Radiation Protection at CERN

An Introduction

H.G. Menzel

CERN, 6th July 2005

Overview

- Introduction
- Physics and biology of radiation induced biological effects
- Radiation risks
- Radiation protection concepts
- Radiation and environmental protection at CERN

Introduction

FACT: Ionizing radiation CAN increase incidence of cancer*, in exposed adults and children

- **definitively known, no room for speculation**
- **very clear from human epidemiology (for moderate and high doses)**
- **plausible biological mechanisms identified**

*** Radiation can cause many, but not all, types of solid cancers and leukaemias**

Questions:

- How much cancer does radiation cause?
  - dependence on radiation type and exposure conditions?

- Can it do so even at very low doses?
  - from natural environmental radiation?
  - from man-made exposures (occupational, environmental, medical)?

- How is scientific knowledge used in current radiation protection concept?

- What is specific for radiation protection at CERN?

Exposure to Ionising Radiation

•Natural radiation:	radionuclides: e.g. ^{40}K, Rn, … cosmic radiation unavoidable
•Medical exposure:	radiological diagnostics (X-rays, CT, nuclear medicine incl. PET) radiation therapy intentional (radiation protection)
•Occupational and environmental exposure	nuclear industry, medical staff, research, industry, air crew undesired radiation protection

Physical Processes

Physical processes in tissue:

photons: photo-effect, Compton-effect, pair production, nuclear photo-effect
result: **secondary electrons,** secondary photons

neutrons: elastic scattering with nuclei, mainly hydrogen
in-elastic scattering, nuclear interactions
result: release of energetic charged particles and γ-rays, **secondary electrons**

charged particles: energy dependent; at lower energies mainly Coulomb interactions
result: secondary electrons, nuclear reactions

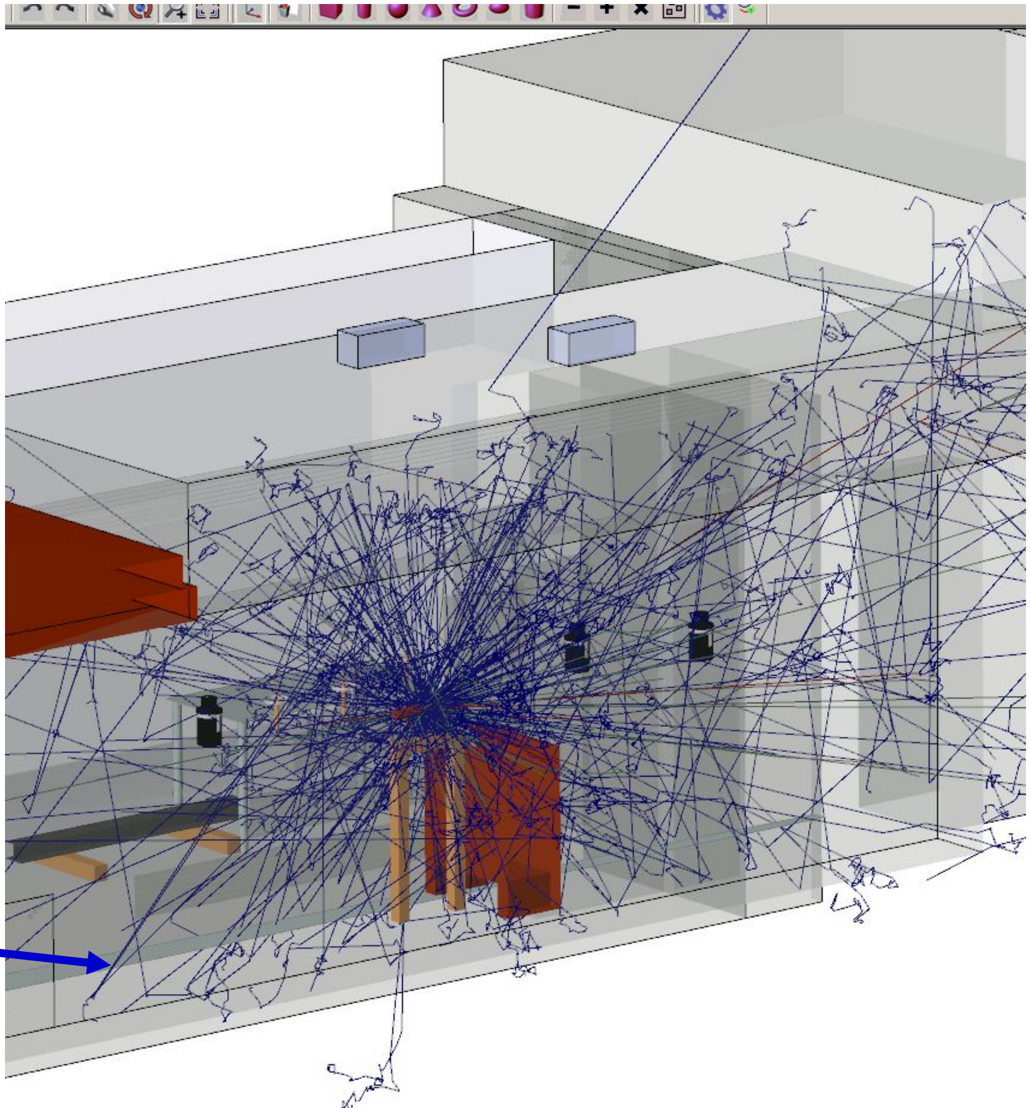
Spontaneous Radiation

CERN
SPS North Area:
hadrons at 120 GeV

1 primary particle ->

hadronic shower

neutrons



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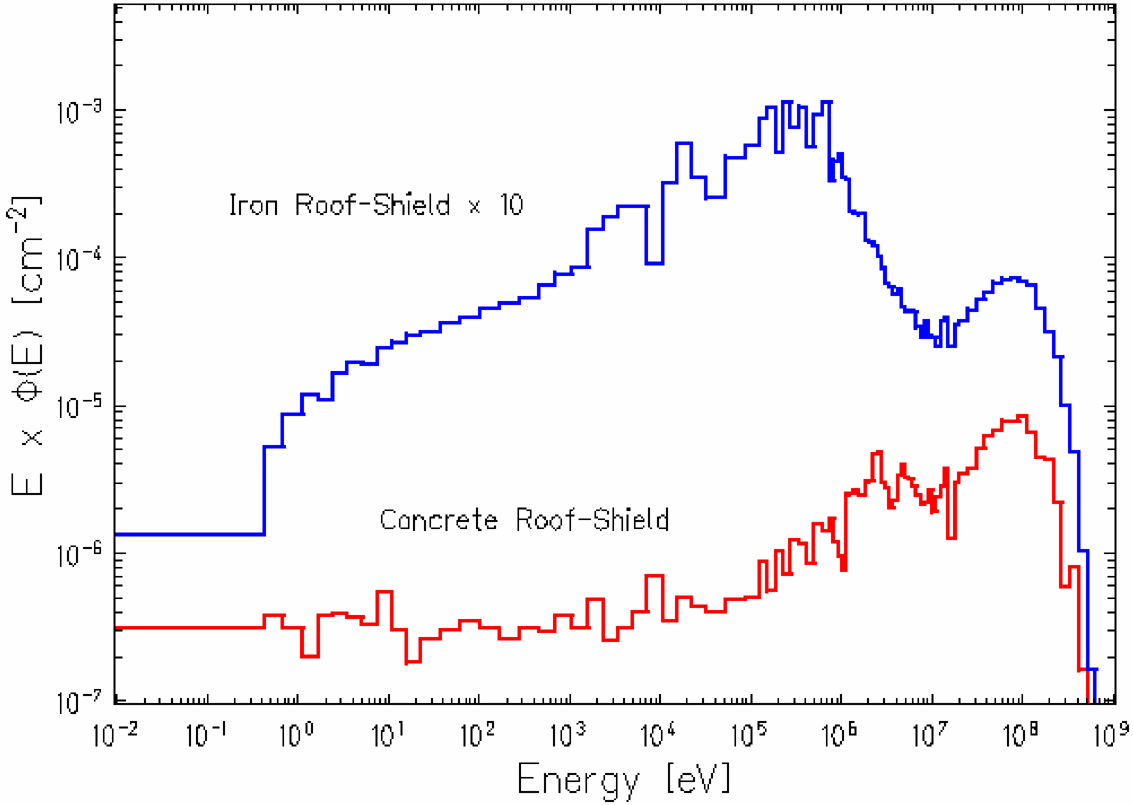
Neutrons outside shielding of high-energy proton accelerator



Neutron spectral fluence outside a 80 cm thick concrete shield and a 40 cm thick iron shield near Cu-target bombarded by 450 GeV protons

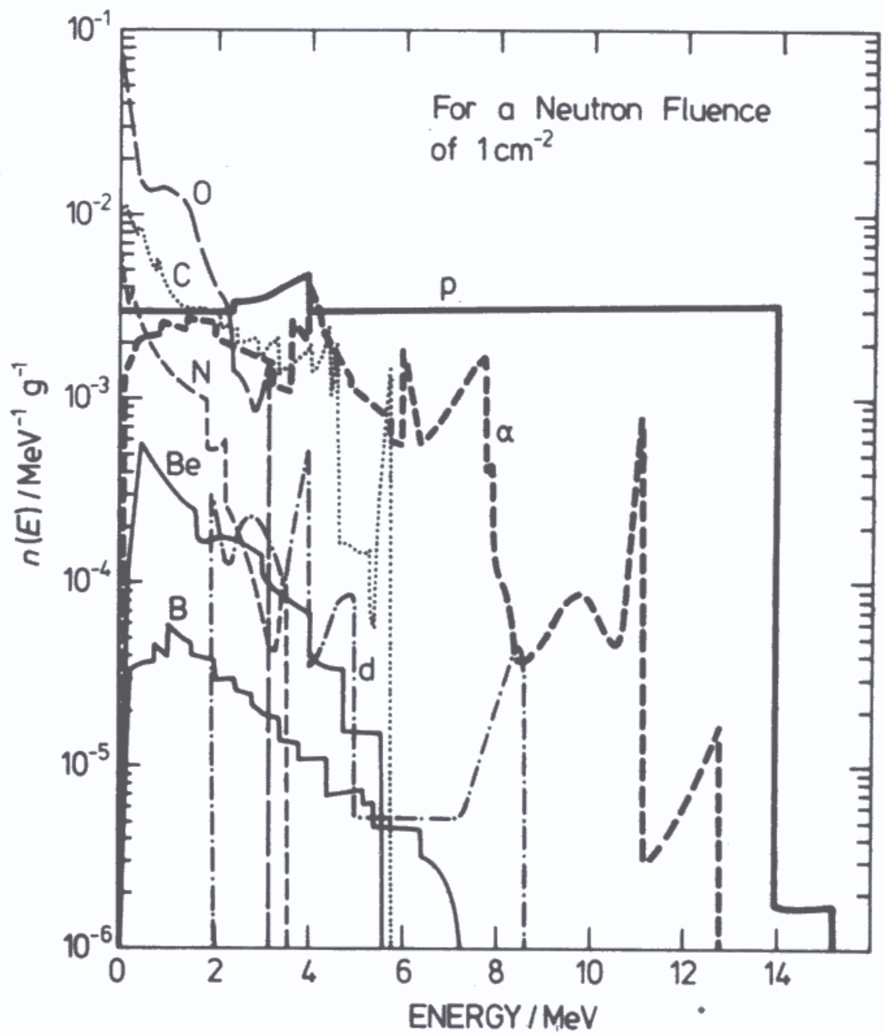


Fig. 6.2. Initial spectrum of charged particles for a neutron fluence of 1 cm^{-2} of 14 MeV neutrons in ICRU tissue (after Caswell and Coyne, 1972). The symbols p, d and α refer to recoil protons, deuterons and alpha particles, respectively.

Secondary particle spectra (tissue)

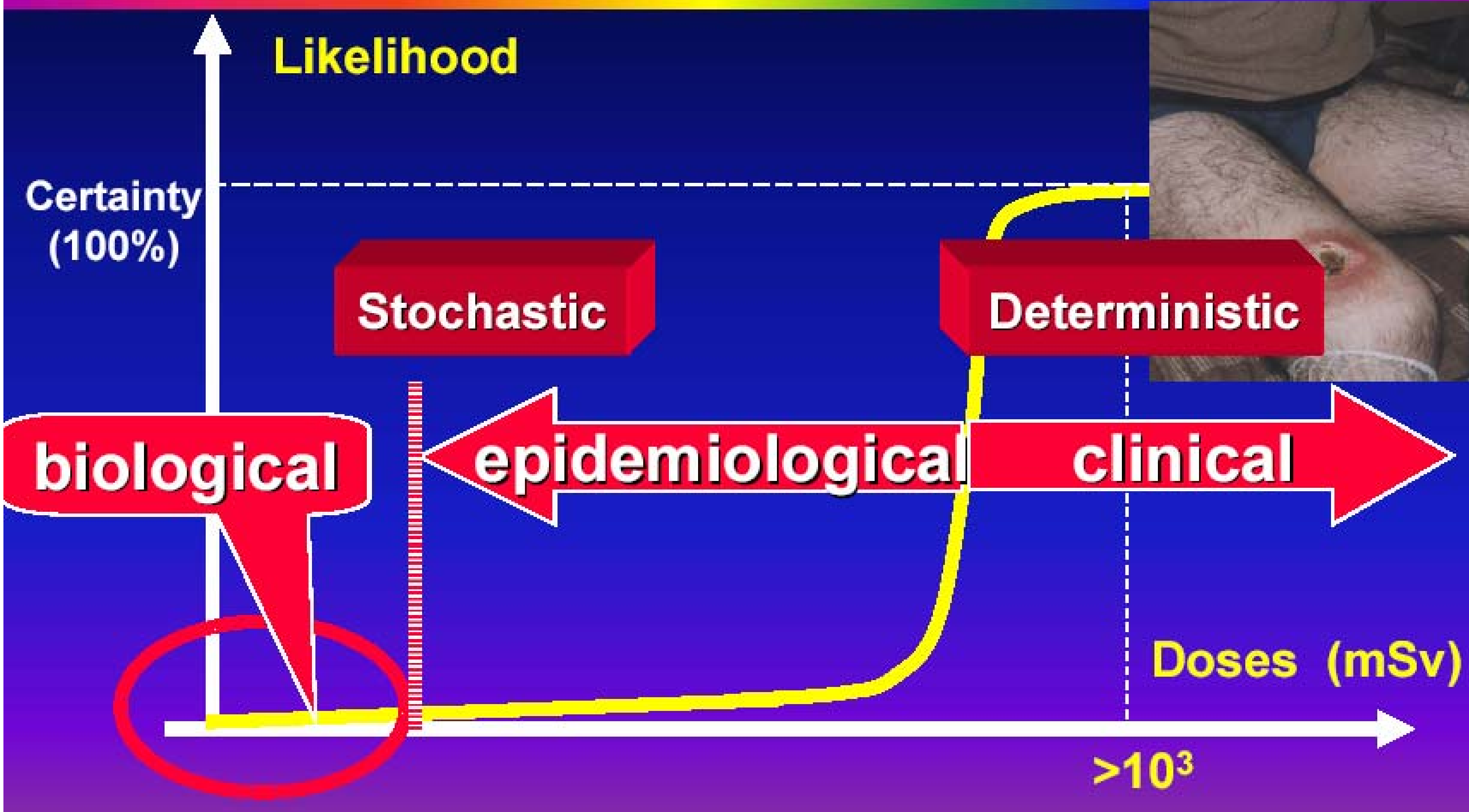
14 MeV neutrons

Radiation Effects

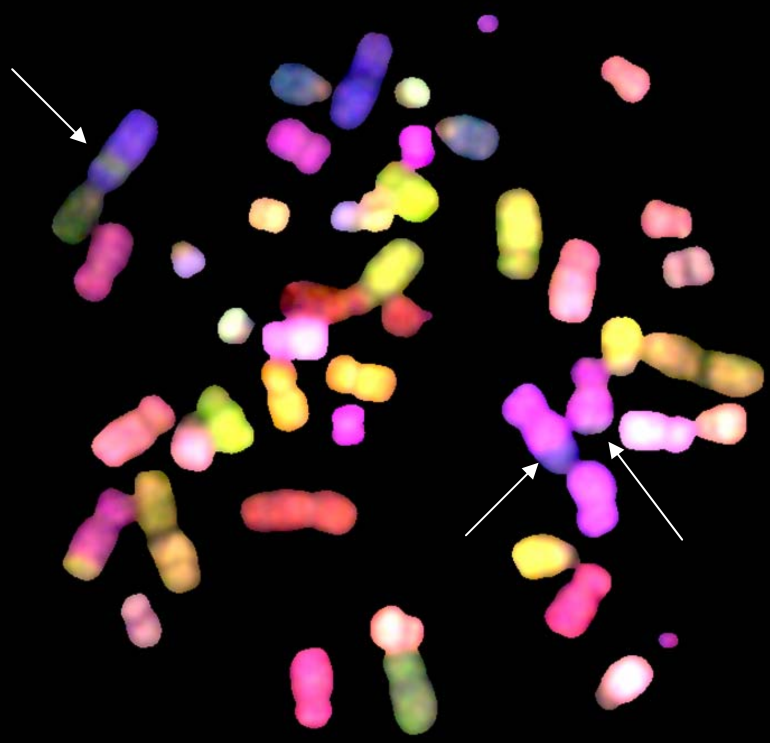
Deterministic effects: High doses will cause inevitable harm, which does not appear below a threshold dose.

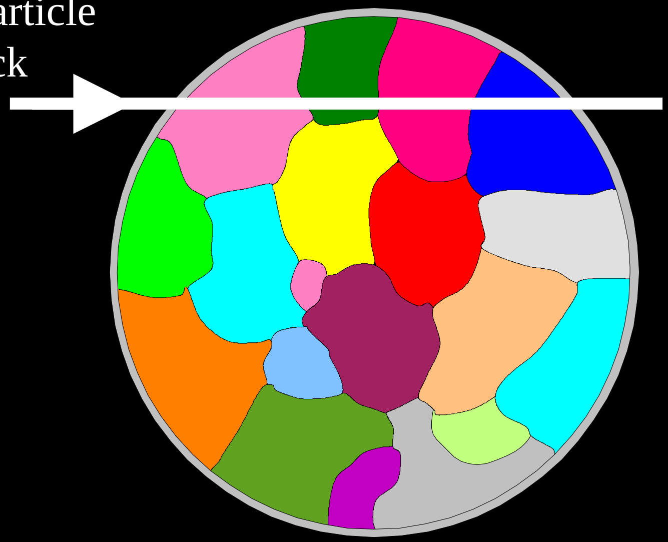
Stochastic effects: Both high and low doses may cause effects. At low doses (of the order of the natural back-ground) these effects will occur with a small probability, which is judged by ICRP to be in proportion to the dose.

Attributability of radiation health effects

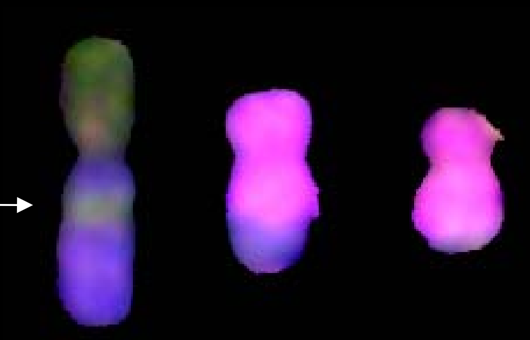


Example of a viable aberration in a human lymphocyte after alpha-particle irradiation





Transmissible insert



Anderson et al, PNAS <u>99</u>, 12167 (2002) (*in vitro*)

Anderson et al, Radiat Res <u>163</u>, 26 (2005) (in humans)

Cell death ⇒ deterministic effects: burns, organ failure, death

Biological Effects
UNSCEAR 2000 REPORT

Information comes from:

- studies of humans (epidemiology)
- studies of animals and plants (experimental radiobiology)
- studies of cells (cellular and molecular biology)

The key to understanding the health effects of radiation

is the interaction between these sources of information

Absorbed dose

An absorbed dose of 1 Gy

corresponds:

to a temperature increase of $2.4 \cdot 10^{-4}$ °C

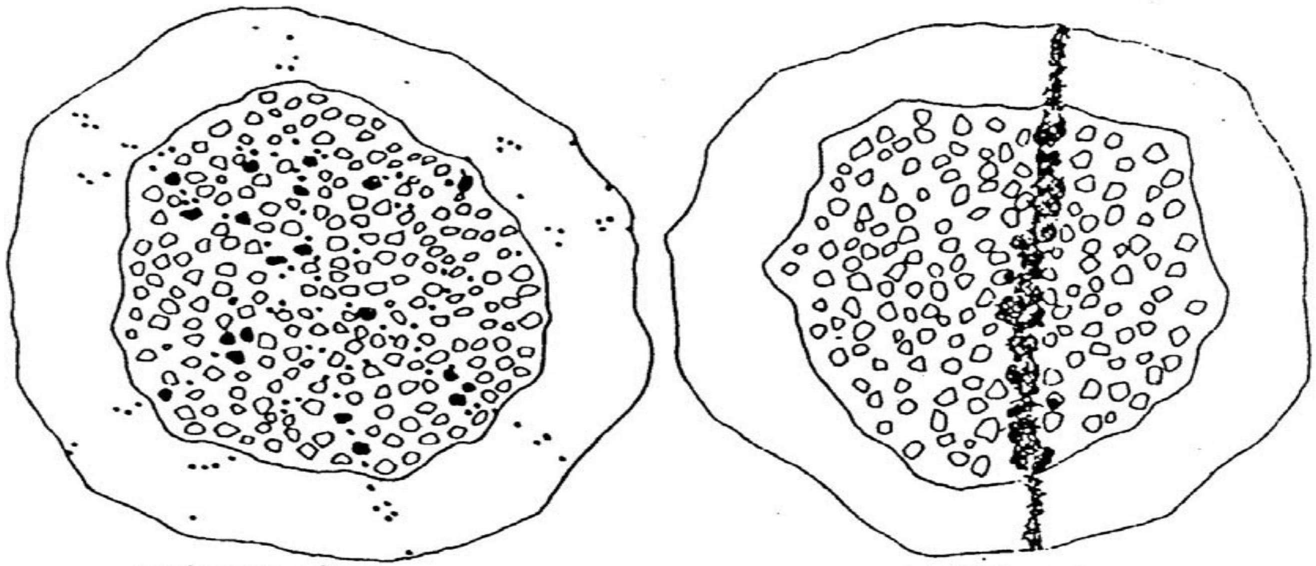
i.e. a lethal dose (mammalians) of around 5 Gy corresponds to a temperature increase of ~ 10^{-3} °C

Stochastic Interactions

- **The special feature of ionizing radiations is their discontinuous interaction with matter. However, absorbed dose and absorbed dose rate are defined as averages that disregard the resulting random fluctuations.**
- **The knowledge of absorbed dose may permit no statement on energy actually imparted to individual cells or to sub-cellular structures.**

Cellular Doses

IONIZATION PATTERN GENERATED IN CELLS BY AN ABSORBED DOSE OF 10mGy (1 RAD) CELL DIAMETER ≃ 5μm



I MeV Gamma Rays

~ 150 ion pairs in a substantially random array. The pattern in all other cells is similar.

I MeV Neutrons

~ 6500 ion pairs in a substantially linear array. This occurs in about 2% of the cells. 98% of the cells receive no energy.

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

Ionizing Radiation = Tracks

Radiation insult is always in the from of <u>tracks:</u>

-- Highly structured (on cell and DNA scales)

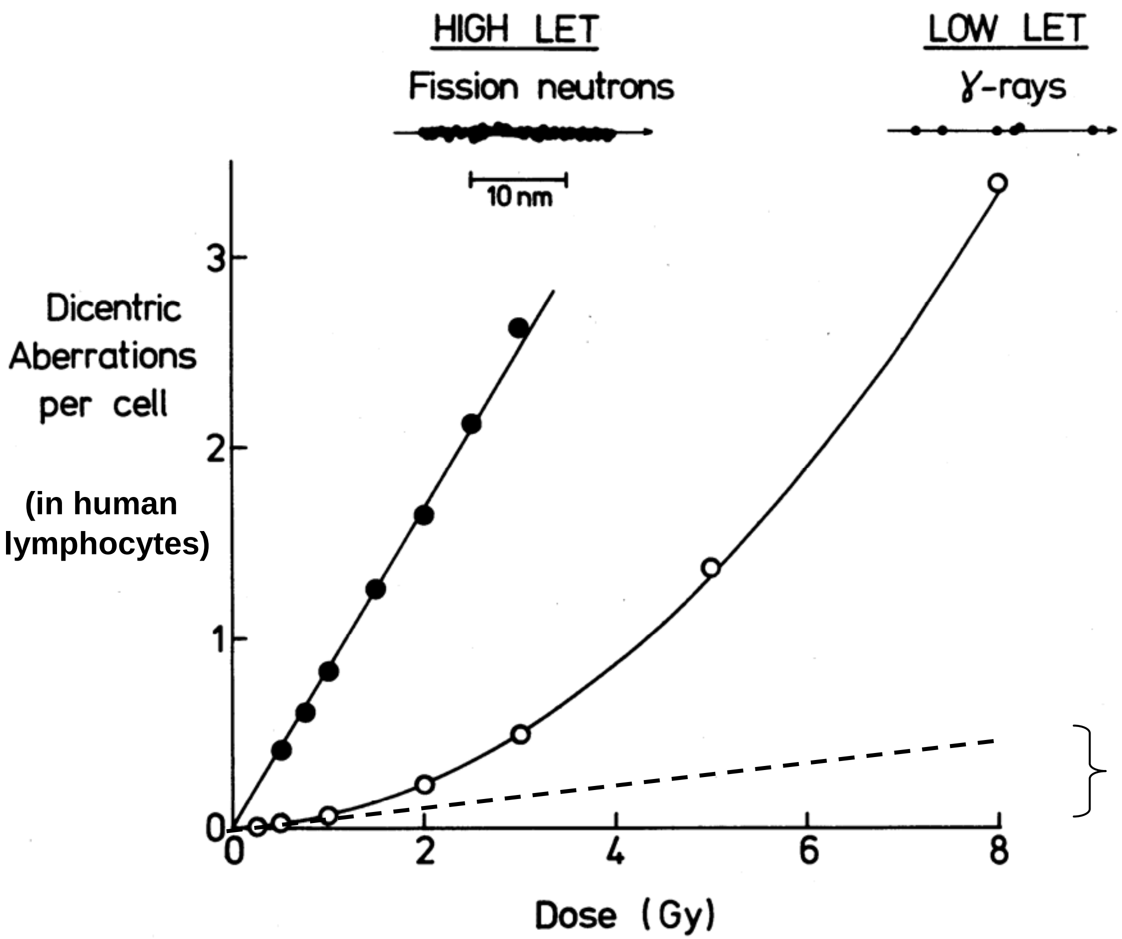
-- Stochastic

-- Contain: isolated ionizations,
ionization clusters of varying sizes

Track structure: -- dominates effects at low doses and low dose-rates;
-- determines numbers of tracks per unit dose;
-- unique compared to other agents and endogenous processes

Ionizing radiations produce chromosome aberrations

- **including by single tracks at low doses**

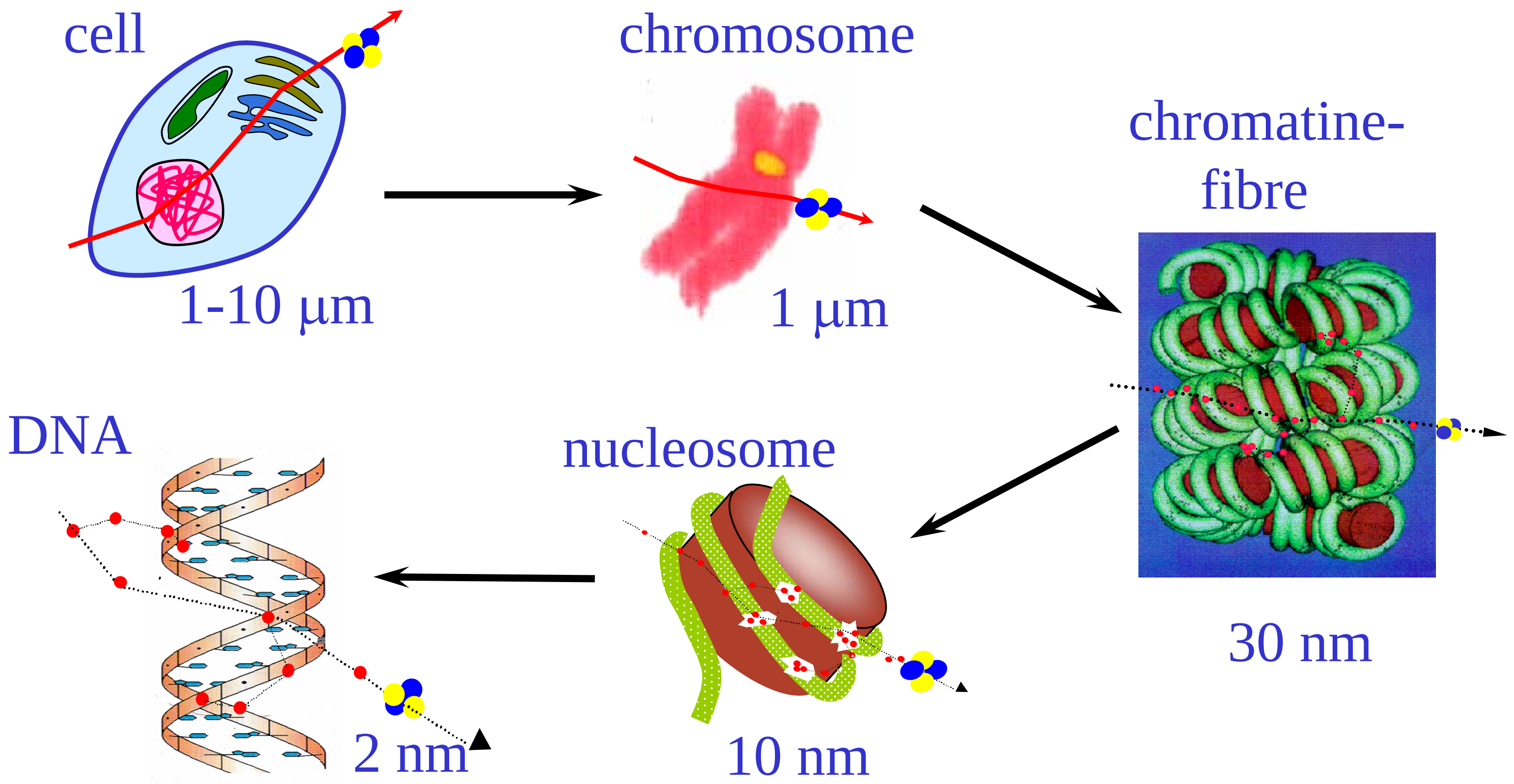


(in human lymphocytes)

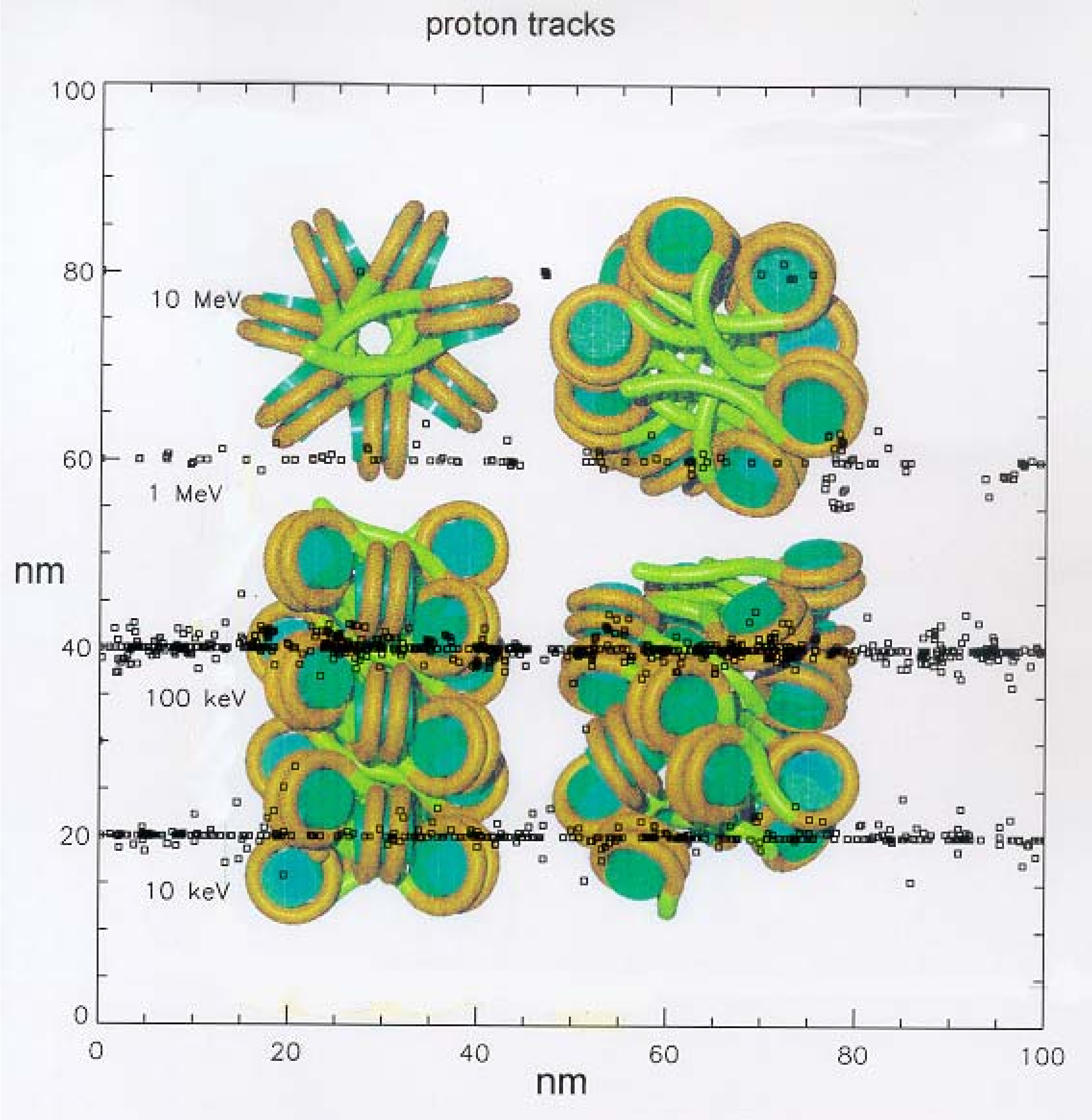
Linear term: one-track

(Data replotted from Lloyd et al)

Cellular and molecular radiation effects



Track structure on DNA scale



Human exposures:

	Mean tracks per month:
Natural background	
Low-LET (1 mSv/y)	Electron-track through 1 cell nucleus in 12
High-LET: Lung (~10 mSv/y)	Alpha-track " 1 " " " 5,000
Marrow (0.1 mSv/y)	" " " 1 " " " 1,000,000
Radiation workers receiving annual limit of 20 mSv/y at uniform 1.7 mSv per month:	
Low-LET gamma-rays	2 electron-tracks though each cell nucleus (ave.)
High-LET fission neutrons	Proton- track through 1 cell nucleus in 1,000
Medical Diagnostics	**Instantaneous:**
1 Chest X-ray (0.2 mGy)	" " " 1 " " " 20
1 Mammogram (2 mGy)	" " " 1 " " " 2
1 CT scan (head, 50 mGy)	20 electron-tracks through each cell nucleus
Radiotherapy	
Single fraction (MV X-rays, ~ 2 Gy)	2,000 electron-tracks through each cell nucleus

Most human exposures are due to single tracks in cells, isolated in space and time, but there are notable exceptions.

Simple picture of radiation induction of cancer:

(conventional view)

Radiation track in a cell

→ Low probability →

DSB

↓ Low probability

Mutation/aberration

↓ Very low probability

In cancer-related gene

↓ In 'stem' cell, precursor cell

Increased chance of cancer

All approximately proportional to number of tracks, ie to Dose (Gy, Sv)

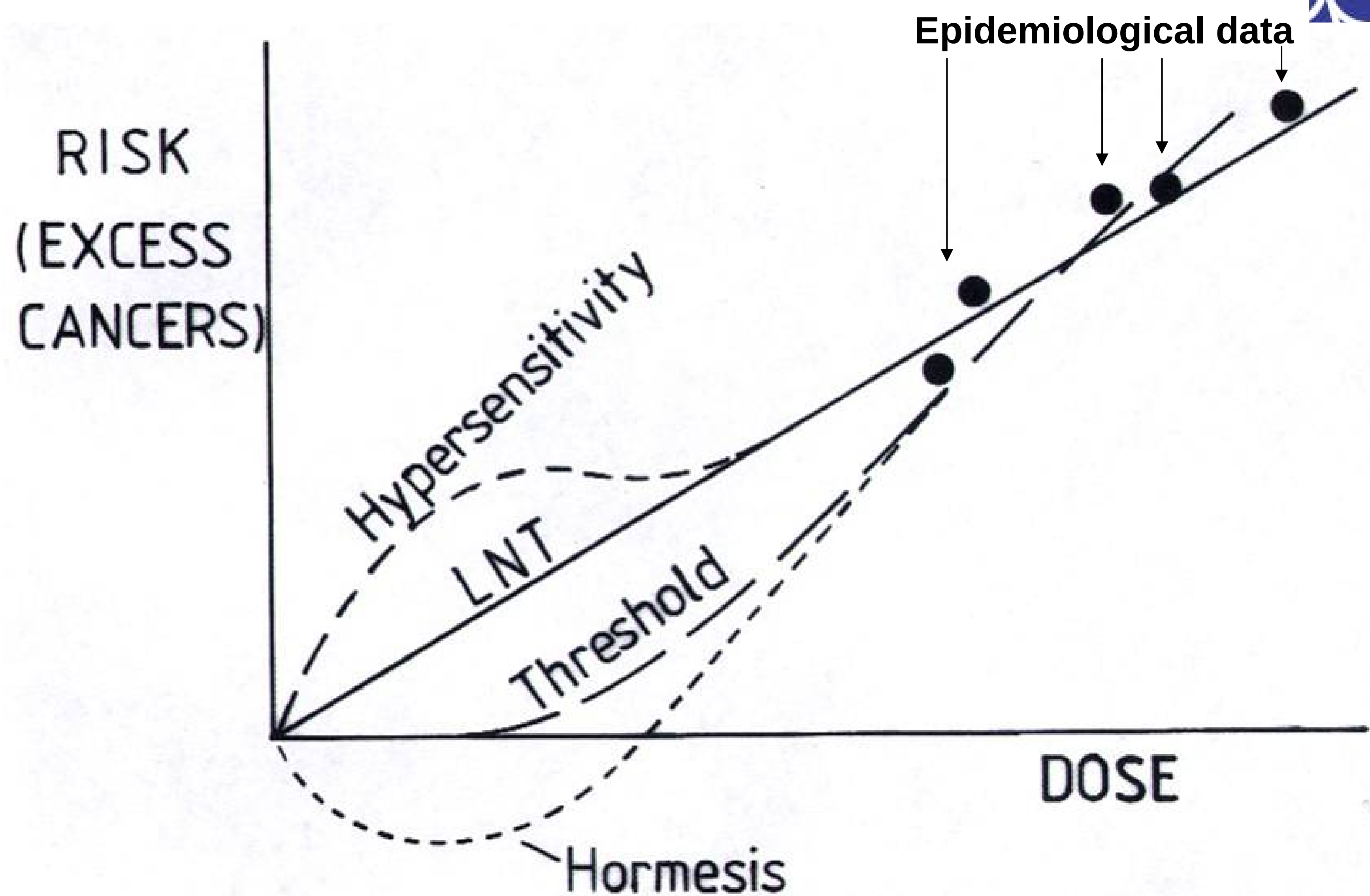
↓

Approx linear extrapolation to low doses

(no threshold)

This combination of low-probability events can, very occasionally, lead to the tragic outcome.

Low-dose risk extrapolation ??



From epidemiology

Cancer increase is readily detectable for 100s or 1000s of tracks per cell

(e.g. A-bomb survivors)

[~1000 tracks/cell/Gy]

But

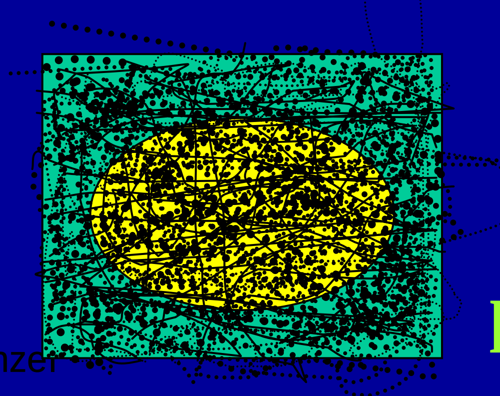
Require risks

for

<u>single</u> isolated track in cell

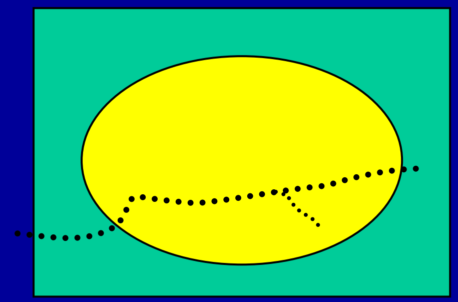
[~ 1 track/cell/year at 1 mGy/year]

How to extrapolate??



?

Simply linear??!!



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Cohort of Hiroshima & Nagasaki
(LIFE SPAN STUDY, LSS)

Primary source of information:

- 86,500 individuals of:
  - ✓ both sexes and
  - ✓ all ages
- dosimetric data over a range of doses

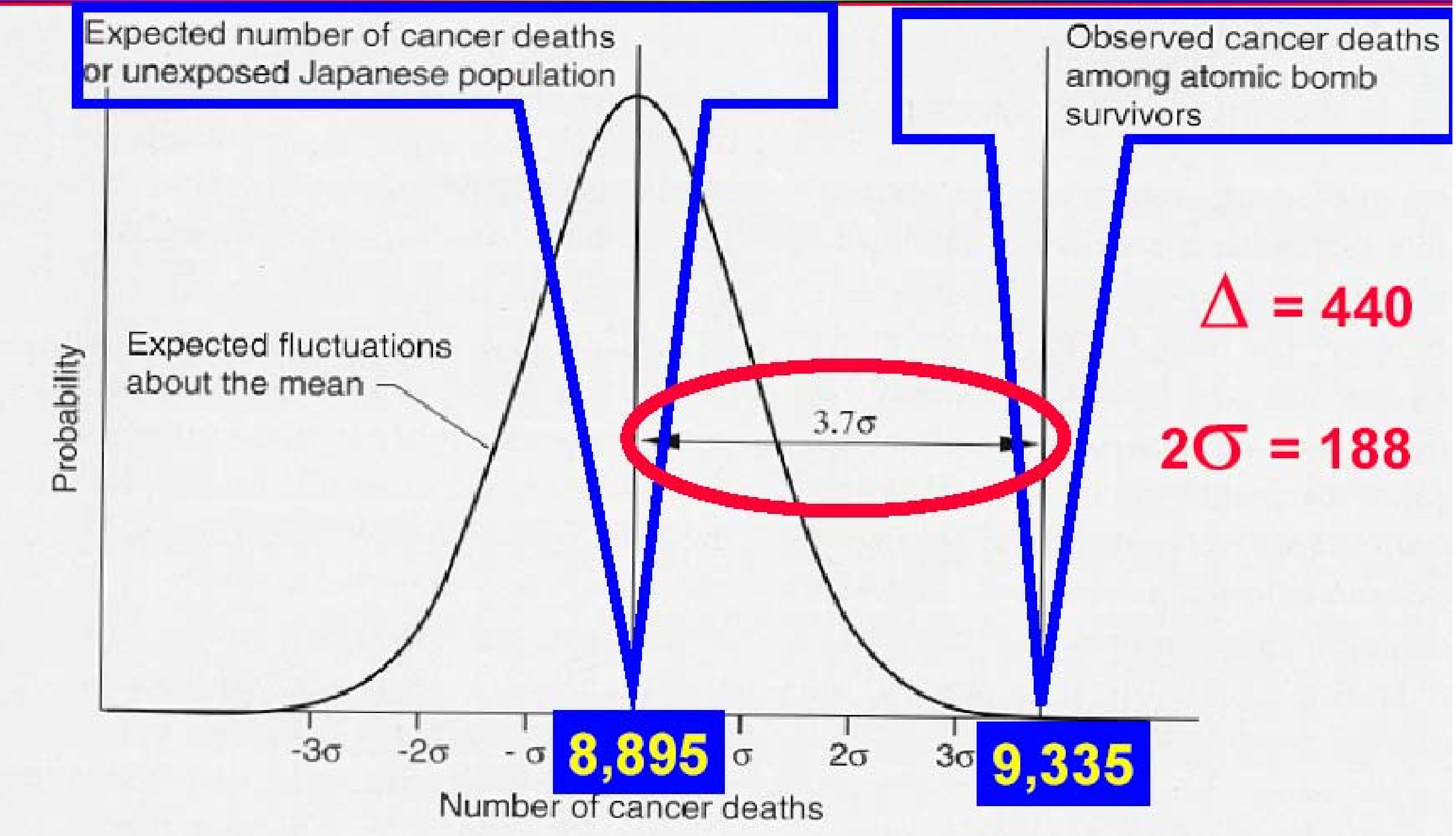
LSS Solid Cancer Mortality

47 years of follow-up (1950-1997)

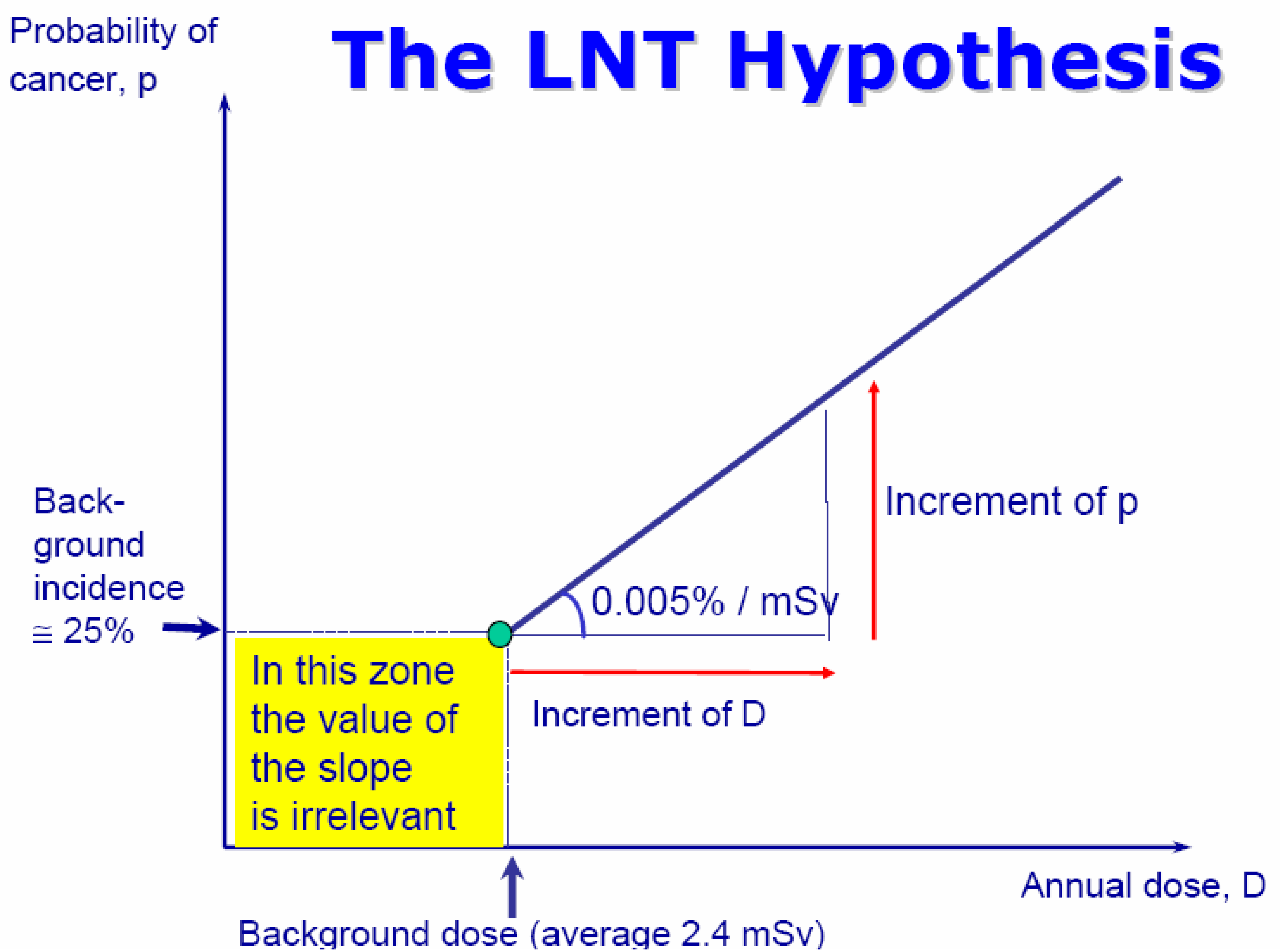
- 9,335 solid-cancer deaths
  - Expected: ~8,895 cancers
  - i.e. ~440 cancers (5%) attributable to radiation

(Preston et al, *Radiat Res* 160:381-407, 2003)

Excess Solid-Cancer Deaths



The LNT Hypothesis



Summary of Epidemiological Estimates

Cancer Risks

Cancer mortality risk (after 1000 mSv acute dose)

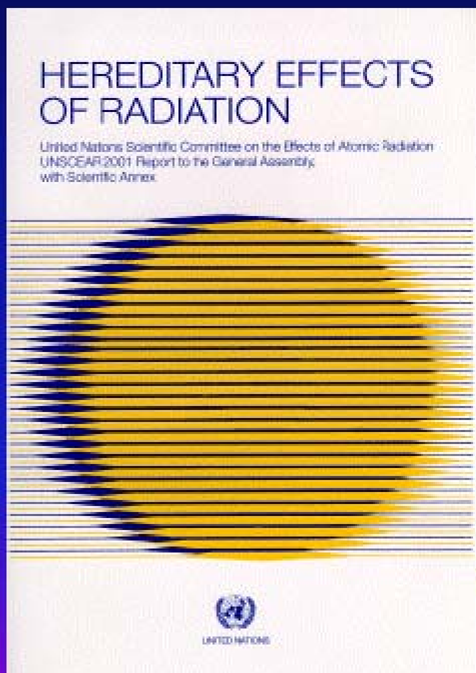
- **~0.9% for leukæmia**

and

- **~11% for solid cancers**

(~9% for men and ~13% for women)

Hereditable Effects



Total risk to first generation following parental exposure:

0.0003 - 0.0005% per mSv

- ✓ 1/10 the risk of fatal carcinogenesis
- ✓ constitutes 0.4-0.6% of baseline

Practical Radiation Protection

- International recommendations (ICRP)
- European and national legislation and regulation
- CERN Radiation Safety Code
- Design of accelerators and experiments incl. shielding (simulations based on radiation transport calculation)
- Ambient and individual radiation monitoring
- Environmental monitoring

Practical Radiation Protection

- **Principles:**
  - **Justification (requires judgement)**
  - **Limitation (requires biological effects)**
  - **Optimisation (ALARA) (requ. cost/benefit analysis)**

  All embedded in ethics and legislation

- **Limits**
  - **Occupational exposure: 20 mSv per year**
  - **Public: 1 mSv per year**

Effective Dose

- **Radiation Protection (ICRP):**
  Empirical weighting factors are used to define such a single dosimetric quantity E (effective dose) to account for
  - **radiation quality (w_R)and,**
  - **for differences in radiation sensitivity of different tissues (w_T)**

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

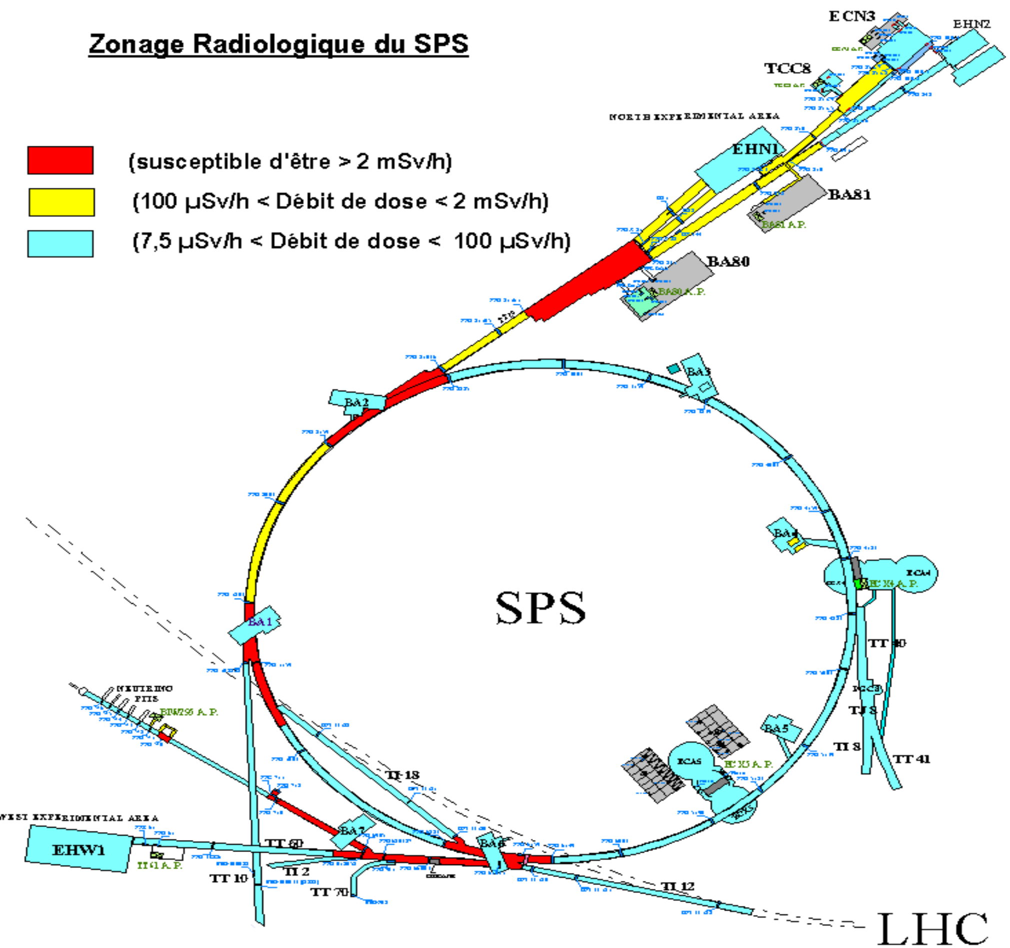
Note: w_R **has values from 1 to 20 and**
w_T **varies between 0.01 and 0.20**

Radiation weighting factors

(ICRP 60 (1991))

Radiation	w_R
Photons, electrons and muons	1
Neutrons < 10 keV	5
10 keV <100 keV	10
100 kev < 2 MeV	20
2 MeV < 20 MeV	10
> 20 MeV	5
Protons > 2 MeV (except recoil protons)	5
Alpha particles and heavy ions	20

Why is radiation protection needed at CERN?

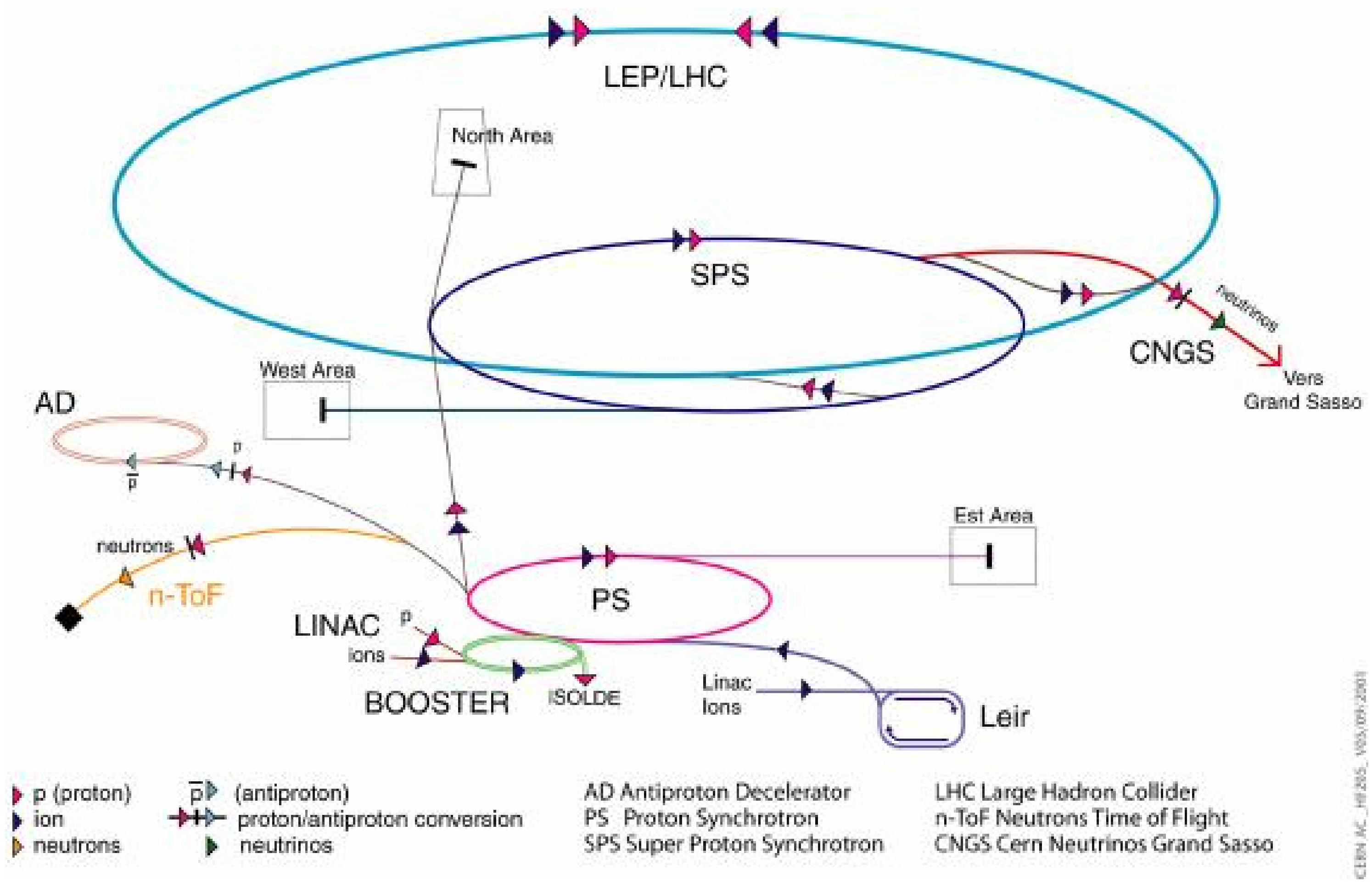


The use of high-energy proton and electron beams for particle physics research automatically

brings with it the **exposure of persons** to radiation escaping from the shielded structures of the accelerators

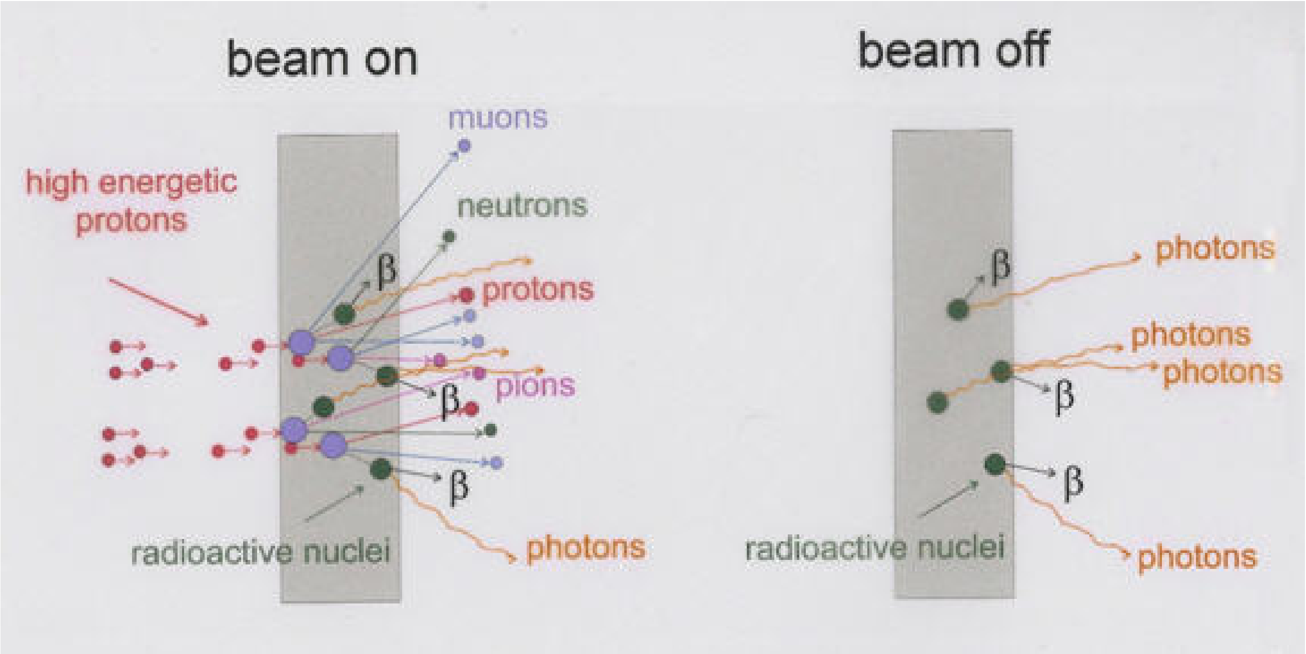
and the production and release of radioactive substances into the **environment** (air, water).

Accelerator chain of CERN (operating or approved projects)



Radiological Risks around CERN Accelerators

Main risks



Instant radiation field

Induced radioactivity

and some few more:

RF cavities

Klystrons

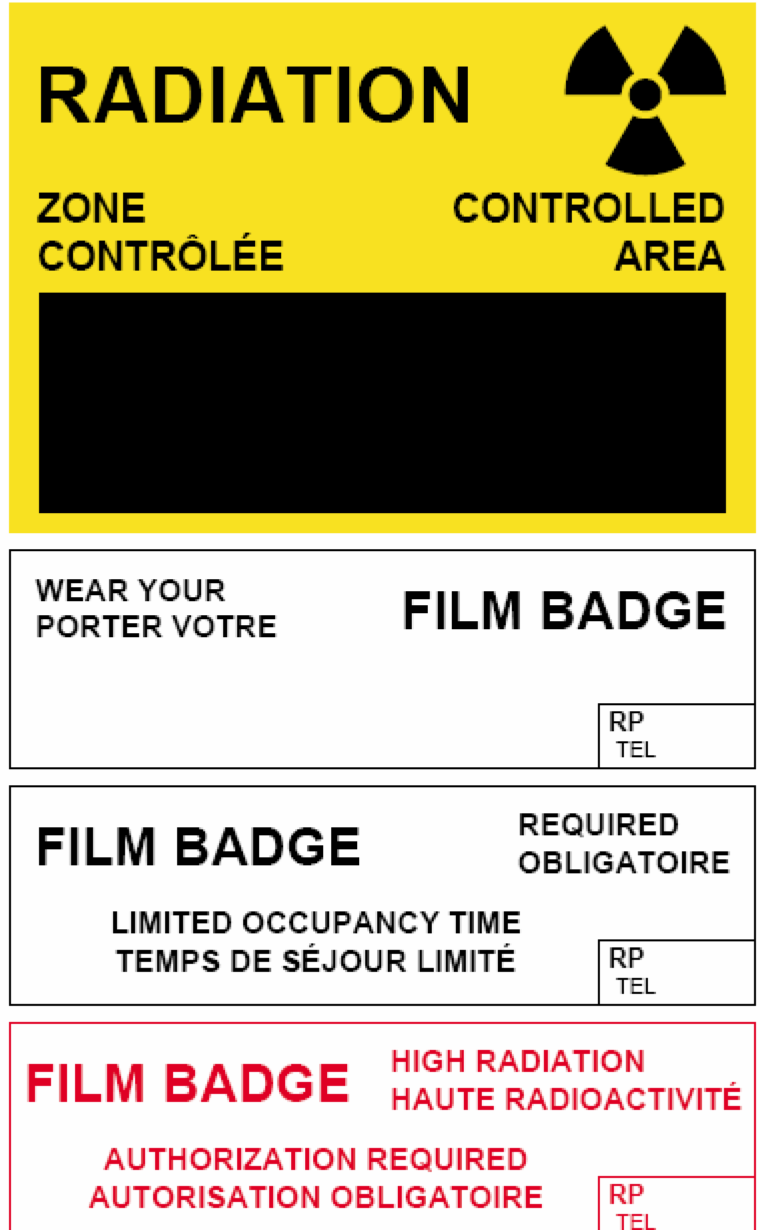
Radioactive sources

(α-, β-, γ-radiation)

How to Ensure Compliance?

- In the planning phase of an installation:
  - Calculation of radiation fields, material activation, and releases (FLUKA),
  - Environmental models,
  - Optimization.
- In the operational phase:
  - Monitoring,
  - Optimization
  - Environmental models.
- In the decommissioning phase:
  - As in the operational phase +
  - Radioactive Waste management.

Designated Areas and Access Control

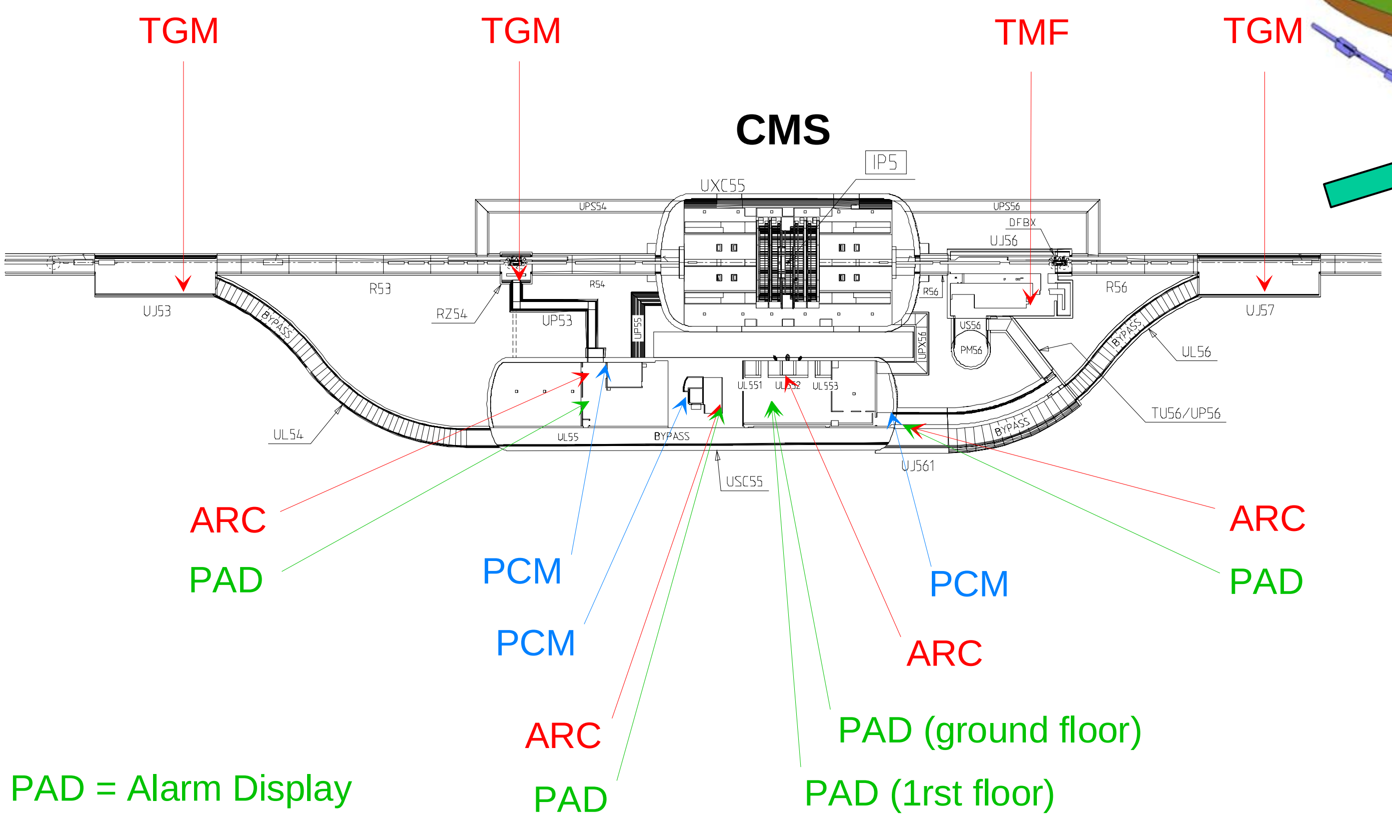


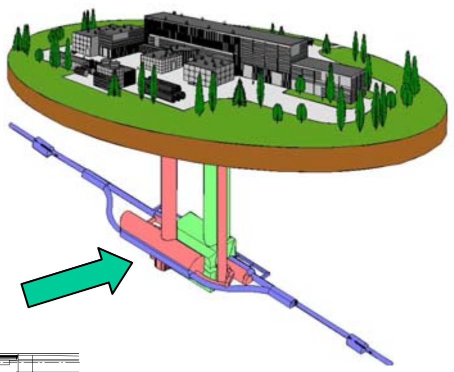
CERN Personal Dosimeter

Distribution of Individual Doses (CERN)

Dose interval (mSv)	Persons 2001	Persons 2002	Persons 2003
Total	6959	6240	5646
0.0	6328	5842	4495
0.2-0.9	511	343	899
1.0-6.0	118	53	86
> 6.0	2	2	4

Ambient monitoring
Example: RAMSES LHC-5



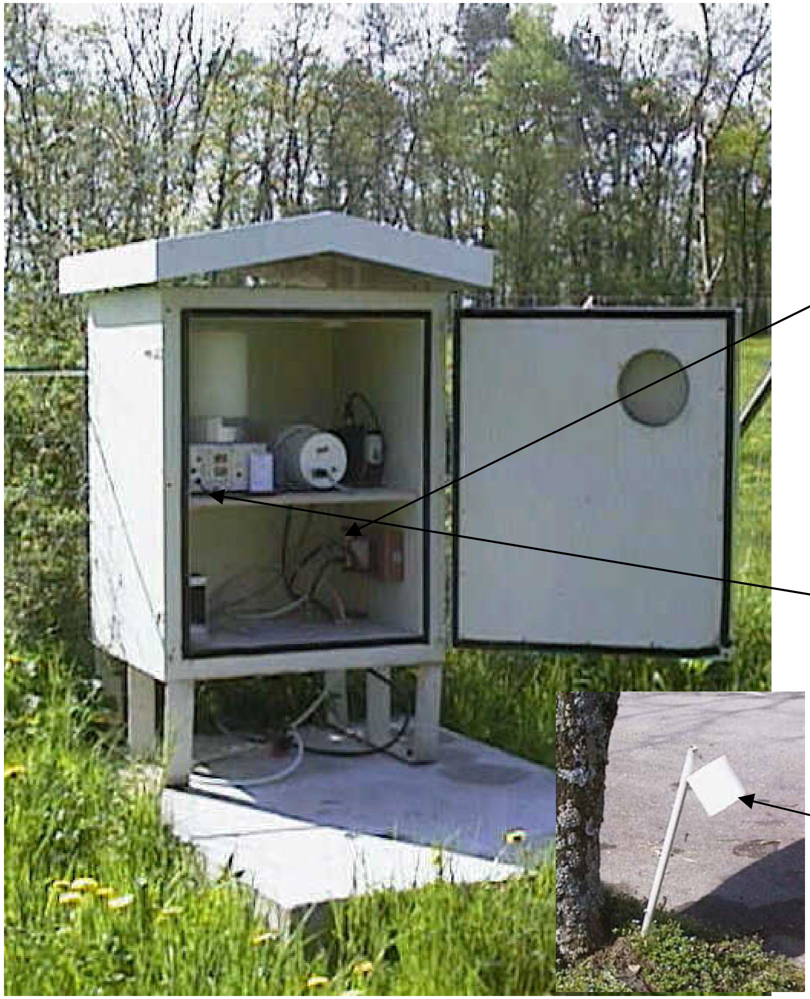


PAD = Alarm Display

Radioactive Emissions

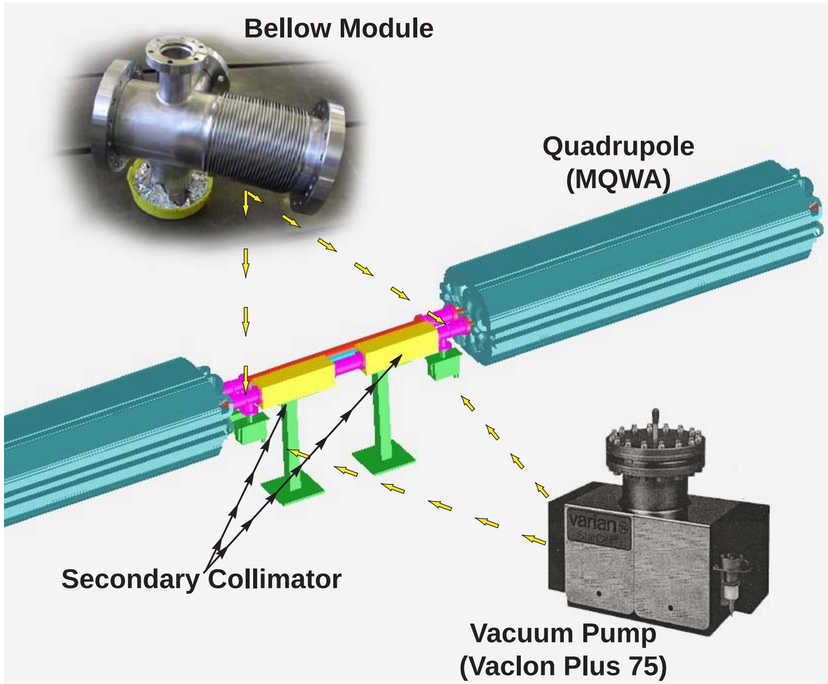
- Air ventilated from accelerator installations may be activated:
  - Directly by (lost) beams,
  - Indirectly by scavenging dust, fragments, etc.
- Short-lived gaseous: ^{11}C ($T_{1/2}$ = 20 min), ^{13}N, ^{14}O, ^{15}O, ^{41}Ar (direct),
- Tritium (HT, HTO),
- Beryllium-7 (direct & indirect),
- Fragments and volatile: ^{48}V, ^{46}Sc, ^{60}Co,

Monitoring: Stray Radiation



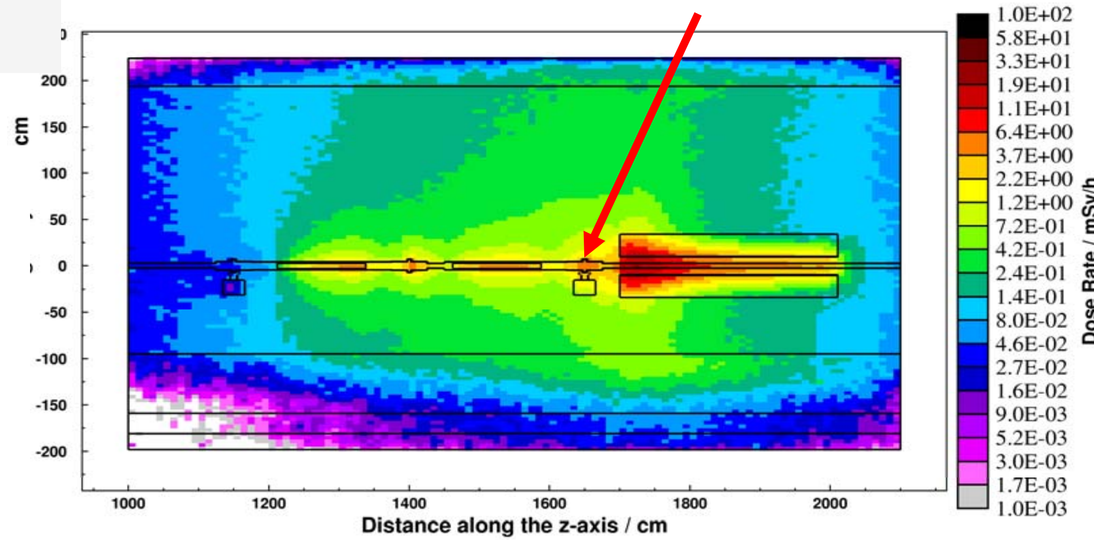
- Active monitors:
  - Pressurized ionization chambers (20 bar Ar),
    - Photons,
    - Muons.
  - Rem-counters,
    - Neutrons.
- Passive dosimeters:
  - $^{6}LiF/^{7}LiF$ annually.

Planning:Maintenance LHC



- detailed case study for the vacuum group
- narrow section between two quadrupole modules

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



Detailed Dose Planning

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**

per person and per intervention

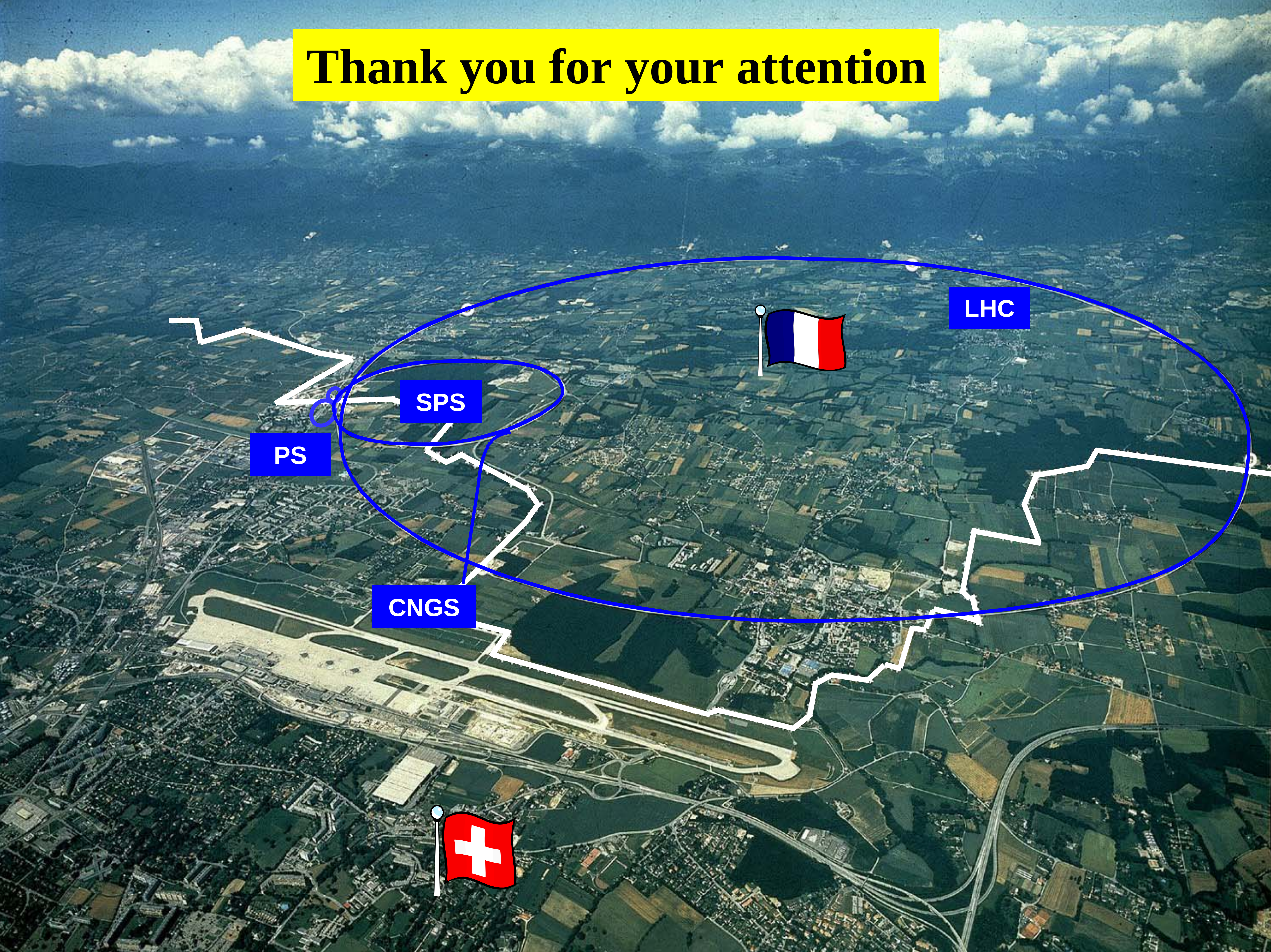
Concluding Remarks

- Our understanding of radiation induced biological effects is far from being complete. Risk factors are associated with considerable uncertainties
- However, current knowledge and its implementation into practical radiation protection is a mature approach.
- CERN is practising state-of-the-art radiation protection.

Acknowledgement

Much of the material used in this presentation has been provided by colleagues in the CERN RP Group and by other colleagues.

Thank you for your attention



Useful References

- CERN Radiation Safety Manual 1996.
- CH: Swiss Ordinance on Radiological Protection 814.501 of 22 June 1994, State of 19 December 2000.
- F: Protection contre les rayonnements ionisants, JO de la République Française, 6th edition, February 1990.
- 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.
- Radiation Protection Group Annual Report 2003.
- P. Vojtyla, Calculation of the effective dose to the public due to releases from the CERN Meyrin site implementing the Swiss directive HSK-R-41, CERN/TIS-TE/98-20 (1998).

Useful Web Links

- http://cern.web.cern.ch/CERN/Divisions/TIS/safdoc/docOnLine_en.html
- http://www.admin.ch/ch/f/rs/rs.html
- http://europa.eu.int/eur-lex/en/index.html
- http://www.admin.ch/bag/strahlen/ion/umwelt/f/index.htm
- http://www.hsk.psi.ch/hsk-publ.html
- http://pvojtyla.home.cern.ch/pvojtyla/Environmental_modeling.html

Epidemiological significance
Solid Cancers

$$N > \sim 10^9 / D^2$$

Dosis, D (mSv)	~ Number of people, N
1	>1.000.000.000
10	>10.000.000
100	>100.000
1000	>1.000