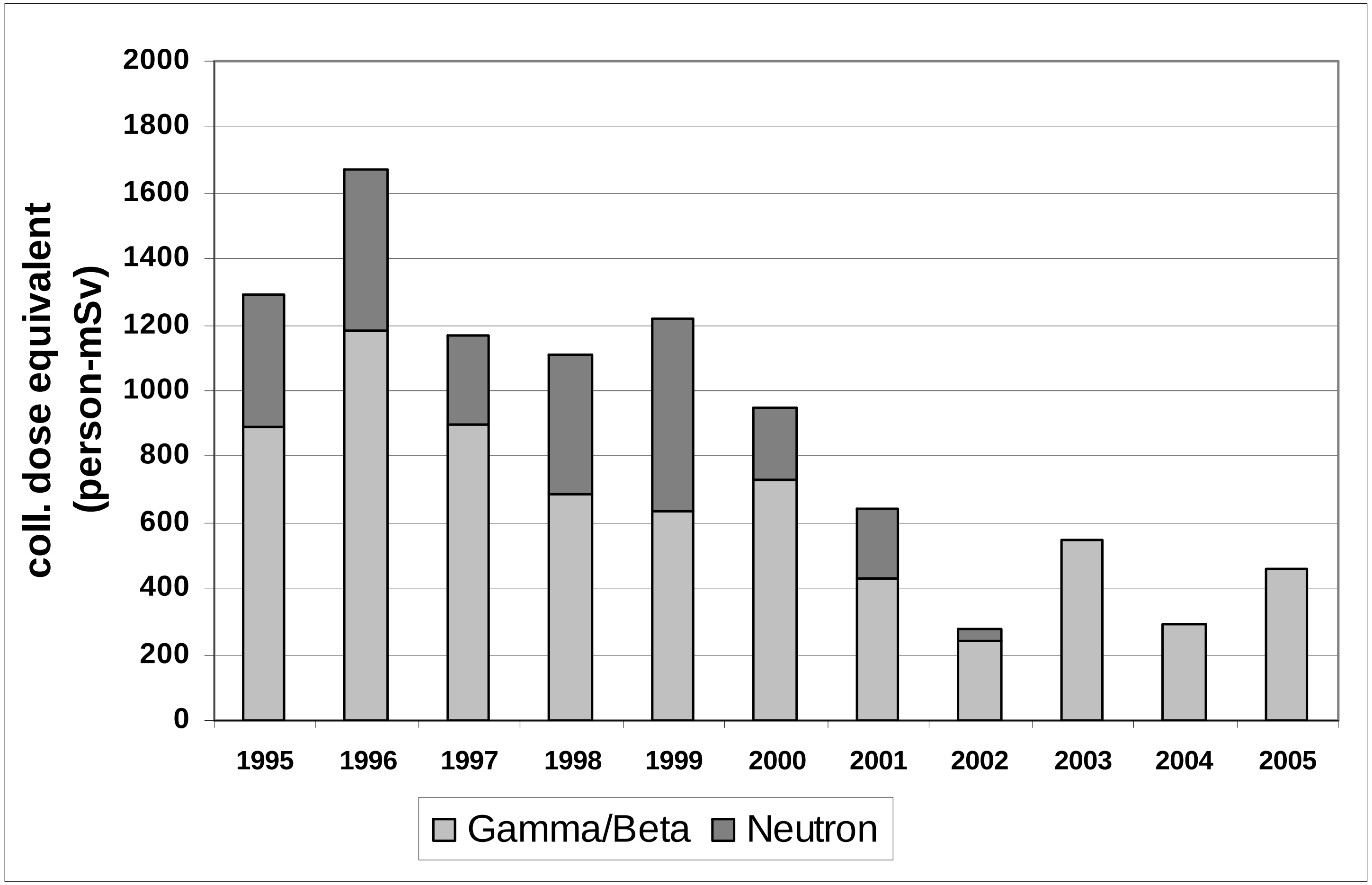
Alarm function

- "Legal" Dosimeter

High accuracy and reliability

Approved

Exposition of personnel



Dose Breakdown

- In 2005: 4666 persons monitored

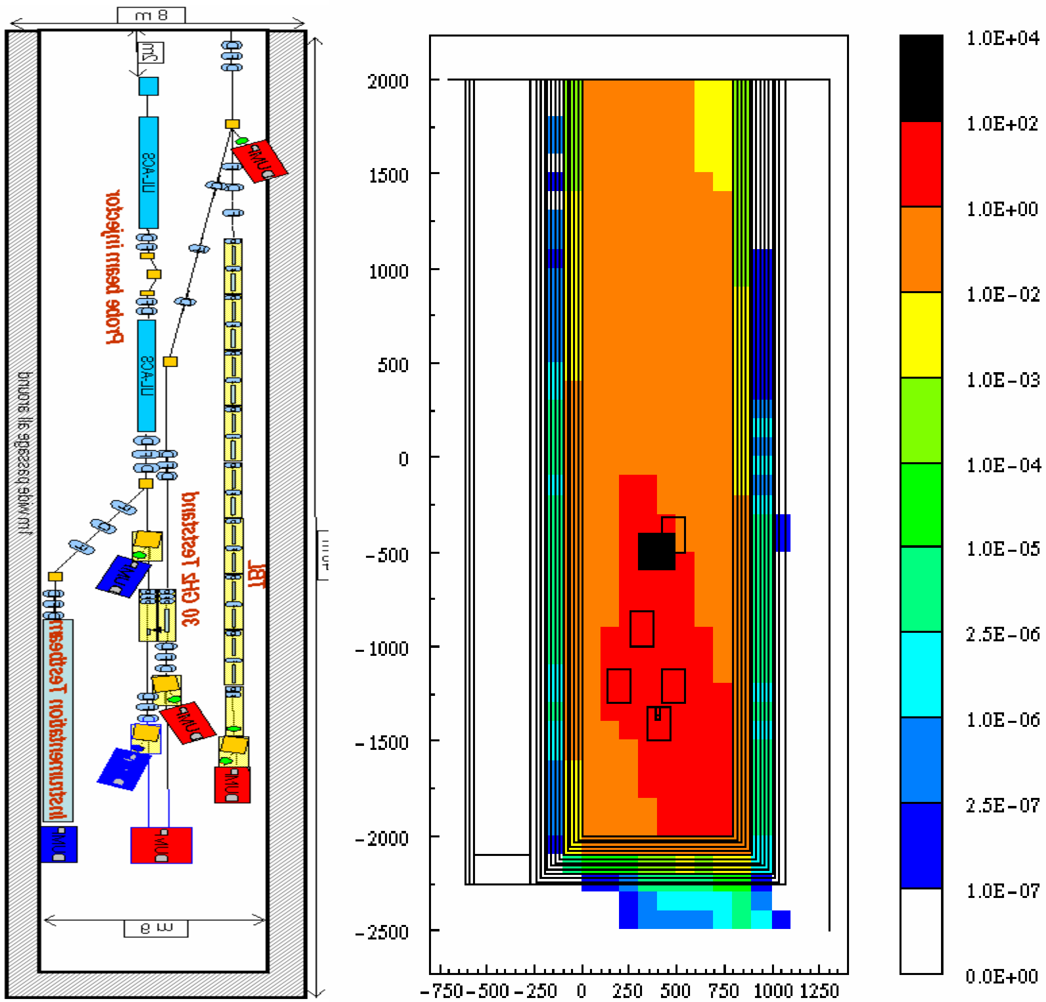
CERN Staff	Users	Contractors
1477	1874	1315

Dose interval (mSv)	Persons 2003	Persons 2004	Persons 2005
Total	5646	5788	4666
0.0	4495	5200	3074
0.1-0.9	899	522	1522
1.0-6.0	86	66	70
6.0 -10	4	0	0

Prediction by Monte-Carlo Methods

- Simulation of radiation transport
  - Design of shielding
  - Estimation of activation
  - Development of monitors
- In the last decade, a few Monte-Carlo radiation transport programs covering the particles and energies occuring at particle accelerators have become available and can be executed on standard PCs
- Use of this method permits better understanding and significant economies compared to older approaches

Accelerator shielding

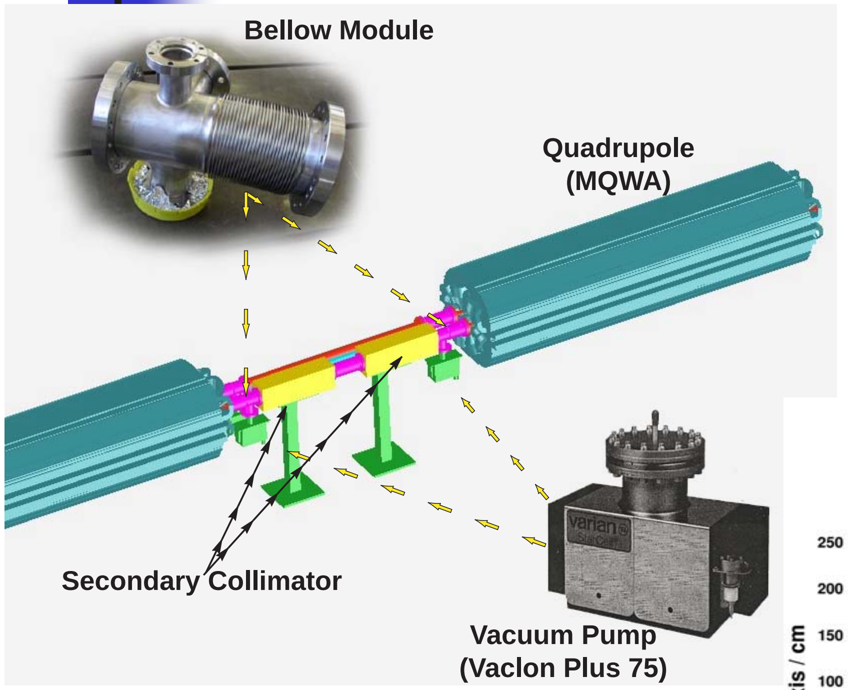


Beam loss in an accelerator building.

5% of total beam intensity leads to dose rates in excess of 1 Sv/h

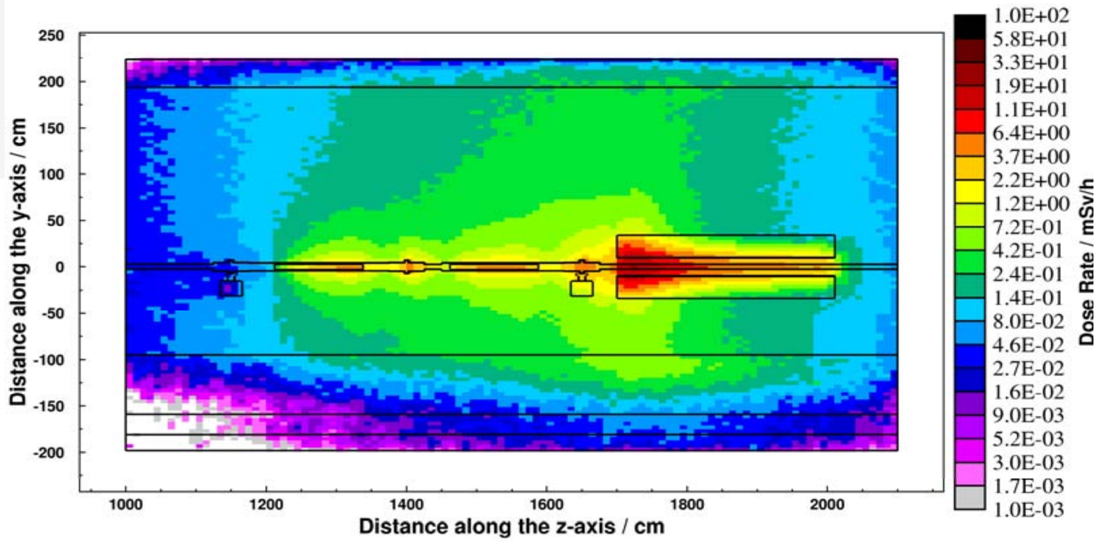
Correctly dimensioned shielding wall of building protects areas outside.

Doserate from activation



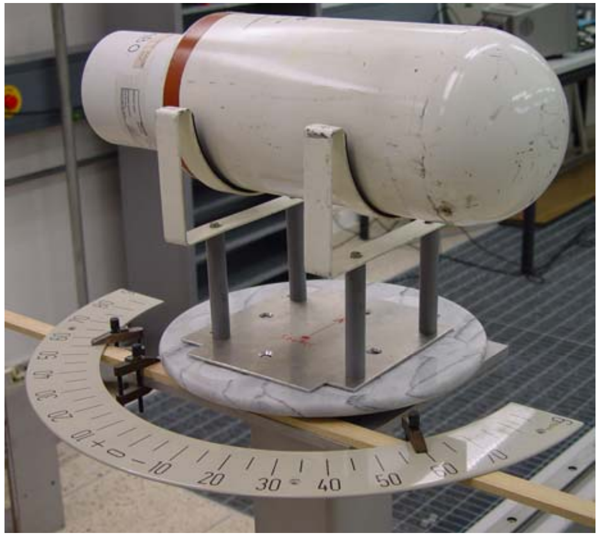
A detailed geometry was implemented in the FLUKA simulations (magnets, collimators, pumps, flanges,…)

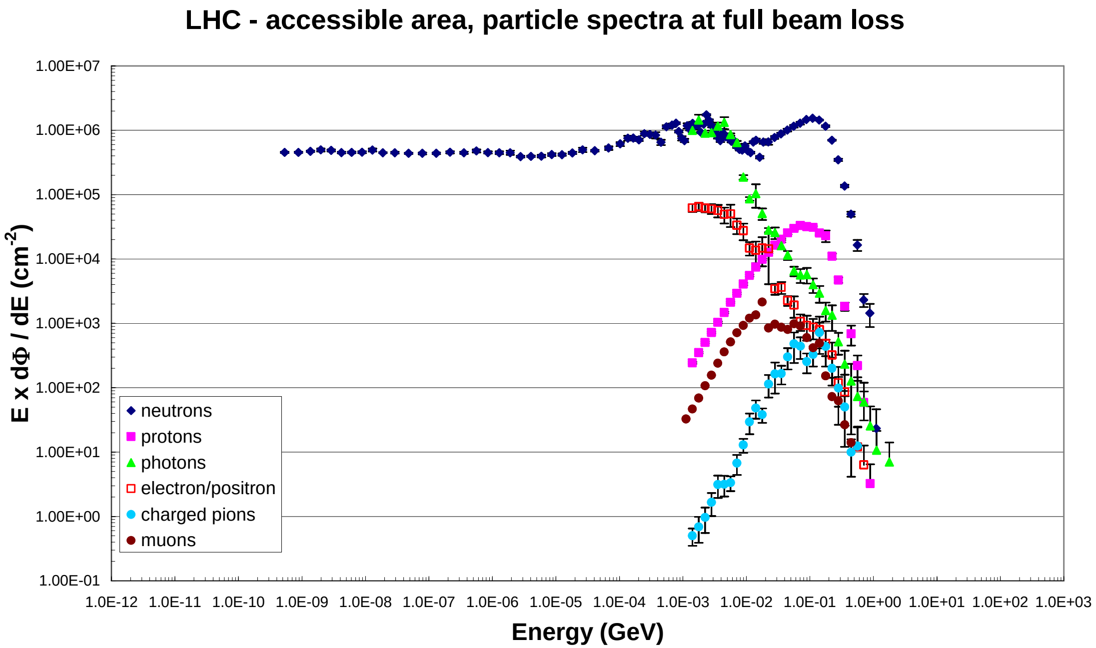
After 180 days of LHC operation and 1 hour of cooling residual dose rates in the order of several mSv/h are reached!



Dosimetry of prompt radiation

- Ambient (Area) Dosimeters are usually optimised for the use in nuclear industry
- Example: Ar-filled ionisation chamber as γ-monitor





In an accelerator-generated radiation filed, the chamber will also respond to charged particles and high-energy neutrons, both absent in nuclear industry.

Summary

- Radiation Protection is an interdisciplinary professional field
  - It is not an "exact" science
  - Scientists have their natural place, e.g. in radiation dosimetry, radiation biology or computer simulation methods
  - Decisions in radiation protection are based on many factors: science & engineering, legal dispositions, economical considerations

Acknowledgements

- Radiation Protection at CERN is not a one-man show, but the combined effort of many persons.
- In this spirit, thank you to all my past and present colleagues in the Radiation Protection Group from whom I used material in this introduction, in particular
  - Markus Brugger, Hans Menzel, Graham Stevenson, Chris Theis, Helmut Vincke

Useful References

- CH: Swiss Ordinance on Radiological Protection 814.501 of 22 June 1994, State of 19 December 2000.
- F: Code du travail, articles L. 231-1 et L. 231-7-1 et articles R.231-73 à R.231-113. .
- EU: Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation, Official journal No. L159, 29/06/1996 pp 1–114.
- http://safety-commission.web.cern.ch/safety-commission/SC-site/sc_pages/sc_rp.htm
- http://www.bag.admin.ch/themen/strahlung/index.html?lang=en
- http://www.asn.gouv.fr/
- http://www.hpa.org.uk/radiation/
- http://www.umich.edu/~radinfo/
- http://www.nrc.gov/what-we-do/radiation.html