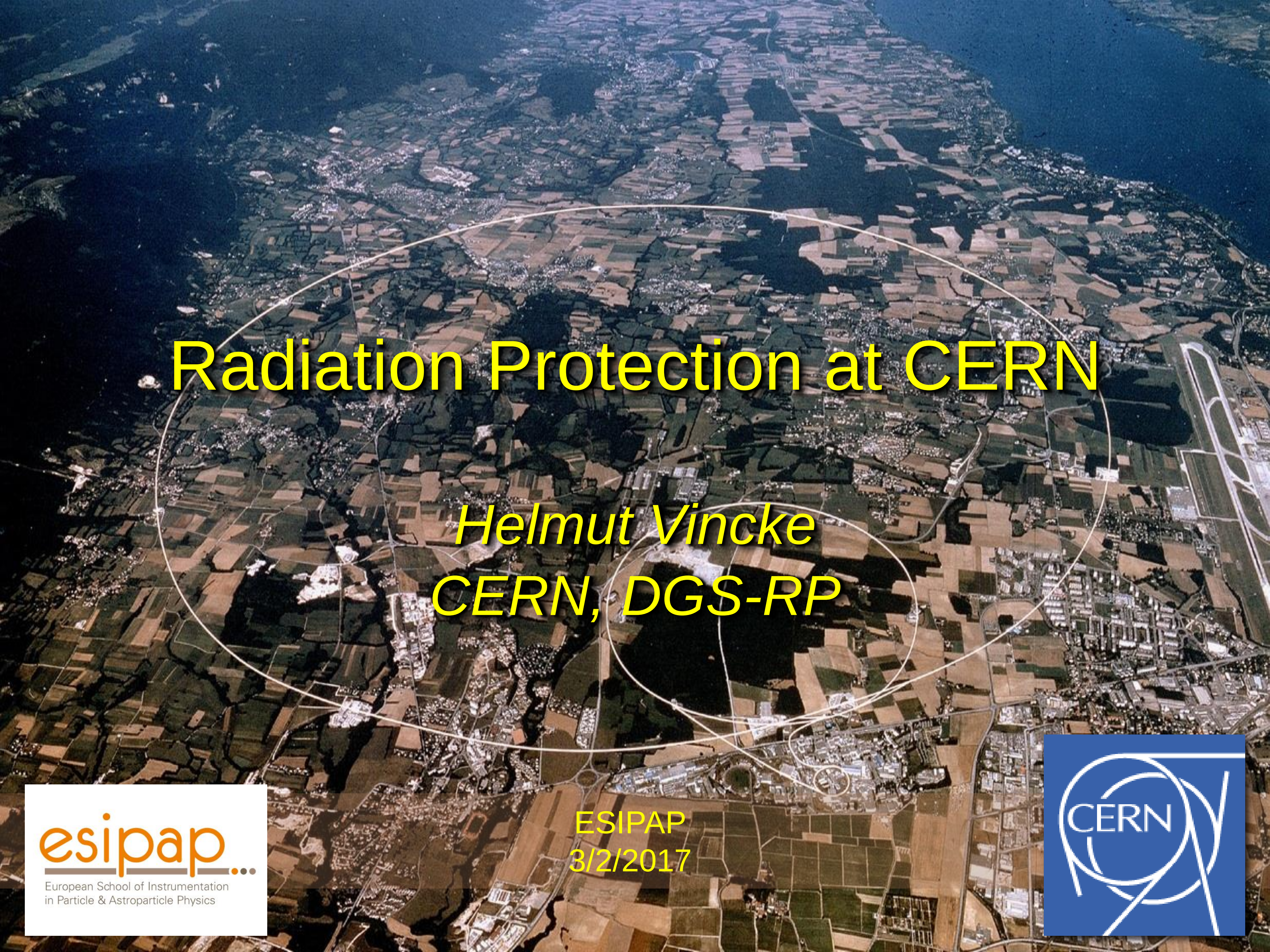


Radiation Protection at CERN

Helmut Vincke
CERN, DGS-RP

ESIPAP
3/2/2017

esipap
European School of Instrumentation in Particle & Astroparticle Physics

CERN

Content

- CERN – Accelerators, our main source of radiation
- Most important quantities used in Radiation Protection
- Radiation Fields occurring at High Energy Accelerators
- A few words about cosmic radiation
- Radiation Protection carried out at CERN
- Detector response calculations by using Monte Carlo codes

CERN - CONSEIL EUROPÉEN POUR LA RECHERCHE NUCLÉAIRE


Sur le terrain du futur institut nucléaire

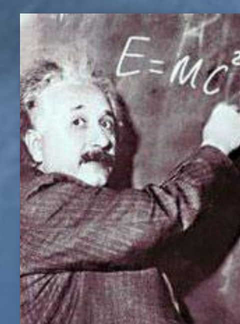
Sous la conduite de M. A. Picot, les membres du Conseil européen pour la recherche nucléaire se sont rendus hier à Meyrin pour reconnaître le terrain où s'élèvera le Centre nucléaire (voir en Dernière heure)

(Photo Freddy Bertrand, Genève)

La Suisse du 30 octobre 1953

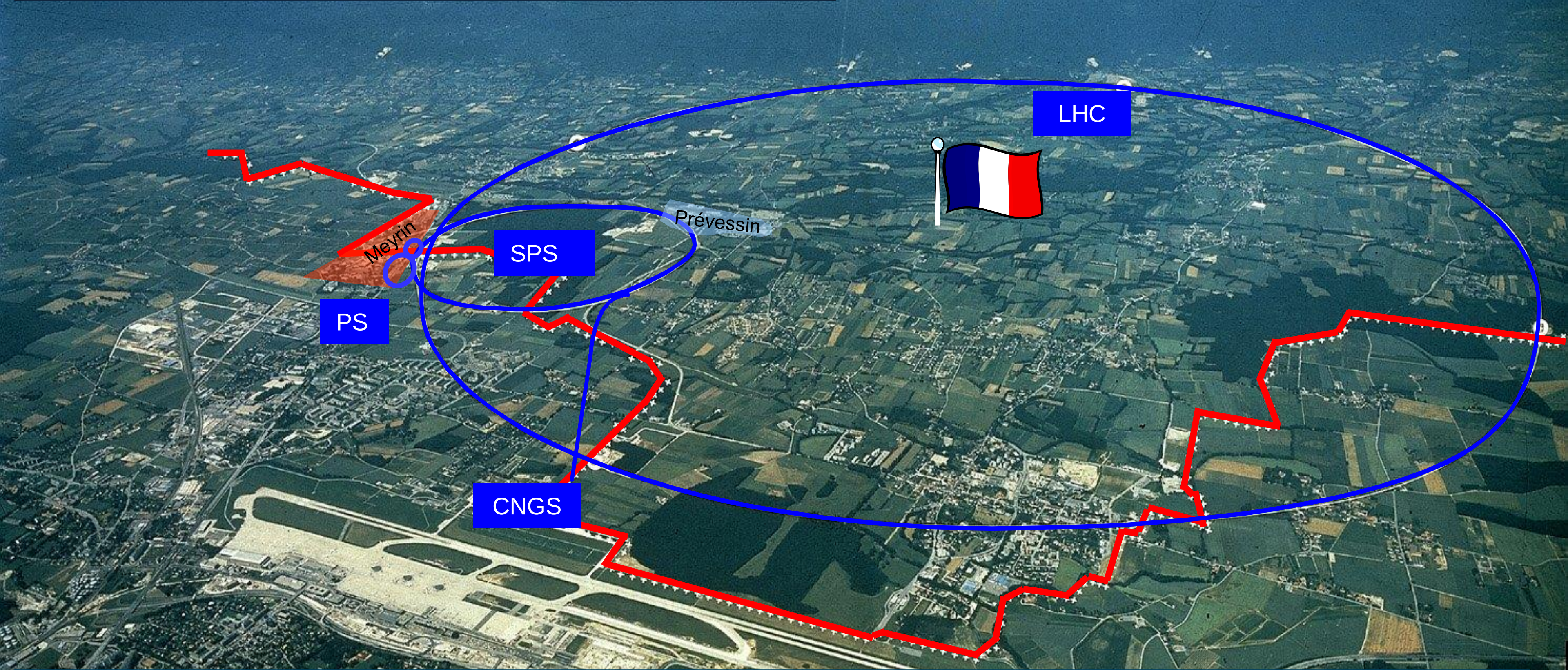
1954:

- Created by 12 European States
- First European Organisation
- Focus on nuclear physics (“nucleaire”)



Today: Particle Physics

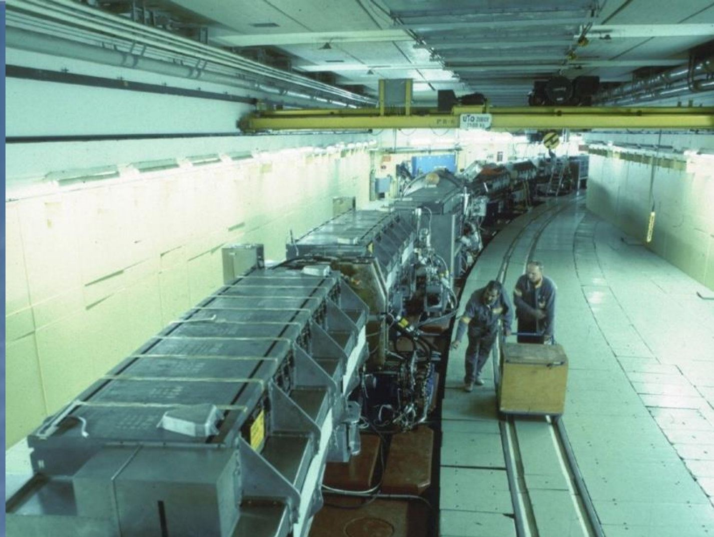
~ 2400 staff
~ 800 other paid personnel
> 11000 registered users from ~ 100 countries
~ 3500 registered contractors

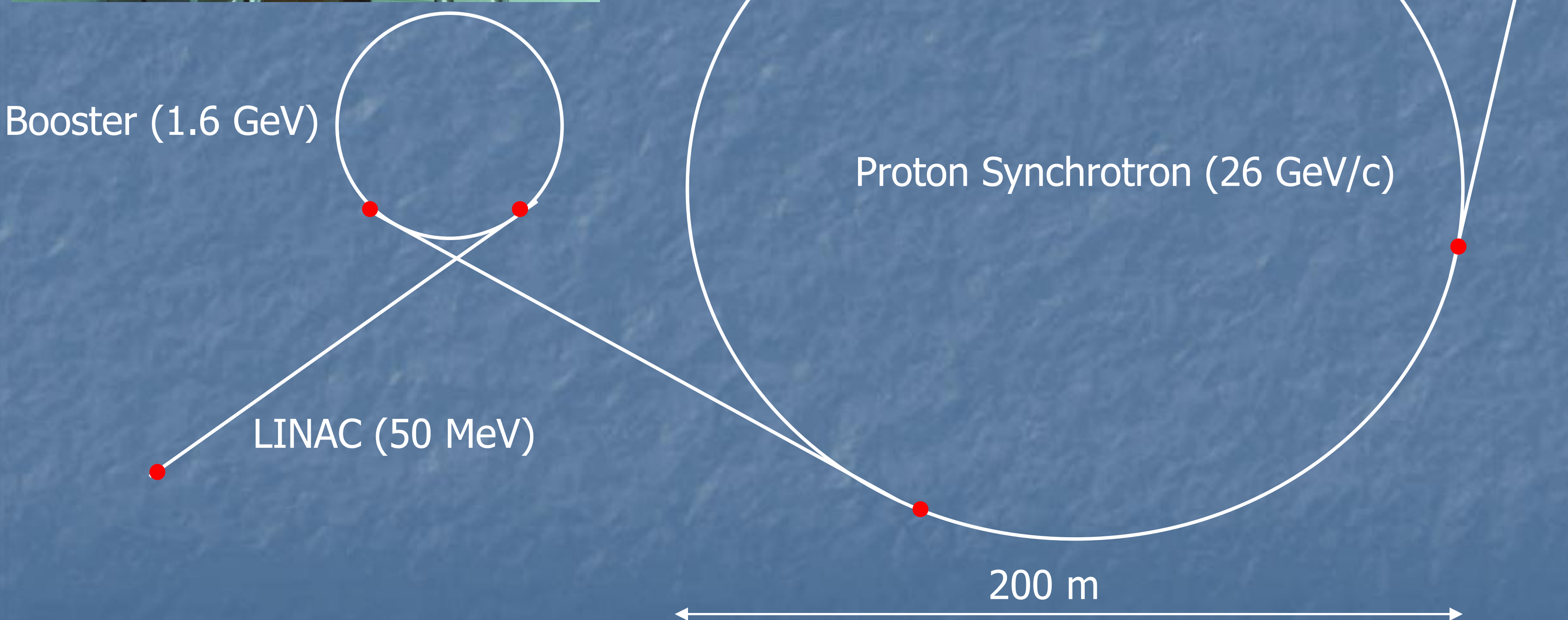


- 22 Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom, India (assoc. member).
- 7 Observers to Council: India, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO

CERN’s main accelerator chain

celerator chain at CERN
(low-energy part)





Accelerators at CERN

(high-energy part)

SPS
Circumference: 7 km

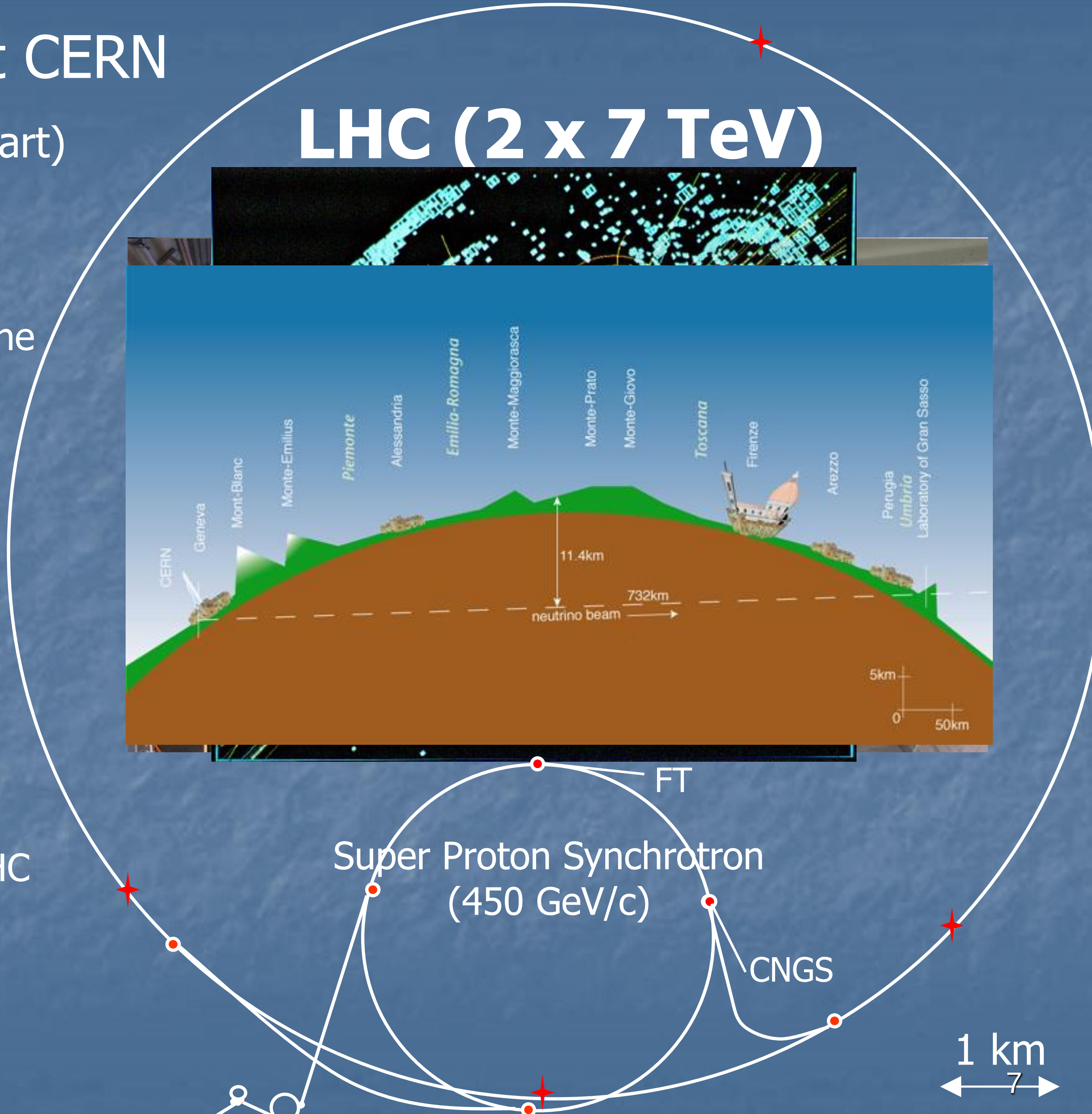
Intensity per filling of the ring: 6E13 protons

SPS beam

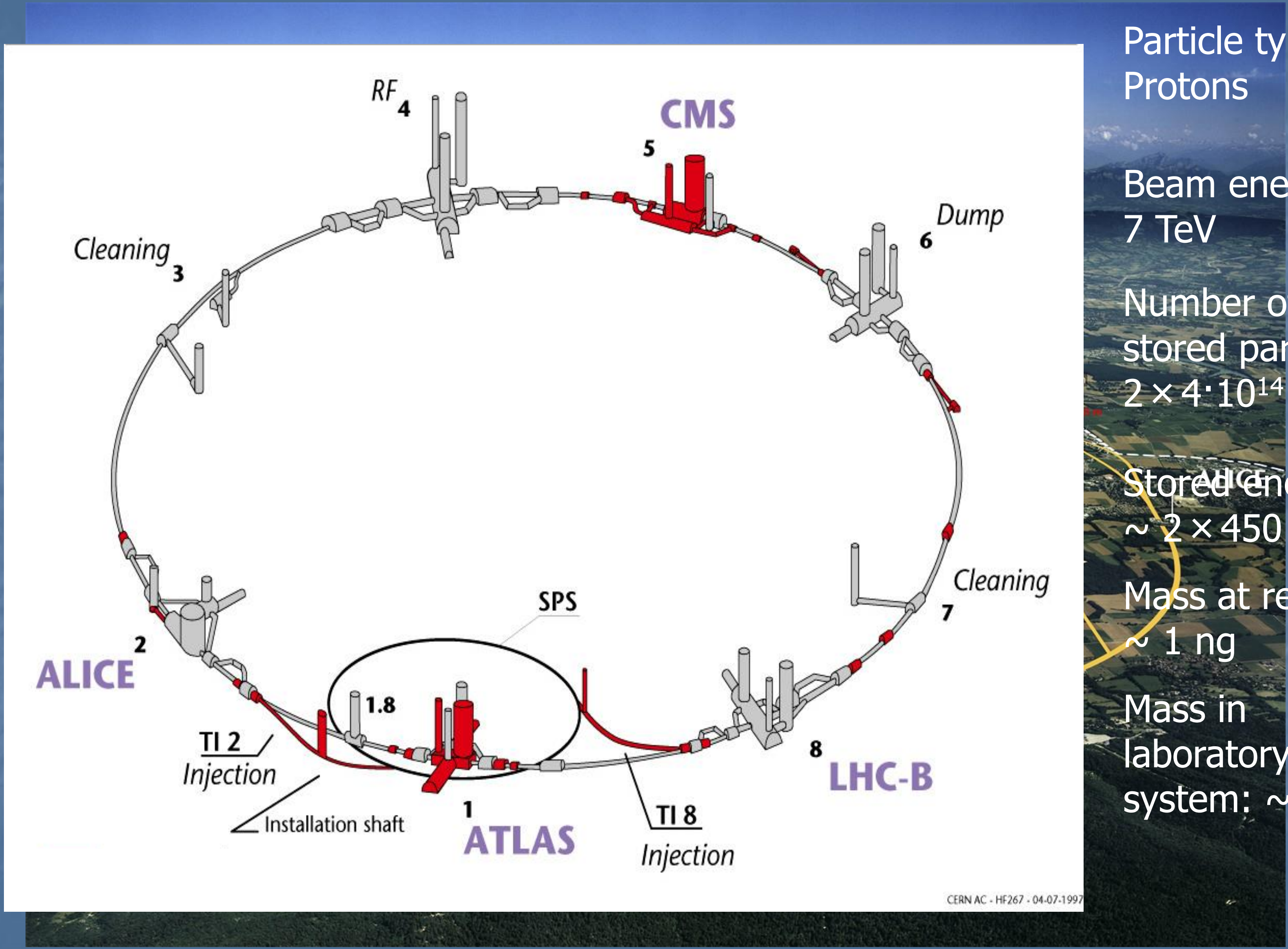
Fixed target experiments

CNGS now AWAKE

LHC



Large Hadron Collider (LHC)



Particle type: Protons

Beam energy: 7 TeV

Number of stored particles: $2 \times 4 \cdot 10^{14}$

Stored energy: $\sim 2 \times 450$ MJ

Mass at rest: ~ 1 ng

Mass in laboratory system: $\sim 10\ \mu g$

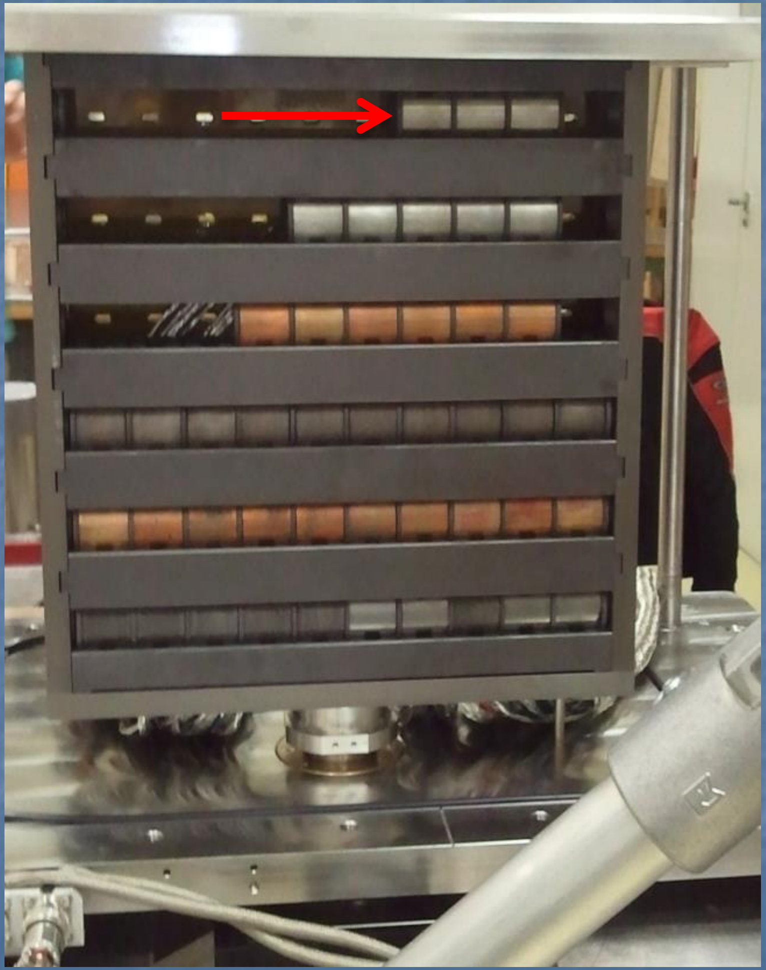
The same amount of energy as in one LHC beam is stored in:

An F16 airplane at supersonic speed (mach 1)

In an aircraft carrier at a speed of 12 km/h

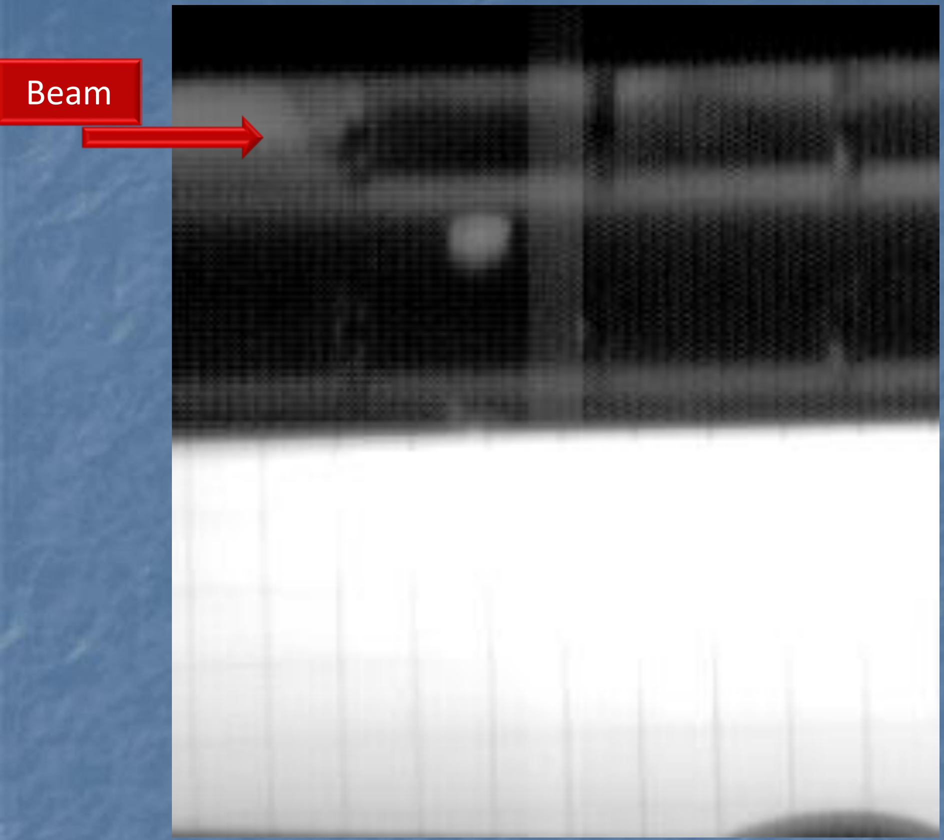
CERN operates powerfull (and dangerous) beams: full impact of a typical high-energy beam on tungsten (~ 0.16 % of the LHC beam energy)

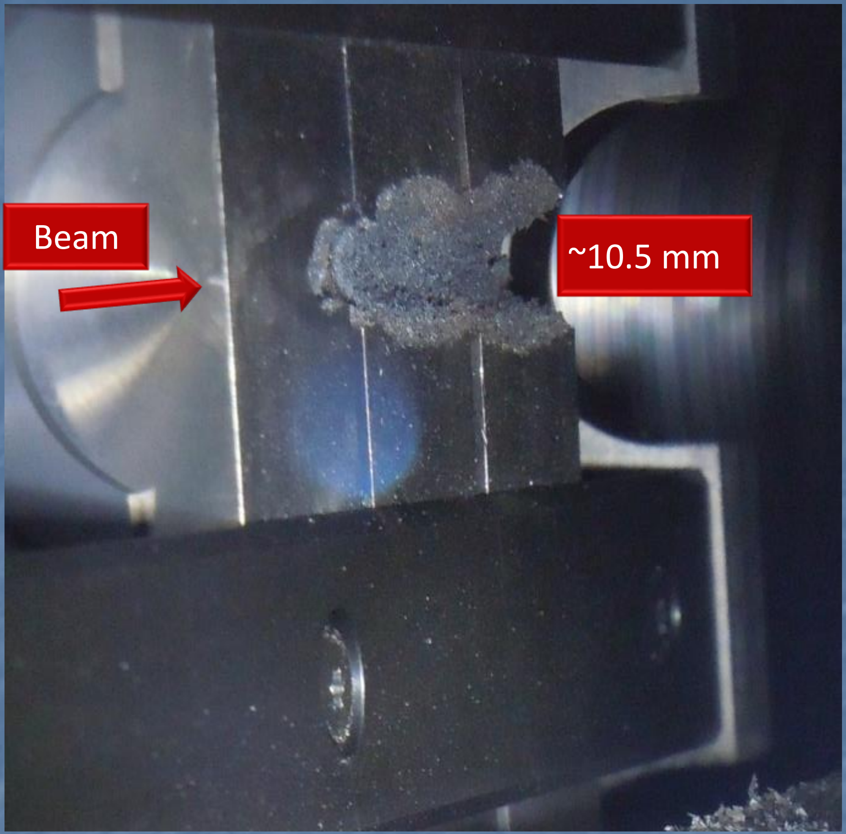
- Beam energy 440 GeV/c (SPS beam momentum)
- 1.08×10^{13} protons on tungsten alloy (Inermet 180)
- Beam impact within ~ 8 us
- **Question: How will the three 3 cm long tungsten alloy blocks digest the beam impact?**



By courtesy of A. Bertarelli

High speed camera catching the beam impact





Details: Bertarelli et al., An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility, Nucl. Instr. Meth. B (2013) http://dx.doi.org/10.1016/j.nimb.2013.05.007

Most important quantities used in Radiation Protection

Absorbed dose

refers to the energy deposited (not released) in matter.

It reflects the sum of the energies dE_{dep} deposited by incident particles in a sample of matter, divided by the mass dm of the sample.

$$D = \frac{\mathrm{d}E_{dep}}{\mathrm{d}m}$$

Unit: J/kg = Gray (Gy)

Equivalent dose in an organ or tissue, H_T

is a measure of the absorbed dose $D_{T,R}$ to tissue T by radiation of type R. It is defined by

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

Unit: Sievert (Sv)

with w_R being the radiation weighting factor which reflects the different radiobiological effectiveness for various radiation types and energies.

ICRP publication 103

Radiation	Energy	W_R (formerly Q)
x-rays, gamma rays, beta rays, muons		1
neutrons	< 1 MeV	$2.5 + 18.2 \cdot e^{-[\ln(E)]^2/6}$
	1 MeV - 50 MeV	$5.0 + 17.0 \cdot e^{-[\ln(2 \cdot E)]^2/6}$
	> 50 MeV	$2.5 + 3.25 \cdot e^{-[\ln(0.04 \cdot E)]^2/6}$
protons, charged pions		2
alpha rays, Nuclear fission products, heavy nuclei		20

The radiation weighting factor (especially for neutrons) has been revised over time and remains controversial

Effective dose, E

equals the sum of various equivalent doses of different organs or tissues, weighted with the respective tissue weighting factor w_T. It is defined by

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

Unit: Sievert (Sv)

with $\sum_T w_T = 1$.

Different organs show different sensitivity to equivalent dose deposited

Organ	Tissue weighting factor	Organ	Tissue weighting factor
Gonads	0.08	Esophagus	0.04
Red Bone Marrow	0.12	Thyroid	0.04
Colon	0.12	Skin	0.01
Lung	0.12	Bone surface	0.01
Stomach	0.12	Salivary glands	0.01
Breasts	0.12	Brain	0.01
Bladder	0.04	Remainder of body	0.12
Liver	0.04		

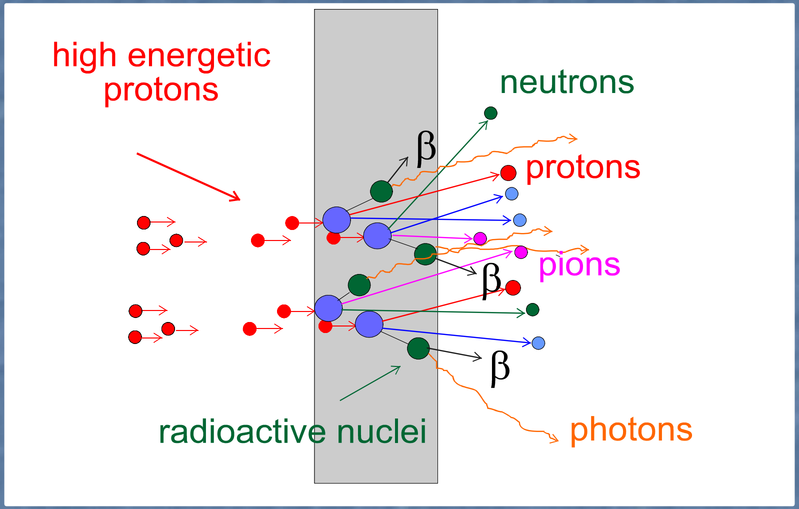
Radiation Fields around High Energy Accelerators

Contents

- Introduction
- Impact of ionizing radiation in accelerators
- Dose to people, shielding
  - Radiation fields lateral to beam impact points
  - Radiation fields downstream of beam impact points

Radiation Fields around High Energy Accelerators

- Prompt ionizing radiation – beam on

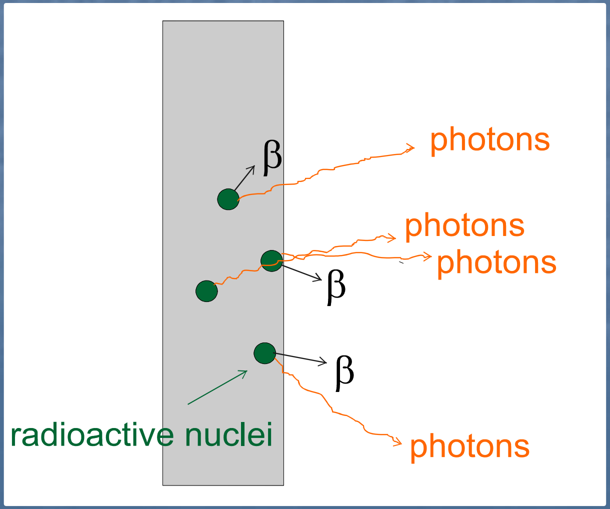


Whole particle zoo with E up to initial beam energy

High pressure ionization chamber

REM counter

- Ionizing Radiation due to induced radioactivity – beam off

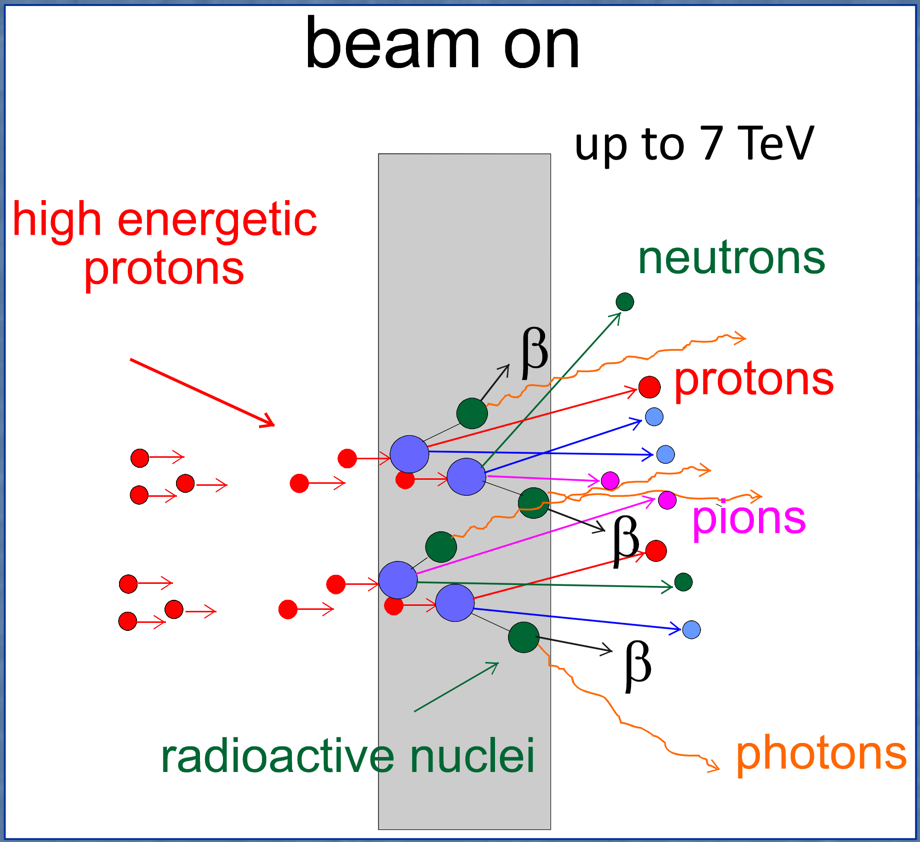


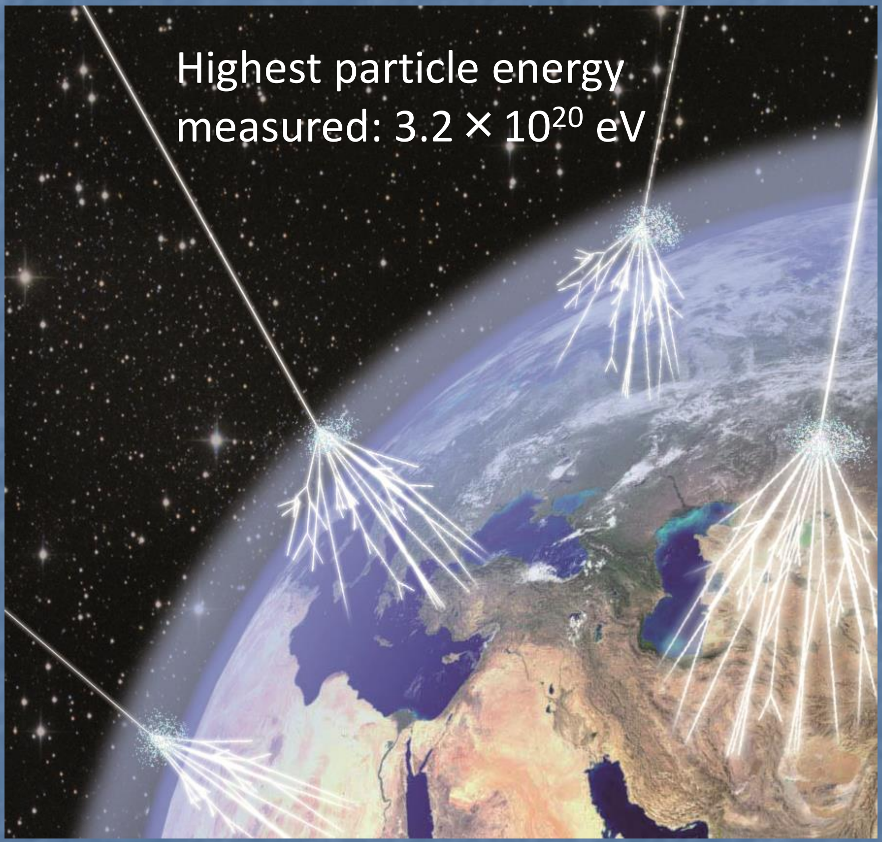
α, β-, γ-radiation,
Main γ energies:
< 2.76 MeV

Air filled ionizat-ion chamber

Handheld devices

Prompt Ionising Radiation





Hadron accelerator

Cosmos

Particle impact creates high-energy mixed radiation fields

Prompt Ionizing Radiation in Accelerators

- Ionizing radiation in accelerators is produced by any beam impacts of high energy particles ➔ secondary radiation
- Impact of very energetic particles produce particle showers

Production of ionizing radiation by **ONE** hadron (120 GeV/c) on copper Target

Hadronic shower only

Hadronic shower + photons

Ionizing particles on matter: Impact and consequences

Dose to people

Aging of organic materials like insulations

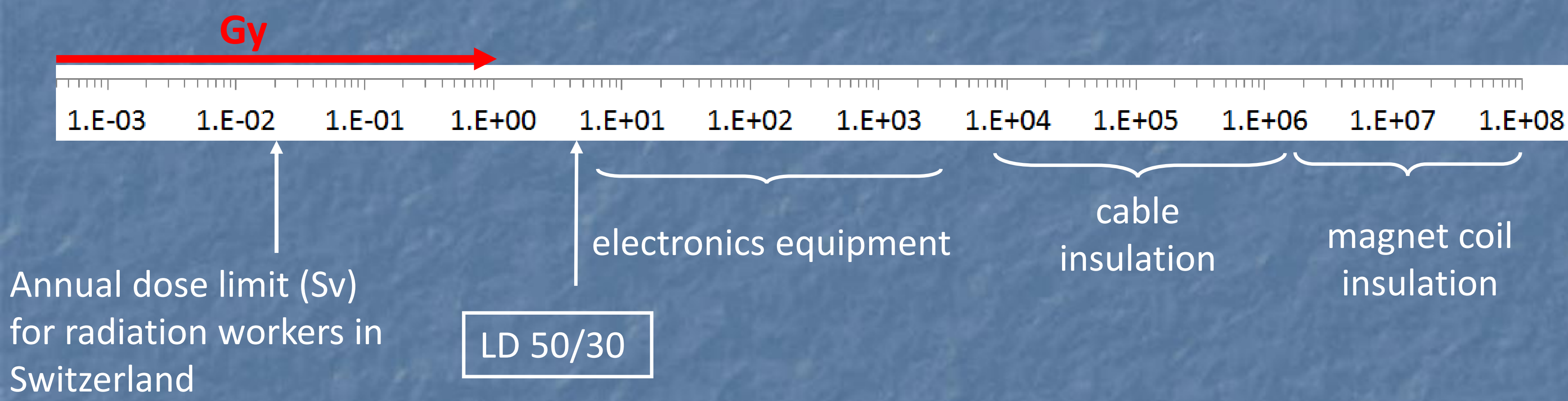
Focused energy deposition in material → heat development, shockwaves→ destruction of materials

Activation of material

Radiation triggered failure of electronics

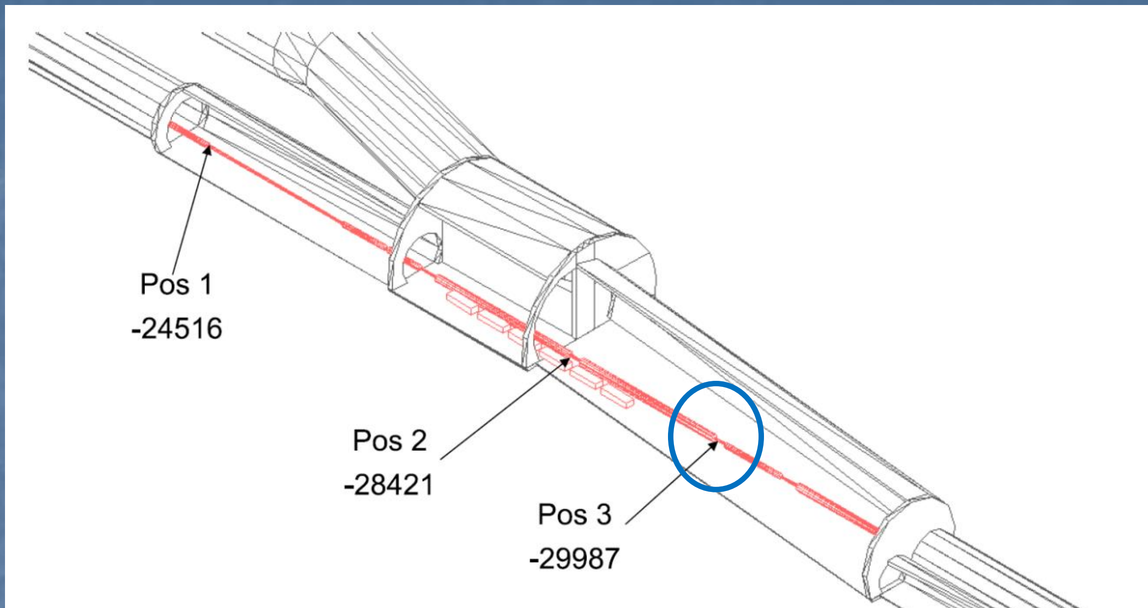
Radiation impact

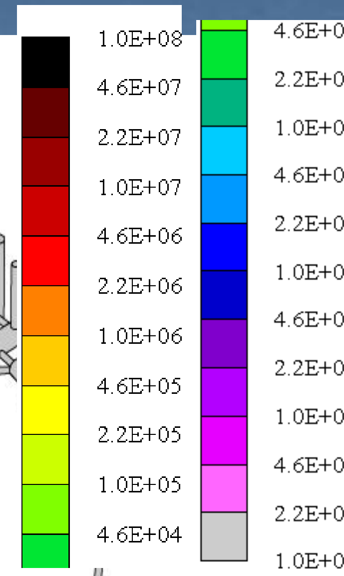
- **Relation between absorbed dose and damage caused by radiation**

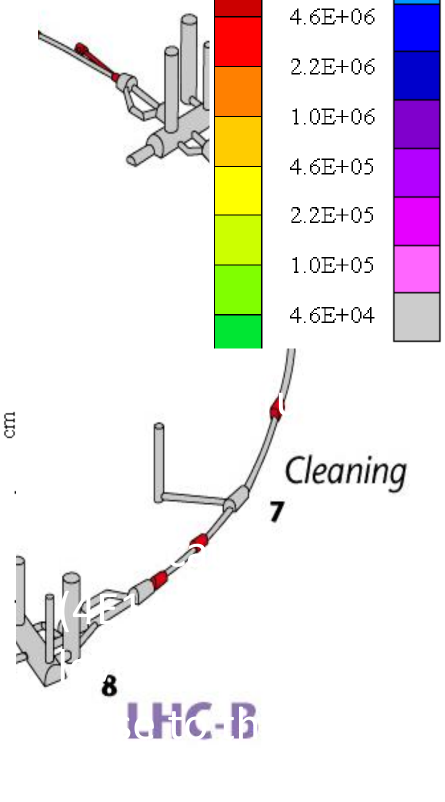


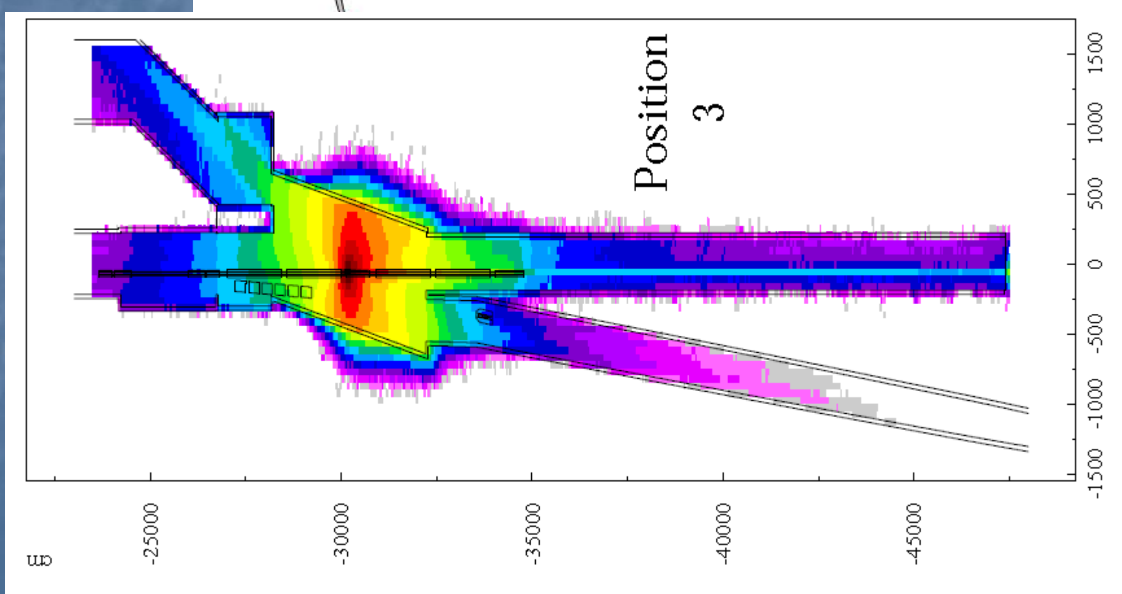
Dose to people

Example of full beam loss (7 TeV) in the LHC









loss

ll beam loss
V) reaches
usands of Sv
nt.

➔ strong shielding required to significantly reduce dose

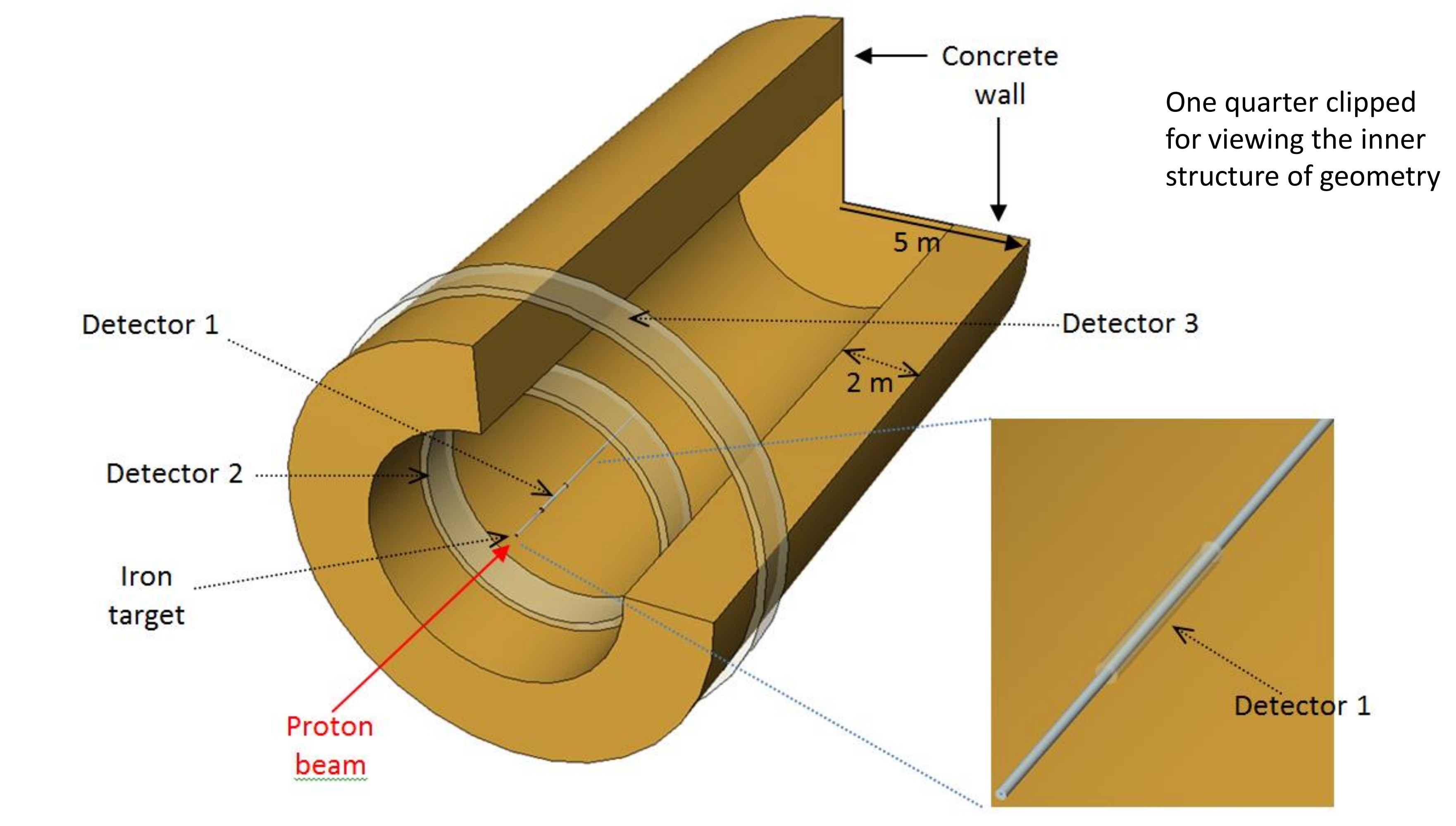
Main aspects of radiation field attenuation in accelerator environments

Lateral to beam impact point

Downstream to beam impact point

Radiation lateral to the beam impact point

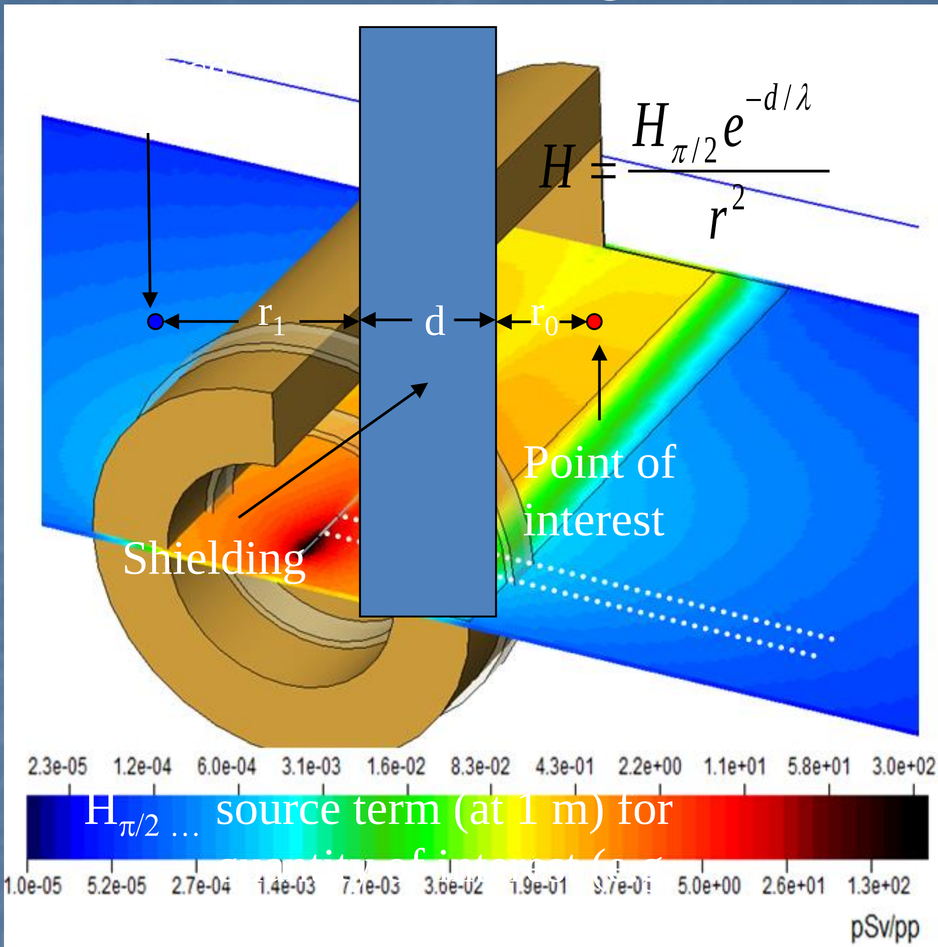
Lateral Shielding Configuration: Simulation to calculate radiation propagation through a lateral shielding wall

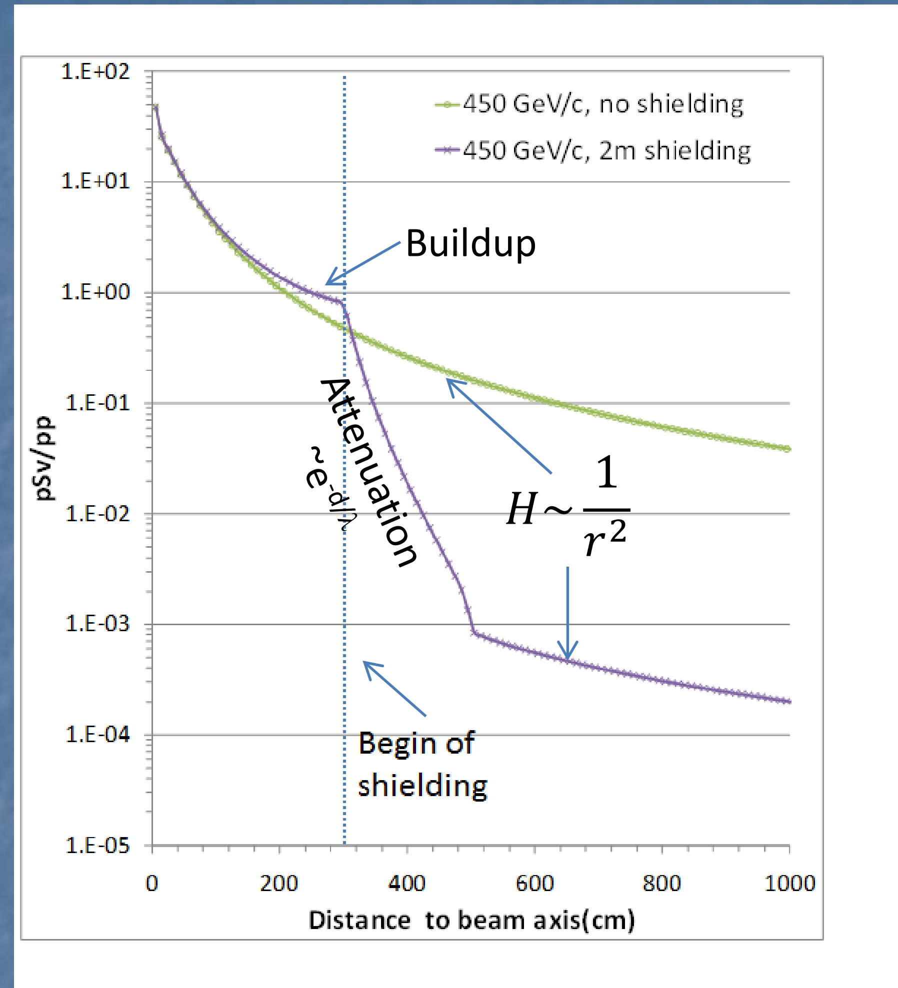


A 450 GeV proton beam is sent onto a 5 m long target with a diameter of 5 cm. Target is surrounded by particle detectors

Dose analysis

Point source/line of sight model

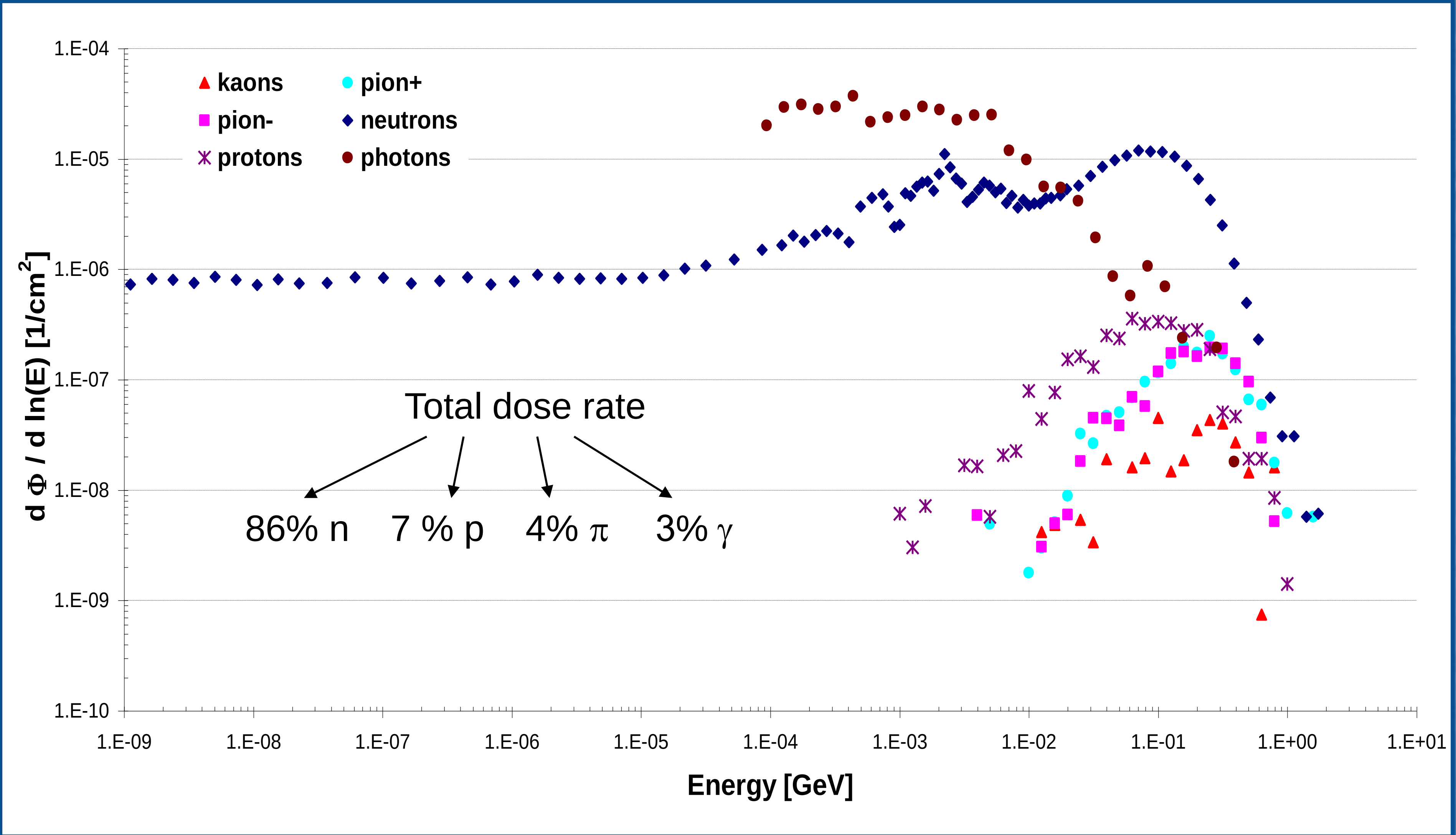




$r = r_0 + d + r_1$ in m

λ… hadronic interaction length

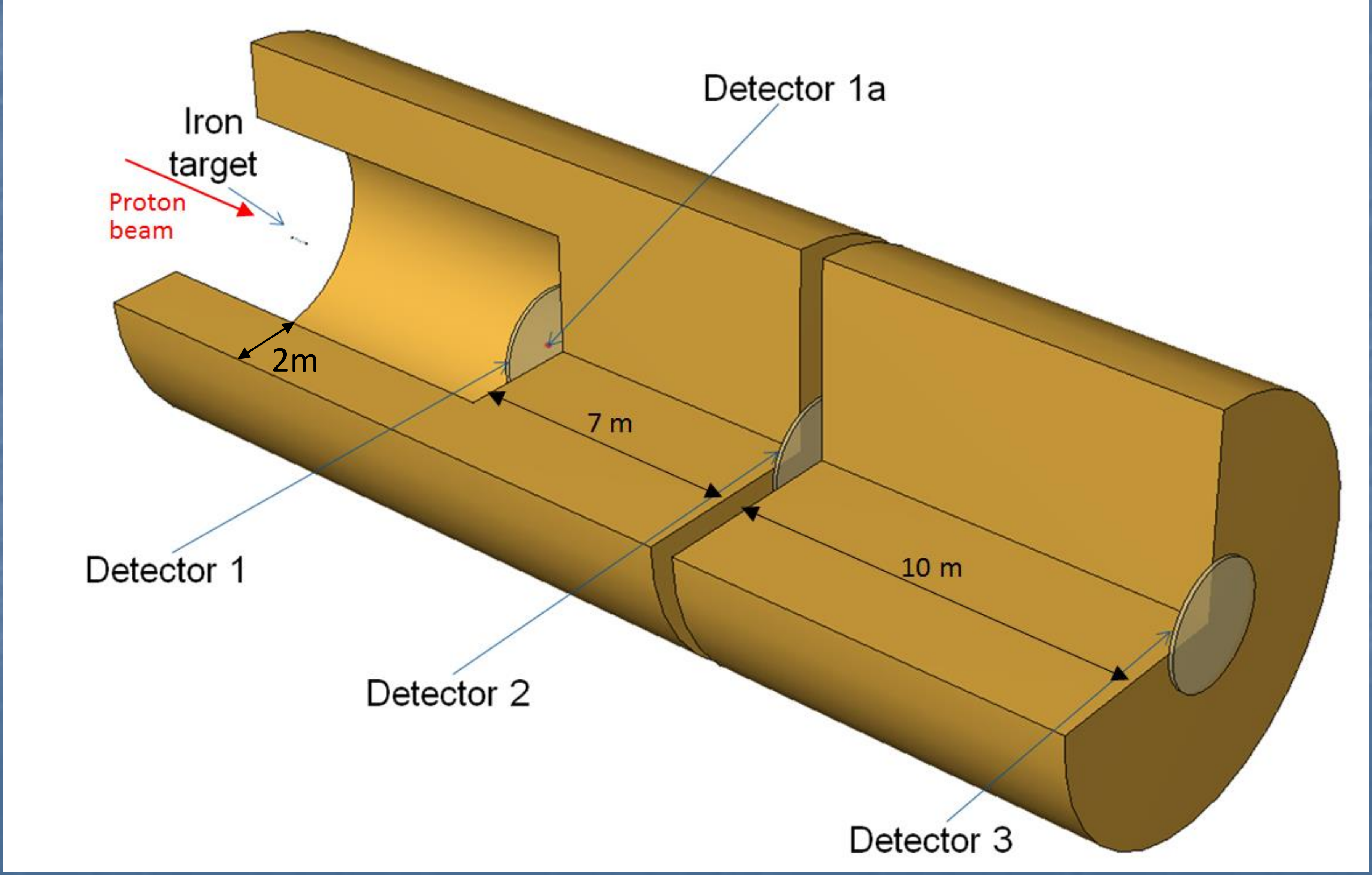
Typical particle fluence spectra at areas located behind lateral thick concrete shielding



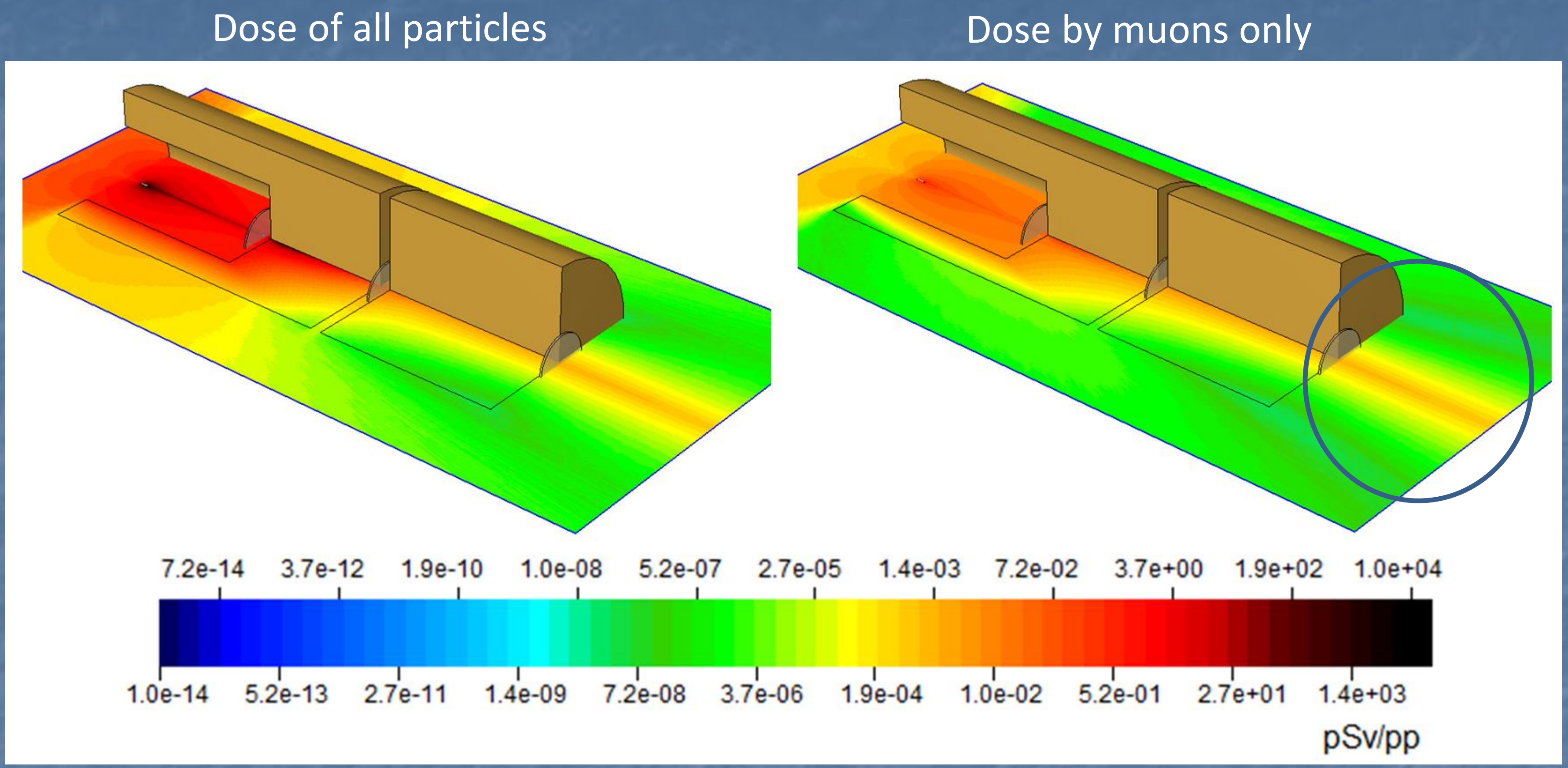
Radiation downstream to the beam impact point

Radiaton fields occurring downstream of an impact point of an high-energy proton beam

450 GeV proton beam on 50 cm long copper target

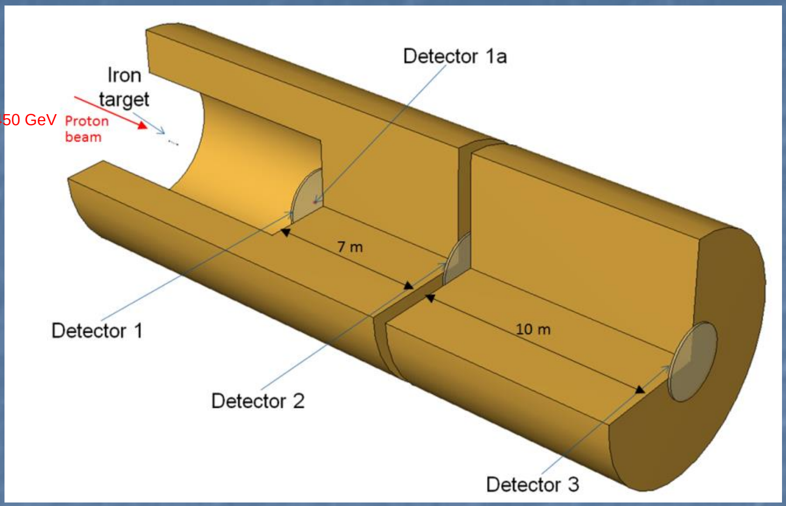


Dose simulation results



Muons strongly dominate the dose seen downstream the heavy shielding

Spectral analysis of the fluence seen in detector 1 and detector 3.

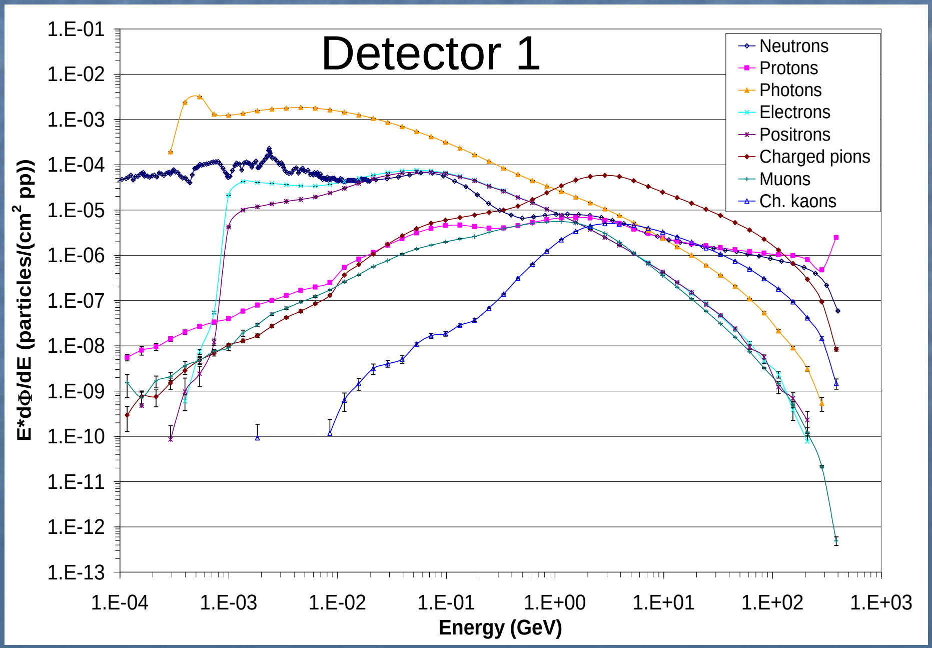


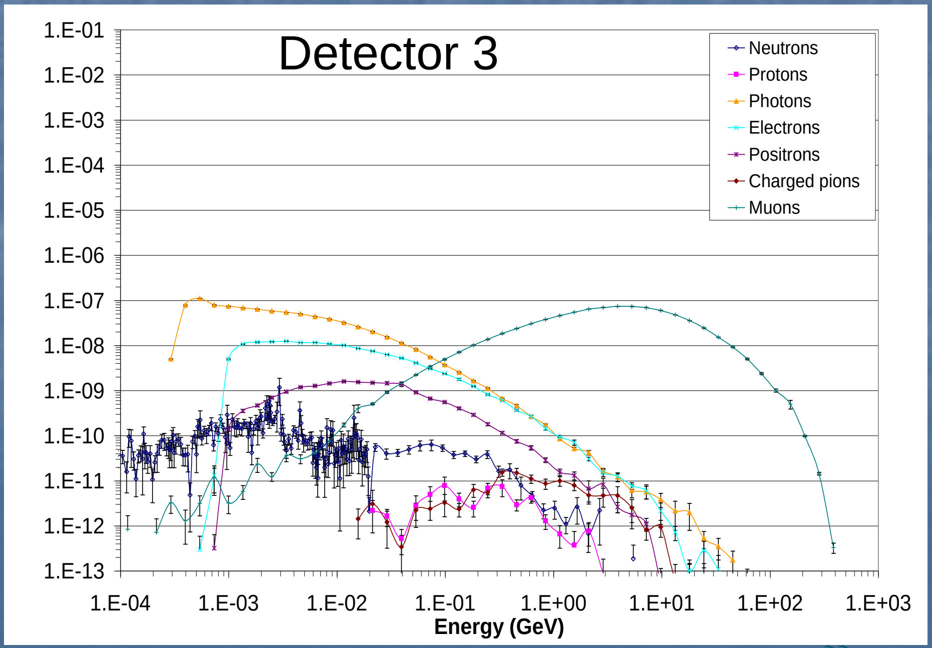
Strong domination of muons downstream the shielding

EM particles at this locations can be traced back to muon interactions

High-energy muons lose ~1 GeV when traveling through 1.8 m of concrete or 70 cm of iron.

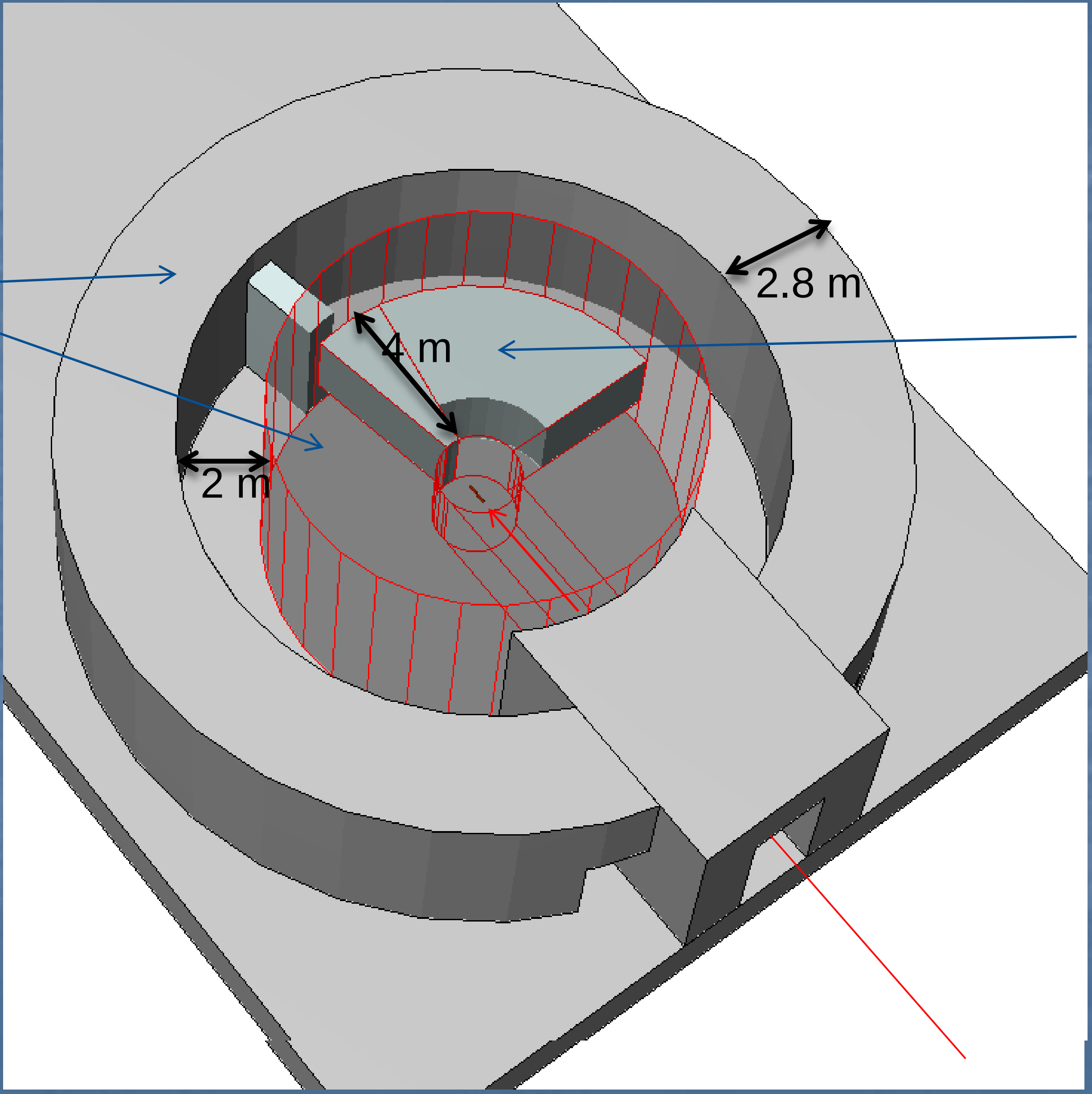
➔ To shield **all** muons a shielding of **~800 m of concrete** or **~300 m of iron** is required.





Conceptual design of an irradiation facility

Concrete shielding



Iron shielding and dump

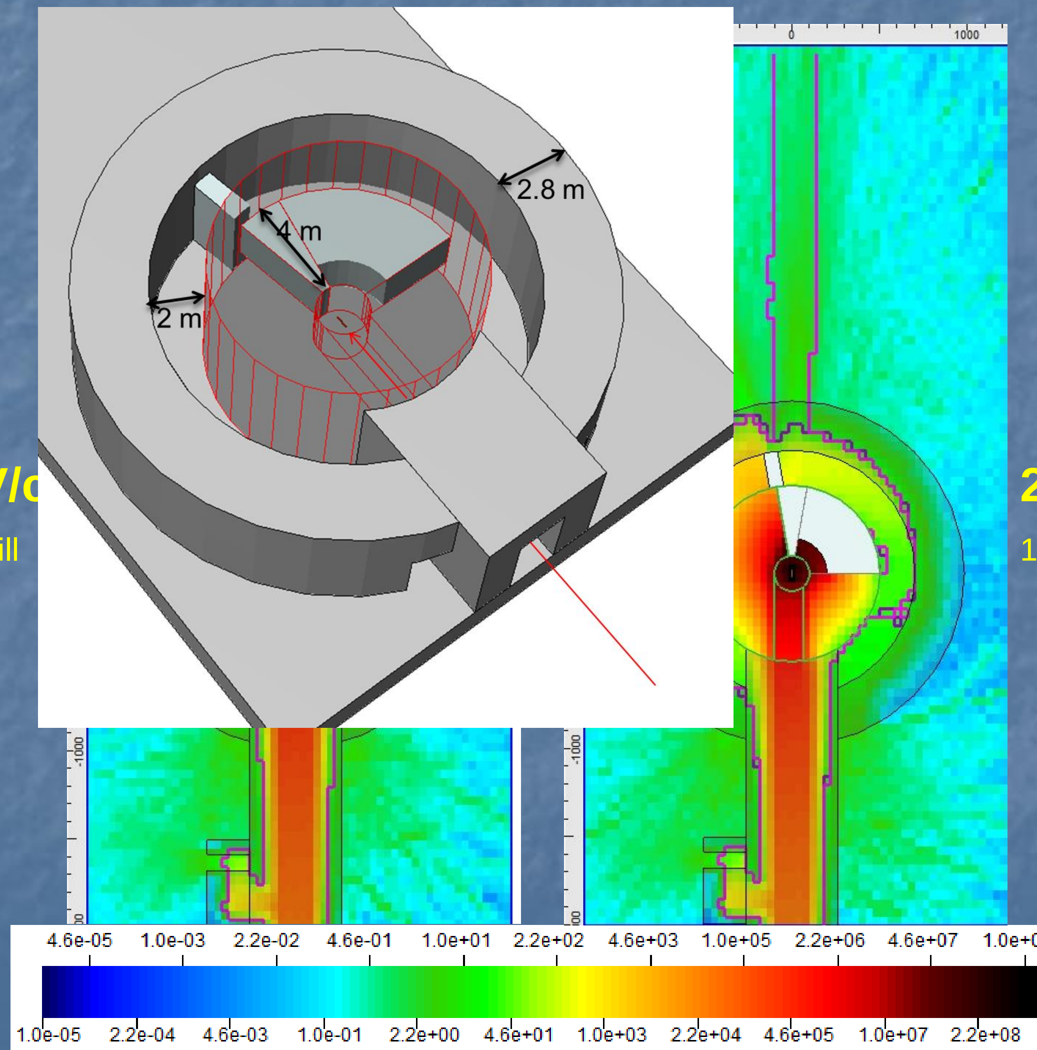
Courtesy of E. Feldbaumer

Dose rate mapping at beam height
Comparison: 450 GeV/c vs 24 GeV/c

Example to show the muon dominance downstream of thick shielding construction in high-energy facilities

450 GeV/c

10^{10} particles/spill



24 GeV/c

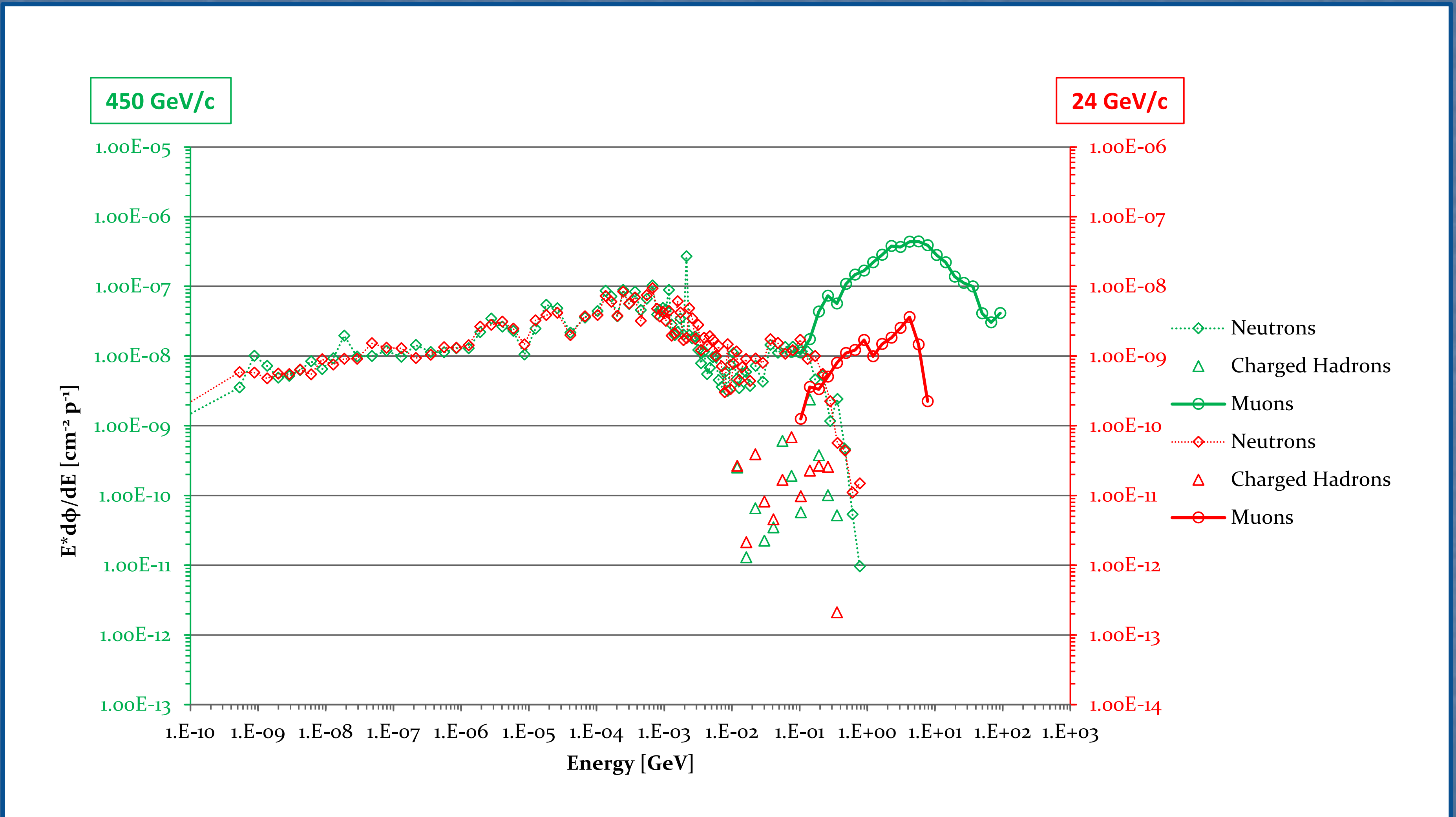
10^{11} particles/spill

Contours:

- 15 µSv/h
- 15 µSv/h

Courtesy of E. Feldbaumer

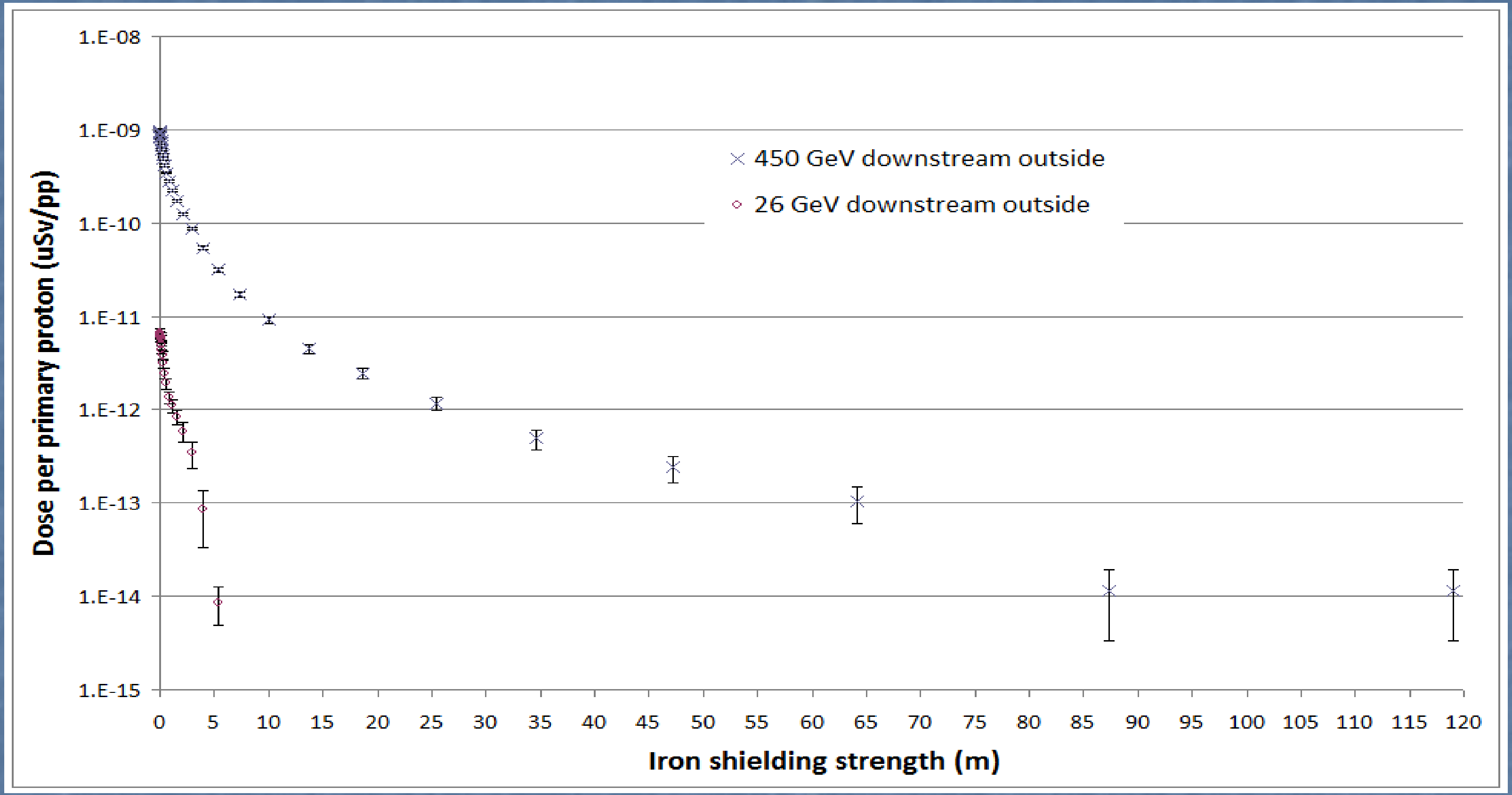
Spectra behind experimental setup consisting of a 50 cm copper target + 2 m of air + 4 m of iron dump



Courtesy of E. Feldbaumer

Rough estimates for the muon dose as a function of shielding strength (collimated beam assumed)

The given shielding strength does not include the 4 m of iron between the target and the reference point.



Concrete shielding strength = Iron strength*2.6

Assuming a beam intensity of 1E11 p/s we would need the following amount of shielding to remain below 2.5 uSv/h (non designated area) a locations downstream the dump

~ 100 m of additional iron for 450 GeV/c
~ 5 m of additional iron for 24 GeV/c

Cosmic radiation environment

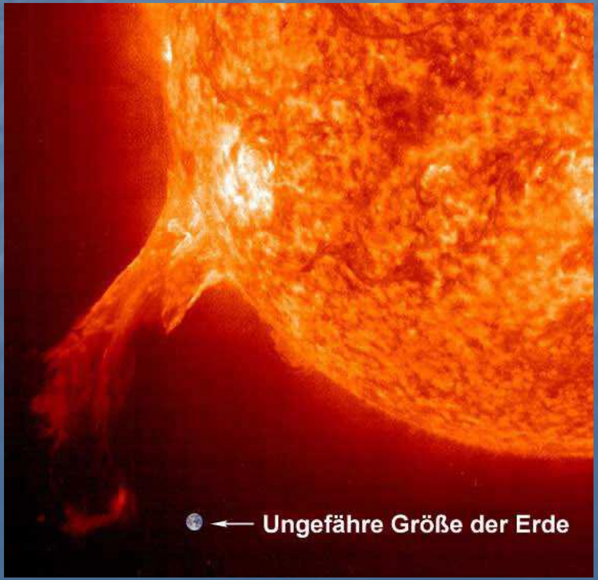
Contents:

- Basic introduction to cosmic radiation fields
- Interesting phenomena at high energies
- Radiation Protection aspects in space

Classification of cosmic (ionizing) radiation

Solar Cosmic Radiation (SCR)

- high-energy particles coming from the sun
- consist of protons, electrons and ions with energies ranging from a few tens of keV to GeV
- Two main processes of their production:
  - solar-flares
  - shock waves caused by coronal mass ejections.



Galactic Cosmic Radiation (GCR)

- Particles which originate from sources outside of the solar system, distributed throughout our Milky Way galaxy and beyond.

Properties of Galactic Cosmic Radiation

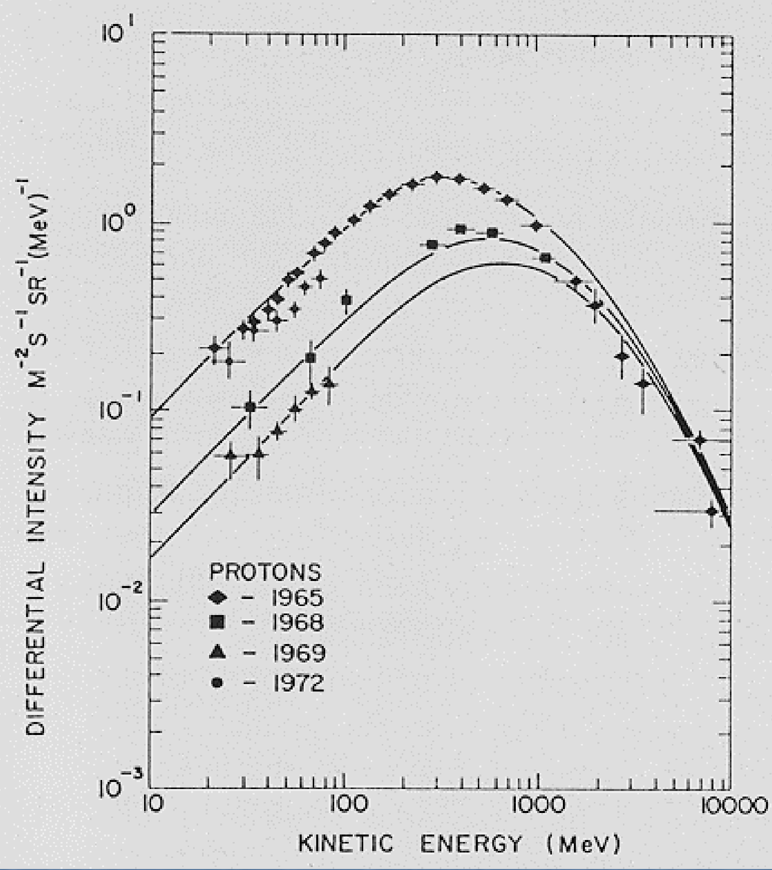
Composition: 2% electrons and 98% nuclei

Composition of nuclei:
87% protons 12 % α-particles 1% heavy nuclei
Almost no anti-matter detected

Spectrum:

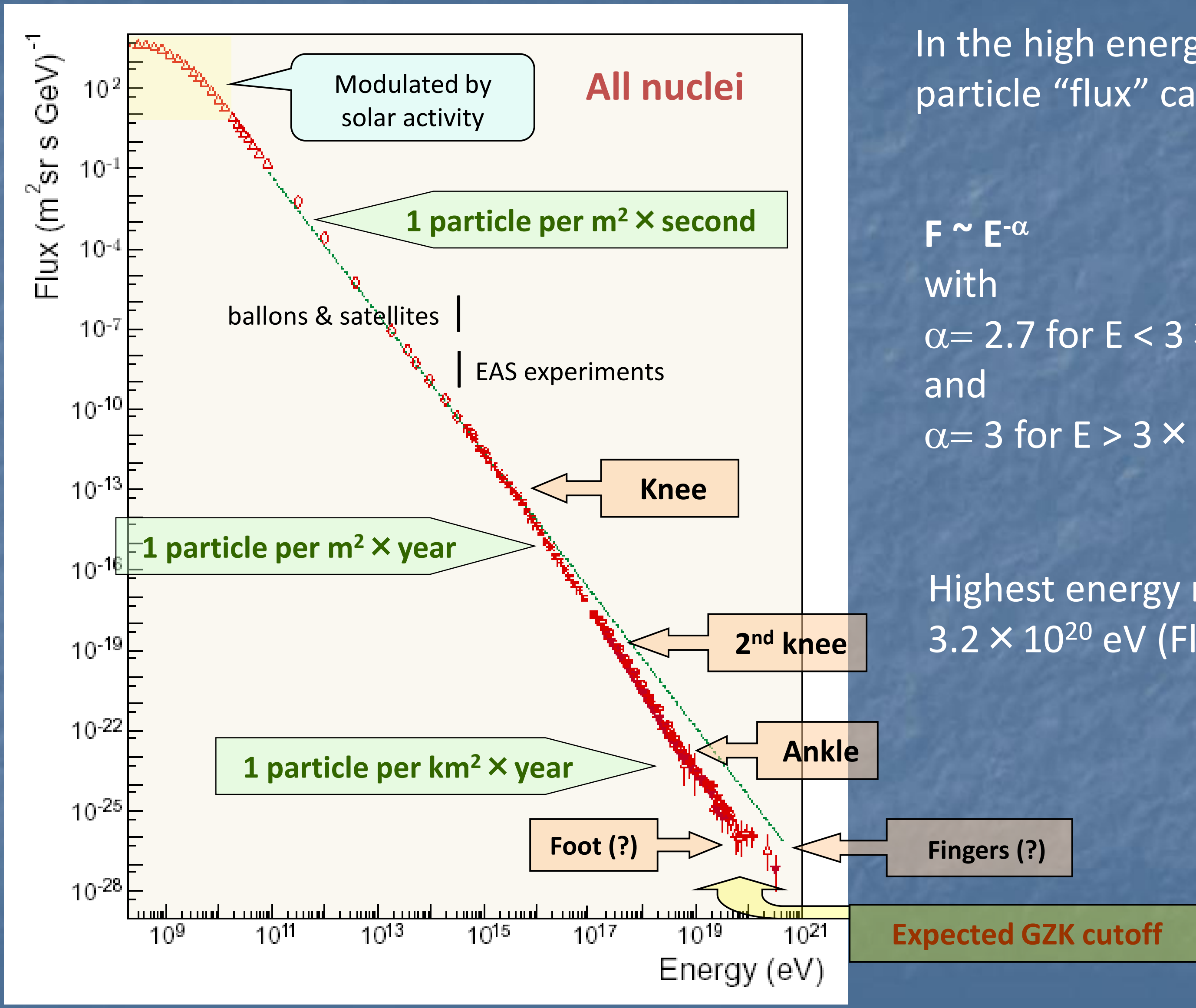
- Main part of the GCR particles have an energy below 10 GeV
- Interaction with solar magnetic field modulate the particle's energy
- → GCR fluence up to 10 GeV shows a dependence on the solar activity
- There is a high-energy component of the GCR spectrum, reaching energies higher than 10^{20} eV.

Proton spectra observed during various years (1965: solar minimum, 1969: solar maximum)



Fisk (1979): Mechanisms for energetic particle acceleration in the solar wind

A BIRD'S EYE VIEW OF THE ALL-PARTICLE CR SPECTRUM



In the high energy region the particle "flux" can be described by:

$F \sim E^{-\alpha}$
with
$\alpha = 2.7$ for $E < 3 \times 10^{15}$ eV
and
$\alpha = 3$ for $E > 3 \times 10^{15}$ eV

Highest energy measured:
3.2×10^{20} eV (Fly's Eye detector)

Picture taken from
http://hep.fi.infn.it/PAMELA/naumov/Eng/UHECR/UHECR.html

Interesting effects at such high energies
(assuming particle was a proton)

Energy of particle : **3.2 × 10^{20} eV = 51 J**

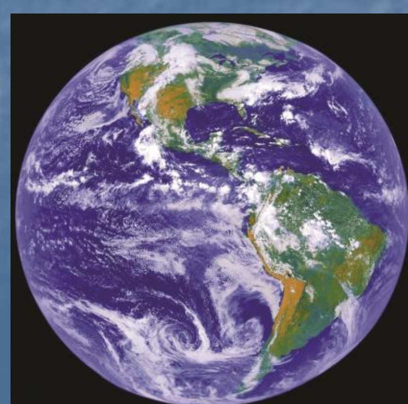
Kinetic energy of a golf ball (170 km/h)

From $$E^2 = m^2c^4 = \frac{m_0^2c^4}{1-v^2/c^2}$$ we calculate Lorentz factor γ: $$\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$$

Time dilatation: $t = t_0 \times \gamma$ ⇒ 1 second for the proton are 10773 years for us!!!

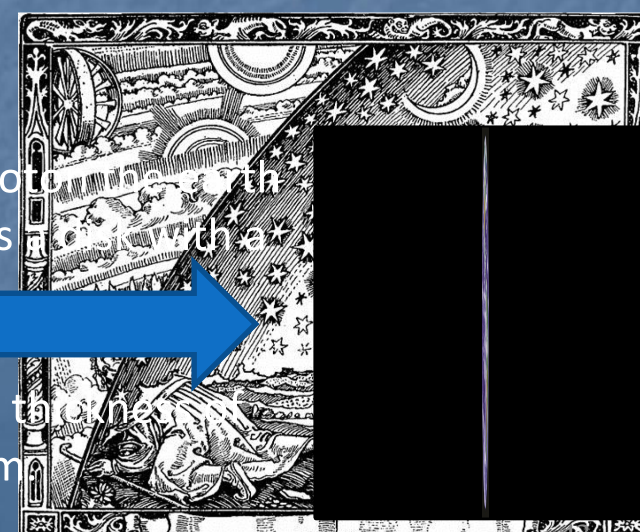
Length contraction:

$$l = \frac{l_0}{\gamma}$$



For the proton the earth appears as a disk with a

maximum thickness of 39 micro m



Relativistic Doppler Effect

High energy particles are subject to Doppler Effect, changing the frequency of photons.

Considering a head-on collision between a proton and a photon the frequency of the photon is seen as:

$$f = f_0\sqrt{\frac{1+\beta}{1-\beta}}$$

With: β=*v/c … (*β *(3.2 ×10*^{20} *eV)= (1 - 4.8 ×10*$^{-24}$)

Typical energy of microwave photon: 1.1 ×*10*$^{-3}$ eV.

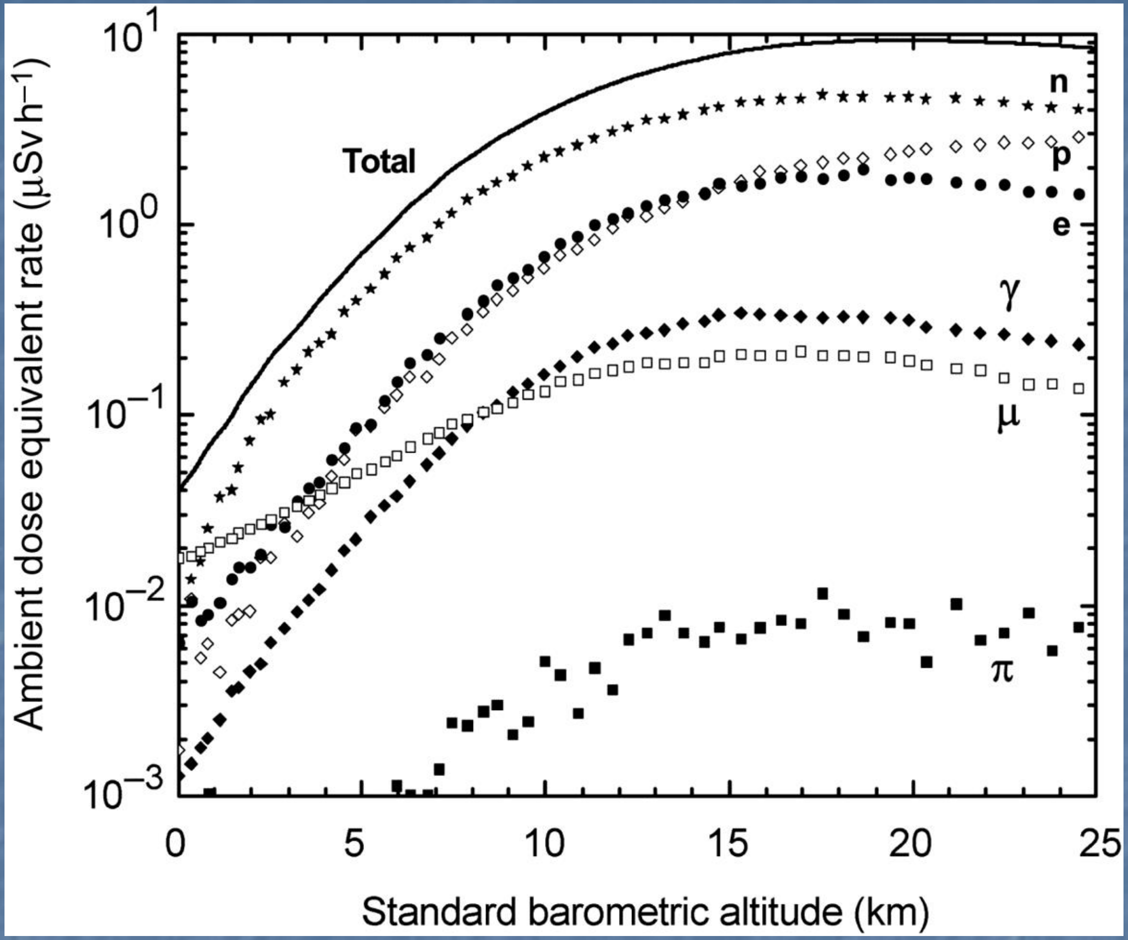
$$E = E_0\sqrt{\frac{1+\beta}{1-\beta}} = 1.1\times10^{-3}\times6.4\times10^{11} = 7.04\times10^{8}eV$$

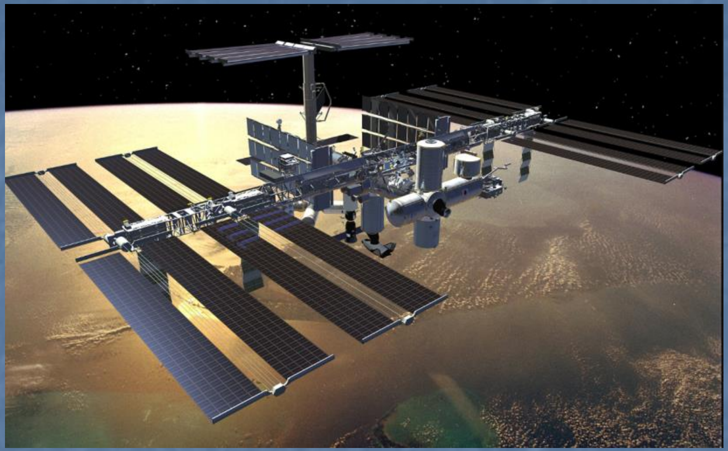
⇨ Proton should interact with microwave photons producing pions.

This calculation coincides with the Greisen–Zatsepin–Kuzmin limit (**GZK limit**), defining a theoretical upper limit for the energy of cosmic rays coming from sources beyond ~ 50 MParsec.

However, we observe such particles, although no sources for such high-energy particles can be pinpointed within this radius. These observations remain an **unsolved riddle**.

Dose to space- and aircraft crews

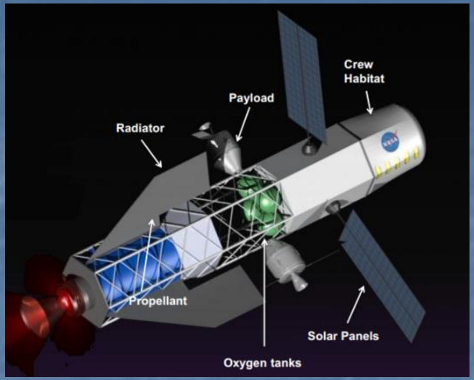




Ambient-dose-equivalent rates as a function of standard barometric altitude

(at 2 GV vertical geomagnetic cut-off rigidity and mid solar cycle, calculated by S. Rollet, taken from Oxford University Press et al. Journal of the ICRU 2010;10:17-21)

Dose exposure during a space trip to Mars



- In space crafts only limited shielding power for the protection of the crew can be provided.
- During a one way trip to Mars the dose received by the crew is estimated to (330 ± 6) mSv, resulting in a dose of 660 mSv for a round trip. Exposure during Mars (no magnetic field protection) is not included in this calculation.
- These results are based on measurements carried out in the Mars Science Laboratory spacecraft*.
- Real dose during flight depends also strongly on the sun activity

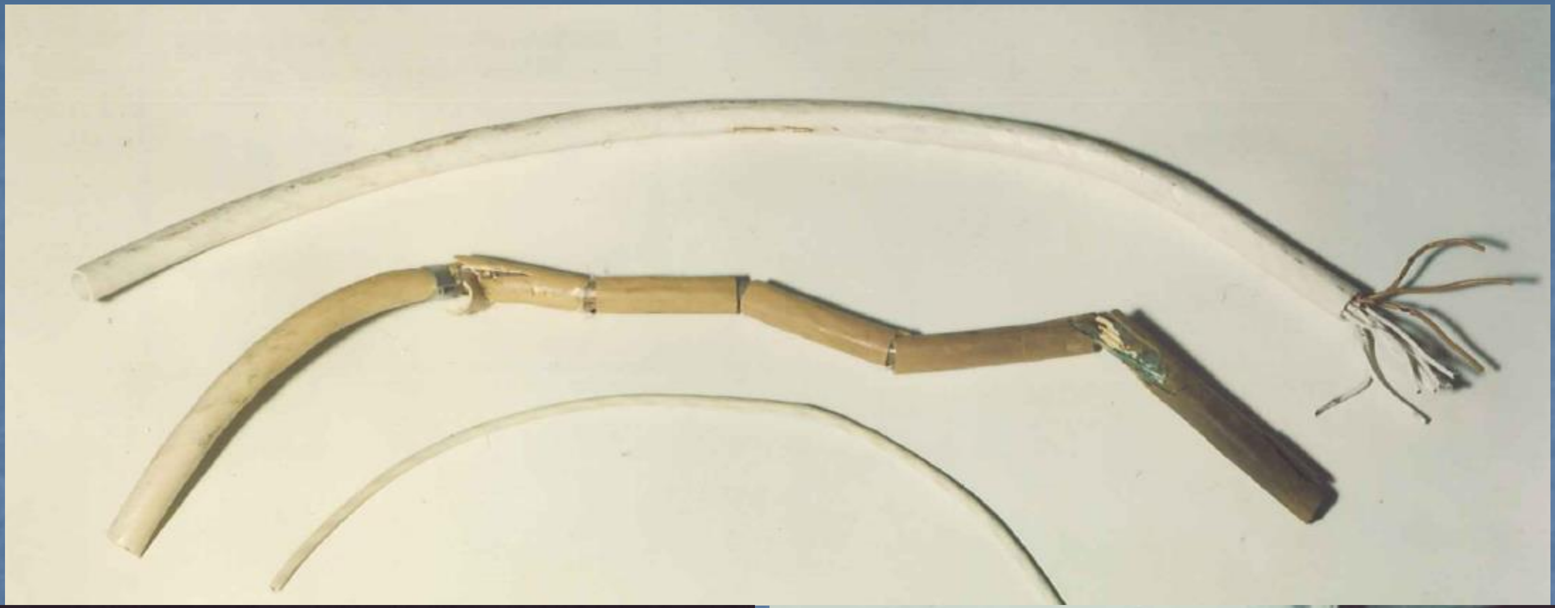
*Science 31 May 2013: Vol. 340 no. 6136 pp. 1080-1084, DOI: 10.1126/science.1235989

Aging of organic materials like insulations

Examples for radiation damage
Resin used for magnet coil insulation

0 | $5x10^6$ | 10^7 | $2.5x10^7$ | $5x10^7$ | D (Gy)

Radiation damage on cable insulations



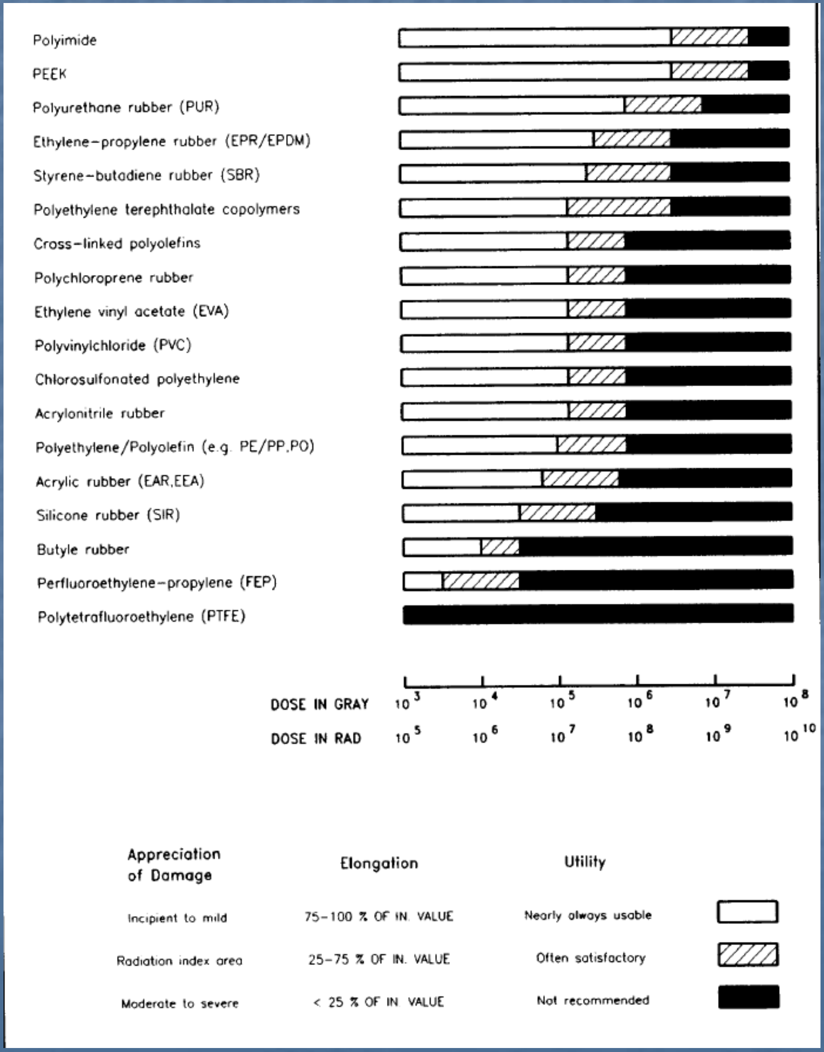
Radiation damage is mainly caused by braking hydrogen bridge bounds in molecules

In radiation facilities insulation material shall be chosen according to the radiation level in the area.

In the last millennium many radiation hardness tests were carried out and documented at CERN.

Material catalogues from the past are available and should be used

Radiation resistance of cable materials



Induced radioactivity in and around (high-energy) particle accelerators

Contents:

- Introduction to radioactivity and isotope decay
- Activation in accelerators
- Calculation procedures to forecast activation in accelerators
- Examples of activation at high-energy accelerators
- ActiWiz: program allowing the evaluation of the radiological impact of materials in accelerators

Radioactivity

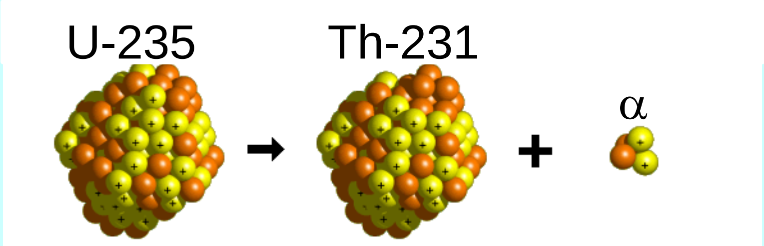
What is radioactivity?

Spontaneous emission of radiation from unstable nuclei. The consequence of most of the radioactivity reactions are combined with the change of the emitting nucleus into another kind of nucleus.

Modes of radioactive decay

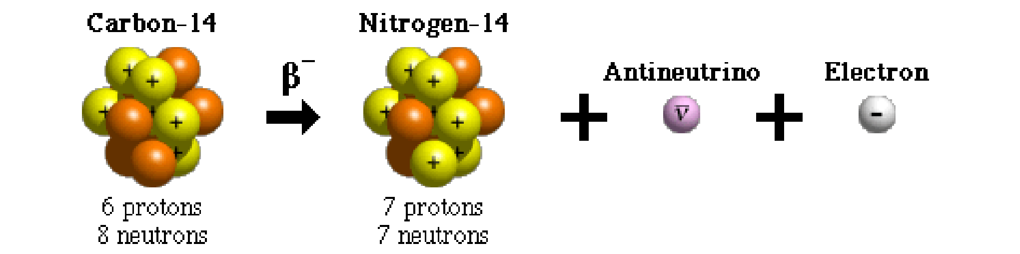
α–decay: Emission of an alpha particle, a part of the nucleus consiting of 2 protons and 2 neutrons. ➔ $A_{new} = A_{old} - 4$ and $Z_{new} = Z_{old} - 2$

Example:



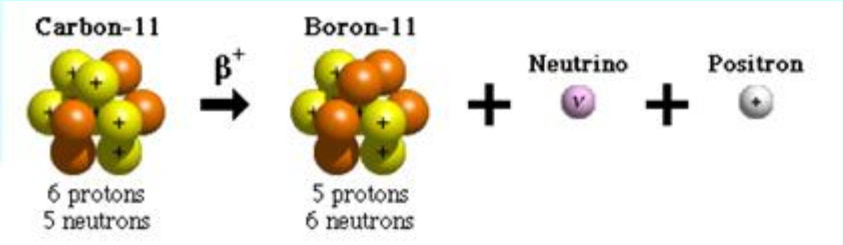
β⁻–decay: A neutron in the nucleus is transformed into a proton via the emission of an electron and an anti-electron neutrino. ➔ $A_{new} = A_{old}$ and $Z_{new} = Z_{old} + 1$

Example:

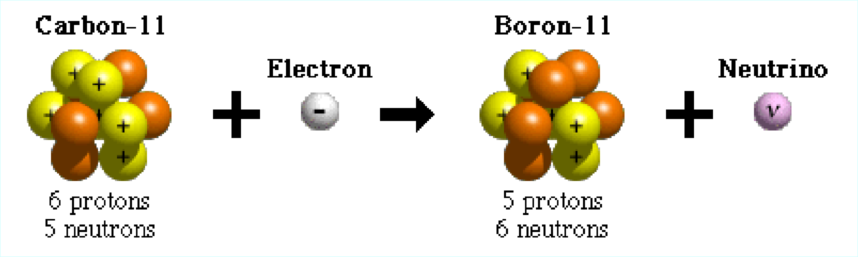


Modes of radioactive decay

β⁺–decay: A proton in the nucleus is transformed into a neutron via the emission of a positron and an electron-neutrino ➔ $A_{new}= A_{old}$ and $Z_{new}=Z_{old}-1$

Example: 

Electron capture: An electron from the atomic orbit is captured by a proton resulting to the transformation into a neutron. ➔ $A_{new}= A_{old}$ and $Z_{new}=Z_{old}-1$

Example: 

Alternative decay of C-11

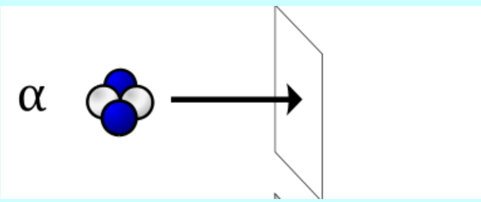
γ-decay: In a gamma decay a nucleus changes from a higher energetic state to a lower energetic state by emitting a high-energy photon (gamma particle). The composition of the nucleus remains unchanged.

All decay pictures taken from Jefferrson lab web page

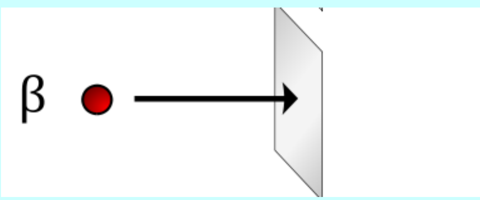
Radiation types emitted by radioactivity

Radioactivity results in the emission of α, β^+, β^- and γ radiation.

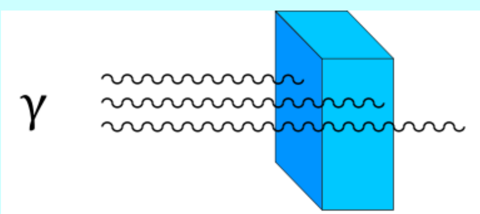
How can we shield these particles?



Sheet of paper



Several mm of aluminium



Heavy shielding

How dangerours are such particles when being incorporated?

The risk caused by α-radiation is highest when being incorporated and decaying inside the body.

Radioactive decay

Decay of a radioactive material per time unit (activity) as a function of time:

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} \sim N$$

Proportionality factor is called decay constant (λ) and it defines the probability of the deacy of a given isotope

$$\Rightarrow \quad A = -\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda \cdot N$$

N... Number of radioactive isotopes
A ... Activity, decay per time unit
λ... Decay constant, defining the speed of decay

$$\Rightarrow \quad \frac{\mathrm{d}N}{N} = -\lambda \cdot \mathrm{d}t$$

With $N(t=0) = N_0$

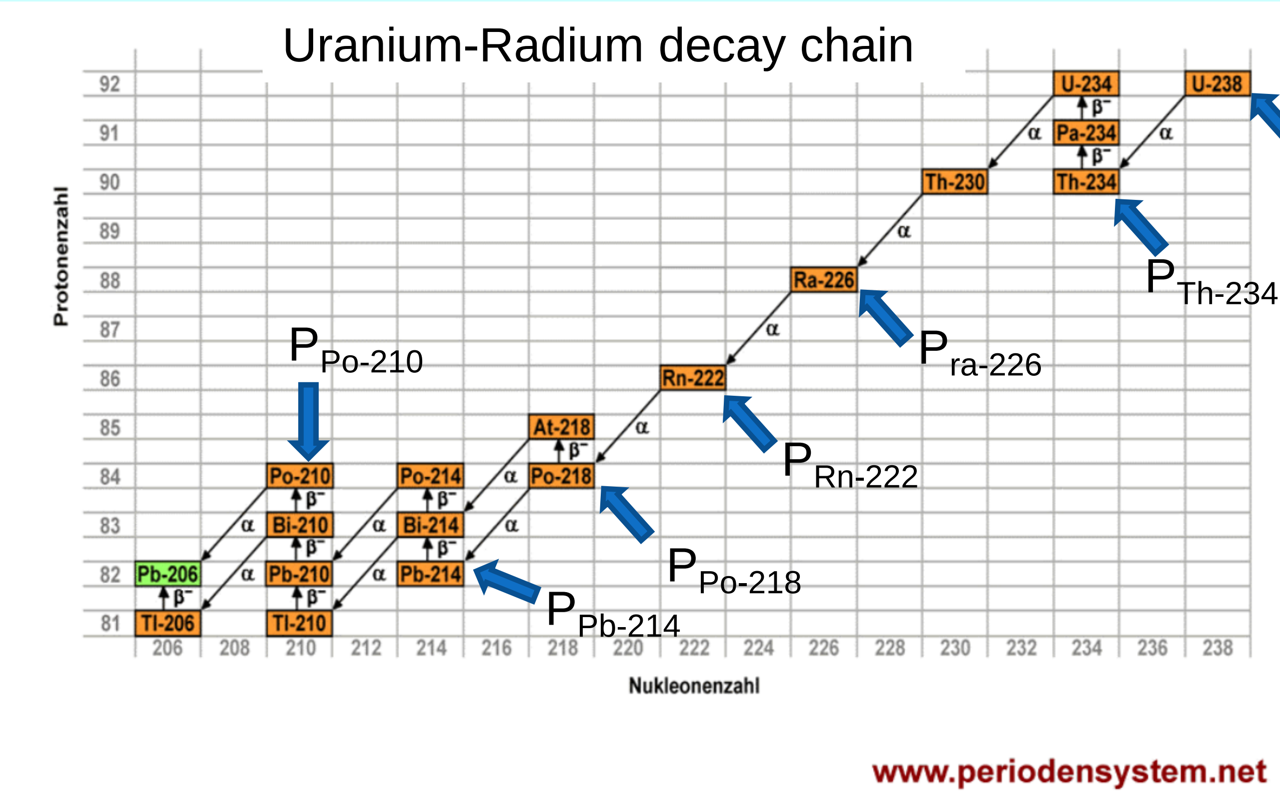
$$\Rightarrow \quad N(t) = N_0 \cdot e^{-\lambda \cdot t} \quad / \ \lambda$$

$$\Rightarrow \quad A(t) = A_0 \cdot e^{-\lambda \cdot t}$$

Unit: Bq: 1 Bq = 1 decay per second

General production-decay chains

- A decay of an isotope can result in a chain (even several chains) of decays



Each possible chain in this tree can be described by coupled differential equations

- Beside via decay some or even all isotopes can be produced by external production processes. E.g.: activation of materials in accelerators.

Mathematical expression of one production-decay chain (Bateman equation)

System of coupled differential equations

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = P_1 - \lambda_1 \cdot N_1$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = P_2 + (b_{1,2} \cdot \lambda_1 \cdot N_1) - \lambda_2 \cdot N_2$$

$$\vdots \qquad \vdots$$

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = P_i + (b_{i-1,i} \cdot \lambda_{i-1} \cdot N_{i-1}) - \lambda_i \cdot N_i$$

$$\vdots \qquad \vdots$$

$$\frac{\mathrm{d}N_n}{\mathrm{d}t} = P_n + (b_{n-1,n} \cdot \lambda_{n-1} \cdot N_{n-1}) - \lambda_n \cdot N_n$$

$$\vdots \qquad \vdots$$

$$\frac{\mathrm{d}N_m}{\mathrm{d}t} = P_m + (b_{m-1,m} \cdot \lambda_{m-1} \cdot N_{m-1}) - \lambda_m \cdot N_m$$

N_n …	Number of isotope n
P_n …	Production rate of isotope n
λ_n …	Decay constant of isotope n
b_n …	Branching ratio from isotope n-1 into n

Solving by Laplace transformation $(\mathcal{L})$ of system of differential equations

Laplace transformation to find solutions for complicated radioactive decay problems

The Laplace transform of a function $f(t)$, defined for all real numbers $t \geq 0$, is the function $F(s)$, defined by:

$$F(s) = \int_0^{\infty} e^{-st} f(t)\, dt$$

It transforms a function being dependent from t into a new function F being dependent from s

Linearity	$af(t) + bg(t)$	$aF(s) + bG(s)$
Differentiation	$f'(t)$	$sF(s) - f(0)$

Laplace transformation of system of differential equations ➔ system of linear algebraic equations

Mathematical expression of one production-decay chain (Bateman equation)

Laplace transformed equations = system of linear equations, to be solved in the Laplace domain as a function of *s.*

$$s \cdot F_1(s) - N_1(t=0) = \frac{P_1}{s} - \lambda_1 \cdot F_1(s)$$

$$\vdots \qquad \vdots$$

$$s \cdot F_n(s) - N_n(t=0) = \frac{P_n}{s} + b_{n-1,n} \cdot \lambda_{n-1} \cdot F_{n-1}(s) - \lambda_n \cdot F_n(s)$$

$$\vdots \qquad \vdots$$

$$s \cdot F_m(s) - N_m(t=0) = \frac{P_m}{s} + b_{m-1,m} \cdot \lambda_{m-1} \cdot F_{m-1}(s) - \lambda_m \cdot F_m(s)$$

N_n … number of isotope n
P_n … production rate of isotope n
λ_n … decay constant of isotope n
b_n … branching ratio from isotope n-1 into n
F_n (s) … Laplace transformed of N_n(t)

Inverse Laplace transformation of F_n *(s)* $\mathcal{L}^{-1}(F_n(s))$ ⟹ $N_n(t)$

$$\Rightarrow N_n(t) = \sum_{i=1}^{n} \left[\left(\prod_{j=i}^{n-1} \lambda_j b_{j,j+1} \right) \sum_{j=i}^{n} \left(\frac{N_i^0 e^{-\lambda_j t}}{\prod_{\substack{p=i \\ p \neq j}}^{n} \lambda_p - \lambda_j} + \frac{P_i (1 - e^{-\lambda_j t})}{\lambda_j \prod_{\substack{p=i \\ p \neq j}}^{n} \lambda_p - \lambda_j} \right) \right]$$

To obtain the final result for a given isotope the contributions of the various chains have to be summed up.

Activation:
Radioactivity production in accelerators

First questions about activation

What is activation?
Activation can be described as the imposed change of nuclear composition of given isotopes resulting in the production of radioactivity.

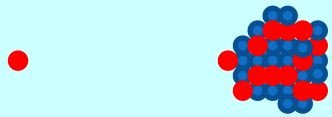
Impact of activation:
- Accelerators: caused by beam operation accelerator and environment will become radioactive ➔ dose to personnel and environment.

What can be done to reduce activation?
- Reduce beam losses
- Reduce activation prone material

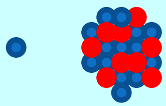
Which production mechanisms of activation occur at high-energy accelerators?

At high-energy accelerators primary particles interact with matter. The primary particle itself or secondary particles interacting with nuclei can produce radioactive isotopes. Main production channels of activation at high-energy accelerators are:

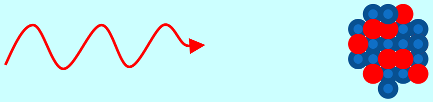
- Spallation processes, (n,2n), (n,p), (n,alpha), ..



- Particle capture (mainly neutrons)



- (γ,n)-reactions (important for electron accelerators)



Questions about activation III/III

Why is activation important for high-energy accelerators?

Environment

Tunnel and accelerator

Air activation

Water activation

Soil activation

Material activation of beam line, tunnel and shielding components

Required information to classify activation:

1. Specific activity: classification of material between radioactive and non-radioactive material
2. Dose rate around the activated components

Parameters responsible for production of radioactivity in a given material sample at high-energy accelerators

Beam type and energy

Material around loss point

Location of sample in given radiation environment

Composition of material sample

Beam intensity

Irradiation history

Cooling time

Radionuclide production in sample per lost proton

Evolution of radioactivity as a function of time

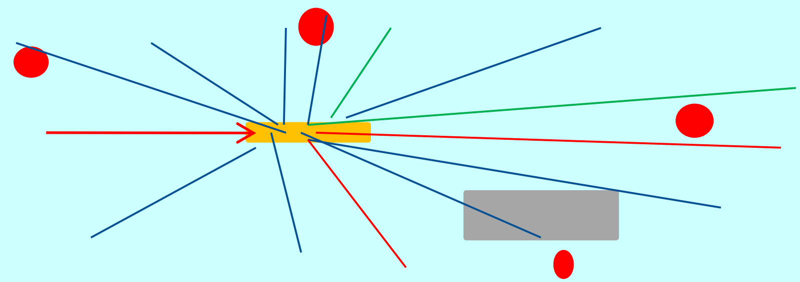
Physics principles of radio nuclide production per lost proton

Beam on target situation:

Target

Sample positions

Shielding



Total production rate of radio-nuclide i

$$P_i =$$

Total track length of particle type k through volume of interest as a function of energy (E)

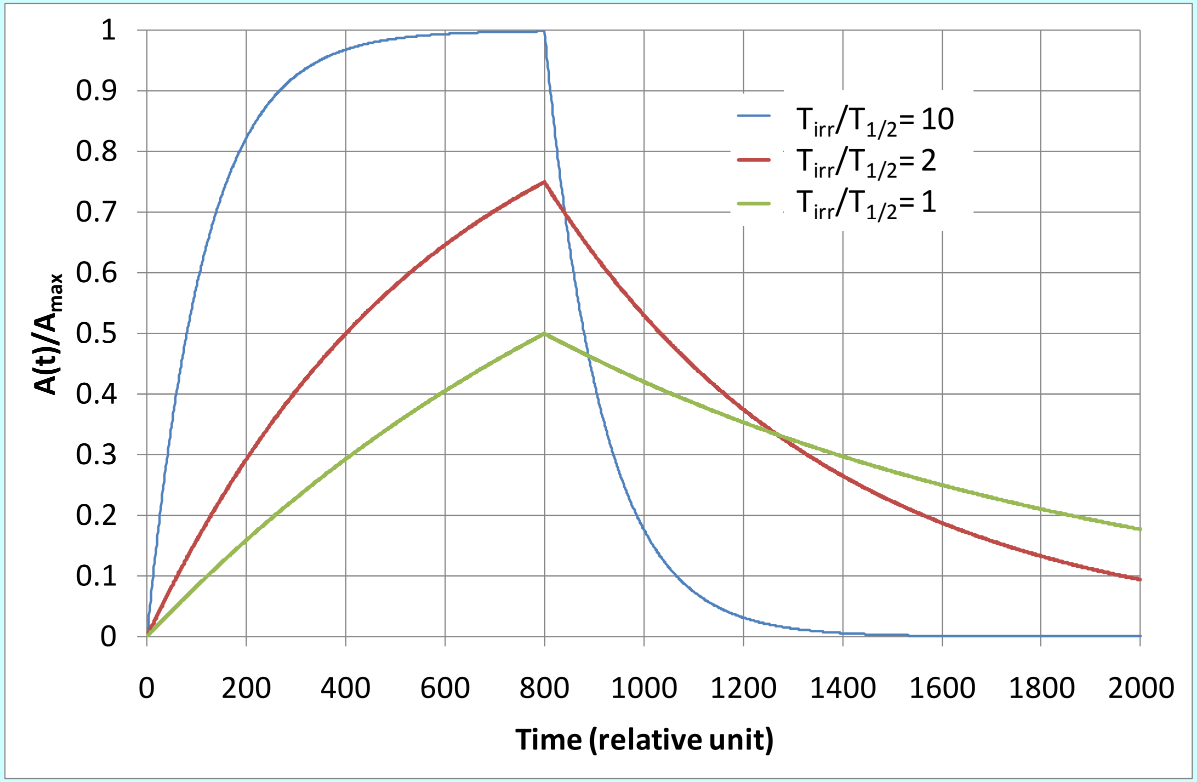
Atomic density of isotope j in given volume

Energy (E) and particle type dependent production cross section to produce nuclide i from isotope j

Activation as a function of beam operation time and cooling time

$$\frac{dN_i}{dt} = -\lambda_i \cdot N_i + P_i \cdot I$$

$$A_i(t_{irr} + t_{cool}) = P_i \cdot I \cdot (1 - e^{-\lambda t_{irr}}) \cdot e^{-\lambda t_{cool}}$$



N_i… Number of isotopes i

λ… decay constant of nuclide i

P_i… production rate of isotope i per proton

I … proton intensity

A_i… Activity of isotope i after t_{irr} and t_{cool}

t_{irr}… irradiation time

t_{cool}… cooling time

Build-up and decay

$A_{i,max} \leq P_i \cdot I$

90% of $A_{i,max}$ are obtained after ~ $3.32 \cdot t_{1/2}$

99% of $A_{i,max}$ are obtained after ~ $6.64 \cdot t_{1/2}$

Video demonstration of radioactivity production, build-up and decay

Calculation procedures to forecast activation and dose rates in high-energy accelerators

Analytic method

Full Monte Carlo calculation

Analytic methods

$$P_i = \sum_{j,k} n_j \int dE\, \sigma_{i,j,k}(E)\Lambda_k(E)$$

$$A_i(t_{irr} + t_{cool}) = P_i \cdot I \cdot (1 - e^{-\lambda t_{irr}}) \cdot e^{-\lambda t_{cool}}$$

Analytical estimate of activation

Required input parameters:

- Track length spectra for all relevant particle types, $\Lambda_k(E)$
- Cross sections for radio nuclide production $\sigma_{i,j,k}$
- Irradiation and cooling history

Pro:

- Fast activation result if input parameters are available

Cons:

- Track length of various particles fields are required (very often Monte Carlo results)
- Only rough dose rate estimate without self shielding effects

Full Monte Carlo calculation of activation

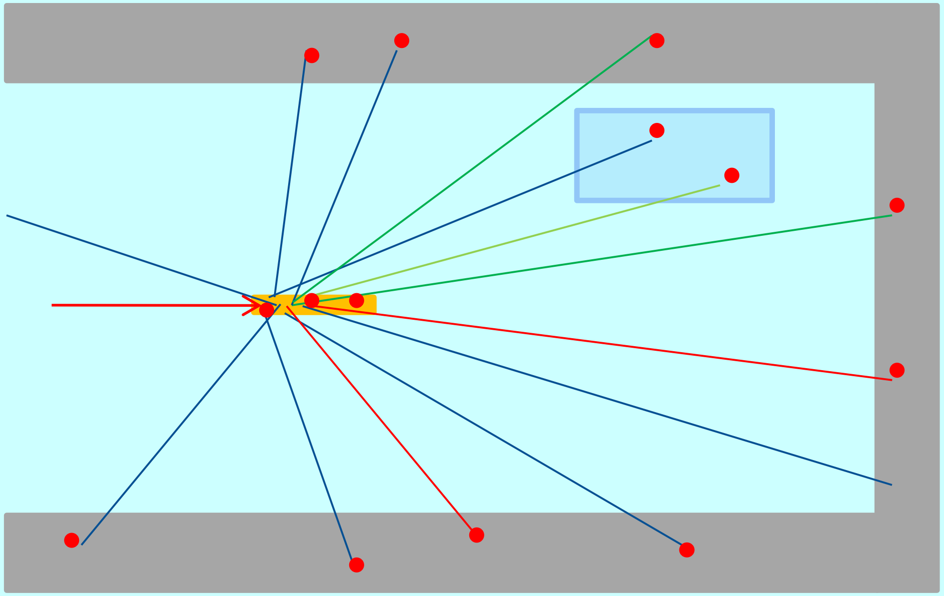
Input required:

- 3D geometry description
- Beam energy and intensity
- Irradiation history and cooling time(s)

Procedure inside code:

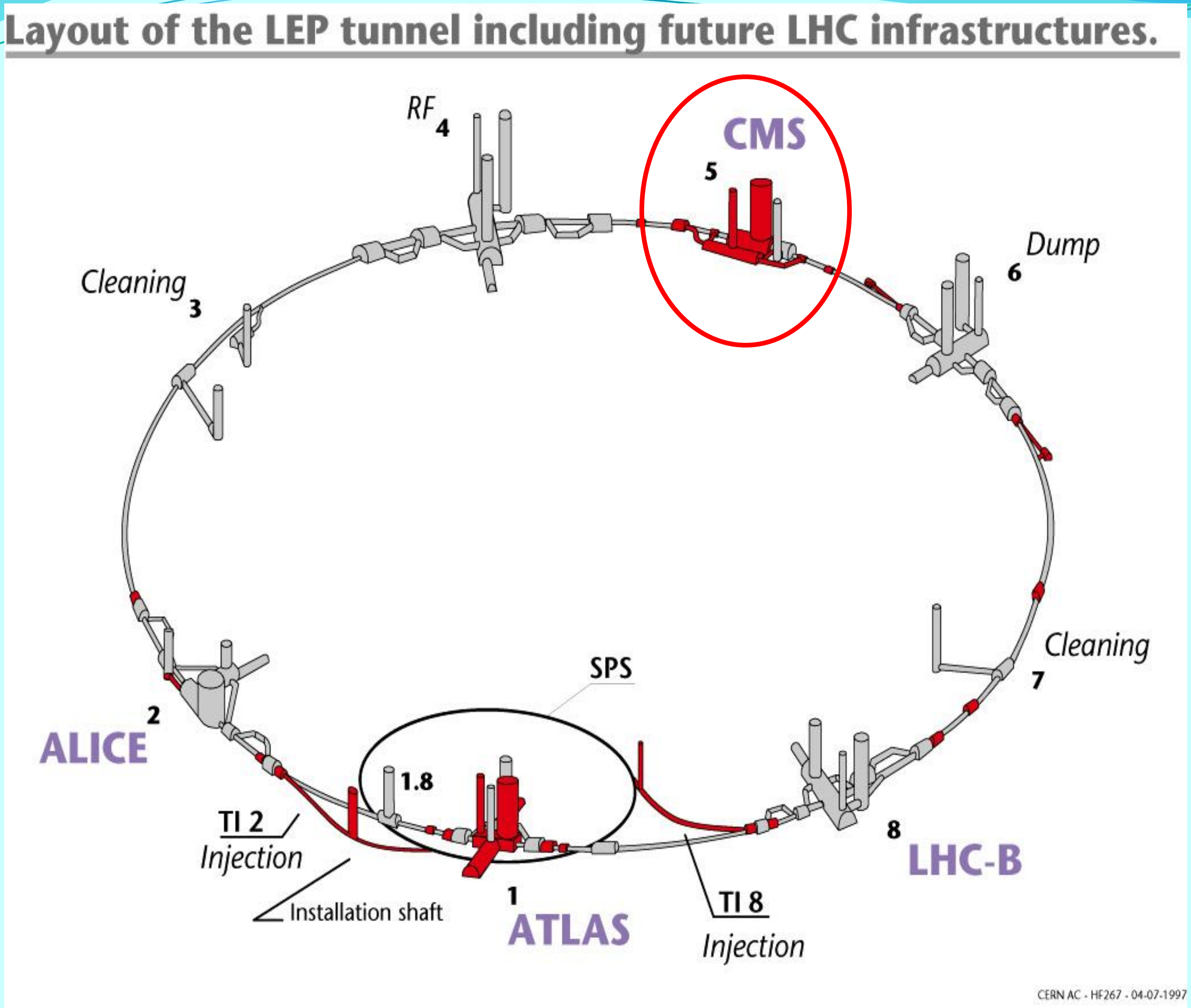
1) Simulation of particle cascade and isotope production around beam impact point

2) Radiation emerging from radio-isotopes are further transported to calculate dose rate in the surroundings of activated material



Applications for FLUKA activation simulations

Applications at the Large Hadron Collider (LHC)

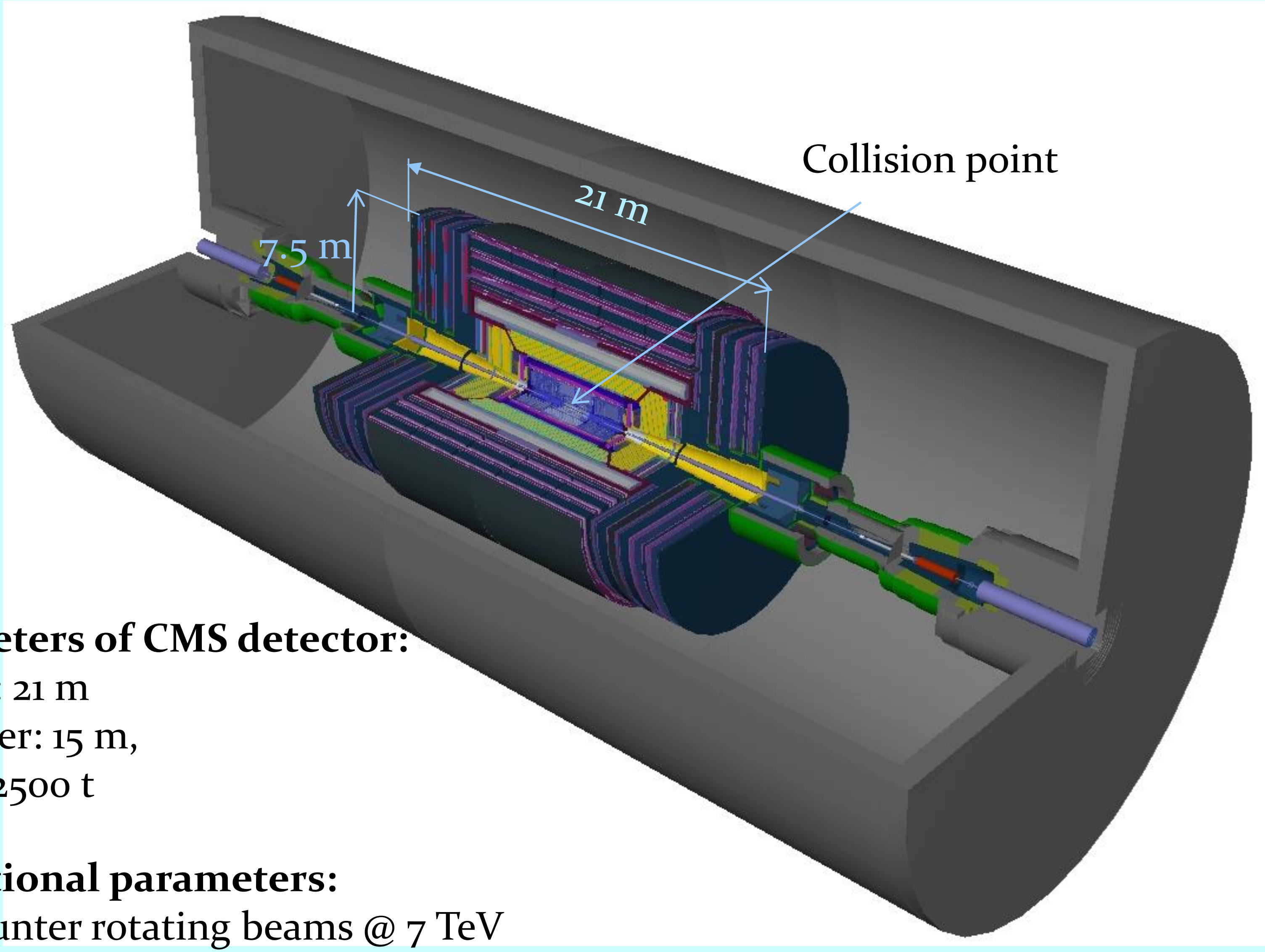


Particle type:
Protons

Beam energy:
7 TeV

Number of stored particles:
$2 \times 4 \cdot 10^{14}$

CMS detector



Parameters of CMS detector:

Length: 21 m

Diameter: 15 m,

Mass: 12500 t

Operational parameters:

Two counter rotating beams @ 7 TeV

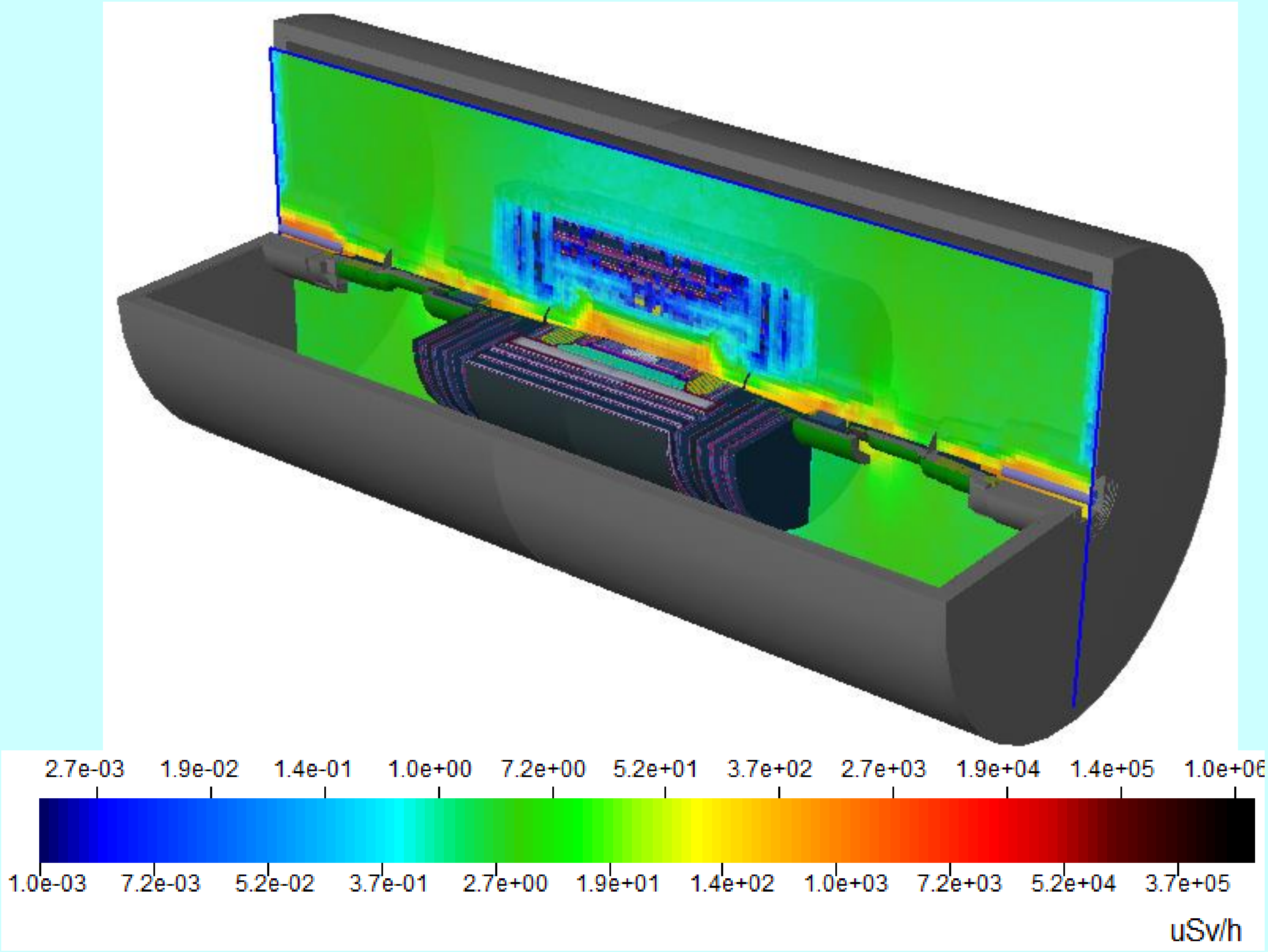
Luminosity: 10^{34} cm^{-2} s^{-1}

➔10^9 proton-proton collisions/s

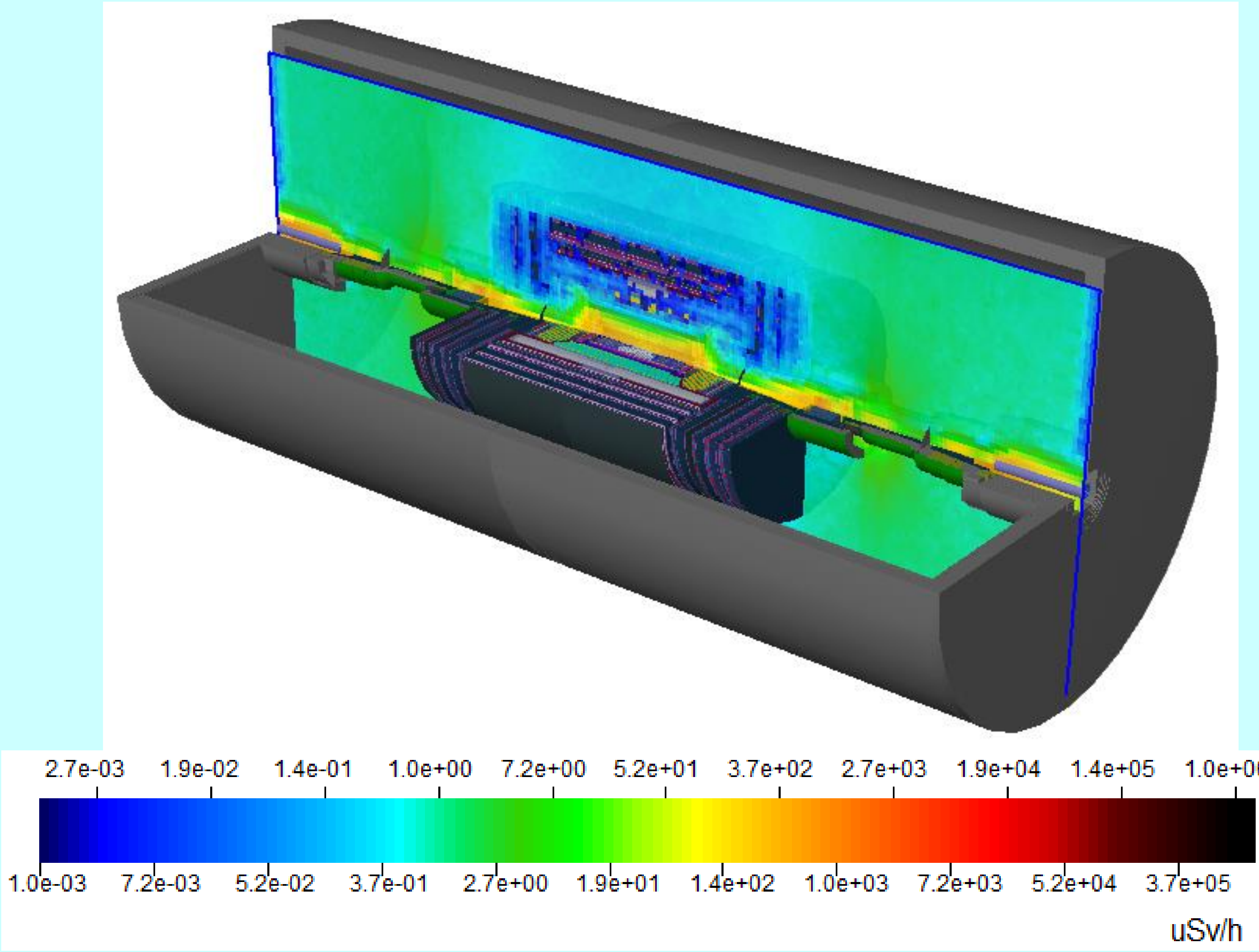
Residual dose rates to be expected after beam operation

Residual dose rate expected after 1st year of operation:
180 days of operation +
6 cooling times: 1 h, 1d, 1w, 1m, 4m

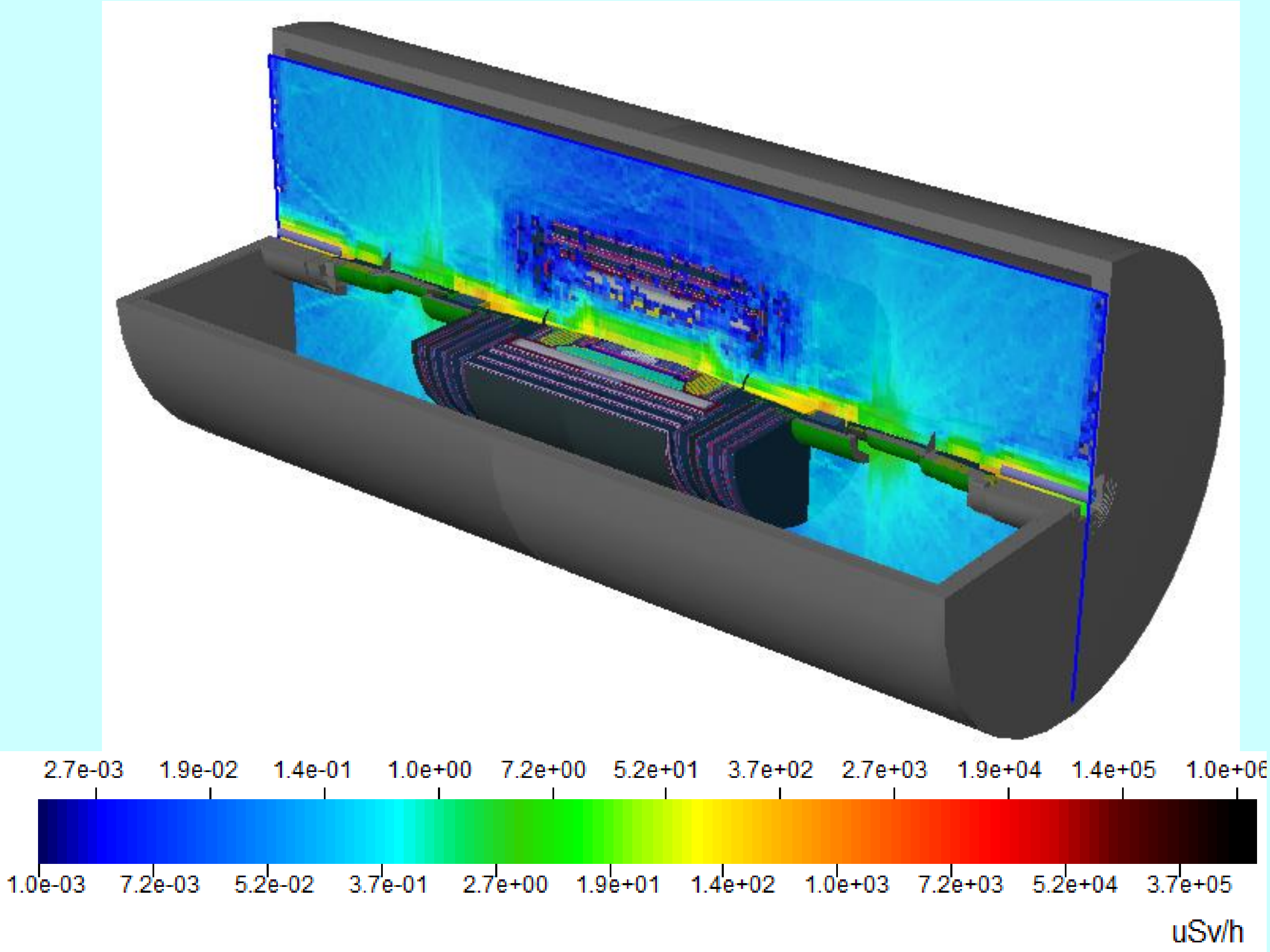
180 days of irradiation, 10^9 pp/s, 1h of cooling



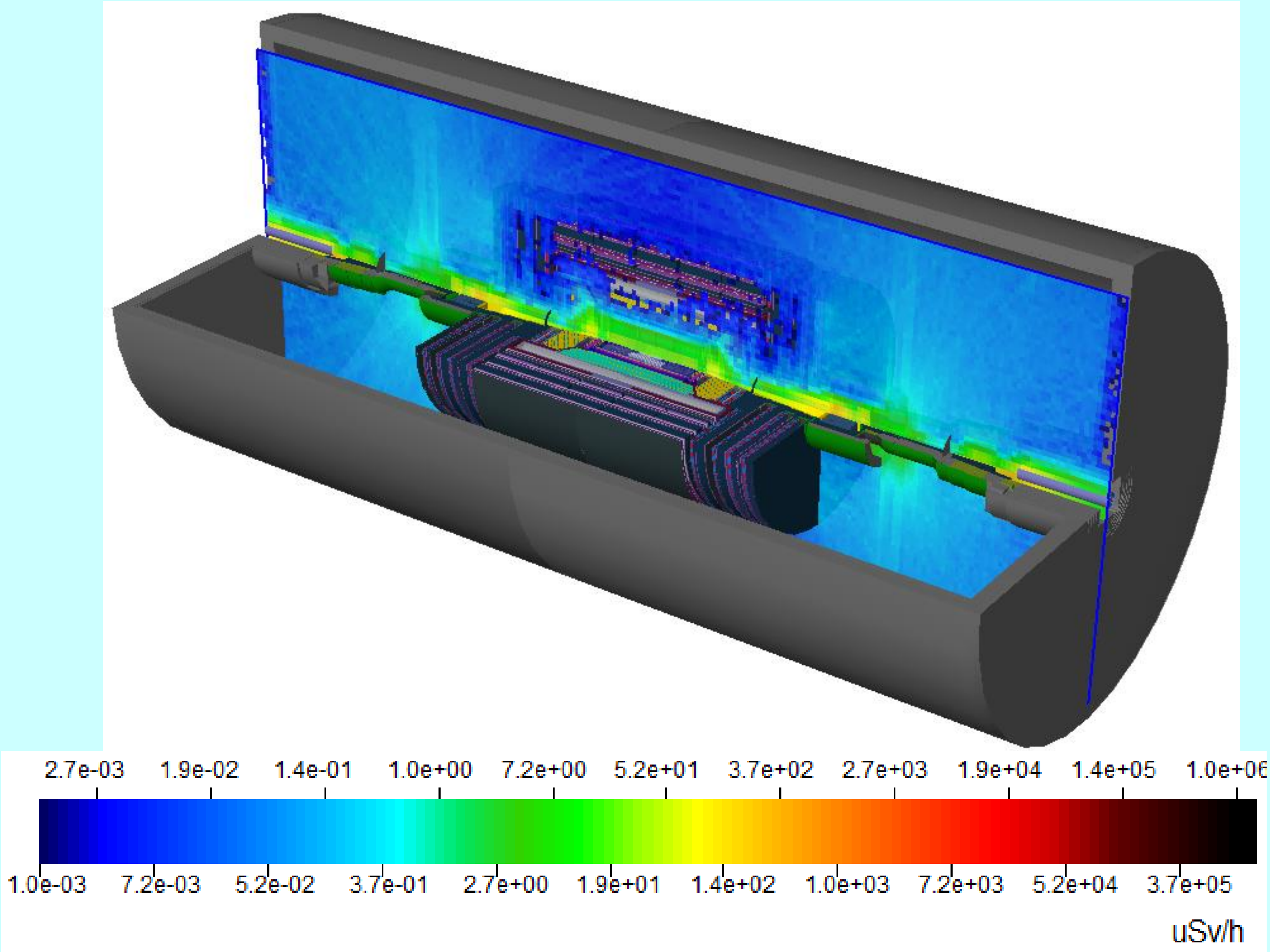
180 days of irradiation, 10^9 pp/s, 1d of cooling



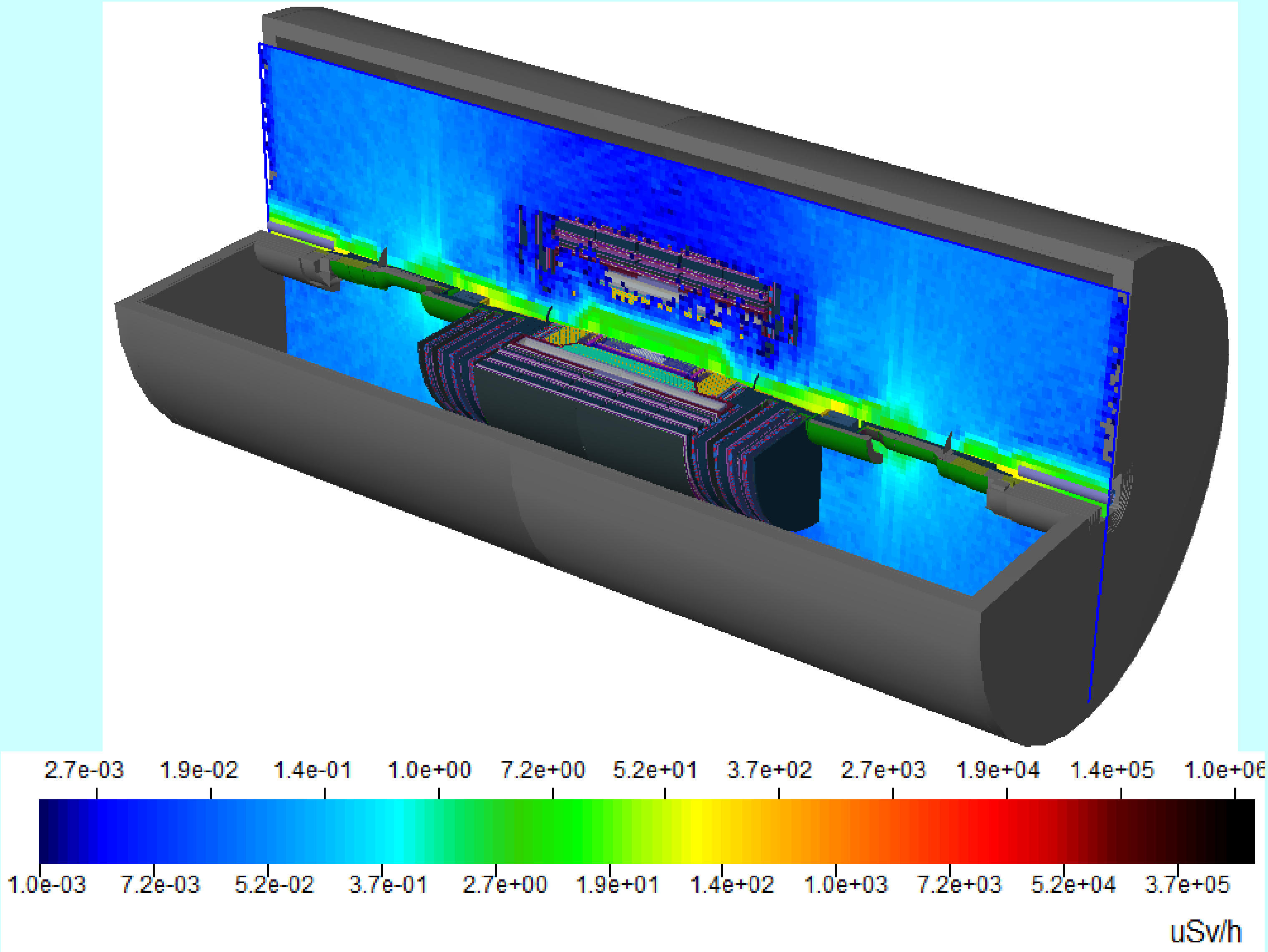
180 days of irradiation, 10^9 pp/s, 1w of cooling



180 days of irradiation, 10^9 pp/s, 1m of cooling



180 days of irradiation, 10^9 pp/s, 4m of cooling

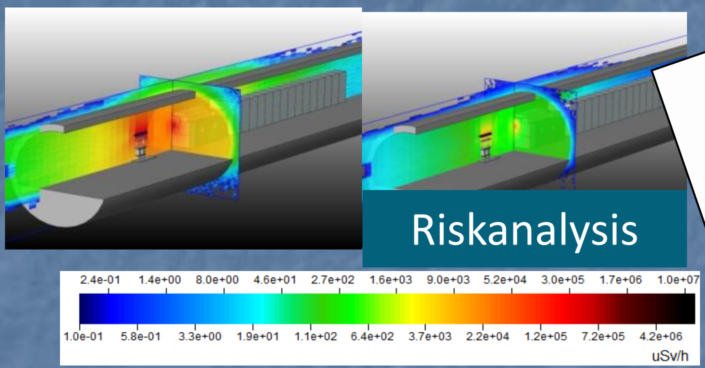


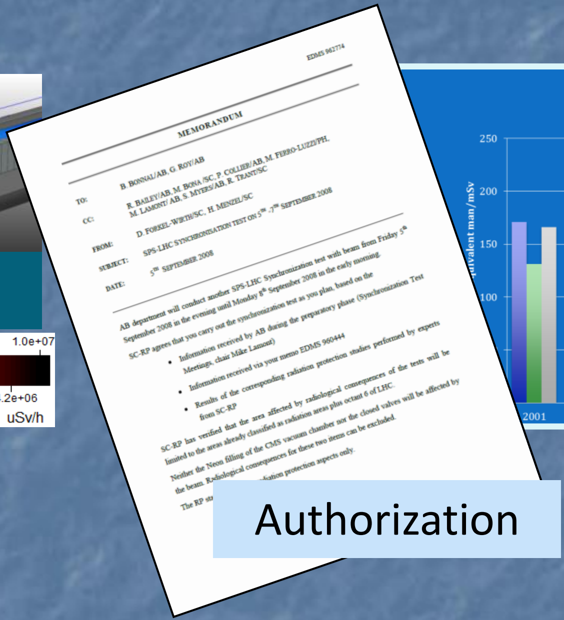
Radiation Protection at CERN

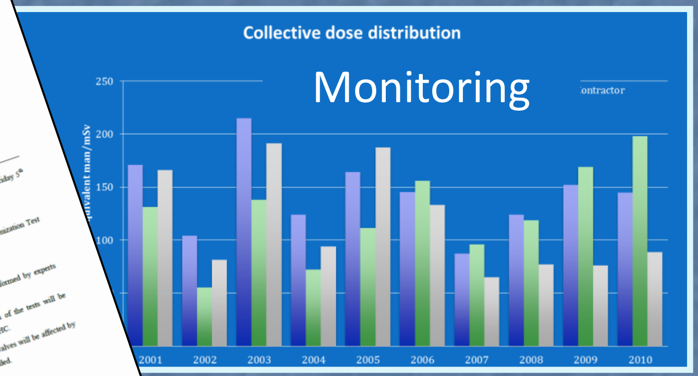
Contents

- Mandate
- Radiation Protection Regulations
- Dose limits and objectives
- Dosimetry, Operational Radiation Protection and Radiation Monitoring
- Radioactive waste: treatment and elimination
- ALARA at CERN

Radiation Protection at CERN: Mandate



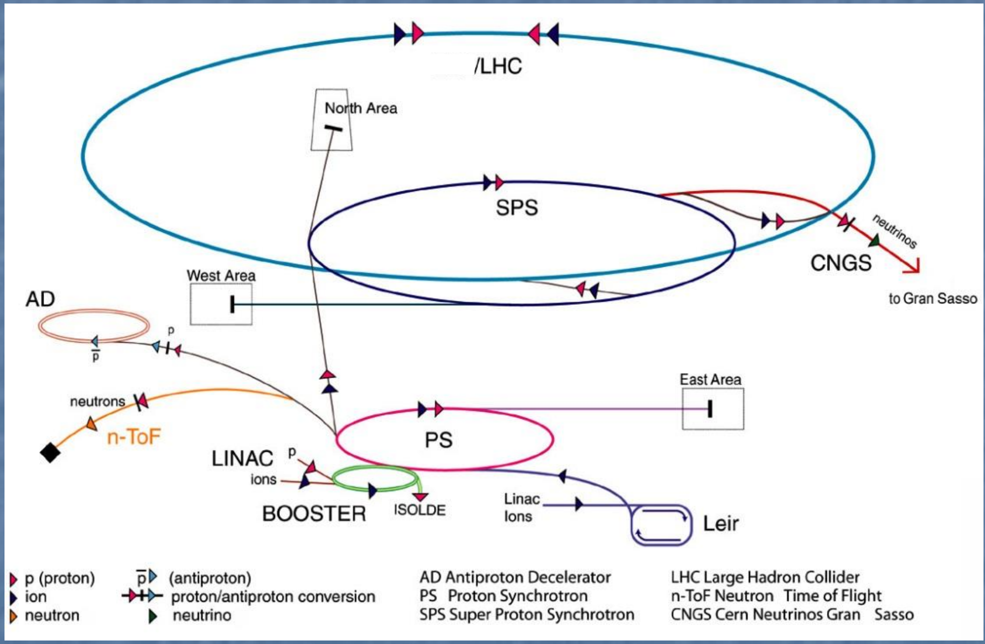




Some Key Figures…

Radiation Areas and Radioactive Laboratories:

- ~ 45 km accelerator tunnel
- Class A, C laboratories
- RIB facility ISOLDE
- Spallation source n-TOF
- ~ 50 - 60 access points
- ~ 160 experiments
- ~ 7000 radiation workers
- new projects



Radiation Protection Regulation

General Principles of Radiation Protection

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

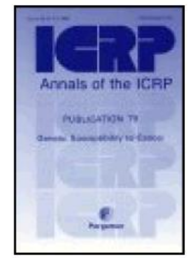
3) Optimization

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

CERN's Radiation Protection Regulation

CERN is an intergovernmental organization and not bound to any national law* - but

ICRP INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION



IAEA Basic Safety Standards

Guideline 96/29 Euratom laying down the basic standards for protecting public and workers against the risk of ionising radiation

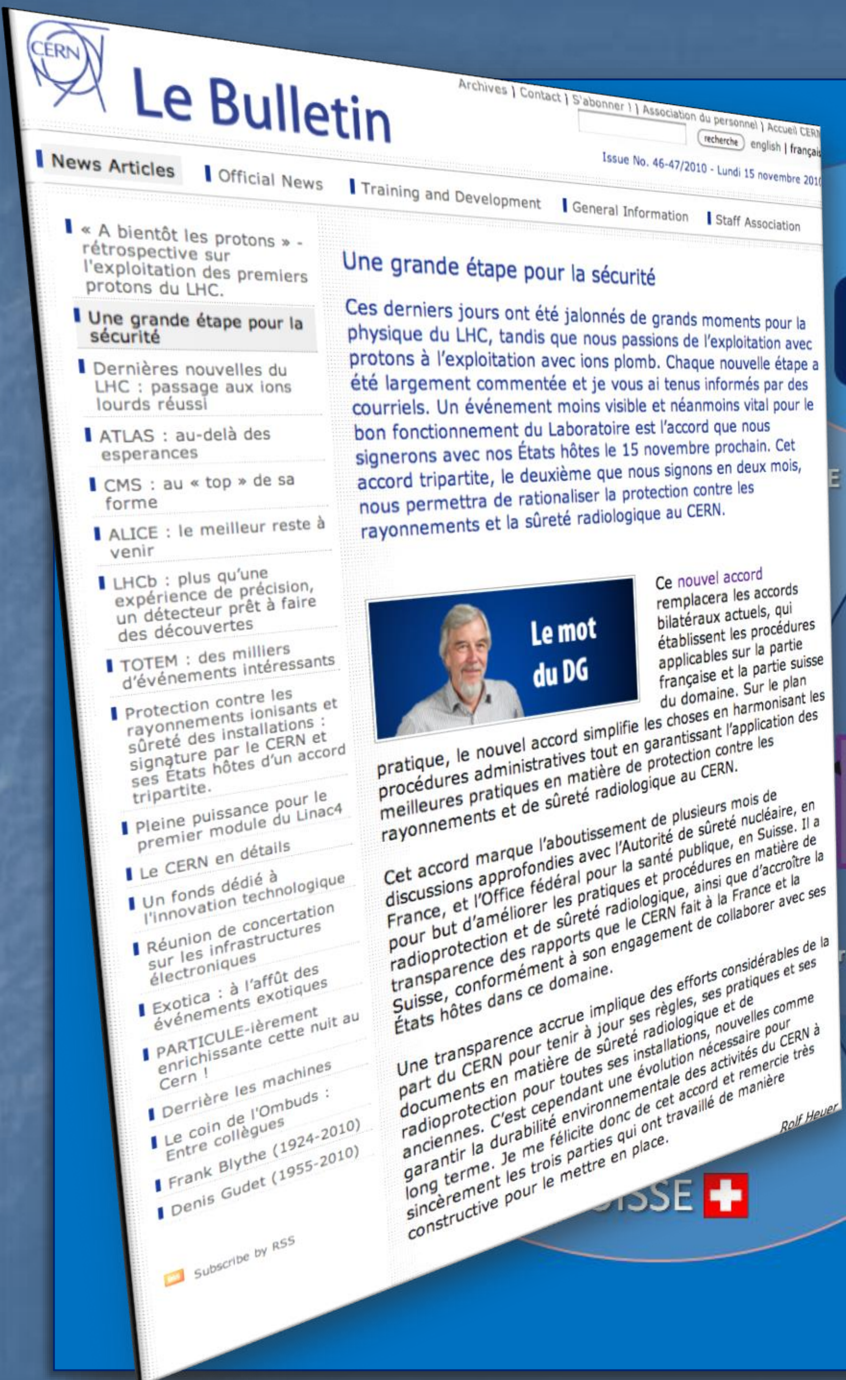
CERN Safety Code F (Radiation Protection Ordinance) and underlying safety instructions, guidelines, etc.

\) CERN's relation with its two Host States is defined in conventions between the parties

Taken from B. Lorenz, WKK Symposium April 2008 and modified

RATIFICATION OF THE TRIPARTITE AGREEMENT ON SAFETY AND RADIATION PROTECTION

(September 2011)



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- Dernières nouvelles du LHC : passage aux ions lourds réussi
- ATLAS : au-delà des esperances
- CMS : au « top » de sa forme
- ALICE : le meilleur reste à venir
- LHCb : plus qu'une expérience de précision, un détecteur prêt à faire des découvertes
- TOTEM : des milliers d'événements intéressants
- Protection contre les rayonnements ionisants et sûreté des installations : signature par le CERN et ses États hôtes d'un accord tripartite.
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- Le CERN en détails
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- Réunion de concertation sur les infrastructures électroniques
- Exotica : à l'affût des événements exotiques
- PARTICULE-ièrement enrichissante cette nuit au Cern !
- Derrière les machines
- Le coin de l'Ombuds : Entre collègues
- Frank Blythe (1924-2010)
- Denis Gudet (1955-2010)

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Une grande étape pour la sécurité

Ces derniers jours ont été jalonnés de grands moments pour la physique du LHC, tandis que nous passions de l'exploitation avec protons à l'exploitation avec ions plomb. Chaque nouvelle étape a été largement commentée et je vous ai tenus informés par des courriels. Un événement moins visible et néanmoins vital pour le bon fonctionnement du Laboratoire est l'accord que nous signerons avec nos États hôtes le 15 novembre prochain. Cet accord tripartite, le deuxième que nous signons en deux mois, nous permettra de rationaliser la protection contre les rayonnements et la sûreté radiologique au CERN.

Ce nouvel accord remplacera les accords bilatéraux actuels, qui établissent les procédures applicables sur la partie française et la partie suisse du domaine. Sur le plan pratique, le nouvel accord simplifie les choses en harmonisant les procédures administratives tout en garantissant l'application des meilleures pratiques en matière de protection contre les rayonnements et de sûreté radiologique au CERN.

Cet accord marque l'aboutissement de plusieurs mois de discussions approfondies avec l'Autorité de sûreté nucléaire, en France, et l'Office fédéral pour la santé publique, en Suisse. Il a pour but d'améliorer les pratiques et procédures en matière de radioprotection et de sûreté radiologique, ainsi que d'accroître la transparence des rapports que le CERN fait à la France et la Suisse, conformément à son engagement de collaborer avec ses États hôtes dans ce domaine.

Une transparence accrue implique des efforts considérables de la part du CERN pour tenir à jour ses règles, ses pratiques et ses documents en matière de sûreté radiologique et de radioprotection pour toutes ses installations, nouvelles comme anciennes. C'est cependant une évolution nécessaire pour garantir la durabilité environnementale des activités du CERN à long terme. Je me félicite donc de cet accord et remercie très sincèrement les trois parties qui ont travaillé de manière constructive pour le mettre en place.

Rolf Heuer

ACCORD

ENTRE

L'ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE,

LE CONSEIL FEDERAL SUISSE,

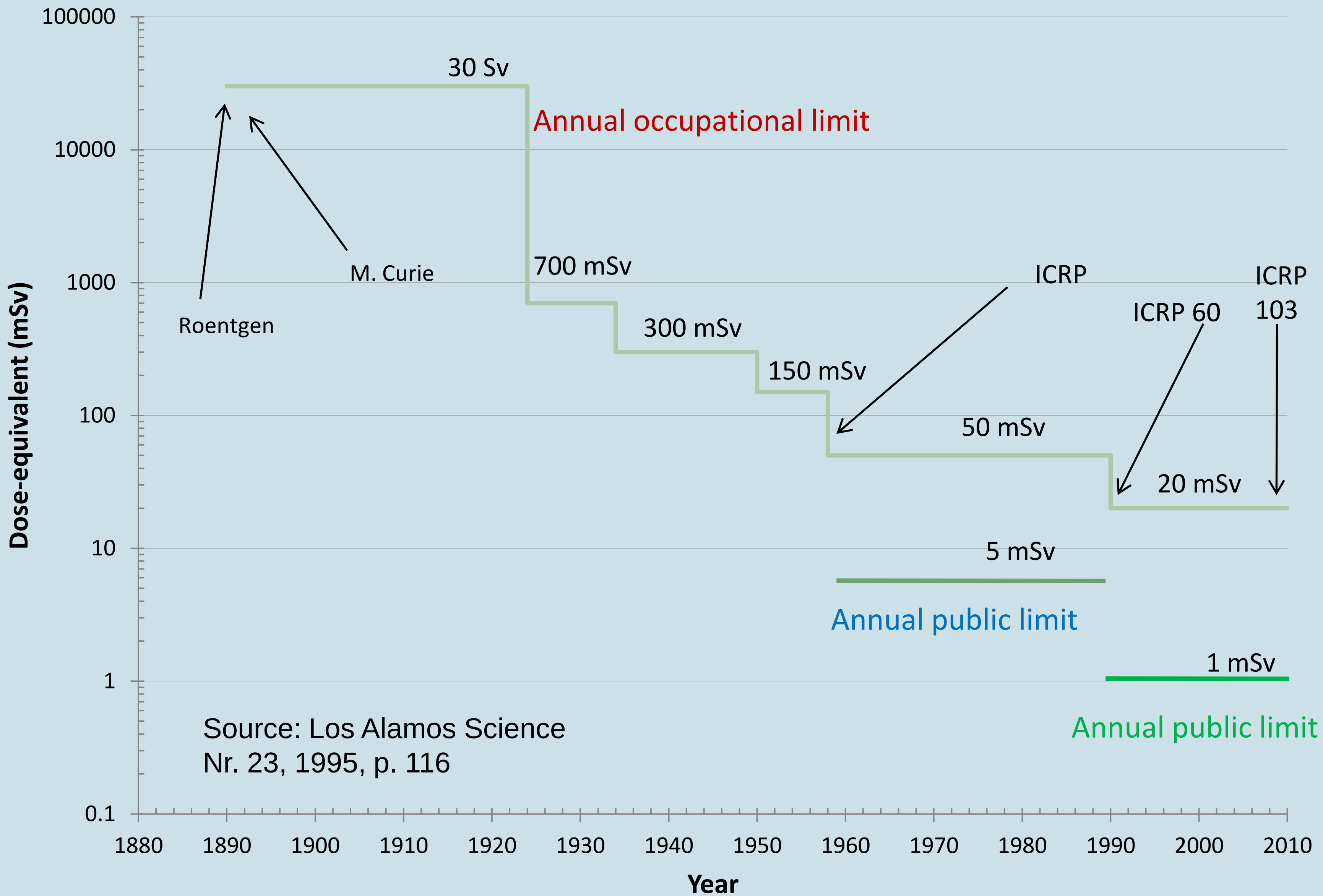
ET

LE GOUVERNEMENT DE LA REPUBLIQUE FRANÇAISE

relatif à la Protection contre les rayonnements ionisants et à la Sûreté des Installations de l'Organisation européenne pour la Recherche nucléaire

Pour l'Organisation	Pour le Conseil fédéral suisse	Pour le Gouvernement français
Rolf Heuer	Pascal Strupler	André-Claude Lacoste
Directeur général	Directeur de l'Office fédéral de santé publique	Président de l'Autorité de sûreté nucléaire

History of Radiation Protection



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	

CERN's Dose Objectives

Category	Dose/Year
Critical Group of Public	< 10 uSv
Non-professionally exposed personnel	< 100 uSv
Professionally exposed personnel	< 6 mSv

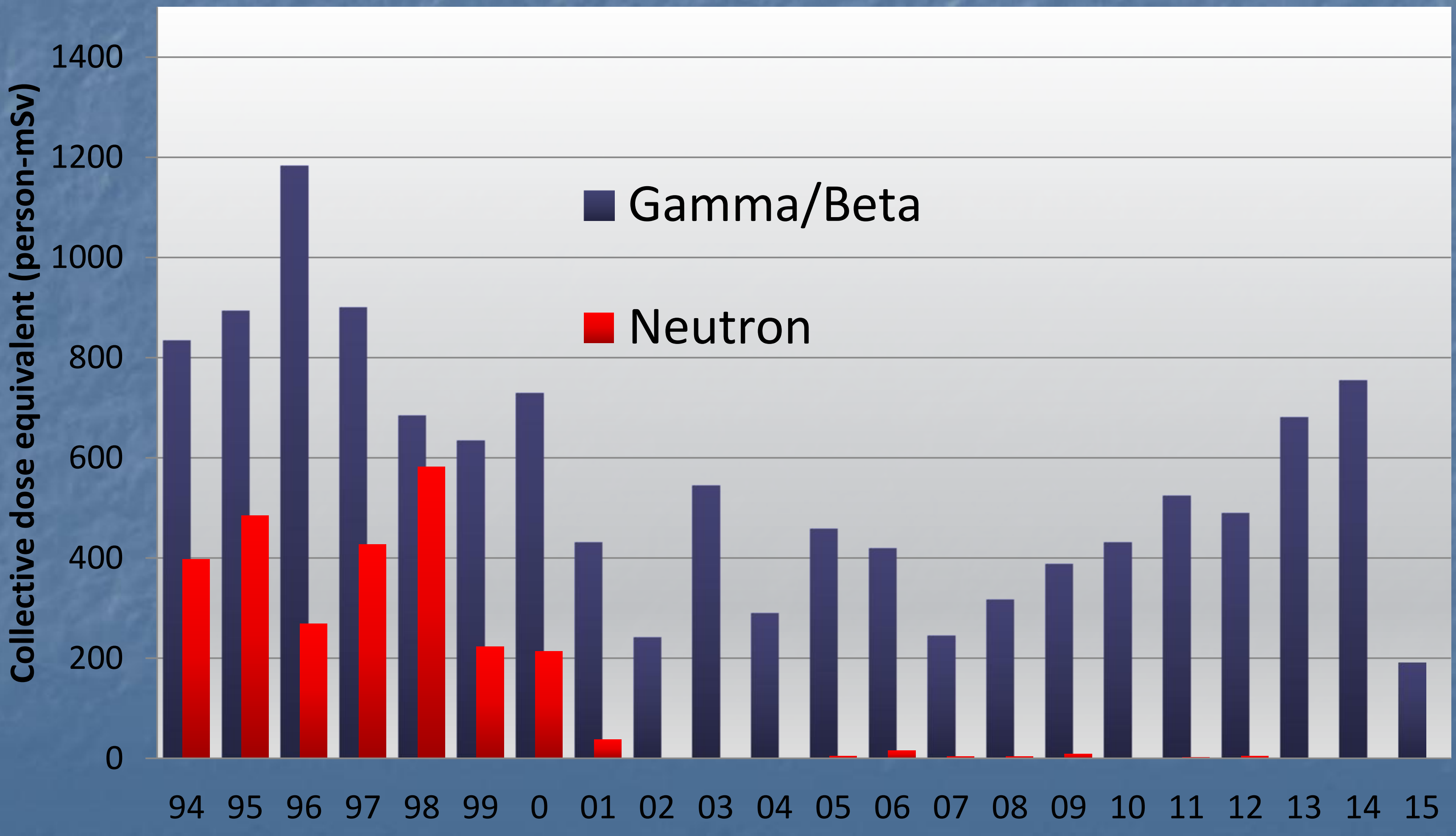
Dosimetry, Operational Radiation Protection and Radiation Monitoring

Individual Dosimetry

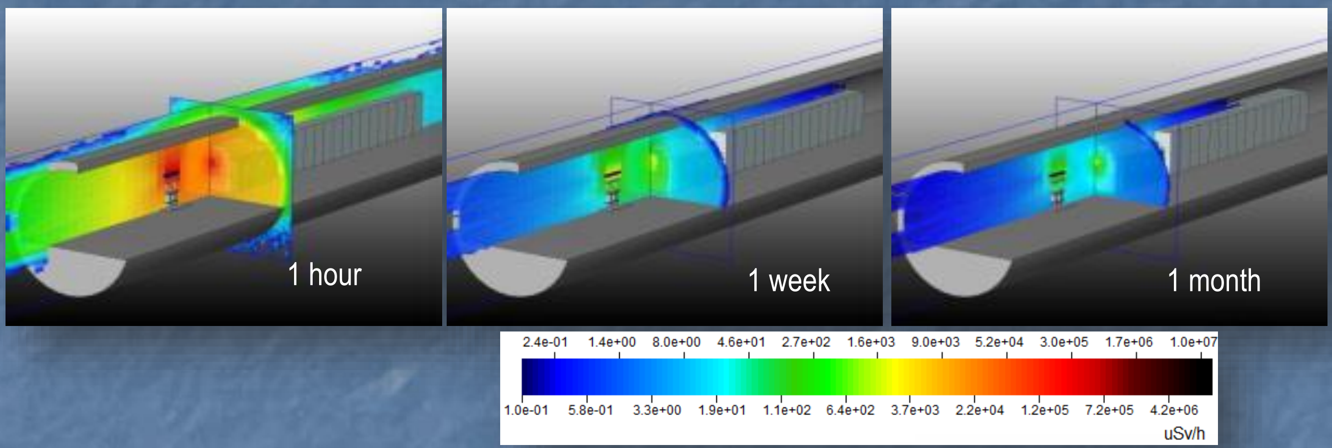
Dose interval (mSv)	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned	Persons Concerned
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
0.0 – 0.1	4192	5131	5143	5042	5418	5315	6002	6273	7616	7688
0.1 – 1.0	1738	898	1020	1219	1514	1984	2030	2188	1816	1026
1.0 – 2.0	37	33	40	39	31	31	29	82	133	2
2.0 – 3.0	17	2	3	13	6	7	0	3	14	0
3.0 – 4.0	4	1	1	2	0	0	0	0	1	0
4.0 – 5.0	2	1	1	0	0	0	0	0	0	0
5.0 – 6.0	0	0	0	0	0	0	0	0	0	0
> 6.0	0	0	0	0	0	0	0	0	0	0
SUM PERS	5990	6066	6208	6315	6969	7337	8061	8546	9580	8716

- ~ 7000 monitored persons per year
- 98 - 99% of individual doses < 1 mSv

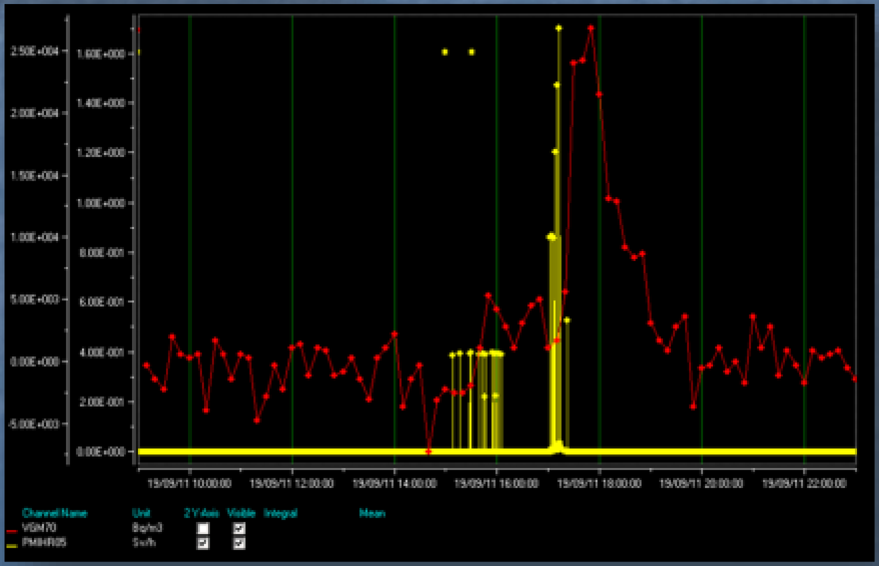
Collective Personal Dose Equivalent Summary over the last 22 years



Operational Radiation Protection

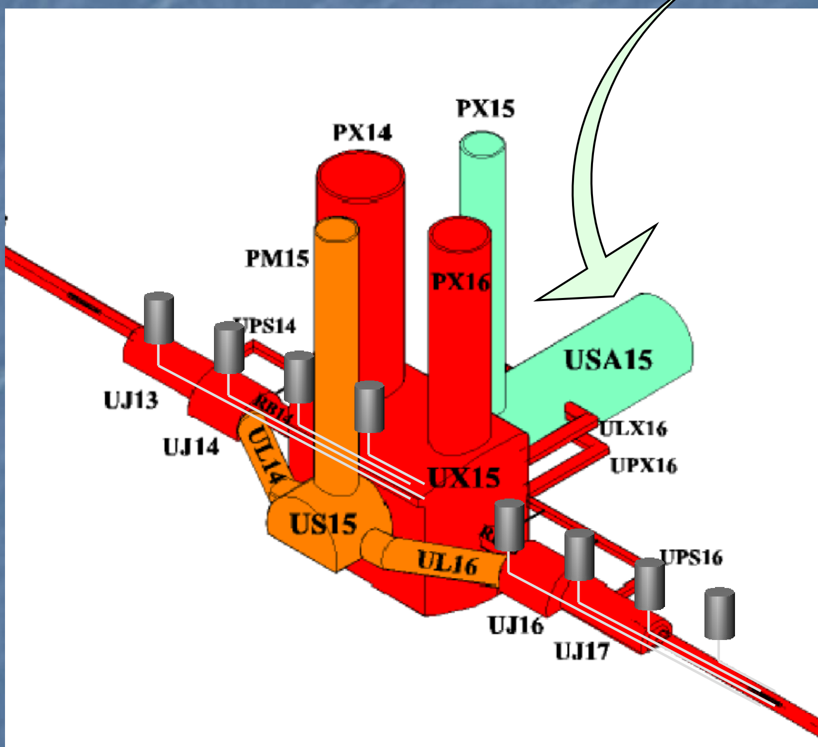


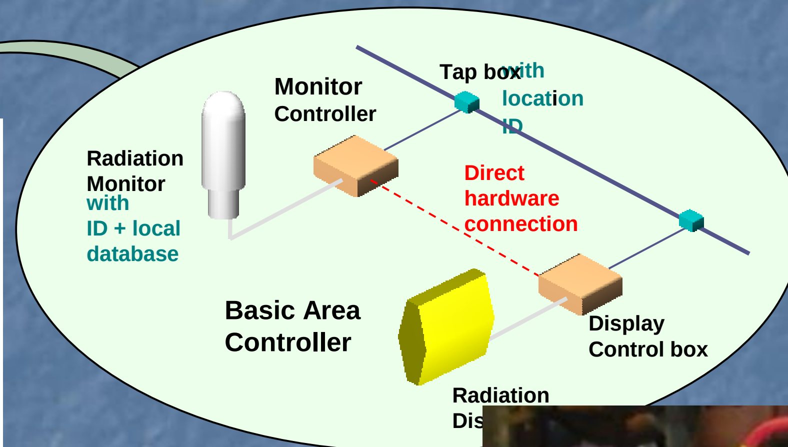
From design



to reality

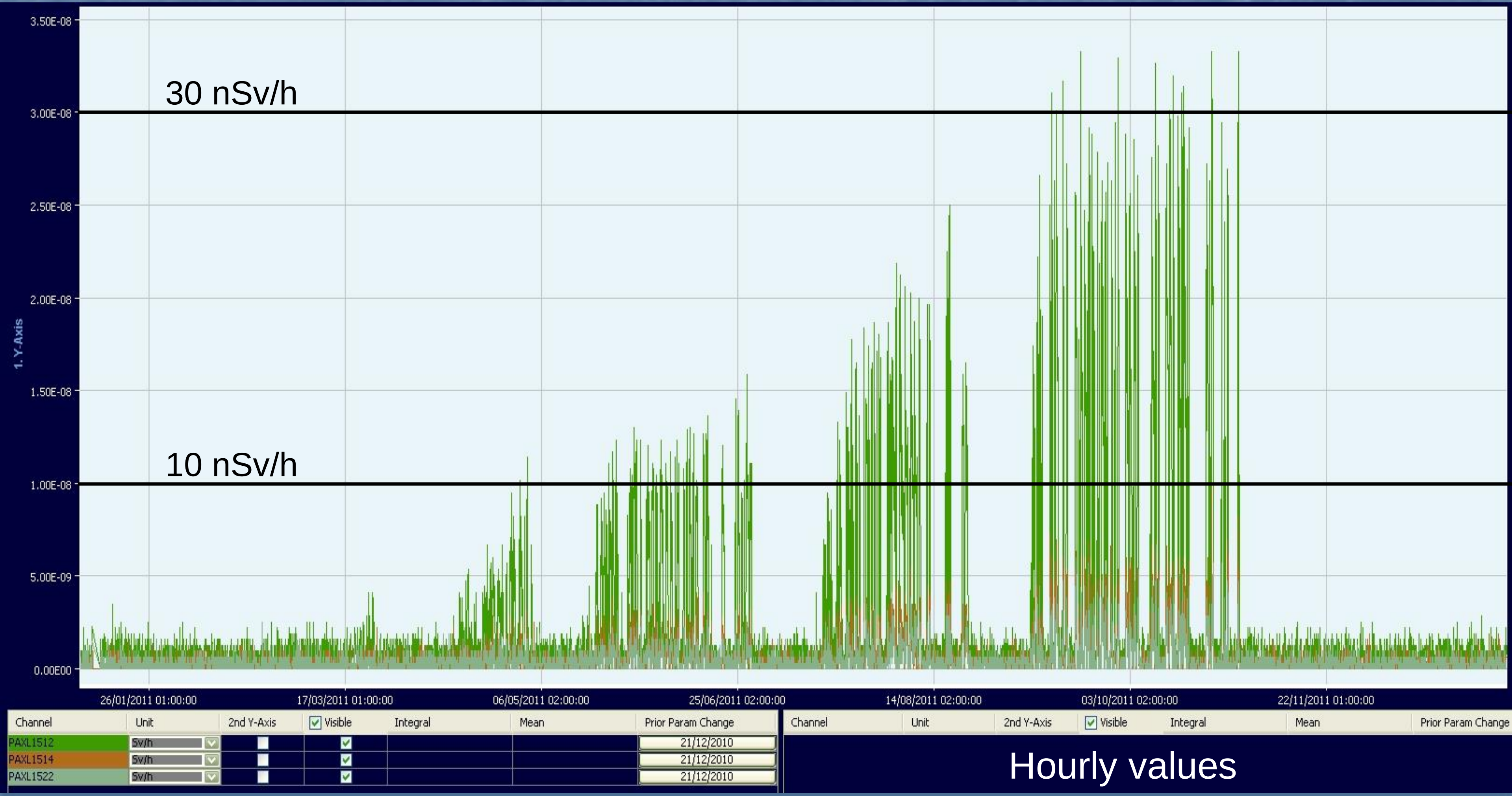
Radiation Monitoring



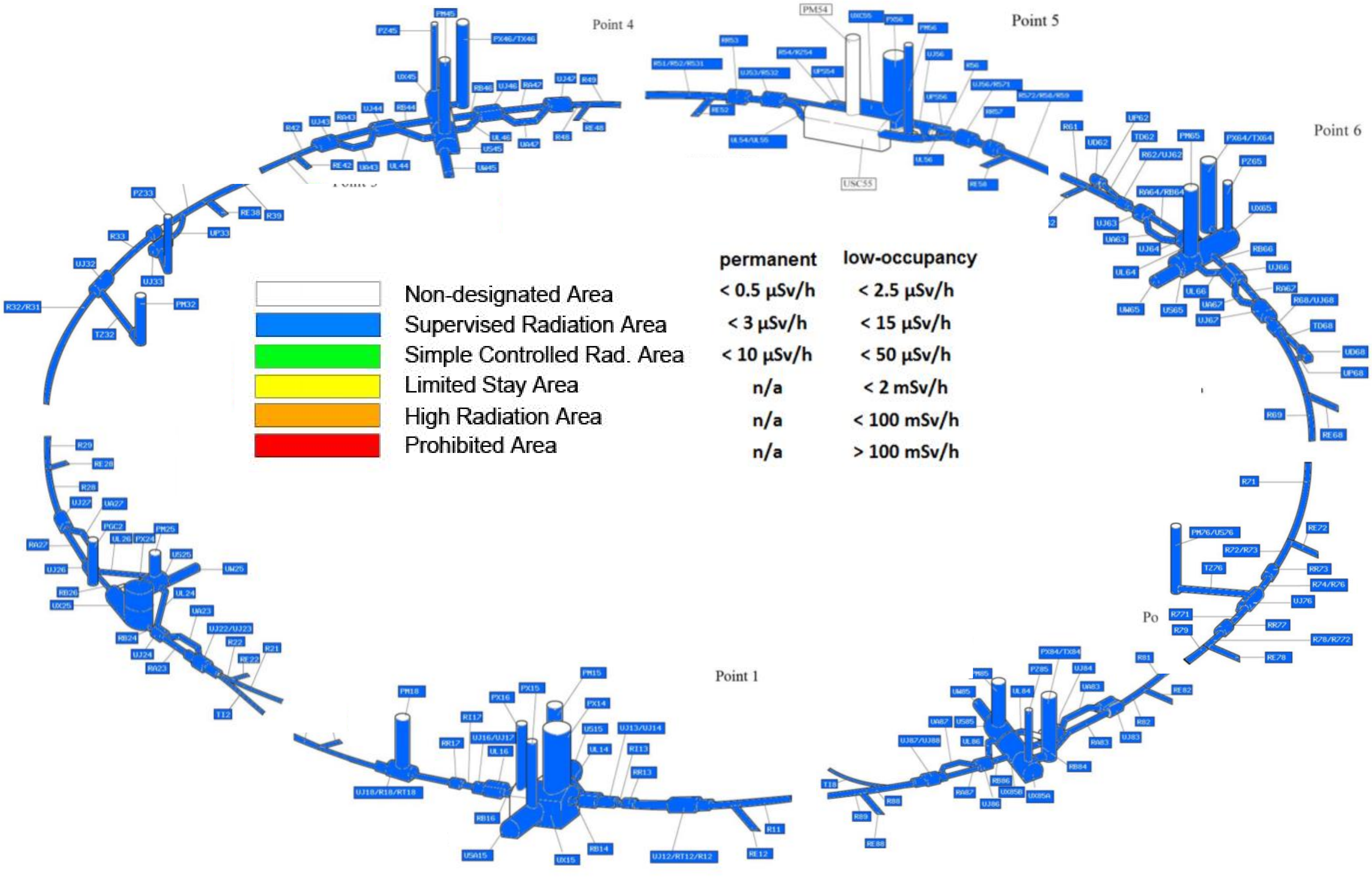


Instrumentation

Run 2011 – Seen by neutron monitors in USA15

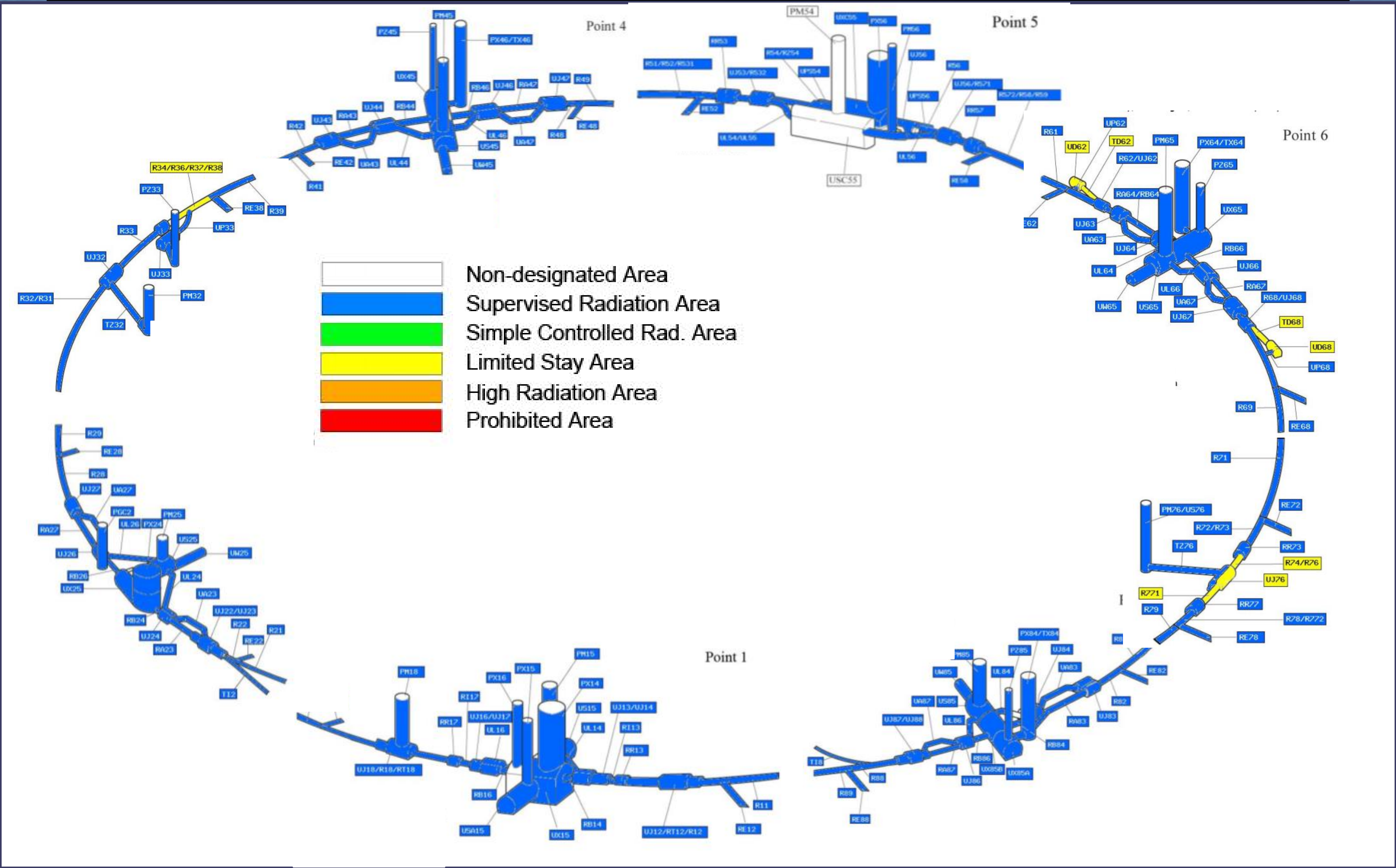


Area classification: LHC - 2010

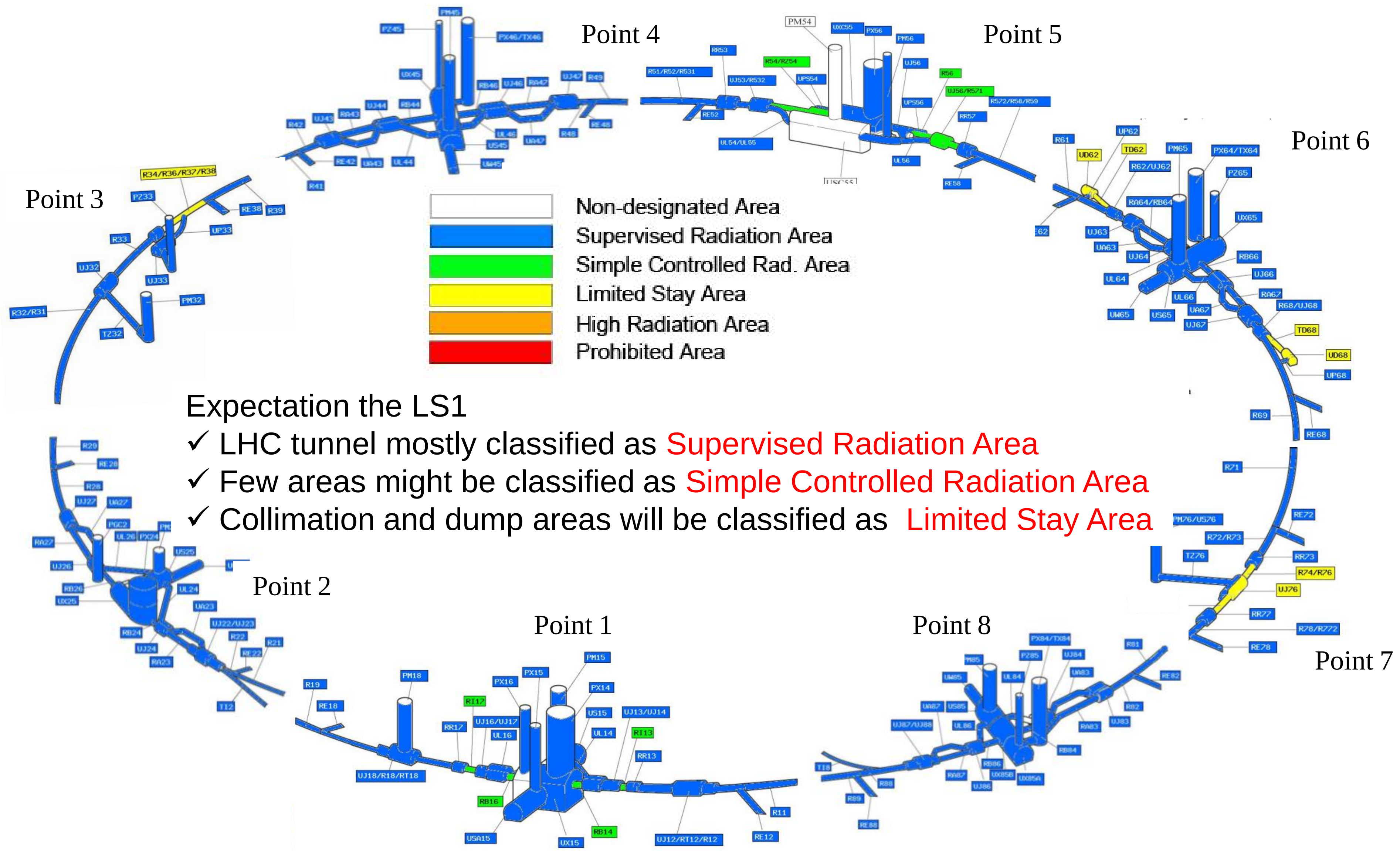


Area	permanent	low-occupancy
Non-designated Area	< 0.5 µSv/h	< 2.5 µSv/h
Supervised Radiation Area	< 3 µSv/h	< 15 µSv/h
Simple Controlled Rad. Area	< 10 µSv/h	< 50 µSv/h
Limited Stay Area	n/a	< 2 mSv/h
High Radiation Area	n/a	< 100 mSv/h
Prohibited Area	n/a	> 100 mSv/h

LHC - 2011


Point 1
Point 4
Point 5
Point 6
Non-designated Area
Supervised Radiation Area
Simple Controlled Rad. Area
Limited Stay Area
High Radiation Area
Prohibited Area

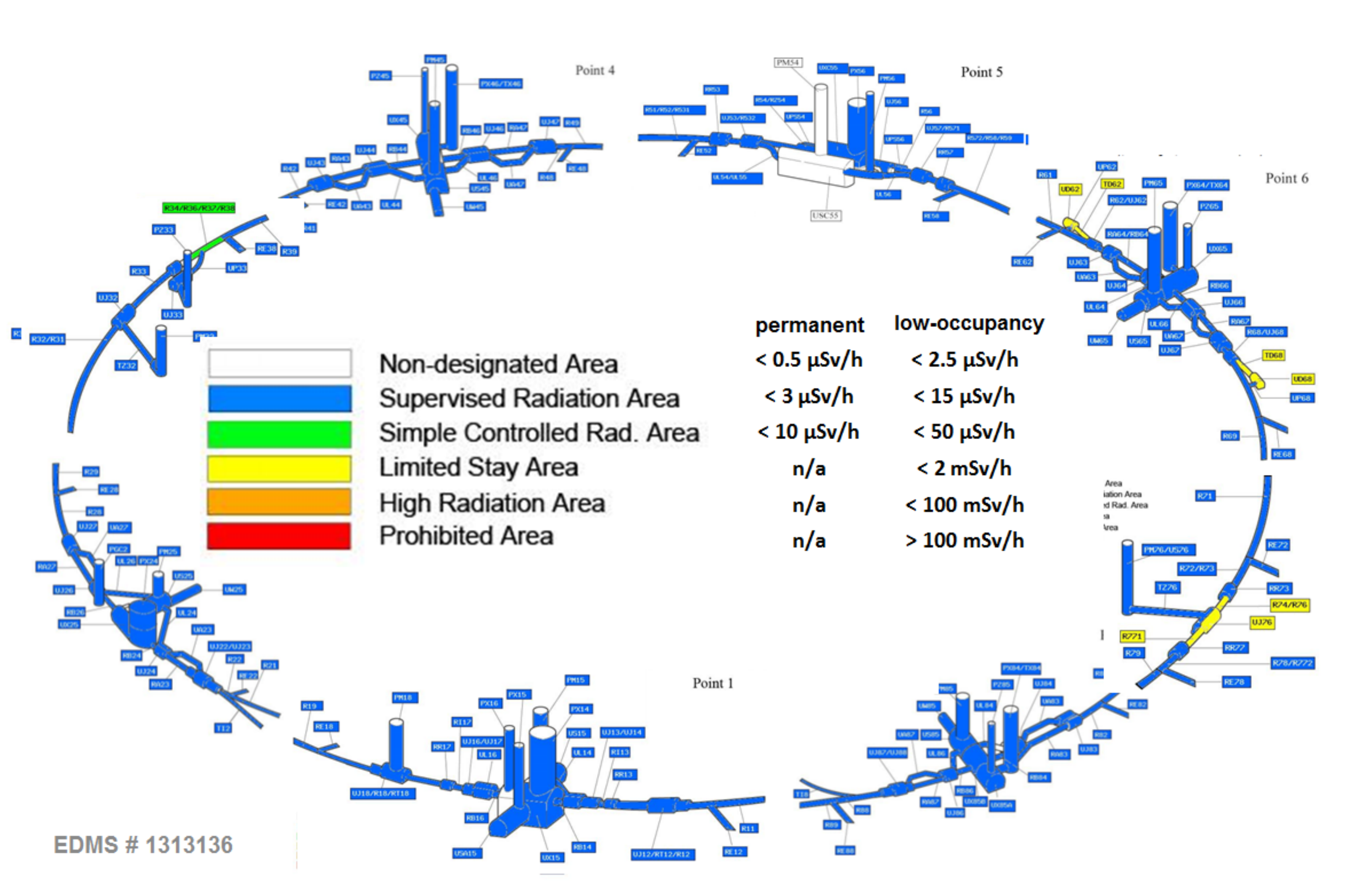
LHC - 2012



Expectation the LS1

- ✓ LHC tunnel mostly classified as Supervised Radiation Area
- ✓ Few areas might be classified as Simple Controlled Radiation Area
- ✓ Collimation and dump areas will be classified as Limited Stay Area

LHC during LS1



Radioactive waste: treatment and elimination

Waste received

Analyzed

Conditioned

Eliminated to final repository

ALARA at CERN

1 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 :

	100 µSv	1 mSv
niveau I	niveau II	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 :

	500 µSv	5 mSv
niveau I	niveau II	niveau III

CRITÈRE DE DÉBIT DE DOSE

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

	$50\ \mu Sv{\cdot}h^{-1}$	$2\ mSv{\cdot}h^{-1}$
niveau I	niveau II	niveau III

CRITÈRE DE CONTAMINATION ATMOSPHÉRIQUE

Activité aérienne spécifique CA :

	5 CA	200 CA
niveau I	niveau II	niveau III

CRITÈRE DE CONTAMINATION SURFACIQUE

Activité surfacique spécifique CA :

	10 CS	100 CS
niveau I	niveau II	niveau III

ALARA procedure – 3 Levels:

I Optimisation

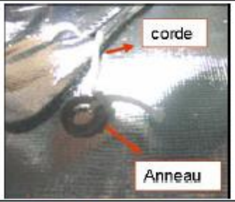
II Optimisation, documentation

III Optimisation, documentation, ALARA Committee

Includes risk analysis

ALARA

- Mock-up training
- Procedures
- Approval by "stakeholders" – radiation protection incl.
- Lessons learned

	technicien aidera à soutenir la manchette pour la déplacer sur le coté • il faut 3 personnes pour cette opération		
5	• Protéger l'entrée des interconnexions avec du film plastique avant de retirer les écrans thermiques • Mettre du scotch pour fixer le film de plastic ⚠ • Mettre du film plastique des deux cotes de l'interconnexion		8' (2 personnes)
6	• Enlever la première couche de matelas de MLI ⚠ • Mettre des gants blancs pour réaliser cette opération (protéger le matelas MLI)		3' (2 personnes)
7	• Attacher un petit anneau à la fin de la corde qui traverse le matelas MLI		1' (1 personne)
8	• Plier le matelas de MLI ⚠ • Mettre des gants blancs pour réaliser cette opération (protéger le matelas MLI)		3' (2 personnes)

ALARA example 1:

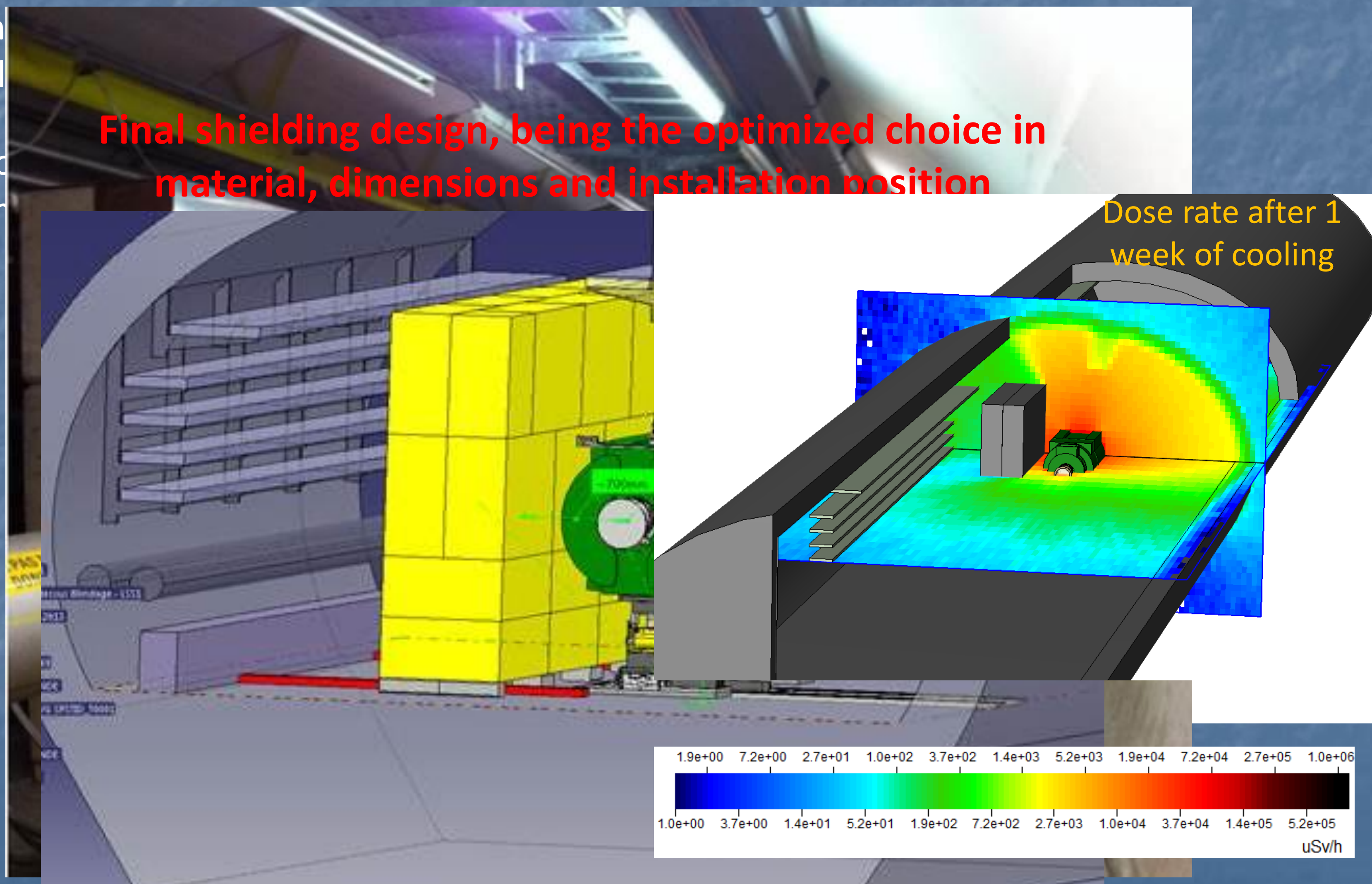
SPS-LSS1 cabling and dump shielding wall design (ALARA III)

Cable exchange campaign in SPS-LSS1

- The LSS1 area is the most radioactive zone in the SPS
- Any work has to be fully optimized allowing to reduce dose to personnel to a bare minimum
- Removal of highly radioactive equipment prior the 22 weeks lasting cable exchange campaign
  ➔ average dose rate in the LSS1 ar… uced by a factor of 3.2
- Remote handling with robots
- Special equipment allowing for dose …ization

SPS beam dump shielding

- The former shielding located beside the TIDV dump caused significant problems due to its high activation and contamination levels.
- In th
  shiel
- Ten c
  optir



ALARA example 2:

Dismantling of former SPS target area

Job and Dose Planning

For all working steps i, the $time_i$ required and the given dose $rate_i$ need to be assessed beforehand.

$$\text{Total dose} = \sum_i Dose\ rate_i \times Time_i$$

Dose rates based on measurements and simulations

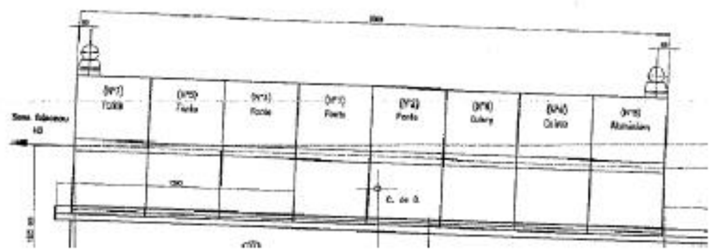
Example: Work in a former SPS target area

Dose estimate based on:

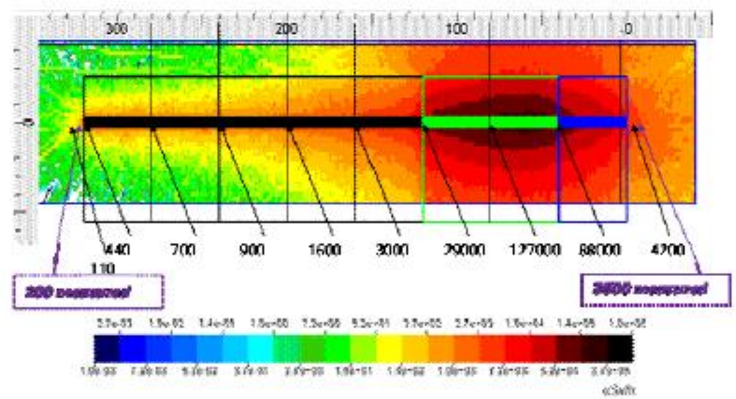
-Real measurements (accessible areas)

-Fluka calculation

SURVEY TCX shielding 17/12/09
Dose rates [µSv/h] AD6 @ 10cm et 1m from the blocks



FLUKA - TCX Dose rate estimates



Ambient dose rate along the hole

Removal of highly radioactive blocks being located in a former SPS target area

110

ALARA example 3:

Repair work of CNGS horn and reflector

CNGS Horn und Reflector Repair

level II
→ optimisation and documentation
→ 1.6 mSv collective dose

Monte-Carlo simulations as a tool for detector response evaluation

Motivation

High-energy hadron accelerator – LHC, SPS ...

↓

High-energy mixed radiation fields

↓

Radiation detectors must be characterized for these fields

↓

Measured detector counts ←→ desired quantity (Sv, Gy)

Detector response evaluation with Monte Carlo simulation tools

Simulation of irradiation situation + simulation response of detector

Simulation provides knowledge of particle fields and the response of the chamber to this radiation field

↓ ↓

Field calibration factor

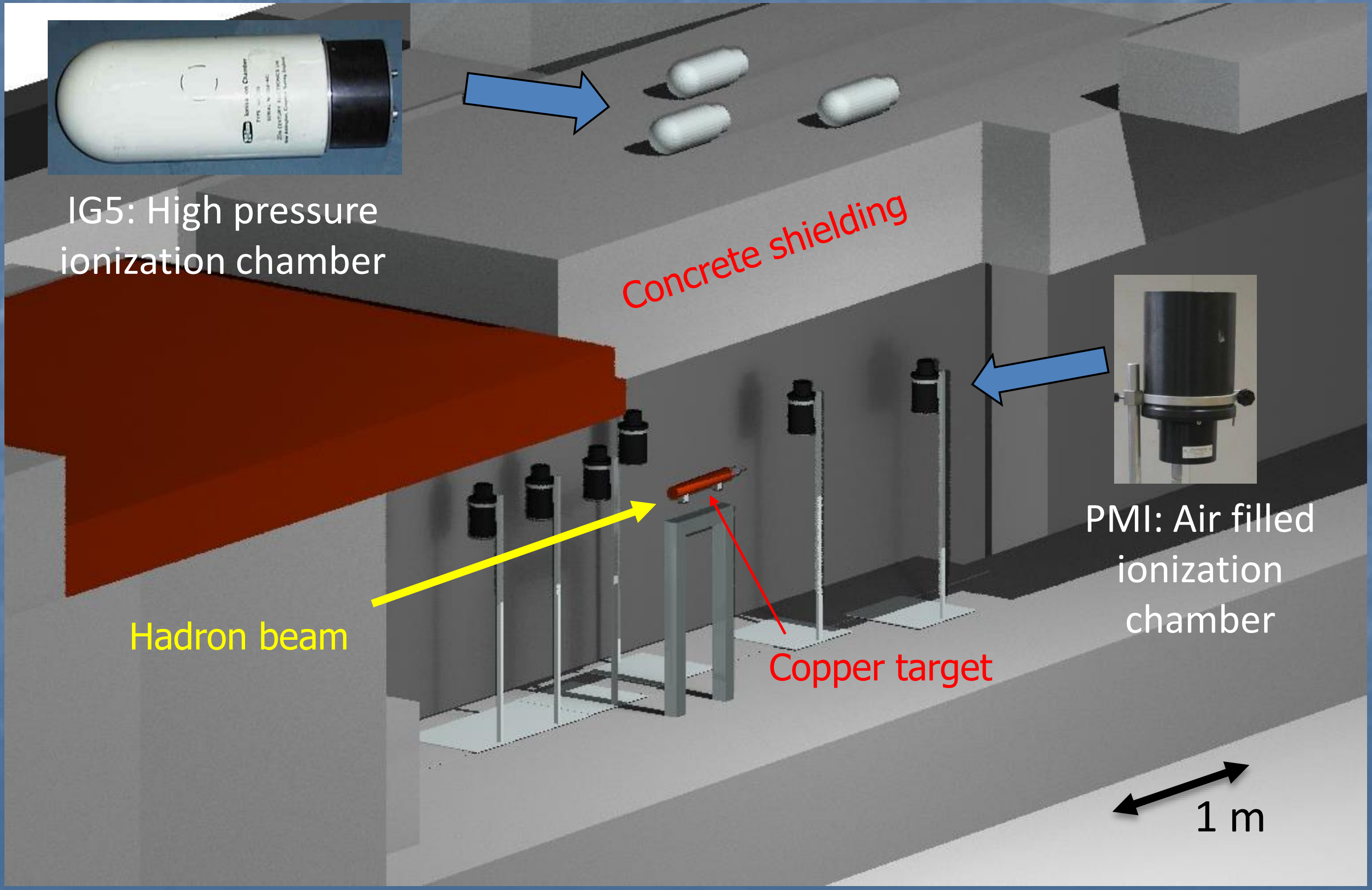
The following question remains: Does the simulation also reflect the reality?

Comparison between simulation and measurement
= Benchmarking of simulation

Benchmark experiments in the CERF radiation field to test reliability of Monte Carlo program FLUKA

Two ionization chamber types were irradiated with secondary particles produced in high-energy hadronic interactions (like beam loss in accelerator)

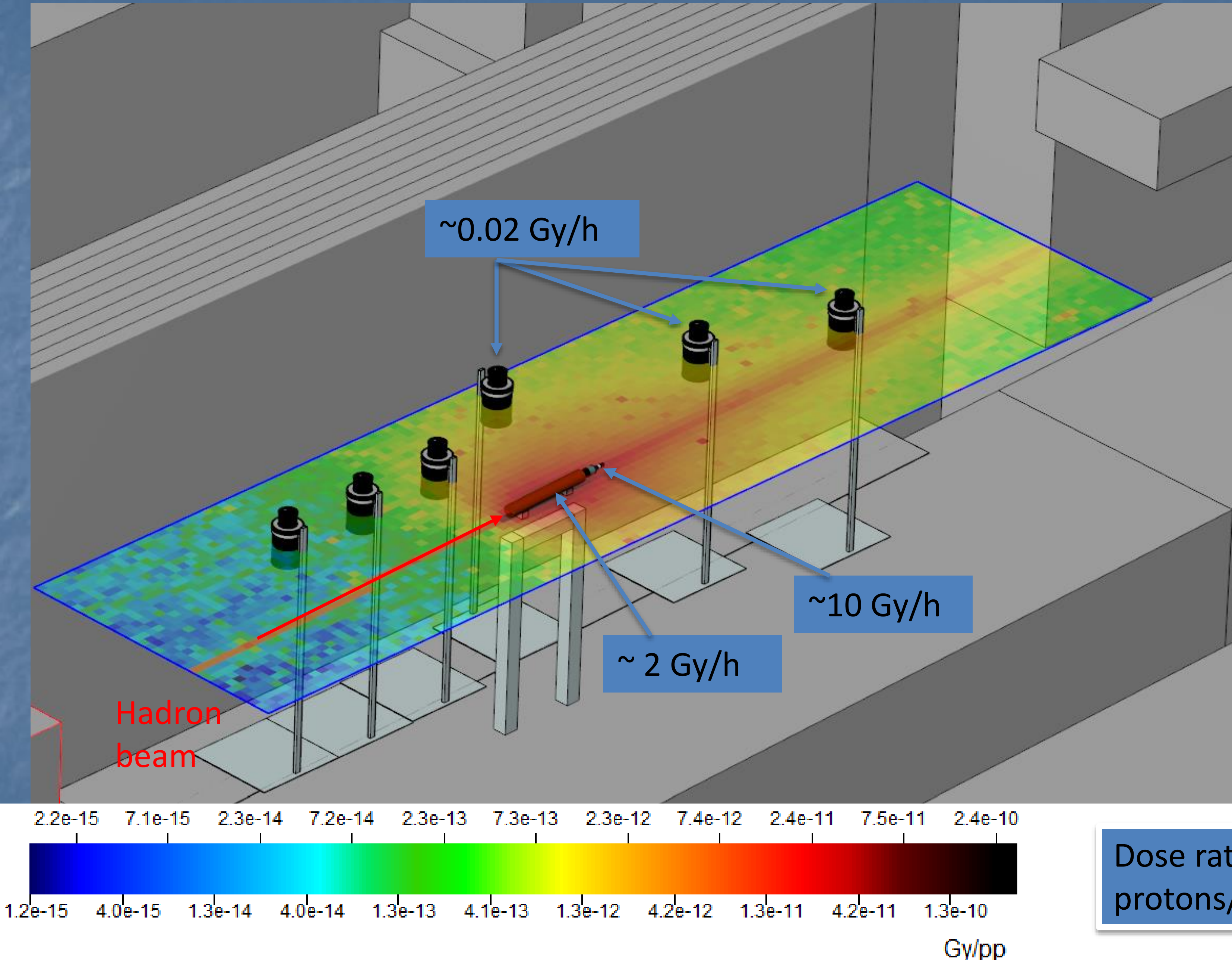
- PMI chambers: exposed to high-energy particles occurring close to a target
- IG5 chambers: exposed to the same radiation field, however attenuated by 80 cm of concrete.



What is CERF?
An irradiation facility at CERN providing high-energy mixed radiation fields

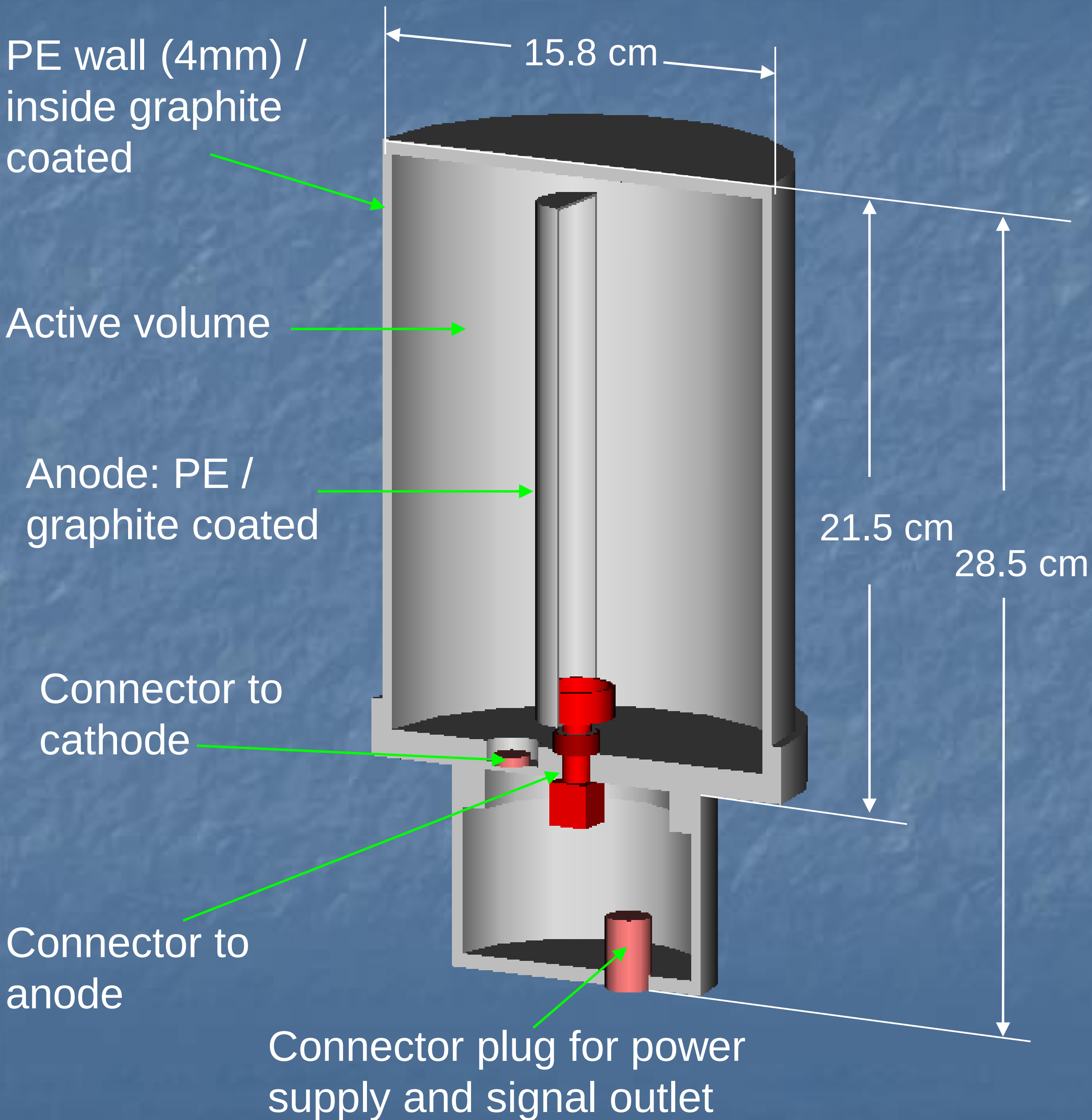
How? ➔ A mixed hadron beam (in this setup 120 GeV/c) is intercepted by a copper target ➔ high-energy mixed radiation field produced by EM and hadronic cascades

Detector benchmarking at the CERF facility:
Copper target irradiated with a mixed hadron beam at 120 GeV/c



Dose rate at 1E8 protons/spill

Simulation picture of the PMI chamber



Wall composition: C-H_2

Filling gas: air atmospheric pressure

Active volume: 3l

Working voltage: ~460 V

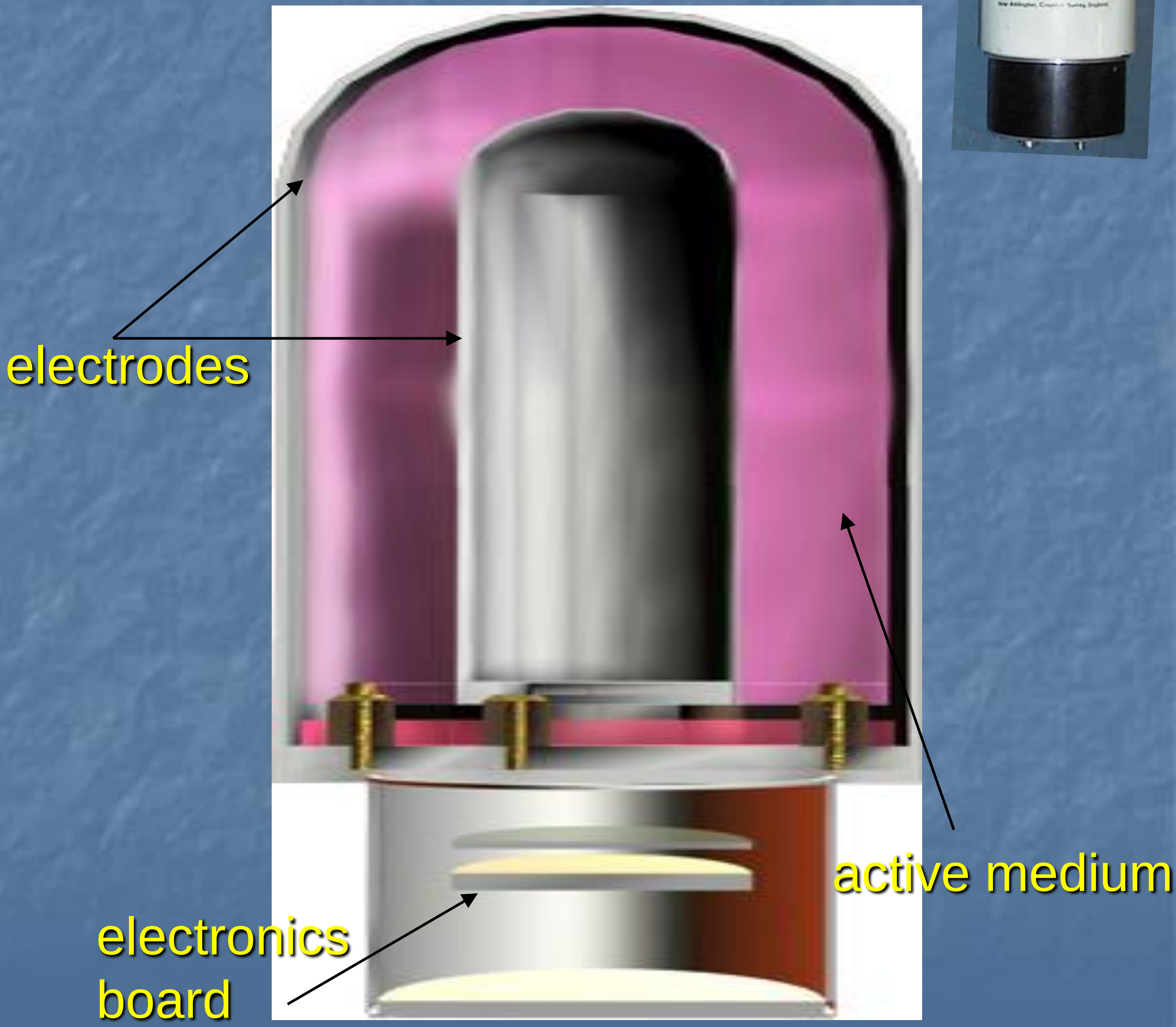
IG5 - Geometry

Properties

2 types (Ar or H filled)
5,2 l active volume
pressurized at 20 bar
1200 V high-voltage

Dimensions

diameter – 18.33 cm
height – 45.6 cm



2 ways to calculate detector response

Way 1 (indirect approach)

Used to calculate IG5 response

A) Calculate detector fluence response [C cm^2]

B) Calculate particle fluence spectra [cm^{-2}]

C) Combination of A and B

Simulated counting rate of detector

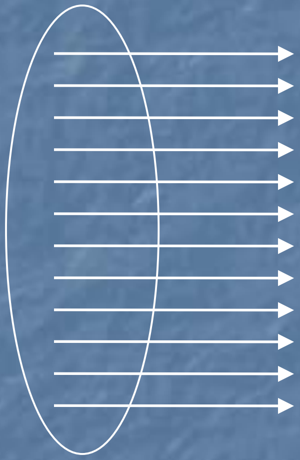
A) Simulation of Response Fuctions

Circular parallel beam

Energy deposition in active volume

Calculate number of ion pairs created

Charge created within active volume

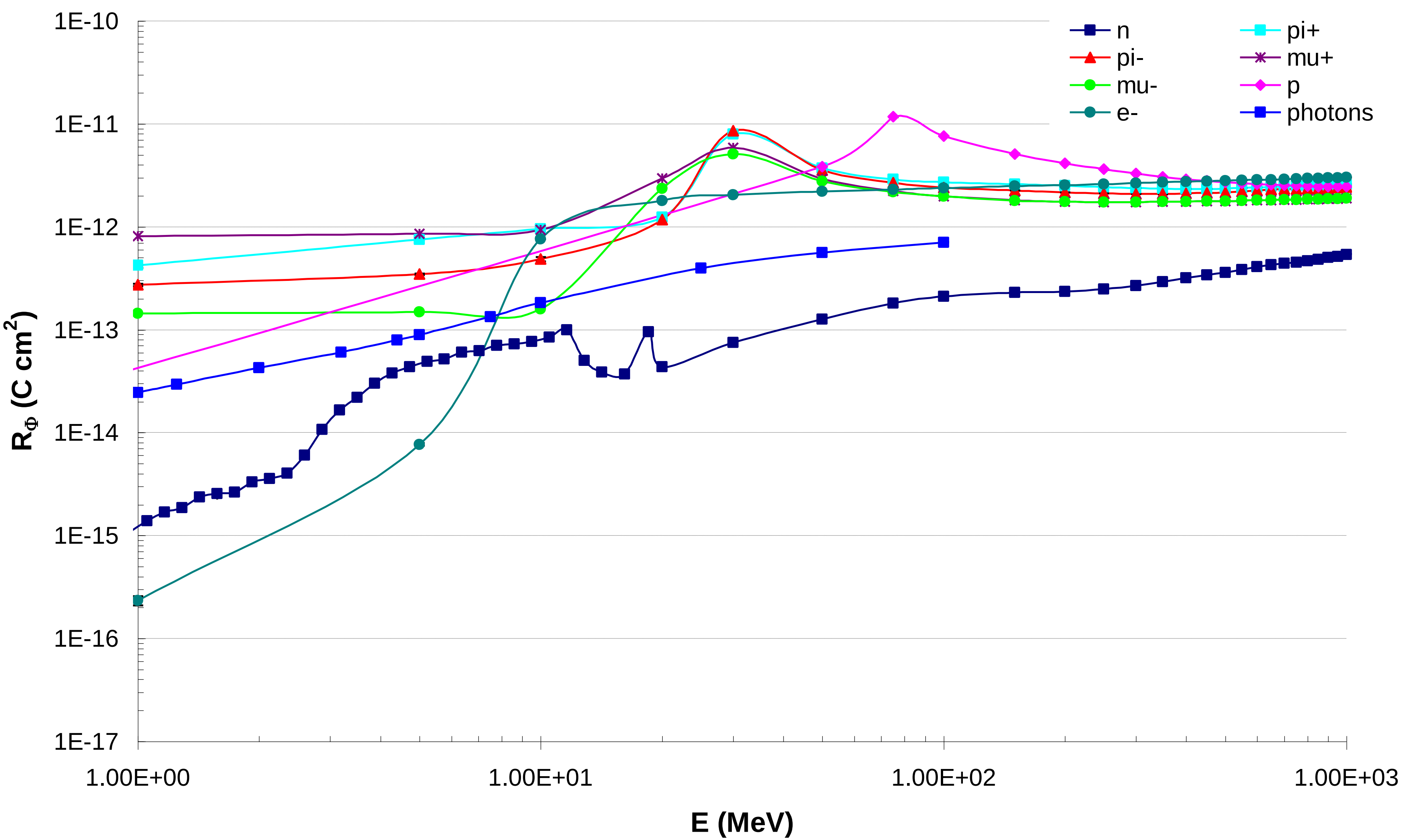


Conversion factors

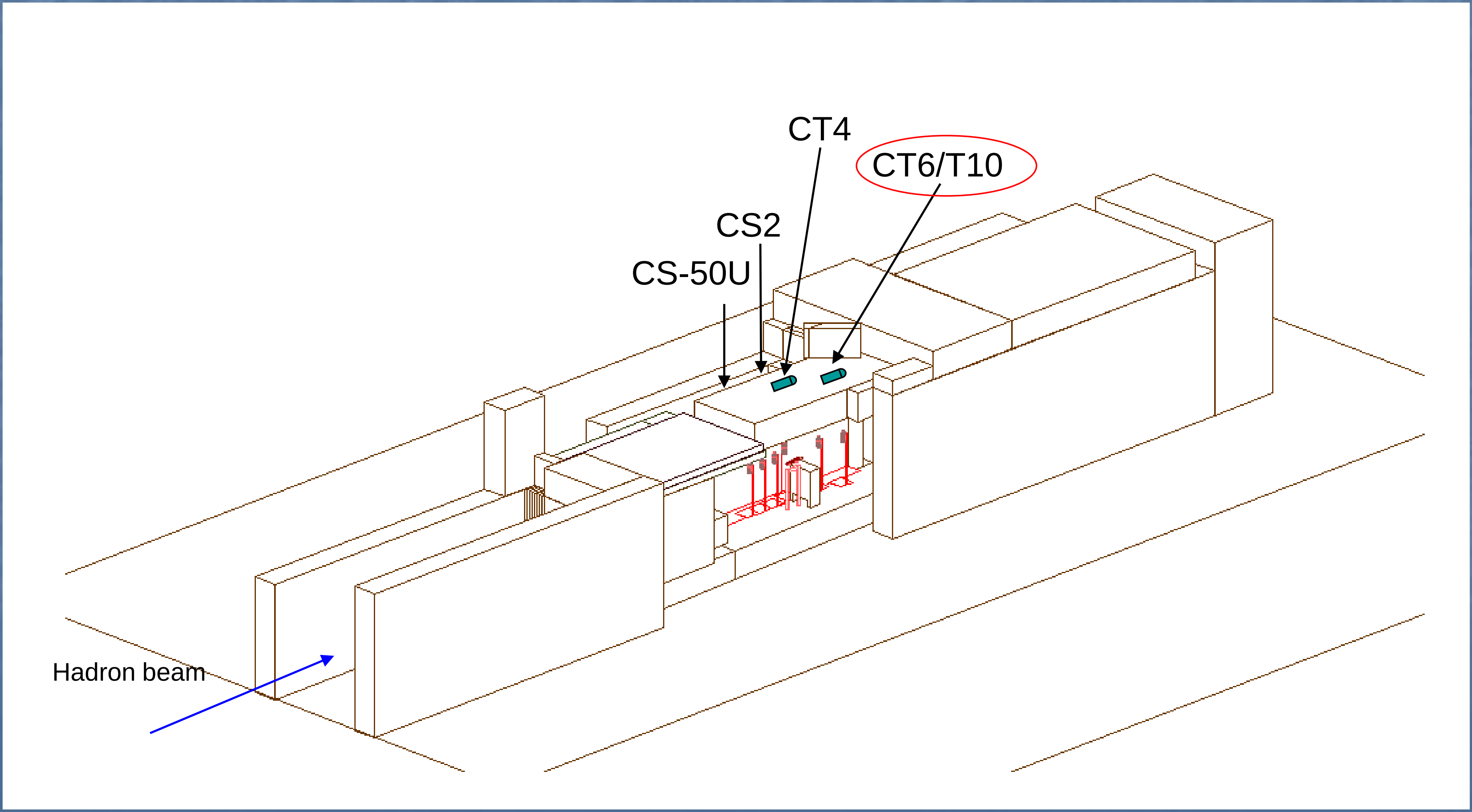
Response R_{Φ} [C cm^2]

Response R_{Ka} [C/Gy], R_{H*10} [C/Sv]

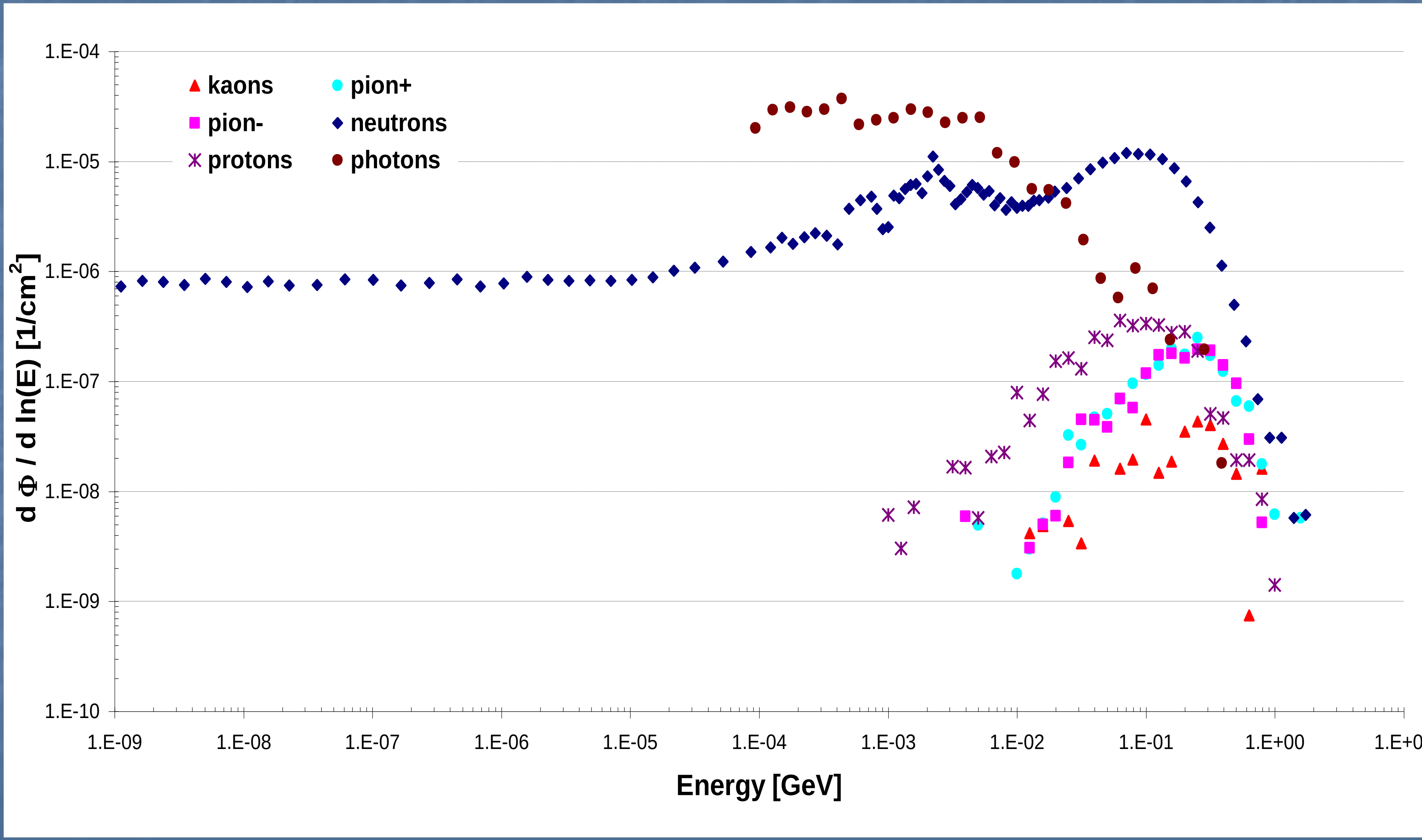
Response to var. particles (R_Φ for Ar)



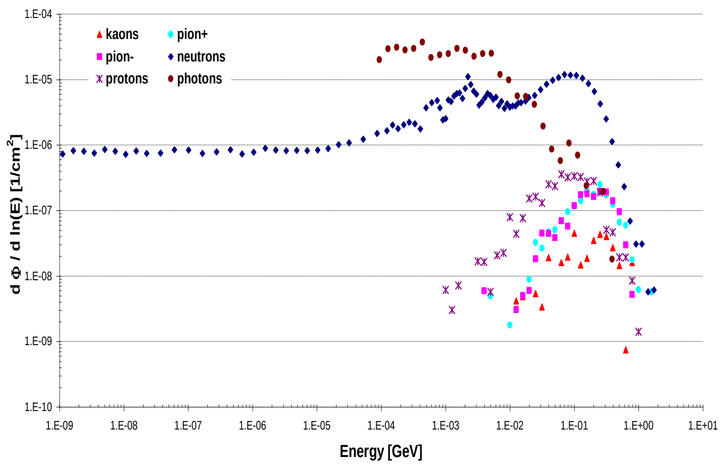
B) Calculation of fluence in the range of the measurement positions



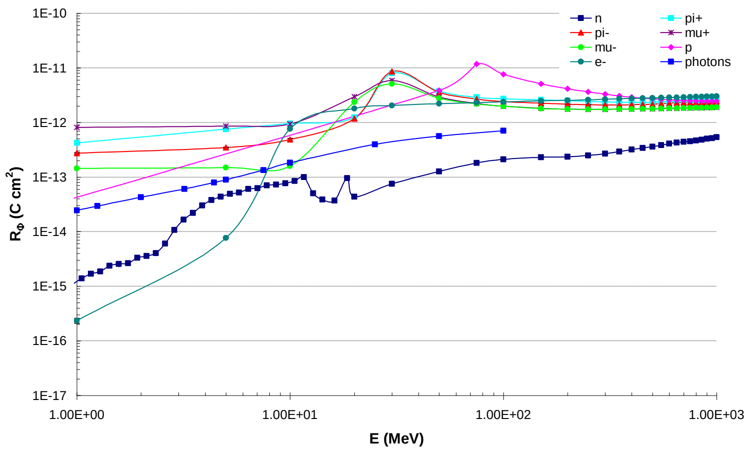
B) Particle fluence at detector position (CT6/T10)



C) Combination of A and B



X



$$\text{Charge} = \sum_{particletype} \int dE \, \frac{d\phi}{dE} R_\phi(E)$$

Charge leads to counting rate of detector

Convolution between fluence and response functions (CT6/T10)

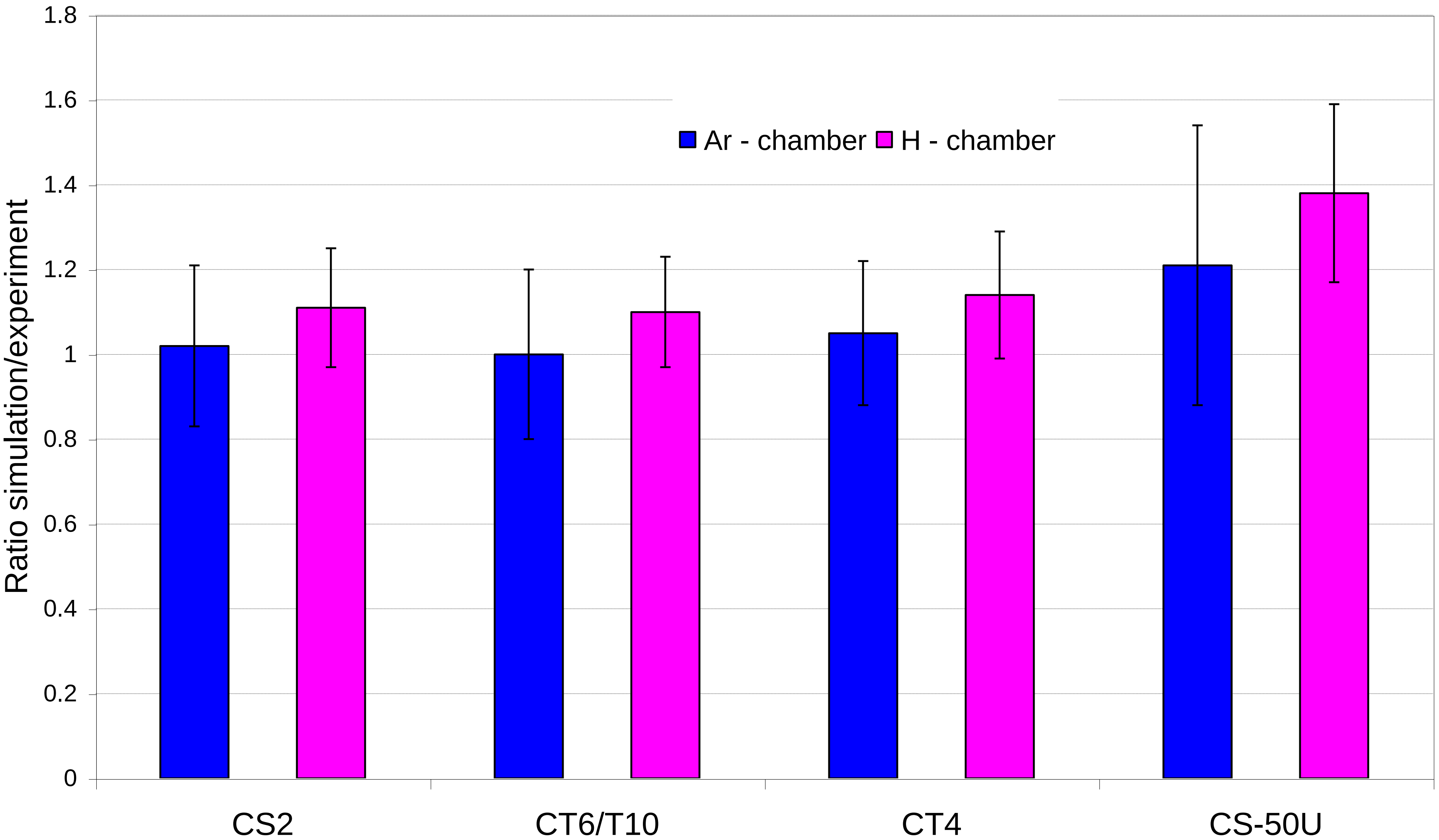
Total contribution to response (Ar)

Neutron	Proton	π	γ
$(30 \pm 1)\%$	$(24 \pm 3)\%$	$(11 \pm 1)\%$	$(35 \pm 4)\%$

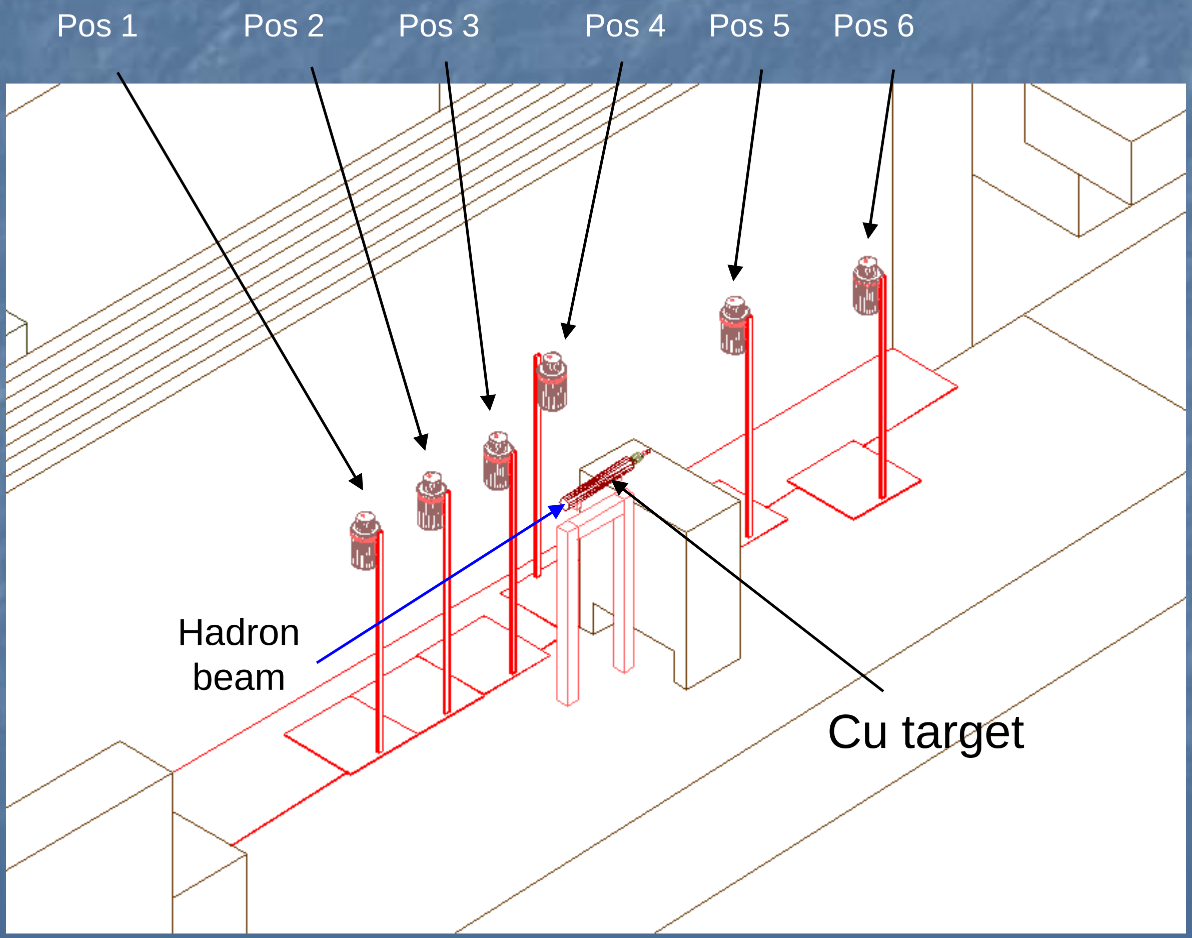
Total contribution to response (H)

Neutron	Proton	π	γ
$(59 \pm 3)\%$	$(17 \pm 2)\%$	$(4 \pm 1)\%$	$(20 \pm 2)\%$

Ratio between simulation and experiment



Experimental set-up in the CERF target area



Beam parameters:

Momentum:

120 GeV/c

Intensity:

$9*10^7$ hadrons/ SPS extraction (16.8 s with 4.8 s continuous beam)

Beam composition:

60.7 % π^+

34.8 % protons

4.5 % K^+

Way 2 (direct approach)

Used to calculate PMI response

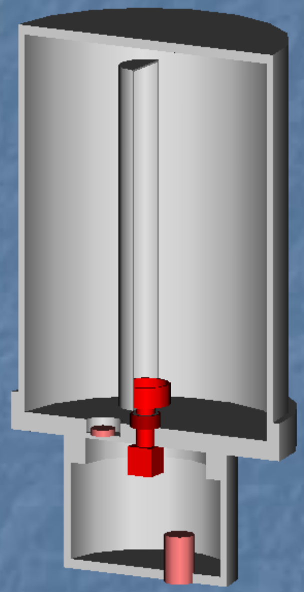
FLUKA calculation of the whole particle cascade in the experimental setup

Within this simulation calculation of energy deposition in active volume of chamber

"Energy to ion$^+$/e$^-$" conversion factor leads to number of produced ion$^+$/e$^-$ pairs.

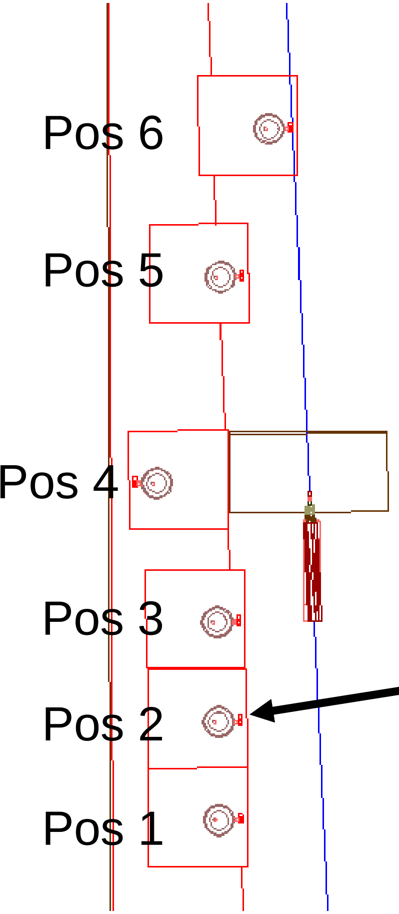
Conversion of number of ion$^+$/e$^-$ pairs into pC.

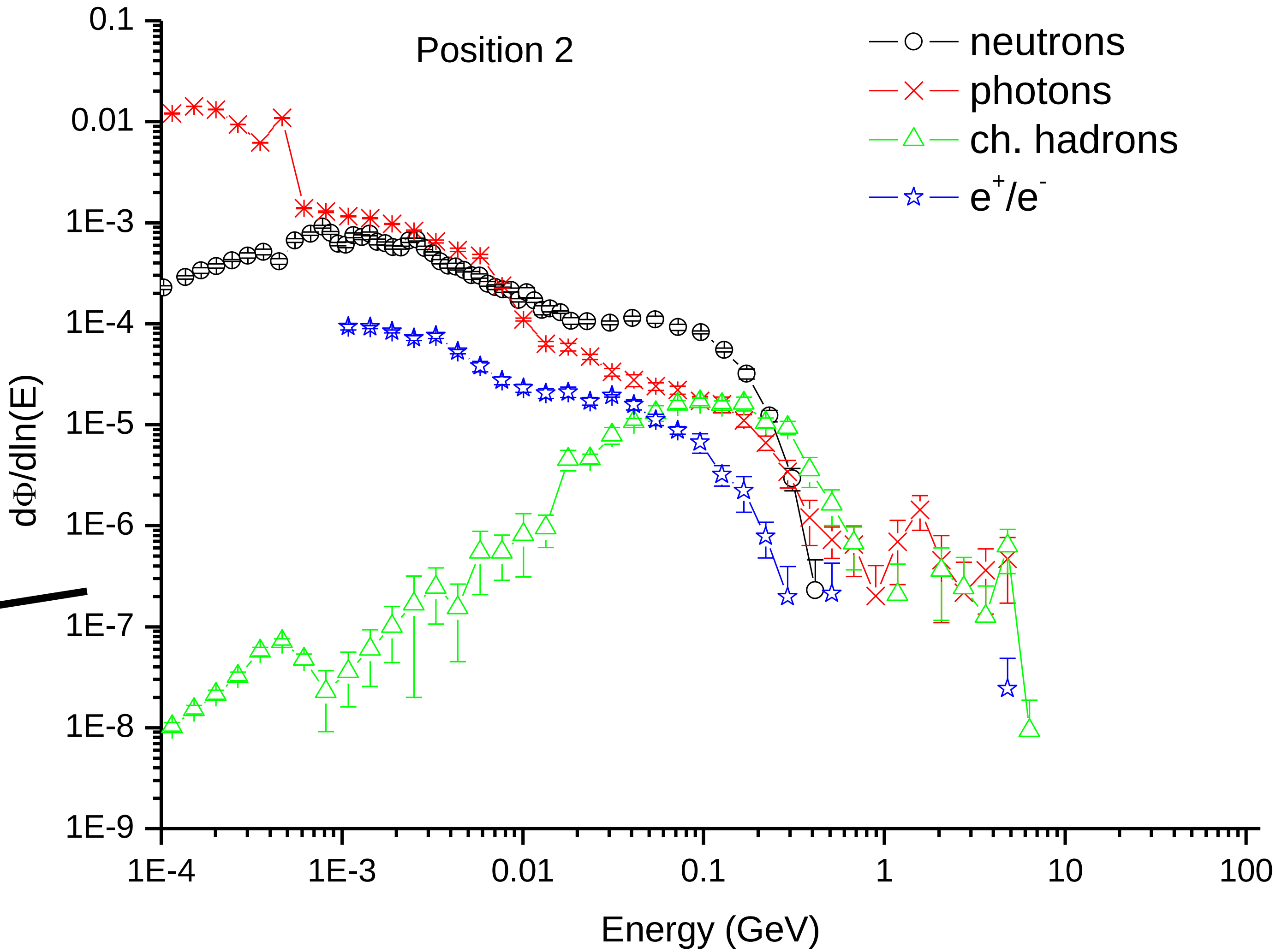
One pC corresponds with one PMI counts.



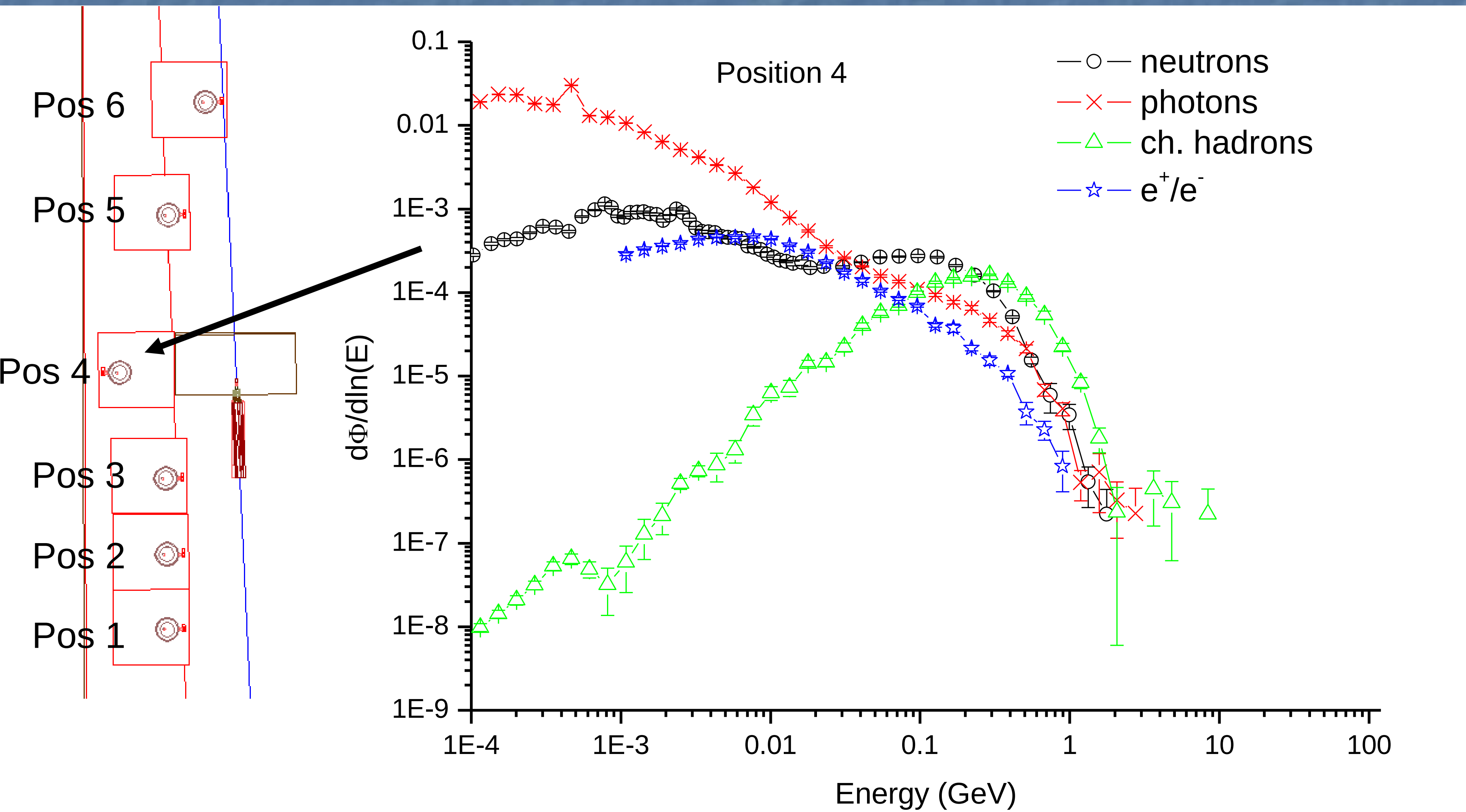
Analysis of the fluence reaching the various detector positions

Particle fluence at detector position 2

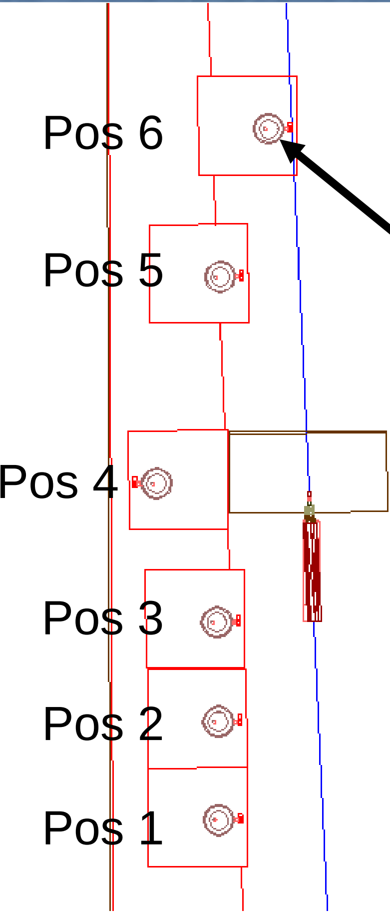


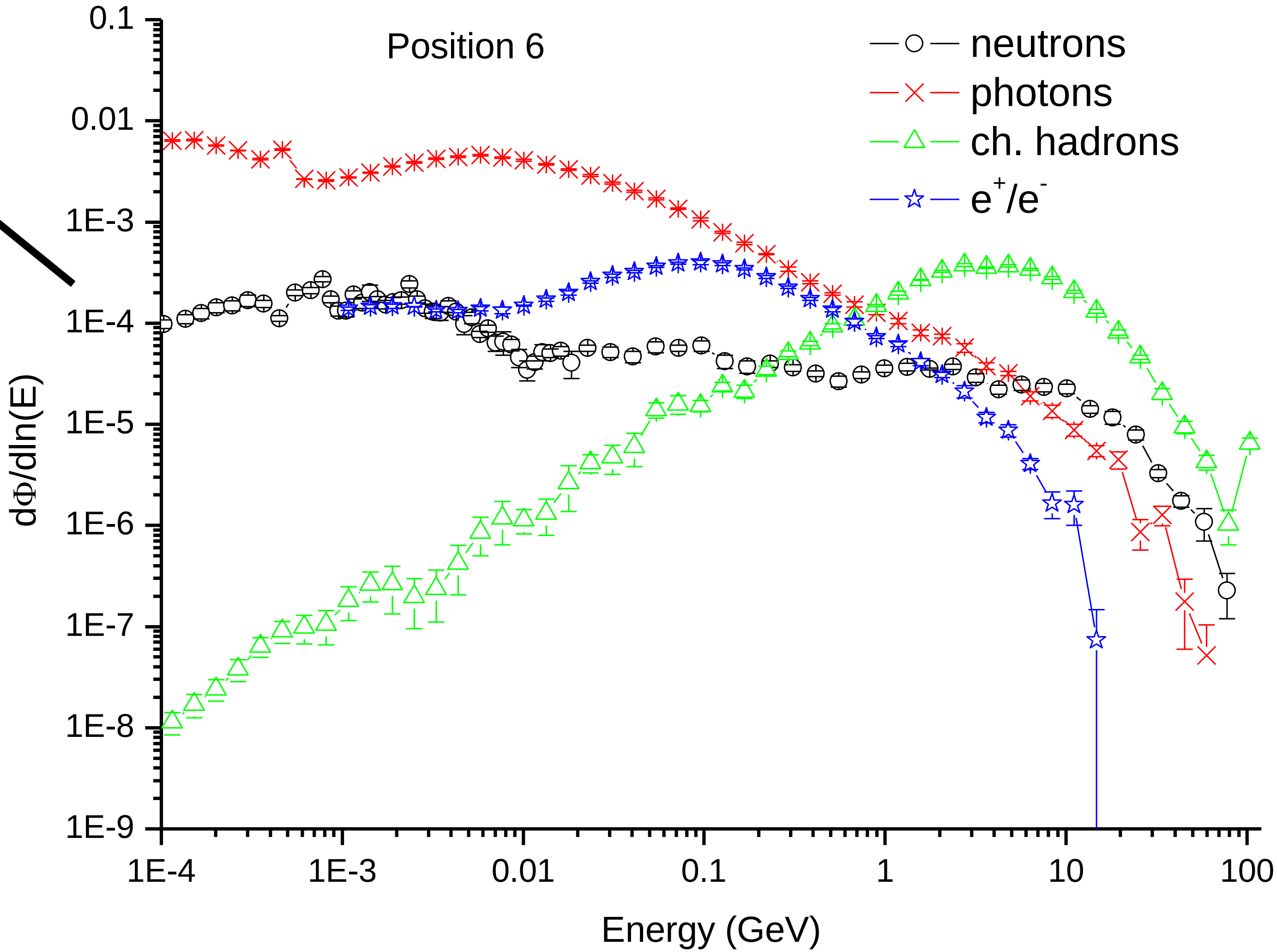


Particle fluence at detector position 4

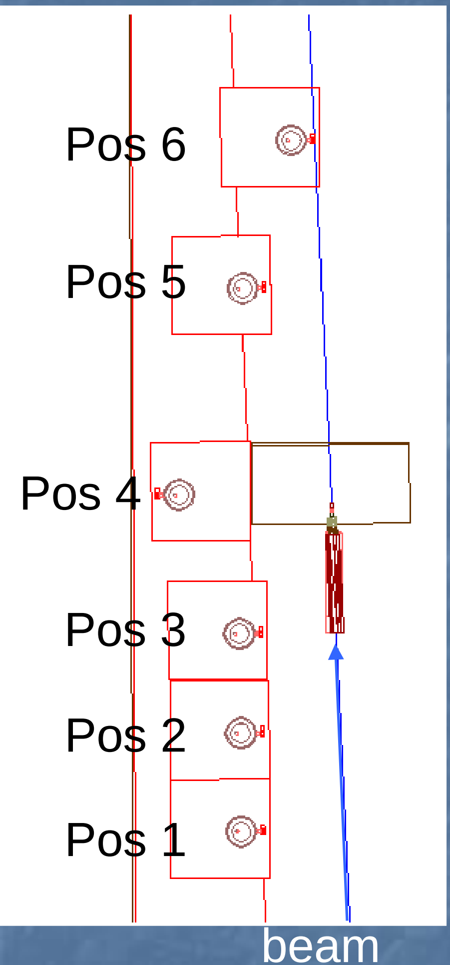


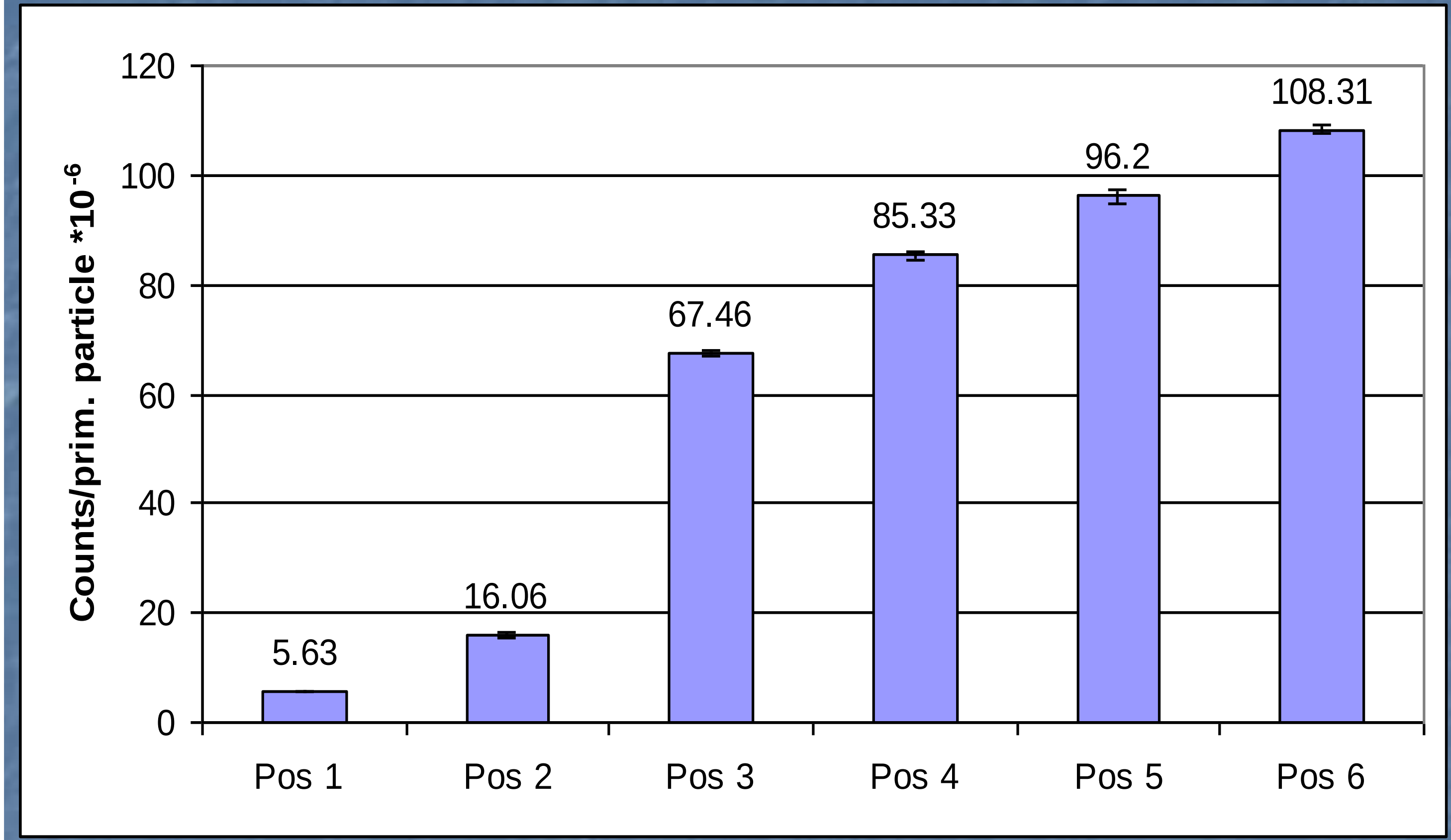
Particle fluence at detector position 6



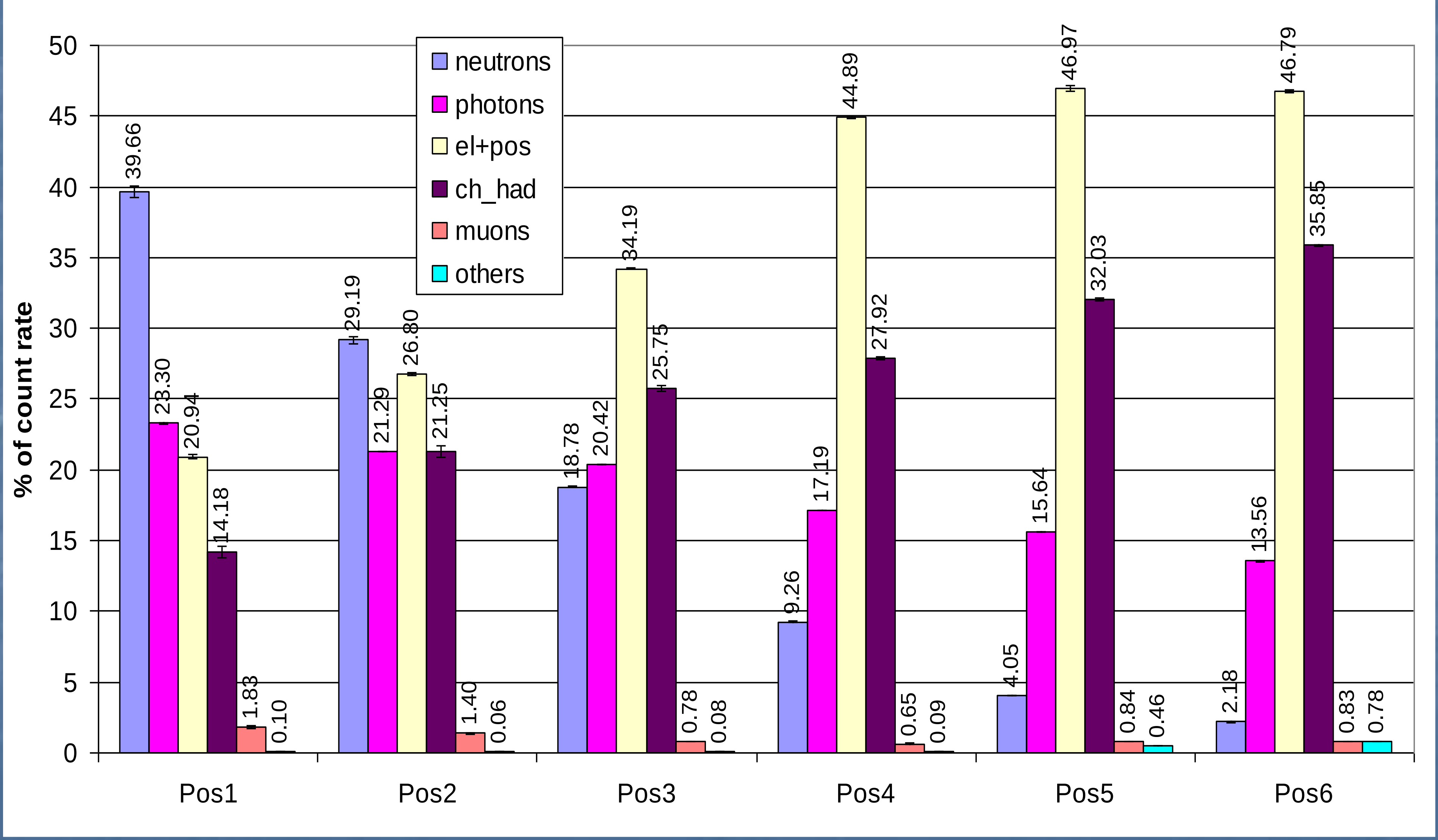


Simulation result of the counting rate





Influence of the different particle types (%) to the final counting rate of the detectors at the various positions



Comparison between simulation and measurement results

	Simulation Counts/ prim. part. $*10^{-6}$	Simulation error $*10^{-6}$	Measurement Counts/ prim. part. $*10^{-6}$	Measurement error $*10^{-6}$	Simulation/ Measurement	Error
Pos 1	**5,63**	**± 0,12**	**5,64**	**± 0,56**	**0.998**	**± 0.102**
Pos 2	**16,06**	**± 0,44**	**15,58**	**± 1,56**	**1.031**	**± 0.107**
Pos 3	**67,46**	**± 0,73**	**67,25**	**± 6,93**	**1.003**	**± 0.104**
Pos 4	**85,33**	**± 0,64**	**79,00**	**± 8,67**	**1.080**	**± 0.119**
Pos 5	**96,20**	**± 1,26**	**89,39**	**± 9,47**	**1.076**	**± 0.115**
Pos 6	**108,31**	**± 0,82**	**115,74**	**± 17,99**	**0.936**	**± 0.146**

Summary of MC based calibration

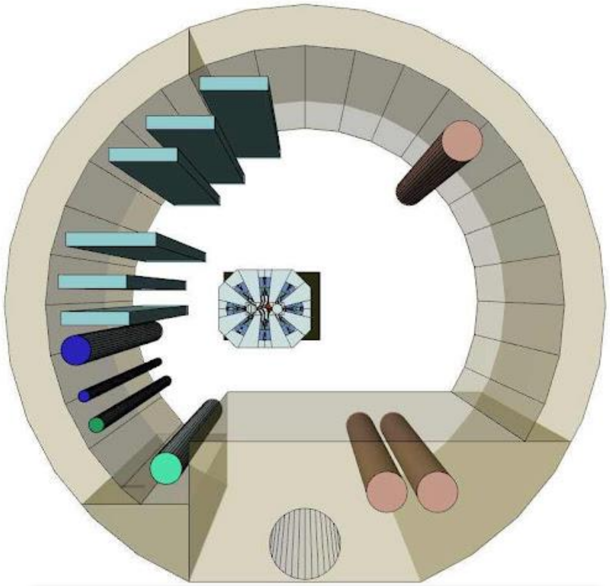
- ✓ FLUKA benchmarking experiments were performed at CERF
- ✓ Very good agreement between simulation and measurement results in the radiation field occuring at the CERF facility.
- ✓ The results prove that:
  - ✓ FLUKA calculates mixed high-energy radiation fields correctly.
  - ✓ FLUKA calculates detector response of ionisation chambers correctly.
- ✓ **FLUKA can be used to calculate a suitable field calibration factors for high-energy radiation fields occuring at CERN**


Merci Beaucoup !

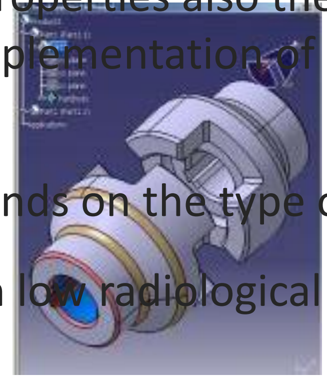
Backup slides

ActiWiz
Nuclide inventory optimization in accelerators

Motivation for optimization of nuclear inventories of materials placed in accelerators



- Beside other material properties also the radiological consequences of the implementation of a material have to be considered
- Level of activation depends on the type of the material
- Choosing materials with low radiological impact results in several benefits



Safety benefit	Operational benefit	End of life-cycle benefit
• Lower dose rates and committed doses	• Reduced downtime due to faster access • Less restrictions for manipulation & access	• Smaller amount and less critical radioactive waste • Smaller financial burden

Strategy to develop a tool allowing an optimization of nuclear inventories

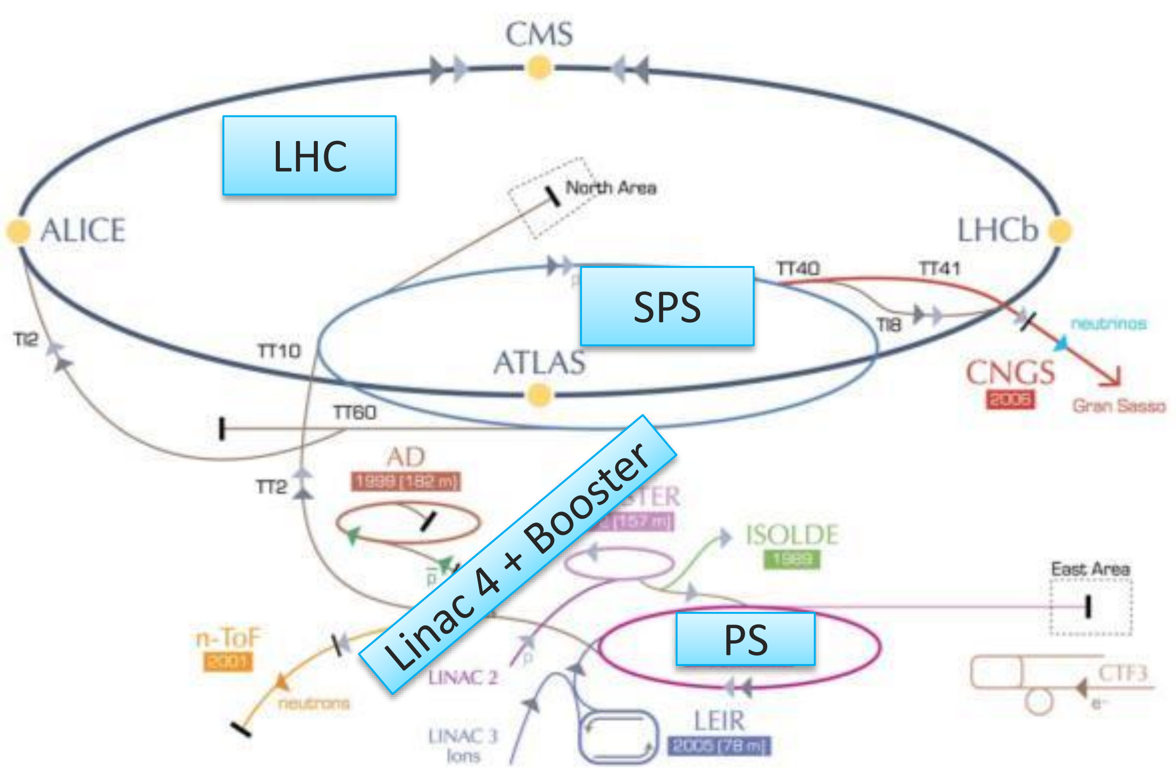
Categorization of radiation environments

Development of ActiWiz –
code assessing radiation risks, dominant nuclides etc., for arbitrary materials

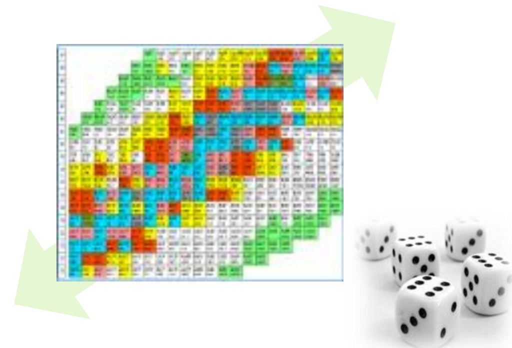
Radiological hazard catalogue for materials

Categorization of the radiation environments

FLUKA calculations of typical hadronic particle spectra (p, n, π^+, π^-) in CERN's accelerators



160 MeV (Linac4), 1.4 GeV (Booster), 14 GeV/c (PS), 400 GeV/c (SPS), 7 TeV (LHC)



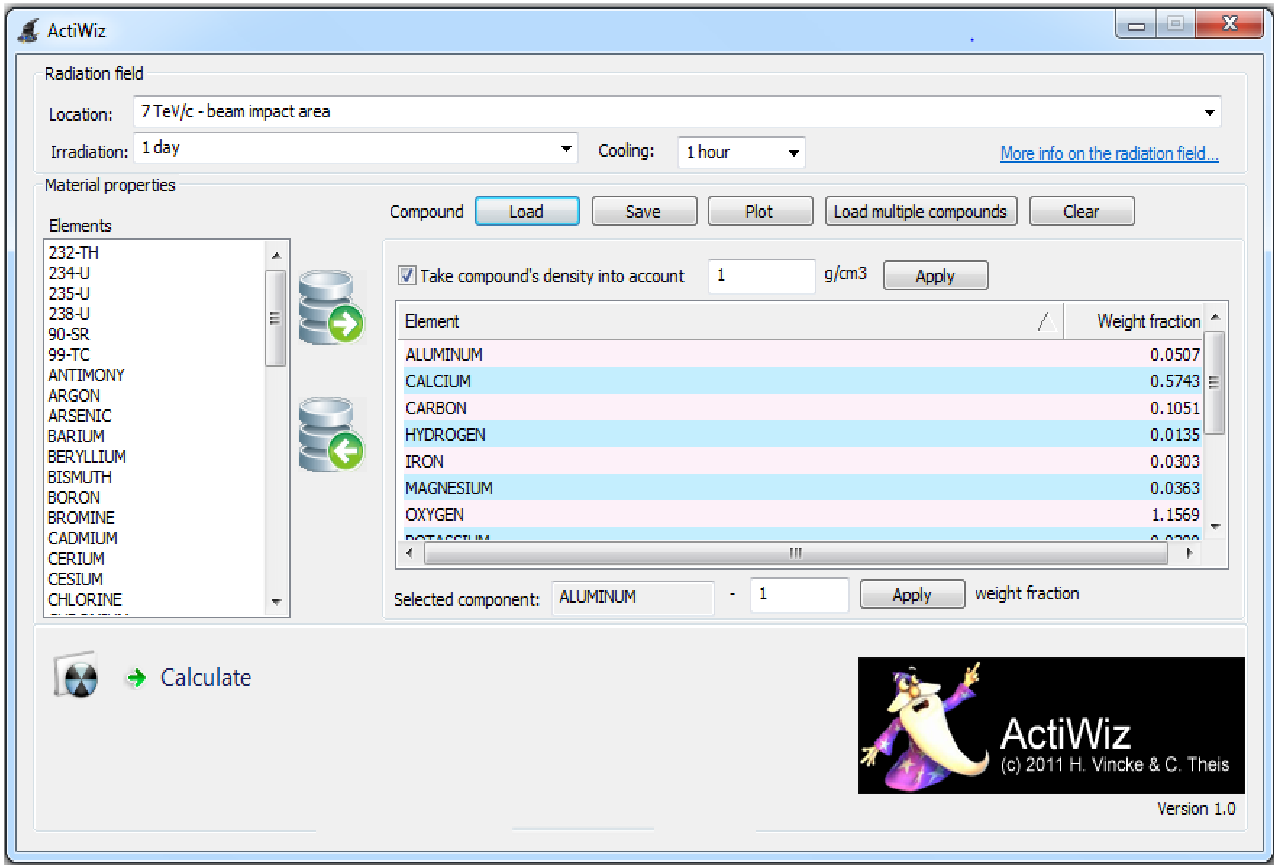
2400 single Monte Carlo simulations
→ 157.000 nuclide inventories (10 GB of data)

↓

Used as base for the ActiWiz program

ActiWiz – program interface

Evaluate radiological hazard for arbitrary materials with a few mouse clicks



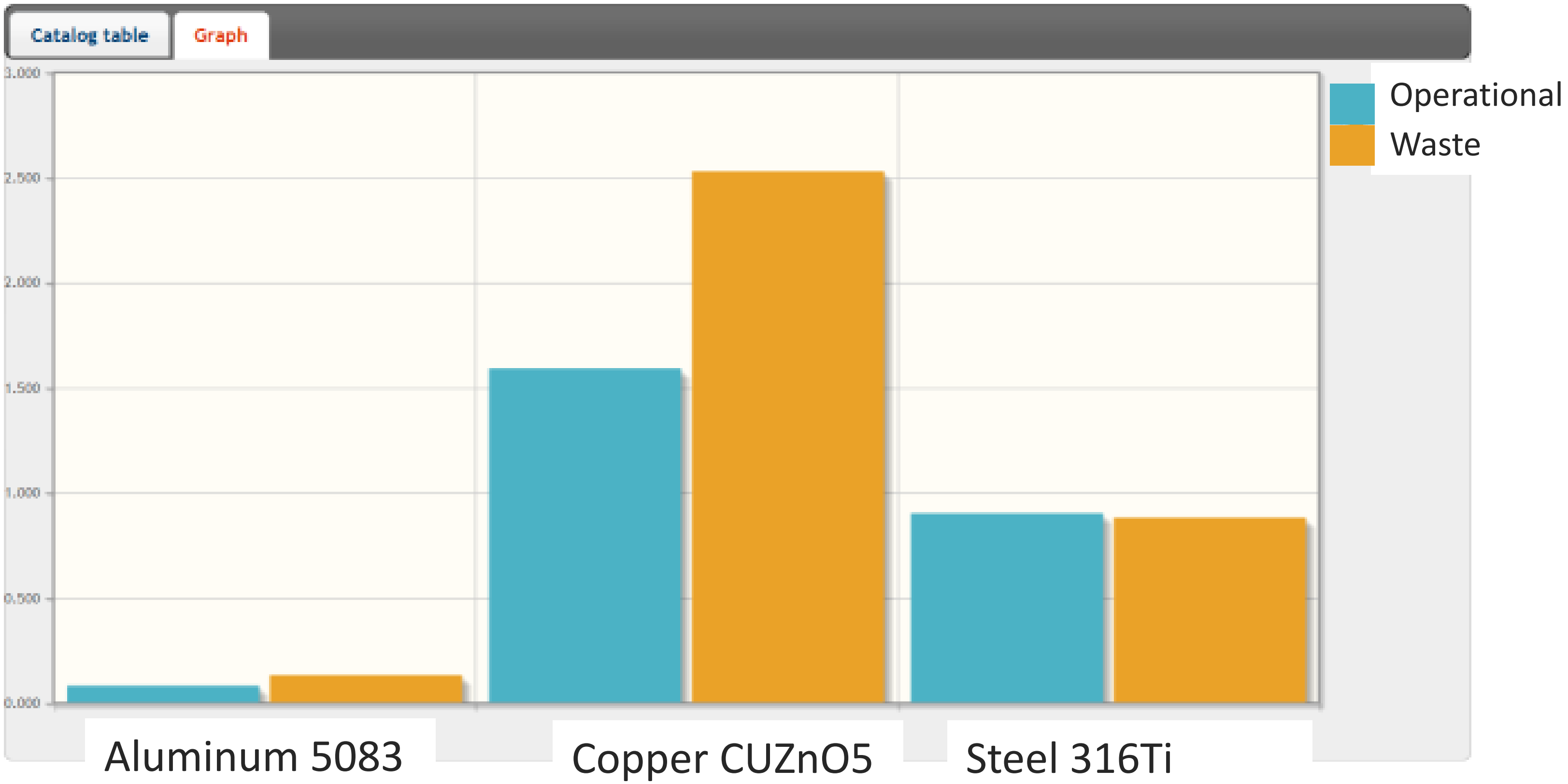
1.) Select energy / location / irradiation times

2.) Define material composition based on 69 chemical elements

* Many thanks to **R. Froeschl** for providing activation data on Zinc

Main output of ActiWiz: Material categorization

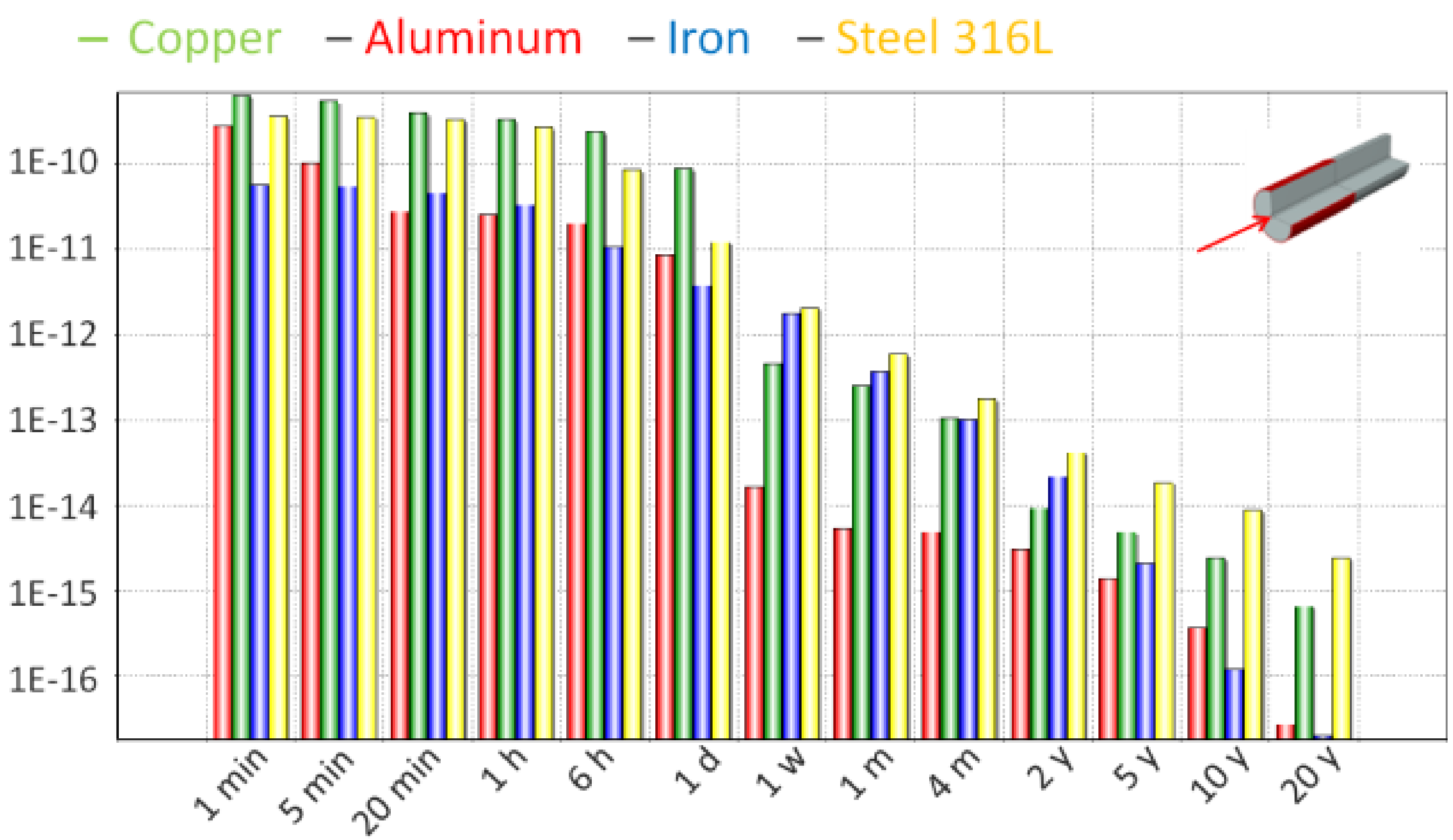
Radiological hazard assessment of material allowing for radiological comparison of materials



Secondary output of ActiWiz: RP quantities Example

For a given irradiation scenario we obtain:

- Information about ambient dose equivalent rate for various materials as a function of cooling time



Some relevant units for radiation protection and radiation physics

Quantities discussed

- Flux
- Fluence
- Fluence rate or Flux density
- Differential fluence
- Current
- Kerma
- Absorbed dose
- Equivalent dose
- Effective dose
- Ambient dose equivalent
- Cross section
- Surface density
- Activity
- Particle momentum versus particle energy

The description of these quantities are taken from the relevant ICRU and ICRP reports

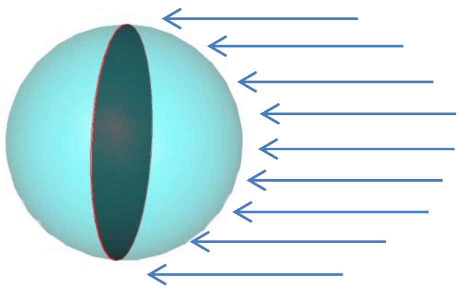
FLUX (g: Flußl)

$$\dot{N} = \frac{\mathrm{d}N}{\mathrm{d}t}$$

N … number of particles
t … time

No surface through which particles traverse is considered

Fluence (Flußdichte)



$$\phi = \frac{\mathrm{d}N}{\mathrm{d}\alpha}$$

N .... Number of particles incident on a sphere of cross-sectional area $d\alpha$

α ... Cross section of an infinitesimal sphere surrounding point of interest

$$\phi = \frac{\mathrm{d}l}{\mathrm{d}V}$$

l ... track length of particles traversing the infinitesimal sphere of volume *dV*

More general for macroscopic bodies: average fluence in a given body

$$\phi = \frac{\sum l}{V} \longrightarrow \text{For a sphere:} \quad \phi = \frac{N}{\alpha} = \frac{N}{r^2\pi} = \frac{N}{\frac{4}{3}r^3\pi} \cdot \frac{4}{3}r = \frac{N}{V}\bar{l} = \frac{\sum l}{V}$$

$\bar{l}$ ... average cord length of a sphere

Fluence is a quantity that is proportional to effects such as induced activity, dose, radiation damage. The longer the integrated track length of particles through matter the higher the number of interactions inside the body

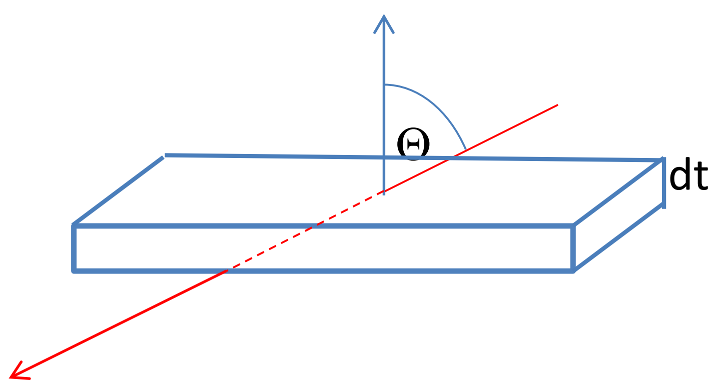
Average fluence on a surface

- For a given surface with a infinitesimal thickness of dt the following can be concluded:

$$\mathrm{d}l = \frac{\mathrm{d}t}{\cos(\Theta)} \Rightarrow \phi = \frac{\sum \mathrm{d}l}{\mathrm{d}V} = \frac{\sum \mathrm{d}t}{\cos(\Theta)\cdot A\cdot dt} = \frac{N\mathrm{d}t}{\cos(\Theta)\cdot A\cdot dt} = \boxed{\frac{N}{A}}\frac{1}{\cos(\Theta)}$$

Considering a constant Θ

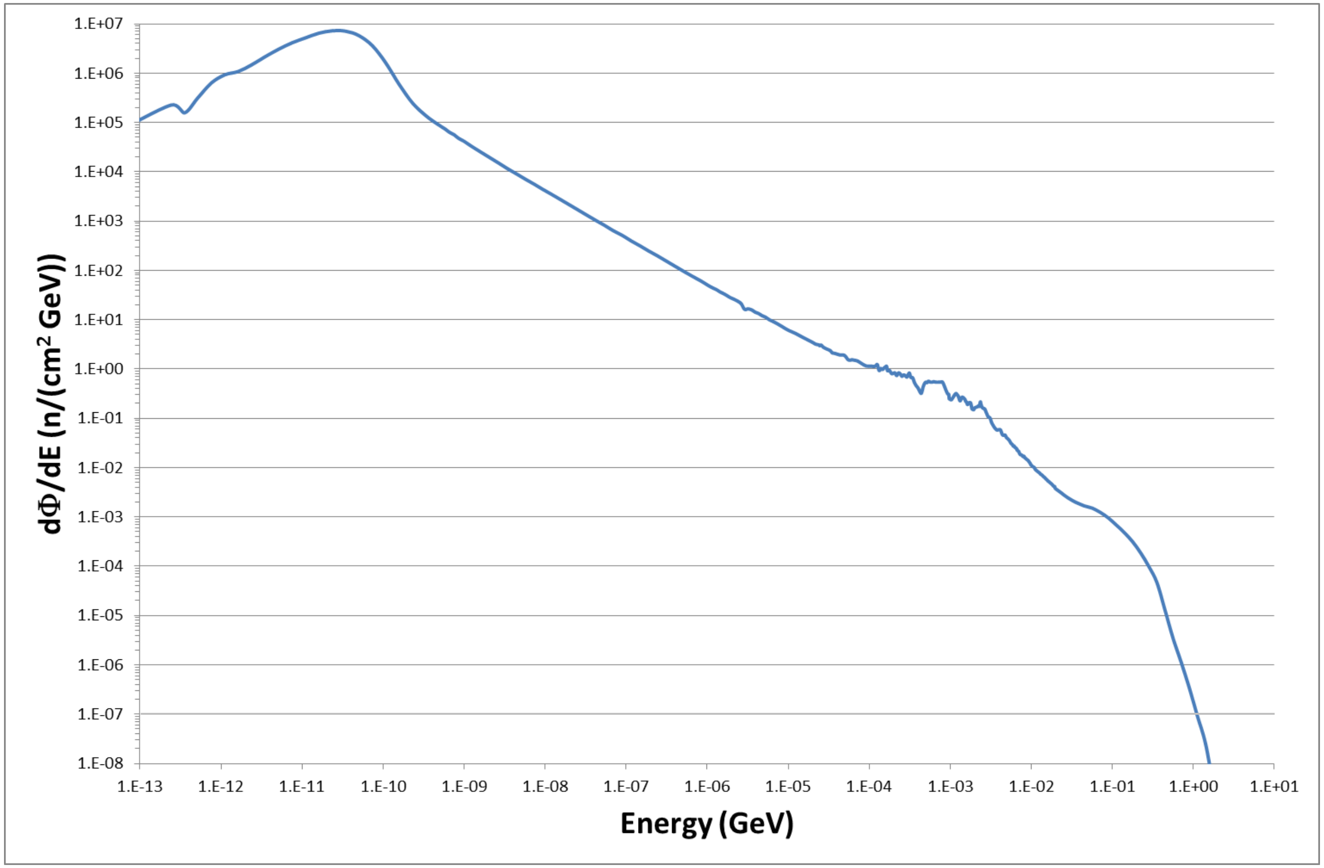
Quantity called current



Differential fluence

$$\phi_E = \frac{\mathrm{d}\phi}{\mathrm{d}E}$$

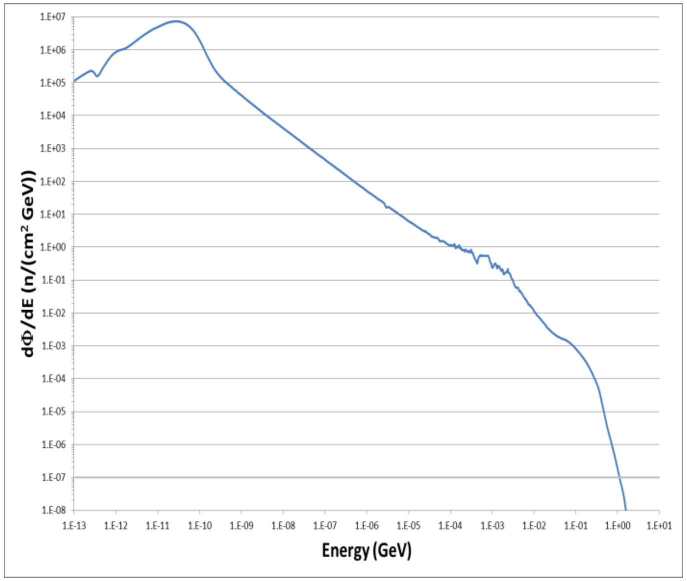
Fluence per energy occurring in the energy interval [E, E+dE]



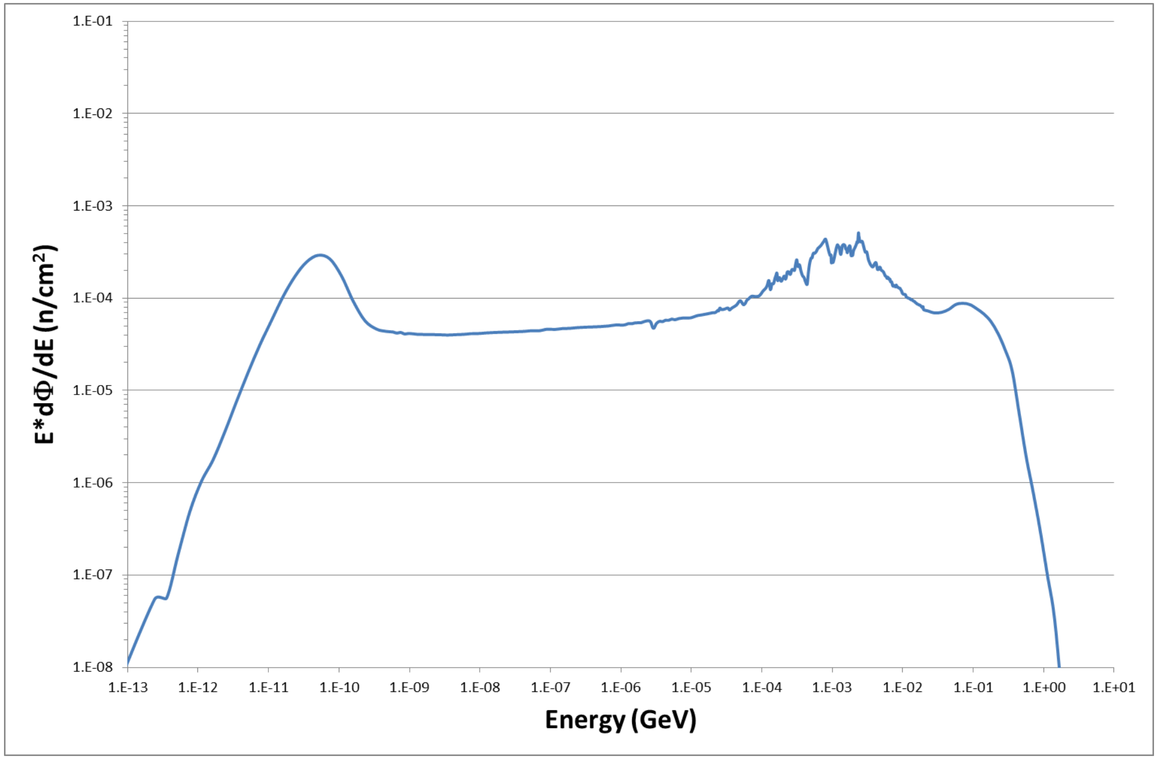
Different ways to display differential fluence

$$\phi_E = \frac{\mathrm{d}\phi}{\mathrm{d}(ln\frac{E}{E_0})} = E \cdot \frac{\mathrm{d}\phi}{\mathrm{d}E}$$

$$\phi_E = \frac{\mathrm{d}\phi}{\mathrm{d}E}$$



Lethargy plots



Reflects better the real amount of particles around a given energy

Derivation

From $\phi_E \dfrac{\mathrm{d}\phi}{\mathrm{d}(ln\frac{E}{E_0})}$ to $E \cdot \dfrac{\mathrm{d}\phi}{\mathrm{d}E}$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}(\ln\frac{E}{E_0})} = \frac{\mathrm{d}\Phi}{\mathrm{d}\,E} \cdot \frac{E_0}{E_0} \frac{\mathrm{d}E}{\mathrm{d}(\ln\frac{E}{E_0})} = \frac{\mathrm{d}\Phi}{\mathrm{d}\,E} \cdot E_0 \frac{\mathrm{d}\frac{E}{E_0}}{\mathrm{d}(\ln\frac{E}{E_0})} = \frac{\mathrm{d}\Phi}{\mathrm{d}E} \cdot E_0 \cdot \frac{\mathrm{d}(e^{\ln\frac{E}{E_0}})}{\mathrm{d}(\ln\frac{E}{E_0})} = \frac{\mathrm{d}\Phi}{\mathrm{d}E} \cdot E_0 \cdot \frac{E}{E_0} = \frac{\mathrm{d}\Phi}{\mathrm{d}E} \cdot E$$

Current

- Particles (N) crossing a given surface (A)
- No weighting with cos(Θ)
- Pure counting of particles through a surface

$$C = \frac{N}{A}$$

Fluence rate or Flux density

$$\dot{\Phi} = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\partial N}{\partial \alpha \partial t}$$

Φ … Fluence
N … number of particles
t … time

Kerma (K)

is the abbreviation of ***k***inetic ***e***nergy ***r***eleased in ***ma***tter. It reflects the sum of the initial kinetic energies dE_{tr} of charged particles that are liberated by uncharged particles in a sample of matter, divided by the mass dm.

$$K = \frac{\mathrm{d}E_{tr}}{\mathrm{d}m}$$

Unit: J/kg = Gray (Gy)

Kerma must not be mixed up with Absorbed dose, having the same unit (Gy).

Absorbed dose

refers to the energy deposited (not released) in matter.

It reflects the sum of the energies dE_{dep} deposited by incident particles in a sample of matter, divided by the mass dm of the sample.

$$D = \frac{\mathrm{d}E_{dep}}{\mathrm{d}m}$$

Unit: J/kg = Gray (Gy)

Equivalent dose in an organ or tissue, H_T

is a measure of the absorbed dose $D_{T,R}$ to tissue T by radiation of type R. It is defined by

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

Unit: Sievert (Sv)

with w_R being the radiation weighting factor which reflects the different radiobiological effectiveness for various radiation types and energies.

The radiation weighting factor (especially for neutrons) has been revised over time and remains controversial

ICRP publication 103

Radiation	Energy	W_R (formerly Q)
x-rays, gamma rays, beta rays, muons		1
neutrons	< 1 MeV	$2.5 + 18.2 \cdot e^{-[\ln(E)]^2/6}$
	1 MeV - 50 MeV	$5.0 + 17.0 \cdot e^{-[\ln(2 \cdot E)]^2/6}$
	> 50 MeV	$2.5 + 3.25 \cdot e^{-[\ln(0.04 \cdot E)]^2/6}$
protons, charged pions		2
alpha rays, Nuclear fission products, heavy nuclei		20

Effective dose, E

equals the sum of various equivalent doses of different organs or tissues, weighted with the respective tissue weighting factor w_T. It is defined by

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

Unit: Sievert (Sv)

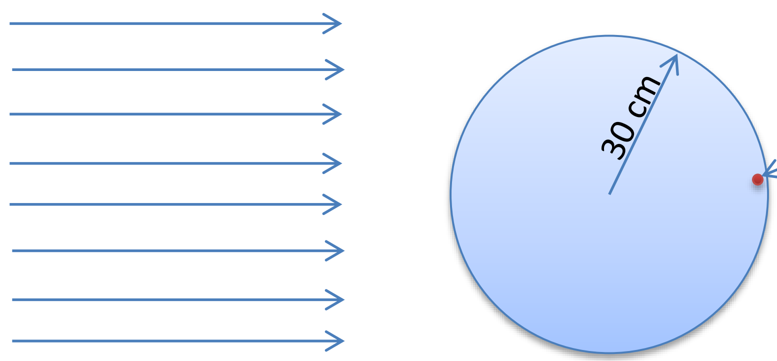
with $\sum_T w_T = 1$.

Different organs show different sensitivity to equivalent dose deposited

Organ	Tissue weigthing factor	Organ	Tissue weigthing factor
Gonads	0.08	Oesophagus	0.04
Red Bone Marrow	0.12	Thyroid	0.04
Colon	0.12	Skin	0.01
Lung	0.12	Bone surface	0.01
Stomach	0.12	Salivary glands	0.01
Breasts	0.12	Brain	0.01
Bladder	0.04	Remainder of body	0.12
Liver	0.04		

Ambient-dose-equivalent, H*(10)

denotes the operational dose quantity used for area monitoring of penetrating radiation. Such a quantity is required since the effective dose is not directly measurable (different weighting factors for organs and particles). The H*(10) quantity is measured via the ICRU sphere:



Dose equivalent in this point (10 mm inside the sphere)

Unit: Sievert (Sv)

ICRU sphere: A sphere of 30 cm diameter made of tissue equivalent material with a density of 1 g/cm^3 and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen

Ambient dose equivalent is a conservative measure for effective dose.

Cross section

- The cross section (σ) of a target entity, for a particular interaction produced by incident particles is defined as:

$$\sigma = \frac{P}{\phi}$$

Using the definition of the fluence applying the track length allows to use each target shape and size

P … probability of interaction occurring in a given volume

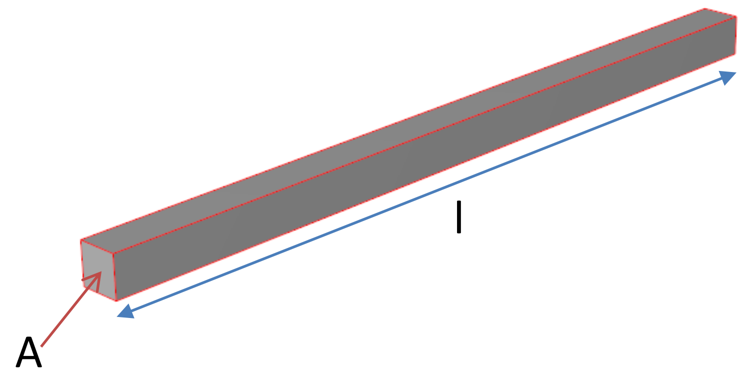
Φ fluence through the given volume

Unit of the cross section is m^2. A special unit for the cross section used is barn, which is defined by:

1 barn= 10^{-28} m^2= 10^{-24} cm^2

Surface density (Flaechendichte)

Mass per unit area:
Explanation: Mass along a straight line starting at a given surface normalized to the size of the surface



$$\rho_A = \frac{m}{A} = \int \rho \cdot dl = \rho \cdot l$$

If ρ = const.

ρ_A ... surface density
ρ ... density

Unit: kg/m^2

Activity

- Decays of a radioactive material per time unit

$$A = \frac{\mathrm{d}N}{\mathrm{d}t}$$

Unit: Bq: ➔ 1 Bq = 1 decay per second

Particle momentum versus particle energy

$$E^2 = m^2 c^4 = \frac{m_0^2 c^4}{1 - v^2 / c^2} \Rightarrow$$

$$E^2 = m_0{}^2 c^2 + p^2 c^2$$

E …	total energy
p …	momentum
m…	mass of particle
m_0…	mass of particle at rest
v…	velocity of particle
c…	speed of light in vacuum

In natural units where $c = 1$, the energy-momentum equation reduces to

$$E^2 = m_0{}^2 + p^2$$

E in GeV m in GeV p in GeV/c

Don't forget considering mass: $E_{kin} = E$ – *Energy equivalent of particle*